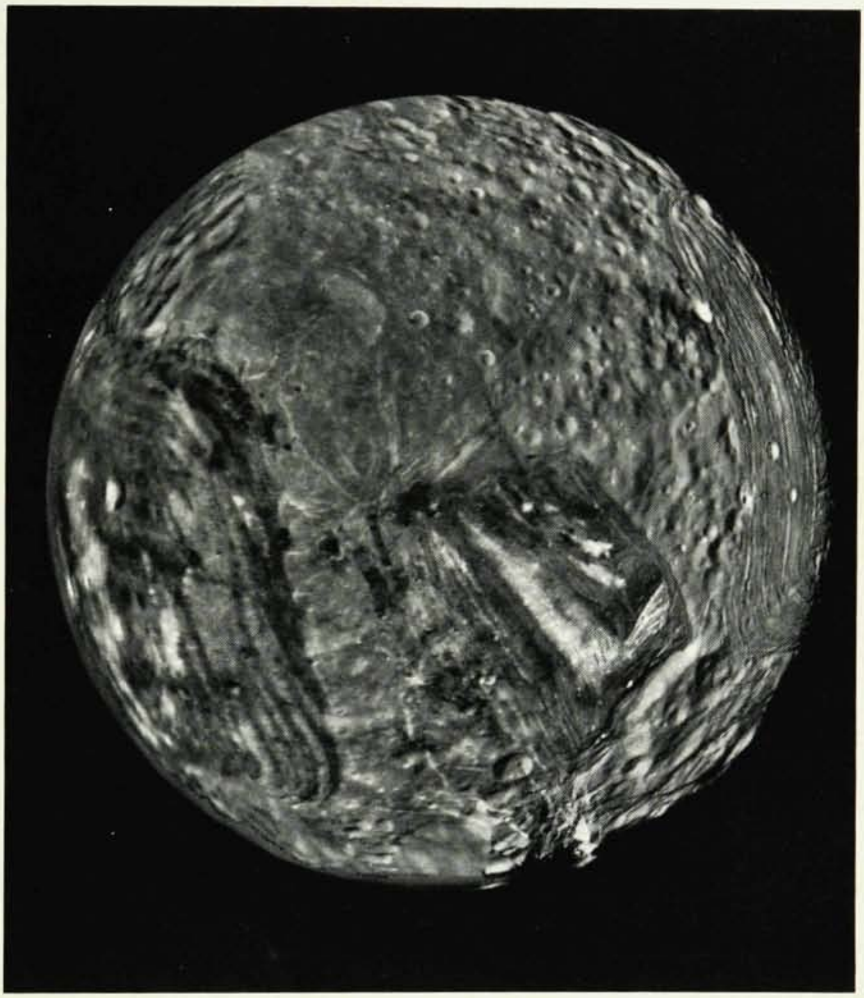
Voyager visits Uranus and observes rings and moons

Last January, having survived the hazards of interplanetary space, previous close encounters with Jupiter and Saturn, four Administrations and numerous budget cycles, Voyager 2 passed within 107 000 kilometers of the planet Uranus. The data collected on its historic flyby took 2 hours and 45 minutes to reach radiotelescopes on Earth, 2.8 billion kilometers away. And while the aptly named Voyager coasts off to an encounter with Neptune and its large moon Triton in August of 1989, the Voyager scientists will be busy analyzing their precious data for clues to the origin and evolution of the Uranian system. In January of 1987 the world's scientific community will be granted full access to the Voyager 2 Uranus data. Until then they will have to be satisfied with the Voyager team's preliminary conclusions, which were published[1] last month.

Before Voyager's visit, what little was known of the distant Uranian system could be quickly summarized. Discovered in 1781 by William Herschel, Uranus orbits about the Sun once every 84 years. Five small moons—Miranda, Ariel, Umbriel, Titania and Oberon—discovered between 1787 and 1948 were known to circle Uranus; their radii were measured and it was known that they had dark surfaces covered with water ice. In 1977 nine narrow, coal-black rings inside Miranda's orbit were detected by stellar-occultation experiments. The rotation axis of Uranus is strangely tipped: Right now the south pole points almost directly at the Sun; in 40 years it will be the north pole's turn. Viewed from the Earth, the rings and moons, which orbit about Uranus's equator, form a celestial bull's-eye through which the Voyager probe neatly passed.



A computer-assembled mosaic consisting of nine images of Miranda, Uranus's innermost and smallest moon (480 kilometers in diameter), shows it to be one of the Solar System's most fascinating objects. Miranda's surface consists of two strikingly different types of terrain: old, rolling terrain of uniform albedo, and young, banded, ridged and scarped terrain, as in the ovoid regions at right and left and in the "chevron" feature below and to the right of center.

The rotational period of Uranus was believed to be anywhere from 16 to 24 hours. The moons were believed to be geologically dead, uninteresting chunks of ice and rock. Indirect, inconclusive evidence for a magnetic field existed. Theories of the Uranian atmosphere, which is peculiar among the known planets' because it is heated from the pole and not the equator, had been developed. But many conjectures about the nature of the Uranian system proved either partially or totally wrong when confronted with the Voyager 2 data.

Here we report primarily on the Voyager 2 findings concerning the rings and moons of Uranus.

Rings. Ring theorists did slightly better than others in their speculations about Uranus. Earth-based occultation experiments provided excellent data on the nine most prominent Uranian rings. The most striking feature

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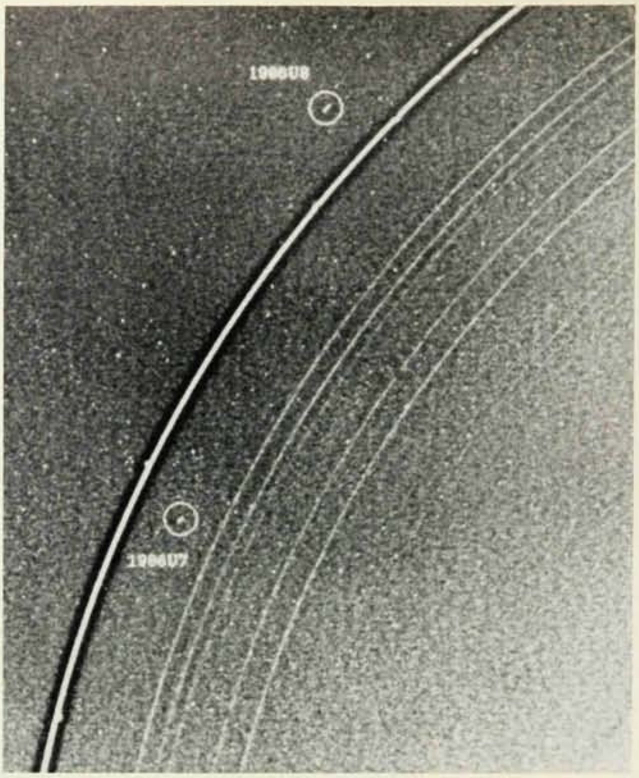
of the rings when viewed from Earth was their extreme narrowness and slight eccentricity. Collisions among the particles of rock and ice that make up the rings should rapidly have caused them to disperse and their orbits to become quite circular. To explain the observed narrowness, in 1978 Peter Goldreich (Caltech) and Scott Tremaine (University of Toronto) hypothesized the existence of unseen "shepherding" moons, perhaps one on each side of each ring. As many as ten shepherding moons were needed to keep the nine observed rings in line. One of the major coups of the Voyager 2 flyby was the discovery of a pair of shepherds that keep the flock of ice and stone in Uranus's outermost and widest ring from wandering.

Detection of the tiny, coal-black shepherds was one of the many technological triumphs of the Voyager mission. One of the major difficulties was that Uranus is twice as far from the Sun as Voyager's last photographic subject, Saturn. Consequently, it receives only one-fourth as much illumination, making long exposures necessary, which lead to motion smearing. Maneuvers were devised to minimize this smearing—even the torque of starting and stopping the on-board tape recorder was taken into account.

Two scans were made to look for the shepherds. The highest resolution was a kilometer-square pixel. Though the orbital period of the rings is 8 hours, clever design allowed 80% of the rings to be imaged. A longer scan performed at a resolution of 35 kilometers per pixel, during which all the ring matter could be scrutinized, uncovered a pair of shepherds surrounding the epsilon ring. This is Uranus's outermost ring, and its widest. In fact its width, which varies from 20 to 100 kilometers, made it the only ring that could be directly resolved by Voyager's cameras—though the other rings were easily detected within ten days of Voyager's closest approach. Subsequent calculations showed that the two shepherds indeed create orbital resonances at approximately the inner and outer boundaries of the epsilon ring, and that these resonances can coax errant ring particles back into their narrow orbits.

Another triumph of the Voyager mission was the measurement of the albedos and colors of the rings. One of the initial ring images, when computer enhanced and colored, seemed to show that the rings were brightly and variously colored. This caused a flurry of excitement: Different ring colors would indicate that the rings have different compositions and origins, a revelation that would be rather difficult to fathom. But a closer look at the data showed that the color differences



A major triumph of Voyager's encounter with Uranus was the detection of a pair of so-called shepherding moons, one on either side of the epsilon ring, that maintains the ring's svelte, eccentric form.

were not statistically significant. One Voyager scientist, looking at the rainbow-colored ring picture, remarked that it was the most expensive piece of abstract art ever created. Further analysis has so far shown that at least the epsilon ring is gray. The ring systems of Saturn and Jupiter are red. This color difference has yet to be explained.

The rings of Uranus reflect back only about 4% of the light incident on them. The most popular theory, so far, to explain this darkness, which is darker than anything found in the Jovian or Saturnian systems, is that the ring particles were made from a mixture of water ice and methane. High-energy particles from the solar wind and the Uranian magnetosphere have caused the methane to dissociate into its components, hydrogen and carbon. In the process much of the hydrogen was lost, and the remaining elements recombined into polymer chains, with a residue of pure carbon.

The epsilon ring is less than 150 meters thick and is devoid of particles smaller than a beach ball. This is surprising, since collisions among ring particles should create debris of all sizes. A possible explanation for this lack of small ring particles is drag from Uranus's extended atmosphere of neutral, atomic hydrogen. Calculations show that this atmosphere causes the orbits of small particles and dust to decay quickly.

Moons. Before the arrival of Voyager 2 the moons of Uranus were already known to be small, so the natural assumption was that they would also be dark, heavily cratered and devoid of any signs of geologic activity. The reasoning was based simply on the observation that the smaller a body is, the more rapidly it cools and the less chance there is of faulting and flow activity. Even as the first pictures were received at the Jet Propulsion Laboratory it immediately became clear that some new theories were needed: Every one of the Uranian moons, with perhaps the exception of Umbriel, had sometime in its past been extraordinarily geologically active.

The star of the show was Miranda, the smallest and innermost of the previously known moons. Voyager images showed some areas of the moon at resolutions of a kilometer or less. Fault canyons possibly as deep as 20 kilometers (Miranda is 484 kilometers in diameter) and features that the excited scientists immediately dubbed "racetracks" and "chevrons" were spotted. As scientific sobriety gained hold, the racetracks became "ovoids," but the puzzle of their formation remains.

One clue to the origin of the surface features of Miranda comes from crater counts, which reveal that the inside of the ovoids is older than the outside. This may indicate that the interior of Miranda at some point rearranged itself. One elaborate scenario holds that Miranda, like other moons, originally formed from tiny rock and ice particles orbiting Uranus. This proto-Miranda was heated unti it became molten. Eventually the heavier rock formed a core surrounded by the lighter ice. How the heating occurred is still not well understood, but two mechanisms have been proposed. The first relies on the decay of hypothesized short-lived radionuclides. The other mechanism is tidal heating: Proto-Miranda, according to this idea, was held in an elliptical orbit by resonance effects of the outer Uranian moons; as it followed this elliptical orbit it was continually squeezed by tidal forces, heating the moon's interior. At any rate, proto-Miranda now consisted of separate regions of rock and ice.

Then a catastrophe occurred. Something in Uranus's orbit—possibly some of the original material from which the planet itself formed—smashed proto-Miranda to bits. Its orbit became filled with large chunks of ice and of rock. Calculations show that these chunks would, within a few tens of thousands of years, reassemble into Miranda. But the resulting Miranda consisted of lumps of heavy rock randomly mixed with lighter ice. The heavy rock sank toward the center and the ice rose, until at some point the entire conglomerated mess froze and all activity ceased. Features like the ovoids could perhaps be explained as reflecting later subsidence of chunks of proto-Miranda.

Ariel is the next most active of the Uranian moons. It is covered by large fault valleys and smooth areas that are intepreted as evidence for either liquid or glacial flow. Many of the faults are evidently stretch lines, indicating that the smooth areas could have been viscous oozings of material from below the surface.

Umbriel is the picture of what all Uranian moons were supposed to be—dark and pitted with craters, but otherwise geologically uninteresting. It is the darkest of the five moons, with an albedo of only about 19%. Its unusual darkness is thought perhaps to result from a coating of dark dust that was somehow confined to Umbriel's orbit.

Titania, the next moon out, follows Ariel in geological activity. It is covered by a large, planetwide fault system and relatively young craters. The lack of older craters may indicate that Titania's features also were formed by resurfacing.

Oberon is a relatively sedate moon, with one or perhaps two fault systems. The ejecta from its craters are bright, but some of the crater floors are filled with dark material. This might indicate that the dark material bubbled up later, filling the craters, or perhaps the material was light to begin with and was darkened later by radiation or some unknown process.

—Bruce Schechter

Reference

1. E. C. Stone, E. D. Miner, Science **233**, 39 (1986). G. L. Tyler *et al.*, Science **233**, 79 (1986).

Committee reviews DOE inertial-confinement fusion program

Inertial-confinement fusion clearly works. It's demonstrated every time a hydrogen bomb is detonated. But is it possible to ignite a small deuterium–tritium pellet under controlled conditions in the laboratory—driving the requisite implosion with anything less drastic than a fission bomb?

The answer is not yet known. In the long run one wants to know whether one can ignite a pellet using an implosion driver frugal enough to yield more energy than it expends—a necessary condition for a commercial inertial-confinement fusion reactor. "But first we have to demonstrate that the thing can be done at all, irrespective of driver efficiency," says William Happer (Princeton), chairman of the National Academy of Sciences committee whose review of the DOE inertial-confinement-fusion program, undertaken early last year, was recently released[1] for publication.

In a December 1984 letter to the academy, George Keyworth II, the President's science adviser, requested that the NAS put together a committee to "review the accomplishments, management, goals and anticipated contributions of the [Department of Energy's] Defense Inertial Confinement Fusion program." Keyworth's charge asks that a committee "of individuals highly qualified in scientific disciplines associated with the development and testing of nuclear weapons . . . review all major areas of the inertial confinement program, . . . prioritize activities within the present and future ICF program, and present an appropriate time scale for attaining the program goals." The establishment of a review group, Keyworth's letter pointed out, had been mandated by Congress.

The relative emphasis on military issues in Keyworth's charge reflects a different environment today from that of the early 1970s, when the ICF program began to grow. Today, as the committee's published review puts it, "the energy crisis is dormant for the time being; the demand for electrical power has been much less than anticipated, and the growth of fission power has essentially stopped. . . . New programs, notably third-generation weapons and the Strategic Defense Initiative, are competing for funds and scientific talent."

With the exception of the heavy-ion-driver program, the entire ICF effort at DOE has, from the beginning, been funded by the department's Defense Program. Thus the review committee's report deals only briefly with the heavy-ion-driver effort. This should not be construed as a judgment on the long-term promise of heavy-ion beams relative to lasers or light-ion beams as ICF implosion drivers, Happer told us. It's just that the requirement for expensive particle accelerators places the heavy-ion ICF effort more properly in other parts of the overall DOE program.

None of present generation of ICF lasers, led by the ten-armed, 100-kilojoule Nova laser at Livermore, can deliver sufficient pulse energy to drive a deuterium–tritium pellet to ignition. Building a suitable laser with present-day Nova technology would be a very expensive proposition. "I think it would be a great mistake to stop the program now to try and design such a laser," Happer asserts. "It's clear that a laser-driven power reactor is an issue for the next century. The real question *now* is whether any laser, no matter how efficient, can implode these pellets to ignition." The review committee concludes that the laser ICF program at Livermore, Los Alamos, KMS Fusion, the University of Rochester and the Naval Research Laboratory should continue the study of pellet-implosion physics with its existing lasers, to determine the parameters necessary for an ignition laser. Given the expense of such a laser, one cannot afford the luxury of overbuilding it by a factor of two.

The new PBFA-II light-ion-beam accelerator just now beginning operation at Sandia is described by the committee as "the only laboratory-scale facility with the potential capability of delivering a megajoule in the next few years." This is very likely to be adequate energy for pellet ignition. The principal problems with light-ion beams lie elsewhere. Laser pulses are much more easily shaped in space and time than are pulses of light (lithium) ions. Driving a pea-sized D–T pellet to ignition will require a power density of about 10^{14} W/cm^2 on target. This is a hundred times the power density thus far achieved at PBFA-II. The limited focusing capability of light-ion accelerators at present requires that the beam travel no more than a few centimeters from the accelerating diode to the target, raising the problem that the diode would have to be replaced after