The Planets and Their Satellites

Fools have said that knowledge drives out wonder from the world;
They'll say it still, though all the dust's ablaze with miracles at their feet.
— Alfred Noyes

1. The Planets’ True and Apparent Motions

We have seen how the earth’s diurnal motion of rotation on its axis gives to the distant stars an apparent diurnal motion of rising and setting, how the earth’s motions of rotation and revolution together give the sun both an apparent diurnal motion across the sky and an apparent annual motion along the ecliptic. The final degree of complication is to be found in the apparent motions of the planets. Though we can regard the sun and stars as stationary, we know that the planets are in motion about the sun. We on the earth are therefore viewing moving objects — the planets — from a moving station — the earth. What may we expect to see?

To be able to answer this question, we must know the positions of the planets (the earth included) relative to the sun and stars. For many purposes, this is most conveniently done by specifying unambiguously (1) the orbit of each planet and (2) its position in that orbit. As we have already seen, the size and shape of a planetary orbit can be given by a statement of the orbit's major semi-axis, \(a\), and eccentricity \(e\). It remains only to characterize the orientation of the orbit.

To begin with, the orbit of each planet is in a plane, but no two planets revolve in the same plane. The plane to which the rest are referred is, naturally, the plane of the earth’s orbit, the plane of the ecliptic. The angle by which each planet’s orbital plane is inclined to the ecliptic is called the \textbf{inclination}, \(i\), of the orbit. The inclinations of the planets' orbits are given in the Table.

The five orbital elements shown here completely determine the orbit of any planet.
The inclination alone is not enough to specify completely the orientation of a planet's orbit, however; there are infinitely many different planes with the same inclination. To be of interest, a plane must pass through the center of the sun, for the orbit of every planet contains the sun. Consequently, every planet's orbital plane will intersect the plane of the ecliptic in a straight line which passes through the sun's center; this line of intersection is called the line of nodes. The line of nodes, being in the earth's orbital plane, is directed toward two diametrically opposite points on the ecliptic called the nodes. Viewed from the sun, any planet will be seen to cross northward from “below” the earth's orbit at one node, the ascending node; at the other, the descending node, the planet will cross southward from “above” the earth's orbit to “below”. The position of the ascending node is given by its angular distance from the vernal equinox, measured in degrees along the ecliptic. This angle is called the heliocentric longitude of the ascending node and is given the symbol $\Omega$. The inclination and the longitude of the ascending node together uniquely determine the position of an orbital plane.

The orientation of an orbit in a given orbital plane is fixed by the longitude of the perihelion point, $\omega$. It is the angle in the orbital plane between the line of nodes and the direction of perihelion, measured in the direction of the planet's orbital motion. The five quantities $a$, $e$, $i$, $\Omega$ and $\omega$ serve to describe any planet's orbit completely and are called the orbital elements. They are given for all nine planets in the table.

A planet’s actual position in its orbit can be had from a knowledge of a sixth orbital element; this is the time of perihelion passage, $T$. If it is known when a planet was once at perihelion, its exact position can be found at any previous or later time with the aid of Kepler’s laws.

### Orbital Elements of the Planets (1960.0)

<table>
<thead>
<tr>
<th>Planet</th>
<th>$a$</th>
<th>$e$</th>
<th>$i$</th>
<th>$\Omega$</th>
<th>$\omega$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.2056</td>
<td>7° 0' 14'</td>
<td>47° 45'</td>
<td>28° 57'</td>
<td>1950.993</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.0068</td>
<td>3° 25' 79'</td>
<td>76° 14'</td>
<td>54° 39'</td>
<td>1950.700</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>0.0167</td>
<td>3° 31' 14'</td>
<td>102° 6'</td>
<td>2051.100</td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>0.0934</td>
<td>1° 51' 0'</td>
<td>49° 11'</td>
<td>285° 59'</td>
<td>1950.998</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.203</td>
<td>0.0484</td>
<td>1° 18' 21'</td>
<td>99° 57'</td>
<td>273° 35'</td>
<td>1951.691</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.539</td>
<td>0.0557</td>
<td>2° 29' 25'</td>
<td>113° 14'</td>
<td>338° 52'</td>
<td>1944.684</td>
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<tr>
<td>Uranus</td>
<td>19.182</td>
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<td>73° 45'</td>
<td>96° 7'</td>
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<td>Neptune</td>
<td>30.058</td>
<td>0.0066</td>
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<td>272° 57'</td>
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<td>Pluto</td>
<td>39.439</td>
<td>0.2502</td>
<td>17° 10' 12'</td>
<td>109° 53'</td>
<td>114° 16'</td>
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</table>

The six orbital elements may be given not only for the major planets but also for any other bodies in the solar system which have elliptical orbits about the sun. The orbits of all bodies change with time, however, because of their mutual perturbative interactions. These changes are usually discussed in terms of the rates at which any or all of the elements vary. For example, the earth's orbital eccentricity will decrease for the next 24,000 years and its present rate is -0.00004 per century. Mercury’s longitude of perihelion is increasing at a rate of 5.74 seconds of arc per century, etc. Only in the cases of lesser bodies which experience substantial perturbations during relatively near approaches to a major planet are the changes in orbital elements very great or very rapid.
The orbital elements of any body in the solar system are known, of course, only after a tedious analysis of three or more observations of the body's apparent position. As long as the elements so obtained do not change appreciably on account of perturbations, they are of the greatest use in predicting the body's location in the solar system. For the planets, these predictions are tabulated in the American Ephemeris and Nautical Almanac prepared at the U.S. Naval Observatory.

Let us try to visualize the positions and motions of the planets, earth included, as they would be observed from somewhere “above” the sun. The planets will be seen to revolve in a counterclockwise sense about the sun, very nearly in the same plane, and in ellipses of small eccentricity. As Kepler's Harmonic Law specifies, their periods increase with their mean distances.

Suppose we fix our attention upon the earth and one other — Jupiter, for example. Jupiter has a period of nearly 12 years, while the earth's period is exactly 1 year. Therefore, as the earth goes one revolution about the sun, Jupiter goes but a twelfth of a revolution. To keep track of Jupiter and the earth with their different paces, consider a diagram of their respective paths for a period of 15 months or so, marking the positions occupied by each at several dates. Then lines drawn between like-dated positions will indicate Jupiter's relative directions and distances.
By an observer who refers the positions of the sun and Jupiter to the earth will find that they follow the paths indicated.

Because we are in fact viewing Jupiter from the earth rather than the sun, we shall appreciate only Jupiter's relative motion. Therefore a diagram of Jupiter's motion relative to the earth is what is wanted, and this may be gotten by laying off from the seemingly fixed earth the appropriate distance (as measured in the first diagram) in the direction which Jupiter appears to have at that time. The result is the second diagram. It shows that Jupiter's motion is generally eastward through the background of stars but that at times it will appear to reverse itself. Its eastward motion in the sky is called direct motion; its westward motion is called retrograde motion. At the same time, because the orbits of Jupiter and the earth are inclined to each other, Jupiter will appear to have a northward or southward motion. The combined effect of this motion and the simultaneous direct or retrograde motion causes Jupiter to appear to follow a path on the sky that contains a loop, a “Z”, or an “S”. It is this apparently more complicated motion of Jupiter and the other planets which led the ancients to call the planets “wanderers”, the literal translation of “planets”.

Jupiter’s relative motion projected onto the celestial sphere is shown for the same period of time as the two preceding figures.
The relative motion curves of all the planets are alike in character and differ only in their scales of time and distance. The planets’ motions are not all alike, however, in their apparent relation to the sun in the sky. Consider the apparent relative dispositions or arrangements of the sun and planets on the celestial sphere; such arrangements are called configurations.

Celestial latitude and longitude form an ecliptic coordinate system analogous to the equatorial coordinate system of declination and right ascension.

The sun’s apparent position on the celestial sphere is generally taken as the point of reference with respect to which the positions of all the other bodies are compared. The comparison is expressed in the planets’ elongations from the sun. A planet’s elongation is its angular distance from the sun. Often only the east-west projection of this elongation is given; sometimes the projection parallel to the ecliptic is given. In any case, it is expressed in degrees with an indication of which side of the sun it is on.

It is also often the practice to give elongations in celestial longitude rather than right ascension. Celestial longitude and celestial latitude form a system of ecliptic coordinates based upon the ecliptic as reference plane and the vernal equinox as reference point. This system is entirely analogous to geographical longitude and latitude: The celestial latitude of any object measures its angular distance north of south of the nearest point on the ecliptic; its celestial longitude measures the angular distance of this latter point east along the ecliptic from the vernal equinox.* A planet’s elongation in celestial longitude is the difference between the celestial longitude of the planet and that of the sun, expressed in degrees east or west of the sun.

* From the definition of celestial latitude, it is plain that the sun always has a celestial latitude of $0^\circ$. It’s celestial longitude at the vernal equinox is evidently $0^\circ$, at summer solstice, $90^\circ$.
To an observer high above the earth’s orbital plane, the earth, sun and planets would have the indicated relative positions in space at times of the various planetary configurations.

The elongations which the inner planets Mercury and Venus can attain are definitely limited. Since Mercury, for example, can never actually be more than 0.4 astronomical units (an astronomical unit is the earth’s mean distance from the sun) from the sun in space, it can never appear very far from the sun in the sky when seen from the earth. A configuration of note for both of the inner planets is therefore that of maximum elongation, the instant when the planet’s elongation is greatest. The value of Mercury’s maximum elongation ranges between 18° and 28° because of the considerable eccentricity of Mercury’s orbit; the maximum elongation of Venus is 48°. The existence of maximum elongations for these planets accounts for their never being seen very long after sunset or before sunrise, for they must follow the sun down in the west very promptly when east of it, and cannot precede the sun very greatly at sunrise when west of it.

Special designations are also given to other configurations of interest. One of these is conjunction, in which the east-west elongation of a planet from the sun is 0°. A superior conjunction occurs when the planet is beyond the sun from the earth. Each of the planets is periodically at superior conjunction. The two inner planets may also sometimes be at inferior conjunction; the planet is then between the earth and sun.
The outer planets, those with greater mean distances than the earth’s, are not limited to maximum elongations as are Mercury and Venus. When one of these planets attains an elongation of $90^\circ$, it is said to be at quadrature. When the planet’s elongation becomes $180^\circ$, it is said to be at opposition; then the planet rises as the sun sets and vice versa.

The time interval between successive superior conjunctions of any planet is known as the synodic period of that planet. This is to be distinguished from its sidereal period, which is the length of time required for a planet to traverse its orbit once. The two are not equal because the synodic period depends upon the relative positions of the sun, planet and revolving earth whereas the sidereal period depends upon the positions of the sun, planet and fixed stars. Thus the number of revolutions any planet makes about the sun in a given time depends upon its sidereal period; on the other hand, the frequency with which a planet is visible from the earth at a given time of night depends upon its synodic period.

For example, the two planets nearest the earth, Mars and Venus, have the longest synodic periods though not the longest sidereal periods. This is due to the fact that since their sidereal periods are more nearly equal to the earth's than any of the rest, the one can manage to overtake the earth only slowly while the other will be but slowly left behind. Mercury, by contrast, finds the earth no match and hustles around the sun, leaving the earth far out of the race. At the opposite extreme, Pluto proceeds at a celestial snail’s pace (an average of $1.5^\circ$ per year on the sky); but little more than a year is required, therefore, to return it to conjunction. For comparison, the sidereal and synodic periods of the planets are given in the table.

<table>
<thead>
<tr>
<th>PLANET</th>
<th>SIDEREAL PERIOD</th>
<th>SYNODIC PERIOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YEARS</td>
<td>DAYS</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.2409</td>
<td>87.969</td>
</tr>
<tr>
<td>Venus</td>
<td>0.6152</td>
<td>224.701</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0000</td>
<td>365.257</td>
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<tr>
<td>Mars</td>
<td>1.8809</td>
<td>686.980</td>
</tr>
<tr>
<td>Jupiter</td>
<td>11.8622</td>
<td>.......</td>
</tr>
<tr>
<td>Saturn</td>
<td>29.4577</td>
<td>.......</td>
</tr>
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<td>Uranus</td>
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</tr>
<tr>
<td>Neptune</td>
<td>164.7883</td>
<td>.......</td>
</tr>
<tr>
<td>Pluto</td>
<td>247.6968</td>
<td>.......</td>
</tr>
</tbody>
</table>

The relation between synodic and sidereal periods is quite simple. For example, let $P$ be the sidereal period of Mercury, $E$ the earth’s period of revolution about the sun and $S$ Mercury's synodic period. Mercury will on average move $1/P$ revolutions each day while the earth moves $1/E$ revolutions in pursuit. Mercury’s net daily gain on the earth is therefore $1/P - 1/E$ revolutions. Since Mercury gains one whole revolution on the earth in one synodic period, it will gain an average of $1/S$ revolutions per day. In other words, it must be true that

$$\frac{1}{S} = \frac{1}{E} - \frac{1}{P}, \quad S = \frac{EP}{(P-E)}, \quad \text{or} \quad P = \frac{ES}{(S-E)}$$

Since the earth overtakes the outer planets rather than being overtaken by them, the equations must be modified accordingly; for an outer planet like Jupiter
During each planet’s synodic period it goes through a fixed cycle of configurations. For an inner planet, the sequence of events following superior conjunction is: (1) direct motion to maximum eastern elongation; (2) decelerating direct motion and then retrograde motion to inferior conjunction; (3) continued retrogression followed by accelerating direct motion to maximum western elongation; and (4) direct motion to superior conjunction. During phases (1) and (2) the planet is an “evening star”; during phases (3) and (4) it is a “morning star”.

An outer planet behaves somewhat differently. The sequence after superior conjunction is: (1) decelerating direct motion that is slower than the sun’s until some time after western quadrature; (2) accelerating retrograde motion until opposition; (3) decelerating retrograde motion for an equal time after opposition; and (4) direct motion (though always less rapid than the sun’s) until superior conjunction. Between the times of superior conjunction and western quadrature, the planet will be visible some time between midnight and dawn; at the time of opposition, the planet will be visible the whole night through; between eastern quadrature and superior conjunction the planet can be seen only during part of the hours from sunset to midnight.

The figure shows schematically the simplest form of the Ptolemaic theory. Refinements of the simple system would replace the planets with further epicycles.
The ancients invented a variety of explanations for these apparent motions of the planets, as well as for those of the sun and moon, which to them were also planets. In devising their theories, most of them saw no reason to suppose anything other than that the earth is stationary and at the center of the universe. Because of this latter assumption, their theories are described as geocentric theories. Of all the theories, the most important was that set forth by the Alexandrian astronomer Claudius Ptolemy in the second century A.D. His work was highly regarded by the Arabs who dominated the south Mediterranean and the Near East after the collapse of the Roman Empire, and to Ptolemy's theory they gave the name “Almagest” (corrupted from its original Greek title “Megiste Syntaxis”).

Ptolemy's explanation of the planets' apparent motions was suggested by their relative motion curves. To be sure, Ptolemy did not know the planets' distance from the earth, but he could observe their changing brightnesses and he concluded, correctly, that decreased brightness was the result of increased distance; by this argument he was able to construct relative motion curves qualitatively similar to the true ones. His system placed the earth at the center of the universe. The earth was surrounded by a concentric crystal sphere on which the stars were set. Within this sphere, the sun, moon and planets moved about the earth. Mars, Jupiter and Saturn (the only outer planets then known) had a motion which was compounded of two motions: each of these planets circled in an epicycle about a point called the fictitious planet. The fictitious planet was situated on a larger circle about the earth called the deferent. The rotation of the deferent was presumed to carry the fictitious planet eastward at a uniform rate, once about the sky in one sidereal period of the planet. The simultaneous rotation of the epicycle about the fictitious planet in one year would then produce a loop and retrograde motion every synodic period.

\[
\text{Simultaneous motion of the epicycle and deferent carry a point on the epicycle along a looped path. The epicycle radius from fictitious planet to true planet is shown in a number of positions during the course of a single cycle.}
\]

A similar arrangement was postulated for Mercury and Venus except that their respective fictitious planets were to be always on the straight line from earth to sun; then and only then would these two planets swing back and forth from one side of the sun to the other. Only the motions of the sun, moon and stars were not epicyclic. However, the motions of all bodies were circular or combinations of simultaneous circular motions, for the ancients seemed obsessed with the “perfection” of the circle and the obligation of heavenly bodies to observe perfection in every detail.
Then in 1543 a Pole named Nicholas Copernicus revived the idea, once considered by the ancient Greeks and long since discarded, that the sun -- not the earth -- is the center of the universe. His advocacy of a heliocentric theory was in his day a rash if not dangerous act. However, he died (of natural causes) so soon after the publication of his radical “On the Revolutions of the Celestial Bodies” (in Latin) that he was spared the probable punishment and humiliation that might otherwise have befallen him.

While adhering to the “perfection” of circles, Copernicus supposed a rotating earth to be but one of a family of planets revolving about the sun. He could then explain in the same general way one now does the direct and retrograde motions of the planets, the sun's annual motion on the ecliptic, and the diurnal motion of all celestial objects. He could not offer proof of his hypotheses, however, and his principal defense was that his system was much simpler than the intricate and unsuccessful Ptolemaic system. Arguments of this nature carried little weight with the authorities of his day, however, and those of the church, in particular, were prone to see the Copernican theory as blasphemy; they placed his work on the Index of Prohibited books, where it remained until 1835.

A Danish nobleman, Tycho Brahe, sought to reach a rational decision as to the relative merits of the Ptolemaic and Copernican systems. Tycho, like Ptolemy but unlike Copernicus, was an excellent observer of the heavens, undoubtedly the greatest before the invention of the telescope. Of several decisive tests between the Ptolemaic and Copernican theories, the only one Tycho could conceivable attempt to apply with the means available to him was that of measuring the nearby stars' annual parallactic displacements. He attempted the test, the results were negative, and he therefore rejected the Copernican hypothesis. He could hardly have guessed how much beyond the power of the unaided eye it is to discern so minute an effect. But neither could Tycho accept the Ptolemaic system, whose difficulties and defects were becoming ever more apparent. Hence he devised a Tychonic system having a central stationary earth about which revolved the sun and moon; all the other planets circled about the sun, as in the Copernican theory.

The Tychonic theory, though actually short-lived, was soon to assume an added significance, for the Ptolemaic system presently received the blow that was finally to dispose of it. Since according to the Ptolemaic system the planets Mercury and Venus were always between the earth and sun, then from the earth they could never appear fully illuminated, as they would if they were to pass around to the far side of the sun and as they could according to either the Copernican or Tychonic systems. The great Florentine physicist and astronomer, Galileo, was the first to put the Ptolemaic system to this test, being the first to use a telescope for astronomical observations. In the years following 1610, he watched Venus go through all phases like those of the moon, waxing from crescent to full, then waning. This was decisive evidence against the Ptolemaic theory, in which the full phase was impossible. The choice was now between the Tychonic and Copernican systems, and Galileo favored the latter. The Copernican system recommended itself with particular force after his seeing Jupiter, for he saw the planet accompanied by four satellites which circled about it, all in nearly the same plane; it was a miniature Copernican solar system.

But the Copernican theory had defects, as did every theory which insisted on circular orbits for the planets. The details of the planets’ motions were still unaccounted for by any system when, in the hope of describing them accurately, Johannes Kepler undertook the staggering task of analyzing by the most elementary mathematical means the very extensive lifetime’s observations of Tycho Brahe, his predecessor as royal astronomer and mathematician at the court of Rudolf II in Prague. Through correspondence with Galileo, Kepler was encouraged to consider the heliocentric theory of Copernicus. The
results of his work were his three laws of planetary motion and represent many years of painstaking trial and error. Kepler’s estimate of his final triumph may be judged from his own statement: “The die is cast, the book is written, to be read now or by posterity, I care not which. It can await its reader. Has not God waited six thousand years for an observer?”

The presumption in favor of the heliocentric theory was finally clinched by Isaac Newton, who deduced the law of gravitation from his own three laws of motion and Kepler's laws of planetary motion. The law of gravitation has shown itself to have a range of validity that has justly earned it the title “universal”. The Tychonic system is quite incompatible with the law of gravitation and Newton's laws of motion. Since Newton's day, a continual increase in general scientific knowledge and the greater power of new and improved instruments have provided the answers to all the various and sundry objections which originally seemed to make anything but a geocentric theory of the universe both absurd and contrary to all experience.

It is difficult to appreciate in full in this day the significance of the step from geocentrism to heliocentrism. It is one of the most notable steps men have taken in their perennial efforts to disenslave themselves from dogma. It encouraged a new and more exciting conception of how the universe is constructed. The small, highly contrived Ptolemaic universe gave way to an immense cosmos. No distinction was any longer necessary between physical laws governing terrestrial affairs and those governing celestial ones. The abandonment of a geocentric conception gave mankind a radically different perspective of its place in the physical universe. Since Copernicus' day, the universe has continually expanded, apace with increasing knowledge. At present, one cannot assign any point as the unique center of the universe. However, none of the changes made since Copernicus challenged the geocentric theory has been suggested at such peril or had so much effect.

**Mercury**

Until the era of telescopic observations was begun by Galileo in 1610, the planets were objects of much mystery and very little concrete knowledge. A great deal of the mystery was dispelled and the store of concrete knowledge about the planets was greatly increased in the more than three and a half centuries since 1610 with the aid of ground-based telescopes. Since the 1960s, study of the planets with radio telescopes has contributed greatly to further knowledge, and beginning in the 1970s, the greatest step of all has been initiated with the launching of the various space probes. Let us therefore consider what is known of the individual planets, taking them in order outward from the sun.

The planet Mercury is named for the messenger of the Olympian gods, and his caduceus or wand has been conventionalized to *, the planet's symbol. Mercury is, aptly, the swiftest of the planets for it is nearest to the sun; its orbital velocity varies from 36 to 23 miles per second as its distance from the sun varies from 28.5 million miles at perihelion to 43.5 million miles at aphelion.

For so small an orbit (the mean distance of Mercury is 0.39 astronomical units), this range of distance from the sun is considerable, indicating a fairly eccentric orbit. In fact, Mercury's orbital eccentricity of 0.2056 is more than that for any other planet except Pluto. Mercury speeds around the sun in 88 days, a little less than 3 months. It will therefore seem to us to swing back and forth about the sun in 116 days, its synodic period. Half this time it will be a morning star, the other half an evening star. Some of the ancients did not realize that these morning and evening “stars” were one and the same and so called the planet Mercury when seen after sunset, Apollo when seen before dawn.
The large eccentricity of Mercury's orbit is responsible for Mercury's maximum elongation varying from $16^\circ$ to $28^\circ$, depending on whether maximum elongation occurs at the time of Mercury's perihelion or aphelion. For example, Mercury was at greatest eastern elongation on February 21, 1947. Since perihelion occurred only 15 hours before, this elongation was one of the smallest, amounting to only $18^\circ 7'$. The following April 5, it was at greatest western elongation, $27^\circ 48'$ from the sun, visible low in the southeast a little before dawn.

It is plain that the planet is elusive, never straying far from the blinding sun in whose glare it hides most of the time. As a result, comparatively few people have ever seen Mercury, although at times it appears brighter than any of the stars save one (Sirius).

Telescopic observations of the planet are usually made in broad daylight, for it can then be studied at its greatest height above the horizon. Surface markings are not pronounced and are difficult to detect, for when the planet is nearest the earth, practically none of the illuminated surface is visible. Even at such times, it is 50 million or more miles away and its disk has an apparent diameter of only 13 seconds of arc. Most observations have to be made under considerably less favorable circumstances.

In late 1973, the Mariner 10 satellite was launched. Following a flyby past Venus in February, 1974, it passed Mercury within a few thousand miles on March 29 and was diverted into an orbit which returns it to the vicinity of the planet every two sidereal periods. It therefore encountered Mercury again on September 21, 1974, and for a third time on March 16, 1975. Its fuel supply was by then exhausted so that subsequent flybys have been scientifically incommunado. Most of what is now known about Mercury, however, has been a harvest from those three rendezvous between Mercury and Mariner 10.

The diameter of the planet, known to within about a mile, is 3031 miles. Its mass is $1/18.31$ as much as the earth's, hence its density is 5.37 times that of water. It is thus easily the most dense of all the planets other than the earth. The surface gravity of Mercury is 37.2 per cent of the earth's, whence the velocity of escape is 2.63 miles per second. At Mercury's lesser distance from the sun, solar radiation is on the average seven times as intense as on the earth. It is not surprising, therefore, that the midday equatorial temperature rises to $800^\circ F$. This temperature and the low velocity of escape would lead one to expect that Mercury could not have retained an atmosphere, and it hasn't.

It was therefore somewhat of a surprise when infrared telescopic measurements indicated that the temperature of the dark side of the planet fell no lower than $280^\circ F$. This was surprising because it was then believed that Mercury kept one face perpetually away from the sun, just as the moon keeps one face away from the earth. The temperature of such a dark face should then have approached absolute zero, or $-459^\circ F$. Two explanations were possible: (1) a thin atmosphere transports heat from the sunlit to the dark hemisphere or (2) the planet does not always keep one face toward the sun. As things turned out, both contingencies were true.

The first to be demonstrated was the fact that Mercury rotates on its axis in 58.64617 days. This was proven by the discovery that radar reflections showed one limb of the planet approaching and the opposite limb receding as Mercury rotates on its axis. From the velocities of approach and recession the period could be calculated approximately; it was close to 58 days, nowhere near the 88-day sidereal period of revolution which it would have been had the rotation been bound. Later, photographs taken during the Mariner 10 flybys were used to determine the rotation period with great exactness.
Almost at once, it was noted that the 58-day rotation period was very nearly two thirds of the 88-day sidereal period of revolution. This suggested that the ratio might well be exactly 2:3, in which case Mercury's rotation and revolution would be resonantly coupled, or locked together in this simple proportion. This anticipation has since been confirmed. Mercury makes three rotations on its axis every two revolutions about the sun.

This relation between the periods of rotation and revolution has several interesting consequences. Since two of Mercury's "years" are three of its sidereal "days", the "solar day" will be two years long and the sun will appear at the zenith of the same subsolar point (longitude 0° at alternate perihelia. At the perihelia between, the subsolar point will be a location on the planet diametrically opposite the first (longitude 180°). At these two points, "noon" occurs alternately at perihelion and aphelion. However, the intensity of sunlight is 2.3 times as great at perihelion as at aphelion so that at these points alternate "days" are "hot" and "hotter". At the intermediate longitudes (90° and 270°), noon occurs at alternate aphelia. At these points, the days are "less hot".

Another curiosity follows from Kepler's law of areas. Because of Mercury's considerable orbital eccentricity, the angular velocity of its orbital motion is 2.3 times as great at perihelion as at aphelion and actually exceeds its angular velocity of rotation. During the time this is so, a period of approximately 8 days near perihelion, the sun reverses its normal westward motion in the Mercurian sky and moves slowly eastward. This prolongs the daylight hours on the sunlit side and the nighttime hours on the dark side. At one terminator (the sunrise zone), one would have the unaccustomed experience of seeing the sun rise in the east, then set in the east, and rise again in the east all in less than a seventh of a Mercurian sidereal day. At the same time, at the sunset line the sun would set in the west, rise in the west, and finally set in the west. (Think how this might complicate "westerns" on Mercury!)

Since Mercury's equator is inclined no more than about 1° to its orbital plane, no perceptible seasons could be brought about as they are on the earth. On Mercury, such seasons as exist are due to the temperature variations between longitudes 0° and 180° on the one hand and 90° and 270° on the other.

Mercury is very slightly bulged along a diameter which coincides with the direction of the sun at perihelion and aphelion. This "handle", presumably tidal in origin, has over several billion years forced the period of rotation to take the commensurable value of two thirds of the period of revolution.

Mercury's rotation accounts for the fact that the planet's dark side is at a temperature sensibly above absolute zero. It was also shown by Mariner 10, however, that Mercury has a thin transient atmosphere as does the moon. It consists almost entirely of helium atoms waylaid from among the particles of the solar wind; no trace of hydrogen, argon or oxygen has been found. The pressure of the Mercurian atmosphere is not more than 2 trillionths 2^10 of the earth's atmosphere. Collisions are rare among atmospheric atoms which therefore follow free-flight trajectories as in the earth's exosphere. After a dalliance which on the average lasts about 200 days, a helium atom is whisked on by the solar wind which substitutes a newcomer in its place.
A distinctly surprising result from the Mariner 10 flight was the unexpected discovery that Mercury has a dipole magnetic field about 1 per cent as strong as the earth's, tilted about 7° to its axis of rotation. It is presumably generated, as the earth's magnetic field is generated, by the dynamo action induced by the rotation of an iron core. The resultant magnetic field creates a modest magnetosphere (though no van Allen belts) which assists the temporary capture of helium atoms from the solar wind. The existence of the magnetic field is surprising in view of the slowness of the planet's rotation.

Mercury’s surface, like the moon’s, is generally dark. It reflects from 13 to 39 per cent of the light which falls on it and is described as having a pinkish cast. Most of the brighter areas are the result of crater rays.

The thousands of Mariner photographs have a resolution as much as 5000 times greater than any achieved before, and the best show features as small as 150 feet. The surface appears very much like the moon's, being heavily cratered. One half the surface has been observed in great detail, but because Mariner 10 returned at intervals of precisely three Mercurian days, it always saw the same sunlit side; the other side has not yet been seen.

Because Mercury’s reflection spectrum is similar to the moon’s, and because the manner in which the temperature of the dark side falls between sunset and midnight is characteristic of porous material, it is concluded that Mercury has a regolith similar to the moon's. Mercury's surface generally shows lesser brightness contrasts than those between lunar highlands and maria, perhaps because its regolith contains more iron and less titanium. Mercurian rocks must surely be igneous and brecciated.

Mercury’s surface gravity is more than twice the moon’s. Therefore its craters are shallower, the ejecta and secondary craters (formed by debris blown out during the primary impact) scatter over only about one fifth the area they would on the moon. For this and perhaps other reasons, Mercury’s surface is nowhere saturated with craters as the lunar highlands are; intercrater plains are characteristic, not exceptional.

Surface features unique to Mercury are the lobate scarps. These are scalloped cliffs sometimes a hundred miles in length which cross both plains and craters. They appear to be reverse faults, compression features formed as a result of shrinkage of Mercury’s cooling core which has decreased the planet's radius a mile or so.

One fascinating possibility for future Mercurian explorers is that steep-walled craters near the poles, into which the sun cannot shine, may serve as cold traps like those of laboratory vacuum pumps. If so, they may have preserved deep-frozen samples of volatile materials from Mercury's early history.

One individual feature of special note is a great impact basin, 875 miles in diameter, called Caloris Basin because it is near the “hot” longitude 180°. It is quite similar to Mare Orientale on the moon's far side. Since Mariner observed it on one terminator of Mercury (sunrise or sunset line), its antipodal point was also visible on the opposite terminator. At this latter point one finds a rippled surface known as weird terrain. Here the surface appears scabby, crater rims have slumped, and landslide-like gouges appear on the downslopes of the crater rims. It is suggested that these features may have resulted from the internal focussing of shock waves generated by the impact which formed Caloris Basin.
Mercury must have fractionated chemically early in its history. Being a much smaller planet than the earth, the pressures deep inside it cannot be nearly as great as those near the center of the earth. Therefore the density of iron and nickel in the core cannot approach the density attained in the earth's core. Even so, Mercury's overall density is almost as great as the earth's, while at the same time its presumably basaltic mantle cannot be denser than the earth's. It seems inescapable, therefore, that the core of the planet must occupy at least three fourths of the planet's radius; the core is itself as large as the moon. This conclusion reinforces the expectation that the heavy refractory elements, especially those of the iron group, constitute a larger proportion of Mercury than of the earth. This might have been expected since Mercury formed much closer to the sun, where volatiles would escape in a more thoroughgoing fashion.

The history of Mercury must be approximately parallel to that of the moon. The craters now to be seen on Mercury's surface were formed since the last epoch of widespread igneous activity. It was this vulcanism which formed the plains. No atmosphere could have been present, for there is no trace of atmospheric erosion. Mercury's crust did not form as quickly as the moon's and its greater proportion of radioactive elements extended the period of igneous activity longer. Therefore the present surface is a record only of the terminal phase of planetesimal bombardment.

One fascinating possibility is that Mercury's comparatively large orbital eccentricity is a vestige of a very early impact by a large planetesimal. If such a body had struck the planet in such a way as to diminish Mercury's orbital angular momentum by a mere 2 per cent, Mercury's orbital eccentricity would have become what it now is.

Of scientific interest are Mercury's transits of the sun. A transit is a passage of the planet across the solar disk. As in the case of the moon, a transit does not occur at every inferior conjunction but only at those when the sun is near a node (in May and November), again because of orbital inclination. There are 13 transits per century on the average, but they are not evenly spaced; the intervals between transits at either node are 7, 13, and 46 years, since these intervals very nearly contain 22, 41 and 145 synodic periods, respectively. The last transit of Mercury was on [November 13, 1986]. Transits of Mercury and Venus are of scientific interest because they offer a means of determining accurately the positions, and hence the motions, of these planets.

The motion of Mercury was for a long time puzzling in one detail. The axis of its orbit was observed to turn slowly, advancing the position of its perihelion by about 574 seconds of arc per century, some 43 seconds more than could be accounted for by Newton's law of gravity. This phenomenon was first explained by the theory of general relativity, which predicted almost exactly the observed rate of advance over what can be expected from the perturbations of the other planets. It is now realized that this effect is due to Mercury's variation of mass as it gains and loses energy as a result of the sun's gravitational attraction while it goes from aphelion to perihelion and return. The motion of Mercury thus offers one of the few instances* of an observable divergence between classical and relativistic mechanics; it gave the first observational demonstration of the mass-energy equation \( E = mc^2 \), though this had not been realized until recently.

*Venus' motion will not do because the orbit of Venus is so nearly circular that the position of perihelion cannot be determined with sufficient accuracy. In recent years, a slow relativistic advance (4 seconds of arc per century) of the earth's perihelion has been detected. There is also prospect of noting the effect in Mars' motion. For the more distant planets, however, the effect is too small to observe since it decreases with distance from the sun.
Venus

Venus, namesake of the goddess of beauty, has been given the symbol * representing a looking glass, perhaps on the strength of the apothegm “Vanity, thy name is woman”.† As an inner planet, it will appear to swing back and forth about the sun. For 220 days (over seven months) after superior conjunction, it works slowly east of the sun in the sky until it is at a maximum eastern elongation of $48^\circ$. Then, in a brief 72 days, it moves west to inferior conjunction, on to greatest western elongation in another 72 days, then slowly back to superior conjunction in 220 days more, the whole requiring 584 days, its synodic period. Thus Venus alternates every 292 days between roles of morning and evening “star”. Like Mercury, Venus was in consequence given a split personality by the ancients, being Phosphorus before dawn, Hesperus after sundown.

Though at first surprising, it is obvious why Venus requires more than three times longer to go from greatest western elongation to greatest eastern elongation than it requires to return. It really has that much farther to go, as may be seen from the figure.

Like Mercury, Venus shows all phases from new at inferior conjunction to full at superior conjunction. Also like Mercury, but unlike the moon, its distance from the earth varies greatly as the phases change. Unfortunately, we see none of its illuminated face when it is nearest the earth, see the whole of it only when it is farthest from us. The two effects of varying phase and simultaneously varying distance evidently work at cross purposes, with the result that Venus appears brightest 36 days before or after inferior conjunction.

At its brightest, Venus may be seen in broad daylight by anyone who knows where to look. It is then 15 times brighter than Sirius (the apparently brightest star in the sky) and is capable of casting a visible shadow after dark. It is the brightest of the planets.

At inferior conjunction, Venus comes nearer the earth than any other planet, being then only 26 million miles away. Its mean distance from the sun is 67 million miles. The eccentricity of its orbit, 0.0068, is the smallest of any of the planets' orbital eccentricities. The mass of Venus has been determined to be 0.815 as great as the earth's. With a diameter of 7523 miles, it thus has a surface gravity 90 per cent as great as the earth's, a density 5.22 times the density of water.

Unlike the moon and Mercury, Venus has a cloud-covered surface never visible to direct observation from the earth. On this account, most of the new information about Venus has been acquired from the flybys of American Mariner space probes or from the brief transmission of data by the soft-landed Soviet Venera spacecraft. These new and marvelous tools of astronomical exploration have shown Venus to be a planet which contrasts sharply with the earth in spite of superficial similarities of diameter, mass, density, surface gravity and position in the solar system.

The dissimilarity of Venus and the earth was presaged by early attempts to determine the period of Venus' axial rotation. Without surface markings to observe the motion of, as on Mercury and Mars, astronomers were forced to resort to indirect methods. All such methods make use of the Doppler effect. To understand the underlying principle, imagine that a planet is rotating upon an axis which is perpendicular to the line of sight. A point on the equator will then be carried around the planet by the rotation in such a way that

† With apologies to Shakespeare.
when it first appears in the hemisphere facing the earth it will be approaching with the
equatorial velocity of rotation. Half a rotation later, it will disappear at the opposite limb
with a similar velocity of recession. The spectral lines of atmospheric molecules will give
evidence of such motion by the appropriate Doppler shifts to shorter and longer
wavelengths, respectively. Thus a spectrograph whose slit is oriented along the equator
of a rotating planet will show spectral lines which exhibit a progressive Doppler shift
from one end to the other, corresponding to projected rotational velocity from
approaching to receding limb. Such a method works very successfully on Saturn and the
sun, for example.

On Venus, the spectroscopic method for determining the planet’s rotation was
generally inconclusive for two reasons: (1) the rotation appeared to be rather slow and
therefore difficult to determine with accuracy, and (2) the rotation seemed to be
retrograde, a conclusion so extraordinary that it should be regarded with suspicion. The
suspicion was dispelled and the matter was settled in 1963, however, by using a radar
technique. This method relies upon the observation of echoes from a radio signal beamed
to the planet and reflected from its surface. The echo takes the place of natural reflected
radiation. There is also the further difference that the returning radio echo, being at radio
wavelengths, cannot be analyzed with a slit spectrograph. This means that some other
way must be found to discriminate a reflection from the approaching limb from a
reflection from the receding limb.

The desired discrimination is achieved by sending forth a radar pulse of very short
duration. It will first arrive at, and be reflected from, the subradar point, the point on
Venus’ surface nearest the earth. The radar pulse will then encounter and be
progressively reflected from rings of Venus’ surface concentric to the subradar point
outward to the limb. The pulse echo is therefore strung out over an interval of time
longer than the duration of the transmitted pulse, and the straggling echo from the limb
will come back last. It is like the echo in a cave; the reflection from the back of the cave
is the last to be returned. As with the spectroscopic method, radiation from the
approaching limb will be Doppler shifted to shorter wavelengths and that from the
receding limb to longer wavelengths. The limb echo is therefore separated from the rest
by time delay and the approaching limb is separated from the receding limb by Doppler
shift.

This method, considerably refined since it was first tried, has given the remarkable
result that Venus rotates retrograde on its axis once in 243 days! This result is
remarkable both for the length of the period (some 18 days longer than its sidereal period
of revolution about the sun) and for the retrograde sense of the rotation.

Although the sun is never seen from Venus’ cloud-covered surface, the sun “rises”
in the west (because the rotation is retrograde) and “sets” in the east. If Venus did not
revolve around the sun, the Venussian “day” would be 243 terrestrial days. However,
because Venus revolves once every 225 days, the sun moves eastward around the
Venussian ecliptic in that length of time. The combined additive effects of the rotation and
the revolution therefore produce a “day” on Venus that is 116.8 terrestrial days long.

Five Venussian days is 584 terrestrial days, just one synodic period of Venus. This
means that at each inferior conjunction of the planet the same hemisphere faces the earth.
If this commensurability were the work of mere chance, it would be such an
extraordinary coincidence as to be suspect. It is therefore inevitable that some causal
relation has been sought, such as a resonant coupling produced by tidal effects of the
earth upon Venus. The existence of any such effects would require that Venus have some
tidal bulge or similar asymmetry of form. The Mariners gave no indication of any
asphericity, however, and therefore the reason why Venus has the particular rotation
period it has is a mystery for the present.
Another oddity is that both the spectroscopic determinations of Doppler shift and the Mariner flyby photographs show a rotation period of about 4 days for the upper atmosphere. This implies that there are winds of 230 miles per hour at a height of some 40 miles above the surface of the planet.

Evidently the atmosphere is deep. It is also much more massive than the atmosphere of the earth, for although the planet's surface gravity is only 91 per cent that of the earth, its atmospheric pressure reaches the terrestrial sea level value at a height of 30 miles and is 90 times that amount at Venus' surface. This is a pressure such as exists at a depth of 3000 feet in the ocean! High resolution spectra show that about 97 per cent of the atmosphere is carbon dioxide, of which more than 5000 spectral lines have been identified, some of them never before seen in any other source.

The high clouds in Venus’ deep and relatively massive atmosphere cause some 80 - 85 per cent of the incident sunlight to be reflected back into space, a greater proportion than for any other planet. The fraction of solar energy actually retained by the planet is about the same as or a little less than that kept by the earth, which is 40 per cent more distant from the sun. In spite of this, Venus has a surface temperature of \(800^\circ F\) \(\approx 425^\circ C, 700^\circ K\)! This is \(175^\circ F\) above the melting point of lead. In the solar system, only the sun has a higher surface temperature.

The reason for Venus’ very high surface temperature is the great effectiveness of the atmosphere in blanketing the surface. Incident sunlight not returned by reflection is absorbed by the clouds and the surface of the planet. These re-radiate the energy at infrared wavelengths to which the abundant carbon dioxide is to a large degree opaque. The solar radiation can thus enter the planet's atmosphere with far greater ease than it can exit. It therefore accumulates until the rate of re-radiation by the hot planet equals the solar input. This greenhouse effect is the same as that experienced by the earth but much exaggerated.

At the surface of Venus the atmosphere has a tenth the density of water. It would therefore seem like a superheated dilute fluid. Because the density of Venus' atmosphere is about 80 times our own, its refractive effects would be much greater than those of the earth's atmosphere. In particular, it would produce mirages and a “fishbowl horizon”.

The two successful Venera spacecraft sent back views of the surface in which were to be seen a horizon at an estimated distance of several hundred yards and unweathered rocks and boulders in the foreground. The boulders were somewhat surprising, for it had been commonly assumed that intense weathering by wind and heat would have reduced small scale surface material to crumbled fragments. The level of general illumination was also higher than the anticipated 1 per cent of full sunlight. Shadows were distinct. Surface winds, in contrast to those at the level of the cloud deck, are only 5 to 10 miles per hour. The relative humidity is less than 1 per cent, for water is scarce and, of course, could not exist in liquid form. It is estimated that if all the water on Venus were to condense, it would form a planet-wide ocean only a foot deep, whereas the water on the earth would average 3000 feet in depth.

The atmosphere of Venus beneath the clouds is relatively transparent. Seasonal and diurnal temperature changes are relatively small. The planet's surface is quite smooth overall. It has been mapped by radar reflections which show gross features larger than about 50 miles. The most important topographic feature is a peak approximately 2 miles high. The planet's surface slopes gently up to it from the west for more than 3000 miles, then drops off to the east in but a few hundred miles. Lesser peaks have been mapped, as have valleys. Some large craters have been detected.
The temperature in the atmosphere drops steadily from its value at the surface of Venus until the top of the cloud layer is reached at a height of about 40 miles. Most of the solar energy retained by Venus is absorbed in the cloud layer, which begins at a height of about 16 miles. At the top of the clouds, the temperature has fallen to about $<E^{-10} \, \text{K}$ (about $<E_{250} \, \text{K}$). Above the clouds is a 12-mile layer of haze.

The cloud markings are visible only in ultraviolet light. The clouds move from east to west, once around the equator in about four days, in shorter periods as one moves toward either pole. A characteristic cloud feature at the point directly under the sun is probably an area of large-scale vertical currents. Bright jet-like streams wind spirally toward the poles where they merge into a circumpolar band or cap.

The surface and atmosphere of Venus are each studied at wavelengths appropriate to the depth concerned. Only radio waves can penetrate to or exit from the planet's surface. The clouds emit infrared radiation because they receive the heat from Venus' surface by vertical convective circulation such as that in the earth's troposphere. Carbon monoxide molecules (CO), less abundant than carbon dioxide by some 450,000 times, are observed at heights of 40 to 70 miles in the radiations of the first microwave spectral line to be detected in the atmosphere of a planet other than the earth. The cloud-drops are observed in reflected ultraviolet radiation. This radiation shows a polarization, somewhat like light reflected from the surface of a lake, which implies that the clouds are made of spherical droplets of the order of 4 thousandths of an inch in diameter. The droplets cannot be water, for the cloud tops are far too cold; any water would be in the form of ice crystals. Furthermore, the droplets bend light which passes through them more strongly than water droplets could.

If the clouds are not of water droplets like those in the earth's atmosphere, what are they? The droplets ability to exist at below-freezing temperatures, to bend light more strongly than water droplets, and to absorb microwave radiations from levels of the atmosphere below 30 miles, are taken as evidence that they are made of sulfuric acid. Sulfuric acid is perhaps the only substance which meets all these requirements. It fails, however, in one particular; it cannot account for the clouds' yellowish color which must be ascribed to some as yet unknown constituent. In any case, Venus' high surface temperature and strongly corrosive clouds make it infernally inhospitable.

The radioactivity of the surface of Venus as reported by the Venera spacecraft suggests a crust like that of the earth, composed of granites and basalts. Given the planet's similar diameter and density, this suggests a similar interior. How did a planet so like the earth in many ways come to have an atmosphere and surface conditions in such strong contrast to the earth?

The present differences are almost certainly evidence of a dramatic divergence in the evolutions of the two planets' atmospheres. Like the earth, Venus probably acquired a secondary atmosphere by out-gassing from its interior. The critical difference must have lain in the fact that Venus is nearer the sun and therefore somewhat warmer. Because of this, the water vapor on Venus did not condense into oceans on Venus. Without large amounts of liquid water, carbonates did not form and remove carbon dioxide from Venus' atmosphere. Venus' atmosphere has about as much carbon dioxide as is locked in the carbonates of the earth's crust. It is therefore Venus' atmosphere which is "normal", the earth's which is abnormal. The high temperature and pressure of Venus' atmosphere is therefore both a cause and an effect of the normal carbon dioxide abundance. The fact
that the earth is at a temperature between the freezing and boiling points of water is pivotal in assuring it those very conditions which make it the only habitable planet of the solar system.

The earth is more fortunate than Venus in one other respect: it has a magnetic field whereas Venus does not. Though Venus, like the earth, very probably has a liquid iron core, its rotation is evidently too slow to generate a magnetic field by the dynamo process. It is therefore relatively unshielded from cosmic rays, yet another hazard to life on Venus.

Mars

Ruddy Mars, named for the god of war, has the symbol %, representing a shield and spear. Of all astronomical bodies, Mars has been the object of greatest popular interest because it was thought to be a possible abode of life, perhaps intelligent life which has developed an advanced technological civilization. The popular interest is to a large degree a reflection of the interest which has been shown by astronomers because of the fact that Mars is the nearest planet whose surface can be observed from the earth; though Venus comes closer, it is perpetually cloud-covered and even if it were not, its dark side is toward the earth at the planet's close approach.

Mars is nearest the earth and most favorably placed for observation from the earth at or near the time of its opposition. It is then brighter than any other planet except Venus. Though Mars does not exhibit all the phases as does Venus, it becomes gibbous near and at its quadratures; at such times the earth would appear from Mars to be at its maximum elongation of 47°.

Oppositions of Mars occur every 780 days (2 years and 50 days), its synodic period. Not all oppositions are equally favorable, however. This is because Mars’ orbit is rather eccentric as planets’ orbits go (e = 0.0933), so that an opposition which occurs near the time of Mars’ perihelion is decidedly more favorable than one which occurs near Mars’ aphelion. In fact, Mars’ opposition distance can vary from 34,600,000 miles to 63,000,000 miles — nearly a factor of two — on this account. The most favorable oppositions occur at intervals of 15 or 17 years (as in 1939, 1956, 1971, 1988 and 2003) and always in August or September, for the earth is nearest Mars’ perihelion on August 28. The absolutely most favorable approach will take place in 2729 A.D., though the approach in 2003 will be the most favorable of the last several thousand years.*

*Mars comes nearer to the position which the earth occupies in late August than to any other.

The closest approaches are gradually becoming closer because of a very slow increase in Mars’ orbital eccentricity on account of planetary perturbations. Thus the approach of 2287 (= 2003 + 284) will be closer than that of 2003. Close approaches are also falling later in the year because of the advance of Mars’ perihelion.
Thanks to telescopic observations made of Mars as long ago as 1666, it has been possible to determine the planet’s period of rotation to within 2 thousandths of a second! Mars rotates once eastward $24^h 37^m 22.662^s$. The axis of rotation is directed some 9 degrees northeast of the star Deneb ($\alpha$ Cygni) and is inclined some 24º from the perpendicular to Mars’ orbit.

Mars' period of rotation is one of the few pieces of information about the planet which has not been supplanted or greatly improved by observations returned from the Mariner space probes and the Viking orbiters and landers. Mariner 4 observed the planet during a flyby in July, 1965. Mariners 6 and 7 skirted Mars in late July and early August of 1969, while Mariner 9 reached its goal on November 14, 1971, and was made to become Mars' first artificial satellite. Vikings 1 and 2 were launched in late summer 1975 and arrived at Mars in July of 1976. Each Viking consisted of an orbiter, which has become another artificial Martian satellite, and a lander which descended to Mars' surface to report on conditions there.

Mars' diameter has been determined to be 4211 miles and its mass is 0.106 earth's masses. It must therefore have a mean density of 3.88 times the density of water and a surface gravity of 12.0 feet per second per second. Hence the velocity of escape is 3.1 miles per second.

With an equatorial inclination so nearly like the earth's, Mars will have climatic zones and seasons (but not climate!) almost exactly like the terrestrial ones. The seasons will differ in two ways: (1) they will be nearly twice as long because Mars' sidereal period is 687 days (1.88 years) and (2) Mars' greater orbital eccentricity causes a greater inequality in the lengths of the seasons. In Mars' southern hemisphere, spring is 199 days, summer 182 days, fall 146 days, and winter 160 days. The seasons in the two hemispheres are complementary, as on earth.

Mars' surface gravity, though less than three-eighths the earth's and only twice the moon's, is sufficient to guarantee some atmosphere. The most certain and detailed information about the atmosphere comes from the Viking landers. The landers, after having made the trip from the earth to Mars with the orbiters, separated on command and entered the Martian atmosphere at about 800,000 feet. Their heat shields absorbed approximately 90 per cent of the kinetic energy. At 19,000 feet, they deployed a parachute which was jettisoned at 5,000 feet after decelerating the lander to about 200 miles per hour. The rocket engines then braked the descent to a landing speed of a mere 5.5 miles per hour. The whole procedure required only about ten minutes.

For scientists concerned with the Viking missions, the landings were highly suspenseful. A combination of good fortune and careful planning was necessary if a lander were not to be wrecked by landing on a boulder as small as 10 inches in diameter. Guidance from the earth was not possible, for the 40-minute round-trip communication time was four times as long as the duration of the descent. The landing therefore had to be fully automatic.

Previous Mariner photographs had given general indications as to likely regions in which to land, but the uncertainties of timing, velocity, distance, and atmospheric parameters necessitated the targeting of a hazard-free area with dimensions about 60 by 175 miles, approximately the size of Massachusetts. The first lander set down just 16 seconds after the predicted time and 19 miles from the center of the targeted ellipse. News of it reached the earth 20 minutes later. It was a magnificent scientific and technological achievement.
The Martian atmosphere is very thin. At the surface of Mars, the atmospheric pressure is about 1/150th the sea level pressure on the earth, about a tenth of a pound per square inch. This is less than a tenth the anticipated value, what would be found at about a height of 65,000 feet above the earth.

The atmosphere has a composition at Mars’ surface of 95 per cent carbon dioxide, 2 to 3 per cent nitrogen, 1 to 2 per cent argon, and 0.1 to 0.4 per cent oxygen. In the Martian heterosphere, however, the atmosphere is half nitrogen at a height of 60 miles. The 27º F temperature at 125 to 150 miles above the surface drops to -216º F at 85 miles’ elevation. At the Martian equator, surface temperatures fluctuate from a daytime high of 65º F to -10º F at sunset and a pre-dawn low of -100º F. In the polar regions, the thermometer plummets to -190º F.

Because the atmospheric pressure is so low, neither water nor carbon dioxide can exist in liquid form. Because of the low temperature, water vapor is no more than about 0.01 per cent of the atmosphere. It is estimated that if all of it were precipitated upon the planet, it would form a layer only 1/2500th of an inch deep.

The case of the more abundant carbon dioxide is rather different, however. The Martian polar regions get so cold that some carbon dioxide will sublimate directly from the gaseous to the solid (“dry ice”) state. The extensive whit polar caps in the winter hemisphere of Mars are therefore of solid carbon dioxide. Because the atmosphere is so largely carbon dioxide, the removal of a portion of it by sublimation produces a drop in atmospheric pressure. There are on this account seasonal variations of pressure.

Winds measured by the Viking landers averaged 8 miles per hour. Sustained winds reached a maximum of 20 miles per hour while gusts attained 35.

Clouds are observed over Mars. Three kinds are recognized — white, blue and yellow. The white and blue clouds appear when and where it is coldest — at the sunrise or sunset lines, over the poles, and during the Martian autumn and winter. The yellow clouds, on the other hand, are seen only when Mars is near perihelion. Generally speaking, however, Mars' weather is monotonously “clear and cold”.

An exception to this prevailing state of affairs is the appearance of a yellow cloud which encompasses and envelops the entire planet. Such planet-wide obscurations have been observed in 1909, 1924, 1928, 1956 and, most recently, in 1971. In the latter year, picture taking by Mariner 9 was delayed for three months during which Mars' surface features were hidden from view by a yellow cloud. Had Mariner 9 been a flyby mission, it would have been an almost complete failure.

The progress of these clouds indicates that 25 miles per hour is a common velocity but that they sometimes attain 60 miles per hour. This speed is a matter of some significance, for the most common interpretation of the yellow clouds is that they are dust storms. Prior to the Viking landers' measurements of actual wind velocities on Mars, estimates of what wind speeds would have to be in order to raise such great quantities of dust into the thin Martian atmosphere and to keep the particles suspended for a matter of weeks ranged from 100 miles per hour to half the speed of sound. Though there is unquestionably much dust on Mars' surface, actual wind speeds appear to be substantially less than what had been thought necessary to create and sustain planet-wide, totally obscuring clouds. Eventual settling of so much dust might also be expected to modify the large-scale coloration features of Mars' surface, but this does not occur. The true nature of the Martian clouds is therefore a somewhat unsettled matter, notwithstanding various assured statements to the contrary.
Mariner 4, the first of the three flyby missions, returned to the earth photographs showing features as small as 2 miles. It was so briefly in Mars' vicinity, however, that it had time to photograph only about 1 per cent of the planet's surface with this resolution. Mariners 6 and 7 which followed supplied more than 200 photographs with an improved resolution of 1/5 mile and extended the coverage to about 1/10 the entire surface. Mariner 9, from its parking orbit about Mars, returned photographs showing details as small as 100 yards. In its first year of operation, it made 698 revolutions about Mars and sent back 7,329 photographs. This represents more than 100 times as much information as had been collected in three and a half centuries of terrestrial observations and the three previous flybys. Mariner 9 will continue to revolve about Mars for another 50 to 100 years before spiraling into the Martian atmosphere.

The two subsequent Viking orbiters have prodigious information-gathering capabilities. Each has tape recorders which can receive two million bits of information every second and store 55 television frames simultaneously. Every 4.5 seconds a complete picture image can be stored as 8.7 million separate bits of information, later to be relayed to earth by a mere 20-watt transmitter. It is from these pictures that most of the detailed information about Mars' surface features and topography comes.

The first Mariner photographs unexpectedly revealed that the surface of Mars was pocked with craters. The craters look much like those of the moon and Mercury except that they show some evidence of erosion by wind and, in certain instances, by water. They represent some of the oldest features on the planet. They are presumed to have been formed by the infall of planetesimals from the region between Mars and Jupiter. Later photographs added the further surprise that most of the craters are in Mars' southern hemisphere. There are also several huge ringed basins similar to the large maria of the moon; Hellas, for example, is half again the size of Mare Imbrium.

Since there are no bodies of water on Mars, there is no “sea level” to which to refer the altitudes or depths of surface features. One can simply note, therefore, that various parts of the planet range in elevation by as much as 7 to 10 miles. Weathering agents have operated less vigorously on Mars than on the earth.

The most arresting features are the polar caps. They grow in the winter hemisphere and recede in the summer hemisphere. At their greatest, they extend down to latitudes 60º. They consist of a permanent cap of water ice, having a visibly laminated structure, to which is added in winter an extended superficial mantle of frozen carbon dioxide. Both water and carbon dioxide were detected in the polar regions by an infrared spectrometer aboard Mariner 9. The permanent icecaps constitute the planet’s principal “stockpile” of water; it is estimated that the water locked into these caps would produce a layer 30 feet deep if it could be distributed evenly over the planet’s surface.

Another large scale feature is Valles Marineris (Mariner Valley),* a huge canyon some 2500 miles long, 125 miles wide, and 3.5 miles deep. It runs more than one sixth of the way around Mars just south of Mars' equator. The great canyon, with its vast network of tributary channels and gullies, was almost certainly cut into the planet's surface by the action of fast-moving water. The immature form of the tributary channels indicates that their formation was quite rapid. The Valles Marineris system constitutes one of the major puzzles of the Martian topography: how can one account for the large but ephemeral and localized quantities of water needed to carve out the Valles Marineris system?

* Designated Coprates prior to the space program’s Mariner space probes.
One possible solution to the puzzle depends upon the fact that the temperature is below freezing just a few feet below the surface everywhere on the planet. A great deal of water may thus be impounded in this permafrost layer — amounting to an estimated 1 per cent of the surface material. The rapid melting of this ground ice could have supplied the water which cut the Valles Marineris canyon system.

What would cause a thawing of the permafrost? Locally, the impact of a crater-forming meteorite could generate enough heat to melt much ground ice, but probably not on the scale needed to produce Valles Marineris. Perhaps an abortive attempt at continental drift created a rupture which exposed ground ice to sunlight. Mars' crust is more rigid than the earth's, however, and internal circulation has probably never occurred on a planet-wide scale.

Yet another possibility, perhaps acting in concert with the previous two, is that sufficient heat has been released by volcanism. The evidence for volcanoes, first supplied by Mariner photographs, is the existence of a number of huge volcanoes in Mars northern hemisphere. The largest of them, Olympus Mons, is a cone some 80,000 feet high, nearly three times the height of Mt. Everest. Lava from the volcano has built a cone which would cover the entire state of Missouri. Outgassing from Martian volcanoes is presumed to be the origin of Mars' atmosphere.

The great size of Olympus Mons (and three other giant volcanoes) is undoubtedly due to its great age, perhaps a hundred million years. In contrast, terrestrial volcanic cones such as Mauna Loa in the Hawaiian Islands are comparatively short lived. This is because continental drift carries the volcano away from the hot spot at which the lava is supplied. The Martian volcanoes are rooted to a fixed hot spot, however. In addition, the lower surface gravity of Mars facilitates a greater buildup of cone.

Certain characteristic types of Martian terrain have no strict terrestrial counterparts except possibly on a small scale. Such are the jumbled chaotic terrain and the hummocky terrain. It seems probable that such typically Martian topography arises from typically Martian processes such as collapse following the decay or melt of subsurface ice or permafrost.

The nature of the Martian surface was made known in detail by photographs and data returned by the two Viking landers. Both landing sites were aptly described as “a forest of rocks”. Both have been compared to the desert areas of the American Southwest. Panoramic vistas radioed back to earth show a landscape billowing with sand dunes. The rocks at the second site differed from those at the first, however, in being porous like lava, therefore presumably of volcanic origin.

Samples of the Martian soil were analyzed, like some of those from the moon, by subjecting them to X-ray bombardment and observing what scattered and induced radiations were forthcoming. It was thus established that iron is abundant and that light aluminum silicates (sial) predominate over the heavier magnesium silicates (sim). The iron is thought to be in the form of the minerals hematite or magnetite.

The high abundance of iron and the fact that it appears to be widespread, judging from the reddish color of most of Mars' surface, suggests that the body of the planet is not as strongly differentiated as the earth. Other evidence such as its lower mean density and greater rigidity support such a conclusion. The crust is estimated to be 30 to 50 miles thick.
Neither the Mariners nor the Vikings could find a magnetic field as much as 1/5000th the earth's. Since Mars rotates almost as rapidly as the earth, it would thus appear that Mars has at best a very small molten iron core, perhaps none. The absence of atmospheric oxygen also implies that there is no ozone layer. The surface of Mars is therefore subject to both ultraviolet radiation and high energy particles of the solar wind and cosmic rays. Probably no forms of terrestrial life could survive both these hazards.

5. Life on Mars

Nevertheless, a search for possible living organisms on Mars was admittedly one of the principal motivations for the Viking missions. The two landers therefore carried experiments specifically designed to test for organic material, past or present. The only organic substances detected in Martian soil samples were several terrestrial contaminants. No slightest hint could be found of any life process such as respiration, photosynthesis or metabolism. The Martian soil appears to as totally devoid of life as inert lunar samples. Tests sensitive to about one part on 20 billion were negative. This represents a sterility far greater than that of soil samples from Antarctica, more even than that of some meteorites. There is no escape from the conclusion that Mars is a lifeless planet and almost certainly always has been.

The famous (or infamous) Martian canals are now known to be, in most cases, merely synthetic constructions in the eye of the beholder, suggested by systems of linear faults, borders between areas of different colors, or rough alignments of markings in much the same way as are the lunar “rays”. They were first seen in 1869 by the Italian astronomer Father Secchi, who applied to them the Italian term “canali”. At the favorable opposition of 1877, the astronomer Schiaparelli saw them as a network of fine lines upon the reddish desert areas. They appeared to crisscross the face of the planet along straight courses quite unlike those of streams or rivers. Some of these “channels” (which is the preferable English equivalent of the Italian “canali”) were of such fineness as to tax the most skilled observers. The clarity with which they could be seen appeared to vary capriciously from week to week. They were described as intersecting one another at all angles, and at their intersections were small dark areas designated oases. Every channel originated in what was then thought to be a sea, lake, or another channel; none terminated in mid-desert.

At the time of the melting of the polar cap in either hemisphere, arterial channels were reported to appear as extensions of the rifts in the retreating polar cap. They darkened and pressed toward the equator at a rate of 50 miles a day, ultimately crossing into the opposite hemisphere. At the same time, many of them underwent gemination, or doubling; two parallel canals appeared where only one had been. Gemination did not occur simultaneously for all those canals which showed the phenomenon and, in different years, the second canal might have been of a different width, intensity and configuration. Seasonal changes in color and form of the dark areas gave the first proof that these areas were not bodies of water, as had been assumed. It was concluded that they were areas of vegetation, for with the approach of summer they changed from a lighter to a darker green, then to yellow and brown. Some changes of a nonseasonal character were also observed. The reddish desert areas remained almost immutable.

Such highly suggestive results encouraged the American astronomer Percival Lowell to advocate the thesis of intelligent life upon the planet Mars. Schiaparelli had already noted, after observing the canals, that “their singular aspect, and their being drawn with absolute geometrical precision, as if they were the work of rule or compass, had led some to see in them the work of intelligent beings”. Lowell provided the motive for the canals’ constructing by calling attention to the scarcity of water on the planet. He
noted that the low velocity of escape meant the inexorable depletion of water, a process already far advanced. Only intelligent beings capable of abstract concern could attempt to offset the tide of events with a countermeasure such as a monumental network of artificial watercourses to convey the small remaining reserves of water from their sources in the polar caps to the habitable, arable equatorial regions. The entire economy of the planet must be addressed to the conservation and optimum use of the remaining scanty supply of water. To this end, a vast pumping system forced water of the polar cap through the canals and beyond the equator; it must be inferred from this that the Martians are engineers of great skill. As the water becomes available each spring, vegetation flourishes along the canals in a pattern that spreads from pole to equator. Oases like those of terrestrial deserts thrive at the points of distribution.

It weighed heavily against Lowell's theory, however, that some of the most skilled observers failed to see the channels as Lowell did; indeed, with telescopes of aperture greater than 30 inches (some of the largest then in existence), the “canals” are lost. Even Schiaparelli said of the theory of the canals’ artificial origin that “the examination of these ingenious suppositions leads us to conclude that none of them seems to correspond entirely with the observed facts”.

Nevertheless, Lowell’s proposition that on Mars there are kindred beings, engaged in a heroic rear-guard action against the forces of a hostile environment, had a curiously intense and widespread credence. (Misery loves company?) Lowell evangelized his thesis in several popular books which reached a large readership.

So pervasive was the belief in life on Mars and the existence of an advanced Martian civilization that some twenty years after Lowell's death a radio dramatization of H. G. Wells’ “War of the Worlds” created panic and alarm on a mass scale. On October 30, 1938, in a skit appropriate to the observance of Hallowe’en, simulated news reports told of a landing of “Martians” on a farm in New Jersey. Though the “Martians” were militarily invincible, they shortly succumbed to the unanticipated hazard of terrestrial bacteria, thus sparing earthlings a conquest by Martian invaders.

Announcements were made at the opening, middle and close of the broadcast that the program was fictional. Nevertheless, heedless citizens swamped civil and military authorities with frantic inquiries for succor and protection. Some prepared to do battle with the advancing legions of Martians. Some repaired to remote hideouts. On the other hand, one enterprising landowner rented parking space to curiosity seekers who thronged to the reported landing place. The local water tower was fired upon by some who mistook it for a hovering space ship in the foggy darkness.

Eleven years later, a similar broadcast was aired in Quito, Ecuador. When listeners discovered that their credulity had been imposed upon, a mob stormed the building which housed the radio station and set fire to it; fifteen people lost their lives in the blaze.
6. The Satellites of Mars

Mars’ two little moons were discovered as a result of a search conducted during the favorable opposition of 1877. The inner is named Phobos (Fear) and the outer Deimos (Dread) after the fiery steeds of the chariot of the god of war. They can be seen only in the largest telescopes, for Phobos' longest diameter is only 17 miles and Deimos' but 7.5 miles. The masses of these two pygmies are minute by comparison even with the moon; a 150-pound man would weigh only 2 or 3 ounces on Phobos.

Phobos is only 3730 miles above Mars’ surface. It is therefore so near the planet that it can be seen only over a range of 138ºlatitude, rather than a full hemisphere; if Phobos were over Mars’ equator, it would be below the horizon in latitudes greater than 69º north or south. Deimos is 14,600 from the center of the planet.

Because Phobos and Deimos are so near to Mars, they revolve about the planet in short periods – Phobos in only and Deimos in . Phobos’ period is shorter than that of any other satellite in the solar system, . Phobos is only one of three known satellites which revolve about their primary in less than the planet's period of rotation. Since Phobos revolves more rapidly than the planet rotates, it will be seen on Mars to rise in the west every ; it could thus rise twice in a single night! It would remain above the Martian horizon no more than to any fixed observer and would in this time go through just over two thirds of its phases.

Deimos, on the other hand, revolves only a little more slowly than Mars rotates and so would seem to rise reluctantly in the east, not setting (on the average) until 2 2/3 days later, having in the meantime gone through its phases twice.

Seen from Mars, Phobos would have one half the diameter of our full moon and be only one ninth as bright. Deimos would have an apparent diameter of only one fifteenth the apparent diameter of the full moon and be but one fortieth as bright as Phobos; it would therefore look much like Venus does from the earth. Most of the Martian year, the satellites would be visible only in the morning or evening twilight, for they would be either invisible against the daytime sky or immersed in the umbra of Mars. Only in midsummer or midwinter would they avoid Mars’ shadow enough to be seen entirely across the sky.

One of the most curious items relating to these two little bodies is purely historical. Kepler, often given to fanciful speculation, once wrote to Galileo of the probability of Mars’ having two small moons. The coincidence is made more remarkable by Voltaire’s mention of these two satellites in his imaginative “Micromegas”. But the most incredible anticipation of Deimos and Phobos was made by Dean Jonathan Swift, famous satirist and a contemporary of Newton. In his “Gulliver's Travels” he describes the work of astronomers of Lilliput who were possessed of very superior telescopes; they had “discovered two lesser stars, or satellites, which revolve about Mars; whereof the innermost is distant from the center of the primary planet exactly three (1.4)* of his diameters, and the outermost five (3.5); the former revolves in a space of ten hours (7 2/3) and the latter in twenty-one and a half (30.3)”. This was written in 1726, a century and a half before their discovery!

* Figures in parentheses indicate the true values.
One hundred years after Phobos' discovery, it was being observed by the Viking 1 lander from Mars' surface. More important, Viking 1 Orbiter passed within 60 miles of Phobos and radioed high-resolution photographs back to earth. The satellite's surface is peppered with craters; the largest has been named Stickney, about 6 miles in diameter. Phobos itself is ellipsoidal in shape, 40 per cent longer than it is wide, and its longest axis points toward Mars.

A unique feature of Phobos' surface is a network of long narrow grooves or striations running more or less radially from the crater Stickney. They may be fractures created by the impact which formed Stickney. The material of which Phobos is made is dark like the material of the moon and of low density. The surface of the satellite is covered with a dusty regolith estimated to be perhaps 300 yard deep.

Deimos has been observed by Viking 2 Orbiter at a distance of 14 miles. Like Phobos, it is ellipsoidal and cratered, though without grooves. Those craters less than 50 yards across are buried under a blanket of regolithic dust 20 to 30 yards deep.

One of the most interesting matters concerning Phobos is a result of the fact that it is near to Mars and at the same time of low density — about twice the density of water. Because Phobos is so near to Mars, it is subject to a considerable tidal force. If the body of the satellite were pulverized so that it were held together only by its gravitational cohesive force, this force would not be sufficient to withstand the tidal forces seeking to pull the near and far sides apart. The satellite would then be sundered. The maximum distance from the planet at which such an eventuality could occur is called the Roche limit. For a satellite the same density as the planet, the Roche limit would be 2.44 planetary radii. Actually, Phobos is 2.77 Martian radii from the center of the planet, but because Phobos is considerably less dense than Mars, the Roche limit is somewhat greater than 2.44 radii. This implies that Phobos is not held together by its weak internal gravity alone, but by the chemical bond which provides the strength of the material of which it is made.

Jupiter

A little more than five times farther from the sun than the earth is Jupiter, given as a symbol the Egyptian hierglyph * representing an eagle, “the bird of Jove”. Jupiter revolves about the sun in 11.86 years, passing through one constellation of the zodiac each year. Except for Mars at opposition and for Venus, Jupiter is the brightest of the planets; only occasionally is it less bright than the brightest star, Sirius.

The planet deserves the kingly preëminence its name implies, for next to the sun, it is the dominant body of the solar system, being more massive than all the rest put together, some 318 times as massive as the earth. It is likewise the largest, having a diameter of 88,729 miles; this is more than 11 times the earth's diameter. Its volume is therefore 1400 times the earth's volume. It is evidently more voluminous than it is more massive than the earth, so much so that its mean density is only 1.24 times that of water. Its surface gravity, however, is 2.51 times the earth's. Semipermanent features on the planet's surface have permitted highly accurate determinations of its period of rotation — 9h 55m 29.7s — shorter than that of any other planet. At Jupiter's equator, matter whirls about the planet's axis at more than 28,000 miles per hour.
What is seen of the planet is not its solid surface, for different latitudes rotate in
different periods; this is obviously impossible for a solid surface. The apparent period of
rotation increases from \(9^\circ 50'30''\) at the equator to \(9^\circ 55'51''\) near the poles, though
the period is not the same for corresponding northern and southern latitudes.

The rapid rotation produces a considerable equatorial bulge, the equatorial diameter
exceeding the polar diameter by 5700 miles. The planet thus appears to be flattened by
1 part in 16, an effect easily visible on photographs or in a telescope.

Jupiter’s appearance is distinguished by prominent reddish belt markings on a
creamy white background. The belts run parallel to Jupiter's equator. The light bands
between the darker belts are called zones. Zones are regions of warmer ascending
currents; belts are regions of cooler descending currents. Zones are also regions of higher
atmospheric pressure, belts regions of lower atmospheric pressure.

On earth, the Coriolis forces make low-pressure regions centers of in-spiraling
winds, clockwise as seen from above in the southern hemisphere and counterclockwise
in the northern. On the much larger and more rapidly spinning Jupiter, the much larger
Coriolis forces string the low-pressure regions into planet-girdling belts. At the interface
between zones and belts are high-velocity winds analogous to the stratospheric jet
streams on earth. On the side of a belt nearest the equator, the winds blow eastward; on
the poleward side of a belt, they blow westward. In Jupiter's high latitudes, the surface
velocity of the planet’s rotation approaches zero and the Coriolis force dwindles to
nothing. As a result, Jupiter's polar regions are not belted.

The Pioneer space probes 10 and 11 executed close flybys of Jupiter in December of
1973 and 1974, respectively. As with the other planetary flybys, these reconnaissances
added greatly to what is known of the planet. For example, they showed that the density
of infalling meteorites is about 170 times as great at Jupiter as it is near the earth. These
meteorites therefore contribute about 8 calories per minute per square foot to heating
Jupiter's upper atmosphere, an addition of energy of meteorologically significant
proportions.

The Voyager 1 and 2 space probes, making their closest approach to Jupiter in March
and July of 1979, added vastly more to what is known of Jupiter and its satellite system.
The best photographs from the Voyager mission show detail fifty times finer even than
the unprecedented pictures sent back by the Pioneers.

From occultations of stars by Jupiter, it is inferred that the planet’s atmosphere is
stratified. When Jupiter passes between the earth and a star, the star's light is not cut off
abruptly but fades out in a manner which depends upon the structure of the Jovian
atmosphere. At least four strata have been thus identified.

Jovian atmospheric phenomena, aside from local detail, show great overall stability,
a characteristic due to the great heat capacity of such a massive atmosphere and to the
absence of an underlying solid surface. The structure and phenomena of Jupiter's
atmosphere are determined by its composition, temperature and source of heat. In all
three respects, Jupiter offers a great contrast with the earth, Venus and Mars. On the earth
and Mars, sunlight provides the heat and is absorbed at the solid surface of the planet; the
input is therefore primarily at the base of the atmosphere. On Venus, the sun is likewise
the principal source of heat but the sunlight is largely absorbed by the atmosphere before
it can reach the surface of the planet; the energy input is therefore at great altitude. On
Jupiter, however, the sun is the source of barely one fourth the energy input; the energy
radiated by Jupiter itself is nearly three times what is received from the sun. It must
therefore come from internal residual sources.
One anticipated consequence of this difference is the fact that diurnal effects are secondary on Jupiter; the weather is about the same day and night. Another consequence is the fact that the polar regions do not differ from the equatorial regions on Jupiter as much as on earth since solar insolation is a secondary source of heat input.

Jovian meteorology is determined to a considerable extent by the composition of the planet's atmosphere. Because of Jupiter's high velocity of escape — 37 miles per second — Jupiter might be expected to retain all elements, volatiles as well as refractories. Its low average density shows that it has, for it is only a little less dense than the sun. It is therefore reasonable to expect that the composition of Jupiter must be nearly the same as the sun's — mostly hydrogen, secondarily helium, with about 1 per cent of all other elements together. Until the Pioneer flyby, hydrogen was known only from its presence in ammonia (\(\text{NH}_3\)) and methane (\(\text{CH}_4\)); cold helium could not be detected at all in the visible region of the spectrum. The Pioneers, however, returned direct spectrographic evidence in the far ultraviolet that there are about 10 molecules of hydrogen (\(\text{H}_2\)) to each atom of helium (He) and 50 molecules of hydrogen to one atom of all other molecules combined. Spectroscopic identification has been made of the additional molecules water (\(\text{H}_2\text{O}\)), ethane (\(\text{C}_2\text{H}_6\)), acetylene (\(\text{C}_2\text{H}_2\)), phosphine (\(\text{PH}_3\)), hydrogen sulfide (\(\text{H}_2\text{S}\)), cyanide (\(\text{HCN}\)), and the somewhat surprising and exotic germanium tetrahydride (\(\text{GeH}_4\)). There must be others as well.

The ammonia molecules and the sulfides can combine with the aid of sunlight into long chains of ammonium polysulfides, which are yellow and orange. It may be these which give the belts their reddish or brownish color; it cannot be any of the molecules heretofore positively identified.

The uppermost clouds are of ammonia crystals. The strength of the ammonia bands in Jupiter's spectrum is such as to indicate that the atmospheric pressure at the uppermost cloud level is 10 atmospheres (150 pounds per square inch). The infrared radiation from these levels indicates a temperature of about -220 °F. Some 20 miles beneath the ammonia crystals are clouds of ammonium hydroxide crystals (\(\text{NH}_4\text{SH}\)). Another 25 miles still deeper are clouds of ordinary water ice. Below them the temperature rises above the freezing point to +90 °F.

It is apparent that warm gas — mostly hydrogen and helium with some water vapor and ammonia — rises from deep in the atmosphere. As it encounters cooler layers, the water vapor condenses and releases considerable heat of vaporization. This maintains the rising column at a higher temperature than its surroundings and the column therefore continues to rise, just as on earth. The condensation of ammonia extends the process to still greater heights in analogous fashion. When the original gases within a zone reach their maximum height, they cool by radiation and roll over into an adjacent belt. Now cool, they descend and repeat the circulation. As was the case with Venus, the investigation of the different levels of the Jovian atmosphere can be achieved by selecting wavelengths which derive primarily from the various molecular levels.

Most famous of the features on Jupiter is the Great Red Spot. It is an elliptical marking of the same color as the belts but independent of any of them. It is located about 22° south latitude, extends about 8700 miles north-to-south, and varies between 19,000 and 25,000 miles east-to-west. It was first noticed in 1664 but not until 1878 was it recognized as a permanent feature of Jupiter.* Its prominence has fluctuated greatly since its discovery as the intensity of its coloration changes unpredictably. It was prominent during the Pioneer flybys but had faded somewhat by the time of the Voyager flybys over five years later.

* Kepler unwittingly anticipated the discovery of the Great Red Spot in 1611. In that year, Galileo announced the discovery of the phases of Venus in a Latin anagram which, correctly translated, said that “Venus mimics the shapes of the moon”. The ingenious Kepler offered an alternative decipherment “There is a ruddy spot on Jupiter which rotates mathematically”. As with his anticipation of the satellites of Mars, this could only have been a prophetic coincidence.
The Red Spot has been found to be a high pressure center; the pressure within the Spot is above even the high pressure of the South Tropical Zone in which it is embedded. The Spot's period of rotation about the planet varies from $9^h55^m31^s$ to $9^h55^m43^s$. Because of this, it has regressed westward about the planet some three revolutions over the past century.

The Spot is an ascending anticyclonic column. The higher it ascends, the longer its period of rotation and the darker its color. It is the highest cloud structure on Jupiter; because of its great height, it is cooler than adjacent features. The most nearly comparable terrestrial phenomenon is a tropical thunderstorm whose clouds rise to the upper limits of the troposphere, where they flow outward in all directions. Their tops have cross sections some hundred times that of their bases. Were it not for their being detached from a source of warm moist air as they encounter land masses, or being to diurnal variation of heat input, these storms might also persist for long times.

Lesser spots appear occasionally on Jupiter but do not survive for any length of time. For example, a spot one third the size of the Great Red Spot appeared in Jupiter's North Tropical Zone early in 1972. It was photographed in December, 1973, by Pioneer 10 but had disappeared by the time of the Pioneer 11 flyby a year later.

On the basis of Jupiter's mass, diameter, chemical composition, temperature and oblateness, it is possible to calculate a theoretical model of its constitution. The near-perfect symmetry of Jupiter's gravitational attraction implies that there are no mascons within it; Jupiter must therefore be fluid except for a possible relatively small rock and iron core of about 10 to 20 earth's masses. Outside it is a sheath of about 225 earth's masses of hydrogen and approximately 75 earth's masses of helium.

The core is thought to have about twice the diameter of the earth. At its center, the pressure must be about 100 million atmospheres and the temperature of the order of 36,000°K. Out to about 29,000 miles, the hydrogen sheath is constituted of hydrogen atoms which have been dissociated from the molecular form by the enormous pressure. Furthermore, at pressures greater than several million atmospheres the hydrogen acquires an electrical conductivity much like that of ordinary copper or silver and is therefore described as *metallic hydrogen* in such a state.

Out from the center of Jupiter between 29,000 miles and 44,000 miles, where the pressure is below 3 million atmospheres and the temperature below 11,000°K, the hydrogen assumes its molecular form. Though it has not condensed from the gaseous state in the same sense as that water condenses from steam, it possesses a density and a viscosity (“stickiness”) which allow it to be described frequently as “liquid hydrogen”. Above such an interior floats the atmosphere some 600 miles deep, made principally of gaseous molecular hydrogen. The considerably indefinite interface between these two shells is Jupiter’s “surface”.

The Pioneer flybys confirmed the anticipated existence of a large magnetosphere, first encountered some 100 radii from the planet. At a distance, the field is approximated by that of a dipole inclined 11° to Jupiter's axis of rotation, having a sense reverse to the earth’s and about ten times as strong; it departs substantially from a pure dipole structure close to the planet. Again, it is presumed to be the result of dynamo action, probably by the metallic hydrogen shell. If Jupiter’s magnetosphere were visible, it would appear to cover 16 times the area of the full moon in our sky.
The great size and rapid rotation of the magnetosphere strongly flattens what would be the Jovian equivalent of the van Allen belts into a thin current sheet which lies very nearly in the plane of Jupiter's magnetic equator. Electrons in the current sheet are accelerated nearly to the speed of light. As a result, they emit a characteristic radiation of short wavelength (several inches) such as that produced in the type of “atom smasher” known as a synchrotron; on this account, such decimeter radiation is known as synchrotron radiation.

In addition to the decimeter synchrotron radiation, Jupiter’s magnetosphere generates intense bursts of longer wavelength radiation (30 feet) identified as decameter radiation. It is thought to be produced when quantities of electrons are dumped from the current sheet into Jupiter’s upper atmosphere, much as coronal electrons are dumped into the earth’s upper atmosphere in the auroral zones. Artificial satellites revolving about the earth have detected radio emissions from the earth analogous to Jupiter’s decameter radiation.

Because of the tilt of Jupiter’s magnetosphere to the line of sight from the earth, the Jovian radio radiation fluctuates in intensity with the period of the magnetosphere's rotation. This is the $9^h55^m$ period taken to be the true period of the planet itself, for the magnetosphere is generated deep inside the metallic sheath. The shorter $9^h50^m$ period of most of the cloud markings implies high west-to-east winds of 250 miles per hour near the Jovian equator.

The Jovian magnetosphere has provided an unexpected explanation of a previously puzzling enhancement of cosmic ray electrons impinging on the earth. The increase was observed every 13 months, which interval, it is now recognized, is Jupiter's synodic period of revolution. When Jupiter and the earth lie along the same line of force of the interplanetary magnetic field, electrons escaping outward from Jupiter’s electron sheet spiral back along the magnetic line of force to the earth. These circumstances recur every 13 months.

8. Jupiter’s Satellites

The first of any planetary satellites to be discovered were the four brightest of Jupiter's brood; they were discovered by Galileo in 1610, and in his honor are known as the Galilean satellites. For more than 280 years they remained the only known satellites of the planet; 12 more were discovered between 1892 and 1978. An uncertain number of others has been discovered by the Pioneer and Voyager space probes. The four Galilean satellites are numbered I, II, III and IV in order of increasing distance from the planet and further bear the names Io, Europa, Ganymede, and Callisto, respectively. The rest are usually known only by Roman numeral designations given them in the chronological order of their discovery, but have been given names as well. As a result, the order of Jupiter's first sixteen satellites to be discovered is XVI, V (Amalthea), XV, I, II, III, IV, VI (Himalia), VII (Elara), X (Lysithea), XIII (Leda), XII (Ananke), XI (Carme), VIII (Pasiphae), and IX (Sinope). Little is yet known of the recently discovered satellites.

The Galilean satellites are just within the limit of visibility of the unaided eye and therefore could be seen alone but for the overpowering brilliance of nearby Jupiter. All four move about Jupiter in almost circular orbits, very nearly in the plane of Jupiter's equator. Their actual distances range from 261,000 miles to 1,167,000 miles and their periods from 1.75 days to 16.67 days. All are large enough to show perceptible disks and barely discernible markings in powerful telescopes. These satellites are 2260 miles (I), 1950 miles (II), 3280 miles (III) and 3050 miles (IV) in diameter, respectively. Only one
is not as large as the moon; one is larger than Mercury and would be counted a planet in its own right if it did not revolve about Jupiter. It is something of a surprise to learn, then, that their combined light would appear from Jupiter only 20 per cent as bright as the full moon appears to us; this is, of course, a result of the much weaker sunlight at Jupiter's distance. Their brightnesses are observed to vary in the same period as that in which they revolve; they thus keep the same face toward Jupiter as the moon does to the earth. Satellites I to III so perturb each other that their periods remain in the ratio 1:2:4. From their mutual perturbations the masses of these bodies are found to range from two thirds to twice that of the moon. Ganymede (III) is the brightest, largest and most massive. Most unusual is Callisto (IV), whose density is only 0.6 that of water.

The fifth satellite, Amalthea, was discovered in 1892. It had escaped discovery until then because of its small size (about \(80 \times 140\) miles and nearness to the bright planet (113,000 miles from Jupiter's center, 68,000 miles from its surface). Its period of revolution is just less than 12 hours; hence its orbital velocity is approximately 17 miles per second (60,000 miles per hour), the largest orbital speed of any known satellite except the recently discovered J XVI, which is still closer to the planet. Because Amalthea is so near Jupiter and the latter has such a considerable equatorial bulge, the nodes of the satellite's orbit will regress at the remarkable rate of \(2.5\)° per day, once completely in four and a half months, over \(1\)° per revolution. The satellite is so close to Jupiter that at moonrise it would appear 40 per cent smaller than at the zenith. Like the diminutive satellites of Mars, Amalthea is irregularly ellipsoidal with its long axis always directed toward its primary.

The remaining satellites are so faint that even on Jupiter an observer would need a six-inch telescope to see them. Apart from the newly discovered satellites XV and XVI, they divide themselves very naturally into two groups: VI, VII, X and XIII at a distance of roughly 7.5 million miles from Jupiter, and XII, XI, VIII and IX about 15 million miles from the planet. It is not yet known how XIV is related to the others. In both groups, the orbits loop through one another. However, they make sufficient angles and are eccentric enough that the satellites are always considerable distance apart. For example, the orbital planes of VI and VII intersect at an angle of \(28\)°, and although their orbits interlock, the two bodies never come closer than 2,000,000 miles to each other. The period of revolution of the first group is about 275 days. All are estimated to be less than 100 miles in diameter.

The four small outermost satellites have periods of over two years. They are the most distant of any satellites from their primary. Their orbits appear even more entangled than those of the first group, but their most interesting feature is the fact that the motion of all four is retrograde. This is almost certainly no coincidence, for it has been shown by celestial mechanicians that a distant satellite whose motion is direct can be robbed more easily from the planet by the powerful sun than one whose motion is retrograde. As it is, the sun produces drastic changes in the orbits of the outer satellites. For example, in only four revolutions, the period of VIII varied between 713 and 768 days, its eccentricity between 0.29 and 0.45, the inclination of its orbit between \(28\)° and \(34\)°. It is not surprising that this satellite was lost between 1922 and 1938.

Some of the most interesting of the satellite phenomena, ones visible with only modest optical aid, are the frequent eclipses, occultations and shadow transits of the Galilean satellites. Because these satellites are so nearly in the plane of Jupiter's equator and their periods of revolution are not long, Jupiter occults, eclipses or is eclipsed by one or more of them almost daily; only IV, because of its distance, can at times miss. Since the earth is seldom near the line from sun to Jupiter, a satellite will seldom appear to
cover its shadow on Jupiter's disk but will either precede or follow it. Passage of a shadow is called a **shadow transit**. Predictions of these phenomena can be found in the Ephemeris and Nautical Almanac. Satellites VI, VII, X and XIII will be seen from Jupiter to transit the sun about once every 80 years; the outermost satellites transit probably no oftener than once every several centuries.

Observations of the eclipses of Jupiter's satellites served to give the first demonstration of the fact that light travels with a finite velocity and, moreover, gave an estimate of its value. It was noticed in 1675 by the Danish astronomer Roemer that satellite phenomena occurred behind schedule when the earth was receding from Jupiter, ahead of schedule when the earth was approaching. He reasoned correctly that the light from the planet and its satellites required respectively more or less time to reach the earth according as its distance from them was more or less. His observations gave an estimate which is now known to be only about 15 per cent too low.

Until the Pioneer flybys of 1973 and 1974 and the two Voyager space probes' flybys in March and July of 1979, almost nothing was known of the surface features of Jupiter's satellites. The Voyagers' close encounters, in particular, revealed a wealth of astonishing detail. The Galilean satellites were found to be highly individualistic, whether compared with other satellites or among themselves.

Io's surface shows not a single crater; in its present state, therefore, it cannot be older than 10,000,000 years and probably much younger. The absence of craters is directly due to extensive and vigorous volcanic activity. Eight volcanoes erupted during the passage of Voyager 1; six were active during Voyager 2's flyby four months later and a dozen might have been seen if the whole surface could have been viewed. It must be concluded that volcanic eruptions are a daily occurrence. Io is the most active volcanically of any body in the solar system.

Beside the outpouring of lava from volcanic cones, there are flows from fissures and more than one hundred caldera, upwelling into lava lakes. Craters would be inundated in an astronomically short time and all but the grossest topographic features would be overspread by magma. If such a degree of activity has gone on for the last billion years, the outermost 100 miles of Io's surface must have been recycled at least once.

What could bring about such unparalleled vulcanism? It is credited to the heat generated by the tidal friction when Io, which is rotationally bound to Jupiter, passes nearest to the next-nearest satellites Europa and Ganymede. The heat of friction melts a substantial portion of the interior which then seeks release through the heaving 10 to 15 mile crust. The volcanoes erupt with great violence, spewing forth hot frothy magma at a speed as great as half a mile per second. This matter is seen as geyser-like plumes rising as much as 175 miles above Io's surface and raining down upon it to a distance of more than 500 miles.

As the issuing sulfurous magma approaches the surface, some of the sulfur spontaneously vaporizes and propels the liquid magma as do the bubbles which cause champagne to erupt from an uncorked bottle. After the melt cools, it forms a blanket of sulfur snow about the volcano, but because the color of sulfur and its compounds depends upon temperature as well as chemical composition, the material assumes a variety of shades of red, orange, yellow and brown. The Voyagers also detected sulfur dioxide vapor over Io in an amount of about one ten billionth the density of air at sea level.
Not the least surprising aspect of these discoveries is the predominance of sulfur. Where did it come from? One suggestion is that it is the sulfurous fraction from the melt of approximately one fifth of Io's rocks. The only certainty is that Io's surface offers a prototype of the infernal fire and brimstone.

Since Io is far within the rapidly rotating Jovian magnetosphere, ions accelerated by Jupiter's strong magnetic field impinge at high velocity upon the surface and atmosphere of the satellite, ionizing them as they do. The ions thus produced are swiftly caught up in the magnetic field and whisked into a circumjovian orbit centered upon Jupiter's magnetic equator, thus forming Jupiter's plasma torus, half the thickness of Jupiter itself. Radiations from the plasma torus show it to contain ions of sulfur, hydrogen, oxygen, sodium, potassium and a number of heavy atoms. Thus Io has a singular type of atmosphere (an Ionosphere?). Its temperature is about 100,000 °K. The ions of the plasma torus emit about 1 trillion watts of ultraviolet radiation!

The plasma torus would dissipate and disappear if new ions and additional energy were not continually supplied to it. It is therefore a phenomenon contingent upon Io's volcanoes and Jupiter's magnetic field. Indeed, a variation in volcanic activity may account for a ten-fold increase in the brightness of the torus between 1973 and 1981. The torus must be very slowly decelerating Jupiter's rotation.

The ions of Jupiter's plasma torus generate decametric (10-meter) radio radiation. Such radiation appears to be narrowly limited in direction, like the beam from a searchlight, for it is received on earth only when Io is at specific locations relative to the line from earth to Jupiter.

Europa's crust is the smoothest in the entire solar system, with topographic features no higher than 50 yards. The surface must be that of an icy crust possibly 50 or so miles thick. It shows linear markings which are taken to be fractures, extending in many directions for 500 miles or more. The surface temperature on Europa is typically 90°K (-297°F) but may rise to 125°K at local noon.

Ganymede is characterized by rayed craters and many grooves entirely unlike anything observed on any other satellite. The grooves may be five miles wide, hundreds of miles long and several hundred yards deep. They appear to be faults. Ganymede must be composed of a mixture of rock and ice. Tidal friction may have kept its surface too warm and too soft to have retained impact craters during its early history. Its atmosphere has less than one hundred billionth the density of air at sea level. Ganymede is larger than Mercury, a comparison made somewhat less remarkable by the fact that its density is only one third as great.

Callisto, the darkest of the Galilean satellites, is saturated with craters less than 50 miles in diameter. It is also the least dense of the Galilean satellites and must be composed of a large fraction of water ice. One noteworthy feature is an enormous circular basin 1600 miles across, surrounded by 8 or 10 fracture rings at 100-mile intervals; it is suggestive of Mare Orientale on the moon's far side and is the largest permanent surface feature in the solar system. The contrast between Callisto and Ganymede may be an indication that tidal friction has not been as great on Callisto, allowing it to cool earlier in its history. Its older crust bears scars from the terminal phases of planetesimal bombardment.
Ranking with the welter of the Voyagers’ remarkable discoveries concerning the Galilean satellites is the revelation that Jupiter is surrounded by a faint ring. It is located about 35,000 miles above the Jovian cloud tops, has a width of approximately 4000 miles and a thickness of no more than a mile or two. It appears brighter from behind than from in front; the strong forward scattering thus implied indicates that the ring particles must be about a millionth of an inch in diameter. Since particles this small would not persist indefinitely in such orbits about Jupiter, the present ring could not last more than a few million years. It must be continually replenished or it must be a transient phenomenon.

9. Saturn

Beautiful ringed Saturn is the most distant of the planets known to the ancients, 886 million miles from the sun. On account of its distance, it takes 29.458 years to make one revolution about the sun. It is because of its deliberate pace that the ancients gave it the name of the god of time and likewise his symbol, an ancient scythe *. It appears yellow in color and is always among the half dozen or so brightest objects in the sky.

The ball of the planet, whose dimensions have been determined by Pioneer 11 and Voyager 1 to within 200 feet, has an equatorial diameter of 74,930 miles, making it the second largest. It is also second most massive, being 94 times greater than the earth. These two statistics yield the amazing result that Saturn has a mean density only 0.7 that of water; it is the second least dense of the planets, next after Pluto. One can also determine from its mass and radius that the average surface gravity of Saturn is a mere 6 per cent greater than the earth's.

The cloud deck above Saturn is observed to rotate once in $<E10 sup h^14 sup m>$ at the equator, only slightly less rapidly than Jupiter. As with Jupiter, the rotation period increases with latitude and has been found to be $<E10 sup h^38 sup m>$ near Saturn's poles. These periods have been determined from observation of occasional spots on Saturn's disk, one having appeared in 1876, another in 1903, the most recent in 1970. Large spots are very infrequent on Saturn as compared to Jupiter. As a check on these determinations of Saturn's period, the spectroscope has been used to find the speed of the planet's spinning, and the period therefrom agrees with the others.

The Voyager 1 spacecraft picked up radio bursts from the polar regions of Saturn, signals too weak to be detected on earth, and thereby determined that the period of rotation of the magnetosphere (and hence of the planet) is $<E10 sup h^39.4 sup m>$, certain to within 10 seconds. The apparently more rapid equatorial rotation is a result of 1100-mile-an-hour winds in the upper cloud layer.

The rapid rotation naturally produces a considerable equatorial bulge; in fact, the equatorial and polar diameters differ by 8240 miles, one part in 9.5; among all the planets, this is the greatest proportional difference. This difference between equatorial and polar diameters and the considerable centrifugal force at the equator result in a 16 per cent increase of surface gravity from equator to pole.

Saturn’s clouds are covered by a 50-mile layer of ammonia crystal haze which back-scatters about half the sunlight which falls on it. The haze is thicker than Jupiter’s because of the lower temperature on Saturn, about 300ºF. Because of the haze’s greater thickness, it more effectively obscures the clouds beneath so that Saturn's visible surface is considerably lacking in colorful detail when compared to Jupiter. What can be seen suggests turbulent belts and zones like those of Jupiter. The darker belts are about 10º F warmer than the lighter zones.
The planet’s low temperature is a result of its receiving only one ninetieth as much sunlight per unit area as the earth. Unlike Jupiter, though, Saturn will experience marked seasons, for its equator is inclined by 26° 45’ to its orbital plane. Each Saturnian season is 7.5 earth years long or 6300 Saturnian days.

From the earth, methane ($\text{CH}_4$) is identifiable in Saturn’s atmosphere. The infrared spectrum of Saturn also shows the presence of ethane, ethylene and acetylene, as on Jupiter, formed from methane by the action of sunlight. Most of the atmosphere, however, is hydrogen with about 11 per cent helium by weight.

Saturn radiates about 2.5 times as much energy as it receives from the sun, relatively more than Jupiter. This is taken as evidence that the planet is still shrinking, thereby converting gravitational potential energy to thermal energy. Related to this contraction is the fact that Saturn's helium, while the same overall fraction of the mass of the planet as in Jupiter, has partially separated from the lighter hydrogen and settled into the planet's core. Evidence of this is the lower atmospheric helium abundance — 11 per cent for Saturn as compared to 19 percent for Jupiter.

10. The Satellites of Saturn

The number of Saturn’s satellites is difficult to specify with exactness. By mid-1981 fifteen had been identified, of which twelve had well determined orbits. The first was discovered in 1655, the most recent ones by Pioneer 11 and Voyager 1 flybys in 1979-80. Nine are of long standing and have received names; the rest bear only numerical designations as yet. In order outward from Saturn, those presently known are S-15, S-14, S-13, Janus (also referred to as S-10), S-11, Mimas, Enceladus, Tethys, Dione, S-12, Rhea, Titan, Hyperion, Japetus and Phoebe. Variations in their brightnesses indicate bound rotations, each keeping one hemisphere always toward Saturn.

Largest and first to be discovered is Titan. It was also the first of any satellites in the solar system to be found to possess an atmosphere. The only constituent detectable by ground-based telescopes and spectrosopes is methane, which, as space probes have shown, probably represents only 1 per cent of its atmosphere. Nearly all the rest is nitrogen, with traces of ethane, ethylene, acetylene and hydrogen cyanide.

A cloud layer has thus far prevented any inspection of Titan’s surface features, though Voyager 1 flew past the satellite at a mere 1500 miles’ distance. The clouds may be of liquid nitrogen 30 miles above Titan’s surface, an altitude where the temperature is about 335º F. At ground level, Titan’s atmospheric pressure is thought to be at least 1.5 times sea level air pressure and its atmospheric density five times the density of air.

The diameter of Titan is 3200 miles, larger than Mercury and Callisto but smaller than Ganymede. Its density is 1.92 times that of water, indicating that it is probably a mixture of rock and ice in roughly equal proportions. The low temperature and comparatively large velocity of escape on Titan has permitted it to retain water ($\text{H}_2\text{O}$), ammonia ($\text{NH}_3$) and methane ($\text{CH}_4$). The water has frozen out. The sun’s radiation has broken the ammonia molecules into nitrogen and hydrogen, allowing the latter to escape. The effect of sunlight on the methane has been to produce various hydrocarbons, which precipitate onto the surface.

Hydrogen escaping from Titan has formed a light, thin, cool torus of gas about Saturn from Rhea to Titan and 180,000 miles beyond. It is maintained by the loss from Titan of a mere two pounds of hydrogen per second.
Japetus is remarkable for the difference between it forward and trailing hemispheres. The former reflects about half the sunlight incident upon it (probably because it is ice-covered) and the latter, as dark as powdered black coal, reflects only 3 per cent.

Mimas has a crater 60 miles across with a central peak 5 miles high. The crater is thus about a quarter of the diameter of the satellite. Had it been much larger, Mimas might well have been shattered by the impact. Phoebe, the most distant satellite of Saturn, (8 million miles), has a period of 546 days. It was the first satellite in the solar system to be known to revolve retrograde. Unlike Jupiter's retrograde satellites, however, Phoebe's motion about its primary is stable; it could not be pilfered from Saturn by the sun even in a direct orbit.

Satellite S-12 is known also as Dione B because it revolves about Saturn in the same orbit as Dione, oscillating slowly about the Lagrangian point sub 4. It is much smaller than Dione and was discovered only in 1980 by earth-based instruments. It is the first known instance of a planetary satellite which illustrates Lagrange's equilateral triangle solution of the three-body problem.

Satellites Janus (S-10) and S-11 revolve in the same orbit but on opposite sides. They appear to be resonantly coupled with Enceladus, which has twice their period of revolution. The identity of their orbits is thus caused by their common interaction with Enceladus, not by any mutual cooperation.

Saturn's satellite system is distinguished by its dynamical complexity. Quite as remarkable is the interaction of the satellite system with Saturn's rings.

11. The Rings of Saturn

Saturn owes both its beauty and its greatest distinction to its system of rings. They were first seen by Galileo in 1610, but their true nature was not suggested until 45 years later by the Dutch lensmaker Huyghens. They have an overall diameter of 171,000 miles and their innermost edges skirt Saturn's cloudtops. Their thickness is too small to be measured at such great distance, but has been found by the space probes to be only a mile or less. Supposing their thickness and diameter to be in the ratio 1 to 100,000, they are much thinner, relatively, than a 100-inch circle of the thinnest tissue paper; Saturn's and Jupiter's rings are the flattest and relatively thinnest natural structures known in the universe.

The rings appear to be precisely in the plane of Saturn's equator and therefore are inclined by about 28° to the plane of the ecliptic. Since Saturn's equator and its rings maintain a fixed orientation in space, we see first one hemisphere of the planet and one side of the rings, then the other as Saturn moves from one side of the earth to the other. The rings will therefore seem to close and open as viewed first from an angle of 28° above, then on edge, then from 28° below. Since Saturn's period of revolution is about 29.5 years, the rings will pass through one complete cycle of closing, opening to the other side, closing, and re-opening to the original orientation in this length of time. It is one indication of their extreme thinness that at the times they are viewed edgewise, they cannot be seen at all; it is at such times that the discoveries of faint satellites can be and have been made. Although the rings appear edgewise about every 15 years, it takes the better part of a year for the plane of the rings to cross the earth's orbit from one side to the other. The earth may therefore cross their plane once to three times within a year. In 1950, the earth crossed the plane of the rings once. In 1965-66 and again in 1979-80 it crossed three times. When widest open, the rings reflect 1.7 times as much light as the ball of the planet.
Seen in a small telescope, the rings appear to be in two concentric parts, named the A and B rings. A very faint C ring interior to the bright B ring was detected in 1850. A still fainter D ring was discovered in 1970 between the C ring and the ball of the planet. A faint narrow F ring outside the A ring was discovered in 1979 by Pioneer 11.

The progressively revealed complexity of Saturn's ring system was climaxed in a dramatic way by the remarkable photographs returned from Voyager 1 in 1980. With the aid of the new information therefrom, the presently known structure of Saturn's ring system stands thusly: the D ring from the cloudbottom out to 5300 miles; a 2500-mile gap known as the Guerin Division; The C ring from 8,000 to 18,000 miles; the 2600-mile French Division, predicted jointly by several French astronomers; the B ring from 20,000 to 35,000 miles; the 3,000-mile Cassini Division; the A ring from 38,000 to 48,000 miles, including the narrow Eneke gap; the 2200-mile Pioneer Division discovered by Pioneer 11; the narrow 300-mile F ring; a newly-discovered E ring of undetermined extent; and finally a G ring from 350,000 to 520,000 miles.

Superimposed upon this large-scale structure is an astonishing and unlooked-for fine structure unsuspected prior to the space probes. The large A and B rings, for example, are formed of hundreds of narrow sub-rings 5, 10, 30 miles wide. Their number and fineness give the appearance of grooves on a phonograph record.

When the ring system appeared to consist simply of A and B rings separated by the Cassini Division, an understanding of them seemed comparatively straightforward. The Cassini Division was taken to be a region cleared of ring particles by orbital resonance with the satellite Mimas. A particle in the Cassini Division would revolve twice during each revolution of Mimas. Mimas' perturbative effects upon the particle would therefore be repeated over and over in identical fashion. The accumulated perturbations would thus modify the particle's orbit as to clear the particle from the Cassini Division.

In light of the newly discovered complexity of the ring, such an accounting is woefully inadequate. Indeed, the Cassini Division itself has at least 20 narrow sub-rings within it. A possible clue to an understanding of such a complex ring structure may be provided by the F ring. This narrow ring is confined within the adjacent orbits of the small satellites S-13 and S-14. The outer satellite revolves just a little more slowly than any ring particle and therefore on average exerts a drag which will prevent a particle's outward escape. The inner satellite, conversely, will prevent a ring particle's inward escape. These two little satellites therefore "herd" particles of the F ring into their narrow confines. Conceivably, hundreds of other faint small moons, lost to sight in the intricacies of the ring, may account for the myriad narrow sub-rings. This is at least a plausible conjecture.

The Pioneer and Voyager space probes provided not only a closer look at Saturn and its rings but also views from an entirely different perspective. The rings were seen both from front and back and at all angles in between. Such perspectives are extremely revealing. The B ring, for example, appears bright from the sunlit side, dark from the back. This shows that the particles of the B ring are large compared with a wavelength of light. Reflected radio waves gave indication of the presence of some chunks as big as a house. On the other hand, the ring particles passed into Saturn's shadow, their infrared radiation showed that they cool at a rate characteristic of particles of the order of an inch in diameter. Clearly, the particles are of a variety of sizes.

In contrast to the B ring, the Cassini Division appears dark from the sunward side but bright from the back. This implies the presence of particles comparable in size to the wavelength of light; such particles reflect poorly but scatter light forward well. Bordering the A and B rings are dark bands which appear dark from both front and back and therefore must be empty.
From the particles' sizes and reflecting powers their total mass is estimated to be a ten millionth the mass of Saturn. It is equivalent to a ball of ice about 300 miles in diameter. The particles derive their yellowish color from damage to the crystal structure of the ices of which they are made. The damage is inflicted by long exposure to the bombardment of energetic ions of Saturn's magnetosphere.

Saturn's magnetic field is about 1/20th as strong as Jupiter's. It is distinguished from every other planetary magnetic field by being symmetric about Saturn's axis of rotation, not tilted like Jupiter's or the earth's. The magnetic field creates radiation belts, mostly of protons and electrons supplied by the evaporation from the ices of the satellite surfaces and the atmosphere of Titan. Though the radiation in the belts is not nearly as strong as in Jupiter's belts, it would nevertheless be lethal to an unshielded astronaut.

12. Uranus and Its Satellites

Distant Uranus has the distinction of being the only planet discovered by accident, in 1781. The discoverer was William Herschel, whose acuteness is attested to by the fact that it was later realized that recorded observations had been made a score of times in the preceding century, but the planet had always been mistaken for a star. Herschel himself thought it to be a new comet, but its more nearly circular motion soon marked it as a planet. A considerable number of names for the new planet were proposed, but general acceptance was finally granted to the name “Uranus”; Herschel's own choice was Georgium Sidus (“Georgian star”), in honor of his king and patron, George III of England. The Uranus of mythology was god of the skies and the planet’s symbol is therefore an arrow directed from earth to sky. Under the best of conditions Uranus is just barely visible to the unaided eye; it is no surprise that it escaped notice for so long, however, for there are at least 5,000 stars which are as bright or brighter. The cause of Uranus’ being so much fainter than any of the other planets so far is, of course, its much greater distance; it is over 19 times as far from the sun as the earth, a vast 1,782,000,000 miles. From Uranus, the earth would always appear within 3º of the sun, sunlight would be only 1/368 as intense as on earth, the temperature would be a bitter -350º F, and the year would be a little over 84 times as long as the earth’s.

Uranus is 31,565 miles in diameter, and therefore has 64 times the volume of the earth, and is 14.4 times as massive. Consequently, its mean density is 1.26, a value rather like that of the other giant planets, but its surface gravity is, surprisingly, about 10 per cent less than the earth’s.

The planet is bluish or greenish in color and shows only occasional very faint markings of the nature of belts like those of Jupiter and Saturn. The color derives from the atmospheric methane which heavily absorbs the yellow and red from the reflected sunlight.

The absence of distinct markings makes it impossible to determine Uranus’ period of rotation from observations of surface detail, as has been done so successfully for Mars, Jupiter, and even Saturn. It has been necessary to resort to the more difficult and less accurate spectroscopic method, which has fixed the planet’s period of rotation as 16h 19m. The rapid rotation produces a considerable bulge of 2,000 to 3,000 miles.

One of the most remarkable things about the planet is the fact that it rotates from east to west whereas all the other planets but Venus go from west to east; What is more, the plane of its equator is inclined 82º to its orbit, nearly a right angle. To visualize what would be the state of terrestrial affairs corresponding to those on Uranus, imagine this
experiment: Let the plane of the earth’s equator, now inclined 23.5° to its orbit, be tilted still more to 90° and then 8° in addition. At 90° inclination the earth’s axis would lie exactly in the plane of its orbit. The additional 8° would cause the original north pole to be directed “below” the ecliptic, the original south pole to be directed “above” it. If the terms north and south were now interchanged so as to conform with their original sense (north in the hemisphere “above” the orbital plane), one would find the United States in the new southern hemisphere, Florida on the west coast, California on the east coast, and everything reversed. At the times of the equinoxes, the sun would still be on the celestial equator and day would equal night. But at winter solstice, the sun would execute a circle 8° from the “south” celestial pole, and at summer solstice the land of the midnight sun would extend to Panama and central Africa.

The extreme contrast between summer and winter seasons on Uranus may explain an observed 30 per cent increase in radio emissions from Uranus in the decade of the 1970s. As Uranus’ north pole approaches its midsummer position, the transparency of the Uranian atmosphere may increase, allowing the escape of radio emission from lower, warmer layers. Unlike Jupiter and Saturn, Uranus has no internal heat.

Uranus’ five satellites — Miranda, Ariel, Umbriel, Titania and Oberon — are interesting because they revolve very nearly in the plane of the planet’s equator and in the direction it rotates, i.e., retrograde and nearly at right angles to the plane of Uranus’ orbit. They are 400 to 1000 miles in diameter but very faint because of the great distance of Uranus from the sun. They are from 66,000 to 364,000 miles from the planet. Because of the unique orientation of the orbits, the orbits are seen sometimes fully open, as in 1945 and 1987, sometimes edgewise, as in 1924 and 1965.

Uranus, like Jupiter and Saturn, has in addition to its five orthodox satellites a system of rings. Unlike Saturn’s rings, Uranus’ rings are very faint and very narrow with sharply defined edges. In fact, the rings were so faint that they were first detected only by an ultrasensitive photometer which recorded the dimming of a star as the rings passed over it. The first photograph was taken in 1979 by the 200-inch telescope at Mt. Palomar, using a highly sophisticated infrared technique.

The rings are nine in number, somewhat unimaginatively designated by Greek letters. Alpha is approximately 11,000 miles above the Uranian cloud tops and Epsilon is about 16,000 miles. Alpha is perhaps 5 miles wide and Epsilon, the widest, is of the order of 50 miles. They are elliptical in shape and variable in width. The narrow rings subtend no more than 0.001 seconds of arc as seen from the earth. They appear to be stony in composition.

It is a matter of historical curiosity that Sir William Herschel, Uranus’ discoverer, reported in 1787 that he had observed rings about the planet. He later conceded that these observations could not be sustained; the rings discovered in 1977 could not possibly have been seen by the most acute observer using the telescopes available in Herschel’s day.

13. Neptune and Its Satellites

It might fairly be said that Neptune was discovered on paper and not once but twice. Its existence was predicted independently by a Frenchman and an Englishman. The young Frenchman was Leverrier, the young Englishman was Adams. Working unbeknown to each other, both were attempting to explain by the presence of a new planet certain unaccountable deviations in the observed motion of Uranus. The predictions made for this latter planet simply did not hold, and Leverrier was able to show that its observed motion just could not be reconciled with any possible orbit
calculated so as to include only the effects of the then known planets. Later in the same year (1846), he completed an extremely difficult calculation to determine the position of the disturbing body. He communicated his result to the astronomer Galle in Berlin. Galle, after only half an hour’s search on the night of the same day on which he received Leverrier’s prediction, found the new planet within 52 minutes of arc of the predicted position.* The accumulated discrepancy in Uranus’ motion for 60 years, an amount barely perceptible to the unaided eye, had led to the discovery of a new planet. This remarkable feat is a monument to the exactitude and power of the scientific method in general and of mathematical astronomy in particular.

The less fortunate Adams had made a similar prediction to Leverrier's, actually some weeks before, but the astronomer to whom he sent his results failed, for one reason or another, to capitalize on his unparalleled opportunity.

In conformity with immemorial precedent, the new planet was named after one of the Greek gods. It was given Neptune's trident as a symbol.

If Neptune were five times brighter, it would be just at the limit of naked-eye visibility. Its faintness bear witness to its great distance from the sun — 30 times the earth's, some 2,793,000,000 miles. Light, whose velocity is 186,000 miles per second, spends four hours on its way to Neptune from the sun. In view of the distance Neptune must travel to go once around its orbit, its speed of 3.3 miles per second is a laggardly pace, and the trip requires 164.79 years. Since Neptune's discovery, it has gone through less than one revolution, which will have been completed only by the year 2011.

Neptune is rather like Uranus, often called “Uranus’ twin”. Its diameter is 30,198 miles (as compared to 31,565), its mass 17.0 times the earth's (as against Uranus’ 14.4), and hence its mean density is 1.7 (instead of 1.26). Its surface gravity is 1.17 times the earth’s (slightly more than Uranus’ 0.91 times). Moreover, it too shows a small greenish disk (about 2 seconds of arc in diameter) in a telescope. The color is due to methane, as on Uranus, which seems to be the only detectable gas left in any abundance at about -370º F. A spectroscopic determination of its period of rotation gives about 23 hours.

A Neptunian, if there were such, would get a poor view of the solar system. The sun would appear smaller than Venus does from the earth when nearest; it would appear only 1/900th as bright as from the earth but still some 520 times as bright as our full moon. Mercury, Mars and even Uranus, would require telescopic aid to be seen. Jupiter and Saturn would have maximum elongations of only 10º and 17º, respectively, and would appear as inconspicuous “stars”. The earth and Venus would never be farther than 2º and 1.5º, respectively, from the sun and could be seen faintly only during an eclipse of the sun by one of Neptune’s two satellites.

Neptune's larger satellite is called Triton. Its distance from Neptune (220,000 miles) is almost the same as the moon's distance from the earth, but because Neptune is 17 times as massive as the earth, Triton's period is slightly less than 6 days. Its size, estimated from its brightness, would make it larger than the moon, perhaps 3,000 miles in diameter. Its mass is 1.8 times the moon's. Most interesting item concerning this satellite is the fact that though it is not at great distance from the planet, its near-circular motion is retrograde, while Neptune's rotation is direct. The satellite has a tenuous atmosphere in which methane has been detected.

*In 1612, Galileo recorded the position of Neptune in sketches which he made of Jupiter and its satellites. The two planets were in the same field of view. Galileo even noted the relative motion of the faint planet but failed to grasp the fact that he had observed a new and distant planet.
Neptune's second satellite is called Nereid, a mythological sea nymph attendant on Neptune. It is too faint to be observed visually with any existing telescope and was found by photography. Its orbital eccentricity of 0.76 is the greatest of any known satellite. Because the eccentricity is so great, Nereid's distance from Neptune varies from 867,000 miles to more than 6,000,000 miles. Its motion is direct in a period of about a year.

Because Triton's motion is retrograde even though Triton is not distant from Neptune and because Nereid's orbit is so eccentric, it has been suggested that both satellites have been captured or re-captured by Neptune.

Shortly after the discovery of Neptune, announcement was made that it had been found to possess a system of rings. The discoverer was a reputable amateur astronomer who had found two of the satellites of Uranus and Neptune's Triton. His “discovery” of Neptune's rings was vouched for by a leading astronomer of the day. Further confirmation has been wholly lacking, however, and the episode is just another historical curiosity of astronomical exploration.

14. Pluto and Its Satellites

Skulking about the outskirts of the known solar system is Pluto. The circumstances of its discovery are reminiscent of the discovery of Neptune. Unaccounted-for perturbations of both Uranus and Neptune suggested the existence of a still more distant planet. Independently, two American astronomers, Lowell and Pickering, attempted the extremely difficult task of predicting its position. Like Adams, Pickering was denied success (in 1919), this time because of a flaw in a photographic plate and the nearness of Pluto to a bright star whose image hid it. Unlike Leverrier, Lowell never lived to see his prediction verified, for he died in 1916. But at the Lowell Observatory, which he founded and endowed, a search for a trans-Neptunian planet X was undertaken. The effort was rewarded in 1930 when on January 21 the faint new planet was discovered on a photographic search plate by Clyde Tombaugh, a young observing assistant. Its motion was observed carefully for several weeks following to make certain of its planetary nature.

An announcement of the discovery was made on March 13, Lowell’s birthday and the anniversary of Herschel’s discovery of Uranus. The name Pluto was conceded to be most appropriate for the new planet, for Pluto, the god of the lower world, reigned over the regions of outer darkness. Then too, the obvious symbol $\mathbf{P \ L}$, formed of the initials P and L would commemorate Percival Lowell, moving spirit of the posthumously successful search.

One decided difference between the discoveries of Neptune and Pluto is the comparative lack in the latter instance of the directness which characterized the former. This has been the origin of much discussion as to how relevant the predictions may have been to the actual discovery. Pluto has been found to have such a small mass that it could not possibly have produced the perturbations of Uranus and Neptune which had been attributed to it and therefore these perturbations could not possibly have been the direct cause of Pluto's discovery. Finding Pluto near the position predicted for it has been described as “a fantastic coincidence”. The discovery must be credited more to the efficacy of deliberate systematic search than to the power of scientific prediction.

* Although Pluto comes within the orbit of Neptune, the two orbits are so inclined that the two planets can never come closer than 240 million miles to each other.
A determination of Pluto's orbit shows that the planet's mean distance is 39.5 astronomical units or 3,670,000,000 miles, nearly another billion miles beyond Neptune. The orbit has the highest inclination and eccentricity of any of the planets, \( \varepsilon \) and 0.25, respectively. The large eccentricity will cause a large difference between perihelion and aphelion distances, the former being nearly 50 astronomical units, the latter 29.7 astronomical units. In fact, when nearest the sun in September of 1989, Pluto was 35 million miles within the orbit of Neptune; there was no possibility of a collision, however, for because of the considerable inclination of Pluto's orbit, Neptune and Pluto can never come nearer to each other than 240 million miles. Pluto is closer to the sun than Neptune from January 21, 1979, to March 14, 1999.

Pluto is about 4000 times too faint to be seen without a telescope. It gives the appearance of a small yellowish star. Variations in brightness in a period of 6.498 1.7\(^6\) have been taken to indicate that the planet rotates in this length of time. It may in fact do so, but in 1978 Pluto was discovered to have a close satellite with exactly this period; it may well be that the revolution of the satellite caused the light variations, though a bound rotation is entirely credible.

The spectrum of Pluto indicates a coating of methane frost, whose freezing point is -299º F. The planet's average surface temperature is -392º F. The frost should reflect at least 40 per cent of incident sunlight and perhaps as much as 60 per cent. By means of the highly sophisticated method of speckle interferometry, the diameter of Pluto has been found to be almost exactly the same as that of the earth's moon, a little less than 2200 miles.

Pluto's satellite, appropriately named Charon after the boatman who ferried the souls of the departed across the River Styx into Pluto's infernal realm, is at a mean distance of 10,500 miles. The satellite's motion therefore indicates a Plutonian mass about 1/600th the mass of the earth, 1/7th the mass of the moon. Pluto's mean density is less than 0.8 times the density of water, probably less than Saturn's. A large part of it may well be ices of various sorts. Its surface gravity is so low that in spite of the low temperature, it cannot have retained much atmosphere of any kind.

The satellite Charon is at least 750 miles in diameter. This means that Pluto and Charon are the most nearly comparable planet and satellite pair in the solar system.

The facts that Pluto at perihelion comes closer to the sun than Neptune, that Neptune's satellite Triton revolves retrograde even though it is not a remote satellite, and the fact that Neptune's satellite Nereid has the most eccentric orbit of any satellite have inspired speculation that Pluto may once have been a satellite of Neptune. If Pluto had been a satellite of Neptune and had experienced a close encounter with the large satellite Triton, Pluto could have been expelled from Neptune's control while Triton was being cast into a retrograde orbit.

For the present, at least, such a hypothesis would be very difficult to test, for Pluto and Neptune have been found to have commensurable periods; three orbital periods of Neptune equal two periods of Pluto. This makes their present relation one of stable resonance; their motions are thus interlocked in a way which would obscure any previous non-resonant interaction and frustrate attempts to follow their behavior backward in time.
Questions

101. Identify the planets best described by the following characterizations: (a) most massive; (b) least massive; (c) densest; (d) least dense; (e) largest; (f) smallest; (g) hottest; (h) coldest; (i) most rapidly rotating; (j) prominently belted; (k) ringed; (l) perpetually cloud-covered; (m) shows polar caps; (n) has atmospheric free oxygen; (o) most eccentric orbit; (p) orbital motion provides a test of relativity theory; (q) rotates retrograde; (r) heavily cratered; (s) has strong magnetic field; (t) discovered accidentally; (u) existence predicted; (v) found after extended search; (w) shows phases; (x) has the most satellites; (y) has no satellites; (z) brightest.

102. Identify the satellites best described by the following characterizations: (a) helped determine the velocity of light; (b) revolves in a shorter period than the parent planet rotates; (c) revolves retrograde; (d) motion not dominated by its parent planet; (e) ellipsoidal in shape; (f) has an atmosphere; (g) accompanied by a sodium cloud; (h) largest in the solar system; (i) has the most eccentric orbit; (j) revolves within the Roche limit; (k) largest with respect to its primary; (l) has active volcanoes; (m) has the smoothest surface of any body in the solar system; (n) is less dense than water.

103. (a) What are a planet’s orbital elements and what function does each serve? (b) What are the configurations of an inner planet (in chronological order)? (c) What are the configurations of an outer planet? (d) At what configuration is a planet farthest from the earth? (e) At what configuration is an outer planet nearest the earth? (f) At what configuration is an inner planet nearest the earth? (g) How did Ptolemy explain retrograde motion? (h) How did Copernicus explain retrograde motion? (i) What important change of world perspective was implied by the heliocentric theory?

104. (a) Why is Venus so hot? (b) Why is Venus’ atmosphere so different from the earth’s? (c) Why has Mercury no atmosphere? (d) Why is Venusian clouds made of? (e) Contrast the meteorologies of Venus, earth and Jupiter. (f) Why do the giant planets have low densities? (g) Why do the terrestrial planets have high densities?

105. (a) How are the periods of rotation of Jupiter and Saturn determined observationally? (b) Of Mars? (c) Of Venus and Mercury? (d) How are the chemical compositions of their atmospheres determined?

106. (a) Which planet comes nearest the earth? (b) Which planet is best observed from the earth? (c) What surprising features are found on Mars? (d) What are the Jovian belts? (e) Why are there no belts in Jupiter's polar regions? (f) What tests were made for life on Mars? (g) What conclusion do they indicate?

107. (a) Describe the internal constitution of Jupiter. (b) What is Jupiter’s Great Red Spot? (c) How does Jupiter produce radio radiations?

108. (a) Why is Saturn more bulged than Jupiter? (b) How many rings are there in Saturn’s system? (c) Of what are they made? (d) What causes the Cassini Division? (e) What is the probable cause of the fine sub-rings? (f) How do Uranus’ rings differ from Saturn’s? (g) What reason is there to think that Jupiter’s retrograde satellites are captured minor planets? (h) That Neptune’s satellites are captured?

109. (a) How is Pluto’s mass determined? (b) Its diameter? (c) What composition is implied by its density? (d) What does this suggest as to its origin?