the solar system

JOHN A. WOOD

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It is not easy to be an expert in such a broad range of topics as this book attempts to address. Certainly it was impossible for the author: to the extent that I have summarized a diversity of subjects successfully, it is because my friends and colleagues in these various areas were kind enough to read sections of the book and try to tell me where I was confused. I am sincerely grateful to them: Edward Anders, Geoffrey Briggs, Alistair Cameron, Clark Chapman, Steven Croft, Fraser Fanale, George Field, Owen Gingerich, Ray Hawke, James Head, William Kaula, William Noyes, Sean Solomon, Jeffrey Warner, Fred Whipple, and Charles Whitney. (These names alone are worth the price of the book.)

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contents

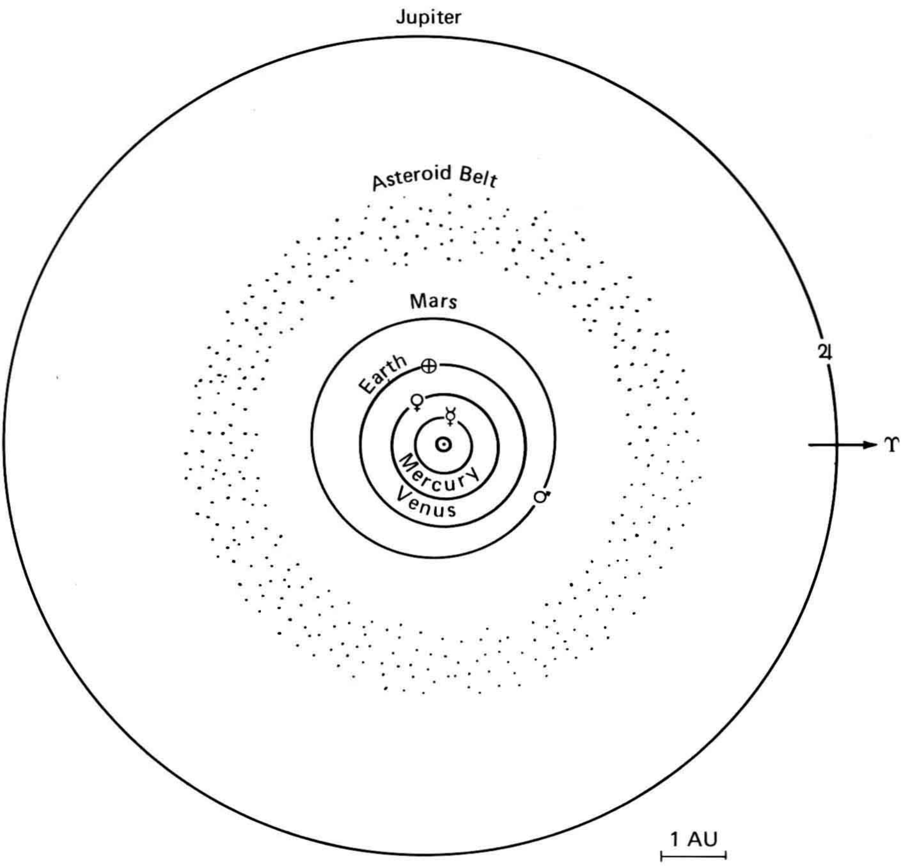
one

introduction to the solar system

A good way to begin this book would be to pretend to stand off at a distance, hands on hips, and survey our solar system. Unfortunately the scale of the system and the objects in it do not permit this. If one stands far enough away to take in the whole solar system, the planets disappear because of their smallness and distance; if one stays close enough to see some of the planets, the form and scale of the system are lost. It is not even practical to draw a single map of the whole solar system to scale, because of the wide range of dimensions of planetary orbits (Fig. 1-1).

From the distance of a neighboring star, using the observational techniques currently available on Earth, nothing could be seen of our solar system except the sun. This would appear as a small, yellowish star of a type that is extremely commonplace in the galaxy. Our planetary system could not be detected. (By the same token, we are not able to confirm which of the other stars in our immediate neighborhood, if any, have planetary systems. It has seemed appropriately humble in recent decades to assume that there is nothing whatsoever extraordinary about our star and its circumstances; therefore, planetary systems are probably rather abundant in the galaxy, and life may have arisen on favorably located planets circling countless other stars. Most recently, however, as discussed in Chapter 7, this has begun to appear doubtful. It seems likely that the solar system *does* have some special properties, and relatively few other stars may have planetary systems.)

The solar system consists of very little else than the sun, in fact. This ball of incandescent gases, mostly hydrogen and helium, comprises 99.87 percent of the mass of the solar system. Most of the remaining 0.13 percent resides in a

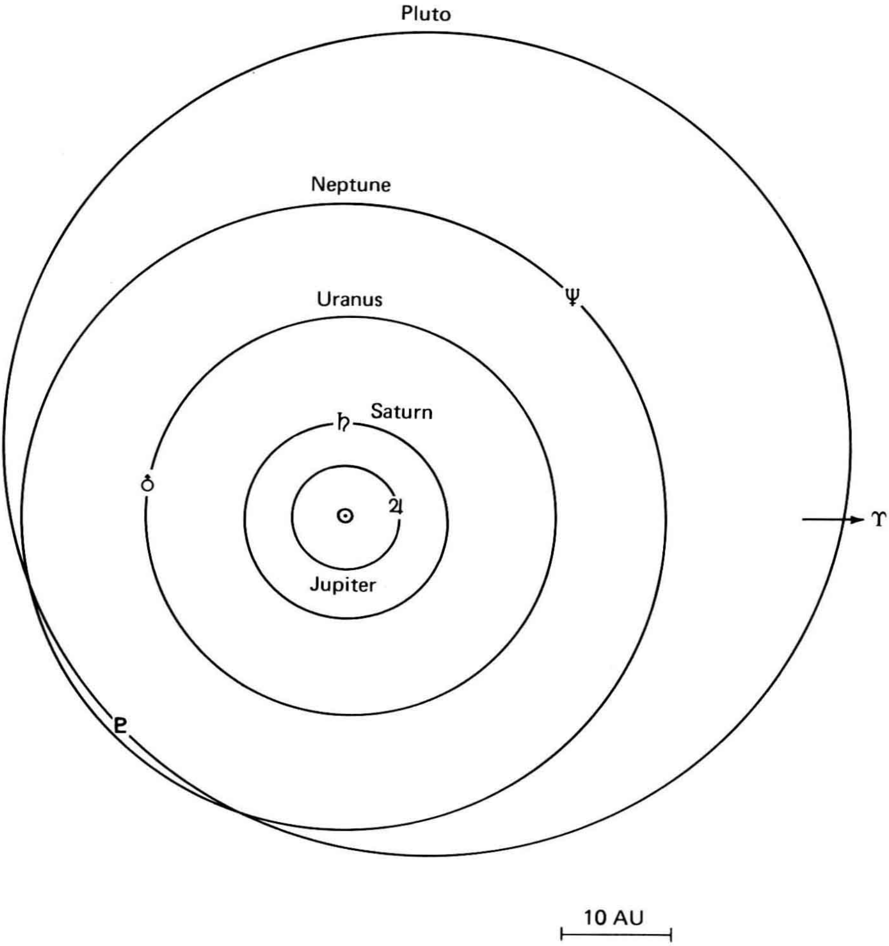


A

FIG. 1-1 Map of the solar system, to two scales. (A) Orbits of Jupiter and the (terrestrial) planets interior to it, and position of the asteroid belt. (B) Orbits of Jupiter and the (Jovian) planets exterior

single object, the planet Jupiter, again a ball of hydrogen and helium, in some ways similar to the sun, but much smaller, cooler, and nonluminous. If one could model the solar system so that the sun was the size of a basketball, Jupiter would be somewhat smaller than a golf ball, and would be located 500 feet away from the basketball. Analogies of this sort have been overworked, but they seem to be the only way of conveying the great range of dimensions in the solar system.

The gravitational coupling between the sun and Jupiter causes the latter to move along a near-circular path or orbit around the sun. Jupiter's motion would appear very slow in the model mentioned above, only about a third of an inch per hour.



B

to it. ♈ is the direction of the vernal equinox, a reference axis in our galaxy. The astronomical symbol for each planet is entered at the perihelion of its orbit.

The other members of the solar system can be summarized briefly, as befits their negligible mass compared with the sun and Jupiter. There are (1) three more *Jovian planets*, similar to Jupiter but smaller, composed largely of hydrogen, helium, and other light elements, that follow orbits outside of Jupiter's; (2) four even smaller *terrestrial planets*, composed chiefly of rock materials, that move inside of Jupiter's orbit; (3) one small planet (Pluto) of unknown character, which orbits at the outer limit of the planetary system; (4) countless tiny asteroids; (5) several dozen satellites of planets; and (6) comets.

The motions of the planets and asteroids about the sun are remarkably regular. Almost all move in nearly circular orbits that lie in planes very nearly coincident with the plane of Jupiter's orbit, and all the visible planets and asteroids have the same direction of motion around the sun. Their rates of orbital revolution are unequal; the closer a planet is to the sun, the shorter its orbital period. Mercury circles the sun 1,180 times for every one time that Pluto does.

The several satellite systems are also highly organized, for the most part forming miniature "solar systems" in which one of the Jovian planets substitutes for the sun and its satellites for the planets. The comets are another matter: billions of these tiny balls of ice are distributed through a vast volume of space, thousands of times greater in dimension than our planetary system; they surround the sun and planets on all sides like a cloud of gnats. For the most part they maintain their distance, but from time to time a comet drops from its remote position toward the sun, swoops around it, and recedes again to unfathomable distances.

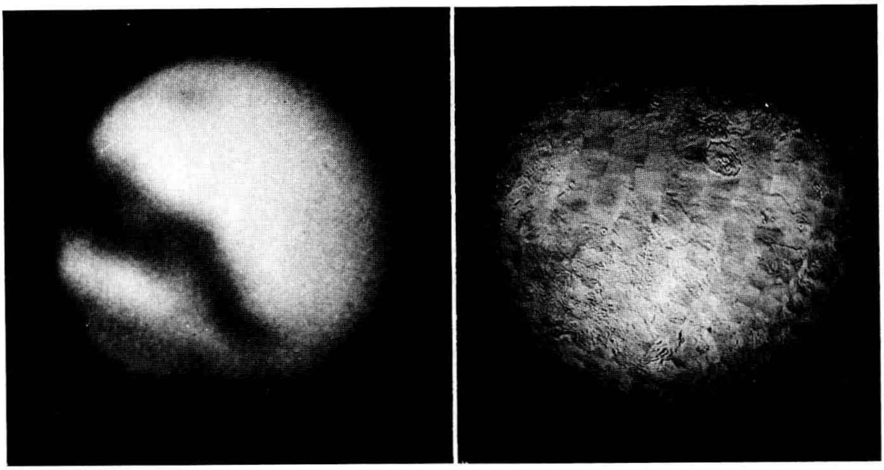
THE TERRESTRIAL PLANETS

As Earth scientists, our principal interest is in the terrestrial planets, those four innermost companions of the sun that are composed of the same types of minerals and governed by most of the same laws of petrology, geochemistry, and geophysics as Earth. Because the same can be said of Earth's moon, it is convenient to include this fifth object with the terrestrial planets, even though technically it is a satellite, not a planet.

Our knowledge of the terrestrial planets has grown dramatically since the early 1960's, largely as a result of the programs of scientific exploration carried out by the U.S. National Aeronautics and Space Administration. It is difficult to exaggerate the scope of the new knowledge gained, or to fully appreciate its long-term significance. Its immediate effect has been to transform the planets from astronomical objects—fuzzy images dancing in the ocular of a telescope (Fig. 1-2)—to geologic provinces, where, if it is still not possible for us to walk at will and sample outcrops, we can send sophisticated machines that analyze the soil, listen for seismic activity, and map the details of the landscape (Fig. 1-3). The opportunity to exploit these new techniques and integrate the terrestrial planets into the science of geology will fall to the generation of Earth scientists currently being educated.

The terrestrial planets fall into three classes, as a result of differences in their sizes (Fig. 1-4).

1. The smallest planets, Mercury and the moon, are airless bodies, having lost any atmospheres they may once have possessed. Gravitational attraction acts to hold an atmosphere around a planet, but other processes tend to strip it away, such as thermal escape of the gas molecules and the erosive effects of the solar wind (Chapter 4). Gravity lost this competition in the case of Mercury and the moon because of the small size and feeble gravitational acceleration of these bodies.



A

B

FIG. 1-2 Mars before and after the space age. (A) Photograph of Mars made by one of the best ground-based telescopes. Lick Observatory photograph. (B) Mosaic of photographs made in 1972 by the Mariner 9 mission, which came to within 2,000 km of the planet. NASA photograph.

FIG. 1-3 (Above) Landscape of rock fragments and sand dunes on the surface of Mars, photographed by Viking 1 (1976).

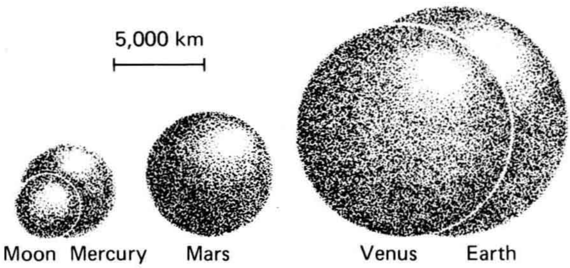


FIG. 1-4 (Left) Sizes of the terrestrial planets compared.

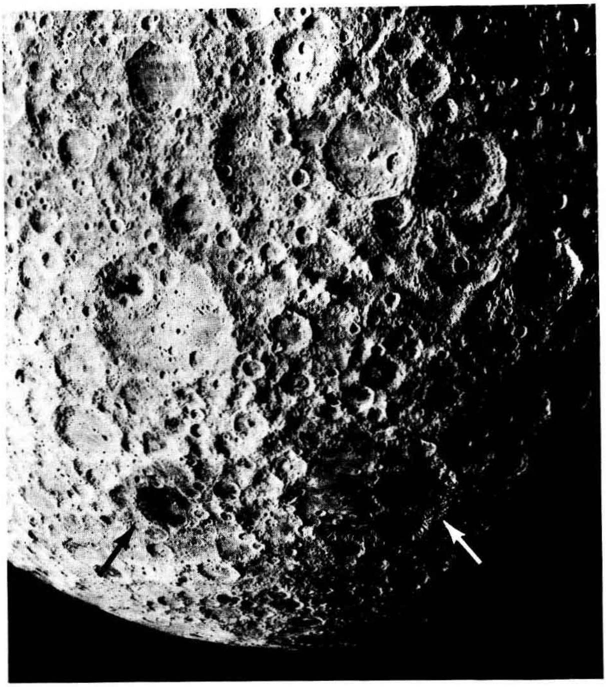


FIG. 1-5 Heavily cratered highland terrain on the farside of the moon, photographed by the Lunar Orbiter II spacecraft in 1966. Relatively young, dark volcanic rock (mare basalt) has flowed into the crater Jules Verne and Mare Ingenii (left and right arrows), but most of the farside surface consists of ancient, light-colored crustal rock. NASA photograph.

Internal geologic activity is related to the interior temperature of a planet, and this too is sensitive to the planet's size. Objects as small as Mercury and the moon tend to cool down rapidly, and internally driven geologic activity has effectively ceased early in their history (this observation is based largely on our knowledge of the moon from studies of samples collected by the Apollo astronauts).

Impact craters caused by the bombardment of meteorites over most of geologic history have come to dominate the surface morphologies of Mercury and the moon (Fig. 1-5), since there are no atmospheres to erode the craters or continuing geologic activity (such as lava eruptions) to bury or otherwise destroy them.

2. The largest planets, Earth and Venus, display the opposite conditions. They have retained substantial atmospheres, and in the case of Earth at least (we know very little about Venus) internal heat continues to drive complex geologic processes. Geologic activity, including atmospheric and hydrospheric erosion, eliminate impact craters in a short time so these features are of minor importance on the surface of Earth.

3. Mars, intermediate in size, is also nicely intermediate in the properties discussed above. It has an atmosphere, but only a very thin one. Geologic activity appears to have continued to very recent times, but never as vigorously as the activity that shapes the earth (specifically, Mars displays no evidence of

plate tectonics or mountain building). Consequently, Mars displays the effects of internal geologic activity and impact cratering in approximately equal abundance (Fig. 3-16).

The plan of this book is not to treat the planets one by one, but to examine various properties and processes that the planets have in common. This *comparative planetology* approach is becoming increasingly common as our knowledge of planets as geologic objects increases. The next chapter will discuss motions of the planets, Chapter 3 considers their surface features, and Chapter 4 the interiors and atmospheres of planets. The remainder of the book is concerned with the fascinating but conjectural questions of the origin and early evolution of the planets.

Chapter 5 briefly discusses the properties of meteorites and lunar samples. Meteorites are specimens of planetary material that have survived from the very beginning, the time when the planets were being put together; lunar samples, which are only slightly younger, witnessed the earliest stages of geologic evolution of a small planet. These rocks contain information crucial to an understanding of the beginning of geologic history, and we are fortunate enough to be able to bring them into our laboratories and study them in painstaking detail.

It is widely understood that the planets were formed as a by-product of the creation of the sun (a star), so Chapter 6 discusses star formation. It also asks where the particular atoms that comprise our solar system came from, and why the various chemical elements are present in the relative abundances that exist. Finally, Chapter 7 asks what there was about the formation of our particular star that might have spawned planets as a by-product. Several currently advocated models of planet formation are discussed.

ABOUT MODELS

> I wonder who was the very first geologist to get it into
> his noddle
> That an educated guess about something would sound better
> if he called it a model?
> When I was a lad, models were of trains and ships,
> But that was before the new generation with geology had
> come to grips.
> Now they give us models of everything from the origin of
> dolomite to why the mid-ocean ridges are faulted,
> And somehow the whole operation seems very serious and
> exalted.
> I believe the word model so bewitches
> Because it's a dignified term for a more or less ragged cluster
> of cerebral itches . . .*

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*From R. L. Bates, "Petulant Questions," *Geotimes*, v. *22*, no. 6 (June 1977), 46.

The word "model" occurs a number of times in this book. It is worth discussing the source and use of the term in planetary sciences, since it sheds light on methods and attitudes that underlie present-day research in the field.

The word "model" first came into extensive use in scientific discussions when large, high-speed electronic computers became a major research tool, about 1960. These made possible a new approach to many problems. Formerly, whenever a complex problem (such as the constitution, thermal history, or seismic motions of a planet) needed to be studied quantitatively, it was necessary to express the problem in mathematical equations (typically partial differential equations), and then solve them. Not all equations can be solved formally: to cast an equation in a form amenable to solution generally requires that the natural system it describes be greatly simplified and approximated. The answers obtained by this method are not always very enlightening.

Computers made possible a different approach. These infinitely patient and hardworking machines are able to solve a complex problem by the numerical method, which amounts to breaking the situation studied into tiny pieces, then adding, moving around, or otherwise manipulating the pieces a huge number of times.

As an example of this procedure, let us consider a study of the temperature history of the interior of a planet. Each box in the grid shown in Fig. 1-6 represents a memory location in a computer. This array of memory locations has been made to represent temperatures in a planet at various depths and times. Each column in the array expresses the temperature profile at a particular time; each row expresses the progression of temperature with time, at a particular depth. In the example shown, the first row in the array represents temperatures at the surface of the planet; the second row represents temperatures at a depth of 100 kilometers (km) in the planet; and each subsequent row represents temperatures at a level 100 km deeper than the last. The lowermost row represents the center of the planet.

The first column represents temperature throughout the planet at the beginning of the time period through which thermal history is to be investigated; this may be the time when the planet was formed. Each subsequent column represents temperatures one million years later than the last.

At the outset the boxes in the array are empty. The study is begun by the investigator filling in the first column with the initial temperature distribution in the planet, probably using a hypothetical temperature profile that he wants to test the ultimate consequences of. He may also supply other boundary conditions: in the example shown, it was specified at the outset that the surface of the planet remains at 243.0°K (which is an average value for the temperature at the surface of the moon) at all times. Thereafter, the computer, following instructions in its program, fills in the remaining boxes. It uses the temperature profile in the first column to calculate temperatures one million years later (the second column); the second column is used to calculate the two-million-year (third) column; and so on through time until the investigator halts the repetitive process.