

scend to earth far from the point where his leap began, for the earth would move beneath him while he was in the air. Rocks and trees, cows and men must be hurled from a rotating earth as a stone flies from a rotating sling. Since none of these effects is seen, the earth is at rest. Observation and reason have combined to prove it.

Today in the Western world only children argue this way, and only children believe that the earth is at rest. At an early age the authority of teachers, parents, and texts persuades them that the earth is really a planet and in motion; their common sense is reëducated; and the arguments born from everyday experience lose their force. But reëducation is essential – in its absence these arguments are immensely persuasive – and the pedagogic authorities that we and our children accept were not available to the ancients. The Greeks could only rely on observation and reason, and neither produced evidence for the earth's motion. Without the aid of telescopes or of elaborate mathematical arguments that have no apparent relation to astronomy, no effective evidence for a moving planetary earth can be produced. The observations available to the naked eye fit the two-sphere universe very well (remember the universe of the practical navigator and surveyor), and there is no more natural explanation of them. It is not hard to realize why the ancients believed in the two-sphere universe. The problem is to discover why the conception was given up.

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THE PROBLEM OF THE PLANETS

Apparent Planetary Motion

If the sun and stars were the only celestial bodies visible to the naked eye, modern man might still accept the fundamental tenets of the two-sphere universe. Certainly he would have accepted them until the invention of the telescope, more than half a century after Copernicus' death. There are, however, other prominent celestial bodies, particularly the planets, and the astronomer's interest in these bodies is the principal source of the Copernican Revolution. Once again we consider observations before dealing with interpretive explanations. And once again the discussion of interpretations will confront us with a new and fundamental problem about the anatomy of scientific belief.

The term planet is derived from a Greek word meaning "wanderer," and it was employed until after Copernicus' lifetime to distinguish those celestial bodies that moved or "wandered" among the stars from those whose relative positions were fixed. For the Greeks and their successors the sun was one of the seven planets. The others were the moon, Mercury, Venus, Mars, Jupiter, and Saturn. The stars and these seven planets were the only bodies recognized as celestial in antiquity. No additional planets were discovered until 1781, long after the Copernican theory had been accepted. Comets, which were well known in the ancient world, were not considered celestial bodies before the Copernican Revolution (Chapter 6).

All of the planets behave somewhat like the sun, though their motions are uniformly more complex. All have a westward diurnal motion with the stars, and all move gradually eastward among the stars until they return to approximately their original positions. Throughout their

motions the planets stay near the ecliptic, sometimes wandering north of it, sometimes south, but very seldom leaving the band of the zodiac, an imaginary strip in the sky extending for 8° on either side of the ecliptic. At this point the resemblance between planets ends, and the study of planetary irregularities begins.

The moon travels around the ecliptic faster and less steadily than the sun. On the average it completes one journey through the zodiac in $27\frac{1}{2}$ days, but the time required for any single journey may differ from the average by as much as 7 hours. In addition, the appearance of the moon's disk changes markedly as it moves. At new moon its disk is completely invisible or very dim; then a thin bright crescent appears, which gradually waxes until, about a week after new moon, a semi-circular sector is visible. About 2 weeks after new moon the full circular disk appears; then the cycle of phases is reversed, and the moon gradually wanes, reaching new moon again about 1 month after the preceding new moon. The cycle of phases is recurrent, like the moon's journey through the signs of the zodiac, but the two lunar cycles are significantly out of step. New moon recurs after an average interval of $29\frac{1}{2}$ days (individual cycles may differ by as much as $\frac{1}{2}$ day from this average), and, since this is 2 days longer than the period of an average journey around the zodiac, the position of successive new moons must gradually move eastward through the constellations. If new moon occurs at the position of the vernal equinox one month, the moon will still be waning when it returns to the vernal equinox $27\frac{1}{2}$ days later. New moon does not recur for about 2 days more, by which time the moon has moved almost 30° east from the equinox.

Because they are easily visible and conveniently spaced, the moon's phases provided the oldest of all calendar units. Primitive forms of both the week and the month appear in a Babylonian calendar from the third millennium B.C., a calendar in which each month began with the first appearance of the crescent moon and was subdivided at the 7th, 14th, and 21st days by the recurrent "quarters" of the moon's cycle. At the dawn of civilization men must have counted new moons and quarters to measure time intervals, and as civilization progressed they repeatedly attempted to organize these fundamental units into a coherent long-term calendar — one that would permit the compilation of historical records and the preparation of contracts to be honored at a specified future date.

But at this point the simple obvious lunar unit proved intractable. Successive new moons may be separated by intervals of either 29 or 30 days, and only a complex mathematical theory, demanding generations of systematic observation and study, can determine the length of a specified future month. Other difficulties derive from the incommensurable lengths of the average lunar and solar cycles. Most societies (but not all, for pure lunar calendars are still used in parts of the Middle East) must adjust their calendars to the sun-governed annual climatic variation, and for this purpose some systematic method for inserting an occasional thirteenth month into a basic year of 12 lunar months (354 days) must be devised. These seem to have been the first difficult technical problems encountered by ancient astronomy. More than any others, they are responsible for the birth of quantitative planetary observation and theory. The Babylonian astronomers who finally solved these difficulties between the eighth and third centuries B.C., a period during most of which Greek science was still in its infancy, accumulated much of the fundamental data subsequently incorporated into the developed structure of the two-sphere universe.

Unlike the moon and sun, the remaining five planets appear as mere points of light in the heavens. The untrained naked-eye observer can distinguish them from stars with assurance only by a series of observations that discloses their gradual motion around the ecliptic. Usually the planets move eastward through the constellations: this is their so-called "normal motion." On the average, both Mercury and Venus require 1 year for each complete circuit of the zodiac; the length of Mars's cycle averages 687 days; Jupiter's average period is 12 years; and Saturn's is 29 years. But in all cases the time required for any single journey may be quite different from the average period. Even when moving eastward through the stars, a planet does not continue at a uniform rate.

Nor is its motion uniformly eastward. The normal motion of all planets except the sun and moon is occasionally interrupted by brief intervals of westward or "retrograde" motion. Compare Mars retrogressing in the constellation Taurus, shown in Figure 15, with the normal motion of the sun through Taurus, shown in Figure 9 (p. 22). Mars enters the diagram in normal (eastward) motion, but as its motion continues, the planet gradually slows until at last it reverses its direction and begins to move westward, in retrograde. Other planets

behave in much the same way, each one repeating the interlude of retrograde motion after a fixed length of time. Mercury briefly reverses its motion through the stars once every 116 days, and Venus retrogresses every 584 days. Mars, Jupiter, and Saturn show retrograde motion every 780, 399, and 378 days, respectively.

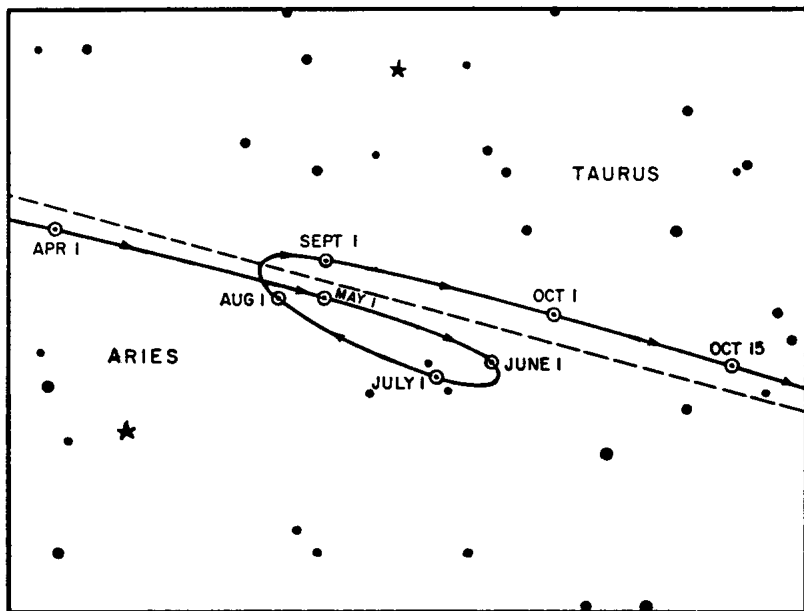


Figure 15. Mars retrogressing in Aries and Taurus. The section of sky is the same as that shown in Figure 9 and in the box on the star map of Figure 8. The broken line is the ecliptic and the solid line the path of the planet. Note that Mars does not stay on the ecliptic and that, though its over-all motion is eastward among the stars, there is a period from the middle of June to early August during which it moves to the west. The retrogressions of Mars are always of approximately this form and duration, but they do not always occur on the same date or in the same part of the sky.

In their gradual eastward motions interrupted by periodic westward retrogressions, the five wandering stars behave quite similarly. But there is an additional characteristic of their motion which divides them into two groups; this is the correlation between their position and the sun's. Mercury and Venus, the two so-called inferior planets, never get very far from the sun. Mercury is always found within 28° of the sun's moving disk, and Venus's maximum "elongation" is 45° . Both planets move in a continuous slow shuttle, back and forth across the

moving sun; for a time they move eastward with the sun, then retrogress across its disk, and finally reverse themselves to overtake the sun once more. When to the east of the sun, either of these inferior planets appears as an "evening star," becoming visible shortly after sunset and then rapidly following the sun below the horizon. After retrogressing westward across the sun's disk, the planet becomes a "morning star," rising shortly before dawn and disappearing in the brilliant light of sunrise. But in between, when close to the sun, neither Mercury nor Venus can be seen at all. Therefore, until their motion was analyzed with respect to the sphere of the stars, neither of the inferior planets was recognized as the same celestial body when it appeared as a morning and as an evening star. For millennia Venus had one name when it rose in the east shortly before dawn and another when, weeks later, it again became visible just over the western horizon shortly after sunset.

Unlike Mercury and Venus, the superior planets, Mars, Jupiter, and Saturn, are not restricted to the same part of the sky as the sun. Sometimes they are very close to or "in conjunction" with it; at other times they are 180° across the sky or "in opposition" to the sun; between these times they assume all the intermediate positions. But though their positions are unrestricted, their behavior does depend upon their relation to the sun. Superior planets retrogress only when they are in opposition. Also, when in retrograde motion across the sky from the sun, superior planets appear brighter than at any other time. This increased brilliance, which has usually been interpreted (at least since the fourth century B.C.) as indicating a decrease in the planet's distance from the earth, is particularly striking in the case of Mars. Normally a relatively inconspicuous planet, Mars in opposition will frequently outshine every celestial body in the night sky except the moon and Venus.

Interest in the five wandering stars is by no means so ancient as a concern with the sun and moon, presumably because the wandering stars had no obvious practical bearing upon the lives of ancient peoples. Yet observations of the appearance and disappearance of Venus were recorded in Mesopotamia as early as 1900 B.C., probably as omens, portents of the future, like the signs to be read in the entrails of sacrificial sheep. These scattered observations presage the much later development of systematic astrology, a means of forecasting whose inti-

mate relation to the development of planetary astronomy is considered in the next chapter. The same concern with omens clearly motivated the more systematic and complete records of eclipses, retrograde motions, and other striking planetary phenomena compiled by Babylonian observers after the middle of the eighth century B.C. Ptolemy, the dean of ancient astronomers, later complained that even these records were fragmentary, but fragmentary or not they provided the first data capable of specifying the full-scale problem of the planets as that problem was to develop in Greece after the fourth century B.C.

The problem of the planets is partially specified by the description of the planetary motions sketched in the preceding pages. How are the complex and variable planetary motions to be reduced to a simple and recurrent order? Why do the planets retrogress, and how account for the irregular rate of even their normal motions? These questions indicate the direction of most astronomical research during the two millennia from the time of Plato to the time of Copernicus. But because it is almost entirely qualitative, the preceding description of the planets does not specify the problem fully. It states a simplified problem and in some respects a misleading one. As we shall shortly see, qualitatively adequate planetary theories are easily invented: the description above can be reduced to order in several ways. The astronomer's problem, on the other hand, is by no means simple. He must explain not merely the existence of an intermittent westward motion superimposed upon an over-all eastward motion through the stars, but also the precise position that each planet occupies among the stars on different days, months, and years over a long period of time. The real problem of the planets, the one that leads at last to the Copernican Revolution, is the quantitative problem described in lengthy tables which specify in degrees and minutes of arc the varying position of every planet.

The Location of the Planets

The two-sphere universe, as developed in the last chapter, provided no explicit information about the positions or motions of the seven planets. Even the sun's location was not discussed. To appear "at" the vernal equinox (or any other point on the stellar sphere) the sun need merely be somewhere on a line stretching from the observer's eye to or through the appropriate point in the background of stars.

Like the other planets, it might be either inside, on, or perhaps even outside the sphere of the stars. But though the two-sphere universe fails to specify the shape or location of the planetary orbits, it does make certain choices of position and orbit more plausible than others, and it therefore at once guides and restricts the astronomer's approach to the problem of the planets. That problem was set by the results of observation, but, from the fourth century B.C., it was pursued in the conceptual climate of two-sphere cosmology. Both observation and theory made essential contributions to it.

Within a two-sphere cosmology, for example, the planetary orbits should if possible preserve and extend the fundamental symmetry embodied in the first two spheres. Ideally the orbits should therefore be earth-centered circles, and the planets should revolve in these circles with the same regularity that is exemplified in the rotation of the stellar sphere. The ideal does not quite conform to observation. As we shall see presently, an earth-centered circular orbit located in the plane of the ecliptic provides a good account of the sun's annual motion, and a similar circle can give an approximate account of the somewhat less regular motion of the moon. But circular orbits do not even hint at an explanation of the gross irregularities, like retrogression, observed in the motions of the other five wandering "stars." Nevertheless, astronomers who believed in the two-sphere universe could, and for centuries did, think that earth-centered circles were the natural orbits for planets. Such orbits at least accounted for the over-all average eastward motions. Observed deviations from the average motion — changes in the rate or direction of a planet's motion — indicated that the planet itself had deviated from its natural circular orbit, to which it would again return. On this analysis the problem of the planets became simply that of explaining the observed deviation from average motion through the stars in terms of a corresponding deviation of each planet from its single circular orbit.

We shall examine some of the ancient explanations of these deviations in the next three sections, but first notice, as the ancients also did, how far it is possible to proceed by neglecting the planetary irregularities and assuming simply that all orbits are at least approximately circular. Almost certainly, in the two-sphere universe, the planets move in the region between the earth and the stars. The stellar sphere itself was often viewed as the outer boundary of the universe, so that the