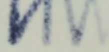

MARS, THE RED PLANET

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MARS,

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ISAAC ASIMOV

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THE RED PLANET

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1

THE MOTION OF MARS

Blood and Iron

The people of ancient times noticed that the stars in the sky seemed to turn about the Earth all in one piece, as though they were pinned, or fixed, to the turning sky. They are the "fixed stars."

There are seven objects in the sky, however, that do not move with the stars. They change positions with respect to the stars, night after night, and follow paths of their own. Two of these are the Sun and the Moon. The other five are dots of light like the stars, but brighter.

These seven objects were called "planets" from a Greek word meaning "wandering," because they wandered on paths of their own. The five starlike planets were given the names of gods by the ancient peoples, according to a scheme which seemed to them to be logical.

For instance, four of the starlike planets shine with a white or yellow-white light, but the fifth is distinctly reddish in color. The name of that fifth should have something to do with its special color.

Red is naturally associated with blood, with wounds, danger, war, and death. The red planet would get a name implying all these evil things.

The ancient Sumerians, who ruled the region now known as Iraq more than four thousand years ago, were the first to study the planets. They noted the red one and named it Nergal (NEHR-gahl), which was the name of their god of war, destruction, and death. Ever since then, the red planet has been named for one war-god or another.

Sumerian learning was passed to the later people who occupied the land and from there to the Greeks, who borrowed the old Sumerian system of naming the planets. The Greeks named the red planet Ares (AY-reez) after their god of war. The Romans, who picked up astronomy from the Greeks, changed the name to Mars, who was their god of war. That is the name we keep to this day. The red planet is Mars.

Naturally, with Mars the color associated with blood and bearing the name of the war-god, it was considered a planet that cast a destructive influence over the Earth. It was felt that whenever Mars was high in the sky and particularly bright, there would be war on Earth. This is nonsense, of course, but over the centuries Mars has been considered a planet of ill omen.

The other four starlike planets also carry Roman names, which were taken from the Greeks. The other four planets are Mercury, Venus, Jupiter, and Saturn. Since ancient times, three more planets have been discovered which are too faint to have been seen when there were no telescopes. These newly discovered planets also were named for ancient gods in order to keep the old fashion. They were Uranus, Neptune, and Pluto.

Each planet was given a symbol in ancient times so that astronomers could refer to them without having to take the trouble to write out the full name. In each case, the symbol was chosen so as to have something to do with the god for whom the planet was named. For Mars, for instance, the symbol is ♂ because that represents a shield and a spear, which you would expect an ancient war-god to be carrying.

As another example, consider the planet Venus. It is the brightest and the most beautiful of the planets in the sky, so naturally it was named after the goddess of love and beauty. Its symbol is ♀, which represents a mirror, the kind of object you would expect a goddess of beauty never to be without.

In the ancient myths, Mars and Venus were described as being in love with each other. Since the goddess of love would be a perfect female and a war-god would be a perfect male, ♂ and ♀ are nowadays used to symbolize "male" and "female."

The ancients knew seven different metals: gold, silver, copper, iron, tin, lead, and mercury. They got the idea that these metals were associated with the planets since there were seven of each. For instance, gold and the Sun seemed to go together; so did silver and the Moon. For Mars, it seemed that iron was the natural association, since it was with iron weapons that men waged war.

To this day, certain chemical substances which contain iron atoms have names that refer to Mars. There are colored pigments, for instance, which are called "Mars yellow" or "Mars violet" because they contain iron atoms.

Because of the seven planets, the Sumerians and those who followed them divided the year into weeks, each week being made up of seven days, and each day being associated with a planet. The first and second days were associated with the Sun and the Moon, and we still speak of "Sunday" and "Monday" as the first two days of the week.

The other five days were associated with the five starlike planets, and it was the third day of the week that was associated with the war-god planet, Mars. The Romans called it *dies Marti*, or "Mars's day."

That name hasn't changed much in the languages which are derived from the Latin language which the Romans spoke. The third day of the week is *mardi* to the French, *martedi* to the Italians, and *martis* to the Spaniards.

Some of the ancient Germanic peoples used the name of their war-god, Tiw or Tiu, for the purpose. In English, therefore, the third day of the week is Tuesday.

The Backward Motion

Once the ancients had noticed that the planets existed and that they moved in particular paths across the starry sky, they grew very much interested in studying just how they moved. It seemed to them that the pattern of the planets among the stars must control events on Earth. After all, the motion of the Sun among the stars controlled the seasons. When the Sun was in one part of the sky it was winter, and when it was in another part it was summer. Why shouldn't the changing positions of the other planets also have an effect?

Astronomers thought that if they could work out the details of the motions of all the planets, so that they could predict what the positions of each would be at any particular time in the future, they could foretell events on Earth. We call this sort of thing "astrology" from Greek words meaning "science of the stars."

Nowadays, astronomers are quite certain that astrology is nonsense, even though many millions of people who know no better still take it seriously. In ancient times, however, astrology seemed to make sense and we can't blame people for believing in it then. In fact, because astronomers believed in astrology and studied the sky carefully in an attempt to learn how to foretell the future, many important scientific discoveries were made.

One thing the ancient astronomers noticed was that each planet moved at a different speed against the background of the fixed stars. It seemed reasonable to suppose that the more rapidly a planet seemed to move, the closer it must be to us. (You may notice for yourself that an airplane that is fairly low in the sky seems to be moving much more rapidly than one that is so high in the sky it seems little more than a dot.)

The ancients therefore decided that since the Moon moved most rapidly against the stars, it was the nearest planet. Beyond it was Mercury, then Venus, then the Sun, then Mars, then Jupiter, and then Saturn. All of them seemed to be moving in large circles around the Earth, and the ancient astronomers thought that was what they were really doing.

The Sun and the Moon had the simplest motions. Each one drifted from west to east against the stars, steadily, day after day. The Sun made a complete circle around the sky in about fifty-two weeks; that period is called a year. The Moon made a complete circle in about four weeks; that period is called a month.

The other planets had more complicated motions. Most of the time, each one would move from west to east across the starry sky as the Sun and Moon did. In each case, though, there would come a time when the planet would move more and more slowly. Eventually it would come to a complete halt for a moment and then start moving backward, from east to west, for a time. Then it would stop and begin to move forward again.

This backward motion is called "retrograde motion" from Latin words meaning "backward steps."

Venus and Mercury, in their motion across the sky, never move very far from the Sun. They can be observed only in the evening or at dawn, and their motions are therefore not so easy to study as those of the other three starlike planets.

Mars, Jupiter, and Saturn can be seen at any distance from the Sun and can often be observed in the midnight sky. Saturn goes into retrograde motion twenty-eight times as it makes its very slow way completely around the sky. Since it takes twenty-nine and a half years for Saturn to move around the sky, the retrograde periods come a little over a year apart.

Jupiter, which takes nearly twelve years to make a circuit of the sky, has eleven retrograde periods. These also come a little over a year apart. Mars takes nearly two years to make a circuit and it has just one retrograde period.

Mars is the most unusual of the three for two reasons. First, Mars makes a longer backward sweep during its retrograde period than either Jupiter or Saturn does. Second, while Jupiter and Saturn change only slightly in brightness in the course of the year, Mars changes quite a bit. Mars is always particularly bright when it is in its retrograde period. Although there are times when Mars is dimmer than Jupiter or Saturn, there are occasions during retrograde motion when it is the brightest planet of the three.

Nowadays, we measure the brightness of objects in the sky in "magnitudes." A dim star, just barely visible to the eye, has a magnitude of 6. A star two and a half times brighter than that has a magnitude of 5, and one that is two and a half times brighter still, a magnitude of 4, and so on. Bright stars have a magnitude of 1 and are "first-magnitude stars."

A few very bright stars are too bright for magnitude 1. They have a magnitude of 0, or even –1. All the planets are so bright that they are in the negative magnitudes of brightness.

Astronomers can now measure brightness so accurately that they can assign magnitudes in decimals. An object can have a magnitude of 1.3 or 5.6 or –1.8.

In Table 1 the magnitudes of Mars, Jupiter, and Saturn are given, both for maximum brightness and minimum brightness. As you see, Jupiter's brightness changes by only four fifths of a magnitude, at most, as it shifts position in the sky, and Saturn's changes by only two fifths of a magnitude. Jupiter is twice as bright at some times as at others, and Saturn is one and a half times as bright at some times as at others. (Both are at their brightest during retrograde motion.)

Mars, on the other hand, changes by a total of 4.2 magnitudes as it makes its circle of the sky. At its brightest, Mars is 15 times brighter than at its dimmest. The ancient astronomers didn't have instruments with which to measure brightness, so changes in the brightness of Jupiter and Saturn weren't at all obvious. There was no mistake in the case of Mars, though. It changed.

The retrograde motions of various planets, together with other changes such as in the brightness of Mars, bothered the astronomers of ancient Greece. They felt the heavens ought to be more orderly than that. They felt, for instance, that the planets ought to move in perfectly regular speeds in perfect

TABLE 1

Planetary Magnitudes

PLANET	MAGNITUDE AT MAXIMUM BRIGHTNESS	MAGNITUDE AT MINIMUM BRIGHTNESS
Mars	**—2.8**	**+1.4**
Jupiter	—2.5	—1.7
Saturn	—0.4	0.0

circles (and to this day we call the path of one heavenly object about another an "orbit" from the Latin word for "circle").

In order to account for the observed facts that the planets (even the Sun and the Moon) moved at changing speeds and sometimes in complicated paths, the Greeks worked up intricate schemes. The planets were pictured as moving about the Earth in complicated combinations of circles.

The schemes grew more and more complex as the centuries passed and it was all put into final form by a Greek astronomer named Ptolemy (TOL-uh-mee) who lived in Egypt about A.D. 150. Such a system, in which all the planets are viewed as moving about the Earth, is called "geocentric" (jee-oh-SEN-trik) from Greek words meaning "earth-centered."

The Sun at the Center

Even in ancient times, there were astronomers who felt that part of the complications in planetary motions arose because of the assumption that the Earth was at the center. They tried to argue that all the bodies, including even the Earth, moved about the Sun.

It seemed so unlikely that the Earth moved through space, however, that for fourteen centuries after Ptolemy, his geocentric theory was accepted.

Then a Polish astronomer, Nicolas Copernicus (koh-PER-nih-kus, 1473–1543), wrote a book on the matter, one which was finally published in 1543 just as he was dying. In this book, he described in detail a "heliocentric system" (HEE-lee-oh-SEN-trik), from Greek words meaning "sun-centered."

According to Copernicus, the Moon revolves about the Earth as had always been supposed. The other planets, however, and the Earth, too, revolve about the Sun.

Nowadays we apply the word "planet" only to bodies that revolve about the Sun (or about other bodies like the Sun); the Sun itself is not a planet. The Moon revolves about the Earth, so it isn't a planet either. It is called a "satellite" and so is any other body that revolves about a planet. Mercury, Venus, Mars, Jupiter, and Saturn are still called planets. So are the planets discovered in modern times: Uranus, Neptune, and Pluto. And since Earth revolves about the Sun, it is a planet also.

In Copernicus's system, the planet closest to the Sun is Mercury. Next come Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto in that order.

The heliocentric system at once increased the importance of Mars. In the old way of looking at the planets, Mars was thought to be quite far away, with Mercury, Venus, and the Sun all closer to us than Mars was (to say nothing of the Moon). In the new way, the Moon was still closer to Earth than was any other body, but beyond that Mars was one of the two planetary neighbors of Earth. The other was Venus.

The heliocentric system explains retrograde motion without any trouble. Suppose we consider Earth and Mars, each one racing around the Sun. Earth is closer to the Sun so it makes a smaller circle and completes one lap in 365.25 days, or 1 year. Mars is farther from the Sun so it revolves in a larger circle, completing one lap in 687 days, or 1.88 years.

Imagine Earth and Mars starting even in their race around the Sun. Earth completes its turn and is back at the starting point at a time when Mars is only a little over halfway around its orbit. After a while Earth catches up to Mars and passes it. This happens every 780 days, or 2.14 years.

When Earth is catching up to Mars and is passing it, it seems to observers on Earth that Mars is moving backward. We see that sort of thing when two trains are moving in the same direction and one is moving faster so that it catches up to and passes the other. To someone sitting in the faster train, it looks as though the slower train is moving backward.

The heliocentric system also explains why Mars changes its brightness and is brightest when it is moving retrograde.

Again suppose Earth and Mars start side by side. As Earth races ahead, it moves farther and farther away from Mars. After a little over a year has passed, the two planets are on opposite sides of the Sun, and very far apart. To people watching from Earth, Mars would seem to grow dimmer and dimmer.

But then Earth starts gaining on Mars again, and Mars begins to grow brighter. When Earth overtakes Mars and passes by it, both are on the same side of the Sun and are quite close. That is when Mars is brightest. But when Earth is overtaking it, Mars also seems to be moving backward, so that is why Mars is brightest when it is in retrograde movement.

When Mars is on the other side of the Sun from Earth, we can't really see it because the Sun is in the way. Mars moves behind it or skims closely above or below it. Mars and the Sun seem to come together in the sky, so Mars is then said to be in "conjunction," from Latin words meaning "join together."

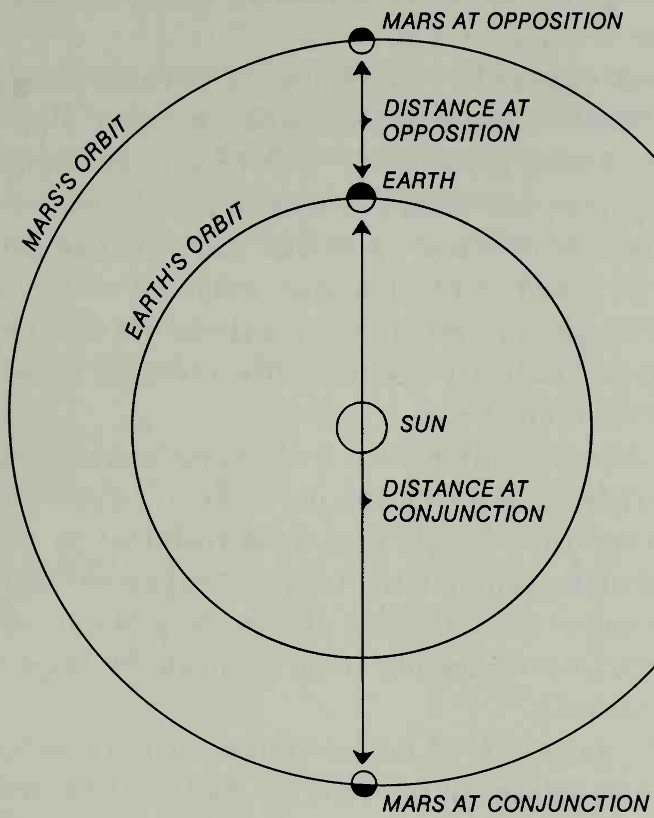
When Mars is on the same side of the Sun as Earth is, then Earth is between Mars and the Sun. That means that if people on Earth see the Sun in one part of the sky, Mars is in exactly the opposite side of the sky. At that time, therefore, Mars is said to be in "opposition."

Mars is farthest away from us when it is in conjunction. Even if the Sun did not interfere with seeing it, Mars would then be at its dimmest. Mars is closest to us when it is in opposition. It is brightest then and it is easiest to see. Mars is about five times as far from Earth at conjunction as it is at opposition (see Figure 1). No wonder it shows such changes in brightness.

The retrograde motions of Jupiter and Saturn can be explained in the same way as that of Mars. Because Jupiter and Saturn are much farther away from Earth than Mars is, they make huge circles about the Sun. The Earth's orbit is so small in comparison that it doesn't make much difference whether Earth is on the same side of the Sun as Jupiter and Saturn or on opposite sides. When Jupiter is in conjunction it is only 1.5 times as far away from Earth as when it is in opposition. When Saturn is in conjunction, it is only 1.25 times as far away. That is why Jupiter and Saturn do not change in brightness as much as Mars does.

Despite all the things the heliocentric system explained (and I have mentioned only a few), it took a long time for astron-

Fig. 1—Opposition and Conjunction



omers to accept it. For one thing, even with the Sun at the center it was still hard to explain the motions of the planets. Those motions were still uneven in that the planets did not seem to move around the Sun in perfect circles, anymore than they had seemed to in moving around the Earth.

It might be possible, though, to work out just how the planets were moving if their changing positions in the sky could be determined accurately enough.

In ancient times, and even in Copernicus's time, there were very few instruments that could help astronomers measure the exact distance between a planet and a nearby star. Therefore the exact location of a planet among the stars could be estimated only roughly. That made it difficult to decide what the precise motion of a planet was.

A Danish astronomer, Tycho Brahe (TIGH-koh BRAH-uh, 1546–1601), tried to correct this situation in 1580. With the financial help of King Frederick II of Denmark, he completed an observatory that was equipped with the best instruments any astronomer had ever had up to that time. He had devices along which he could sight at a star and then at a planet, marking the change in direction along a circle. He could make measurements of planetary positions five times as closely as Ptolemy had ever been able to.

Tycho (he is commonly known by his first name) concentrated particularly on Mars. Of the planets that could shine at all distances from the Sun and that could therefore be studied at any time of night, it moved the fastest. That meant you had to wait less time to get a definite change in position so that more and better measurements could be made of Mars than of the other planets.

Tycho made thousands of measurements of the position of Mars at different times. By the time he died, though, he had not yet had time to analyze those positions to see just how Mars moved.

Ellipses

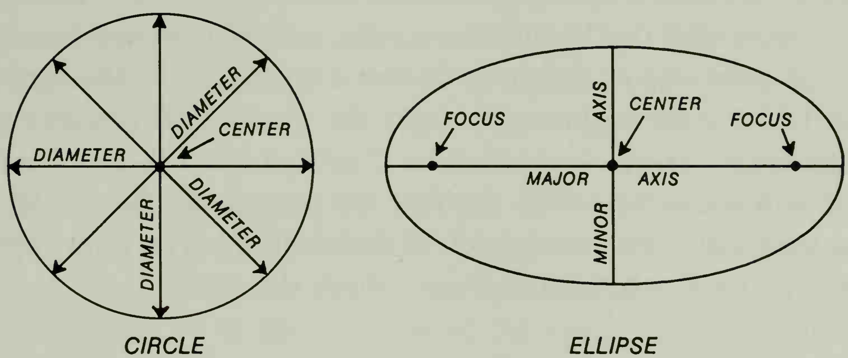
In the last years of his life, Tycho moved to Germany and there he hired a young assistant named Johann Kepler (1571–1630). He set Kepler to work analyzing the measurements of Mars's positions and Kepler continued to work on them after Tycho died.

Kepler's careful analysis showed that Mars's movement across the sky could not be made to fit a circle around the Sun. He wondered, then, if there might not be some other curve, one that was not a circle, that would fit Mars's movement.

Kepler tried several and met with success when he tried an ellipse.

An ellipse looks like a flattened circle that is exactly alike on both ends. In a circle, any line passing through the center is a diameter and all the diameters of a particular circle are equal in length. In an ellipse, the diameters are of different lengths (see Figure 2). The diameter that is the longest runs from one

Fig. 2—Circle and Ellipse



narrow end to the other and is called the "major axis." The diameter that is the shortest is the "minor axis." The two axes cross at right angles (that is, if one goes horizontally, the other goes vertically). Where the two axes cross is the center of the ellipse.

On the major axis of the ellipse are located two points called "foci" (FOH-sigh). Each one of them is a "focus" (FOH-kus). The foci are on opposite sides of the center and at equal distances from it. The foci are located in such a way that if a straight line is drawn from one focus to any point on the ellipse, and from that point to the other focus, the sum of the lengths of the two straight lines is always equal. The sum is always equal to the length of the major axis, too.

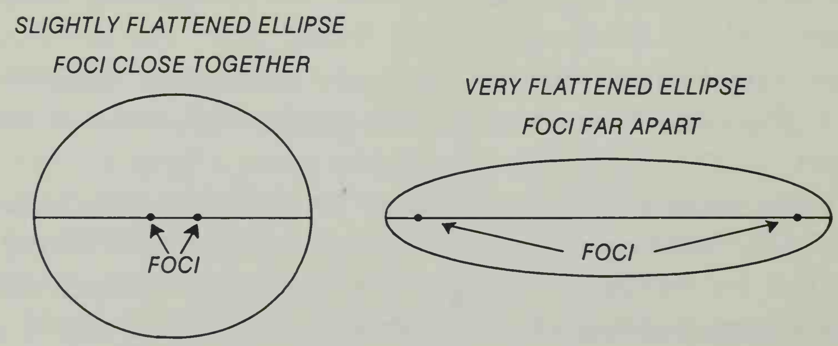
Kepler announced, in a book he published in 1609, that Mars moved around the Sun in an elliptical orbit. What's more, the Sun was not at the center of the ellipse, but to one side of the center. It was, in fact, located at one of the foci of the ellipse.

Kepler showed that this was true of all the planets, including Earth. Each one had an elliptical orbit with the Sun at one of the foci. As for the Moon, its orbit about the Earth was also elliptical, with the Earth at one of the foci.

Ellipses can be of different shapes, depending on how flattened they are. The more flattened an ellipse is, the narrower the ends, and the longer the major axis is compared to the minor axis. Again, the more flattened an ellipse is, the farther the foci are from the center and the closer to the ends (see Figure 3).

The amount by which the foci are away from the center is the measure of the "eccentricity" of the ellipse. The term comes from Greek words meaning "away from the center."

Fig. 3—Different Ellipses



If the foci are only 1/100 of the way from the center to the ends, the eccentricity is 0.01. With such a small eccentricity, you can't notice the flattening and the ellipse looks so much like a circle you can't tell the difference without making careful measurements. (For a circle, the foci are exactly at the center and the eccentricity is 0.)

If the foci are halfway from the center to the ends, the eccentricity is 0.5 and the ellipse looks like an egg that has the same curve on both sides. If the foci are nine tenths of the way from the center to the end, the eccentricity is 0.9, and the ellipse looks rather like a cigar.

Each planet moves in an elliptical orbit with a certain eccentricity which can be measured from the motions of the planet in the sky. Table 2 gives the eccentricity of these orbits.

Please notice that only a few of the planets are included in this table. In this book, we are going to deal only with the planets whose orbits are fairly near the Sun: Mercury, Venus, Earth, and Mars.* These four planets are very like each other in many ways, and quite unlike the planets that are farther from the Sun. Mercury, Venus, Earth, and Mars are therefore often referred to as the "terrestrial planets"—that is, "Earth-like." Although the Moon is not a planet, it is similar to the terrestrial planets in many ways, and I will therefore deal with the five "terrestrial worlds," including the Moon.

As you see, the eccentricity of Earth's orbit is quite low. If you were to draw a line from the Earth to the Sun, the center of the ellipse would be only 1/60 of the way from the Sun to the Earth along the major axis. If such an ellipse were drawn to scale, you couldn't tell it from a circle by eye.

* The planets beyond Mars, particularly Jupiter, have been dealt with in another of my books, *Jupiter, the Largest Planet* (Lothrop, Lee & Shepard, 1973 and 1975).

TABLE 2

Orbital Eccentricities

TERRESTRIAL WORLD	ORBITAL ECCENTRICITY	ORBITAL ECCENTRICITY (EARTH = 1)
Mercury	0.2056	12.3
Venus	0.0068	0.4
Earth	0.0167	1.0
Moon	0.055	3.3
Mars	**0.093**	**5.6**

The orbit of Venus is even less eccentric, only ⅖ as eccentric as that of Earth. (The last column in Table 2, which gives the eccentricities compared to Earth, shows the differences more clearly than if the eccentricities themselves are used as in the middle column.)

The orbit of Mercury, however, is considerably more eccentric than those of Earth and Venus. The ellipse in which Mercury moves is flattened enough to be visible to the eye. The Moon and Mars have eccentricities that are intermediate in amount.

The eccentricity of Mars's orbit, as we shall see, plays an important part in the way it can be viewed from Earth.

2

THE DISTANCE OF MARS

Parallax and the Moon

From his elliptical orbits and from his studies of planetary motions, Kepler was able to draw a model of all the planetary orbits known in his time. He could tell just how large each was with respect to the others. That meant he could tell the average distance from the Sun of each planet with respect to the others.

Suppose, for instance, we assume that the average distance of the Earth from the Sun is set as equal to 1. Then the Moon, which circles the Earth at a much smaller distance than either is from the Sun, also has an average distance from the Sun of 1. The figures for the other terrestrial worlds are given in Table 3. As you see, Mercury, the closest planet to the Sun, is at roughly two fifths the distance from the Sun that Earth is. Venus is about three fourths as far from the Sun, and Mars, the most distant of the terrestrial worlds, is one and a half times as far from the Sun as the Earth is.

Kepler's model of the planetary orbits explained the planetary motions so beautifully and simply that there could be no further doubt that all the planets really moved about the Sun. The system of planets therefore came to be called the "solar system" from the Latin word for "sun."

The model, however, was not sufficient, all by itself, to help astronomers work out the actual distances of the planets from

TABLE 3

Relative Distances from the Sun

TERRESTRIAL WORLD	AVERAGE DISTANCE FROM THE SUN (EARTH = 1)
Mercury	0.387
Venus	0.723
Earth	1.000
Moon	1.000
Mars	**1.524**

each other and from the Sun. It could tell us that Venus was three fourths as far from the Sun as Earth was, or that Mars was one and a half times as far from the Sun as Earth was, but what were all these distances in actual kilometers or in miles?

If the distance between any two planets of the solar system were known at any one time, you could work out the distance between those two planets at any other time, making use of Kepler's model. In fact, from that one determination and the model, you could work out the distances between all the other planets and between them and the Sun. But how do you get that first distance to start with?

In Kepler's time, the only way of judging the distance of a heavenly body was to make use of "parallax," from Greek words meaning "change of position."

You can see how this works if you hold a finger out in front of your eyes at arm's length. If you close one eye, you will see the finger against some object in the background. If you hold your finger steady and close the other eye, you will see a change in its apparent position against the background. The change in position is the parallax.

If you bring the finger closer to yourself you will see that the change in position, as you use first one eye and then the other, becomes greater. Parallax changes with distance, becoming greater as the distance becomes smaller, and smaller as the distance becomes greater. By measuring the parallax, you can determine the distance of your finger from your eye.

By using your eyes one at a time, you cannot measure very great distances; only those of several feet at most. For objects farther away than that, the parallax becomes too small to be measured accurately. Fortunately, the shift depends not only on distance but on the separation of the two points from which the object is viewed. Your eyes are separated by only a few inches and that isn't much of a "base line." You could use a larger one.

Suppose you planted two stakes six feet apart. If you viewed an object first from one stake, then from the other, you would increase the amount of the parallax for a given distance, and an object could then be much farther away before the parallax became too small to measure. Your base line might also be greater than six feet—even much greater.

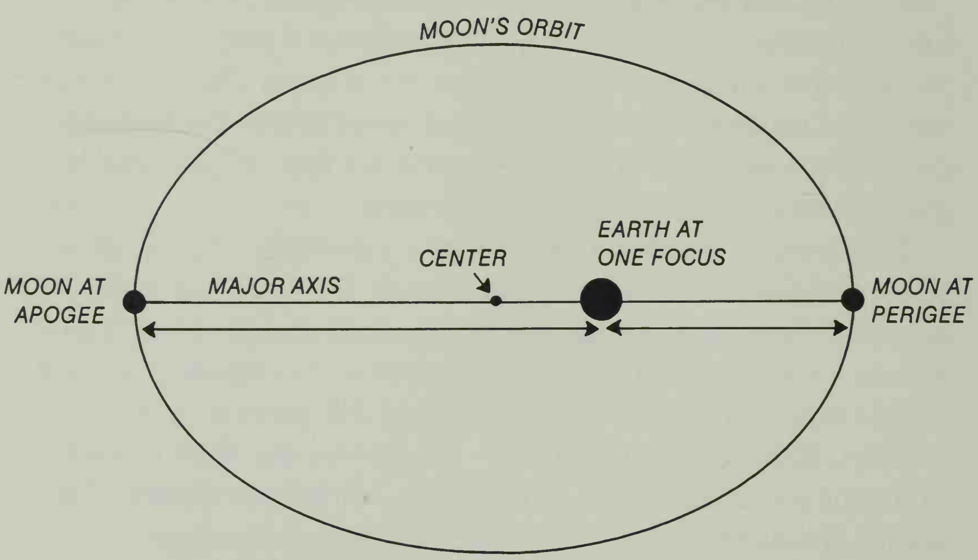
Suppose the Moon is observed at a particular time from a particular position on Earth's surface. At the same time, someone else observes it from another position hundreds of kilometers away. The first observer will see it at a certain distance from a nearby star; the second observer will see it at a slightly different distance from that same star. From the shift of position and from a knowledge of how far apart the two observation points are, the distance of the Moon can be calculated.

The Moon is so close to the Earth that the shift it makes against the stars is big enough to measure even without any fancy instruments; the distance of the Moon was, in fact, known for a long time. Even some of the ancient astronomers had a good idea of how far away from Earth the Moon was. The average distance of the Moon from the Earth is now known to be 384,400 kilometers (238,900 miles).

If the Moon's orbit about the Earth were a perfect circle, the Moon would always be at the same distance from the Earth. The Moon's orbit is an ellipse, however, and the Earth is at one of the foci of that ellipse. Since the focus of an ellipse is closer to one end of the major axis than to the other end, the Moon's distance from Earth changes as it moves in its orbit.

The Moon is nearest the Earth when it is at the end of the major axis of its orbital ellipse that is on the side of the focus at which the Earth is located (see Figure 4). That point is called

Fig. 4—Perigee and Apogee



Note: This diagram is exaggerated to make the difference in distance clear. In the real orbit, the distance between focus and center is much smaller than shown in the diagram.

the "perigee" (PEHR-ih-jee) from Greek words meaning "near the Earth."

Once the Moon passes perigee on its journey around the Earth, it moves farther and farther from the Earth until it reaches the other end of the major axis. That is the farthest point from the Earth and is the "apogee" (AP-uh-jee) from Greek words meaning "away from the Earth."

The changing distance of the Moon from the Earth is given in Table 4. This is not a very great change, for the Moon's orbital ellipse is not very eccentric.

When the Moon is at apogee it looks a little smaller and moves a little more slowly than when it is at perigee. These changes are too small to be noticeable to the casual observer, but astronomers with proper instruments can detect them easily. The Moon's changes in size and speed of motion as it moves around the Earth are good evidence that the Moon's orbit is elliptical and not circular.

Parallax and Mars

Knowing the distance of the Moon doesn't help us learn how

TABLE 4

Distance of Moon from Earth

	DISTANCE		
	KILOMETERS	MILES	AVERAGE DISTANCE = 1
Moon at Perigee	356,000	220,000	0.926
Moon at Average Distance	384,400	238,900	1.000
Moon at Apogee	407,000	252,000	1.059

far away the other worlds of the solar system are. The Moon is not part of Kepler's model. What is needed is the distance of some planet at some particular time.

The trouble with this is that all the planets are much farther from the Earth than the Moon is. Each planet shows a parallax against the stars when it is viewed from different places on the Earth, but these parallaxes are very small compared to the Moon's, too small to be measured by eye alone. Although the ancients had worked out the distance of the Moon, they couldn't work out the distance of any other body. Even in Kepler's time, no other distance was known but that of the Moon.

In Kepler's time, however, things were beginning to change rapidly. In 1608, the telescope was invented in the Netherlands. An Italian scientist, Galileo Galilei (1564–1642), usually known by his first name (GAL-ih-LAY-oh), having heard of the invention, constructed one of his own and in 1609 used it to study the heavens. It trapped far more light than the eye itself could and made things look larger and brighter.

Telescopes were rapidly improved. They magnified the distance between heavenly bodies so that small changes in position could be more easily seen.

In 1656 a Dutch astronomer, Christian Huygens (HY-genz, 1629–1695) constructed the first pendulum clock. For the first time, astronomers could tell time accurately to the second. Two astronomers, located in far different places, could tell if they were both viewing an object at exactly the same time. In 1658 Huygens also invented a micrometer, which could be used with a telescope to measure small distances between objects seen in the sky, and do so far more accurately than the eye itself could.

Now it became possible for astronomers to measure very small parallaxes.

Which planet should be tackled for the purpose? Venus and Mars were the planets which, according to Kepler's model, could approach Earth most closely. They should therefore have the largest parallaxes (tiny, of course, but larger than the even tinier parallaxes of the others).

When Venus, however, is closest to Earth it is between Earth and the Sun and is hard to observe. On the other hand, when Mars is closest to Earth it is on the other side of Earth from the Sun. It shines in the midnight sky and is easy to observe. It made sense, therefore, to try to determine the parallax of Mars rather than any other planet.

In 1670 the Italian-French astronomer Giovanni Domenico Cassini (ka-SEE-nee, 1625–1712) tackled that problem. He worked at the Paris Observatory and made measurements of Mars's position from there. He sent another astronomer, Jean Richer (ree-SHAY, 1630–1696), to French Guiana to make measurements at the same times as he did. French Guiana is about 6000 kilometers (3700 miles) from Paris in a straight line drawn through the bulge of the round Earth, so there was a long base line.

When Richer returned to Paris in 1673, he brought his measurements with him. Cassini compared them with his own and was able, for the first time in history, to determine the parallax of a body other than the Moon. He had the parallax of Mars and knew how distant Mars was from Earth at a particular time, when Mars and Earth were in particular places in their orbits.

From this he could calculate all the other distances in the solar system, using Kepler's model. He could calculate the distance from the Earth to the Sun; the distance from Mars to the Sun, and so on. His values were a little low, actually, but they were very good for a first try.

In Table 5 are listed the modern values for the average distance from the Sun of the terrestrial planets. In Table 6 are listed the values for the average distances from Earth of the three other terrestrial planets at their closest approach. As you see, Venus is the planet which makes the closest approach to us and is our nearest planetary neighbor. Mars and Mercury are roughly twice as far from us as Venus is, and the outer planets are far away indeed.

The Changing Distances

Can we be satisfied with Tables 5 and 6 and say that when Venus is closest to us it is about a hundred times as far away as the Moon is? Can we say that Mars, when it is on the same side of the Sun as we are, is two hundred times as far from us as the Moon is, and that when it is on the opposite side of the Sun it is a thousand times as far from us as the Moon is?

No. Tables 5 and 6 deal with average distances only. They would be accurate if the planetary orbits were circles, but they are not. The planetary orbits are ellipses, with the Sun not at the center but at one of the foci. This means, as in the case of the Moon going around the Earth, that the distance of a planet from the Sun varies. At one end of the major axis of the ellipse, the planet is closest to the Sun, and at the other end of the major axis it is farthest from the Sun.

TABLE 5

Planetary Distances from the Sun

	AVERAGE DISTANCE TO SUN	
	KILOMETERS	MILES
Mercury	57,800,000	35,900,000
Venus	108,200,000	67,100,000
Earth	149,500,000	92,900,000
Mars	**227,900,000**	**141,600,000**

TABLE 6

Planetary Distances from the Earth

		NEAREST TO EARTH (AVERAGE)	FARTHEST FROM EARTH (AVERAGE)
Mercury	Kilometers	91,700,000	207,300,000
	Miles	57,000,000	128,800,000
	Earth-Moon Distance = 1	238	539
Venus	Kilometers	41,300,000	257,700,000
	Miles	25,800,000	160,000,000
	Earth-Moon Distance = 1	108	670
Mars	**Kilometers**	**78,400,000**	**377,400,000**
	Miles	**48,700,000**	**234,500,000**
	Earth-Moon Distance = 1	**204**	**982**

In the case of a planet revolving about the Sun, the point of least distance is the "perihelion" (PEHR-ih-HEE-lee-on) from Greek words meaning "near the Sun." The point of greatest distance is the "aphelion" (uh-FEE-lee-on) from Greek words meaning "away from the Sun."

The elliptical orbit of Venus is so nearly a circle that the distance of Venus from the Sun hardly changes in the course of its revolution. The change is greater in the case of Earth, still greater in the case of Mars, and greater yet in the case of Mercury, as you will see in Table 7.

As you see, the difference in the distance of Venus from the Sun amounts to only 1,500,000 kilometers (900,000 miles), or only 1.4 percent of its average distance from the Sun. The difference in the case of the Earth is 3.3 percent, of Mars 18.6 percent, and of Mercury 41 percent.

Now, then, consider Venus revolving about the Sun. It moves in a smaller orbit than Earth does and therefore catches up to the Earth and passes it now and then. Every time it passes Earth, it makes its closest approach.

Venus catches up to Earth every 584 days, so that if it passes Earth, say on March 1 of a particular year, it will pass Earth again on October 6 of the next year, and then again on May 12 of the year that is two after that and so on. If we wait long enough, Venus will pass us on every date of the year.

On January 2, Earth passes its perihelion and it is then

TABLE 7

Perihelia and Aphelia

		DISTANCE TO THE SUN		
		KILOMETERS	MILES	EARTH-SUN AVERAGE DISTANCE = 1
Mercury	perihelion	46,000,000	28,600,000	0.308
	aphelion	69,800,000	43,400,000	0.467
Venus	perihelion	107,500,000	66,700,000	0.719
	aphelion	109,000,000	67,600,000	0.729
Earth	perihelion	147,100,000	91,200,000	0.984
	aphelion	152,100,000	94,300,000	1.017
Mars	**perihelion**	**206,500,000**	**128,000,000**	**1.381**
	aphelion	**249,000,000**	**154,400,000**	**1.666**

2,400,000 kilometers (1,700,000 miles) closer to the Sun than average. On July 2, Earth passes its aphelion and is that much farther from the Sun than average. At perihelion, when the Earth is nearest the Sun, it would also be nearest Venus if Venus should happen to pass it and make its close approach on that day. At aphelion, Earth is farther from Venus, if that is the day of close approach. In other words, from year to year, Venus passes Earth at slightly different distances, depending on the exact time of year at which it passes us. (Venus also has a perihelion and an aphelion, but its orbit is so nearly circular, that makes very little difference.)

With Mars, the situation is more complicated, because Mars has an even more eccentric orbit than Earth has. As it happens, Mars passes its perihelion on August 28, and it is then nearest the Sun. Earth, as I said above, passes through its aphelion on July 2 and is then farthest from the Sun.

Earth can pass Mars on any day of the year, if we wait long enough. If it passes it in July or August, when Earth is farther out from the Sun than it is on the average, and when Mars is nearer in to the Sun than it is on the average, the near approach of the two planets is considerably closer than average. On the other hand, if they pass in January or February, when the Earth is farther in and Mars farther out, the near approach is farther than average.

Table 8 gives the extremes of the near approach to Earth for the three other terrestrial planets.

You see, then, that if Mars should happen to be in opposition at the right time of year, there is a "favorable opposition"—one in which it is considerably closer than it would be ordinarily. Even at the most favorable opposition, however, Mars is still in second place among our neighbors. It is, at best, still 1½ times as far from us as Venus can be.

But wait. In one all-important respect, Mars is in first place.

When Venus makes its closest approach, it is between us and the Sun so that it is the other side of Venus, the one away from us, that is sunlit. The hemisphere facing us, the one we see, is dark. Even if the nearby presence of the Sun did not blank out Venus, we could still see nothing at all if we looked at it.

Mars, on the other hand, lies exactly on the other side of the Sun when it makes its close approach, for it is Earth which

TABLE 8

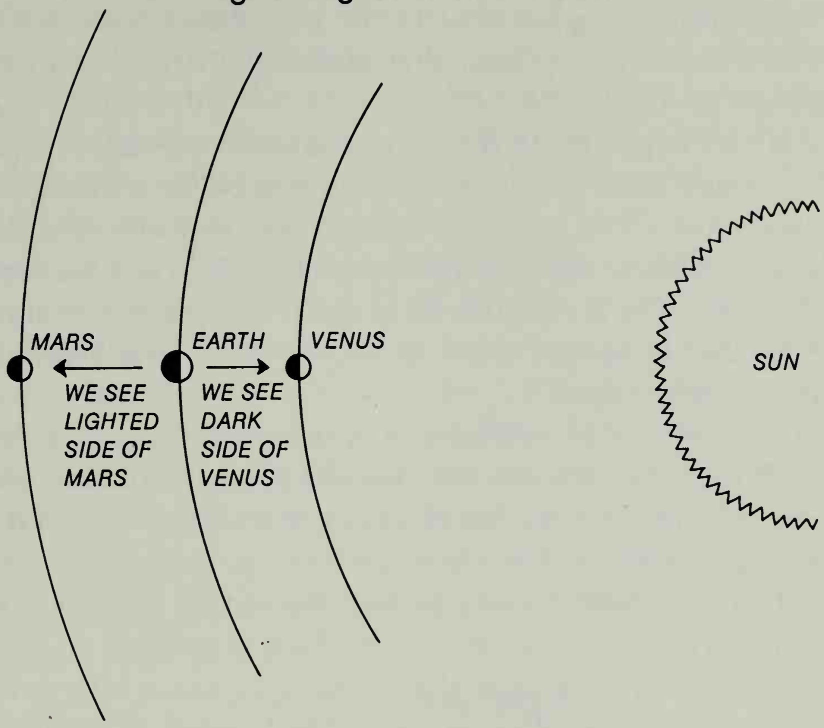
Planetary Near Approaches

		DISTANCE FROM EARTH		
		KILOMETERS	MILES	EARTH-MOON DISTANCE = 1
Mercury	nearest-near	80,000,000	49,700,000	208.1
	farthest-near	103,400,000	64,300,000	269.0
Venus	nearest-near	38,900,000	24,100,000	101.2
	farthest-near	43,900,000	27,200,000	114.3
Mars	**nearest-near**	**56,000,000**	**34,800,000**	**145.7**
	farthest-near	**99,000,000**	**61,500,000**	**257.5**

then lies between Mars and the Sun. Mars is therefore high in the sky at midnight at such times and we see its lighted hemisphere (see Figure 5).

Through this combination of closeness and sunlit visibility, Mars is, of all the planets, the one we can see best and in most detail, particularly at favorable oppositions. For that reason, Mars has been the most closely observed of all the planets.

Fig. 5—Light and Dark Sides



When do the close oppositions come? We pass Mars and experience a Mars opposition every 780 days. If there is an opposition on August 1 of a particular year, a very good time, then the second opposition is 780 days later, the third opposition 1,560 days later, and so on till the sixteenth opposition is 11,700 days later. This is equal to just a little over 32 years, so that an opposition in that year happens at August 11 and is still very good. We can therefore expect favorable oppositions at 32-year intervals.

After a few such 32-year intervals, with the opposition moving 11 days onward each time, the oppositions become poorer and poorer, but by then a different cycle is starting and we can expect sometimes three and sometimes four favorable oppositions each century. In the twentieth century, for instance, there were favorable oppositions in 1924, 1956, and 1971. There will be four favorable oppositions in the twenty-first century.

There is one other factor that affects the nature of the oppositions of Mars.

It is easy to picture all the planets as revolving about the Sun in the same plane. That is, suppose you begin by imagining a plane (like a vast, perfectly straight and perfectly thin sheet of paper) passing through the center of the Sun and the center of the Earth. The Earth, as it turns about the Sun, would always stay in that imaginary sheet of paper, which thus represents Earth's "orbital plane."

If that plane were extended, and if it turned out that Mars and all the other planets also remained in it as they revolved about the Sun, then all the planetary orbital planes would coincide with Earth's. The distance between the planets could then be determined entirely by how far each is from the Sun.

However, that is not how it works. Each planet has an orbital plane of its own and each plane makes an angle with that of Earth. This angle is called the "orbital inclination" of the planet. The orbital inclination of the terrestrial planets is given in Table 9 .

TABLE 9

Orbital Inclinations

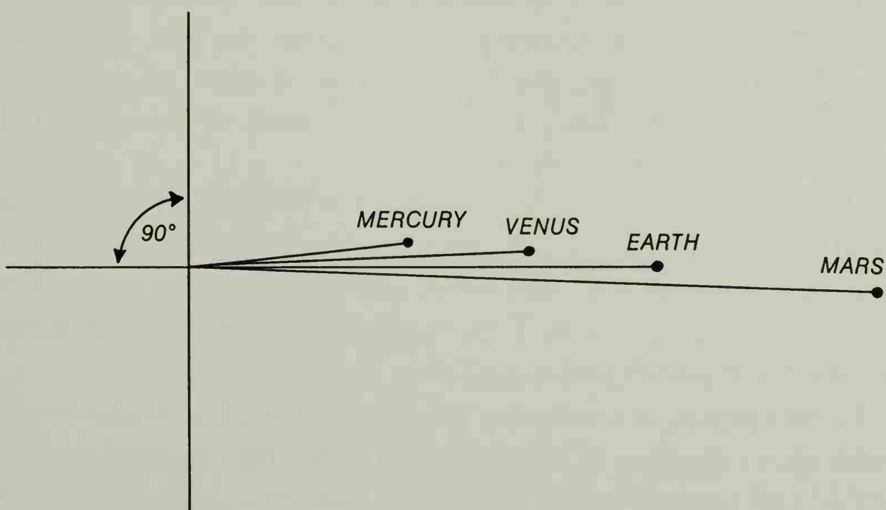
PLANET	ORBITAL INCLINATION (DEGREES)
Mercury	7.0
Venus	3.24
Mars	**1.85**

The orbital inclinations listed in Table 9 are not great. One complete turn is 360 degrees. A right angle, which is a quarter of a turn, is 90 degrees. In other words, if Earth's orbital plane were viewed as perfectly horizontal, another orbital plane that was perfectly vertical would have an orbital inclination of 90 degrees. An angle of 7 degrees is a little over 1/12 of the way to vertical, while an angle of 1.85 degrees is a little over 1/50 of the way to vertical (see Figure 6).

Such small inclinations don't seriously affect the distances of the planets from us. When Mars is close to us and is only about 60 million kilometers away, the change in distance introduced by its having an orbital plane inclined to ours is only about 250,000 kilometers (155,000 miles). This change can be, and is, taken into account by astronomers, but it doesn't amount to much. The same is true for Mercury and Venus too.

In another respect, however, the orbital inclination of Mars affects the ease with which Mars can be viewed.

Fig. 6—Orbital Inclination



The half of Mars's orbit that contains the perihelion is tipped 1.85 degrees southward, while the other half, containing the aphelion, is tipped by that amount northward.

This means that when Mars is at a favorable opposition and is located near its perihelion (as it must be on such occasions), it is lower in the sky in the northern hemisphere than it would be if it had no orbital inclination, or if the inclination were in the other direction. Of course, the situation is reversed in the southern hemisphere and Mars is higher in the sky than it would be with no orbital inclination or with a reversed one.

The lower an object is in the sky, the more interference there is from Earth's atmosphere and the harder it is to view in detail. This means that, at favorable oppositions, Mars would be viewed somewhat better from the southern hemisphere than from the northern hemisphere. However, most of the world's great telescopes have always been in the northern hemisphere and that is a slightly bad break for Mars-viewers.

Years and Speeds

Once the distance of the planets is known, the length of the circumference of the orbit of each about the Sun can be calculated. Naturally, the farther a planet is from the Sun, the larger its orbit and the longer the distance it must travel to make one complete turn. The distance traveled by each of the terrestrial planets is given in Table 10.

We expect a planet to take longer to complete one turn in its orbit if it is farther away from the Sun and has a greater distance to travel, and that turns out to be so. The time taken for one turn in the orbit (the "period of revolution") is given for each terrestrial planet in Table 11.

Earth's period of revolution defines our year: Earth makes one orbit about the Sun in one year. The term can be used for the periods of revolution of other planets as well. A Venus year is

TABLE 10

Lengths of Planetary Orbits

PLANET	LENGTH OF ORBIT: KILOMETERS	MILES	EARTH = 1
Mercury	371,000,000	231,000,000	0.396
Venus	679,000,000	421,000,000	0.723
Earth	939,000,000	584,000,000	1.000
Mars	**1,430,000,000**	**890,000,000**	**1.523**

(NOTE—If the planetary orbits were perfectly circular, the lengths of the orbit would be in the same ratio as the distances from the Sun. The same would be true if they were ellipses with the same eccentricity. Increasing the eccentricity lengthens the orbit, and that is why Mercury is 0.387 times as far from the Sun as Earth is, but has an orbit 0.396 times as long as the Earth's.)

TABLE 11

Periods of Revolution

PLANET	PERIOD OF REVOLUTION: DAYS	YEARS
Mercury	88.0	0.241
Venus	224.7	0.615
Earth	365.25	1.000
Mars	**687.0**	**1.881**

about ⅗ of an Earth year; a Mars year is about 1⅞ Earth years, and so on.

The increase in the length of the year is not equal to the increase in the length of the orbit. Venus's orbit is 0.725 that of Earth's and yet it takes Venus only 0.615 Earth years to make the trip. It must move faster than Earth does to do this. On the other hand, Mars's orbit is 1.524 times as long as that of Earth, yet it takes Mars 1.88 Earth years to complete its journey. Thus it must move more slowly than Earth does.

We can divide the length of the orbit by the time it takes a planet to complete one turn and in this way work out the speed with which a planet travels in its orbit. The values are given in Table 12.

As you see, the farther a planet is from the Sun, the more slowly it moves. This holds not only for the terrestrial planets, but for all the planets. It even holds for a single planet as its distance from the Sun changes.

The orbital speed for Mars, for instance, is given in Table 12 as 24.1 kilometers per second (15.0 miles per second). That, however, is merely an average value.

TABLE 12

Orbital Speeds

	ORBITAL SPEED		
PLANET	KILOMETERS PER SECOND	MILES PER SECOND	EARTH = 1
Mercury	48.8	30.3	1.64
Venus	35.0	21.7	1.17
Earth	29.8	18.5	1.00
Mars	**24.1**	**15.0**	**0.81**

As Mars nears its perihelion, it moves steadily faster, reaching its fastest speed when it is at perihelion and nearest the Sun. It then slows up as it travels away from perihelion and moves most slowly when it is at aphelion. At perihelion, Mars moves at a rate of 26.4 kilometers per second (16.5 miles per second), while at aphelion it moves at only 22.0 kilometers per second (13.6 miles per second).

Kepler, who worked out the elliptical orbits for planets ("Kepler's first law") in 1609, also worked out that same year this change in orbital speed with distance from the Sun ("Kepler's second law"). "Kepler's third law," presented in 1619, showed how to calculate the length of a planet's year from its distance from the Sun, and vice versa. Kepler pointed out that the square of the period of revolution of a planet is proportional to the cube of its distance from the Sun. If we calculate it in the proper way we can make the square of the period of revolution equal to the cube of the distance, as in Table 13.

TABLE 13

Kepler's Third Law

	PERIOD OF REVOLUTION		DISTANCE FROM SUN	
PLANET	EARTH = 1 (P)	SQUARE (P × P)	EARTH = 1 (D)	CUBE (D × D × D)
Mercury	0.241	0.0581	0.387	0.0580
Venus	0.615	0.387	0.723	0.378
Earth	1.000	1.000	1.000	1.000
Mars	**1.881**	**3.538**	**1.524**	**3.539**

(NOTE: Notice that the columns headed "square" and "cube" are just about equal, in accordance with the third law.)

Kepler didn't know why his laws were so. He just noted that this was how the solar system seemed to work.

In 1687, however, the English scientist Isaac Newton (1642–1727) worked out the "law of universal gravitation." According to the law, any particular object in the universe attracted any other particular object. The strength of the attraction depended on the product of the masses of the two objects. (The mass of an object, under ordinary conditions, is a measure of the quantity of matter it contains.) The greater the product of the masses, the greater the gravitational attraction.

The strength of the attraction also depended on the distance between the centers of the two objects. The greater the distance, the less the strength of attraction. In fact, the strength falls off as the square of the distance. If the distance is increased by 2 times, the attraction weakens by 2 × 2 or 4 times. If the distance is increased by 5.5 times, the attraction weakens by 5.5 × 5.5 or 30.25 times, and so on.

Working from the law of universal gravitation, and considering the gravitational attraction of the Sun for each of the planets, Newton showed why Kepler's laws worked out as they did.

3

THE SIZE OF MARS

The Planets as Worlds

Until 1609, the planet Mars was just a dot of light as far as Earthly observers were concerned. Indeed, all the heavenly bodies, except for the Sun and Moon and an occasional comet, were visible merely as dots of light.

Even as nothing more than a dot of light, Mars yielded the information presented in the first two chapters of this book. More was wanted, though: information that was beyond what could be obtained from a dot of light. For instance, is Mars a world? That is, is it an Earthlike body in size and nature?

It seemed reasonable to suppose it was. After all, the Moon was. As soon as the ancients had determined the distance of the Moon, it was at once possible to determine its size. An object that was nearly 400,000 kilometers away and yet looked as large as the Moon did would have to be very large. It had to about 3,500 kilometers (2,100 miles) across, and that made it a sizable world.

Mars was just a dot of light, but it was much farther away than the Moon. Even at its very closest it was nearly 150 times as far away as the Moon. It could be considerably larger than the Moon and yet still appear only as a point of light. If that point of light could be measured and its diameter determined, its size could be calculated. Unfortunately, there was no way

Mars's apparent diameter could be determined by just looking at the point of light. The size of that point was too small to measure.

In the same year that Kepler advanced his first two laws, however, Galileo was looking at the sky with his telescope, and that altered everything.

Galileo looked at the Moon, for instance, and in the telescope the Moon's image was expanded and he could see details he could not see with the unaided eye. He could see mountains and craters and flat dark areas which he called "seas" because he thought they were regions of water. It was clear when the Moon was viewed through a telescope that it was a world, one much like the Earth in some ways.

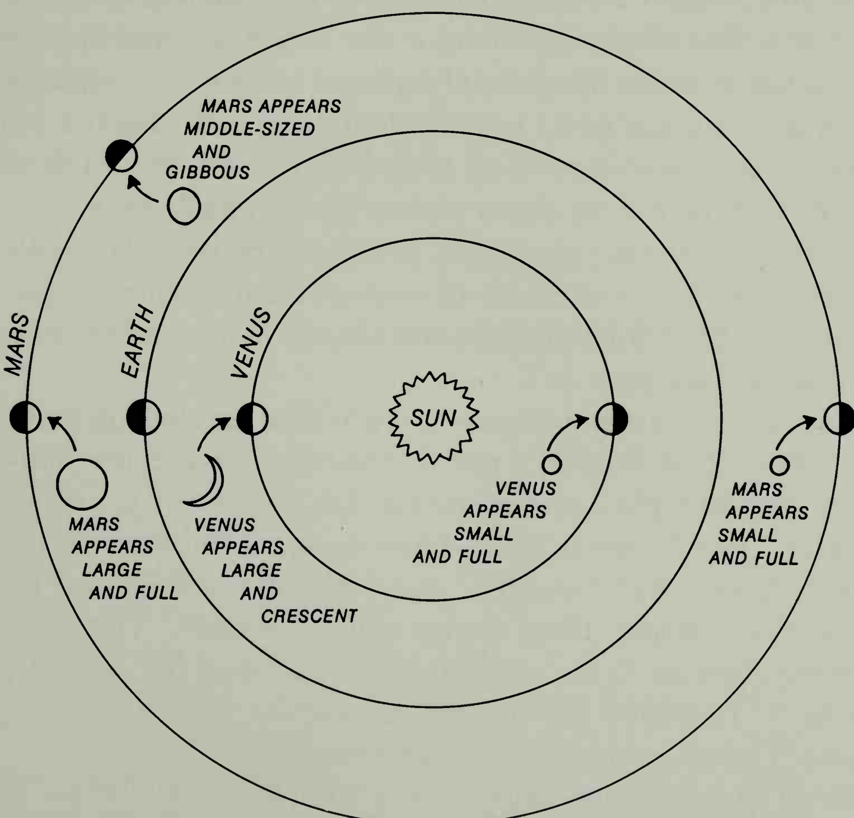
If the Moon was a world, surely the planets were worlds too. The planets were much farther away than the Moon, and Galileo couldn't expect to see the kind of detail in them that he saw on the Moon. He saw enough, though, to settle the question as to whether they were worlds. As seen through the telescope, the planets were no longer dots of light, but were expanded into definite shapes.

Venus and Mercury, being closer to the Sun than the Earth is, are often more or less between the Sun and ourselves. They show their night sides to Earth observers in varying amounts at those times. When the planets are exactly between the Earth and the Sun, all that can be seen is the night side. When either Mercury or Venus is a little to one side of being just in between, astronomers can see a little bit of the lighted side and the planet looks like a thin crescent. A little more to one side and it is a fatter crescent.

As Venus and Mercury move around the Sun, astronomers can, in fact, see them go through all the phases, just as the Moon does. The chief difference is that the Moon stays at almost the same distance from us at all times so that it doesn't change in size as it changes phases. Venus and Mercury change their distances from Earth greatly, however, as they go around the Sun. Astronomers see the crescents when the planets are between us and the Sun, and they see the stages when the planet is nearly full when it is on the other side of the Sun. The crescents are considerably larger, therefore, than the full phase (see Figure 7).

We always see the farther planets like Mars, on the other hand, with the Sun shining on them over our shoulder, so to

Fig. 7—Changes in Size and Shape



speak. We always see them full or nearly full. When they are exactly in opposition or in conjunction, they are perfectly full. When they are out of a direct line with Earth and Sun, a little sliver of the night side can be seen.

In the case of the planets beyond Mars, the sliver of the night side is so small as to be unnoticeable even at its thickest. Those planets always look full. Mars is close enough to us to show a noticeable bit of night side when it is to one side of the Earth-Sun line, and then Mars is not perfectly full. This not-quite-full phase is called "gibbous" (GIB-us). There are changes in size there, too (see Figure 7).

Once the telescope magnified the planets into distinct shapes, it became possible to measure how large they were as seen from the Earth. The micrometer, once it was invented, could measure the distance across the globe of a planet as seen in a telescope. Since astronomers could easily calculate by how much a particular telescope magnified an object, they could then work out the distance across the object as seen by the unaided eye.

Those measurements are not, of course, made in kilometers or miles, but in a special set of measurements called "angular measure." I have used this measure already in discussing orbital inclination (see page 42).

The distance around any circle—whether the circle is that of the letter "o" or that of a planet revolving around the Sun—is divided into 360 equal segments. Each segment is called a "degree." The degree is divided into 60 equal "minutes of arc," often simply called "minutes," and each minute is divided into 60 "seconds of arc," often simply called "seconds." The degree is symbolized as °, the minute of arc as ′, and the second of arc as ″. Therefore 52° 14′ 33″ is read as fifty-two degrees, fourteen minutes, and thirty-three seconds.

Since there are 360 degrees to a complete circle, there are 360 × 60, or 21,600, minutes of arc to a complete circle. There are 21,600 × 60, or 1,296,000, seconds of arc to a complete circle.

If one were to measure the width of the Moon, and then mark off that width in a circle all around the sky, there would be room for about 720 Moons, placed side by side. The Moon, therefore, is roughly half a degree wide, or 30 minutes of arc wide, or 1800 seconds of arc wide.

Planetary Diameters

The planets are, of course, much smaller in appearance than the Moon is and show an apparent width of but one minute of arc or less. In Table 14 the apparent widths of the terrestrial worlds other than Earth are given.

TABLE 14

Apparent Diameters

	APPARENT DIAMETER	
TERRESTRIAL WORLD	SECONDS OF ARC	MARS AT MAXIMUM = 1
Mercury (closest)	12.7	0.51
Mercury (farthest)	4.7	0.19
Venus (closest)	64.5	2.57
Venus (farthest)	9.9	0.39
Moon (closest)	2010	80.1
Moons (farthest)	1761	70.2
Mars (closest opposition)	**25.1**	**1.00**
Mars (farthest opposition)	**13.8**	**0.55**
Mars (conjunction)	**3.5**	**0.14**

As you can see, even when Mars is closest to us and looks widest, it would still take about 70 objects the size of Mars, placed side by side, to stretch across the Moon when it is at its smallest. No wonder Mars looks like a mere dot of ruddy light.

Venus, at its closest, has a diameter two and a half times that of Mars, but remember that Venus, at its closest, is just about between us and the Sun and it can't be seen. When it is far enough out of line with the Sun to be seen, it isn't much larger than Mars at its largest, and Venus is then only a crescent, whereas Mars is full or nearly full at all times.*

As for Mars, notice the difference between a close opposition in August and a far opposition in February. At close opposition, Mars is nearly twice as wide as at far opposition. What's more, it isn't merely the diameter that counts. If one circular object is twice as wide as another, it is twice as wide from side to side and twice as wide up and down. The larger body therefore has four times the surface area of the smaller. The apparent surface area of the terrestrial worlds is given in Table 15.

As you see, it would take five to six thousand dots of light such as Mars appears to be, even at its largest, to cover the face of the Moon. Fortunately astronomers have telescopes with which they can enlarge the image of Mars.

At its closest opposition, Mars shows over three times the area that it shows at its farthest opposition, and fifty times the

* Jupiter is always wider in appearance than Mars is at its widest. Saturn is always wider than Mars at its smallest, and even distant Uranus appears wider at times than Mars at its smallest. As for the Sun, that is larger in appearance even than the Moon (very slightly). These bodies appear large, however, because they are all so much larger than the terrestrial worlds. They are all far more distant than Mars is when Mars is at its closest, and although these giant bodies are wide they cannot be seen in the detail Mars can. Except for the Moon, there is no object in the sky that can be studied in the detail Mars can.

TABLE 15

Apparent Areas

TERRESTRIAL WORLD	APPARENT AREA: SQUARE SECONDS OF ARC	APPARENT AREA: MARS AT MAXIMUM = 1
Mercury (closest)	127	0.26
Mercury (farthest)	17.3	0.035
Venus (closest)	3267	6.6
Venus (farthest)	78	0.16
Moon (closest)	3,170,000	6,400
Moon (farthest)	2,430,000	4,910
Mars (closest opposition)	**495**	**1.00**
Mars (farthest opposition)	**150**	**0.30**
Mars (conjunction)	**9.6**	**0.019**

area that it shows at conjunction. No wonder astronomers grow excited as the time for a close opposition comes around.

Once the apparent size of Mars and the other planets came to be known and the distance determined, the actual sizes of the planets could be worked out. It is not very difficult to calculate how large a body must be to show a width of so many seconds of arc at a distance of so many million kilometers. There is a branch of mathematics called trigonometry which is particularly useful in answering such questions.

In Table 16, then, we have the true diameters of the five terrestrial worlds.

It turns out that Earth is the largest of the terrestrial worlds, with Venus close behind. As for Mars, that has only a little over half the diameter of the Earth. Still, Mars is considerably larger than Mercury and has twice the diameter of the Moon.

Another way of comparing the planets is to consider their equatorial circumferences as in Table 17.

The ratios of the circumferences are the same as those of the diameters, and in this respect Mars remains at a figure of little more than half that of Earth. Still, the journey of 21,300 kilo-

TABLE 16

Diameters

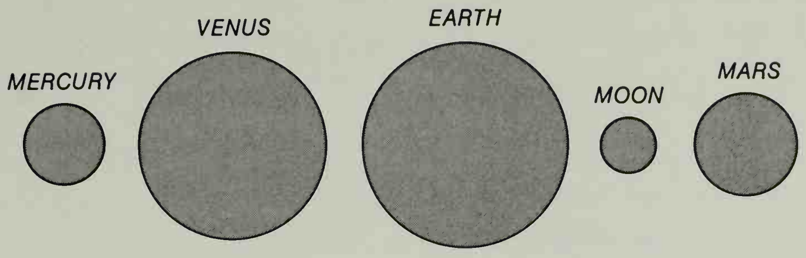
TERRESTRIAL WORLD	DIAMETERS KILOMETERS	MILES	EARTH = 1
Mercury	4,860	3,020	0.38
Venus	12,100	7,520	0.95
Earth	12,740	7,920	1.00
Moon	3,475	2,160	0.27
Mars	**6,790**	**4,220**	**0.53**

TABLE 17

Equatorial Circumferences

TERRESTRIAL WORLD	EQUATORIAL CIRCUMFERENCE KILOMETERS	MILES
Mercury	15,270	9,490
Venus	38,000	23,600
Earth	40,000	24,900
Moon	10,900	6,790
Mars	**21,300**	**13,250**

Fig. 8—Size of the Terrestrial Worlds



meters (13,250 miles) required to girdle Mars is no small distance. It is almost exactly the distance by air from San Francisco to Rio de Janeiro and back.

The comparative size of the five terrestrial worlds is shown in Figure 8.

Planetary Areas and Volumes

We might also ask what the surface area of each of the terrestrial worlds is. This can be easily calculated from the diameter of the world and the results are given in Table 18.

The surface area of Mars is just about twice that of Mercury and four times that of the Moon, but it is only 2/7 that of the Earth. Nevertheless, its 149,000,000 square kilometers (56,000,000 square miles) is roughly equal to the area of dry land on Earth. This means that the surface area of Mars is equal to that of all Earth's continents and islands put together, and that makes a respectable world.

We can also calculate the volumes of the terrestrial worlds. These figures are given in Table 19.

One way of interpreting the figures in Table 19 is to say that if Earth were hollow, nearly seven worlds the size of Mars could be dropped in (provided they were squeezed together so as to leave no empty space between).

TABLE 18

Surface Areas

TERRESTRIAL WORLD	SURFACE AREA: MILLIONS OF SQUARE KILOMETERS	MILLIONS OF SQUARE MILES	EARTH = 1
Mercury	74	29	0.15
Venus	460	178	0.90
Earth	496	197	1.00
Moon	38	15	0.076
Mars	**149**	**56**	**0.28**

TABLE 19

Volumes

TERRESTRIAL WORLD	VOLUME: BILLIONS OF CUBIC KILOMETERS	BILLIONS OF CUBIC MILES	EARTH = 1
Mercury	60	14.4	0.055
Venus	930	220	0.85
Earth	1080	260	1.00
Moon	22	5.3	0.020
Mars	**165**	**39**	**0.15**

The total volume of the five terrestrial worlds is 2,257 billion cubic kilometers (539 billion cubic miles). It follows that the volume of Earth is just about equal to that of the other four terrestrial worlds put together. Earth and Venus together make up nine tenths of the total.

Planetary Views of the Sun

Another point of interest can be determined from the data we already have. That is the size of the Sun as it would appear if it were viewed from each of the terrestrial worlds.

Here on Earth, the average apparent diameter of the Sun is 1919 seconds of arc, which is about 54 seconds more than the average diameter of the Moon. This difference is not very large, and to the eye, the Moon and the Sun appear to be just about the same size (which is rather a remarkable coincidence, actually).

Of course, the Sun varies somewhat in apparent size depending on what part of its orbit the Earth happens to be moving through. At perihelion it is 1950 seconds of arc in diameter but at aphelion only 1888 seconds of arc.

When the Moon passes squarely in front of the Sun, the Moon does not usually cover the Sun entirely, but leaves a thin ring of light around its edges (an "annular" eclipse, from the Latin word for "ring"). When the Sun appears smaller than usual and the Moon larger than usual, the Moon's globe can completely cover the Sun's and the eclipse is "total."

The size of the Sun as seen from the Moon is just about exactly the same as its size seen from the Earth. The Moon is nearly 400,000 kilometers closer to the Sun than the Earth is, when the Moon is new, and nearly 4,000 kilometers farther from the Sun than the Earth is, when the Moon is full. This means that the Sun as seen from the Moon can be about 4 seconds of arc wider than it ever gets on Earth and about 4 seconds of arc narrower, too, depending on which portion of their respective orbits Earth and Moon are in.

Seen from Mercury and Venus, the Sun appears distinctly larger than it does from Earth, while from Mars the Sun appears distinctly smaller (see Table 20).

Because the orbit of Venus is so nearly circular, the apparent size of the Sun as seen from Venus changes only very slightly. On the other hand, the eccentricity of Mercury's orbit is quite high for a planet. That is why the Sun, as seen from Mercury, changes apparent size so enormously.

TABLE 20

Apparent Diameter of the Sun

TERRESTRIAL WORLD		APPARENT DIAMETER OF THE SUN: SECONDS OF ARC	APPARENT DIAMETER OF THE SUN: AVERAGE DIAMETER AS SEEN FROM EARTH = 1
Mercury	maximum	6252	3.26
	minimum	3996	2.08
Venus	maximum	2676	1.39
	minimum	2640	1.37
Earth	maximum	1950	1.02
	minimum	1888	0.98
Moon	maximum	1954	1.02
	minimum	1884	0.98
Mars	**maximum**	**1380**	**0.72**
	minimum	**1140**	**0.59**

As for Mars, the diameter of the Sun as seen from its surface varies from ⅗ to ¾ the diameter as seen from Earth. However, it is not diameter which indicates how much heat a planet receives from the Sun, but its apparent surface area. This is given in Table 21.

Earth, as you see from Table 21, gets about three percent more heat from the Sun at perihelion than it does on the average, and about three percent less than that average at aphelion. The Moon goes just a trifle further at either extreme. Venus gets roughly twice as much heat from the Sun as the Earth does.

TABLE 21

Apparent Area of the Sun

TERRESTRIAL WORLD		APPARENT AREA OF THE SUN: SQUARE SECONDS OF ARC	APPARENT AREA OF THE SUN: AVERAGE AREA AS SEEN FROM EARTH = 1
Mercury	maximum	30,700,000	10.65
	minimum	12,500,000	4.33
Venus	maximum	5,620,000	1.94
	minimum	5,470,000	1.89
Earth	maximum	2,990,000	1.03
	minimum	2,800,000	0.97
Moon	maximum	3,000,000	1.04
	minimum	2,790,000	0.96
Mars	**maximum**	**1,500,000**	**0.52**
	minimum	**1,020,000**	**0.35**

As for Mercury, thanks to its eccentric orbit it gets from four to ten times as much heat from the Sun as Earth gets. At perihelion, Mercury gets two and a half times as much heat from the Sun as it gets at aphelion.

Mars gets, at best, half as much heat from the Sun as Earth does, and at aphelion the amount sinks to one third. Its orbit is sufficiently eccentric so that at perihelion it gets nearly one and a half times as much heat from the Sun as at aphelion.

4

THE ROTATION OF MARS

Days and Years

Once the telescope extended the senses, there was a natural desire to see detail on the surface of the planets.

The Moon is so near to Earth that a great deal of detail could be seen on it even with the primitive telescopes of the 1600s. (Some detail, in the form of shadowy blotches, can be seen on the Moon even with the unaided eye.)

The planets were another matter. They are all much farther than the Moon and even with telescopes there was considerable difficulty in seeing any detail. The planet that comes closest to Earth is Venus. When it is close, however, it is between Earth and the Sun and presents its night side to us. What's more, when at least part of Venus can be seen it is covered by a perpetual thick cloud layer that leaves its surface always white and unmarked.

Mars, which approaches closer to Earth than any planet but Venus, is another thing altogether. To observers on Earth, Mars always seems full or nearly full and it has no obscuring cloud cover. It was Mars, then, that next to the Moon offered the best chance for observing surface detail, and it was on Mars that astronomers concentrated.

The first person to try to draw a map of the surface of Mars was the Italian astronomer Francesco Fontana (fon-TAH-nuh, 1600–?). In 1636 he observed Mars when it was at opposition and published a drawing that showed a dark circle around the rim of its globe and a circular dark spot in the center. It seems quite certain, however, that what he saw was simply the result of using a telescope with a defective lens.

In 1659 Huygens did better. His drawing of Mars showed a triangular dark shape near the center, and this triangular dark shape has been commonly observed by all astronomers since. Huygens, therefore, noted the first feature on Mars that really existed. The name this feature eventually received was "Syrtis Major" (SER-tis), which is Latin for "large bog."

It was generally assumed at first that dark markings on the face of a world were water, and light markings were dry land. This was at first thought to be true of the Moon, for instance, and so the dark markings on that body were called "mare" (Latin for "seas"). In the case of the Moon, telescopic observation quickly showed that the dark markings were not bodies of water and that, in fact, there was no free water on the Moon.

Mars was so much farther away than the Moon that it took a long time to decide whether dark markings like "Syrtis Major" were really water or not. The general opinion, right into the 1900s, was that they represented water.

Huygens did something very useful with the markings he noted on Mars. By following those markings as they moved across the face of Mars with the passage of time, he was finally able to show that the planet rotated about its axis as the Earth did, and to determine how long it took to complete a rotation. The time of rotation, as it happened, was very much like that of the Earth. Huygens judged it to be 24½ hours, which was a good estimate indeed. Later astronomers found it to be nearer 24⅝ hours and managed to get the time of rotation measured exactly to the thousandth of a second.

Mars is the only one of Earth's neighbors in space to have an Earthlike rotation. The Moon, for instance, keeps one side always toward the Earth. This is because it makes a single rotation, with respect to the Sun, in that month. Its rotation with respect to the stars is slightly shorter than a month. As for Mercury and Venus, observations of them were so difficult that it has been only in the last couple of decades that their periods of rotation have been correctly determined. Those periods proved to be even slower than that of the Moon.

Notice that I said the Moon rotates on its axis relative to the Sun in a longer time than it does relative to the stars. This is true of other bodies in the solar system, too.

For instance, as the Earth rotates, the stars seem to mark out a circle in the sky. The circle is completed after 23.935 hours, or 23 hours and 56 minutes. In that time, however, the Sun, as seen from Earth, has moved a small distance backward against the background of the stars, an effect produced by the steady motion of the Earth around the Sun. As a result the Sun has not yet completed its circle when the stars have. It takes four more minutes for the Sun to complete its circle, so that Earth's period of rotation relative to the Sun is exactly 24 hours.*

The Moon rotates so much more slowly than Earth does that it takes the stars in the lunar sky fully 27⅓ days to make a complete circle. In that time, though, the Sun has moved such a distance backward in the lunar sky that it takes over two more days for it to complete its circle.

The time or rotation relative to the stars is the "sidereal day" (sigh-DEE-ree-al) from the Latin word for "star." In Table 22 the length of the sidereal day is given for each of the terrestrial worlds.

***Naturally, it is motion relative to the Sun that is more important to human beings since that is what determines night and day. It is therefore rotation relative to the Sun that is broken up into an even number of hours.**

TABLE 22

Sidereal Days

TERRESTRIAL WORLD	SIDEREAL DAY HOURS	SIDEREAL DAY DAYS
Mercury	1,409	58.7
Venus	5,834	243.1
Earth	23.935	0.9973
Moon	655.7	27.32
Mars	**24.623**	**1.026**

The time of rotation relative to the Sun is the "solar day." When a planet rotates from west to east as the Earth does, the solar day is longer than the sidereal day. When a planet rotates in the other direction (as Venus does), the solar day is shorter than the sidereal day. The slower the rotation, the greater the difference in length between the two kinds of day. In Table 23, the length of the solar day is given for each of the terrestrial worlds.

If a person were to stand on the surface of any of the other worlds of the solar system, only on Mars would the day-night progression seem Earthlike. The distant planets rotate so quickly (Jupiter completes a rotation in just under 10 hours) that the Sun would seem to race across the sky. On the Moon, on the other hand, it would take two weeks for the Sun to move from its rise to its set.

On Venus, which rotates in the direction opposite to that of the other planets, the Sun would rise in the west and, after a period of two months, set in the east. Mercury is the strangest of all for there, because of the eccentricity of its orbit about the

TABLE 23

Solar Days

TERRESTRIAL WORLD	SOLAR DAY HOURS	SOLAR DAY DAYS
Mercury	4,224	176
Venus	2,808	117
Earth	24	1.000
Moon	708.7	29.53
Mars	**24.66**	**1.0275**

Sun, the Sun seems to change direction. For the most part it moves from east to west across the sky since Mercury rotates in the normal direction. At times, however, the Sun's motion slows and, for a period, it moves west to east before returning to its usual direction.

On Mars, however, the Sun (making allowance for its smaller apparent size) would seem to behave in Mars's sky just as it does in Earth's. Since Mars, like Earth, rotates from west to east, the Sun in Mars's sky rises in the east, crosses the sky at just about the normal rate, and sets in the west. The time from noon to noon is just forty minutes longer on Mars than on Earth.

Earth's year is 366.25 times as long as Earth's sidereal day. It is 365.25 times as long as Earth's solar day. Because the solar day is more important to us, and unless we are astronomers we are not even aware of the sidereal day, we say that Earth's year is 365.25 days long.

For other worlds, the year (which is the time it takes for a world to make one orbit about the Sun) is different in length from that of the Earth. (The Moon is an exception; the length of its year is exactly that of the Earth since the two go about the Sun in step.) On each world, the length of the solar day is also different. For each world, then, we can calculate the length of its year not only in Earth days (as in Table 11) but in the planet's own solar days, which we can abbreviate as "sols."

This is given in Table 24. Someone on the surface of Mars would see 1.83 times as many sunrises and sunsets in the course of Mars's year as we on Earth see in the course of Earth's year.

The Axis of Rotation

When a solid ball such as the Earth rotates, it does so about an imaginary line passing through its center. This line is called the "axis of rotation." The axis reaches the surface of the spinning body at two opposite points, or poles. One is the North Pole and the other the South Pole.

If we think of the Earth going around the Sun, we might imagine it spinning with its axis in an upright position, at right angles to the direction from which the sunlight was coming,

TABLE 24

Length of Years

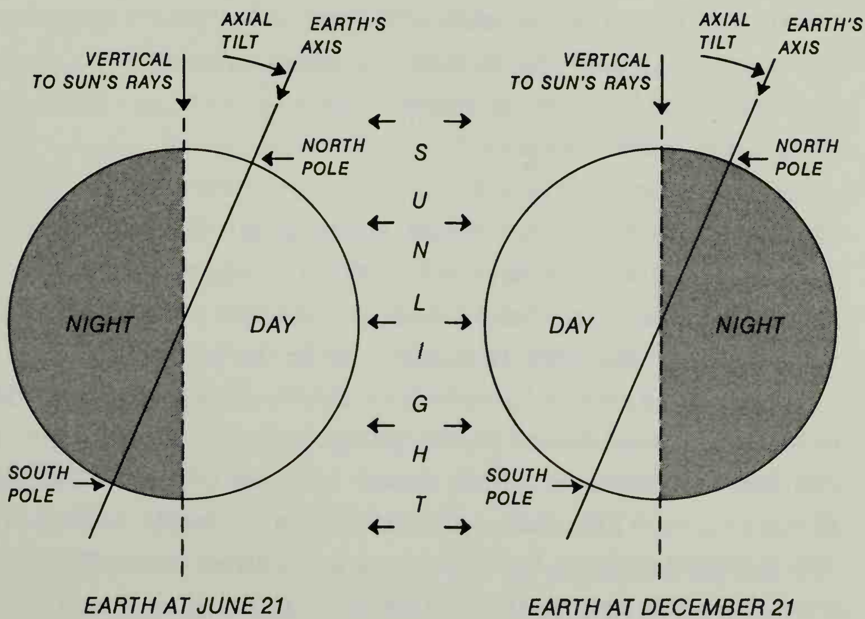
	YEAR	
TERRESTRIAL WORLD	EARTH DAYS	SOLS
Mercury	88.0	0.50
Venus	224.7	1.92
Earth	365.25	365.25
Moon	365.25	12.37
Mars	**687.0**	**668.61**

with the North Pole at the top and the South Pole at the bottom. That would strike us as normal, somehow.

Actually, that is not the way it is. Earth's axis is tipped at an angle to this upright position. In some parts of the Earth's orbit the North Pole points part way toward the Sun, while the South Pole points part way away from the Sun. On June 21 the North Pole points as nearly toward the Sun as it ever does, and the South Pole as far away from it as it ever does. The poles are tipped about one quarter of the way from the vertical toward the horizontal position.

The direction of the axis doesn't change as the Earth revolves about the Sun, so that when the Earth reaches the opposite side of its orbit, on December 21, it is the North Pole that points as far away from the Sun as it ever does, and the South Pole that points as nearly toward it as it ever does (see Figure 9).

Fig. 9—Earth's Axial Tilt



This tipping of the axis accounts for the seasons. When the North Pole is tipped toward the Sun, it remains tipped toward it as the Earth rotates. The northern hemisphere of the Earth has longer days than nights and gets more than an average amount of sunlight and heat. The southern hemisphere has shorter days than nights and gets less than an average amount of sunlight and heat. It is summer in the northern hemisphere and, of course, winter in the southern hemisphere.

The situation is reversed at the other end of the orbit so that it is then winter in the northern hemisphere and summer in the southern hemisphere. At intermediate points in the orbit, Earth experiences spring and autumn.

In the northern hemisphere we see the noonday Sun rise higher and higher in the sky from December 21 to June 21, as the Earth's orbital motion gradually carries the axial tilt at the North Pole end more and more toward the direction of the Sun.

At June 21 the noonday sun is as high as it ever gets. It then begins to move lower until December 21, when it is as low as it ever gets. These dates represent the "solstices," from Latin words meaning "Sun stands still," since for just a moment the Sun seems to stand still before changing direction. In the northern hemisphere, June 21 is the "summer solstice" and December 21 the "winter solstice."

As it happens, when Earth is at perihelion it is winter in the northern hemisphere and summer in the southern hemisphere. That means that the northern winter is made a little milder by the extra heat from the slightly nearer Sun, while the southern summer is made a little hotter.

When the Earth is at aphelion, it is summer in the northern hemisphere and winter in the southern hemisphere. The northern summer is made a little cooler because of the slightly more distant Sun, while the southern winter is made colder. Thus, the northern hemisphere has, on the whole, less extreme seasons than the southern hemisphere has.

Since Earth moves a little faster in its orbit at perihelion, the northern winter, which is then taking place, is a few days shorter than the northern summer. Likewise, the southern summer is a few days shorter than the southern winter.

From the direction in which the markings on Mars seem to move as Mars rotates, it is plain that the Martian axis of rotation is also tipped. In fact, it is tipped to very much the extent that Earth's axis is tipped. This was first noted by the German-English astronomer William Herschel (HER-shul, 1738–1822) in 1781. This, too, makes Mars unusual among the terrestrial worlds. The slowly rotating worlds of Mercury, Venus, and the Moon have axes that are hardly tipped at all (see Table 25).

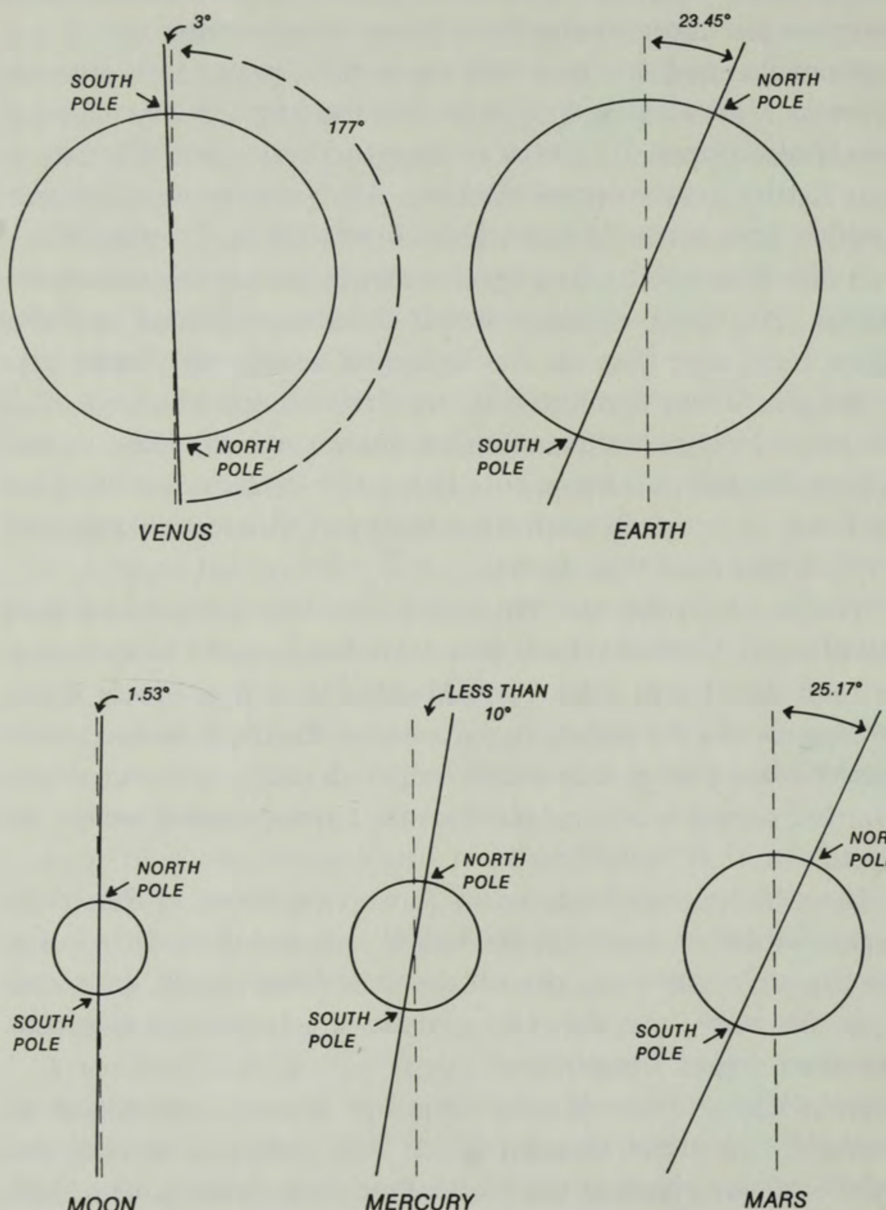
Because Venus is rotating in the direction opposite from that of the other planets, astronomers place its north pole at the bottom instead of the top. It is as though Venus is standing on its head, so to speak, with its axis tipped through an angle of 177 degrees (see Figure 10).

The fact that the Martian axis is tilted by the amount that Earth's axis is tilted means that Mars has seasons in the same fashion that Earth does. Each Martian season is nearly twice as long as the corresponding season on Earth, however, since the Martian year is that much longer than Earth's year. Each Martian season is also colder than the corresponding season on Earth.

Nevertheless, on Mars as on Earth, the noonday Sun rises higher in the sky each day for half a year and then sinks lower for the other half year; then higher and lower again, over and over. On Mars, too, there is a summer solstice and a winter solstice for each hemisphere.

As it happens, the Martian axis tips in such a way that at perihelion it is the Martian South Pole that tilts toward the Sun, while at aphelion the North Pole does. In this, too, Mars resembles Earth. On Mars as on Earth, it is the northern hemisphere that has the less extreme seasons and the southern

Fig. 10—Axial Tipping



hemisphere that has the more extreme seasons. Since the Martian orbit is more eccentric than is Earth's, the difference between the seasons is more pronounced in the case of Mars.

Then, too, since the Martian orbit is more eccentric than Earth's orbit is, the difference in Mars's speed at the perihelion

TABLE 25

Axial Tipping

TERRESTRIAL WORLD	AXIAL TIPPING (DEGREES)
Mercury	less than 10
Venus	3
Earth	23.45
Moon	1.53
Mars	**25.17**

end and at the aphelion end is greater than is the case with Earth. That means that the difference in the lengths of the seasons is greater on Mars than on Earth (see Table 26).

As you can see from Table 26, the difference in the lengths of the seasons on Earth is, at most, five percent, while on Mars the spring in the northern hemisphere is one third longer than the fall.

Suppose the Earth's axis is extended in imagination till it reaches the sky. It then intersects the sky at the "celestial poles." There is, of course, a North Celestial Pole and a South Celestial Pole.

As the Earth rotates about its axis, the sky, to an observer on Earth's surface, seems to rotate in the opposite direction about the same axis. The North and South Poles on Earth's surface don't take part in the rotation, and neither do the North and South Celestial Poles in the sky. The stars, as they turn, seem to turn about the celestial poles.

The North Celestial Pole happens to be near a fairly bright star, Polaris (poh-LAH-ris). This is a remarkable concidence since there are only a few dozen bright stars in the sky, and the chance of having a celestial pole end up very close to one of those bright ones is something like 1 in 300.

Polaris is about 1 degree away from the North Celestial Pole, a distance equal to twice the width of the full Moon. This is not a very great distance, and when Polaris makes its daily circle about the North Celestial Pole the star seems to stay more or less in the same place. To see Polaris from anywhere in the northern hemisphere, one must face almost due north. Naturally, Polaris is therefore commonly called the North Star.

The South Celestial Pole is in the constellation Octans (OK-tanz) the Octant (a navigational instrument), and the nearest visible star to the South Celestial Pole is Sigma Octantis (SIG-muh ok-TAN-tis) which is just barely bright enough to be seen with the unaided eye.

TABLE 26

Seasons on Earth and Mars

		LENGTH ON MARS			LENGTH ON EARTH	
NORTHERN HEMISPHERE	SOUTHERN HEMISPHERE	MARTIAN DAYS	EARTH DAYS	NORTHERN WINTER = 1	EARTH DAYS	NORTHERN WINTER = 1
Spring	Fall	194.2	199.2	1.25	92.9	1.04
Summer	Winter	176.8	181.4	1.13	93.6	1.05
Fall	Spring	141.8	145.5	0.91	89.7	1.01
Winter	Summer	155.8	159.9	1.00	89.1	1.00

The Martian axis may be extended to the skies too, but neither one of the Martian celestial poles is near a bright star. The Martian North Celestial Pole is in the constellation Cygnus (SIG-nus) the Swan, while the South Celestial Pole is in the constellation Vela (VEE-luh) the Sails. The Martian North Celestial Pole is near a dim star, too dim to be seen by the unaided eye, that is entered in the star catalogs as BD 52° 2880. The nearest bright star is Deneb (DEN-eb) which is 10 degrees away, ten times as far away from the Martian Celestial North Pole as Polaris is from Earth's. BD 52°2880 is about 38 degrees from Polaris (see Figure 11).

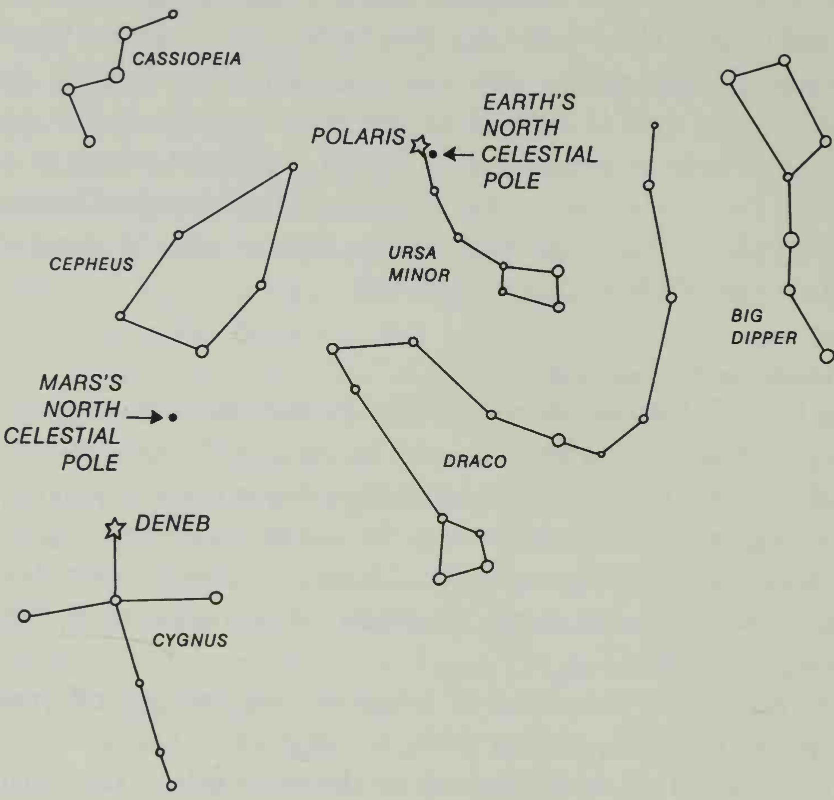
Latitude and Longitude

Like Earth, Mars can be marked off by meridians of longitude and parallels of latitude. There can be north and south latitudes on Mars; with the equator marked as 0 degrees, the North Pole is 90 degrees north latitude and the South Pole is 90 degrees south latitude, just as on Earth. There can also be meridians of longitude with the prime meridian (0 degrees) set at some convenient place.

On Earth, the meridians of longitude are counted off from the prime meridian so that there are degrees of east and west longitude meeting at 180 degrees on the other side of the Earth, opposite to the prime meridian. On Mars, however, it is customary to count the meridians westward from the prime meridian, following the curve of the sphere all the way around till the 360-degree meridian is reached and that corresponds to the prime meridian.

Since the Martian circumference is only 0.53 times that of Earth, the separation between the degrees is 0.53 times that of Earth. The Earth's equator is marked off in 360 degrees of longitude, each degree mark being separated by 111.1 kilometers (69.2 miles). On the Martian equator, each degree mark is separated by 59.2 kilometers (36.8 miles).

Fig. 11—North Celestial Poles



On Earth, the sphere is divided into five zones: a North Frigid Zone surrounding the North Pole; a South Frigid Zone surrounding the South Pole; a Torrid Zone in a central belt about the equator; a North Temperate Zone between the Torrid Zone and the North Frigid Zone; and a South Temperate Zone between the Torrid Zone and the South Frigid Zone.

Mars can be divided in the same way, with a difference that originates in the fact that the Martian axis is slightly more tipped than Earth's. On Earth, the North Frigid Zone includes all those areas where the Sun does not set at all at least one night of the year and does not rise at all at least one day of the year. Because the Earth is tipped by 23.45 degrees, this zone extends for 23.45 degrees from the North Pole in all directions. The North Frigid Zone therefore consists of all the surface of the Earth that is north of 66.55° North Latitude. In the same way, the South Frigid Zone consists of all the surface of the Earth south of 66.55° South Latitude.

On Mars, however, where the axis is tipped 25.17 degrees, the Frigid Zones are correspondingly extended. The Martian Frigid Zones are to be found north of 64.83° North Latitude and south of 64.83° South Latitude.

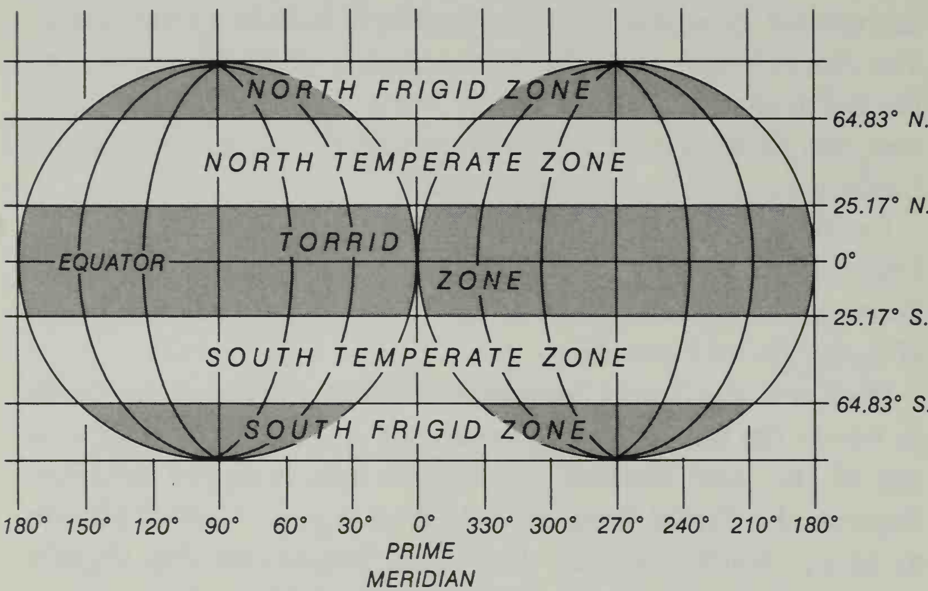
On Earth, the Torrid Zone includes that portion of the Earth in which the Sun is directly overhead at noon on at least one day of the year. Because the Earth's axis is tipped by 23.45 degrees, the Torrid Zone extends from 23.45° North Latitude to 23.45° South Latitude. On Mars, because of the slightly greater axial tipping, the Torrid Zone would be from 25.17° North Latitude to 25.17° South Latitude.

This slightly larger angular size of the Martian Torrid Zone and Frigid Zones are both at the expense of the Temperate Zones. On Earth, the Temperate Zones extend from 23.45° to 66.55° on either side of the equator—a band, in other words, that is 43.10 degrees wide. On Mars, the Temperate Zones extend from 25.17° to 64.83° on both sides of the equator, a band that is 39.66 degrees wide.

Taking into account the fact that Martian degrees are smaller than Earth's degrees, the Temperate Zones on Earth are 4,788 kilometers (2,978 miles) broad from north to south. On Mars, the corresponding figures are 2,337 kilometers (1,453 miles) or just about half the width of the zones on Earth (see Figure 12).

Earth's Temperate Zones have a total area of about 264,-000,000 square kilometers (102,000,000 square miles) or about

Fig. 12—Latitude and Longitude



52 percent of the total area of the Earth. The total area of the Martian Temperate Zones is about 68,600,000 square kilometers (26,500,000 square miles) or about 48 percent of the total area of Mars.

Water and Air

As more and more was learned about Mars, it seemed more and more the smaller, cooler brother of Earth. It was almost our twin in many respects, and in ways that no other planet was. Naturally, the more Mars resembled Earth, the more interested astronomers became—and the more interested the general public became, as well.

There were more similarities to come. Some astronomers had noticed white spots toward the edge of the disc of Mars but had not been able to determine what those spots might be. For Herschel, who had been the first to measure the tipping of Mars's axis in 1781, they were no mystery. Once Herschel had worked out the extent of the tipping, he knew where the Martian poles were. Once he knew that, it was at once clear that the white spots were at the Martian poles, one at the North Pole and one at the South Pole, and at once their nature seemed obvious—they had to be ice.

In 1784 Herschel announced that Mars possessed ice caps at its poles, such as those which existed at Earth's poles. (Actually, not much was known about Earth's ice caps at that time since the polar regions of Earth had not yet been thoroughly explored, but all geographers and astronomers were certain that ice caps were present.)

This was another way in which Mars resembled Earth while other planets did not. The Moon certainly did not have ice caps; in fact, it did not have visible water of any kind. Mercury, so close to the Sun, was almost certain not to have ice caps, and as for Venus, nothing could be seen one way or another through the clouds that shrouded it.

If Mars had ice caps it must have water, and in that, too, it resembled Earth.

Then, too, Herschel had noticed effects on Mars that seemed to show it had an atmosphere as Earth did. The Moon and Mercury did not have an atmosphere. Venus had one but it was perpetually cloud-filled. Only Mars, like Earth, had an atmosphere with a limited cloud cover so that the solid ground of the planet itself could be made out.

As a matter of fact, one can strongly suspect that Mars has an atmosphere simply from its brightness.

If it is known how large a world is, and how far away it is from the Sun, then an observer can calculate how much sunlight will fall upon it. If it is also known how far that planet is from Earth, then an observer can calculate how much sunlight it will reflect to Earth (assuming it reflected every bit of sunlight that fell upon it) and how bright it should seem in the sky.

If the planet is not that bright, that can only be because it does not reflect all the light that falls on it. It absorbs some light instead. (Some light is also absorbed by our atmosphere before it reaches observers on the surface, but that can be allowed for.)

No planet is a perfect reflector, but some are better than others. An atmosphere will reflect more light than bare rock will, and if the atmosphere is particularly cloudy, it will reflect an unusual amount of light.

The fraction of the light falling upon it that a planet will reflect is called the "albedo" (al-BEE-doh) from the Latin word for "white." The albedos of the terrestrial worlds are given in Table 27.

In the case of the Moon, we know that we are dealing with a world without atmosphere and the sunlight is being reflected from bare rock. Only 1/16 of the sunlight is reflected. The rest is absorbed. (Enough is reflected to make the Moon look creamy white, however.)

We can reasonably assume, then, that Mercury, with very nearly the same albedo, also lacks an atmosphere.

Not only does Venus have an atmosphere, as we can easily see in the telescope, but it has a very cloudy one. The clouds are solid and unbroken. It is not surprising then that its albedo is 0.61. It reflects 3/5 of the light that falls upon it; no other body in the solar system does as well.

Earth, which certainly has a thinner and less cloudy atmosphere than Venus does, has an albedo only about 3/5 that of Venus.

As for Mars, it is intermediate. With an albedo of 0.15, it reflects less than half the light that Earth does, but more than twice the light that the Moon does. The conclusion from the albedo alone, then, must be that Mars has an atmosphere but one that is distinctly thinner and less cloudy than that of Earth.

TABLE 27

Albedos

TERRESTRIAL WORLD	ALBEDO	EARTH = 1
Mercury	0.06	0.17
Venus	0.61	1.70
Earth	0.36	1.00
Moon	0.07	0.19
Mars	**0.15**	**0.42**

5

THE SATELLITES OF MARS

Speculations

In one respect, Mars did not seem to resemble Earth. Earth had a satellite, the Moon, but for the first two and a half centuries after the discovery of the telescope, no satellite was found for Mars (or for Venus or Mercury, for that matter).

And yet Earth was not unique among the planets in this respect. Satellites of other planets were discovered. The first were four large satellites of Jupiter. This discovery was made in 1610 by Galileo, and was one of the first discoveries to be made by telescope.

The first satellite of Saturn was discovered in 1655 by Huygens and other Saturnian satellites were discovered later. After the planet Uranus was discovered in 1781 by Herschel, only six years passed before Herschel discovered a couple of satellites to keep it company. When Neptune was discovered in 1846, a satellite accompanying it was discovered in a matter of weeks.

As soon as Jupiter was found to have four satellites,* Johann Kepler, who loved to play with numbers, pointed out that Mars ought to have satellites. If Earth had 1 and Jupiter had 4, then Mars, which was in between, ought to have 2.

Actually, there is nothing to the argument, for the number of

* Nine additional satellites, all small, have been found since.

satellites a planet may have is indefinite and can be any number. Just the same, there is always an attraction to neatness in numbers and Mars's two imaginary satellites cropped up now and then in literature, especially since someone as respected as Kepler had mentioned it.

In 1750, for instance, the French writer Voltaire (vol-TAIR, 1694–1778) wrote a book called *Micromégas* in which giant beings from Saturn and from the star Sirius visited Earth to observe humanity and to marvel at its follies. On their voyage to Earth, Voltaire had them observe Mars's two satellites.

The most famous mention of Mars's imaginary satellites came, however, earlier than that. In 1726 the English writer Jonathan Swift (1667–1745) published *Gulliver's Travels.* In the third part of that book, Swift had Gulliver visit the mythical land of Laputa where the astronomers were supposed to possess advanced telescopes which made it possible for them to discover the two Martian satellites.

Swift's discussion of the two satellites was particularly important because he actually gave his imaginary worlds specific distances from Mars and specific periods of rotation. The values he gave are presented in Table 28.

TABLE 28

Swift's Satellites

	DISTANCE FROM MARS'S CENTER		PERIOD OF REVOLUTION	
SATELLITE	KILOMETERS	MILES	HOURS	MARTIAN DAYS
Swift's Inner Satellite	20,370	12,660	10.00	0.41
Swift's Outer Satellite	33,950	21,100	21.50	0.87

Swift turned out to be surprisingly close to the facts. How had he known? Mystics have tried to make much of this by supposing Swift to have had access to hidden knowledge, or to have some sort of paranormal powers. (Some have even, in joke, suggested he might have been a Martian.)

Actually, there is no secret to Swift's good guess; he was just using his head. As for having Mars have two satellites, that number was in the air, as I said, and the fact that it turned out to be true in the end was pure coincidence. From then on, though, it was just deduction.

Mars is so close to us that if it had good-sized satellites at a reasonable distance from itself, those would have been discovered at once. After all, Jupiter and Saturn are much more distant than Mars is and yet satellites were discovered for both with very primitive telescopes in the 1600s. The conclusion is that if Mars does have two satellites, they must be small so that they are hard to see, and close to the planet so that they are lost in Mars's glare of light.

For that reason, Swift put them close to the planet. Then, if they are close, they must revolve about the planet in short periods. In fact, from the distance, the period of revolution can be calculated by Kepler's third law and Swift refers to it in the passage.*

Discovery

Astronomers, reasoning as Swift did, sought for the satellites close to the planet but failed to find them. For a hundred fifty years after *Gulliver's Travels* was published, failure continued. By 1877 eighteen satellites were known, distributed among five

* To use Kepler's third law accurately, one has to know the strength of Mars's gravitational field and Swift did not know it accurately. Still, he did well enough.

planets. Eight satellites had been discovered for Saturn, four apiece for Jupiter and Uranus, and one apiece for Neptune and Earth.

Mercury and Venus had no known satellites, but the conditions under which Mercury and Venus had to be viewed—usually so close to the Sun and showing only crescents when they were relatively close to Earth—made it difficult to see small satellites if they existed. Apparently none exist, for to this day no satellites have been found circling either Venus or Mercury.

Mars, however, is easy to view, especially at midnight at opposition. It was in the full phase at that time and any satellite would have been in the full phase. A Martian satellite would have had to be very small indeed to escape the telescopes of the 1800s.

In 1877 there was going to be a particularly good opposition of Mars, and astronomers all over Europe and the United States were getting ready to train their best telescopes on the planet.

One of the astronomers was an American, Asaph Hall (1829–1907); it was his intention to use the opposition to search for the satellites. He had at his disposal a refracting telescope with a 26-inch mirror, the largest one of its kind in the world—and the best. When August opened, Hall began to sweep the skies in the neighborhood of Mars as it burned red and bright in the midnight sky.

Hall worked his way systematically inward toward Mars's surface and by August 11 was so close to Mars that its glare was beginning to interfere with his observations. He decided to give up, went home and told his wife, Angelina Stickney Hall, of his decision. Mrs. Hall shook her head. An opposition this good would not come again for many years. "Try it one more night," she said.

Hall agreed to do so, and on that one more night he discovered a tiny moving object near Mars. Unfortunately clouds came in, and he had to wait for five agonizingly suspenseful days for another chance to look. On August 16 he could see the sky again and definitely observed a satellite. On the 17th, he found another.

Hall named the inner one Phobos (FOH-bus), the Greek word for "fear," and the outer one Deimos (DIGH-mus), the Greek word for "terror." In Homer's *Iliad*, Phobos and Deimos are named as the sons of the war-god and it is, of course, appropriate that fear and terror be the children of war.

Phobos and Deimos are as dim in appearance as the smaller satellites of Saturn, even though the Saturnian satellites are some twenty-two times as far away as the Martian satellites are. For the Martian satellites to be as faint as they are, they must be very small indeed.

By 1882 the brightness of the two satellites of Mars had been measured by the American astronomers Oliver Clinton Wendell (1845–1912) and Edward Charles Pickering (1846–1919). Phobos was the brighter and, therefore, was taken to be the bigger one. They were both too small, however, to show as anything but mere dots of light in the largest telescopes.

They were estimated to be only a couple of dozen kilometers across at the most, but for nearly a century after they were discovered there was no way of determining their size accurately. In this chapter, therefore, we will deal with only those properties of the satellites that don't depend on their size. In a later chapter we will come back to these satellites and describe how their size was finally determined and what else was discovered about them.

Satellite Orbits

Even as Swift had guessed, it was the small size of the satellites and their closeness to Mars that had made them so hard to

TABLE 29

The Distance and Rotation Periods of the Martian Satellites

	DISTANCE FROM MARS'S CENTER		PERIOD OF ROTATION	
MARTIAN SATELLITES	KILOMETERS	MILES	HOURS	MARTIAN DAYS
Phobos	9,350	5,810	7.65	0.31
Deimos	23,500	14,600	30.30	1.23

find. The distance of each satellite from the center of Mars and its period of rotation are given in Table 29. If you compare the figures there with those guessed at by Swift, in Table 28, you will see that the agreement isn't as close as some of Swift's more mystical admirers would have us believe, but it's still pretty good.

The closeness of the satellites to Mars is made clear if we compare their relationship to Mars with that of the Moon to the Earth. Whether the distance of the Martian satellites from Mars is compared to the distance of the Moon from the Earth in terms of kilometers or in terms of the size of the planet, you can see from Table 30 that the Moon is far more distant than the Martian satellites. You can see it visually in Figure 13.

In general, the more distant a satellite is from the planet it circles, the weaker is the grip of planetary gravity upon it. We might suppose from Table 30 that the Moon is held far more feebly by Earth than Phobos and Deimos are by Mars. Not so! That leaves out of account the fact that Earth is the larger world and has the more intensive gravitational field.

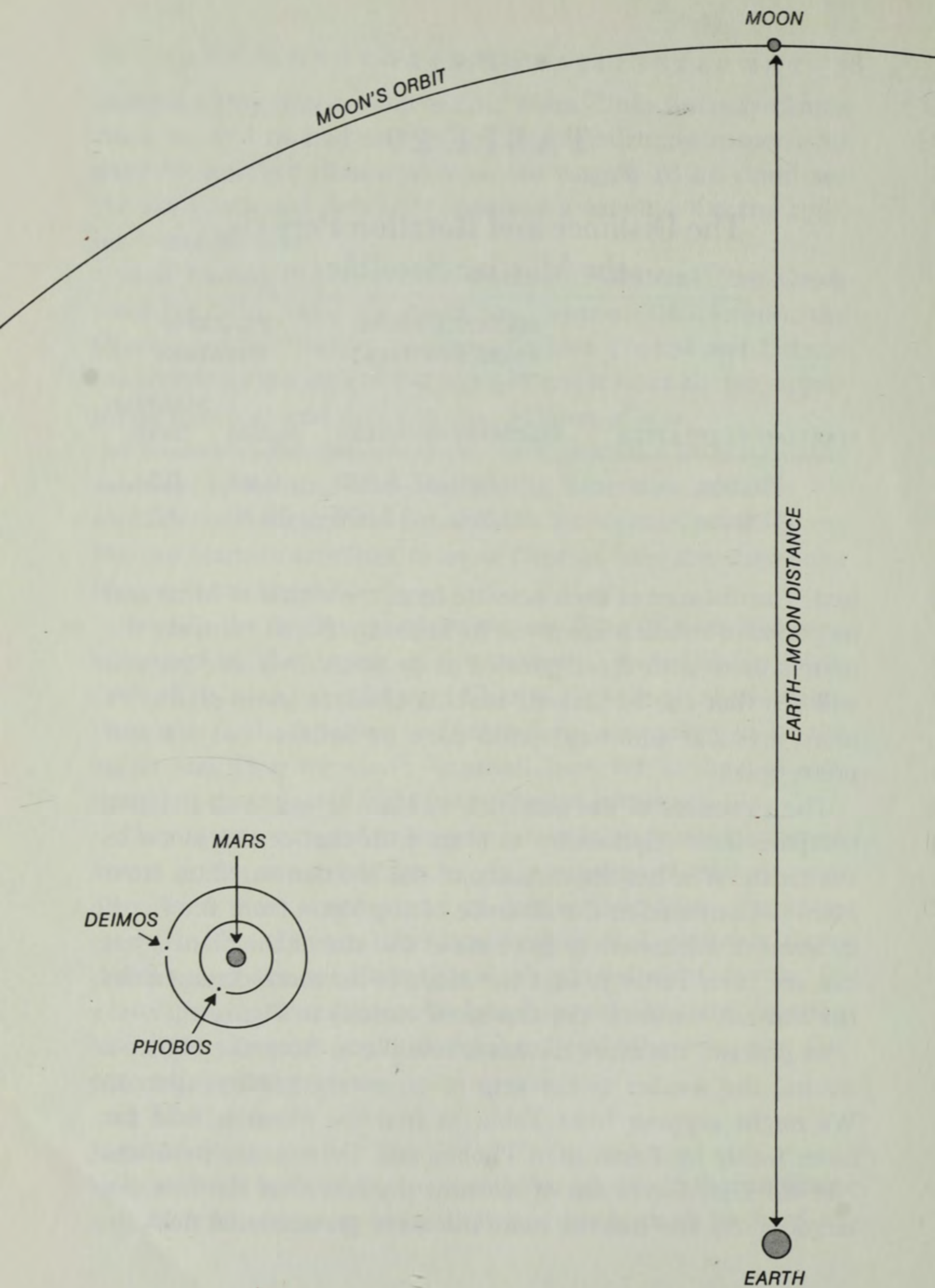


Fig. 13—Satellite Distances

TABLE 30

Satellite Distances

	DISTANCE FROM PLANET	
SATELLITES	DISTANCE OF PHOBOS FROM MARS = 1	PLANETARY RADIUS = 1
Phobos	1.00	2.75
Deimos	2.51	6.91
Moon	41.11	60.27

TABLE 31

Satellite Orbital Speeds

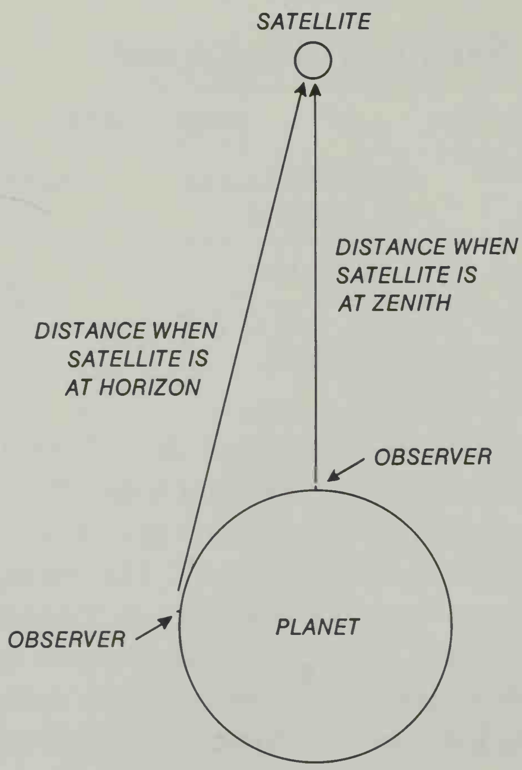
	ORBITAL SPEED	
SATELLITES	KILOMETERS PER SECOND	MILES PER SECOND
Phobos	2.13	1.33
Deimos	1.17	0.73
Moon	1.02	0.64

One way of judging the intensity of the hold of a planet on its satellites is by determining the orbital speed of the satellite as it makes its way around the planet. The faster a satellite moves, the greater the gravitational pull upon it. The orbital speeds of Phobos, Deimos, and the Moon are given in Table 31, and, as you can see, the Moon, for all its great distance from Earth, moves only slightly more slowly than Deimos does.

As we see from Table 30, the Moon's distance from the Earth is just over 60 times the radius of the Earth, and that radius is equal to the distance from the center of the Earth to its surface. This means that as far as observing the Moon is concerned, it makes little difference whether we are at Earth's center or on Earth's surface. The Moon is, on the average, 384,400 kilometers (238,900 miles) from Earth's center, and it is 378,000 kilometers (234,950 miles) from Earth's surface. This is a difference of only about 1.7 percent, which is not much.

When the Moon is at the horizon, an observer on Earth sees it at its full distance from the center, for he is standing on the planet in such a way that a line from the center to himself is

Fig. 14—Satellites at Horizon and Zenith



at right angles to the line from the center to the Moon (see Figure 14). When the Moon is at the zenith, the observer on Earth sees it at its distance from the surface, for he is standing above the center of the Earth, in the direction of the Moon. He is standing, so to speak, on a mountain 6,388 kilometers (3,963 miles) high.

The Moon therefore approaches the observer as it climbs from the horizon to the zenith, but by comparatively so little that there seems to the unaided eye no change in the apparent size of the Moon.*

This is not so in the case of the Martian satellites. They are so close to Mars, compared to the size of the planet, that there is a considerable difference in the distance from the center of Mars as compared with the distance from the surface. Deimos and, even more so, Phobos are much closer when seen at zenith, then, than when seen at the horizon (see Table 32).

As you can see from the table, Deimos is only ⅞ as far from

TABLE 32

Martian Satellites at Zenith

SATELLITE	DISTANCE AT ZENITH: KILOMETERS	DISTANCE AT ZENITH: MILES	DISTANCE AT HORIZON = 1	BRIGHTNESS AT ZENITH (BRIGHTNESS AT HORIZON = 1)
Phobos	5,950	3,700	0.64	2.44
Deimos	20,100	12,500	0.86	1.35

* Actually, the Moon looks considerably larger at the horizon than at zenith but this is what is called "the Moon illusion." Actual measurement shows that the Moon is a trifle wider at zenith than at the horizon.

the observer at zenith as at the horizon, and Phobos is only ⅝ as far. This means that the brightness must increase as each satellite moves from horizon to zenith. Phobos is nearly two and a half times as bright at zenith as at the horizon. The change is less spectacular in the case of Deimos. It increases in brightness only by about a third.

Unfortunately for the Martian observer, the satellites are so small that they are not the impressive sights they might be and the change in appearance is less striking than it would be if the observer were looking at something with the apparent size of our own Moon, for instance. We'll return to this subject in a later chapter.

Across the Martian Sky

The short period of revolution of the Martian satellites, as compared with that of the Moon, for instance, produces interesting effects.

Consider the Moon, to begin with. It revolves about the Earth in the same direction that the Earth rotates. Both move from west to east. The Moon, however, completes its orbit so slowly (27.3 days) compared to the period of Earth's rotation (1 day) that the Earth leaves the Moon behind—far behind—as it rotates. The Moon as seen from the Earth's surface, then, seems to move in the direction opposite from its real motion. It rises in the east and sets in the west.

Deimos, on the other hand, completes its west-to-east rotation in 30.3 hours as compared with Mars's rotation period of 24.7 hours. Mars, as it turns, does overtake Deimos and leave it behind, but only barely. Deimos, because it is overtaken, does indeed rise in the east and set in the west, but it slips back only slowly because it so nearly matches Mars's rotation rate.

Deimos, as it slips from east to west in its barely losing race, takes 65.57 hours to move from rising to setting (about 2.73

Earth-days; 2.66 Mars-days). Then, of course, it takes 65.57 additional hours to move about the other side of Mars and rise again.

Deimos's period of rotation with respect to the Sun is 30.3 hours (like the Moon, it keeps one face to the planet it circles at all times and therefore experiences one rotation relative to the Sun each revolution). This means that Deimos goes through its full cycle of phases, from new to full and back to new, in 30.3 hours. In other words, during the interval that it hangs in the Martian sky between rising and setting, it goes through its complete cycle of phases twice, and a little bit over. If Deimos were large enough to show phases to the unaided eye, that would be impressive indeed. As it is, the effect only causes its brightness to change from maximum at full to minimum at new and back to maximum at full twice over.

This change in brightness because of its phases (as viewed from Mars's surface) is superimposed on the change in brightness that results from its rise to zenith and its fall to the horizon again. And, of course, the Sun crosses the Martian sky at least twice during the period that Deimos remains above the horizon. Deimos is in the dimmer half of its phase change when the Sun is in the sky, and the Sun's presence would tend to wash it out further. What's more, when Deimos was in the full phase it would enter Mars's shadow and be eclipsed.

If we could imagine a race of primitive astronomers on Mars, they would undoubtedly be enormously puzzled by Deimos's behavior and find it difficult indeed to sort out the causes of its changes in brightness.

Phobos is even more remarkable. It completes its period of revolution in 7.65 hours in only about three tenths of a Martian day. It streaks through its circle considerably faster than Mars turns on its axis. It is the only satellite in the solar system that so outpaces the turning of the planet it circles. The result is that

Phobos overtakes the Martian surface and is therefore seen to rise in the west and set in the east. It loses a little ground to Mars, but not much. If Mars did not rotate at all, Phobos would pass from its western rise to its eastern set in half its period, or in three hours and fifty minutes. As it is, with Mars turning, Phobos manages to complete the journey from horizon to horizon in 5.55 hours. It goes about four fifths of the way through a complete cycle of phases as it does so, being eclipsed if this should happen to include the region of the full phase, and washed out by sunlight if it should happen to include the region of the new phase.

Phobos's closeness to the Martian surface adds another peculiarity, which we can understand if we compare its orbit to that of the Moon.

If the Moon's orbit carried it evenly through the Earth's equatorial plane as it circled the planet, the Moon would always pass through the zenith from the viewpoint of anyone standing on Earth's equator. To anyone standing in the northern hemisphere, it would always cut through the southern part of the sky, and to anyone standing in the southern hemisphere, the northern part of the sky. The nearer to the poles the observer was standing, the lower in the sky the Moon would be. From quite near the poles, the Moon would seem to be skimming the horizon as it went around the Earth.

Actually, however, the Moon's orbit is tilted to the plane of Earth's equator to a considerable extent, so that even from the polar regions the Moon can at times be seen quite high in the sky, while at other times it is far below the horizon and invisible.

In the case of Deimos and Phobos, the orbits are tilted only very slightly with respect to the Martian equator (see Table 33). Thus if one went far enough toward the poles, one would expect to see the satellites circling at the horizon—or, to be more precise, lifting above the horizon by a degree or so at one end of the circle, and dropping a degree or so below the horizon at the other end.

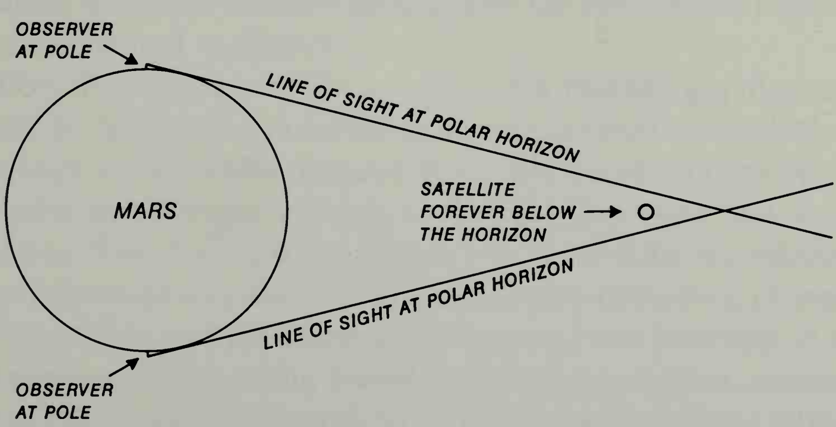
TABLE 33

Orbital Inclination of the Martian Satellites

SATELLITE	ORBITAL INCLINATION (DEGREES)
Phobos	1.1
Deimos	1.8

Actually, it is worse than that. The satellites would be seen from the polar regions of Mars's surface if Mars were a double cone with the wide ends meeting at the equator, providing a smooth straight line from pole to equator. But Mars is a sphere,

Fig. 15—The Hidden Satellites



not a double cone, and bulges between pole and equator. The satellites are so close to Mars that in the neighborhood of the poles the bulge hides the satellites, so that they are *never* seen (see Figure 15).

Anyone standing within 6.5 degrees of either the Martian North Pole or South Pole would never see Deimos.

Phobos, which is closer to Mars, is hidden more effectively still. It cannot even be seen north of 70° North Latitude or south of 70° South Latitude.

6

THE MASS OF MARS

Mass and Density

Every material object has a property called "mass." The simplest way of viewing mass, under ordinary conditions, is as a measure of the quantity of matter contained by an object.

One common way to determine the mass of an object is to determine its response to a gravitational field of known intensity. On Earth, for instance, we determine the mass of an ordinary object by weighing it and seeing how strongly it is pulled down upon by Earth's gravity.

We can't weigh Mars, of course, in this fashion. However, Mars has a gravitational field of its own and if we could determine the intensity of that gravitational field compared to Earth's, that ratio would represent also the ratio of the mass of Mars compared to Earth's.

How do we measure the intensity of a planet's gravitational field? If the planet has satellites, it isn't difficult. A satellite of a planet has a certain distance from that planet and moves in its orbit at a certain velocity. If that satellite were that same distance from Earth, it would move at some different velocity. The difference in velocity is the result of a difference of mass of the planet and therefore a difference in the intensity of its gravitational field. Using Newton's law of gravitation, astronomers can quickly determine what the mass of a planet with a satellite must be.

When a planet does not have a satellite, the matter is more difficult. Such a planet shows gravitational effects on its neighbor planets, and from those effects the mass of the first planet can be determined. However, because such gravitational effects are very small, the calculations are rather uncertain and the mass determined in this way is only approximate.

Mercury and Venus do not have any known satellites. Until recently, the masses of these two nearby planets were not known nearly as well as the masses of distant Uranus and Neptune, which do have satellites.

Mars was in the same class with Venus and Mercury until 1877. Once its satellites were discovered, however, the matter was simplified. With the distance of Phobos and Deimos from Mars known, and with their orbital speeds also known, the mass of Mars could be determined at once.

The mass of the terrestrial worlds is given in Table 34, both in terms of kilograms and of pounds. (A kilogram is equal to 2.205 pounds.)

TABLE 34

Mass

	MASS		
TERRESTRIAL WORLD	TRILLION TRILLION KILOGRAMS	TRILLION TRILLION POUNDS	EARTH = 1
Mercury	0.33	0.73	0.055
Venus	4.87	10.74	0.815
Earth	5.977	13.179	1.000
Moon	0.074	0.163	0.0124
Mars	**0.642**	**1.416**	**0.107**

Where mass is concerned, Mars is even smaller in comparison to Earth than where diameter, surface area, and volume are involved. Mars has only ⅒ the mass of Earth; nevertheless, it has twice the mass of Mercury and eight times the mass of the Moon. (As it happens, Earth has just about as much mass as all four other terrestrial worlds lumped together.)

In comparing volume (see Table 19) and mass, we can quickly see some discrepancies. Mercury has only a third the volume of Mars, yet it has half the mass. Earth has less than seven times the volume of Mars, but it has over nine times the mass.

In Mercury and in Earth, more mass seems to be crammed into a particular volume than in Mars. This is a way of saying that Mercury and Earth are denser than Mars. To determine the density of a planet, one divides its mass by its volume; the results are given in Table 35.

The figures for density in Table 35 are average figures only, of course. The Earth's crust and oceans are much less dense

TABLE 35

Density

	DENSITY		
TERRESTRIAL WORLD	GRAMS PER CUBIC CENTIMETER	POUNDS PER CUBIC FOOT	EARTH = 1
Mercury	5.48	342	0.993
Venus	5.25	328	0.951
Earth	5.52	345	1.000
Moon	3.34	209	0.605
Mars	**3.93**	**245**	**0.712**

than the average. The oceans have a density of only about 1.03 grams per cubic centimeter * (64.3 pounds per cubic foot) and the crust is, on the average, only 2.8 grams per cubic centimeter (175 pounds per cubic foot) in density. The density of Earth-material increases as one goes deeper and deeper, since the weight of material in upper layers is pulled down by Earth's gravitation and squeezes together, or compresses, the layer below, forcing more mass into a given volume.

The outer layers of the Earth are rocky in nature. If Earth were rocky all the way through, even compression by gravity would not bring the average density up to the value we know it has. The inner core of the Earth, however, making up a third of the total mass, is molten metal, chiefly iron with an admixture of nickel. The metal core is considerably denser than the rock layers outside it, and that brings the planet's density up to the high average of more than 5 grams per cubic centimeter.

In this way, from the density figures alone, we can learn something about the general chemical makeup of the planets. Mercury and Venus must, like Earth, have metal cores. The Moon and Mars, on the other hand, can have little or no metal at the core or they wouldn't have so low an average density. The Moon and Mars must be more or less solid balls of rock.

Surface Gravity

Since Earth has 9.31 times the mass of Mars, Earth has a gravitational field that is 9.31 times that of Mars. Any object that is pulled toward Mars with a certain force when it is at a certain distance from Mars, would be pulled toward Earth

* A gram, which is 1/1000 of a kilogram, is equal to about 1/28 of an ounce. A centimeter is 1/100,000th of a kilometer, and is equal to about 2/5 of an inch. A cubic centimeter is equal to about 1/16 of a cubic inch.

with 9.31 times that force if it were at the same distance from Earth.

Mars pulls downward on all objects on its surface, so each surface object has a weight of a certain amount. Earth pulls downward on all objects on its surface, too. The objects on Earth's surface do *not* have 9.31 times the weight they would have on Mars's surface, however, because the two surfaces are not the same distance from the centers of their respective worlds and it is distance from the center that governs the strength of gravitational pull.

An object on the surface of the Earth is 6,370 kilometers (3,960 miles) from Earth's center; while an object on the surface of Mars is only 3,395 kilometers (2,110 miles) from the Martian center. The difference in distance works in favor of a stronger gravitational pull on the surface of Mars because the gravitational intensity increases as the distance decreases; in fact, it increases as the square of the decrease.

The distance from Earth's surface to its center is 1.88 times that of the distance from Mars's surface to its center, and the square of 1.88 is 1.88 × 1.88, or 3.53. Thus the surface gravity of Mars is 3.53 times what it would be if the objects were at the same distance from the center of Earth and of Mars.

Although Earth's gravity is 9.31 times as intense as that of Mars at equal distances, Earth's *surface* gravity is only 9.31 divided by 3.53, or 2.66 times that of Mars's surface gravity. In Table 36, the surface gravities of the terrestrial worlds are given.

The surface gravity figures can be brought home more closely if we imagine a human being weighing 70 kilograms (154 pounds) standing on the surface of each of the terrestrial worlds. His or her weight would in that case be as given in Table 37.

We might say, briefly, that Mars is just halfway between the

TABLE 36

Surface Gravity

TERRESTRIAL WORLD	SURFACE GRAVITY EARTH = 1	MARS = 1
Mercury	0.38	1.01
Venus	0.90	2.40
Earth	1.00	2.66
Moon	0.165	0.44
Mars	**0.375**	**1.00**

TABLE 37

Human Weight

TERRESTRIAL WORLD	WEIGHT OF A 70-KILOGRAM (154-POUND) PERSON KILOGRAMS	POUNDS
Mercury	26.6	58.5
Venus	63.0	138.6
Earth	70.0	154.0
Moon	11.6	25.4
Mars	**26.3**	**57.8**

Moon and the Earth with respect to surface gravity. Earth's surface gravity is roughly two and a half times that of Mars, and Mars's surface gravity is roughly two and a half times that of the Moon.

Oblateness

A large world that does not rotate, or that rotates very slowly, is pulled by its own gravity into a practically perfect sphere. Because of their slow rotations, Mercury, Venus, and the Moon are all just about perfectly spherical. There are unevennesses on the surfaces of these worlds—mountains and gorges and so on—but they represent almost unnoticeable departures from the spherical, the differences in height being very tiny compared to the total width of the world.

Earth and Mars, however, rotate quite quickly, and this produces a "centrifugal effect" ("centrifugal" comes from Latin words meaning "to flee the center"). The centrifugal effect, as the name implies, tends to force matter away from the center of rotation. You can feel this if you whirl a heavy weight tied to a string. The weight will pull at your finger as you whirl, and if you whirl it fast enough the centrifugal effect will break the string. The centrifugal effect increases as the speed of turning increases.

The Earth, or any other spherical body in rotation, turns about an axis, which is an imaginary line passing through the center of the body and emerging at the North and South Poles. The North and South Poles are at the axis and don't move in a circle as the Earth rotates, so there is no centrifugal effect there.

The farther you move away from the pole on the Earth or any rotating world, the farther the surface of that world is from the axis and the faster it must move to make a complete turn in twenty-four hours. That means that the farther you move from either pole, the faster the surface is moving around the axis and the stronger is the centrifugal effect. The surface is moving fastest at the equator. If we consider the centrifugal effect 0 at the poles and 1 at the equator, we can calculate what it would be at any degree latitude, either north or south, and that is given in Table 38.

TABLE 38

Centrifugal Effect

LATITUDE (DEGREES)	RELATIVE STRENGTH OF THE CENTRIFUGAL EFFECT
90 (poles)	0.000
80	0.174
70	0.342
60	0.500
50	0.643
40	0.766
30	0.866
20	0.940
10	0.985
0 (equator)	1.000

The actual speed of motion of a world's surface at the equator is easy to calculate since all you need to know is the circumference of the world and the length of time it takes to make one turn. The speed of motion of the equatorial surface for each of the terrestrial worlds is given in Table 39.

As you can see, the surface speeds at the equator are indeed very small for Mercury, Venus, and the Moon. In the case of Mars, the equatorial speed is more than 130 times that of Venus and you can expect a noticeable centrifugal effect. For Earth, where the equatorial speed is twice that of Mars, you might expect an even greater one.

For any rotating world, the diameter that passes through the center from North Pole to South Pole (the "polar diameter") is the shortest diameter of the planet. That diameter coincides with the axis, so there is no centrifugal effect to lengthen it.

TABLE 39

Equatorial Speeds

TERRESTRIAL WORLD	EQUATORIAL SPEED KILOMETERS PER HOUR	EQUATORIAL SPEED MILES PER HOUR
Mercury	10.84	6.73
Venus	6.51	4.05
Earth	1,669.8	1,037.8
Moon	16.67	10.36
Mars	**865.0**	**537.6**

A diameter passing through the center of a rotating world that ends elsewhere than at the poles is longer than the polar diameter because the centrifugal effect is pushing material away from the axis. If a diameter goes from a point on the equator through the center of the planet to a point on the opposite side of the equator, that "equatorial diameter" is the longest of all, since the centrifugal effect is greatest at the equator.

In Table 40, the polar diameter and equatorial diameter are given for both Earth and Mars. (The other terrestrial worlds are omitted because the centrifugal effect is practically nonexistent, making all their diameters equal. The figures given in Table 16 are both polar and equatorial diameters.)

Since the equatorial diameter on Earth is 42 kilometers (26 miles) longer than the polar diameter, this means a 21-kilometer (13-mile) excess on each side of the Earth. In other words, there is a bulge about the Earth as a result of its rotation. This bulge is thickest at the equator, so it is called an "equatorial bulge." (We can also speak of "polar flattening.") A

TABLE 40

Equatorial and Polar Diameters

	EQUATORIAL DIAMETER		POLAR DIAMETER	
	KILOMETERS	MILES	KILOMETERS	MILES
Earth	12,756	7,928	12,714	7,902
Mars	**6,780**	**4,214**	**6,740**	**4,189**

person standing at sea level on the equator is 21 kilometers (13 miles) farther from the center than a person is when standing at either pole at sea level.

Mars also has an equatorial bulge, one which is almost the same size as that of Earth. Since the Martian equatorial diameter is 40 kilometers (25 miles) longer than the Martian polar diameter, a person standing on the Martian equator is 20 kilometers (12.5 miles) farther from the center than a person standing on either Martian pole, if we disregard minor differences that may exist due to any mountains or ravines.

What counts, of course, is not the thickness of the equatorial bulge, but its thickness as compared to the length of the equatorial diameter. The difference between the two diameters divided by the length of the equatorial diameter is known as the "oblateness." The oblateness of the terrestrial worlds is given in Table 41.

Mars is nearly twice as oblate as Earth since Mars's equatorial bulge is just about as thick as Earth's, yet is built up on a planetary body roughly half the size of Earth.

Why should that be? Since Earth's surface spins twice as fast as Mars's surface (Mars turns just about as quickly, but being a smaller body has only half the distance to turn through) Earth should build up a stronger centrifugal effect.

Earth does do so, but on Mars the weaker centrifugal effect

TABLE 41

Oblateness

TERRESTRIAL WORLD	OBLATENESS
Mercury	0.000
Venus	0.000
Earth	0.0033
Moon	0.000
Mars	**0.0059**

offsets the weaker gravity and can thus have a greater effect than it otherwise might have. For another thing, the smaller the average density of a planet, the easier it is to lift its matter away from the axis of rotation and Mars is distinctly less dense than Earth (see Table 35).

Nevertheless, even if all this is taken into account, Mars still has an oblateness that is too high. It wasn't until just a few years ago that the rest of the explanation was obtained—as we shall see later in the book.

In the case of both Earth and Mars, however, the oblateness is so small as to be noticeable only to careful measurement. If you were to see Mars or Earth from space, neither would show any signs of polar flattening or an equatorial bulge to the unaided eye. They would look as much like perfect spheres as do Mercury, Venus, and the Moon.*

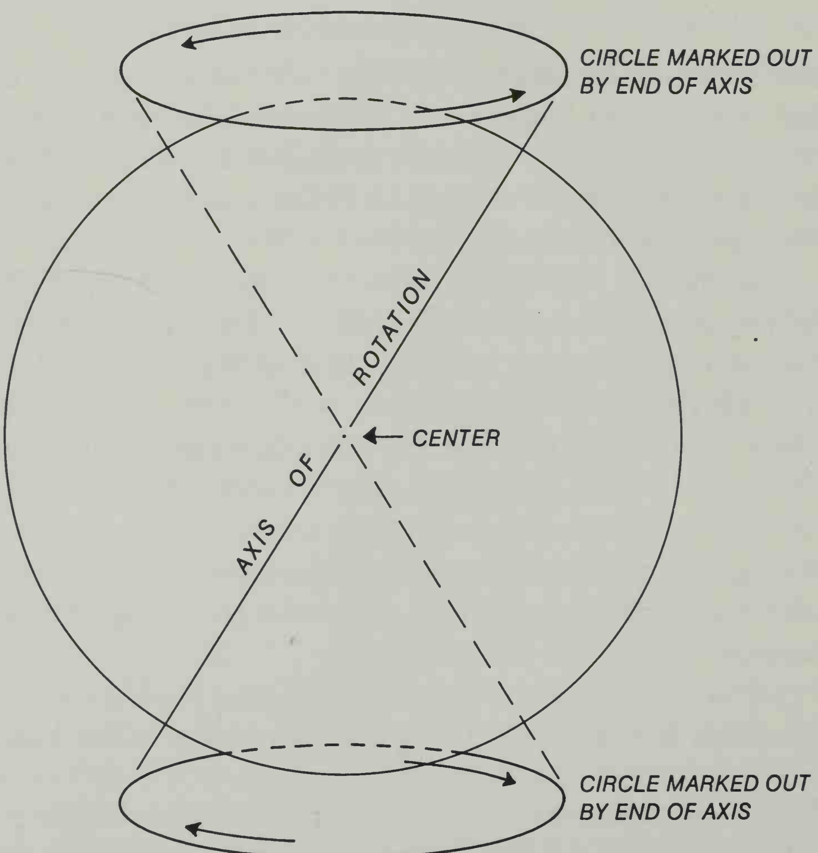
The fact that the Earth is oblate and is not perfectly spherical introduces a complication in its motions. The Moon exerts a

* The outer planets, which turn faster than Earth or Mars and which have lower densities, are much more oblate than any of the terrestrial worlds. The outer worlds actually look oblate to the eye.

gravitational pull on the equatorial bulge of the Earth, in addition to its pull on the Earth generally. So, for that matter, does the Sun, but the Sun's pull is less because it is so much farther away.

These pulls on the equatorial bulge introduce a kind of imbalance so that the Earth's axis of rotation wobbles. The axis stays inclined at 23½ degrees, but both ends of the axis move around in a circle (see Figure 16). This movement is called "precession" and it takes 25,800 years for the Earth to complete one turn.

Fig. 16—Precession



At the present moment the North Celestial Pole, as a result of Earth's precession, is shifting toward Polaris. In 2100 A.D. the North Celestial Pole will skim by Polaris at a distance of only half a degree and will then begin moving away again. It will make a circle in the sky 47 degrees in diameter, and the South Celestial Pole will describe a similar circle at the opposite end of the sky. The celestial poles move about 20 seconds of arc each year and in about ninety years each will have shifted about the apparent diameter of the Moon.

Mars has only small satellites incapable of producing any measurable gravitational effect. The Sun, however, exerts a pull on Mars's equatorial bulge and produces a precession. With nothing like Earth's Moon, and with only the action of a Sun farther from Mars than it is from the Earth, Mars's precession is much slower than Earth's.

The Martian precession takes 97,000 Martian years, or 182,500 Earth years, to complete one turn. The Martian celestial poles drift 3 seconds of arc per Earth year and would take 600 years to move the apparent diameter of the Moon.

Escape Velocity

When we think of the centrifugal effect lifting the surface of a rotating world against its own gravity, we might wonder if a planet could rotate fast enough to tear itself apart.

To see what that would require, let's consider a ball being thrown into the air.

Suppose it is thrown upward with a certain speed. It moves higher and higher, with its speed decreasing continually because of the pull of gravity. Finally, the speed is reduced to zero and the ball goes no higher. Instead it begins to fall, faster and faster, until it is back on the ground. The harder a ball is thrown upward, the faster it moves upward to start with and the higher it reaches before it starts to fall again.

If the Earth's gravitational pull were the same, no matter how high the ball went, the ball would always return to Earth. No matter how rapidly it was hurled upward, gravitation would eventually drain away that speed and cause it to fall again.

Earth's gravitational pull, however, weakens with height as the square of its distance from Earth's center. At Earth's surface, any object is 6,370 kilometers (3,960 miles) from the center. If an object were hurled upward to that distance above the surface, it would be 12,740 kilometers (7,920 miles) from the center. Its distance from the center would have doubled and the force of gravity upon it would be 2 × 2 or 4 times as weak (¼ as strong) as it was on the surface. If the object managed to reach a point three times as distant from the center as the distance from surface to center, the gravitational pull would be 3 × 3 or 9 times as weak (1/9 as strong).

If a ball were thrown hard enough, it would reach heights where gravity was distinctly weaker than it is on the surface. The ball would then lose speed at a slower rate, and attain a greater height before stopping and starting to fall, than we would expect it to do if we didn't take the weakening gravitation into consideration.

In fact, if a ball could be thrown hard enough (far harder than the human arm can throw it), it would rise so rapidly that it would outrace Earth's gravitational field. That is, the ball would climb at such a rate that Earth's ever weakening gravitational field would never manage to slow it all the way to zero. In that case, the ball would never fall back to Earth. It would escape from Earth.

The lowest speed at which this could happen is called the "escape velocity." Any object moving at the escape velocity or more would get away from Earth and not come back. For a world with a weaker gravitational field than Earth's, the escape velocity would be lower; for one with a stronger gravitational field it would be greater. In Table 42 the escape velocities of the terrestrial worlds are given.

TABLE 42

Escape Velocities

TERRESTRIAL WORLD	ESCAPE VELOCITY KILOMETERS PER SECOND	ESCAPE VELOCITY MILES PER SECOND	EARTH = 1
Mercury	4.3	2.7	0.39
Venus	10.4	6.5	0.93
Earth	11.2	7.0	1.00
Moon	2.37	1.47	0.21
Mars	**5.0**	**3.1**	**0.44**

The escape velocity is important in rocketry. The lower the escape velocity, the less the energy required and the less the fuel that must be burned to lift a rocket into space. The Moon has an escape velocity only about ⅕ that of the Earth, and so getting rockets off the Moon is very simple compared with getting them off the Earth. Mars is intermediate in this respect, since its escape velocity is a little over twice that of the Moon and a little less than half that of the Earth.

Another matter of importance in the space age is the question of how quickly an object must move to stay in orbit about a world. This depends partly on how far the orbiting object is from the world. The farther it is from the world, the weaker the world's gravitational field and the slower the object need go to stay in orbit.

Naturally, then, any object orbiting a planet must go fastest if it is doing so just at the surface, moving only high enough to clear the mountains if the planet has no atmosphere. If the planet has an atmosphere, the object must be moving high enough to be outside the atmosphere as otherwise atmospheric resistance would slow its speed and bring it down.

This maximum "orbital velocity" is equal to the escape velocity divided by the square root of 2: that is, by 1.414. In Table 43, the orbital velocities are given for the terrestrial worlds.

TABLE 43

Maximum Orbital Velocities

TERRESTRIAL WORLD	ORBITAL VELOCITY KILOMETERS PER SECOND	ORBITAL VELOCITY MILES PER SECOND
Mercury	3.0	1.9
Venus	7.4	4.6
Earth	7.9	5.0
Moon	1.68	1.04
Mars	**3.5**	**2.2**

An astronaut orbiting the Earth at a height of 150 kilometers (93 miles) where the atmosphere is too thin to interfere with his motion (at least for a time) would be traveling at 7.9 kilometers per second (5.0 miles per second), and it would take him just about 85 minutes to go around the Earth. This would be his orbital period. In Table 44, the orbital periods are given for the terrestrial worlds.

Earth is rotating at such a speed that a point on its equator is moving 1669.8 kilometers per hour (1037.8 miles per hour). This is the same as saying that a point on Earth's equator is moving at about 0.46 kilometers per second (0.29 miles per second).

If the Earth were rotating about 17.3 times as quickly as it

TABLE 44

Minimum Orbital Periods

TERRESTRIAL WORLD	ORBITAL PERIOD MINUTES	ORBITAL PERIOD HOURS
Mercury	84.8	1.41
Venus	85.6	1.43
Earth	84.4	1.41
Moon	108.1	1.80
Mars	**101.4**	**1.69**

is, then it would be turning once every 85 minutes and objects at the equator that were not fixed in place would lift off the Earth and move into orbit. People, animals, and other loose objects would feel no weight at the equator, for the centrifugal effect would completely cancel gravitation. The worst thing

TABLE 45

Orbital Velocity and Equatorial Lift-off

TERRESTRIAL WORLD	ORBITAL VELOCITY FOR EQUATORIAL LIFT-OFF (PRESENT EQUATORIAL VELOCITY = 1)
Mercury	996
Venus	4,080
Earth	17.3
Moon	364
Mars	**14.6**

that would happen would be that the atmosphere would leak off into space.

In Table 45, the amount by which the rotation must be speeded up to bring this about is given for each of the terrestrial worlds.

As you can see from Table 45, Mercury, Venus, and the Moon would have to increase their rotational speeds enormously to be in danger of losing objects at their equators.

The Earth and Mars are closer to that point, though not so close as to cause any worry at all. Interestingly enough, Mars is closer than Earth is. Mars need increase its speed of rotation less than 15 times to begin losing objects at the equator.*

* Saturn, which is the most oblate planet in the solar system, needs to increase its speed of rotation only 6.2 times to start losing objects at its equator.

7

THE MAPS OF MARS

Areography Begins

Mars was the third world whose surface features could be mapped. For all that the astronomers knew in the 1800s, it might well be the last.

The first world was, of course, Earth itself. Maps of the land and sea of that portion of Earth available to explorers had become quite good by the time of the ancient Greeks. In the 1800s, the whole world had been mapped except for the polar regions and the interior of the tropical continents.

The nearest world in space was the Moon. It was very near and had no interfering atmosphere, so the attempt to map it began with Galileo himself, who looked at the Moon through a small and primitive telescope. By the 1800s there were pretty good maps of the Moon, though only of the side that always faced the Earth. As far as astronomers of the 1800s could tell, the far side might very well be hidden from observers on Earth forever.

But what else?

The outer planets beyond Mars were so far away that little detail of their surfaces could be hoped for. In any case, there were no visible surfaces. The outer planets all had thick, clouded atmospheres and if anything could be seen at all, it was merely cloudy streaks and ovals. The satellites of the outer planets were without atmospheres as far as anyone could tell in the 1800s, but they were so far away that no detail at all could be made out on their surfaces.

Among the terrestrial worlds, Mercury was too far away, too small, and too close to the Sun to show much except for an occasional vague shadowy marking. Venus was a featureless globe of snow-white clouds. The satellites of Mars, once discovered, were too small to have anything but a starlike appearance in telescopes. This was also true of the asteroids, while comets showed only as hazy patches.

That left only Mars. No other world at all, outside the Earth and Moon, seemed to have any chance of being mapped by telescope.

Yet Mars was not a simple case either. Mars had an atmosphere which blurred its features. What's more, there were the quiverings and shakings of Earth's own atmosphere to get in the way. Mars had to be telescopically expanded more than the Moon did in order to see its features, and the greater expansion also enlarged the imperfections introduced by the atmosphere.

Nevertheless, astronomers tried. Fontana, Huygens, and Herschel all described what they saw on the Martian surface, though each saw very little.

The description of the Earth's surface is called "geography" from Greek words meaning "Earth-writing." Similarly, the description of the Moon's surface is called "selenography" (seh-leh-NOG-ruh-fee) from Greek words meaning "Moon-writing." About 1800 a German astronomer, Johann Hieronymus Schroeter (SHROI-ter, 1745–1816), who made observations of the Martian surface, invented the term "areography" (air-ee-OG-ruh-fee) from Greek words meaning "Mars-writing," to mean the description of the surface of Mars.

The first real areographer was a German astronomer named

Wilhelm Beer (BAYR, 1797–1850). He was a banker by profession, and one of his brothers was a composer of operas who wrote under the name of Giacomo Meyerbeer.

Beer's hobby was astronomy. He built an observatory and, with the help of an astronomer friend, spent eight years locating the principal features of the Moon with great accuracy, and measuring the heights of a thousand craters and mountains by studying the length of the shadows they cast.

His final map of the Moon, published in 1836, was based on six hundred nights of careful observation and showed the Moon a meter (3.3 feet) in diameter. Through all the years that Beer studied the Moon, not a single change was observed in any lunar feature and that seemed the most convincing evidence yet that the Moon was, in Earthly terms at least, a dead world.

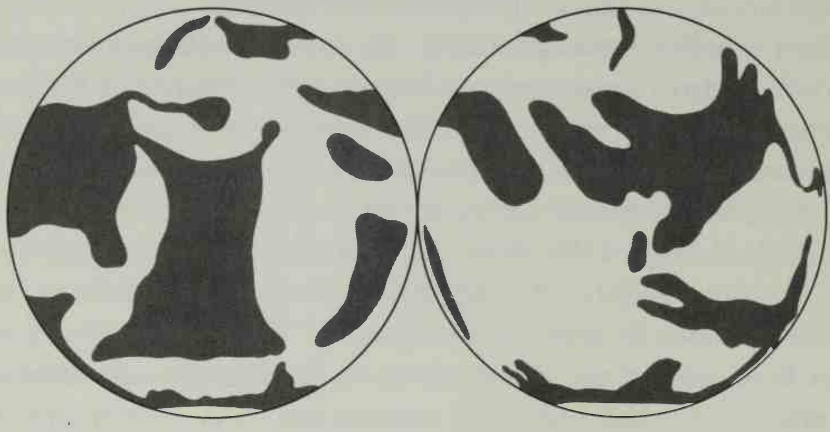
In 1830 Beer began an attempt to map the planet Mars. Though he could see features only hazily, he did his best to show what he could see. There was this advantage at least over his earlier task of mapping the Moon: if one watched Mars night after night, one could eventually see the entire surface of Mars, since Mars rotated with respect to Earth. This was better than the mere half that one could see of the Moon's surface.

Beer was the first to present a map of the entire surface of Mars (see Figure 17). By later standards it was a very poor map, but it was the first to present a pattern of dark and light areas.

Beer was also the first to attempt to divide Mars into latitude and longitude. Latitude was easy. The Martian equator marked the line of 0° and Martian poles were 90° North and South Latitude as on Earth. What about the meridians, though?

On Earth the 0° meridian ("prime meridian") was arbitrarily set as running through Greenwich Observatory near London, with other meridians counted off east and west from that and

Fig. 17—Pattern of Martian Features as Seen by Wilhelm Beer and J. H. von Mädler in 1830-32



meeting at the 180° meridian on the other side of the world. Beer chose a prominent narrow dark marking and set the 0° meridian passing through it. He then marked off meridians westward only, bringing them all the way around the planet till the 360° mark fell on the prime meridian again. Beer's system, with small modifications, has been kept to this day.

Life on Other Worlds

Beer took it for granted that the dark areas were water and the light areas were land. All astronomers did at that time. To be sure, that had been the first assumption with respect to the Moon, too, and in that case it had quickly been shown to be wrong—but Mars seemed different.

The Moon lacked an atmosphere, but Mars had one, and if Mars had enough gravity to hold an atmosphere, it should also have enough gravity to hold water to its surface. Besides, Mars had what certainly seemed to be polar ice caps, which argued the necessary presence of water. In that case, why should not the dark areas be water?

What's more, it would not have surprised people if there were life on Mars. Once the planets were shown to be worlds, many people assumed they were inhabited. In fact, the tendency seemed to be that planets were assumed to bear not only life, but intelligent life and, therefore, humanlike life. It seemed to be a natural feeling that God would not waste a world. If worlds existed, their only purpose, surely, had to be to bear thinking beings.

Romancers inevitably thought so. The first tale we have of flights to another world was written by a Syrian writer, Lucian of Samosata, in the second century. He tells of a ship that was carried up to the Moon by a waterspout. He describes the intelligent beings living on the Moon and tells of the war they were conducting against the intelligent beings of the Sun, conflicting over the attempt both worlds were making to colonize Venus. Science fiction writers have ever since preoccupied themselves with tales of intelligent beings living on worlds other than Earth.

The first evidence astronomers uncovered to the effect that a world might exist, and yet be dead, was in the case of the Moon. Here was a world without an atmosphere, without water, and without change. If there were intelligent life on the Moon, it would have to be radically different from any kind of life we know on Earth. It seemed overwhelmingly likely that there was no life on the Moon at all.

Yet even so, when the *New York Sun* in 1835 ran a series of hoax stories about the Moon, describing Earthlike conditions there and intelligent life, the newspaper found (perhaps to its surprise) that the general public believed the tale. The *Sun*'s circulation boomed until the hoax was exposed.

It was not just the general public that was ready to believe such things, either. Astronomers were pro-life as well. Herschel, who, in the decades immediately preceding and succeeding 1800, was the foremost astronomer in the world, did not even spare the Sun. He suggested that the sunspots were holes in the flaming atmosphere of the Sun; that through those spots the dark and cool surface of the Sun's globe could be seen, and that this dark and cool surface might be inhabited.

But of all the worlds beyond our own, the world which seemed most likely to bear life was Mars. It was, after all, most like Earth. It had the same axial tilt, it had the same rotation period, it had air and it had ice caps, and therefore water. It had seasons like ours and the ice caps could be seen to change appropriately with the seasons, shrinking when it was summer and expanding when it was winter.

There was even reason to suppose that Mars might conceivably be harboring a civilization superior to our own. The basis for such a thought dates back to 1799, when the French astronomer Pierre Simon de Laplace (lah-PLAHs, 1749–1827) put forth his notion on how the solar system began.

He felt that the solar system began as a vast cloud of dust and gas which slowly swirled and which, under the influence of its own gravitation, slowly came together and shrank into a smaller and smaller volume. As it shrank, it rotated faster and faster, in accordance with a natural law called "the conservation of angular momentum." Finally the cloud was swirling so fast that the centrifugal force lifted material from its equatorial bulge. A ring of matter was given off which condensed to form a planet.

The cloud continued to shrink and speed up its rotation, giving up ring after ring of matter, and forming planet after planet, until what was left condensed to form the Sun.

Laplace pointed out a cloudy object in the sky called the "Andromeda Nebula" (an-DROM-uh-duh NEB-yuh-luh), which seemed to be swirling, and offered it as an example of a planetary system in the process of formation. His suggestion is therefore known as the "nebular hypothesis."*

By the nebular hypothesis, as Laplace described it, it would seem that the outermost planet was the oldest, and that as one traveled inward toward the Sun, the planets grew younger and younger. Earth was, in other words, younger than Mars, and Venus was younger than Earth.

Viewed from that angle, it was easy to assume that Venus was as yet a primitive world, still cloudy and dank. Perhaps it was a jungle world in which dinosaurs clumped through swamps and in which the light of reason and intelligence had not yet made its appearance. Indeed, science fiction authors routinely used this picture of Venus well into the 1950s.

Mars, by this same line of thinking, would have to be an aged world, in which intelligent beings had reached and passed the present stage of human beings on Earth millions of years ago. Mars was supercivilized, with its intelligent beings perhaps weary of life, perhaps godlike and beneficent, perhaps awesomely powerful and evil.

The fact that the planet was reddish in color and was named for the war-god rather inclined people to believe the last possibility. That fearful view of Mars was common enough among science fiction writers again until well into the 1950s.

This acceptance of life on other worlds, and on Mars particularly, influenced the areographers and encouraged them to try to devise a map of Mars that resembled, as much as possible, a map of the Earth, with the same kind of features on one as on the other.

* "Nebula" is the Latin word for "cloud" and the particular nebula referred to is in a constellation called Andromeda, hence its name. Over a century later, the Andromeda Nebula was found to be not a planetary system in formation, but a vast cloud of two hundred billion stars—a large galaxy. Still, the nebular hypothesis wasn't a bad idea. Nowadays, astronomers think the solar system was formed from an original cloud of dust and gas but in such a way as to form the Sun and all the planets simultaneously.

Names on the Map

During the oppositions in the mid-1860s, there was a rash of observations of Mars. New maps were drawn and, in general, they tended to be quite different from Beer's maps and from each other. The truth was that the telescopes used were still not quite good enough to make up for the confusing effects of two atmospheres, our own and Mars's, and no two astronomers saw the same thing.

In 1863 the Italian astronomer Pietro Angelo Secchi (SAY-kee, 1818–1878) tried to draw what he saw, in color. Until then, astronomers had drawn black on white—but on Mars the light areas were pinkish rather than white, and the dark areas were usually thought to be a rather grayish-green.

Secchi, like others before him and after him, saw the dark areas as broad in places and as narrow in other places. There were places where the dark areas tailed off into rather narrow markings, straight or curved.

This was not really surprising. If Mars had seas as Earth has, why shouldn't it have narrow arms of the sea, narrow inlets bordering the continents, narrow straits—all of which exist on Earth? Some narrow parts of the Earthly oceans are called "channels," as, for instance, the English Channel between Great Britain and France. Secchi therefore referred to those narrow dark markings as "channels" in 1869. He was the first to do so. Of course, he used the Italian word for it, and that happened to be *canali*. At the time, the use of the word didn't make much of a stir.

In November 1864 there was a middling good opposition of Mars, and an English astronomer, William Rutter Dawes (1799–1868), produced a series of drawings of Mars that seemed better than those of Beer and that looked completely different.

Dawes was also able to show that the reddish color of Mars was not due to anything in its atmosphere. The redness had to be in the Martian soil. That was about the first finding concerning the composition of the Martian atmosphere, and it was negative. It just told us what the atmosphere *didn't* have: it didn't have anything red in it.

By the 1860s, however, chemists had worked out the science of "spectroscopy" (spek-TROS-kuh-pee). In this technique, light from any object can be spread out into a rainbow. Light is made up of tiny waves of different lengths and in the rainbow, the light is spread out in the order of increasing wavelengths from violet to red.

Different substances give out particular wavelengths of light when heated, or, under some conditions, absorb them. The result is that a rainbow of light, or a "spectrum," can contain bright lines against a dark background or dark lines against a bright background. From the exact position of the lines, scientists can determine the nature of the substance that is emitting the light or absorbing it.

In 1867 an English astronomer, William Huggins (1824–1910) and a French astronomer, Pierre Jules César Janssen (zhahn-SEN, 1824–1907), tried to work with light from Mars to see whether they could detect particular substances in the Martian atmosphere. Assuming it was like Earth's atmosphere, they were on the particular lookout for oxygen and water vapor. They failed, and that was the first indication that Mars's atmosphere might be chemically different from Earth's. However, the technique was still very new and its results were uncertain.

The most important bit of areography in the 1860s was performed by an English astronomer, Richard Anthony Proctor (1837–1888). He observed Mars and prepared an elaborate map of the planet, one which didn't look like any of those prepared by others earlier. He introduced something new, though. He gave names to the various markings he saw.

The various features on the Moon had been named two centuries before, and the craters, in particular, had been named for astronomers. Proctor therefore adopted the same practice for Mars, choosing those astronomers who had been involved in the study of Mars.

He called the light areas "continents" and "lands," and the dark areas he called "oceans" and "seas." He placed on the map a "Herschel Continent," for instance, and named other light areas after Secchi, Kepler, Cassini, Lockyer, Fontana, and Laplace. The dark areas he named after Beer, Tycho, Newton, Huggins and so on. He had a "Dawes Continent," a "Dawes Ocean," and a "Dawes Forked Bay" (see Figure 18).

Proctor's notion of naming the Martian features persisted, but the names he chose have been abandoned. Astronomers generally were annoyed by his selection of names. On the whole, they felt he had favored English astronomers too much.

Well aware that all the maps prepared by areographers through the 1860s were different from one another, astronomers waited eagerly for the opposition of 1877, which was going to be particularly good. As I explained earlier in the book, Asaph Hall discovered the two satellites of Mars when the opposition

Fig. 18—Pattern of Martian Features as Seen by Richard A. Proctor in 1867

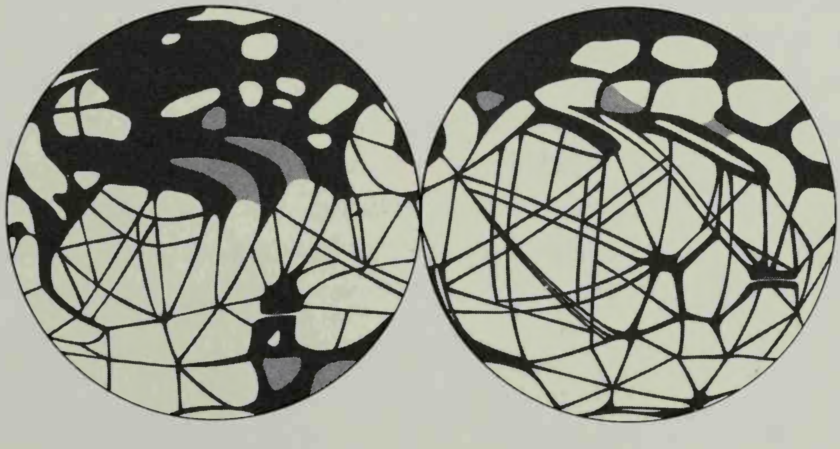
of 1877 finally arrived—but that was by no means the only important discovery announced in that year.

In 1877 small white spots near the edge of the planet could be seen to be separated from the actual body of the planet. Observers were looking between the spots and the planet, so it was clear that they were clouds floating in the Martian atmosphere. It was another similarity between Mars and Earth, though it was plain that the Martian atmosphere was far less cloudy than Earth's, so that Mars must be a considerably dryer planet.

The star of the 1877 opposition, however, was an Italian astronomer, Giovanni Virginio Schiaparelli (skyah-pah-REL-lee, 1835–1910).

Schiaparelli had an excellent telescope, an excellent opposition during which to work, and he made painstaking measurements. He finally managed to draw a map of Mars (see Figure 19) that, once again, looked altogether different from anything that had been drawn before, but this time, the map settled down. It turned out that what Schiaparelli saw, later astronomers also saw, and the features that Schiaparelli drew were retained for almost a century, until astronomers dis-

Fig. 19—Pattern of Martian Features as Seen by Giovanni Schiaparelli in 1877-88



covered something better than telescopes with which to observe Mars.

What's more, Schiaparelli gave the features of Mars's surface names that were accepted by other astronomers. Schiaparelli had learned from Proctor's mistake, and avoided using the names of astronomers. Instead, since he was a student of ancient history, he went back to the days of early Egypt, Greece, and Rome for his names. On the map of Mars he placed names like Thoth (an Egyptian god), Edom and Moab (kingdoms near ancient Israel), Phlegra and Styx (mythical rivers in the Greek underworld), Arcadia and Aeolis (districts in ancient Greece), Libya and Meroe (districts in ancient Africa), and so on.

No one could quarrel with that, and no one did.

8

THE CANALS OF MARS

Schiaparelli's Canali

Schiaparelli, in observing Mars, had noticed, as had Secchi before him, that there were rather thin, dark lines present on Mars. To Schiaparelli, it seemed that they connected larger dark areas, in the way that straits or channels connect two seas. Schiaparelli therefore called them channels as Secchi had done, and also used the Italian word *canali* for the purpose.

What was different about Schiaparelli's *canali* was that he saw so many of them. Others before him, even Secchi, had seen only an occasional dark streak, usually rather short and thick. Schiaparelli, however, saw them long and in considerable numbers, perhaps forty altogether. He included them on his map and gave them the names of rivers in ancient history and mythology.

Perhaps because people had awaited the 1877 opposition with such expectations, and perhaps because the discovery of the satellites of Mars had been so exciting, Schiaparelli's map and his *canali* were greeted with great interest and enthusiasm.

Nobody besides Schiaparelli had seen the *canali* in the course of the 1877 opposition, but afterward astronomers started looking for them in particular and some reported seeing them. What's more, the word *canali* was translated into the English word "canals."

That was important. A channel is any narrow waterway, usually a naturally formed body of water. A canal, however is a narrow, artificial waterway built by human beings. As soon as Englishmen and Americans began calling the *canali* "canals" instead of "channels," they began automatically to think of them as being artificial and therefore as having been built by intelligent beings.

At once there came to be enormous new interest in Mars. The feeling that other worlds ought to be populated by intelligent beings was heightened, and it seemed as though astronomers were on the verge of presenting scientific proof for this feeling—at least as far as Mars was concerned.

Another line of thought in connection with Mars began to become popular at about this time. The dark areas were, perhaps, not open bodies of water after all.

In the 1870s, chemists were beginning to understand how rapidly atoms and molecules moved. Light atoms and molecules moved more rapidly than heavy ones, and light atoms and molecules might actually move faster, at times, than the escape velocity of a particular world. An atmosphere could, in that case, leak away into outer space.

Earth's gravity, for instance, can hold the light molecules of oxygen and nitrogen, but it could not hold the even lighter, more rapidly moving atoms of helium and molecules of hydrogen. That is why there are only traces of hydrogen and helium left in Earth's atmosphere.

The Moon's gravity, on the other hand, is so weak that its escape velocity is only one fifth of Earth's. Oxygen and nitrogen molecules, which move at speeds far less than Earth's escape velocity, move at speeds considerably closer to the Moon's escape velocity. This is especially so on the side of the Moon exposed to the Sun, for all atoms and molecules of gases move faster as they are heated. For that reason, the Moon has no atmosphere at all.

Mars is intermediate between Earth and Moon in that respect. Its atmosphere leaks away far more rapidly than Earth's does, but not as rapidly as the Moon's. That is why Mars still has an atmosphere, but one that is thinner than Earth's.

What's more, water vapor molecules can leak off into space as well, so that while Earth has vast oceans, the Moon is waterless. Again, Mars would have to be intermediate. It has some water, as is shown by the ice caps, but probably not enough to allow seas and oceans to exist.

What were the dark areas, then? People began to speculate that they might be vegetation, growing because the Martian surface was being carefully irrigated by water obtained from the ice caps which represented most of what water was still left on the planet. The canals carried water across desert areas and were seen not so much as themselves, but as bands of vegetation growing parallel to each side of the canal (just as vegetation parallels the Nile River where it crosses the desert.)

The picture created by the consideration of the canals on Mars, then, was of an old planet, a planet older than Earth according to the nebular hypothesis, a planet on which life had been evolving longer and had attained rational and intellectual heights surpassing those of Earth's human beings who had come later on the scene. As Mars slowly dried out, the intelligent Martians strove heroically to keep the planet alive. They built huge canals to transport needed water across the deserts.

It was a very dramatic picture of an ancient race of beings, perhaps a dying race, refusing to give up and keeping their world alive by resolution and hard work. For half a century and more this view remained popular with many people, and even with a few astronomers.

Lowell's Martians

There were astronomers who added to Schiaparelli's reports.

The American astronomer William Henry Pickering (1858–1938) reported round dark spots where canals crossed, and these were called "oases." The French astronomer Nicolas Camille Flammarion (flah-mah-ree-OHN, 1842–1925) was particularly enthusiastic about the canals. In 1892 he published a large book called *The Planet Mars* and in it he argued in favor of a canal-building Martian civilization.

By far the most influential supporter of the notion of Martian canals and of an advanced civilization on that planet was an American astronomer, Percival Lowell (1855–1916).

Lowell was a member of an aristocratic Boston family. His sister was Amy Lowell, a first-rate poet, and his brother Abbott Lawrence Lowell was a political scientist who eventually became the president of Harvard University.

Lowell was only an amateur astronomer to begin with; it was something he had dabbled in as a boy. However, Schiaparelli's discoveries filled him with excitement and astronomy became the passion of his life. Since he was a man of independent wealth, he could do something few professional astronomers could do. He could establish a private observatory in Arizona, where the mile-high dry desert air and the remoteness from city lights made the visibility excellent. The Lowell Observatory was opened in 1894.

For fifteen years Lowell avidly studied Mars, taking thousands of photographs of it. There was no question that he saw the canals, or thought he did. In fact, he saw many more canals than Schiaparelli ever did, and he drew detailed pictures that eventually included over five hundred canals. He plotted the oases at which they met, recorded the fashion in which the individual lines of particular canals seemed to double at times (Schiaparelli had noticed this in 1879), and studied the seasonal changes of light and dark which seemed to mark the ebb and flow of agriculture. He was completely convinced of the existence of an advanced civilization on Mars.

Nor was Lowell bothered by the fact that other astronomers couldn't see the canals as well as he could. Lowell pointed out that no one had better seeing conditions than one could get in Arizona, that his telescope was an excellent one, and that his eyes were equally excellent.

In 1894 he wrote his first book on the subject, which he called simply *Mars*. It was well written, it was clear enough for the general public, and it supported the notion of an ancient, slowly drying Mars; of a race of advanced engineers keeping the planet alive with gigantic irrigation projects; of canals marked out and made visible from Earth by the bands of vegetation on both borders.

Lowell's views were made even more extreme in later books he wrote on the subject—*Mars and Its Canals* in 1906 and *Mars as the Abode of Life* in 1908. Though most astronomers were extremely skeptical of Lowell's theories, the general public found them exciting. The thought of a planet that was populated by an advanced intelligence was dramatic.

Lowell's role in making advanced Martians popular was outpaced, however, by someone who was not an astronomer at all, but an English science fiction writer. His name was Herbert George Wells (1866–1946), and he is better known as H. G. Wells.

In 1897 Wells published a novel called *War of the Worlds* in serial form in a magazine, and the next year it appeared in book form. It combined the view of Mars as presented by Lowell with the situation as it had existed on Earth over the preceding twenty years.

In those decades, the European powers—chiefly Great Britain and France, but including also Spain, Portugal, Germany, Italy, and Belgium—had been carving up Africa. Each nation established colonies with virtually no regard for the wishes of the people already living there. Since the Africans were dark-skinned and had cultures that were not European, the Europeans considered them inferior, primitive, and barbarous and simply disregarded them.

It occurred to Wells that if the Martians were as far advanced scientifically over Europeans as Europeans were over Africans, the Martians might well treat Europeans as Europeans treated Africans. *War of the Worlds* was the first tale of interplanetary warfare involving Earth.

Until then, tales of visitors to Earth from outer space had pictured those visitors as peaceful observers, as in Voltaire's *Micromégas*, for instance. In Wells's novel, however, the outsiders came with weapons. Fleeing a Mars they could barely keep alive, they arrived at lush, watery Earth and prepared to take over the planet to make it a new home for themselves. Earth people were merely animals to them, creatures whom they could destroy and devour. Nor could human beings defeat the Martians or even seriously interfere with them, any more than the Africans could deal with well-armed European armies and navies. Though the Martians were defeated in the end, it was not by human beings, but by Earthly decay bacteria which the Martians' bodies were not equipped to resist.

It was a powerfully written story, and somehow reinforced the age-old suspicion of a planet whose ruddiness struck people as being associated with blood, war, and death. Wells's novel, and the tales of many other science fiction writers who followed him and who wrote in his image, convinced the general public that Mars bore life: intelligent life—even dangerous life.

On October 30, 1938, for instance, nearly forty years after *War of the Worlds* was published, Orson Welles, only twenty-three years old at the time, produced a radio dramatization of the story. He chose to bring the story up to date, and had the Martians land in New Jersey rather than in Great Britain. He told the events in as realistic a fashion as possible, with authentic-sounding news bulletins, eye-witness reports, and so on.

Anyone who had turned the program on at the start would have been informed that it was fiction, but some weren't listening closely enough and others turned it on after the start and were transfixed at the events that were apparently taking place—especially those who were near the sites of the reported landings.

A surprising number of people did not pause to question whether it was at all likely that there was an invasion of Martians, or whether there were even Martians at all. They took it for granted that Martians existed and had arrived to conquer Earth and were succeeding—and fled in terror.

Orson Welles had to apologize. He had never thought anyone would take the program seriously, not having realized just what Lowell and Wells, between them, had accomplished.

Opposition to the Canals

Though Lowell and his theories were successful with the general public, professional astronomers were extremely doubtful. At least, the large majority were.

A number insisted that though they looked at Mars carefully, they never saw any canals, and they were not soothed by Lowell's lofty assurance that their eyes and telescopes just weren't good enough. Asaph Hall, whose eyes and telescope had been good enough to discover the Martian satellites, never saw a canal.

One American astronomer, Edward Emerson Barnard (1857–1923), was a particularly keen observer. In fact, he is often regarded as the astronomer with the sharpest eyes on record. In 1892, for instance, he discovered a small fifth satellite of

Jupiter, more than 160 kilometers (100 miles) in diameter, and closer to Jupiter than the four large satellites that had been discovered nearly three hundred years before.*

To see Jupiter's fifth satellite—so small, so distant, and so close to the brightness of Jupiter itself—required eyes of almost superhuman keenness; yet Barnard insisted that no matter how carefully he observed Mars, he could never see any canals. He said flatly that he thought it was all a mistake; that small irregular patches of darkness were made into straight lines by eyes straining to see them at the very edge of vision.

This notion was taken up by others. An English astronomer, Edward Walter Maunder (1851–1928), even put it to the test in 1913. He set up circles within which he put smudgy irregular spots and then placed schoolchildren at distances from which they could just barely see what was inside the circles. He asked them to draw what they saw and they drew straight lines such as those Schiaparelli had drawn of the Martian canals.

Other astronomers took the attitude that it didn't matter whether anyone saw canals or not. Whatever the canals were, they could not be evidence of an advanced race of intelligent beings on Mars because Mars was uninhabitable.

In 1907, for instance, the biologist Alfred Russel Wallace (1823–1913), who, with Charles Robert Darwin (1809–1882) had advanced the theory of evolution a half-century before, wrote a review of Lowell's *Mars and Its Canals*. The review expanded into a 110-page furious denunciation. Wallace insisted that Mars could not retain water, that it was bone-dry and uninhabitable. If canals existed at all, they were markings that represented wide cracks in the surface produced by the drying and shrinking of the outer layers of the planet.

But if there was no water on Mars, what about the ice caps?

* It was the last satellite to be discovered by eye. Since then, new satellites —all small ones—have been discovered only by photography.

An Irish physicist, George Johnstone Stoney (1826–1911) suggested that Mars was colder than people thought and that the caps might be not ice at all, but frozen carbon dioxide.

Then what about the changes in the appearance of Mars with the seasons? What about the expansion of dark areas as the ice caps melted, an expansion that looked like the spreading of vegetation?

A Swedish chemist, Svante August Arrhenius (ahr-RAY-nee-us, 1859–1927), pointed out that since there was little water on Mars, what water there was might be filled with chemicals in solution which would gradually settle out as water froze in the Martian winter. With the Martian spring, when liquid water reappeared, the light-colored crystals might form a darker solution.

Was there any way of settling the matter between people like Lowell and his followers, who thought that conditions on Mars were bearable and that an advanced civilization existed, and people like Wallace and his followers, who thought that conditions on Mars were unbearable and that no life at all existed there?

What about the canals? If they were really there, intelligent Martians were an attractive explanation; if they were not there, there was no reason at all to think of intelligent Martians.

The astronomers of the 1880s and 1890s couldn't decide the matter, but the art of telescope-making didn't stand still. There was hope that newer, larger, better telescopes in the 1900s might settle the matter once and for all.

An American astronomer, George Ellery Hale (1868–1938), was the moving spirit behind the designing and construction of the large telescopes of the twentieth century. He was a persuasive gentleman who could always manage to get people to contribute the money required to build them.

In 1892, for instance, he talked a hardheaded American financier, Charles Tyson Yerkes (YER-keez, 1837–1905), into putting up the money for a large observatory to be built in Williams Bay, Wisconsin. There a 40-inch refracting telescope was built, the largest telescope of that type built up to that time, or since.

Hale was not satisfied. He established an observatory at Mount Wilson, near Pasadena, California, and there installed a 60-inch reflecting telescope in 1908. In 1911, the keen-eyed Barnard went to Mount Wilson and had the use of the new 60-incher, the largest in the world of any type, for the study of Mars.

It was no use. Barnard could not see the surface of Mars clearly enough to decide the matter of canals. There was nothing wrong with the 60-incher, and for studying the stars it was excellent. For trying to study the surface details of a planet through two atmospheres, however, it fell short. It magnified atmospheric interferences along with the Martian surface.

In later years, Hale was responsible for still larger telescopes: the 100-incher at Mount Wilson, and eventually a 200-incher at Mount Palomar. Neither one would be used to settle the controversy over Martian canals.

As late as the 1950s it seemed as though there would be no way, ever, of settling the matter. Most astronomers suspected that the canals did not exist, but they could not be certain.

Habitability?

The question of intelligent life on Mars might be tackled from the other end.

As Mars was studied with better and better instruments, it might become possible as the years passed to learn so much about the nature of its properties that astronomers could decide that it wasn't a habitable planet. If there could not be any life on it, there certainly could not be any intelligent life on it.

As astronomers advanced into the twentieth century, for instance, instruments were devised which could detect and measure tinier and tinier quantities of heat. It became possible to place such heat-detectors at the focus of a telescope and allow the light of Mars, for instance, to fall upon it. From the distribution of various wavelengths in the light, the temperature of Mars could be deduced.

This was first done in 1926 by two American astronomers, William Weber Coblentz (1873–1962) and Carl Otto Lampland (1873–1951). From such measurements, it seemed that at the Martian equator the temperature rose above 0°C. (32° F.), which is the melting point of ice. At times, when Mars was at perihelion, the temperature might even be what we would consider mild, reaching 25° C. (77° F.) at the equator.

The temperature dropped sharply during the night, however. There was no way of following the temperature at night, for the night side of Mars was always on the side not facing Earth. However, the temperature of the early morning could be taken at the western edge of the Martian globe where the surface of the planet was just emerging from night and into the dawn. After twelve and a quarter hours of dark, the temperature could be as low as −100° C. (−150° F.).

In short, the work of Coblentz and Lampland made it seem that though there were times and places that produced enough mildness to allow water to exist as a liquid, the Martian night was as cold as Antarctica.

This was a bad sign for complex life forms.

Worse yet, the great difference between dawn temperature and noon temperatures meant that the Martian atmosphere was probably thinner than had been expected. An atmosphere acts as a blanket, absorbing and transferring heat. The thicker the atmosphere, the less likely it is, all other things being equal, that the temperature will go up and down very quickly.

The Moon, for instance, is at the same distance from the

Sun that the Earth is, yet the Moon's temperature rises and falls much more rapidly than the Earth's does. During the sunlit period the temperature of some places on the Moon can reach the boiling point of water. If, however, the Earth eclipses the Moon, and the heat from the Sun is cut off for an hour, the Moon's temperature can drop perhaps 200 Celsius degrees (350 Fahrenheit degrees).

While Mars doesn't show temperature change to that extreme, the amount of temperature change that does take place shows the atmosphere to be thinner than had been expected, and that, too, is a point against habitability.

Nor does that end matters. A thin atmosphere introduces still another disadvantage as far as habitability is concerned.

Our atmosphere absorbs the more energetic and dangerous portion of the ultraviolet radiation of the Sun. Were that radiation to reach Earth's surface unabsorbed, many forms of Earthly life would not survive. Primitive one-celled life might not have formed on Earth in the first place.

Although Mars is farther from the Sun and receives less radiation from it than Earth does, more dangerous radiation reaches the surface of Mars through its thin atmosphere. That, too, argues against habitability.

Still later, it became possible to tell something about the chemical composition of the Martian atmosphere. Huggins and Janssen had failed in 1867 because they used ordinary visible light, and the kind of gases likely to occur in the atmosphere of Mars are so transparent to that kind of light that they don't absorb any of the wavelengths and therefore don't reveal their presence.

By the 1940s, however, techniques had been devised for analyzing the infrared light that arrived from the planets. Infrared light possesses waves longer than those of visible light; waves too long to be visible to the eye, so that they have to be detected by special instruments. Those instruments can tell what wavelengths are present or missing, and in this way gases in the atmosphere might be detected.

Naturally it is difficult to tell whether the absorbing gases are in Mars's atmosphere or in Earth's, since light from Mars must travel through both atmospheres to reach us. Still, there were ways of subtracting the known effect of Earth's atmosphere and then assuming that what was left over was to be blamed on Mars's atmosphere.

In 1947 the Dutch-American astronomer Gerard Peter Kuiper (KOY-per, 1905–1973) used infrared spectroscopy to identify a gas in the Martian atmosphere for the first time. It was carbon dioxide, a gas which is present in small traces in Earth's atmosphere.

In a way this was hopeful, because carbon dioxide is essential to the growth of plant life. On the other hand, it raised the suspicion that Stoney might have been right and that the ice caps were frozen carbon dioxide rather than frozen water.

Kuiper's analysis of Mars-light, however, led him to believe that the ice caps were frozen water. Still, the amount of water vapor in the Martian atmosphere was so tiny that it didn't seem as though there could be any liquid water on the surface, just ice and vapor. That seemed to be a strong point against canals.

What's more, Kuiper could not detect either nitrogen or oxygen in the atmosphere. If the Martian atmosphere did not contain oxygen, that was a strong point against animal life and therefore against the canals, since it didn't seem reasonable to suppose that the canals had been built by intelligent plants.

But were there plants of any sort? What about the dark markings which so many people assumed represented vegetation?

In 1956 there was a flurry of interest. The ability to study the infrared region in detail made it possible to detect chemical compounds more and more delicately. There were reports that certain wavelength absorptions were like those that would be expected of green plants.

—But then this proved a false alarm. Closer studies showed that those absorptions were more likely produced by a heavy variety of hydrogen atom.

By the late 1950s, then, it seemed very unlikely that there were advanced forms of either animal or plant life on Mars. But what about microscopic forms of life?

Microscopic forms of life are, in some respects, hardier than more complicated forms of life and can withstand more extreme conditions. There are bacteria that can live on chemicals poisonous to other forms of life. There are lichens that can grow on bare rock, or on mountaintops where the air is so thin and the temperature is so low that one might almost imagine oneself to be on Mars.

Beginning in 1957, experiments were conducted to see if any simple life-forms that were adapted to severe conditions on Earth might survive in an environment which, as far as possible, duplicated what was then known of the Martian environment. Over and over again it was shown that some life-forms would survive. They might not grow very much, but they would survive.

Apparently, then, Mars might support simple forms of life. Some people argued, though, that complex forms of life could not be ruled out; that it was unfair to judge Martian conditions by Earthly standards.

Life on Earth has evolved to fit the Earthly environment. To us, therefore, conditions on Earth seem pleasant, and conditions that are considerably different from those on Earth seem unpleasant.

On Mars, however, life-forms might have evolved to suit the conditions there, and it would then be *those* conditions that were pleasant. Imagine intelligent beings on Mars who had evolved to fit the Martian environment. They might argue that it was Earth's environment that was harsh and forbidding, and that Earth was uninhabitable. They might ask how complex life could be expected on a planet that had the uncomfortable heat and the incredible humidity of Earth. How could life exist, they might wonder, in the absence of invigorating ultraviolet radiation, and in the presence of poisonous oxygen in the air?

So although astronomers grew increasingly of the opinion that Mars did not support life and there were no intelligence-made canals, they could not manage to disprove life, intelligence, and great engineering works altogether.

Even as late as the 1950s, it seemed to many people that the inhabitants of Earth might never find the answer to the riddle of Mars.

If so, they were wrong, for new developments were about to revolutionize the study of the planets, and in the space of twenty years do far more to unravel the mystery of Mars than all the studies prior to that time had been able to do.

9
THE PROBING OF MARS

Rockets

Science fiction writers had been visiting the planets in their imagination for a long time, but toward the close of the nineteenth century some scientists and engineers actually began to try to imagine the kind of vehicles that would take human beings beyond Earth's atmosphere.

The one means that seemed equipped for the task was the rocket. In a rocket, fuel and oxygen are combined in a combustion chamber with a narrow opening. The hot gases that result from the combining force themselves out of the opening at great velocity, and thrust the rocket in the opposite direction.

Since a rocket carries its own oxygen as well as fuel, it works perfectly well in a vacuum—that is, in space where there is no matter at all, not even air. Indeed, it can work better in a vacuum because there is no air resistance to slow it down.

The first person who actually built a rocket of the kind that could move out into space was an American engineer, Robert Hutchings Goddard (1882–1945). He used gasoline and liquid oxygen.

On March 16, 1926, Goddard sent up his first rocket; it was at his aunt's farm in Auburn, Massachusetts. The rocket was about 1¼ meters (4 feet) high, 15 centimeters (4 inches) wide, and was held in a frame like a child's jungle gym. Goddard ignited it and the rocket rose 56 meters (184 feet) into the air, reaching a speed of 95 kilometers an hour (60 miles an hour).

In July 1929 he sent up a larger rocket which went faster and higher than the first. More important, it carried a barometer and a thermometer, together with a small camera to photograph their readings. This was the first instrument-carrying rocket.

He shifted his experiments to New Mexico, where he could perform his experiments without disturbing neighbors. There he devised most of the engineering tricks useful in rocketry and patented them. He showed how to build a combustion chamber of the proper shape and how to keep its walls cool. He showed how to use the rocket exhaust to steer the rocket.

He also worked out and patented the notion of a rocket in more than one stage. A two-stage rocket, for instance, consists of a small rocket built on a large one. The large one burns its fuel and carries itself and the small rocket up into the upper atmosphere. Then the large rocket, empty of fuel, breaks loose and drops away, while the small rocket goes into action.

The small rocket doesn't have the remains of the large rocket to pull, and it is up where the air is too thin to slow it down much. It is already moving upward at considerable speed thanks to the action of the large rocket, and now its own engine makes it go higher and faster still. The small rocket moves considerably higher and faster than the whole rocket would have moved had it all been in one piece.

In the early 1930s, Goddard finally fired rockets that reached speeds faster than the speed of sound—in other words, faster than 1200 kilometers per hour (740 miles per hour). He also sent them as much as 2.5 kilometers (1.5 miles) high.

Other rocket engineers were, at this time, experimenting with rockets in Germany. Among those working there were Willy

Ley (1906–1969) and Wernher von Braun (1912–1977). The German engineers, unlike Goddard, had the support of their government. After Adolf Hitler (1889–1945) took power in Germany in 1933, Willy Ley left the country, but von Braun remained behind and found he could work with large amounts of government funds, because Hitler wanted to use the rockets as war weapons.

By the time World War II began, von Braun was producing rockets capable of flying 18 kilometers (11 miles). By 1944 he had developed the "V-2" rocket, which bombarded London but, fortunately, came too late to win the war for the Germans.

The effectiveness of the V-2 rockets, however, interested both the United States and the Soviet Union in rocketry work and by the 1950s each had developed intercontinental ballistic missiles (ICBMs), large rockets that could carry nuclear bombs to any point on the world in less than an hour and land accurately on target.

But rockets were not used only as war weapons. Some were sent high up into the atmosphere to study conditions there at heights human beings could not otherwise reach. Soon after the war, captured V-2 rockets were used for that purpose and one reached a height of 180 kilometers (115 miles), five times as high as any plane or balloon could reach.

In 1949 the United States put a small American rocket on top of a V-2. When the V-2 reached its maximum height, the small rocket took off and reached a height of 390 kilometers (240 miles).

Such high-flying rockets brought back useful information about the temperature, density, winds, and chemical composition of the atmosphere at great heights. They stayed in the upper air a short period of time only, however. What was wanted was a rocket that could stay up for extended periods of time.

Suppose a rocket were sent up beyond the atmosphere and was then turned so as to move at right angles, more or less, to the Earth's surface. If it moved as quickly as 8 kilometers per second (5 miles per second) it would remain in orbit around the Earth as an artificial satellite. It could then send back information about the large sections of Earth that would be visible to it and, for that matter, about the universe outside. For the first time, astronomers might be able to study other worlds without the blurring and distorting effect of Earth's atmosphere.

The United States and the Soviet Union both made plans to launch such satellites in connection with the "International Geophysical Year" of 1957–1958, during which international teams of scientists were going to study many properties of the Earth as a whole.

The Soviet Union launched its first satellite on October 4, 1957, and the United States followed with its first on January 31, 1958. In the years since, hundreds of satellites have been launched by both nations.

Satellites turned out to have a great many practical uses. They could take photographs of cloud formations, thus helping in weather predictions. They could be used to relay communications from continent to continent. They could help map the Earth and could record data concerning the properties of Earth and the space immediately around the Earth. They detected concentrations of electrified particles in belts around the Earth.

But what about regions beyond the immediate neighborhood of Earth?

Probes

Satellites need not be restricted to the neighborhood of Earth. If they are made to go a little faster than 8 kilometers per second (5 miles per second), their orbits will belly out farther from the Earth. If they are made to go at speeds near the escape velocity, they will move outward as far as the Moon; at still greater speeds, they will break away from Earth altogether and approach other worlds.

If a rocket is made to enter the neighborhood of another world, it is called a "probe."

The first successful "lunar probe"—one that passed near the Moon—was launched by the Soviet Union on January 2, 1959. This probe, Luna 1, passed within 6,000 kilometers (3,725 miles) of the Moon's surface. Luna 2, launched by the Soviet Union on September 12, 1959, actually struck the Moon's surface. Luna 3, launched by the Soviet Union on October 4, 1959, moved beyond the Moon and sent back the first crude photographs of the far side of the Moon, a side no human eyes had ever before seen.

In the decade that followed, numerous other probes were sent toward the Moon until the entire surface of the Moon, both the near side and the far side, were photographed with a detail that would have been completely unthinkable for work done only from Earth's surface. Probes were even landed on the Moon—gently, so that cameras and other equipment were not too badly jarred and could take pictures of the surface and study its texture and chemical composition.

Meanwhile, both the Soviet Union and the United States were sending human beings into orbit and bringing them back safely. The first manned rocket placed in orbit was Vostok I, launched by the Soviet Union on April 12, 1961. It carried cosmonaut Yuri Alekseyevich Gagarin (Ga-GA-rin, 1934–1968) once around the Earth. On February 20, 1962, the first American was placed in orbit. He was John Herschel Glenn, Jr. (1922–) and he orbited Earth three times, in the Mercury capsule Friendship 7.

Manned spaceships were improved and made larger. Two and even three people were placed in them. Spaceships came to be maneuvered and controlled from within. Finally, on July 16, 1969, the American spaceship Apollo 11 was launched with three men aboard. On July 19 part of the ship landed on the Moon, and Neil A. Armstrong (1930–) became the first human being to set foot on a world other than the Earth.

Since then five more trips to the Moon have been made, twelve Americans have walked on our satellite, and large quantities of Moon material have been brought back to Earth for study.

The Moon, however, is so close to us that it may be looked upon as Earth's backyard. What about the planets?

The planets are hundreds to thousands of times as far from us as the Moon is, and it could be quite a while before human beings can reach them by rocket. However, unmanned rockets might reach them first, as was true in the case of the Moon. In fact, before unmanned rockets could reach this goal, something else might.

In the 1950s, for instance, a new technique was developed for the study of the planets. This made use of microwaves, a form of radiation with waves even longer than those of infrared radiation.

Microwaves are used in radar. They can be beamed outward, and because of their long waves will penetrate mist, fog, and clouds as ordinary light cannot do. If a microwave beam strikes something, such as an airplane, some of it will be reflected and the reflected beam can be picked up. From the time that elapses between sending out the beam and receiving the reflection, the distance of the airplane can be determined.

Gradually astronomers learned how to send out beams of microwaves that would strike other worlds and be reflected. In this way, the distance of the world can be detected more accurately than by any other known way. In addition, microwaves are reflected differently by a turning object than by one that is not turning, and are also reflected differently from a rough-surfaced object than from a smooth one. From the nature of the reflection, the speed of rotation can be determined and mountain ranges can be detected.

This turned out to be useful in the case of Mercury. In 1890, Schiaparelli had observed markings on Mercury and, by following them, decided that the planet always kept the same face to the Sun as it circled it every 88 days. This meant that it rotated relative to the stars once in 88 days. In 1965, astronomers using microwaves found that Schiaparelli had been misled by the dim marking he could barely see with the instruments of his day. Mercury rotates relative to the stars once in 58.7 days, a period just two thirds the length of its year.

The year before that, microwaves had yielded even more startling information concerning Venus. There had been no way before then of telling how quickly Venus rotated, because there were no markings on it that could be followed—just white and unbroken clouds. Microwaves could penetrate Venus's clouds, however, and be reflected from the solid surface beneath. The evidence of the microwave reflection showed that Venus rotated in 243.1 days, and in the wrong direction—east to west.

Another piece of unexpected information had come from Venus in the 1950s.

All objects emit microwaves. How much they emit and how long the waves are depends on the temperature of the object. In 1956 microwaves were detected that came from Venus, and they came in such a flood that it seemed the temperature of Venus must be much higher than had been expected. The surface temperature must be about 330° C. (600° F.) to account for the microwaves.

Such a temperature, far above the boiling point of water, was completely unexpected. Could there have been a mistake?

One way to check was to send out a probe carrying instruments that could make measurements at close quarters of the microwaves pouring out of Venus, and beam those measurements back to Earth.

Naturally, then, once rocket engineers learned to send probes out to the Moon, the next target was Venus. Not only was Venus the closest target after the Moon, but it had an interesting mystery about it.

The first Venus probe was Venera 1, launched by the Soviet Union on February 12, 1961. After many months it passed within 100,000 kilometers (62,000 miles) of Venus, but its radio failed and it sent back no data. Then the United States sent out Mariner 1,* but it veered off course and had to be destroyed.

Then, on August 26, 1962, the United States sent out the Venus probe Mariner 2. It passed within 35,000 kilometers (21,000 miles) of Venus and it worked perfectly. It was the first successful planetary probe and it confirmed the high temperature of Venus.

As astronomers found through further Venus probes sent out by both the United States and the Soviet Union,** Venus's atmosphere was about 95 times as dense as Earth's atmosphere, and it was about 95 percent carbon dioxide. Because carbon dioxide traps heat, the temperature of Venus rose to a level higher than it would have, at the same distance from the Sun, had it had Earth's atmosphere.

But what about Mars? Microwaves and rockets had revolutionized our knowledge of the Moon, Mercury, and Venus. What about Mars?

* The Mariner probes are named for the Ancient Mariner in the famous poem "The Rime of the Ancient Mariner" published in 1798 by the English poet Samuel Taylor Coleridge (1772–1834). The Ancient Mariner had made a long trip over empty wastes—though only on Earth's oceans.

** Some of the Soviet probes actually landed on the surface of Venus.

Mariner 4

Two years after the first successful Venus probe, two new Mariner rockets were readied for voyages to Mars. One of them, Mariner 3, was launched on November 5, 1964, but failed. The next, Mariner 4, was launched on November 28, 1964.

Mariner 4 was the first successful Mars probe and, on July 14, 1965, eight months after launching, it reached the vicinity of Mars, making its closest approach at a distance of 10,000 kilometers (6,000 miles). It approached Mars more closely than the outer satellite, Deimos, does.

As Mariner 4 passed Mars it took a series of twenty photographs, which were turned into radio signals, beamed back to Earth, and there converted into photographs again. This began a new era in the history of Martian observation. For the first time it was possible to see Mars at close quarters rather than only from Earth's surface.

What was to be seen? Canals? Clear signs of high civilization or, at least, of life?

What the photographs showed turned out to be completely unexpected, for as they were received, astronomers saw what were clearly craters—craters that looked very much like those on the Moon.

After the first shock was over, however, the results seemed natural. A few astronomers had speculated at times that Mars might be cratered.

After all, if the planets had formed of dust and gas coming together, the dust and gas would first have formed small bodies, which then would have collided to form large bodies and so on. Eventually the planets as we know them would have formed, but the last few smaller bodies joining the main planet would leave their collision marks as craters.

If a world has no atmosphere, no free water, no life, there is nothing to erode or change those craters and they remain

This photograph was taken by Mariner 4 at 5:30 P.M. on July 14, 1965. The location is in the region named "Mare Cimmerium" by Schiaparelli at 34° South Latitude and 199° Longitude. (This location on Earth would be in the Pacific Ocean just southeast of Australia.) *NASA photo*

indefinitely—as on the Moon. On the other hand, if there is an atmosphere and winds; an ocean and rainfall and rivers; life and living activity—then craters are eroded and will vanish, as on Earth.

There seems no question that craters must have formed on Earth, or at least on its land surface, in the past. There is a crater in Arizona, preserved by the desert conditions, where a meteor may have struck 30,000 years ago. There are also signs of long-gone craters here and there on Earth, which can be seen from air as circular formations of one sort or another, often partly or entirely filled with water.

Since Mars has a thinner atmosphere than Earth does, it could be reasoned that there is less erosion activity and craters would last longer than they do on Earth. Therefore many might still be clearly visible. (Indeed, the sharp-eyed Barnard is supposed to have thought he saw a crater on Mars, but he did not make the matter public for fear he would be ridiculed.)

The craters, at least as they showed up on the Mariner 4 pictures, seemed so many and so sharp that the natural conclusion was that there had been very little erosion. That seemed to mean not only thin air, but very little water or life activity. The craters shown in the photographs of Mariner 4 seemed to be the mark of a dead world and this dealt a severe blow to hopes for a civilization on Mars, or even life.

Mariner 4 was designed to pass behind Mars (as viewed from Earth) after its flyby, so that its radio signals would eventually pass through the Martian atmosphere on its way to Earth. The radio signals were like beams of microwaves but with even longer wavelengths. From the changes in the signals, astronomers could deduce the density of the Martian atmosphere, its temperature, and the average weight of the molecules composing it.

It turned out that the Martian atmosphere was even thinner than the lowest estimates. It was less than $\frac{1}{100}$ as dense as Earth's atmosphere. The air pressure at the surface of Mars is about equal to that of Earth's atmosphere at a height of 32 kilometers (19 miles) above Earth's surface. This was another blow to the possibility of advanced life on Mars.

What's more, the average weight of the molecules in the atmosphere was about 40. The two main components of Earth's atmosphere, nitrogen and oxygen, have molecular weights of 28 and 32, respectively. The two chief minor components of Earth's atmosphere, argon and carbon dioxide, have molecular weights of 40 and 44 respectively. It seemed, therefore, that the Martian atmosphere was probably chiefly carbon dioxide, with perhaps argon added.

Kuiper had already detected carbon dioxide in Mars's atmosphere, but the Mariner 4 data made it seem that carbon dioxide might be almost all there was in the atmosphere, and this was still another blow at the possibility of complex life.

The surface pressures of the atmospheres of the terrestrial worlds are listed in Table 46.*

TABLE 46

Atmospheric Surface Pressures

	ATMOSPHERIC SURFACE PRESSURE			
WORLDS	GRAMS PER SQUARE CENTIMETER	POUNDS PER SQUARE INCH	EARTH = 1	MARS = 1
Venus	98,000	1,400	95.2	18,000
Earth	1,033	14.7	1.0	184
Mars	**5.7**	**0.08**	**0.0054**	1.0

* Mercury and the Moon, omitted from Table 46 as having no atmospheres, have measurably thicker densities of gas molecules in the immediate vicinity of their surfaces than exists in outer space. It might be more accurate to say that they have atmospheric traces. Probably most worlds of any size have atmospheric traces.

The surface pressure of the atmosphere depends partly on the gravitational pull of a world. A given atmosphere would be pressed down closer to the surface and have a higher surface pressure on a world with a larger gravity than on one with a smaller. Allowing for the different gravitational pulls and for the different surface areas of the terrestrial worlds, we can calculate the total mass of their atmospheres, as in Table 47.

TABLE 47

Atmospheric Mass

WORLD	ATMOSPHERIC MASS: QUADRILLIONS OF KILOGRAMS	ATMOSPHERIC MASS: QUADRILLIONS OF POUNDS	ATMOSPHERIC MASS: EARTH = 1	ATMOSPHERIC MASS: MARS = 1
Venus	500,900	1,102,000	98.2	22,040
Earth	5,100	11,200	1.0	224
Mars	**22.7**	**49.9**	**0.0045**	**1.0**

Venus's atmosphere has a mass equal to 0.01 percent of the total mass of the planet. None of the other planets or lesser worlds of the solar system comes even close to that mark. Earth's atmosphere is only 0.000085 percent of Earth's total mass. If it were conceivable that there were intelligent beings on Venus who took their own atmosphere to represent the norm, they would consider Earth's atmosphere (let alone that of Mars) to represent a mere trace unworthy of consideration.

Yet, the photographs taken of Mars by Mariner 4 covered a very small area of the planet and it was just possible that what was seen happened to be not characteristic of the world as a whole. Astronomers hesitated to draw too many conclusions too firmly without additional evidence. More probes were needed, and more probes were therefore sent out toward Mars.

Mariners 6 and 7

Mariner 5 was a Venus probe, but after that it was Mars's turn.

Again two probes were prepared, Mariner 6 and Mariner 7. The former was launched on February 24, 1969, and the latter on March 27, 1969. On these two Mariners, the photography equipment was considerably advanced over that on Mariner 4, and the photographs that would be taken could be expected to be far more detailed.

There were plans to take photographs both at long range and at short range. The cameras could be turned so that sites for photography could be selected to some extent.

Furthermore, the two probes were going to skim by Mars at a distance of only 3,200 kilometers (2,000 miles) from its surface, one-third the distance of Mariner 4 and even closer than the orbit of the inner Martian satellite, Phobos.

In addition, Mariners 6 and 7 carried special equipment with which the Martian atmosphere and Martian temperatures could be studied.

This time both probes worked perfectly. Toward the end of July 1969, the probes were approaching Mars. On July 30 Mariner 6 skimmed by the planet, taking fifty photographs at a distance and twenty-five more at its close approach. Mariner 7 passed Mars on August 4, taking ninety-one photographs at a distance and thirty-three at its close approach.

The new and much better photographs showed that there was no mistake about the craters. The Martian surface was riddled with craters—as thickly, in places, as the Moon was. The craters seemed to be more eroded than those on the Moon, which was to be expected since Mars had an atmosphere, even though a thin one.

The new probes, however, showed that Mars was not *entirely* like the Moon. There were regions in the photographs in which the Martian surface seemed flat and featureless. The region known as Hellas, which was near the south polar ice cap, was an example of this.

Then, too, there was the region of Aurorae Sinus, just south of the Martian equator, where the surface seemed jumbled and broken in a way that one didn't see on the surface of either the Earth or Moon. This was called "chaotic terrain."

It was clear that Mars was a more complicated body than it had appeared from the first photographs of Mariner 4.

The chances for life, however, did not improve.

For one thing, there were still no signs of canals. There had been none on the Mariner 4 photographs, but that was not decisive. The Mariner 4 photographs had covered only a small patch of the planet and it might have been that there were no major canals in that region. Then, too, the photographs were of such poor quality that canals might have been there without being revealed.

However, the photographs of Mariner 6 and 7, of much better quality and covering a wider area, also showed no canals. The chances that they existed at all sank low indeed.

Then, too, the more advanced instruments on Mariners 6 and 7 demonstrated that the Martian atmosphere was indeed as thin as had been indicated by the earlier probe. What's more, it was now quite sure that the Martian atmosphere had carbon dioxide as its only important constituent. Everything else was absent or else present in only small quantities.

On Mars, as on Venus, the atmosphere was about 95 percent carbon dioxide as compared to a 0.035 percent figure for Earth's atmosphere. The total mass of gaseous carbon dioxide on each of these three planets is given in Table 48.

We see from Table 48 that although the atmosphere of Mars

TABLE 48

Atmospheric Carbon Dioxide

WORLD	TOTAL MASS OF ATMOSPHERIC CARBON DIOXIDE QUADRILLIONS OF KILOGRAMS	QUADRILLIONS OF POUNDS	EARTH = 1
Venus	476,000	1,050,000	266,000
Earth	1.79	3.9	1.00
Mars	**21.6**	**47.4**	**12.07**

is far smaller in total mass than those of Earth and Venus, in carbon dioxide at least there is twelve times as much as in Earth's atmosphere.

This can be used as an argument either way as far as the question of life on Mars is concerned. It is carbon dioxide rather than oxygen that is an essential atmospheric component for plant life. It would seem, therefore, that Mars's rich supply of atmospheric carbon dioxide offers hope. On the other hand, the reason that Earth's atmosphere is so low in carbon dioxide is that most of what would have been the supply has been absorbed by plants and made part of plant tissue. So much carbon dioxide still in the Martian atmosphere might indicate that there are no plants to absorb it.

What's more, Mariners 6 and 7 revealed the surface temperature of Mars to be lower than had been expected. The fact that the Martian atmosphere was almost all carbon dioxide and contained only tiny traces of water vapor at best now set astronomers to wondering whether there was any water on Mars at all.

To be sure, there were the ice caps, which almost all astronomers had assumed represented frozen water. But what if they were frozen carbon dioxide, as Stoney had suggested over half a century before?

If the ice caps were indeed frozen carbon dioxide, and if there were actually only traces of water on Mars, then Mars would have to be a dead planet in Earthly terms. No form of life as we know it can live without water.

10

THE ORBIT AROUND MARS

Mariner 9

The complexities of Mars's surface, its flat regions and its chaotic terrain, made it seem important to gain still more information about Mars. It was clear that the sort of probe that flew by Mars, taking pictures as it went and then moving onward into deep space never to be heard from again, was insufficient. Each such probe remained in the vicinity of Mars only hours and could take only a limited number of photographs. It would take large numbers of such probes to make enough passes to tell astronomers what they wanted to know about all parts of the Martian surface.

But what if a probe could, as it approached Mars, be slowed by rockets so that instead of passing Mars it would be captured by the planet and would move into orbit about it?

It was the sort of thing that had to be done with great precision. If the probe moved too quickly, it would not be captured; if it moved too slowly, it would be captured in too final a manner for it would crash into the planet. The task of manipulating a probe in just the right way to place it in orbit about a target is difficult, but not impossible.

Some time before Mariners 6 and 7 had been sent out, for instance, this had been achieved with respect to the Moon.

The Soviet Union had launched Luna 10 on March 31, 1966, and placed it in orbit about the Moon. It was the first object to be placed in orbit about a world other than the Earth.

The United States placed Orbiter 1 in orbit about the Moon after launching it on August 10, 1966. A whole series of other Orbiters followed, and the thousands of photographs they sent back sufficed to map the entire Moon.

Now astronomers planned to do the same thing for Mars. Again two probes were to be sent out, with each planned to orbit Mars at different angles to its equator. One, at a relatively low angle, would get good views of the Tropic and Temperate Zones, and the other, at a high angle, would photograph the polar regions. This time there would be photographs not by the dozens, but by the thousands, and not of just a random swatch of the Martian surface but of its every square kilometer.

In addition, devices were to be put on board the probes to detect water vapor and to see what the temperature of the atmosphere was at different heights.

The two probes were Mariner 8 and Mariner 9, and on May 9, 1971, Mariner 8 was launched. Unfortunately, some small part of its intricate mechanism didn't function properly and it fell back into the Atlantic Ocean.

The plans for Mariner 9 were hurriedly changed so that it would circle Mars at an intermediate inclination to the Martian equator and thus attempt to do the job that both probes were originally supposed to do.

Mariner 9 was launched on May 30, 1971, and everything worked well. It sailed through space for 167 days and after one correction of its course six days after launch, nothing further needed to be done. It was perfectly aimed. On November 13, 1971, it arrived at Mars and was put into orbit about it—the first man-made object ever to be placed into orbit about another planet.

However, if the probe behaved beautifully, Mars didn't.

Mars occasionally experiences atmospheric effects that hid its features. Observers on Earth first see white dots appear here and there on Mars. These expand, and little by little the surface features begin to disappear. Every ten years or so there is a particularly bad effect which hides all or almost all of the planet.

Considering how dry Mars is and how much it must resemble Earthly deserts, dust storms seem to be the logical way of accounting for the obscuration. These often take place after the Martian perihelion in the southern hemisphere, which is then experiencing summer. The unusually high level of radiation from the Sun then warms portions of the atmosphere, and the interaction of warm and cold fronts may set up windstorms in the thin atmosphere which are rapid enough to stir up the dust.

On September 22, 1971, when Mariner 9 was well past the halfway point on its voyage to Mars, the first signs of a dust storm began to appear on Mars about halfway between the equator and the South Pole, in just about the region of the Martian prime meridian, a place named Noachis (noh-AK-is) by Schiaparelli. The storm spread and spread, and by the time Mariner 9 arrived and went into orbit the dust storm had proved to be the worst ever observed on Mars. The entire planet was blanked out and even the ice caps could not be seen. It was as though nature were in a conspiracy to keep Mars a secret.

The earliest pictures taken from a distance by Mariner 9 were therefore disappointing. It had been hoped that over-all photographs of the planet would give immediate information as to whether the canals existed and, if they did not, whether there were any formations that could be mistaken for canals if they could just barely be made out. Instead, the photographs were almost as blank and featureless as though they had been taken of Venus.*

Not quite, though. There was a dark spot about 20 degrees north of the equator in these early photographs, and a couple of other less prominent spots nearby. There seemed to be nothing that might coincide with a dark spot at that latitude but a feature which Schiaparelli had named "Nix Olympica" (nix oh-LIM-pih-kuh). This means "Snows of Olympus," Olympus being the mountain in Greece on which the Gods were supposed to live. Schiaparelli had given it the name because it frequently seemed white, as it would if it were a snow-covered mountain.

Microwave measurements had shown the region of Nix Olympica to be indeed mountainous, so Schiaparelli's guess might have been a good one. On the first pictures taken by Mariner 9, a tall mountain might make itself evident because it would thrust upward past the lower levels of the atmosphere, where the dust storm would be at its worst, and into the higher regions where the dust concentration was less and where its top might be dimly seen. Presumably the other dark spots nearby were other mountain peaks.

The photographs were improved by computer techniques and there seemed to be depressions in the peaks—craters. They were not mountain peaks, really, but volcanoes. Thus it was that the first discovery made by Mariner 9, even while the dust storm swirled about the planet, was the existence of volcanoes on Mars. Volcanoes did not exist on the Moon and it showed that Mars, unlike the Moon, was not a dead planet geologically. The interior heat of Mars must, in other words, still be molding and changing its surface.

* Had Mariners 4, 6, and 7 arrived at such a time, their entire missions would have been useless and they might almost as well have stayed at home. Mariner 9, in orbit, could outwait the storm, which shows the advantage of an orbiting probe over a non-orbiting one.

At the time that Mariner 9 was entering its orbit about Mars, paired Soviet probes, Mars 2 and Mars 3, were approaching the planet. They were larger and more elaborate than the American probes, and they were designed to drop sterilized photographic equipment onto the Martian surface, in order that photographs might be taken of the surface at ground level.

For them, the dust storm appears to have been fatal. Mars 2 dropped its package on November 27, 1971, and nothing was ever heard from it. On December 2, 1971, Mars 3 ejected its package. It landed safely, and actually started transmitting photographs. The equipment worked, however, for only 20 seconds and had time to transmit only part of one photograph, which showed nothing but a featureless gray. These were the first man-made objects ever to land on Mars but, unfortunately, they were of no use.

Meanwhile, after its discovery of the volcanoes, Mariner 9 could do nothing more but wait for the dust storm to subside, so attention was turned to the Martian satellites, Phobos and Deimos. This had not been part of the original plan, but fortunately Mariner 9 was flexible enough to make the change while waiting for the Martian weather to improve.

The Size of the Satellites

Ninety-four years had passed since the discovery of the Martian satellites by Hall. In all that time, nothing had been learned about the satellites except for their orbital data—their distance from Mars, their period of revolution and so on.

Even their exact sizes remained unknown. They couldn't be seen as anything but dim dots of light in the immediate neighborhood of Mars, so they had to be very small. Exactly how small could only be estimated. If they reflected only as much light as the Moon did, then their size could be estimated from their total brightness.

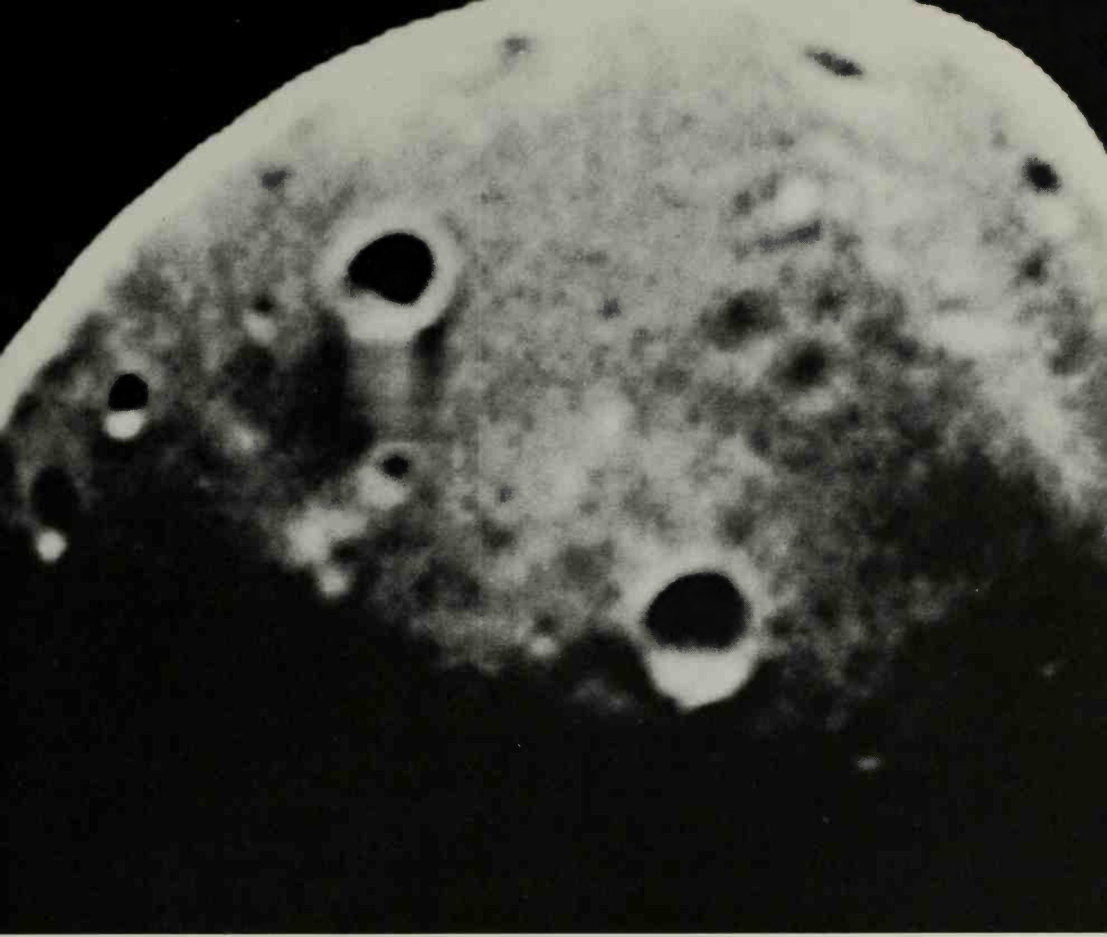
These were not easy measurements to make. In 1956 Kuiper had taken on the job, and from his results he estimated thaat Phobos was about 12 kilometers across (7½ miles) and Deimos about 6 kilometers (3.7 miles) in diameter. They seemed nothing more than mountains-on-the-loose flying about Mars.

The first sight of either satellite from anyplace but the surface of the Earth had come in 1969, when Mariner 7 was taking its photographs of Mars and just happened to take one at a time when Phobos was between Mariner 7 and Mars. Phobos showed up as a black silhouette against Mars.

It turned out that Phobos was unexpectedly dark, so that it reflected less light than would be supposed, and therefore had to be larger than Kuiper had estimated it to be in order to be as bright as it was. It later turned out that Deimos was just as dark as Phobos and was also larger than Kuiper had estimated. (Both satellites seem to be similar in appearance to certain dark rocky meteorites and to be not at all like Mars in structure.)

What's more, Phobos was not spherical, but was irregular in shape. That was, after all, to be expected. A large body, like the Earth or even the Moon, produces a gravitational field strong enough to pull all parts of itself as close to the center as possible. This automatically results in a spherical shape. A small body such as Phobos, however, has an exceedingly weak gravitational field, one that isn't strong enough to pull its substance tightly together. It can, therefore, remain irregular in shape.

From the Mariner 7 photograph, one could see a roughly elliptical silhouette, but Mariner 9 was able to do better still. It took a number of photographs of the two satellites directly, and found that each had to be defined by three measurements. Suppose you imagined a line through the center of one of the satellites drawn in such a way that the distance from edge to edge was greater than any other line through the center. This would be the longest diameter.



This is Deimos, the smaller of Mars's satellites. In this Viking photograph, taken at a distance of 3,300 kilometers (2,050 miles), it is in the half-Deimos phase and its outline from this angle resembles that of an egg. *NASA photo*

You could then draw a series of lines passing through the center, with each of them being at right angles to the longest diameter. Of this series of lines, the shortest is the shortest diameter and the one at right angles to that is the intermediate diameter.

In Table 49, these three diameters are given for the Martian satellites. If Phobos were imagined to be placed on New York City, it would just about cover the boroughs of Brooklyn and Queens. Deimos, placed similarly, would cover the borough of Brooklyn alone.

TABLE 49

Diameters of the Martian Satellites

	LONGEST DIAMETER		INTERMEDIATE DIAMETER		SHORTEST DIAMETER	
SATELLITE	KILOMETERS	MILES	KILOMETERS	MILES	KILOMETERS	MILES
Phobos	28	17	23	14	20	12
Deimos	16	10	12	7.5	10	6

The surface area of Phobos is what it would be if the satellite were a perfect sphere 21.8 kilometers (13.5 miles) in diameter, and the surface area of Deimos is what it would be if it were a perfect sphere 11.4 kilometers (7.1 miles) in diameter. The surface areas and the volumes of the two satellites are given in Table 50.

TABLE 50

Area and Volume of the Martian Satellites

	SURFACE AREA		VOLUME	
SATELLITE	SQUARE KILOMETERS	SQUARE MILES	CUBIC KILOMETERS	CUBIC MILES
Phobos	1,500	570	5,400	1,300
Deimos	400	160	780	190

The surface area of Phobos is just a little over half that of the state of Rhode Island, while the surface area of Deimos is a little over half that of the city of New York. As for volume, if our Moon were hollow, it would take over 4 million bodies the size of Phobos to fill it, tightly packed. It would take 28 million bodies the size of Deimos to do the same job. In terms of volume, Phobos is about 7 times as large as Deimos.

Suppose we assume that the density of Phobos and Deimos is about the density of the kind of meteorites they resemble, say 2 grams per cubic centimeter (187 pounds per cubic foot). In that case, we can calculate the mass of each satellite from the volume, and this is given in Table 51.

TABLE 51

Mass of the Martian Satellites

	MASS	
SATELLITE	BILLIONS OF KILOGRAMS	BILLIONS OF TONS
Phobos	10,800,000	11,900
Deimos	1,500,000	1,700

From the mass of the satellites and the diameters, we can calculate the surface gravity as compared to that of Earth. The surface gravity will be very slight, of course, but will be least at the ends of the longest axis where the surface is farthest from the center, and greatest at the ends of the shortest axis where the surface is nearest the center. The average surface gravity is given in Table 52.

This means that a person weighing 70 kilograms (154 pounds) who was standing on the surface of Phobos would weigh about 47 grams (1.7 ounces). On Deimos, the figure would be about 25 grams (0.9 ounces).

TABLE 52

Surface Gravity of the Martian Satellites

SATELLITE	SURFACE GRAVITY (EARTH = 1)
Phobos	0.00067
Deimos	0.00036

An astronaut on either of the Martian satellites would feel almost weightless, and it wouldn't be difficult to get away from them altogether. The escape velocities are given in Table 53.

TABLE 53

Escape Velocity from the Martian Satellites

	ESCAPE VELOCITY	
SATELLITE	KILOMETERS PER HOUR	MILES PER HOUR
Phobos	25	15
Deimos	12	7

Getting away from either satellite would not represent a total escape, however. The escape velocity from Mars at the distance of Phobos is 3.0 kilometers per second (1.9 miles per second) and at the distance of Deimos is 1.9 kilometers per second (1.2 miles per second).

We can imagine an astronaut or some piece of equipment inadvertently being made to move fast enough to get away from Phobos or Deimos, but whatever it was would have to move three to four hundred times as fast to get away from Mars. For that reason, anyone or anything which managed accidentally to get away from the satellites would nevertheless remain in orbit about Mars.

The View from the Satellites

Both Phobos and Deimos revolve about Mars in such a way as to show the same face to Mars at all times, just as the Moon always shows the same face to Earth as it revolves. Each of the Martian satellites turns so that one end of its longest diameter points always toward Mars.

This means that Phobos and Deimos each make one turn relative to the stars while moving once around Mars. The period of revolution of each is therefore also its sidereal day.

Each time Phobos or Deimos has moved once about Mars, however, it has followed Mars in the revolution of the latter about the Sun. This produces a small apparent motion of the Sun in the reverse direction so that the Sun seems to complete its circuit of the sky, as seen from Phobos or Deimos, more slowly than the stars do. (This is true on Earth also. The Sun moves once about our sky in 24 hours, but each star makes a complete circle in 23 hours and 56 minutes.)

The period from sunrise to sunrise (solar day) on Phobos and Deimos is slightly longer than the period from star-rise to star-rise. The extra length is greater on Deimos, which takes a longer time to make its revolution, giving the Sun a longer time to drift backward.

The length of the two kinds of day for both satellites is given in Table 54.

Suppose, now, that you were standing on the end of the longest diameter of Phobos, the end facing away from Mars. That end would always face away from Mars and you would

TABLE 54

Length of Day on the Martian Satellites

	LENGTH OF DAY	
SATELLITE	SIDEREAL DAY (HOURS)	SOLAR DAY (HOURS)
Phobos	7.65	7.6536
Deimos	30.30	30.356

never see the planet you were circling. On the other hand, you would see the stars wheeling about the sky from east to west, as you do on Earth, but moving a little over three times as quickly. The Sun also would rise in the east and set in the west, but wouldn't quite keep up with the stars.

Each sunrise, the Sun would rise 20 seconds later relative to the stars, and would therefore lose one complete circuit of the sky in 687 days, which is the length of the Martian year. In the course of the year, therefore, there would be exactly one more sidereal day than solar day.

If you were on the end of the longest diameter of Deimos, the end facing away from Mars, you would see the stars moving from east to west at a pace just a little slower than would be the case on Earth. On Deimos, the Sun lags 3.3 minutes behind the stars with each sunrise, but since Deimos makes fewer rotations in the course of the Martian year, the total lag is the same on both satellites. On Deimos as on Phobos, there is exactly one more sidereal day than solar day (see Table 55).

From the diameters of the satellites we can calculate the circumference of each (see Table 56), and from that and the period of rotation we can calculate the speed of rotation at the end of the major axis (see Table 57).

TABLE 55

Number of Days in a Year on the Satellites

	NUMBER OF DAYS IN A YEAR	
SATELLITE	SIDEREAL DAYS	SOLAR DAYS
Phobos	2,155.3	2,154.3
Deimos	544.16	543.16

TABLE 56

Circumference of the Martian Satellites

	CIRCUMFERENCE	
SATELLITE	KILOMETERS	MILES
Phobos	79	49
Deimos	44	27

TABLE 57

Maximum Equatorial Speed of Rotation on the Martian Satellites

	SPEED OF ROTATION	
SATELLITE	KILOMETERS PER HOUR	MILES PER HOUR
Phobos	10.3	6.4
Deimos	1.5	0.9

To walk around the maximum circumference of Phobos, then, would take one the distance between New York City and Trenton, New Jersey. To walk around Deimos would take one the distance from Fort Worth, Texas, to Dallas, Texas.

Because of the smallness of the satellites the speed of rotation is not very great. If we were to trot westward at a brisk but not impossible speed on Phobos, we could keep up with the turning stars. If the Sun were not in the sky, it would never rise for us as long as we managed to keep running.

On Deimos, which is even smaller than Phobos and which takes longer to rotate, a leisurely stroll would do the same. In fact, if we walked briskly westward, we would overtake the Sun and see it rise in the west.

In the same way, if the Sun were in the sky at the time we began our run on Phobos, or our walk on Deimos, we could keep it in the sky as long as we kept moving.

There is, however, the question of Mars. If we begin at the far end of the longest diameter of either satellite and move westward (or in any direction, for that matter) we move toward the side that faces Mars. That means that after we have walked some 20 kilometers (12 miles) on Phobos or 11 kilometers (6.8 miles) on Deimos, we will see Mars appear above the horizon.

At any point on either Phobos or Deimos from which Mars can be seen at all, it will always occupy just about the same point in the sky as long as we don't move ourselves. If we are at the end of the longest diameter facing Mars, then Mars is directly overhead and remains there indefinitely if we don't budge.

When Mars is in the sky of either satellite, then the Sun does not make its circuit of the sky unobstructed. Each time the Sun passes from eastern horizon to western horizon, it passes behind Mars and is eclipsed.

Mars is a much more impressive sight as seen from its satellites than the Moon is as seen from Earth. Not only is Mars larger than the Moon, but it is much closer to its satellites than the Moon is to Earth. The apparent size of Mars in the sky of its satellites is given in Table 58.

TABLE 58

Apparent Size of Mars as Seen from Its Satellites

	DIAMETER OF MARS		AREA OF MARS	
SATELLITE	MINUTES OF ARC	MOON = 1	SQUARE MINUTES OF ARC	MOON = 1
Phobos	2,426	78.3	4,620,000	6,130
Deimos	982	31.7	760,000	1,005

Since Mars, as seen from Deimos, is some thirty times as wide and has a thousand times the area as the Moon does when seen from Earth, we need not be surprised if Mars shines more brightly on Deimos than the Moon does on Earth. Mars shines still more brightly on Phobos, from which it has nearly eighty times the diameter and over six thousand times the area that the Moon shows on Earth. (Mars appears so huge, as seen from Phobos, that four globes the same size would stretch nearly from horizon to horizon and nine would encircle the sky.)

We can determine the brightness of Mars as seen from its satellites by recognizing two factors. First, Mars is farther from the Sun than the Moon is, so Mars receives less light. However, Mars reflects more of the light it does receive, and reflects it from a larger area (as seen from its satellites) than does the Moon. Taking all these factors into account, the brightness of Mars as seen from its satellites is compared to the brightness of the Moon as seen from Earth in Table 59.

TABLE 59

Maximum Brightness of Mars as Seen from Its Satellites

SATELLITE	MAXIMUM BRIGHTNESS OF MARS (FULL MOON = 1)
Phobos	5,700
Deimos	940

From Earth, the Sun outshines the full Moon by a factor of 465,000 times. From Phobos and Deimos, the Sun is dimmer than it appears from Earth, while Mars, at its maximum brightness, is far brighter than the full Moon as seen from Earth.

As seen from Deimos, therefore, the Sun is only 212 times as bright as Mars is at its brightest; and on Phobos, the Sun is only 35 times as bright as Mars is at its brightest.

Mars, however, does not stay at its brightest. As the Sun circles in the sky, Mars goes through its phases just as the Moon does as seen from the Earth. From Phobos, one sees Mars go through a complete cycle of phases, from new-Mars to full Mars and back to new-Mars in 7.65 hours. From Deimos, the cycle takes 30.3 hours. It is when Mars is full that it is at its brightest.

Suppose we were standing on Phobos at the end of the longest diameter facing Mars. Mars is at zenith, huge and bright, but it is just about half full, for it is sunrise and the Sun's light is coming from the east, so that the western half of Mars, as seen from Phobos, is dark.

As the Sun rises rapidly, the lighted portion of Mars shrinks and becomes an ever narrowing crescent. One and a half hours after sunrise the Sun reaches Mars, slips behind it, and is eclipsed. Mars is now totally dark, for only its far side is lit by the Sun. The Sun remains behind Mars for about 51 minutes, then emerges and sinks toward the western horizon.

As the Sun sinks, Mars becomes an ever thickening crescent on its western side. By sunset, which comes an hour and a half after the Sun has emerged from behind Mars, Mars is half full again, its western half being lighted this time.

After the Sun sinks behind the western horizon, the lighted portion of Mars's globe expands further. Just under two hours after sunset, the Sun is shining directly down on the other end of the longest diameter, past Phobos and onto Mars. Mars is now at its full and at its brightest. It then begins to shrink again and in just under two more hours, it is in the half phase and the Sun is rising again.

During most of the time Mars is at this end of the satellite, Phobos is well lighted. When the Sun is in the sky there is, of course, plenty of light. Between sunset and sunrise, when the Sun is not in the sky, Mars is continually more than half full and gives considerable light.

It is only during the eclipse that Phobos is completely dark on the side facing Mars, and the eclipse lasts for only one ninth of a Phobos day. For eight ninths of the time, then, the Mars side of Phobos is well lit.

For Deimos, the cycle is much the same but slower. It takes four times as long for the Sun to go from sunrise to eclipse, from eclipse to sunset, from sunset to sunrise again, on that side of the satellite facing Mars.

Mars as seen from Deimos is smaller than it is as seen from Phobos. However, the Sun, as it moves behind the smaller Mars, does so at a slower pace so that it remains behind Mars for 82 minutes.

Since 82 minutes represents only a little less than than 1/20 of a Deimos day, that portion of Deimos facing Mars is well lit for 19/20 of the time (though not quite as well lit as Phobos, where Mars is larger and brighter).

The side of the satellites facing away from Mars never sees Mars, and is lit only by the Sun, which it sees for half of each day.

The Surface of the Satellites

Mariner 9 did more than make it possible to determine the actual size and shape of the two Martian satellites and the manner in which they face Mars. The photographs it took showed the nature of the surface of the tiny worlds.

Both Phobos and Deimos looked remarkably potato-shaped. They had the general shape of potatoes and even possessed the "eyes," for each little world was pockmarked with craters. Indeed, it now seems they both are saturated with craters. Every portion of their surfaces is part of one crater or another.

The craters probably arose over four billion years ago when the smaller bits of matter that had collected out of the original cloud of dust and gas were forming the planets. The battering they gave each other as they collected to form Mars survives in the cratering of the two small satellites.

Could they be two pieces that did not settle down to Mars but remained in orbit? Why they, of all the pieces, should not have joined Mars but should have remained stubbornly outside the planet for billions of years would then be uncertain.

If they were *not* part of the original cloud of matter that collected together to form Mars, might they have been asteroids which Mars captured at some later time in its history? Their darkness resembles the asteroids rather than Mars, so this seems more likely.

It might also be that Phobos and Deimos were originally parts of a larger satellite, but that the concussion with the last few pieces which formed the craters may have broken up the satellite into smaller bodies. Most of the fragments must have spiraled into Mars or out into space beyond, leaving only Phobos and Deimos in orbit.

One interesting notion about the satellites had been introduced by a Soviet astronomer, Iosif Samuilovich Shklovskii (1916–), a few years before the probes began reaching Mars. At that time, certain measurements of Phobos's motion made it seem as though that world were slowly approaching Mars. The influence of Mars's gravity could produce a "tidal drag" that would account for this, but in order for it to have as large an effect as it seemed to have, Phobos would have to be very light. For Phobos to have so little mass as seemed to be indicated, it would have to be hollow. Shklovskii therefore suggested that it might be a space station built by an advanced Martian civilization.

The notion of "Space-station Phobos" was very exciting to those who thought there might be a civilization on Mars, but even before the probes arrived, new observations showed that Phobos was not approaching Mars at a speed that would require it to be hollow after all.

The photographs of Phobos made it quite certain that it was solid rock, for any space station struck by objects capable of gouging out the craters that were observed would simply have been smashed.

Yet there is reported to be a tiny bit of tidal drag, enough to keep Phobos approaching Mars very gradually. It may be, therefore, that Phobos will crash into Mars in about 100 million years. If Phobos is 4,600 million years old, as the planets generally seem to be, then we are seeing the small satellite in the last 2 percent of its lifetime. Deimos, on the other hand, may be slowly moving away from Mars.

If indeed the satellites are 4,600 million years old, they probably represent the original material out of which the terrestrial planets, including Earth, were formed.

On Earth, the original material has been utterly changed by the action of sea and air and life and volcanoes and shifts in the crust and so on. Even on the Moon, where there is neither sea nor air and no life, there have been volcanic action and crustal shifts in the past. The same would be true to an even greater extent on Mars, Venus, and Mercury.

The Martian satellites, however, are too small to have experienced any upheavals whatever except for the crater collisions. They may be exactly in the state now that they were in after the crater collisions were over, about 4 billion years ago. If we could examine those satellites in detail, we might learn a great deal about the origin of the solar system.

Based on the photographs, a preliminary map of Phobos was made, showing about fifty craters. The equator and the prime meridian cross at the end of the longest axis, the end that faces Mars.

One large Phoban crater near the south pole was named Hall, after Asaph Hall, the discoverer of the satellites. It is about 6 kilometers (3.7 miles) across.

An even larger crater, at the equator, just a little west of the prime meridian, was named Stickney, after Mrs. Hall's maiden name. After all, she had told her husband to try one more night, thus enabling him to make the crucial observation. It is 10 kilometers (6 miles) across and is about 40 percent as wide as the maximum diameter of Phobos.

Since the map was made, new and even better observations have revealed narrow parallel grooves along Phobos's cratered surface, those grooves being more or less parallel to the equator. What this means is not certain. Perhaps they are marks left behind when the original satellite split into smaller pieces.

Deimos, a smaller body, has, as one might expect, smaller craters. The largest, which is 2 kilometers (1¼ miles) wide, is named Voltaire. The next largest, which is half as wide, is named Swift. Thus the two eighteenth-century writers who spoke of the two satellites are memorialized.

The Brightness of the Satellites

With the size of the Martian satellites now known, we can more easily imagine what they must look like in the Martian sky.

Both would be brighter at the zenith, when they are closest to the observer, than at the horizon when they are farthest. Both would be brighter the more nearly full they are. Both therefore would be brightest when in the full phase at the zenith, which is how they would appear from the Martian equator if they reached the zenith at midnight.

At their brightest, as seen from the Martian surface, they would appear to be small ovals with the intermediate diameter in one direction and the shortest diameter at right angles to that. (The longest diameter would be pointing directly toward Mars.) That means that Phobos as seen from Mars would be 23 by 20 kilometers (14 by 12 miles) and Deimos would be 12 by 10 kilometers (7.5 by 6 miles). The apparent size at zenith would be as given in Table 60.

TABLE 60

Maximum Size of Satellites as Seen from Mars

	APPARENT SIZE AT ZENITH		
SATELLITE	INTERMEDIATE DIAMETER (MINUTES OF ARC)	SHORTEST DIAMETER (MINUTES OF ARC)	AREA (MOON = 1)
Phobos	13.3	11.2	0.16
Deimos	2.0	1.6	0.003

After the two Martian satellites were discovered there was much romantic material written about "the two moons of Mars," with the thought that Martian lovers might have twice as much inspiration as Earthly lovers did. Actually, the two satellites make a poor show.

Phobos at its largest is less than half as wide as the Moon is and has only 1/6 the area. At the horizon, where Phobos seems smaller because it is farther away by the distance of half of Mars's diameter, it is only a quarter as wide as the Moon and has only 1/15 the area.

As for Deimos, which is smaller than Phobos and three times as far away, it appears so small that even at its largest it will appear only as a bright star.

And how bright are the two satellites when each is at the zenith in the full phase, and is therefore as bright as it can be? Allowing for the fact that each is dimmer than the Moon because it is farther from the Sun, reflects even less light, and shows a smaller apparent size, we have the results in Table 61.

TABLE 61

Maximum Brightness of Satellites as Seen from Mars

SATELLITE	MAXIMUM BRIGHTNESS (FULL MOON = 1)
Phobos	0.06
Deimos	0.001

Table 61 shows the poverty of Mars's night sky compared to Earth's. Phobos is at best only 1/16 as bright as the full Moon and Deimos is only 1/1000 as bright. In the Martian night sky, however, there can be as many as five objects that can be brighter than the brightest star. These are listed in Table 62.

Despite the poor showing that the Martian satellites make

A close-up picture taken of Phobos by Viking 1, showing the mysterious grooves. The best look we've ever had at any satellite but our own moon. *NASA photo*

TABLE 62

Bright Objects in Mars's Sky

OBJECT	MAGNITUDE WHEN BRIGHTEST
Phobos	—9.6
Deimos	—5.1
Earth	—4.5
Jupiter	—3.1
Venus	—2.6
Sirius	—1.4

compared to the full Moon as seen in the sky of Earth, Phobos and Deimos nevertheless remain the brightest objects in the sky of Mars, except for the Sun.

It is interesting to note that the third-brightest object (not counting the Sun) is Earth, which is as bright when seen from Mars as Venus seems to observers on Earth.

Earth as seen from Mars can achieve a brightness nearly three fifths that of Deimos at its brightest, and yet it is a much more spectacular sight than Deimos is. For that matter, it is a more spectacular sight than any other object that can be seen in either Mars's or Earth's sky.

The reason for this is that Earth is accompanied by the Moon. As seen from Mars, the Moon can attain a magnitude of 0.0. That is only $\frac{1}{70}$ as bright as the Earth, but it is still as bright as a bright star.

To an observer on Mars, Earth and Moon are a double planet which can be seen separated by as much as 23 minutes of arc, or three quarters the width of the Moon as it appears from Earth. An observer on Mars can watch the Moon come closer to Earth, pass it, separate on the other side, return again, pass again, separate on the first side. At the same time, he will see the Earth-Moon system move closer to the Sun, pass it and emerge on the other side, then return.

It would be obvious to any observer on Mars that the Moon is circling the Earth. By analogy he would see that the Earth must be circling the Sun. If there were intelligent Martian astronomers, they would understand at once that the objects in the sky are not really all circling Mars but that they can circle other bodies.

If Venus had a satellite as Earth does, then astronomers on Earth would not have had to establish an Earth-centered planetary system first and then wait two thousand years for a Copernicus to come along. The first astronomers would have worked out a Sun-centered planetary system to begin with.

Volcanoes and Canyons

In December 1971 the dust storm finally settled down and Mariner 9 got to work taking photographs of Mars.

The first thing that these photographs settled was that there are no canals on Mars. Lowell was wrong after all. What he saw was an optical illusion.

It appeared next that the pattern of light and dark areas was not a matter of the light areas being dry land and the dark areas water; nor was it a matter of light areas being desert and the dark areas vegetation.

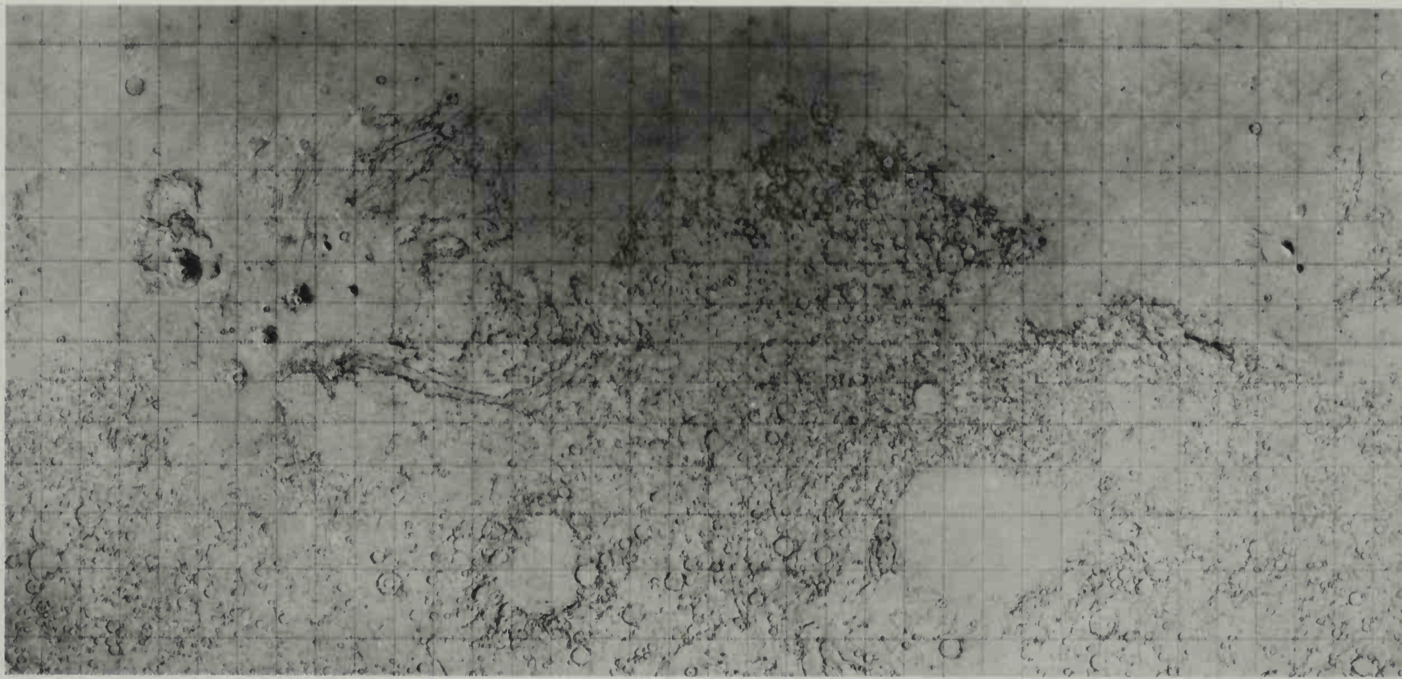
Mars seemed all desert, but here and there one found dark streaks that usually started from some small crater or other elevation. They seemed to be composed of dust particles blown by the wind and tending to collect where an elevation broke the force of the wind, and on the side of the elevation away from the wind.

There were occasional light streaks as well. The difference may be in the size of the particles. Most Martian winds could only lift fine particles; a few stronger winds could lift larger particles too. Thus the wind action could separate the light and dark, if the two tended to be of different sizes.

The possibility that the dark and light areas were differences in dust markings and that the dark areas expanded in the spring because of seasonal wind changes had been suggested a few years earlier by the American astronomer Carl Sagan (SAY-gan, 1935–   ). Mariner 9 proved him to be completely correct.

The fact that dark areas on Mars remained mostly in the same place, as indicated by Schiaparelli's observations a hundred years before, showed that the Martian winds followed a fixed pattern.

To be sure, a close look at the streaks presented an appearance nothing at all like the maps of Mars drawn from Earth. Little irregular markings at the edge of visibility were turned



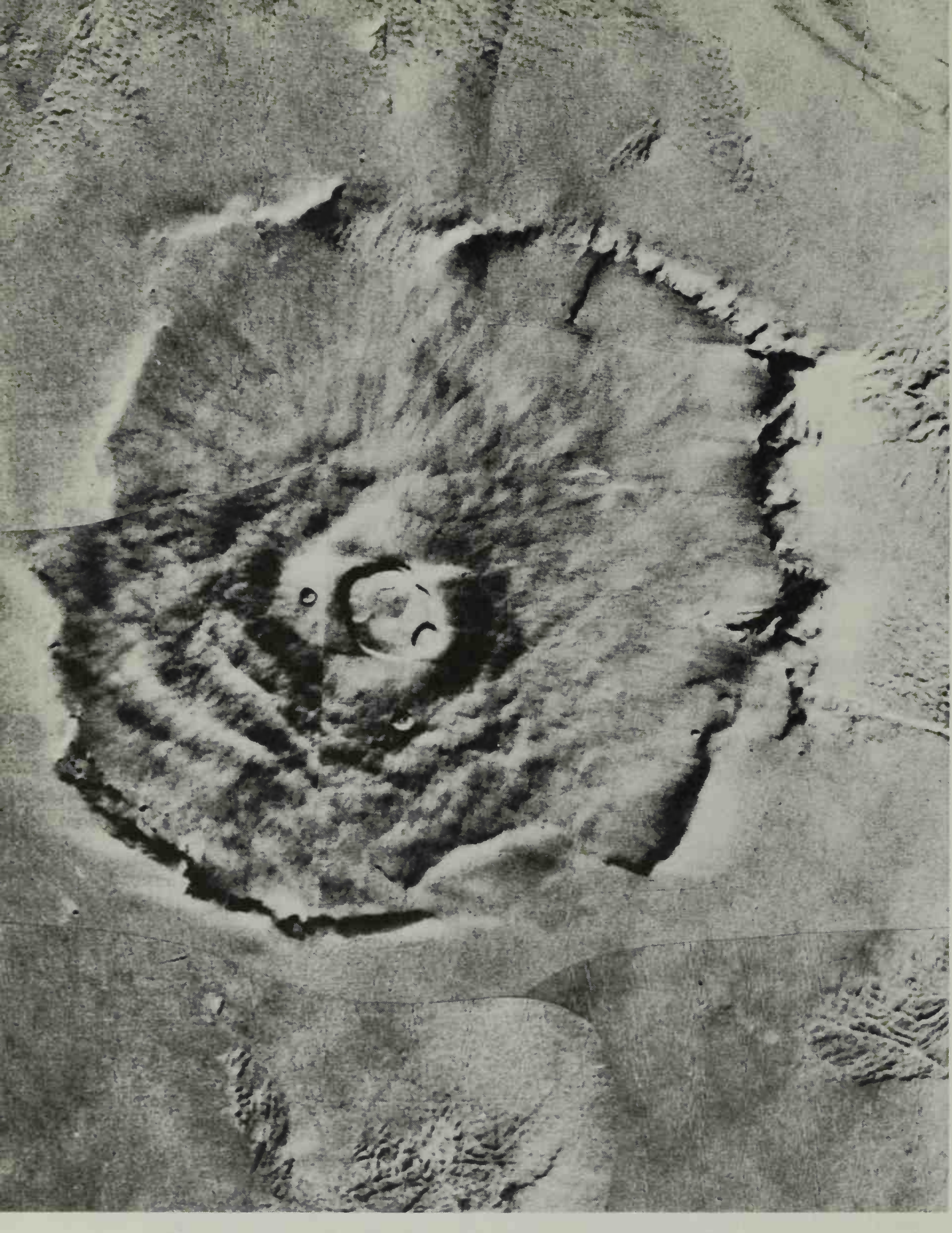
This relief map of the Martian surface was prepared by the U. S. Geological Survey from Mariner 9 photographs which mapped all of Mars. *NASA photo* by the eye into canals that didn't exist, and in the same way the streaking on Mars was turned by the eye into a general pattern of light and dark that didn't really exist.

Mariner 9 succeeded in mapping all of Mars so that a final true map was produced that replaced all that had gone before. From that map it quickly appeared that the surface of Mars was not, after all, entirely cratered in a Moonlike fashion. The three earlier probes that had taken photographs of Mars in a onetime sweep had just happened, by coincidence, to move past the cratered region.

Mars apparently can be divided into two hemispheres of very different appearance. One hemisphere, taking in most of the southern half of the planet and some of the northern half, is indeed cratered and Moonlike. The other half, taking in most of the northern half and some of the southern half, has relatively few craters. This other half seems to have been shaped by volcanic action that took place after the cratering process was over. The craters were obliterated and other surface features were substituted. (There are some volcanic areas even in the cratered hemisphere, and in those areas craters are few.)

It is clear, then, that Mars developed more internal heat than the Moon did and is therefore more geologically alive. Whereas the Moon's surface showed little change after the early cratering period of planetary history, Mars's surface showed considerable change.

Many of the Martian craters were eventually named after astronomers and others who have been associated with Mars in one fashion or another. Prominent craters were named after Lowell, Schiaparelli, Huygens, Herschel, Secchi, Cassini, Barnard and so on. There was room also for others of lesser magnitude. A crater was named for the German-American rocket historian Willy Ley (LAY). Craters were also named for two American science fiction writers who wrote about Mars: Edgar



This photograph of Olympus Mons was taken by Mariner 9 in late January, 1970. As sometimes happens in photographs, there is an optical illusion that makes rises seem like hollows and vice versa. The great volcano which looks like a depression in this photograph actually bulges upward, and the central craters which seem to rise are actually depressions. *NASA photo*

Rice Burroughs (1875–1950) and John Wood Campbell, Jr. (1910–1971).

In the volcanic areas, the most remarkable features are the large volcanoes in the region named Tharsis by Schiaparelli, after the biblical name of a region in southern Spain. The largest of these was Nix Olympica, the name of which was changed in 1973 to Olympus Mons (Mount Olympus).

There is a kind of "sea-level" height on Mars, which has been arbitrarily put as the level at which the atmosphere has a pressure of 6.1 millibars (equal to about $\frac{1}{166}$ of Earth's sea-level atmospheric pressure).

It turns out that Olympus Mons reaches a height of 24 kilometers (15 miles) above this base level. Since there are places on Mars where the surface approaches 6 kilometers (nearly 4 miles) below the base level, this means that the difference in height between the highest and lowest points on Mars's solid surface is about 30 kilometers (19 miles). Compare this with the difference in height between the highest and lowest points on Earth's solid surface—the highest mountain peak and the lowest ocean depth—which comes to 19.75 kilometers (12.75 miles).

The large Martian volcanoes are far larger than any on Earth. The largest volcano on Earth is the one that makes up the island of Hawaii. This is about 120 kilometers (75 miles) wide at the sea-bottom base on which it rests. Its total rise is about 9 kilometers (5.6 miles) above the sea floor. The large Martian volcanoes have base widths of 400 kilometers (250 miles) or more, so that Olympus Mons, the tallest of the Martian monsters, is sometimes spoken of as the largest known volcano in the solar system.

Olympus Mons has a large crater that is 65 kilometers (40 miles) across. The largest volcanic crater on Earth is that of a Japanese volcano which has a longest diameter of 27 kilo-

Five Viking photographs were put together to make this large one of Arsia Mons. Astronomers studying this picture can make out markings which indicate where streams of lava have run down the volcanic slopes. *NASA photo*

meters (17 miles). There are other Martian volcanoes which, although lower than Olympus Mons, have larger craters. Arsia Mons, about 1800 kilometers (1100 miles) southeast of Olympus Mons, has a crater that is 120 kilometers (75 miles) across.

Why are the Martian volcanoes so huge? One theory is that although Mars is alive geologically, it is not quite as alive as Earth is. On Earth, internal heat keeps the planet's crust moving in huge plates. Volcanoes form, but because the crust moves, they form in strings, each one being only moderately large. The Martian crust may not move, so a volcano forms in one spot and builds up to a much larger mass than it would if the crust moved.

Olympus Mons is the youngest of the large volcanoes, which is why it is the tallest. Perhaps only 200 million years old, it has not had much chance to weather down—or else to build up a larger crater. Arsia Mons, lower and with a larger crater, is possibly 800 million years old. Other volcanoes, worn down still lower and in some cases with even wider craters, may be several billion years old.

Whatever forces produced the volcanoes of Mars seem to have fractured the crust of the planet as well. The largest of these fractures, forming a gigantic canyon, runs southeastward from the region of giant volcanoes. It is the site of a dark marking on Mars, as seen from Earth, that had been named Coprates. From Earth this marking looked like a rather wide and stubby canal, and it is the only marking of the sort that turned out to have a real existence.

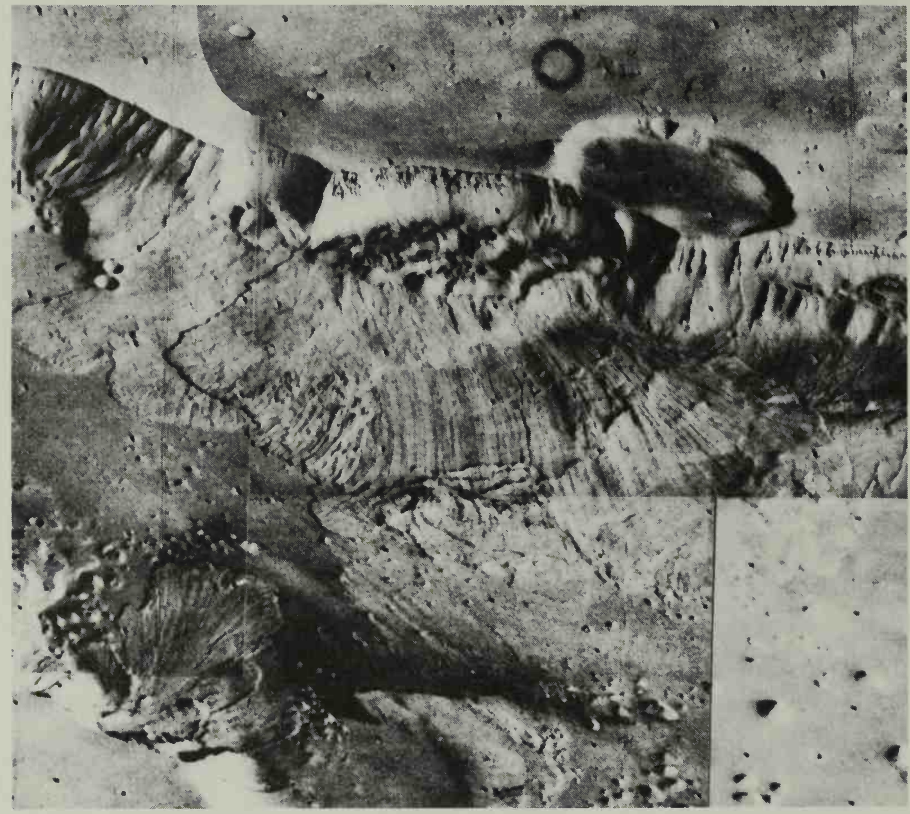
It is not a canal, however. It is a magnificent natural phenomenon—a canyon up to 2 kilometers (1¼ miles) deep and up to 500 kilometers (310 miles) wide that has a length of about 3000 kilometers (1900 miles)! This Martian canyon is nine times as long as the Grand Canyon on Earth, fourteen times as wide, and twice as deep.

If the Martian canyon were imagined to exist in the United States, it would run from San Francisco to Cincinnati, or from New York to Salt Lake City. The canyon is now named "Valles Marineris" ("Mariner Valley").

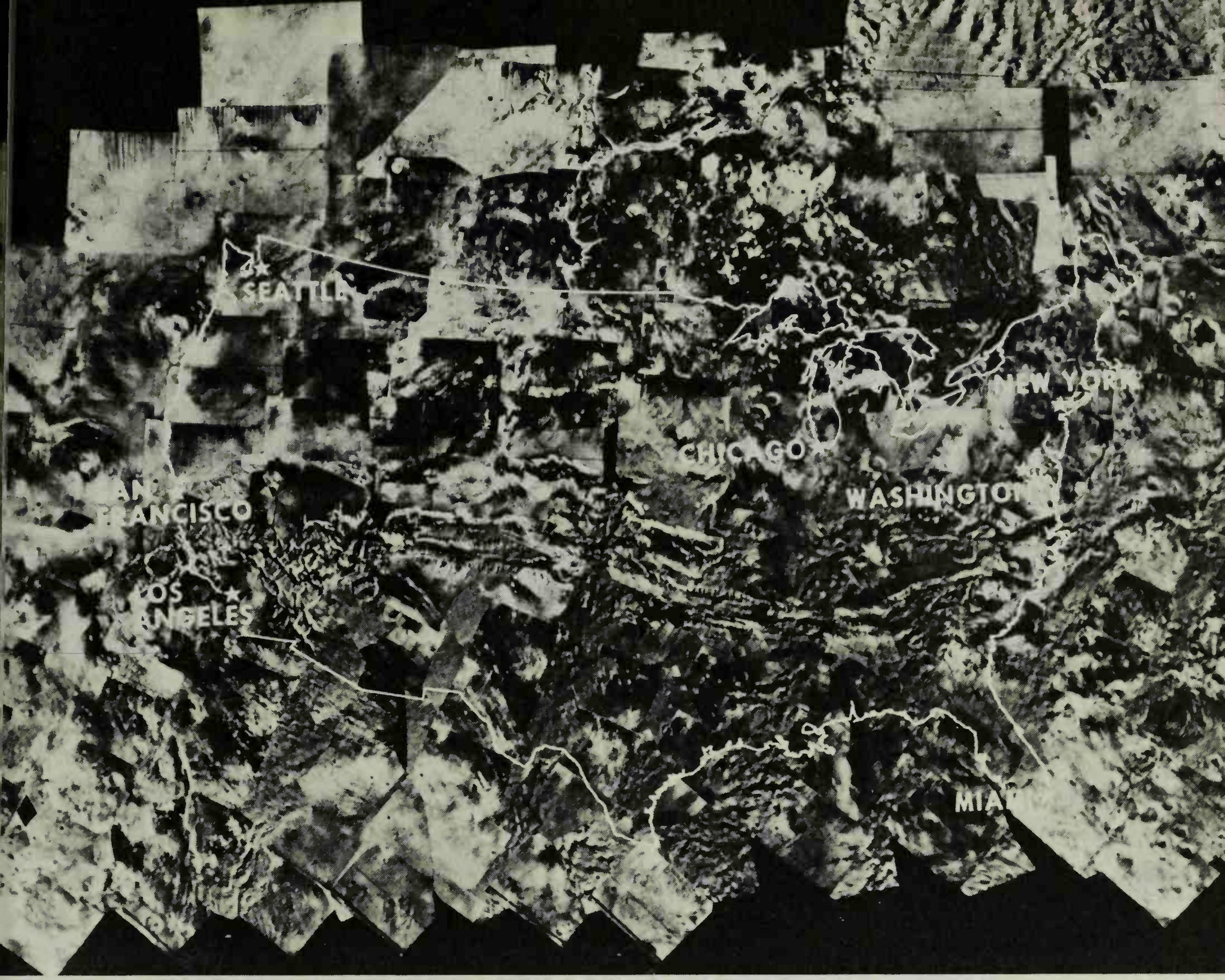
The forces that formed the volcanoes and canyons only about 200 million years ago (making them the youngest features on Mars) also bellied upward the entire surface of the planet in that region. Since the volcanic region is just about at Mars's equator, this makes the equatorial diameter longer than it would otherwise be.

This explains the long-puzzling fact that Mars is more oblate than one would expect it to be from its speed of rotation. Only half the equatorial bulge is due to rotation; the other half is produced by the thrusting up of Tharsis.

That thrusting up almost makes Mars lopsided, as the equatorial bulge is thicker on the volcanic side of Mars than on the other.



This is a Viking photograph of Valles Marineris, or Mariner Valley, taken from a distance of 2000 kilometers (1240 miles). Apparently the canyon was formed by collapse and at one point you can see where an edge of a crater was simply lopped off. There are signs of landslides down into the canyon. *NASA photo*



To illustrate the impressive size of Valles Marineris, it is shown here superimposed on a map of the United States. *NASA photo*

Water and Carbon Dioxide

One feature of the Martian surface roused even more curiosity than the volcanoes or the canyons. There were markings that wiggled their way across the Martian surface and had branches for all the world like rivers, except that there was no water in them. Some were up to 1500 kilometers (940 miles) long and as much as 200 kilometers (125 miles) wide.

Experts studying the photographs sent back by Mariner 9 tried to imagine what could possibly have caused the markings. Could it have been molten lava? Could it have been the effect of high winds? Nothing they could think of seemed likely to produce those riverlike markings except rushing liquids, and the only liquid that seemed even remotely possible on Mars was water. What's more, the markings were found mostly in the equatorial regions where temperatures were highest and flowing water was most likely.

But how could there have been rushing water on Mars? Mars is so dry and so cold that even if liquid water formed, it would quickly either evaporate or freeze.

Could it be that conditions were different on Mars in the past? Maybe there was a time when it was a little warmer, a little damper, and had a little more atmosphere. There could then have been water flowing across the surface and forming those riverbeds. If so, where did the water go?

One possibility was that water vapor had gradually leaked away from Mars and that it was growing dryer as had been supposed after Schiaparelli's report of canals—but even dryer than had then been supposed. However, at Mars's cold temperature, the leak of water vapor would not be great. Alternate possibilities were suggested.

Another way in which liquid water can appear to vanish is for it to freeze. It might be that parts of the Martian soil contained a great deal of permanently frozen water. On Earth, there is such frozen water in the soil in polar regions and it is called "permafrost." It might be that there is permafrost on Mars and that that is where the water is.

It might even be that Mars goes through alternating periods of weather, cold and permafrost at one time, mildness and rivers at another, back and forth. Mars's orbit goes through cyclic changes. The angle at which the axis is tilted slowly changes by rather large amounts, up to 20 degrees back and forth according to some estimates. The eccentricity of the orbit changes also, so that sometimes the perihelion is a little closer to the Sun and then a little farther, back and forth. There are other small changes, too. All these changes in combination may serve to bring about the weather cycle on Mars.*

The freezing of water during the cold period would empty the rivers and fill the soil with permafrost. The melting of the permafrost would fill the rivers, and the sudden disappearance of the frost in regions where it was plentiful could cause the collapse of the soil. It is conceivable that Valles Marineris may have formed through the collapse that followed the melting of permafrost, with the debris carried away by flowing water.

And it may be that we happen to be observing Mars in one of its ice ages—a worse one than any on Earth, of course, since Mars has less air, less water, and is farther from the Sun; but better, in the sense that the lack of water on Mars at least stops huge glaciers from forming.

Another place where the water can go is into the ice caps. Most astronomers had assumed that the ice caps were made of frozen water, but there were a few who had suggested frozen carbon dioxide. Either way, there were interesting possibilities.

Suppose the ice caps were entirely frozen water. When Mars is in a period of milder weather, the ice caps might melt. The melted ice caps and the melted permafrost might give Mars a quite watery period. Some have estimated that there is enough water in the ice caps and the permafrost to yield about 3 million cubic kilometers (730,000 cubic miles) of water. That would be about 1/400 the total amount of water on Earth and that is a respectable quantity.

On the other hand, suppose the ice caps were entirely frozen carbon dioxide. Frozen carbon dioxide does not melt in the ordinary fashion but changes directly into carbon dioxide gas. This change from solid to gas is called "sublimation."

* Some scientists think that similar, but smaller, changes in Earth's axial tilt and orbit produce a swing in Earth's weather, too, and bring about ice ages every so often.

By putting individual photographs together, it was possible to present the entire northern hemisphere of Mars, entirely bathed in light, something that would be impossible in nature. At the center of the visible half of the globe is the North Polar Ice Cap. *NASA photo*

Carbon dioxide sublimes at a temperature of −78.5° C. (−109.3° F.). That means it has to be much colder for carbon dioxide to freeze than for water, since water freezes at 0° C. (32° F.). In reverse, it means that it is much easier for frozen carbon dioxide to vaporize than for frozen water to melt.

When Mars goes through a mild period, the carbon dioxide produced by the subliming ice caps could make the Martian atmosphere nearly as dense as Earth's.

It so happens that carbon dioxide has the property of being transparent to visible light but not to infrared radiation. A planetary surface will absorb visible light in the daytime and warm up. At night it will cool down by radiating infrared. If that cannot get away because of the carbon dioxide in the atmosphere, the planet stays warmer than it would otherwise be. This is how glass works in a greenhouse, so the action of carbon dioxide is called a "greenhouse effect."

If any slight warming of Mars causes the polar ice caps to release carbon dioxide, that would then encourage further warming and end by making Mars quite mild.

Naturally, if the ice caps contain both water and carbon dioxide as now seems certain, we have a combination of the two effects. Any warming trend releases carbon dioxide gas which brings about further warming and melts the water to produce rivers. In the combined effect, the atmosphere would never get so dense as it would if the ice caps were carbon dioxide alone, nor would Mars ever get so watery as it would if the ice caps were water alone—but it would get a moderately dense atmosphere and be moderately watery.

Both polar ice caps seem to exist in layers. At the edge, where there is melting, they look almost like a stack of thin poker chips in which each chip is just a little inward from the one below it. Astronomers are not sure what that means, although some think it may represent a series of smaller swings in the weather cycle, with partial melting and then partial freezing.

Yet on the other hand, all this may be in the past. It is possible that through much of Mars's history such weather cycles did take place, and the stacking of the ice caps, together with the empty riverbeds, is evidence of this. One suggestion is that in the past, Mars's axis was tipped even farther than it is now, so that the polar regions got plenty of sunlight at near equatorial intensity for a good part of the year. In that case, no part of Mars would be sufficiently cold for a sufficient length of time to allow ice caps to form and the planet would be watery.

Then, about 200 million years ago, the Tharsis bulge was thrust up as volcanic action let go. This made the equatorial bulge twice what it had been, and the action of the Sun on the wider bulge somewhat straightened out the axial tilt. At the present tilt, the polar regions do not get warm enough to prevent ice-cap formation and the liquid water has disappeared. Now it may be that Mars is in a permanent ice age—unless further changes in its structure take place.

Mariner 9 was able to observe Mars for nearly a year. Finally, on October 27, 1972, it was no longer able to keep itself in a stable position with respect to Mars and it began tumbling. With that, its useful life was over. Still, it had orbited Mars usefully for 349 days and had sent back 7,329 pictures of Mars, Phobos, and Deimos.

11 THE LANDING ON MARS

The Importance of Mars Probes

The message of each of the Mars probes—Mariners 4, 6, 7, and 9—was identical. The Martian environment was frigid, dry, and very unfriendly to life as we know it here on Earth. It was much more unfriendly than had been thought in the days when people were speculating about the canals—almost as unfriendly as Wallace had suggested in 1907 when he denounced Lowell's views.

Yet there was hope after all that some sort of life might yet exist on Mars. The dry riverbeds and the terraced appearance of the ice caps made it seem possible that Mars had once been mild, even if it wasn't now, and that it might be mild again someday. Life could have formed during the mild periods, and since it would be adapted to Martian conditions, living things might still be active now, or perhaps in a period of hibernation, sleeping through the long Martian ice age.

Carl Sagan is one astronomer who thinks that this might be at least possible. (His wife, Linda, is supposed to have said, "We ought to add water to some Martian soil and see who grows.")

Sagan points out that pictures taken from probes are completely useless in detecting evidences of life. However excellent they might be in detecting geological formations, the activity of life would escape them. Satellites that circle Earth and take pictures of our own planet show no clear evidence of life and its activities when they are at the heights of the Martian probes. And on Earth, at least, we know there is life.

The logical next step after Mariner 9, then, was to attempt a Mars probe that would make a soft landing on Mars—one that would be gentle enough to leave the instruments on board intact. Within such a probe, there would be instruments designed to perform automatic tests on Martian soil which would detect the presence or absence of life.

It would be an expensive task; eventually it turned out to cost about a billion dollars. Was it worth it to the American taxpayer to satisfy the curiosity of astronomers?

This is a question frequently asked in connection with the space program, but what humanity is purchasing is knowledge, and knowledge obtained in any field can be useful in other fields. History shows that increased knowledge is always useful to man, where it is dealt with wisely.

For instance, a great part of the effort of modern science lies in the direction of understanding the machinery of life—the way the brain works, how we age, where our body goes wrong and how to correct it. We all must surely admit that these are important matters to everyone and that the more that is learned about such things the better off each one of us could be.

The difficulty of understanding life, however, is that even in its simplest form here on Earth it is still an enormously complicated system. Furthermore, all forms of Earthly life are basically one; all are built out of the same types of complicated molecules that undergo the same sorts of chemical reactions. The differences between a giraffe, an oak tree, a man, an ant, and a germ are enormous on the outside, but once we get down to the molecules making up each, the differences are small.

Suppose, though, we discover there is life on Mars—

On Earth, all forms of life may have descended from a single first example, so that all forms of Earthly life are distant cousins. On Mars, we would have the first example of life that would be completely independent of Earth life, that began from another first example altogether. Such a discovery would instantly double the number of basic patterns of life we know and could greatly increase our understanding of life generally, and therefore of our own life.

In order to bring this about, the life on Mars would not have to be intelligent or advanced at all. It could be simple, even very simple, only the equivalent of Earthly bacteria. In fact, it might even be more useful if it were very simple, since it might then be easier to understand.

Suppose, though, we found life on Mars and found it to be built out of the same chemicals as Earthly life. That, too, could be important. It might mean that only one basic form of life is possible. Besides, even if Martian life were basically the same as ours, it might still be different in some illuminating details.

But suppose that, after all the expense of sending probes to land on Mars, it turned out that the message was—no life.

That might not be final. The probe might have landed on a barren spot (and there are barren spots on Earth, too). Even if all spots tested seemed to be barren, it might be that we were testing for life by assuming that Martian life would do what Earthly life does. If Martian life is really completely different from our own, we might not know how to test for it.

But suppose there is really no life on Mars. Is the expense of the probing wasted?

Not necessarily. According to experiments that scientists have been carrying on for twenty years, it seems that the common elements of the universe are sure to turn first into simple molecules and then, under the influence of the energy of sunlight, into more and more complex molecules of the type that go on to form life. Chemists can very easily duplicate parts of the process in the laboratory. The process, at least the beginnings of it, seems to have taken place in some meteorites and even in the vast, thin dust clouds of space.

Even if life did not develop on Mars because conditions are not favorable enough, might the process not have gone part way? It may be that even if Martian soil does not contain living organisms, it may contain molecules part way toward life. This, too, could be useful. It would show us, perhaps, what the period of "chemical evolution" that preceded life might have been like on Earth.

If everything failed—if Mars were simply barren of anything at all to do with life—there would be usefulness in studying it. Mars is similar to Earth in so many ways that it could be helpful to study the development of two such similar worlds where one is lifeless and one is full of life. The differences in development could help us understand more about Earth life.

Then, too, Earth and Mars both have atmospheres and both have a 24-hour rotation period, but Earth has oceans and Mars does not. There may be differences in the wind patterns as a result, and by studying the differences in those patterns, we might understand air circulation better on Earth. That would help us understand Earth's weather better, and that is certainly something that is extremely important to us.

Scientists therefore looked forward to a soft landing on Mars with great excitement—life or no life.

Vikings 1 and 2

The probes intended for the Mars landing were named "Viking" after the Norse explorers who had landed on the "new world" of the Americas some 500 years before Columbus.

Two Vikings were prepared and both were safely launched and guided. Viking 1 was launched on August 20, 1975, and Viking 2 on September 9. Both performed excellently and both were placed in orbit about Mars. Viking 1 went into orbit on June 19, 1976.

This alone was good, for the Vikings proceeded to duplicate the work of Mariner 9 with improved technique. Better photographs of the Martian terrain and the Martian satellites were taken than ever before.

The people in charge of the Viking project were concerned over the exact site where the "landers" would come down to the surface. They would have to land upright on a reasonably level section of ground. Unevennesses would overturn them and prevent them from operating.

A site had been chosen for Viking 1 on the basis of the Mariner 9 photographs, but the closer and better look at that spot by the Vikings made it seem too rough for the purpose. For a month Viking 1 remained in orbit about Mars while astronomers agonized over possible landing sites. It had originally been hoped to make the first landing on July 4, the two hundredth anniversary of the Declaration of Independence, but astronomers wisely decided rather to miss the day than take a chance at ruining the mission.

It was not till July 20, 1976, that a landing was risked. On that day, it came down at a point 22.27° North Latitude and 48.00° Longitude. (On Earth, such a position would be in mid-Atlantic, just south of the Tropic of Cancer.) The landing was carried through satisfactorily. Some weeks later, Viking 2 was landed farther north at 47.97° North Latitude and 225.67° Longitude (the equivalent of southeastern Siberia, near the city of Khabarovsk).

Even as they landed, the Vikings could analyze the Martian atmosphere. They discovered small quantities of nitrogen, an element essential to life—and the first time that had been detected on Mars. The composition of the Martian atmosphere as determined by the Vikings, and as compared with Earth's, is given in Table 63.

The argon concentration is important. Argon is made up of heavy atoms that move sluggishly. Even Mars's rather small gravity can hold it, so the planet probably has, right now, all the argon it ever had.

Suppose the Martian atmosphere had a high percentage of argon, as had been thought by some astronomers prior to the Viking probes. That might be so only because the rest of the atmosphere had slowly leaked away. It might then be possible to make a rough guess as to the original density of the atmosphere. The actual figure on argon, however, is low enough to make it seem that the Martian atmosphere may never have been very much more dense than it is now.

Once the Viking landers were on the surface, they could measure the temperature there, and it turned out that Mars was indeed cold. Recorded temperatures at dawn were something like −85° C. (−121° F.) and a maximum temperature, at about 3:30 P.M., was −29° C. (−20° F.). Wind velocities reached as high as 54 kilometers per hour (33 miles per hour), but usually they were considerably less. This is Antarctic weather indeed, and at the Martian South Pole the temperatures may sink to −139° C. (−218° F.). It seems very unlikely that there is liquid water on Mars at any time—at least under present conditions.

At the time of the landing it was winter in the northern hemisphere of Mars and the temperature had to be low enough to freeze carbon dioxide at the North Pole. Indeed, the carbon dioxide concentration in the atmosphere was decreasing very slowly at the rate of about 0.2 percent a day. Once the spring comes, of course, carbon dioxide will begin to be released from the northern ice cap (leaving frozen water behind), but when

TABLE 63

Composition of the Martian Atmosphere

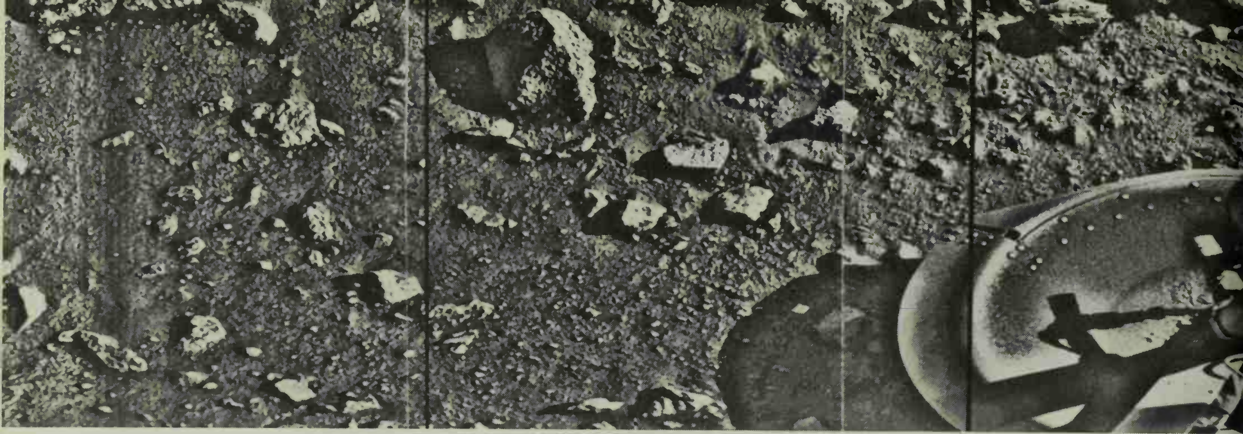
GASES	MARS (PERCENT)	EARTH (PERCENT)
Carbon Dioxide	95	0.03
Nitrogen	2.7	78.1
Argon	1.6	0.9
Oxygen	0.15	20.9

the summer comes it is winter in the southern hemisphere, and the carbon dioxide concentration again sinks as the southern ice cap grows.

In other words, the Martian atmosphere grows less dense, then more dense, alternately, in two cycles per year. In the depth of the southern winter, when Mars is at aphelion and is coldest so that carbon dioxide freezes to the maximum extent, the Martian atmosphere may be only three fourths as dense as it is in spring or fall.

Although the Martian atmosphere contains less water vapor than Earthly deserts do, the trace present was greater than had been expected. It seems that if all the water vapor in the Martian atmosphere were collected and liquefied, it could form a body of water as large as the Great Salt Lake in Utah.

Once the landers were on Martian soil, they took photographs which they beamed back to Earth over a distance of some two hundred million miles. These photographs, seen over television, were the most dramatic immediate results of the probe. For the first time in history, human beings could look at the surface of another planet as seen from that surface itself.



This is the first photograph ever taken of the surface of Mars. It was taken on July 20, 1976, just one minute after Viking I lander landed. The large rock in the center is about 10 centimeters (4 inches) across. The object at the lower right is one of the footpads on which the lander rests. *NASA photo*

Both landers, though widely separated, showed the same kind of landscape—a desolate desert area strewn with rocks of all sizes from small pebbles to boulders. The photographs were in color and they showed the rocks to be a distinct red. The sky is a bright salmon pink, no doubt from the reddish dust in the air.

Samples of Martian soil were analyzed, and Table 64 gives the percentage of the various elements contained compared with average samples of Earth's soil.

Martian soil, like Earthly soil, is composed of silicates, which are combinations of silicon and oxygen with various metals. Silicon and oxygen together make up 71 percent of Earthly soil and 74 percent of Martian soil. An important difference is that Martian soil is richer in iron and poorer in aluminum than Earthly soil is. (Martian soil is also richer in sulfur and poorer in sodium and potassium than Earthly soil is.)

It is the high iron content that must give rise to the color of the Martian soil. It may be that about 80 percent of the Martian soil is an iron-rich clay, and the iron present may be in the form of limonite, an iron compound that is responsible for the color of red bricks, and which gives a reddish tinge to some deserts.

We can therefore see that Mars's ruddy color, which roused fear in early human beings because of the association with blood, has nothing to do with blood, or with war and death. Mars is simply a rusty world.

TABLE 64

Composition of the Martian Soil

ELEMENT	MARTIAN SOIL (PERCENT)	EARTHLY SOIL (PERCENT)
Oxygen	50.1	46.6
Silicon	20.9	27.7
Iron	12.7	5.0
Magnesium	5.0	2.1
Calcium	4.0	3.6
Sulfur	3.1	0.05
Aluminum	3.0	8.1
Chlorine	0.7	0.02
Titanium	0.5	4.4

Mars is probably rock all the way through. This seemed likely since the over-all density of Mars isn't high enough to indicate a metal core. Then, too, Mariner 4 had found that Mars did not have a magnetic field as Earth did (compasses would be useless on Mars) and this, too, is evidence that no metallic core exists.

The Viking landers were on the Martian surface for more than sixty days before registering the first marsquake. Mars may be geologically alive but, as expected, it is not as alive as Earth is.

Life on Mars?

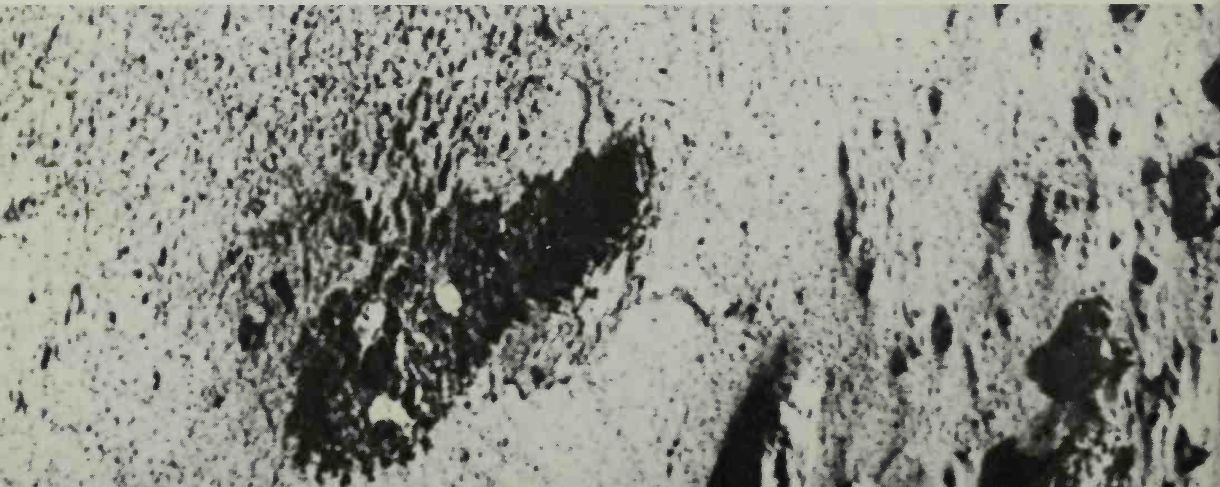
The question of biological life, however, seemed not to be entirely hopeless when the Vikings arrived. The dried rivers seemed even more numerous and more unmistakably rivers in the Viking photographs than they had appeared to be in the Mariner 9 photographs. Then, too, the existence of water vapor in the atmosphere, even in small amount, seemed a hopeful sign.

To be sure, the water in the ground was probably permanently frozen even at the Martian equator, but it was there. The lander could demonstrate that.

Signals from the Earth caused the lander to extend a scoop, dig up a bit of soil, and withdraw it into the lander for treatment and analysis. When the soil was heated, it lost about 1 percent of its weight and that 1 percent is very likely water held to the various molecules in the soil by chemical forces. It is possible that Martian life might be adapted to make use of this chemically bound water.

The landscape looked completely barren at the site of both Viking 1 and Viking 2. This might not be the way Mars looks

The dark mark that looks almost like a footprint is the trench made by the Viking 1 scoop when it dug up a small quantity of Martian soil for study. The scoop did not work at first and scientists had to fiddle with it quite a bit—at a distance of many millions of miles—in order to loosen a stuck boom latch pin, and get it to moving. *NASA photo*



everywhere, but from the nature of its atmosphere and from its temperature, there's a good chance that it does. It that case, there seems just about no hope for complex life or large plants or animals.

What remains is the possibility of microscopic life-forms in the soil. The Viking landers were equipped with small laboratories that could carry out three different experiments designed to detect the kind of activity we associate with life on Earth.

The first experiment is called the "pyrolytic release experiment." In this experiment, a sample of Martian soil is bathed in light and kept in contact with a sample of carbon dioxide that originated on Earth. The carbon dioxide molecules contain the special kind of carbon atom called carbon-14, which is radioactive and which breaks down steadily, giving off high-energy particles which can be easily detected. Ordinary carbon atoms don't do this.

If it were Earthly soil which contained small plant cells of some kind, those plant cells in the presence of light would absorb the carbon dioxide and incorporate it into their own tissues. Then, later on, if the carbon dioxide is flushed away and the soil is heated strongly,* the carbon compounds in the soil break up and carbon dioxide is produced. The carbon dioxide can be identified by the carbon-14. If the same experiment were conducted in the dark, nothing would happen. If the soil were strongly heated *before* the experiment, the life in the soil would be killed and nothing would happen.

Martian soil was subjected to this experiment, and the carbon-14 was detected at the proper time. Martian soil behaved in a way you would expect if it had living cells in it.

* It is this heating to high temperature that makes the experiment "pyrolytic" (pigh-roh-LIH-tik), as the word is from Greek words meaning "break up by heat."

The second experiment was the "labeled release experiment."

Although the first experiment concerned a chemical reaction that would take place only in the light, other kinds of chemical reactions involving life can take place in the dark. Earthly life, for instance, absorbs certain simple carbon-containing chemicals when they are dissolved in water and then incorporates it into its own tissues. Meanwhile compounds in the tissues break down and gases are given off containing carbon atoms, some of them from the simple chemicals that had been absorbed.

Martian soil was therefore treated, in the dark, with a solution of simple carbon-containing chemicals (of the type that Earthly life makes use of) in water. These chemicals contain carbon-14, which is called a "label" since it distinguishes these chemicals from ordinary chemicals with ordinary carbon. That is why the experiment is called a "labeled release."

If there is no life in the soil, there should be no release of gases containing carbon-14 in the course of the experiment. But there *was:* carbon-14 was again detected, and again this did not happen if the soil was baked in advance. Again the result was what might be expected if life were present.

Finally there was a "gas exchange experiment." On Earth, living organisms exchange gases with the atmosphere. We, for instance, absorb oxygen and give off carbon dioxide. Green plants, when engaged in making use of the energy of sunlight, absorb carbon dioxide and give off oxygen.

Samples of Martian soil were moistened with water containing chemicals Earthly life would need to live. The atmosphere above the soil was tested every once in a while. It turned out that there *was* a gas exchange. Oxygen was given off quite rapidly and this, too, didn't happen if the soil was baked in advance. Of course, oxygen would be given off in an experiment with Earthly soil, but only if light were present, and the experiment on Mars was carried out in the dark.

All three experiments, then, gave the kind of results one would expect if there were living things in the Martian soil—but astronomers hesitated. One further experiment seemed to go against the possibility of life.

Soil can be heated and tested for carbon-containing compounds. These are called "organic" compounds because such compounds are usually found in living organisms or are the remains of dead organisms. When Martian soil was tested it proved to have no detectable amounts of organic compounds.

How could there be life on Mars if there were no organic compounds in its soil?

Well, ultraviolet light from the Sun reached the Martian soil in greater quantities than was ever received by Earth's soil (because of the thinness of Mars's atmosphere). Perhaps that broke up the organic-compound molecules. To check that, the Viking lander used its scoop to turn over a small rock, then collect soil from underneath. That soil had not been exposed to ultraviolet light, but it, too, had no organic compounds in it.

In Earthly soil, of course, most of the organic compounds are the remains of dead organisms. Perhaps on Mars all dead remnants are quickly eaten and made part of the few living cells. Perhaps—but how can this be checked?

But then if there are no organic compounds in Martian soil and there is therefore no life, how can we explain the three different experiments which all yielded the kind of results we would expect of life? Some astronomers think that perhaps the ultraviolet light reaching the Martian surface produces peroxides, chemicals which are not present in Earthly soil. Perhaps these peroxides behave the way we would expect living organisms to behave, and account for the positive results of the first three experiments. But this also is uncertain.

What Viking seems to have done is to show us a Martian soil which has either some very interesting chemistry going on in it or some very interesting biology.

So there we are. The human race has come a long way. It began by staring at a red dot in the sky and wondering what it was and what it meant. Now it can send messages across hundreds of millions of miles, ordering a machine to dig up a bit of soil on that red dot and analyze it.

What next?

Surely we can't leave the question of life on Mars at this stage. We must find out more—but how?

We need additional Vikings, more complex ones. We need Vikings that are capable of penetrating deep into the soil to see what is going on down there well out of range of ultraviolet light. We also need Vikings on wheels, capable of maneuvering about the Martian terrain, looking for likely spots to investigate. And we need Vikings capable of carrying out more and better experiments.

Finally, the day may come when human beings will stand on the surface of Mars and investigate it for themselves, as they have already done in the case of the Moon. The day on which we reach Mars may not come soon; it may not come until after human beings have established bases on the Moon and built settlements in space. But if civilization continues, that day will certainly come.

GLOSSARY

ALBEDO—The fraction of sunlight reflected by a planet or satellite.

APHELION—The point in a planet's orbit where it is farthest from the Sun.

APOGEE—Referring to the Moon, the point at which it is farthest from the Earth.

AREOGRAPHY—The study of the surface of Mars, comparable to geography as the study of the surface of Earth.

ASTEROID—A small planet.

ASTROLOGY—The study of the planets for their supposed influence upon human affairs and events on Earth.

ATMOSPHERE—The layer of gases surrounding a planet, satellite, or star.

AXIAL TILT—The angle between the axis of rotation of an object and a line perpendicular to its plane of revolution.

AXIS OF ROTATION—The imaginary straight line about which an object spins.

CARBON DIOXIDE—A gas found in Earth's atmosphere in small quantities; found in the atmosphere of Mars in large quantities.

CARBON-14—A radioactive form of carbon that gives off high-energy particles which can be detected readily.

CELESTIAL POLES—Imaginary points in the sky that are directly above a planet's north and south poles.

CENTRIFUGAL EFFECT—The tendency for anything spinning about a center to move away from that center.

CONJUNCTION—The appearance of a near approach of a planet to the Sun, as viewed from the Earth.

DEGREE—An angular measure equal to $\frac{1}{360}$ the circumference of a circle.

DENSITY—The mass of an object divided by its volume.

DIAMETER—The length of a line passing across the widest part of a circle or sphere and through the center of the circle or sphere.

ECCENTRICITY—The degree to which the ellipse of an elliptical orbit is flattened.

ECLIPSE—The covering from view of an object in the sky by another object that moves in front of it.

ELLIPSE—A curve that looks like a flattened circle.

EQUATOR—The circumference that lies halfway between the two poles of a spinning object.

EQUATORIAL BULGE—The extra thickness of a planet in the equatorial regions due to the centrifugal effect of its rotation.

ESCAPE VELOCITY—The speed with which an object must move to escape from the gravitational pull of a planet, satellite, or star.

FOCUS (plural, foci)—One of two points inside an ellipse. The two foci are at equal distances from the center of the ellipse and on opposite sides, along the major axis.

GEOCENTRIC—"Earth-centered," referring to the early belief that the Sun, the Moon, and the other planets circled the Earth.

GRAVITATION—The attraction exerted by one object on the other objects in the universe.

HELIOCENTRIC—"Sun-centered," referring to the movement of the planets with the Sun, rather than Earth, as the center.

HORIZON—The most distant point on a landscape, where it appears to meet the sky.

ICE CAP—Perennially frozen water, carbon dioxide, or other substance on the surface of a world at its poles.

LATITUDE, PARALLELS OF—Imaginary east-west lines parallel to the equator on Earth or to the celestial equator in the sky.

LONGITUDE, MERIDIANS OF—Imaginary north-south lines stretching from pole to pole of a rotating body.

MAGNITUDE—A figure representing the apparent brightness of an object shining in the sky. The lower the figure, the brighter the object.

MAJOR AXIS—A diameter passing through the foci and center of an ellipse.

MASS—In a general way, the amount of matter in an object.

METEORITE—A small body from space which has collided with Earth's solid surface.

MICROMETER—An instrument used with a telescope to measure minute distances.

MICROWAVES—A form of radiation used in radar. The waves are longer than those of infrared radiation and can be beamed outward to strike other worlds and be reflected.

MINOR AXIS—A diameter at right angles to the major axis of an ellipse; the shortest diameter of an ellipse.

MINUTE OF ARC—An angular measure equal to $1/60$ of a degree.

NEBULA—A cloud of dust and gas in space.

OBLATENESS—The flattening of a planet from spherical form because of the centrifugal force of rotation.

OPPOSITION—The appearance of a planet in the part of the sky opposite to that in which the Sun appears.

ORBIT—The path taken by an object revolving about a larger object.

ORBITAL INCLINATION—The angle made by the orbital plane of each planet with respect to that of the Earth.

ORBITAL PLANE—The flat surface that would result if every point on the orbit of a planet about the Sun were connected with the center of the Sun.

ORBITAL VELOCITY—The speed with which a body travels around a larger body.

PARALLAX—The apparent change of position of a close object compared to a more distant object, when the viewer shifts the position from which he views the object.

PERIGEE—Referring to the Moon, the point at which it is nearest to Earth.

PERIHELION—The point in its orbit where a planet is closest to the Sun.

PERIOD OF REVOLUTION—The time it takes an object to make one complete turn about a larger object.

PERIOD OF ROTATION—The time it takes an object to spin once on its axis.

PERMAFROST—A permanently frozen layer beneath the surface of a world.

PHASES—The different shapes of the lighted part of a planet or satellite that is shining by reflected light from the Sun.

PLANET—A body that circles a star and shines only by reflected light.

POLES—The two points where the axis of rotation reaches the surface of the rotating body.

PRECESSION—The circular movement of both ends of a planet's axis of rotation, causing a shifting of the celestial poles.

PROBE—A rocket-driven vessel designed to pass near some planet or satellite in order to gather information about it.

RETROGRADE MOTION—Motion in the opposite direction from what is usual.

REVOLUTION—The circling of an object about another object.

ROCKET—A jet engine that is thrust forward by the discharge of hot gases produced by combustion.

ROTATION—The spinning of an object about its own central axis.

SATELLITE—An object that revolves about a planet.

SECOND OF ARC—An angular measure equal to $\frac{1}{60}$ of a minute of arc.

SIDEREAL DAY—The length of a planet's period of rotation relative to the stars.

SOLAR DAY—The length of a planet's period of rotation relative to the Sun.

SOLSTICE—One of two dates during the year when the noonday Sun is either at its highest or its lowest point as seen from Earth.

SPECTROSCOPY—The technique of spreading light from any object into its component wavelengths from violet to red.

SPECTROSCOPY, INFRARED—The analysis of the infrared light that arrives from planets to find out what wavelengths are missing, to detect the atmospheric gases that are absorbing those wavelengths.

SPECTRUM (plural, spectra)—Light which has been spread out so that each different wavelength is in a different position, as in a rainbow.

SUBLIMATION—The changing of a solid into a gaseous state directly, without passing through a liquid state.

SURFACE—The outside of any solid object.

SURFACE PRESSURE—The weight an atmosphere exerts upon a unit area of the surface of a world.

TELESCOPE—A tube, containing lenses or mirrors, which makes distant objects look larger, nearer, and brighter.

TERRESTRIAL PLANETS—The small planets—Mercury, Venus, Earth, Mars, and Pluto.

TIDAL DRAG—The differential pull of a body on various parts of another body circling it that may slow the rotation, round the orbit, or alter the distance of that body—or all three.

VOLCANO—A mountain composed of material thrust up as hot rock from a central crater.

VOLUME—The room taken up by any object.

ZENITH—The point in the sky that is directly overhead.

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ISAAC ASIMOV says he writes about anything that interests him. He has written [illegible] books and hundreds of articles and short stories. His pen ranges through and enthusiasm for nearly all branches of science and a wide variety of other subjects including mathematics, language, Shakespeare, the Bible, history, humor, mysteries, and science fiction.

Born in Russia, he came to the United States at the age of three and spent his childhood devouring not the candy, but the books and magazines in his father's stationery store in Brooklyn, New York. At Columbia University he earned the degrees of B.S., M.A., and Ph.D. and then joined the teaching staff of Boston University where he still holds the title of Associate Professor of Biochemistry at the School of Medicine.

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About the Author

ISAAC ASIMOV says he writes about anything that interests him. In more than 180 books and hundreds of articles and short stories, he has entertained and enlightened readers on every branch of science and a wide variety of other subjects, including mathematics, language, Shakespeare, the Bible, poetry, humor, mysteries, and science fiction.

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A noted wit and raconteur, he is in great demand as a speaker, and has received countless awards and honors, including honorary doctoral degrees. He and his wife live in a New York City apartment with a telescope and an unobstructed view of the skies.