A Rocky Start

Pinning down the time of the solar system's hurly-burly birth

By IVARS PETERSON

When Pierre-Simon de Laplace set out nearly two centuries ago to imagine how the solar system might have formed, he turned to the motions of the planets and their satellites for clues.

Laplace noted that all the planets move in the same direction around the sun, following nearly circular orbits that lie in roughly the same plane. He believed the planets spun in the same direction as their forward motion around the sun. Indeed, as far as he could tell, the sun, the planets, and their satellites all rotated in the same sense.

Such regularities inspired Laplace to suggest that the sun's atmosphere once extended beyond the orbits of all the planets. Its rotation produced a flat, gaseous disk, and subsequent cooling and contraction made the disk spin faster. This whirling, ebbing disk spun off one gas ring after another, and each ring later condensed into a hot, fluid ball. Finally, while the sun's atmosphere retreated to its present limit, these balls cooled and solidified into planets.

"One can thus conjecture that the planets were formed on the successive limits of the atmosphere, through condensation of zones of vapor, and on cooling they had to be released by this atmosphere in the plane of its equator," Laplace wrote in 1796.

The inventory of the solar system's contents has grown considerably since Laplace's era. It now includes two additional planets (Neptune and Pluto), a host of rocky asteroids between Mars and Jupiter, complete or partial rings of particles around the larger planets, and a cloud of comet nuclei at the solar system's outskirts.

Today's blueprint for the solar system's creation must take into account not only the solar system's assorted denizens but also a number of surprising quirks in the characteristics of these bodies. For example, Venus, Uranus, and Pluto actually spin in a direction opposite to their orbital motion. Neptune even has a large moon that orbits in the opposite direction of the planet's own rotation and of the motion of its other satellites.

Moreover, the composition of the planets seems to vary systematically. Small, rocky planets orbit near the sun, while gas giants – with the exception of tiny, icy Pluto – occupy the outer orbits. At the same time, Earth and Pluto have moons large enough to qualify these systems as double planets. Mercury has a surprisingly large core, and Uranus has an unusual tilt, tipped almost on its side.

Developing a coherent, consistent model of the solar system's birth that accounts for all these observations has proved remarkably difficult. In the last few years, the consensus among astronomers and planetary scientists has swung away from the notion that the planets formed directly from condensing gas. Instead, they now emphasize the importance of the accumulation of solid particles into planetesimals and the subsequent rapid aggregation of these objects into planets.

"The formation stage was very brief and turbulent," asserts Douglas N.C. Lin of Lick Observatory at the University of California, Santa Cruz.

What emerges is a portrait of an unsettled era – perhaps no longer than 100 million years – that saw the runaway growth of modest chunks of solid material into hefty bodies. It was a time of innumerable collisions and near misses, of drastic changes in orbit, of planet-size masses recklessly careening around the sun with devastating consequences.

Lin described recent observational evidence and theoretical work favoring this particular view of the onset and duration of planetary formation at the American Association for the Advancement of Science annual meeting, held last month in Boston.

Like Laplace, present-day astronomers generally start their creation scenarios with a gaseous disk surrounding a newborn star. Observations of young stars suggest that such disks form quite commonly in regions of our galaxy where star formation is taking place (SN: 1/16/93, p.36).

These young stars typically emit more infrared radiation than one would expect from their temperature and composition. Astronomers attribute this discrepancy to the presence of orbiting dust and gas that is much cooler than the star itself. In similar stars just a few million years older, most of this circumstellar material has apparently disappeared (SN: 10/29/88, p.280).

"The evolutionary time scale of many of these disks is of the order of a few million years," Lin notes. Thus, observations of young stars surrounded by disks furnish revealing snapshots of the various stages in which the solar system may have formed.

"It is this type of information that suggests that we may indeed be identifying the nursery out of which planets form," Lin says.

Meteorites provide the best evidence of when the first specks of solid material appeared in the gaseous disk, or solar nebula, out of which the solar system emerged. In particular, dark, carbon-bearing meteorites known as carbonaceous chondrites contain clumps of crystalline grains that apparently solidified after the disk material had cooled to temperatures less than 1,500°C.

Over the last few years, researchers have determined the ages of a variety of these mineral grains by measuring the proportions of different radioactive isotopes. The measurements consistently point to a time of formation between 4.56 billion and 4.57 billion years ago.

"They all agree fairly well," says Timothy D. Swindle of the University of Arizona in Tucson. "We think we know when this process [of planet formation] . . . started. What we don't know are the exact time scales [of the various stages]."

Nonetheless, a number of new dating

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This example of a carbonaceous chondrite was discovered in the Australian desert in 1975.

techniques, based on relatively short-lived isotopes, suggest that these grains all formed within a few million years.

Because different types of grains have different freezing points, the chemical composition of the crystals in carbonaceous chondrites also provides an indication of what the temperature may have been in various parts of the solar nebula. Moreover, the hodgepodge of crystals typically found in a carbonaceous chondrite hints at the environment in which they formed.

"This suggests that the original solar nebula may have been very turbulent, and the grains were gathered together from regions that had somewhat different temperatures," Lin says.

Collisions and a natural stickiness helped these tiny grains grow into larger objects, including those eventually captured by Earth as meteorites. Oxides of the heavier elements in the solar nebula agglomerated into rocky bodies, and water froze into chunks of ice. At the same time, the sun's gravity gathered these particles into a thin, rotating "pancake" resembling an immense version of Saturn's rings.

Precisely how this clumping of grains into boulders a kilometer or more across occurred isn't completely settled yet. But several groups of researchers have shown in computer simulations that a slight tendency of particles to stick together after collisions is probably enough to form the loose aggregates of material known as planetesimals.

As the planetesimals collided and grew in size and mass, gravitational interactions began to play an increasingly important role. Even when a close encounter didn't result in a collision, the force of attraction between the two bodies could drastically change their speeds and orbits, boosting the likelihood of collisions.

Lin and his collaborators have investigated how the dynamical properties of planetesimals may have regulated their growth in the primordial solar nebula.

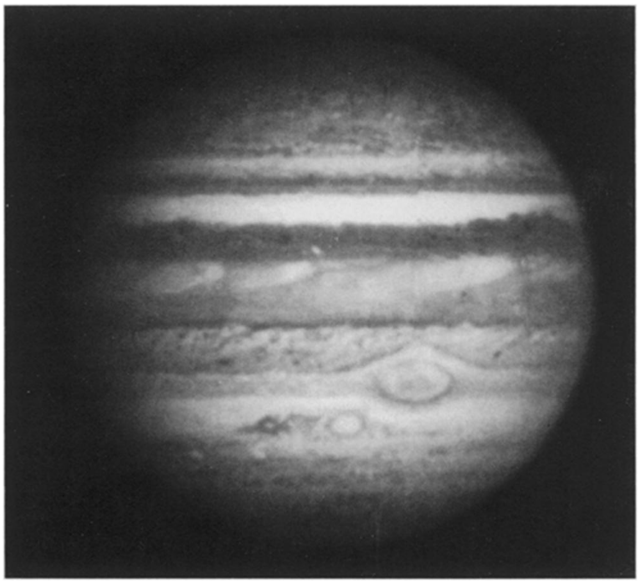
"Our numerical simulations show that, provided there is a sufficient supply of low-mass planetesimals, runaway coagulation can lead to the formation of protoplanetary cores with masses comparable to a significant fraction of an Earth mass," Lin and his co-workers report in the Jan. 20 Astrophysical Journal.

Lin estimates that it would take only about a million years for an Earth-size object to form from planetesimals.

Rings around planets also provide a useful picture of the kinds of gravitational interactions possible in a thin layer crowded with particles of various sizes. "Planetary rings are our best, closest examples of celestial disk systems," says Carolyn C. Porco of the University of Arizona. "Many of the processes going on in planetary rings are very similar — though different in detail — to the processes that likely occurred in the formation of the solar system."

In the turbulent environment of the solar nebula, collisions and close encounters probably occurred not only between small rocks and large planetesimals, but also between large bodies of comparable size. Such interactions would result in chaotic modifications of orbits and extensive mixing of materials.

George W. Wetherill of the Carnegie Institution of Washington (D.C.) has modeled the behavior of about 500 planetesimals, each one roughly the size of the moon, in the region now occupied by the terrestrial planets. His computer simulations show that these objects merge into planets generally resembling those now found in the inner solar system. Moreover, the resulting planets contain a mixture of materials gathered from widely distributed regions of the inner solar system.



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The wide field/planetary camera on the Hubble Space Telescope captured this view of Jupiter on May 28, 1991.

Large-body collisions probably played an important role in establishing the final configuration of the inner solar system. Earth's moon, for example, may have been a by-product of a wayward, Mars-size body crashing into Earth. Mercury may have lost its rocky outer layers in a similar collision. Another encounter may have shifted Mercury to its present orbit close to the sun.

Among planetary scientists, there seems little doubt now that the smaller, solid worlds of the inner solar system built up from microscopic grains. Mainly rock, these planets formed in regions of the solar nebula hot enough to boil away ice. In contrast, the more distant, giant planets may have formed around cores of solid ice.

Some researchers have suggested that icy material in the outer reaches of the solar system built up into protoplanets about 10 times more massive than Earth. These icy giants were then big enough to start gravitationally picking up and retaining hydrogen and helium gas from the solar nebula.

This accumulation of gas eventually stopped when the protoplanet grew so large that its gravitational pull opened up a gap in the nebula similar to the gaps found in Saturn's rings. "Once [it] opens up a gap, the [protoplanet] can no longer accrete gas from the solar nebula," Lin says. "The object is on a kind of self-regulating diet."

The problem with this scenario is that young stars of roughly the sun's mass apparently lose most of the hydrogen and helium in their disks — perhaps blown away by an intense stellar wind — within 10 million or so years. That seems to allow too little time for the accumulation of sufficiently large ice cores, particularly for Uranus and Neptune.

But researchers continue to look for ways around this problem, and the notion of planetary formation by the runaway accumulation of material remains the most viable model.

Refined and modified, Laplace's original notion that the planets condensed out of a gaseous disk long dominated the thinking of astronomers. Now it is largely out of fashion. The present "standard" model of solar system formation, which emphasizes the rapid aggregation of dust and granular material into planets, does a better job of accounting for many features of the present solar system.

Nonetheless, the collision-accumulation scenario leaves a variety of details unexplained, especially in the construction of the gas giants. Whether researchers can resolve all of these problems in the context of runaway planet formation in a turbulent nebula remains an open issue. □