Caged Argon: A Clue to the Birth of Titan

Titan, the largest satellite of Saturn, is the only satellite in the solar system to boast a substantial atmosphere—at the surface it is mostly nitrogen and is 1.5 times denser than Earth's. How did Titan, which is 50 times less massive than Earth, manage to grab so much gas from the preplanetary nebula when it formed? The answer seems to be that water trapped ammonia, methane, nitrogen, and other gases in icy hydrates or in molecular cages known as clathrates. Such entrapment led to methane oceans and perhaps ammonia-water volcanoes on Titan today.

A prime clue to the origin of Titan's thick atmosphere is argon. Although it has never been detected in Titan's atmosphere, researchers have inferred from a variety of Voyager observations that argon makes up 10 to 12 percent of the atmosphere. Ten percent is a large amount of argon, notes Tobias Owen of the State University of New York at Stony Brook. To account for it by conventional means, Owen says, unreasonably low temperatures would be required at the time of Titan's formation to freeze the argon and allow its capture as ice by the protosatellite.

The solution, Owen decided, is to assume that argon and other volatile gases combined with less volatile water to form ice. At theoretically reasonable temperatures, ammonia forms a water hydrate and argon, molecular nitrogen, and methane form water-ice clathrates. In the latter ices, voids formed in networks of loosely bound water molecules are filled by any of a variety of atoms or molecules that happen to fit into the available space. Once accreted onto Titan, the gases could be released by any source of heat, Owen says.

David Stevenson and Jonathan Lunine of Caltech also found that clathrates appear to be the only practical way to capture enough argon. According to their calculations, heat generated by the accretion of Titan would have released methane and other gases from clathrates captured by the satellite, eventually forming a thick, warm (300 to 400 K) methane atmosphere. Although some of the molecular nitrogen could also have arrived in clathrates, a warm early atmosphere would have promoted the addition of nitrogen by photodissociation of ammonia, Stevenson notes.

Once enough cooling occurred, an ocean of liquid ammonia about 100 kilometers deep formed from the atmosphere, according to the calculations. Stevenson and Lunine speculate that, beneath the ocean that remains liquid today, Titan's interior bears some resemblance to the internal structure of Earth—first, a rigid, water-ice layer, resembling a lithosphere; below that a liquid, water-ammonia asthenosphere; finally, a mantle of clathrate and pressure-decomposed clathrate surrounding a core of solid rock. The parallel with Earth might even extend to the presence of volcanism, Stevenson says, with water-ammonia magma oozing to the surface from the asthenosphere.

The Saturn Conference was held 11 to 15 May in Tucson, Arizona, by the Lunar and Planetary Laboratory of the University of Arizona; Tom Gehrels was convenor.

Rings, Rings, What Makes the Rings?

Although most of the newly revealed details of Saturn's rings remain enigmatic, researchers at last month's Saturn meeting in Tucson were pleased with new theories that explain at least a few types of rings.

Theorists tackled the most familiar first. The two small satellites that bound the narrow F ring inside and out must shepherd the ring particles in the same way proposed for the similarly narrow rings of Uranus (*Science*, 5 December 1980, p. 1111). Next came the sets of regularly spaced bands, resembling phonograph record grooves, first detected by Voyager 1's camera. Jeffrey Cuzzi of NASA's Ames Research Center and Jack Lissauer and Frank Shu of the University of California at Berkeley first identified one of these sets of rings as a spiral density wave, a phenomenon studied previously only in the structure of other galaxies.

At Saturn, a satellite orbiting outside the rings generates a spiral density wave by gravitationally perturbing ring particles that orbit in resonance with the satellite. This occurs if the particles' orbit allows them to catch and pass a satellite periodically at the same adjacent points in their orbits. The repeated tug on the particles at the same point sends a wave of more densely packed particles spiraling outward across the ring.

Researchers have found many more density waves in the more detailed observations of Voyager 2. Larry Esposito, Michael O'Callaghan, and Robert West of the University of Colorado searched all 800,000 photopolarimeter observations of a star that passed behind the rings. They found fewer than 30 density waves in all. Similar occultation observations by Voyager's ultraviolet spectrometer detected more effects of resonances, according to Jay Holberg, William Forrester, and Lyle Broadfoot of the University of Southern California's Center for Space Sciences in Tucson. On the basis of less restrictive identification criteria, they found close associations between resonances and additional density waves, and features that appear to result from the interference of density waves. Even so, density waves make a major contribution to ring structure only in the A ring, Holberg notes. In the B and C rings, where there are fewer and weaker resonances, other mechanisms must be at work.

Satellite resonances create other ring features besides density waves, researchers reported. Sharp ring edges, such as the outer edge of the B ring, result from exceptionally strong resonances that can turn back particles attempting to spread outward, according to Nicole Borderies and Peter Goldreich of Caltech and Scott Tremaine of Massachusetts Institute of Technology. Lissauer, Shu, and Cuzzi also found that the slightly inclined orbit of Mimas creates the vertical analog of a density wave, a propagating corrugation or warping of the ring plane called a bending wave. Drawing on previous theoretical work on the warping of galaxies, they identified a set of rings within the A ring as the bright, sunlit peaks of a bending wave set off by the dark, shadow-filled troughs between them.

In spite of these successes, the bulk of the ring structure remains unexplained. A common figure quoted for the total number of ring features is 10,000. It had been hoped that much of the structure might be caused by tiny moonlets embedded in the rings. If they exist, they are too small to detect. Even if a generous total of 50 is allowed for density waves and each has ten "rings," workable theories fail to include 90 percent of the ring structure. Other possible explanations abound, ranging from electromagnetic forces to particle erosion. The front-runner, especially for the B ring, is an innate instability of the ring material. Unfortunately, theorists working on this approach arrived in Tucson only to find that their models produce rings that are far too idealized to fit the Voyager data. They said that they would work on it some more.

Lightning on Saturn or Ring Discharges?

"It's a very mysterious place," remarked one Voyager experimenter. He was referring to the vicinity of Saturn as viewed by Voyager outside the visible electromagnetic spectrum. One of the strangest discoveries there was Saturn electrostatic discharge, SED for short. At the Tucson meeting, researchers debated whether SED is garbled static from a hypothesized Saturnian lightning storm, or blasts of static from a mysterious source orbiting within a unique gap in the B ring.

David Evans, Joseph Romig, and James Warwick of Radiophysics, Inc., of Boulder reported that SED appeared as 30- to 250-millisecond bursts over the radio-frequency range of 20 kilohertz to 40 megahertz scanned by Voyager's radio astronomy instrument. The mean power in a 50-millisecond burst was about 1 billion watts, peak power being at least 10 billion watts. (This is the latest of several sets of updated figures.) The power of a terrestrial lightning stroke at radio frequencies typically reaches about 200,000 watts. The number of SED bursts detected by Voyager tended to peak every 10 hours and 10 $\pm$ 5 minutes.

The approximate 10-hour periodicity of SED suggests two possible locations for its source. One is within the equatorial region of Saturn's atmosphere, where the speed of the wind added to the rotation of the planet would carry a lightning storm around the planet every 10 hours. The second is within the B ring at a distance of 1.81 Saturn radii. The Radiophysics group prefers the ring source because radio-frequency signals generated by atmospheric lightning would probably not make it through the ionosphere. Even if they did, the frequency distribution of lightning-generated signals is never as flat as that of SED, they note.

Joseph Burns and Mark Showalter of Cornell University argued that lightning would appear to be a reasonable source if the effects of the rings are taken into account. The ring shadow probably reduces the strength of the ionosphere, they say, perhaps enough to let lightning signals leak through from the equatorial region. The signals might also be distorted by the rings themselves.

The Radiophysics group believes that the effects of the rings are far from sufficient to explain the signals, and they point to an odd coincidence. After searching all of the Voyager photopolarimeter's stellar occultation observations at the group's request, Arthur Lane of Jet Propulsion Laboratory could find only a single apparent gap in the optically thick B ring. It is about 130 meters wide and is located within 6 kilometers of one of the possible orbital positions of a ring source. That intrigued everyone, but it still gives no clue how an orbiting source might work.

What Battered the Satellites of Saturn?

Everywhere scientists have looked in the solar system, from innermost Mercury to the outer satellites of Saturn, there are craters. Ever since researchers decided that these craters are largely impact rather than volcanic craters, they have wondered where the impacting bodies came from. Voyager's observations at Saturn revealed two episodes of bombardment, which suggests to some that comets are behind much of the pummeling of solar system bodies.

Eugene Shoemaker of the U.S. Geological Survey in Flagstaff argued at the Tucson meeting that objects from outside the Saturn system formed the oldest craters on the Saturnian satellites. A mammoth crater is centered or nearly centered on the leading face of both Mimas and Tethys, he notes, which is the most likely impact site for an object falling into the system. The lack of collisional debris on irregularly shaped Hyperion suggests another impact by a massive external body, Shoemaker says, because the most likely source of the high-energy impactor required to disperse the debris would be outside the system.

If external objects did form the older craters, Shoemaker reasons, then the objects probably came from beyond Saturn. Only in the vicinity of Neptune and Uranus did planetesimals linger long enough after the formation of the solar system to create the observed bombardment, he says. Over the first few hundred million years, close encounters with the major planets scattered these icy bodies in all directions. Of those sent well beyond Pluto, a few still occasionally fall toward the sun as comets. Those sent inward cratered the satellites and planets of the rest of the solar system. That was the earliest bombardment of the satellites of Saturn, Shoemaker says. It was so intense that it probably shattered the smaller, inner satellites. Most reassembled themselves, he says, but some fragments produced the second cratering episode, and others appear to have persisted to the present as small companion satellites sharing the orbits of larger satellites.

Robert Strom and his colleagues at the University of Arizona are not convinced that external objects caused either of the two cratering episodes. They find no heavier cratering on the leading satellite faces than on trailing faces. That suggests to them that the impactors came from within the system, perhaps from debris left after planet formation or satellite disruption. They also conclude that comets cannot dominate the older cratering at both Jupiter and Saturn, as suggested by Shoemaker, because the cratering records on those two sets of satellites are different.

Shoemaker responds that the record has been altered. On the Jovian satellites, large craters have been erased by softening of the surface ice. On the inner planets, comets produced smaller craters because the sun vaporized much of their ice before they hit.

The early solar system, as seen in the cratering record, seems to be at least partly in the eye of the beholder.

—*Richard A. Kerr*—