Solar system

Circular problems

Douglas P. Hamilton

The most striking regularity observed in our Solar System is that the planets all follow nearly circular, nearly co-planar orbits about the Sun. This feature lends strong support to the theory that the planets accreted out of the solar nebula — a flattened disk of gas and dust that surrounded the young Sun (Fig. 1). But do flattened disks of dust and gas inevitably lead to a few massive and widely spaced planets on circular uninclined orbits? Results from numerical simulations discussed at a meeting* in October suggest that, in as far as the inner Solar System is concerned, this may not be so.

The formation of the terrestrial planets — Mercury, Venus, Earth and Mars — can be loosely divided into three stages. Initially, dust grains move slowly through the solar nebula, bumping into one another in low velocity, 'sticking' collisions that gradually build up kilometre-sized 'planetesimals'[1]. Next, gravity from the planetesimals begins to increase the accretion rate; this second stage is characterized by a rapid period of 'runaway growth' in which the largest planetesimals outcompete and ultimately absorb their smaller neighbours[2].

During these first two stages of planetary formation, gas drag from the solar nebula removes energy from the orbits of solid bodies, and damps away their radial and vertical motions as well. Thus solid bodies are thought to follow circular uninclined orbits that gradually evolve inward towards the Sun. The inward migration brings planetesimals together, and their nearly circular orbits lead to low relative velocities and sticking collisions, rather than to high-energy, destructive impacts.

This simple picture is altered by the gravitational perturbations of Jupiter and Saturn, which are traditionally thought to have formed after 10^6–10^7 years (ref. 3), roughly around the time that there were several dozen Mercury-sized 'protoplanets' in the terrestrial region. According to the standard theory, the giant planets formed in a two-step process: first, solid cores of rock and ice accreted, and then the cores captured large quantities of gas from the solar nebula. Alternative theories, however, suggest that the giant planets formed directly from gas instabilities (without preceding core formation) in as little as 100–1,000 years (ref. 4).

New numerical simulations of this second stage of planetary formation have been carried out, working on the assumption that the shorter timescale is correct (S. Kortenkamp and G. Wetherill, Carnegie Inst., Washington, DC). These authors find that, when both gas drag and jovian perturbations are important, different-sized planetesimals follow slightly eccentric orbits which are out of phase with one another[5]. Collisions between these objects are often energetic enough to prevent accretion, thereby hindering the formation of protoplanets.

The magnitude of the effect depends sensitively on the orbits of the giant planets; it is diminished by the fact that Jupiter probably formed further from the Sun than it is now, subsequently migrating inward over 10^7–10^8 years (ref. 6). Nevertheless, if Jupiter formed quickly, this mechanism slows the runaway-growth timescales for the terrestrial planets, and significantly hinders the formation of large planetesimals in the asteroid belt. It also suggests that if large Jupiter-mass planets in other planetary systems formed quickly rather than slowly, then the zone in which Earth-like planets could form might be much reduced.

At the beginning of the third and final stage of terrestrial planet formation, the largest objects have attained sizes of small planets (about 3,000 km in diameter). Several dozen to several hundred of these protoplanets perturb one another gravitationally and merge in giant collisions until ultimately only the four terrestrial planets and the Moon remain. At the meeting, numerical simulations of this stage of planetary formation were reported by two teams — J. Chambers (Armagh Observ.)[7]; C. Agnor (Univ. Colorado), and R. Canup and H. Levison (Southwest Res. Inst., Boulder). These and other groups[8] follow some 50 protoplanets for about 10^8 years. With plausible starting conditions, their models produce inner planetary systems with roughly the correct number, sizes and orbital spacings of planets. All groups, however, find that Earth-sized objects have orbital eccentricities and inclinations that are 5–10 times larger than those of Earth and Venus today. The eccentricities and inclinations are pumped up early in the simulations, primarily by secular interactions between the orbits of the protoplanets[7].

So how did Venus and Earth end up on nearly circular orbits? There are only a few possibilities. First, the simulations may exclude some critical physics which damps orbital eccentricities and inclinations (for example dynamical friction with smaller objects, or larger-than-expected drag from nebular gas); this would cause planets on circular orbits to be formed more readily than the simulations suggest. Second, perhaps the inner planets in our Solar System did form with initially large eccentricities and inclinations, and these have been subsequently damped by some dissipative force (solar tides, for instance, although these are thought to be too weak) over the 4.5 billion years of Solar System history. Finally, perhaps elliptical orbits, rather than circular ones, are indeed the natural product of planetary formation. Using the anthropic principle, Chambers pointed out that if nearly circular orbits are necessary for climatic stability and the development of intelligent life, then Earth's low eccentricity can be understood. This argument is not particularly compelling, however, because it explains neither the low eccentricity of Venus, nor the low inclinations of Venus and Earth.

None of these three possibilities is completely satisfying, and so the circular problem remains. Its solution, which will have important ramifications for understanding our Solar System and extrasolar planetary systems, needs to be pursued. □

Douglas P. Hamilton is in the Department of Astronomy, Univ`ersity of Maryland, College Park, Maryland 20742, USA.
e-mail: hamilton@astro.umd.edu

Figure 1 **The solar nebula, by artist Don Davis. The gaps visible in the gaseous disk are swept clear by the largest protoplanets. One such object, perhaps destined to become Jupiter, is in the foreground.**

1. Weidenschilling, S. J. & Cuzzi, J. N. *Protostars and Planets III* (eds Levy, E. H. & Lunine, J. I.) 1031–1060 (Univ. Arizona Press, Tucson, 1993).
2. Wetherill, G. W. & Stewart, G. R. *Icarus* **106,** 190–209 (1993).
3. Pollack, J. B., Hubickyj, O. & Greenzweig, Y. *Icarus* **124,** 62–85 (1996).
4. Boss, A. P. *Science* **276,** 1836–1839 (1997).
5. Kortenkamp, S. J. & Wetherill, G. W. *Icarus* (submitted).
6. Fernandez, J. A. & Ip, W. H. *Planet. Space Sci.* **44,** 431–439 (1996).
7. Chambers, J. E. & Wetherill, G. W. *Icarus* (submitted).
8. Ito, T. & Tanikawa, K. *Icarus* (submitted).

**Thirtieth Annual Meeting of the Division for Planetary Science (AAS),* Madison, Wisconsin, 11–16 October 1998.