Voyager Finds Uranian Shepherds and a Well-Behaved Flock of Rings

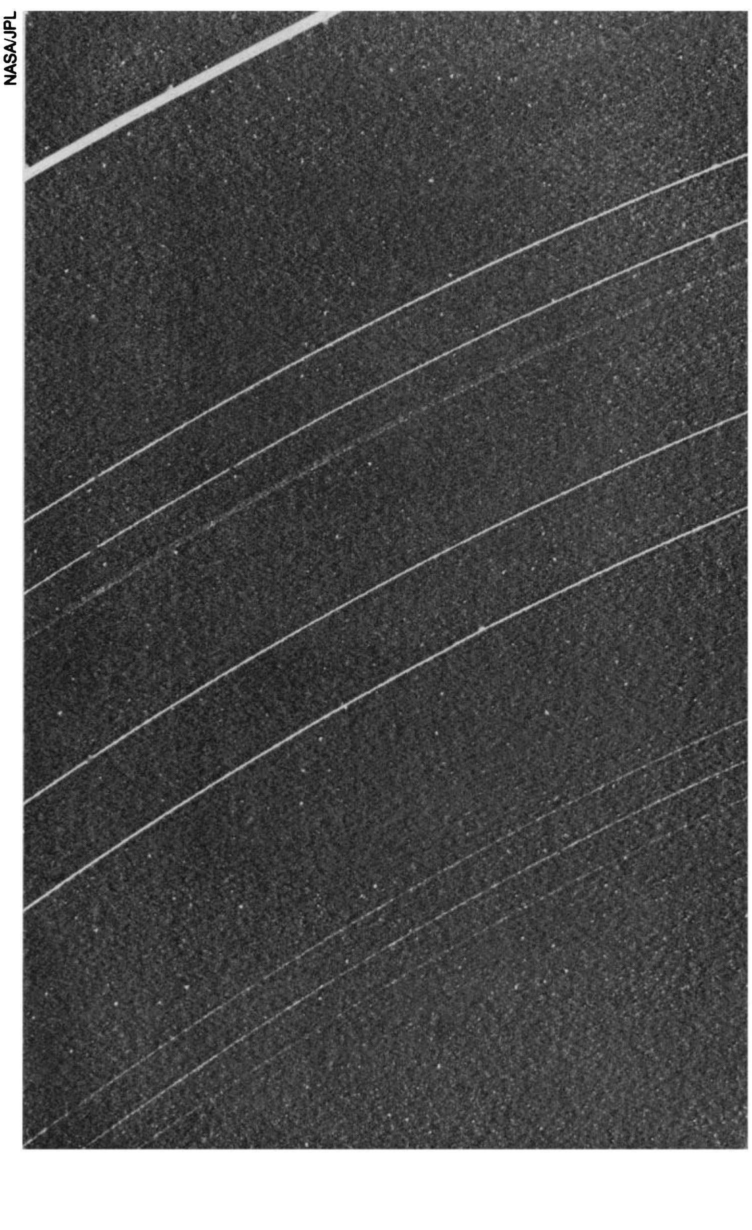
Voyager 2 discovered the moonlets predicted to shape the Uranian rings, two new rings, a predominance of boulders in the rings, and much more

Pasadena, California.
THE Voyager 2 spacecraft took a revealing family portrait of the nine spider web–thin rings of Uranus as it swept by the planet on 24 January. Taken from 10,000 times closer than possible before, the new view revealed the previously undetectable moonlets responsible for the existence of at least the major ring, two new members of the ring family, an exceptionally light sprinkling of dust throughout, new details of individual rings, and a retinue of new satellites outside the rings. All in all, planetary scientists found the Uranian ring family to be quite familiar, related as it is to the F ring of Saturn studied so closely by both Voyager 1 and 2. But there are enough distinctive characteristics, such as a preponderance of boulder-size ring particles and the coal-black color of the rings, and enough variety among the current 11 official family members that researchers should have their hands full for some time.

Among the myriad of ring observations analyzed here at the Jet Propulsion Laboratory during the encounter, Voyager's most satisfying discovery was perhaps the pair of satellites found straddling the epsilon ring, at an average width of 36 kilometers the widest and most massive Uranian ring. Thirty and 40 kilometers wide, these moonlets are invisible from Earth, but two theorists predicted their presence shortly after the discovery of the rings in 1977. The new rings seemed to fly in the face of common sense. Encompassing diameters of up to 100,000 kilometers, they are sharp-edged and as little as a few kilometers across; a spider web on the same scale would have threads a kilometer across. But planetary rings are hardly as substantial as a spider web. Left to themselves, the billions upon trillions of particles, individual satellites really, composing each ring must inevitably collide with each other and spread apart to form a single, uniform disk.

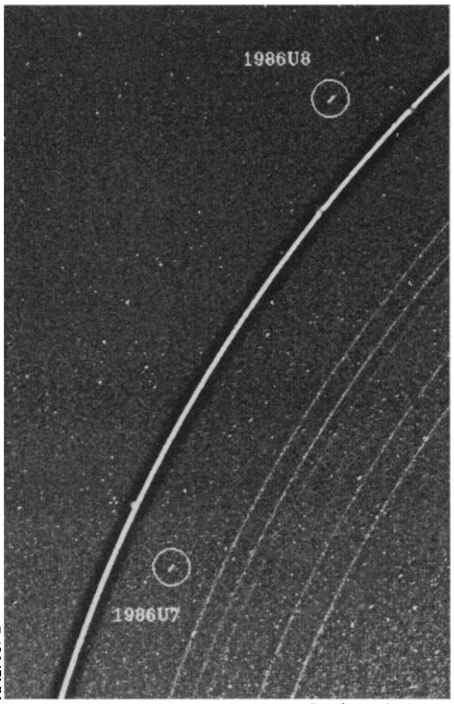
Peter Goldreich of the California Institute of Technology and Scott Tremaine, now at the University of Toronto, proposed solving this apparently intractable dilemma by a seemingly ridiculous means—gravity that can repel. The mechanism, in which a moonlet or "shepherd" on either side herds the particles into a narrow ring, depends in fact on the ring particle collisions that at first seemed to be the problem. By raising a small bump on the ring when satellite and ring particles pass each other, a shepherd on the inside of a ring can push ring particles toward a higher orbit as the shepherd drops to a lower orbit. In an ideal case of an isolated ring particle, the process would be reversed and the original push nullified when the shepherd caught up again, but in the meantime the inevitable collisions between ring particles have smoothed out the bump. The net effect is repulsion between the shepherd and the ring particles. A second shepherd to the outside contains the herd in a narrow ring.

Before Voyager 2 could reach Uranus to confirm or deny the shepherd hypothesis,


NASA/JPL

The rings of Uranus

Voyager caught the nine rings known from Earth observation in this picture starting with the outermost and widest, epsilon at 60 kilometers, in the upper left. The rest are delta, gamma, eta, beta, alpha, 4, 5, and 6. All but epsilon and eta are too narrow—less than 1 to 7 kilometers—to be seen here as more than unresolved lines. Voyager discovered a tenth ring about midway between epsilon and delta that may be visible in this reproduction by sighting along the ring. As is the case with all these images, extensive processing has enhanced brightness and contrast.



Two shepherds and their flock

The gravity of these two tiny moonlets drives ring particles into the narrow epsilon ring through some curious twists to Newtonian physics.

Pioneer Saturn discovered the narrow F ring of Saturn and Voyager 1 found its two satellite companions. That seemed a strong if indirect confirmation of the Uranian ring hypothesis, but the direct confirmation and fine details from Voyager's recent flyby should tell far more about exactly how shepherding works, according to Goldreich.

The epsilon ring of Uranus, it turns out, is far better behaved than the F ring and thus more amenable to study. Saturn's narrow ring kinked, split into multiple strands, apparently braided its strands, and clumped into dense condensations. One shepherd even brushes through the ring every 17 years. Goldreich attributes the F ring's bizarre behavior in part to the torture that it suffers at the hands of its two companions. They are far more massive than required to shepherd the ring. In addition, says Goldreich, the dust and centimeter-size particles of the visible ring constitute only a small portion of the ring's mass, the bulk of it presumably residing in kilometer-size moonlets only hinted at in Voyager observations. Gravity shapes narrow rings and holds sway in proportion to the mass present, but in the F ring most of the mass seems to be invisible.

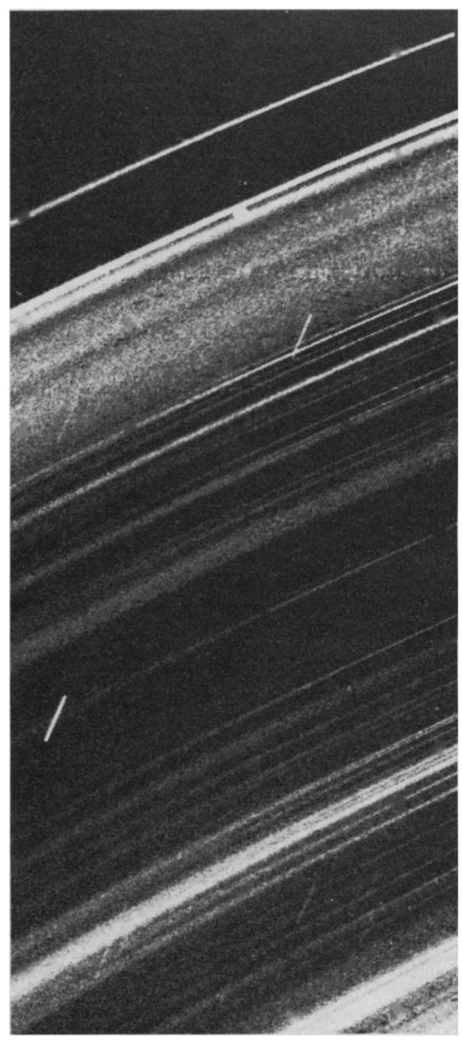
The epsilon ring, on the other hand, has thus far shown no irregularities, probably because its shepherds are about 25 times less massive than the F ring's and most of its particles are in the same size range, being mostly boulders. Thus, the detectable ring particles also carry most of the ring mass. Voyager discovered this peculiar preponderance of large particles when it beamed its radio signal through the rings from the far side of Uranus. The same radio occultation experiment at Saturn revealed a range of particle sizes from golf-ball-size to house-size, but there were about a million 1-centimeter particles for every 1-meter particle. That seemed to fit the expectation that a swarm of particles banging into each other for a few billion years would contain a preponderance of small particles, which are responsible for most of the sunlight reflected by the rings, and a few large particles, which contain much of the mass.

In Uranus's epsilon ring, small particles are hard to find. Len Tyler and his colleagues at Stanford University reported that the epsilon ring obstructed Voyager's microwave signal to about the same extent whether it had a wavelength of 3.6 or 13 centimeters, suggesting that there are relatively few of the centimeter-size particles that block the shorter but not the longer wavelength signals. When instead a star produced the observed signal at the far shorter wavelengths of ultraviolet light, the pattern of flickering light recorded by Voyager's photopolarimeter during an occultation was much the same as at microwave wavelengths, according to Lonne Lane of the Jet Propulsion Laboratory. On the basis of these results and the amount of microwave diffraction detected, Tyler concludes that there are relatively few particles smaller than a meter in diameter, so Voyager detects the same particles that feel most of the gravity involved in ring dynamics.

Researchers have suggested a couple of ways that the dearth of small particles in the Uranian rings could perhaps be maintained. One might be related to the coal-black color of the ring particles. If their composition differed from that of the bright, water-ice particles of Saturn's rings such that Uranian ring particles were stickier or less elastic, any small particles might more easily stick to larger particles during collisions and thus disappear. Whatever makes Uranian particles as dark and colorless as anything in the solar system, the reasoning goes, might also let them clump together.

The Voyager encounter showed that the black material could be an organic polymer. Voyager discovered a magnetic field that has trapped a radiation belt more intense than Earth's, one capable of turning the methane that is likely incorporated in water ice at Uranus into a black, amorphous polymer. Coincidentally, Voyager found the most intense radiation when the spacecraft slipped briefly inside the orbit of Miranda, the innermost major satellite. Inside the orbit of Miranda is also where Voyager found the eight new, dark minor satellites and the two dark epsilon shepherds. Everything bathed in the heaviest radiation—rings, shepherds, and minor satellites—appears to be dark and colorless, implying that radiation is the cause. If radiation creates black material, and it makes particles stickier or less elastic, that could explain the dearth of small particles at Uranus relative to Saturn, where there is no methane in the ice.

Another means of removing smaller particles could be the drag of hydrogen gas leaking away from the planet. As one of the four gas giants, Uranus is rich in hydrogen, but it has less gravity than Jupiter or Saturn to hold onto the hydrogen. Voyager discovered a trickle of this hydrogen seeping away, creating a greatly extended atmosphere. Like an artificial satellite orbiting too close to Earth, speculates Donald Hunten of the University of Arizona, ring particles as large as centimeter-size could have been dragged



A backlit view of the rings

Backlighting highlights fine dust that forms rings and bands of its own.

down by the extended atmosphere and removed from the rings, leaving larger particles that are less sensitive to drag.

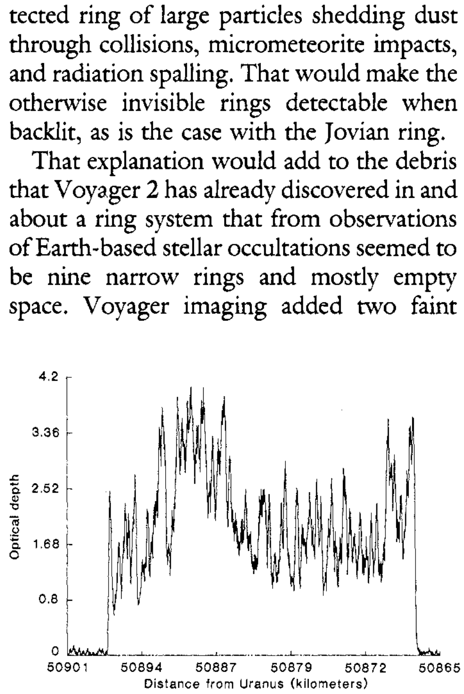
Whatever tends to clear the smaller particles, it has not gotten all of even the finest ones. Voyager, after considerable effort, managed to catch sunlight filtering through particles strewn between the rings in lanes varying from narrow strips to broad bands. Unseen under other lighting conditions, these particles must be micron-size dust because of the way they brighten when the sun is behind them, much the way dust in a theater stands out in the beam of a movie projector.

Although 100 to 1000 times more opaque than the faint dust ring of Jupiter, the Uranian dust lanes represent far less material in and leaking from the nine main rings than most researchers expected. The drag of the extended atmosphere of Uranus might explain all or part of the deficiency, but another mechanism suggested itself from the Voyager observations of the Jovian ring system. There, the 10-degree tilt of Jupiter's magnetic field causes it to wobble with the planet's rotation. The canted field thus sweeps up and down through the ring, throwing dust charged by radiation out of the plane of the ring and eventually into the planet. The magnetic field also acts as an obstacle to the charged dust particles, draining orbital energy from them the way the drag of the atmosphere does.

At Uranus, the magnetic field would shorten the lifetime of charged dust particles even more. Voyager found the Uranian field to be tipped an enormous 55 degrees from the axis of rotation, so dust would be even more likely to be knocked out of the ring plane. Joseph Burns of Cornell University and his colleagues suggested before the Voyager encounter at Uranus that the efficiency of such magnetic sweeping at certain distances from Jupiter might be greatly increased if a given particle felt a similar tug from the magnetic field at the same point on its orbit. Like properly timed pushes of a swing, the net effect would increase sharply if each tug added to the next instead of tending to cancel each other. At Jupiter, such orbital commensurabilities or resonances appear to prune dust away to shape the thin halo of dust inside the main ring. At Uranus, the strongest resonance and thus the greatest effect of any sweeping appears to fall within the rings themselves.

The other problem with the dust is why, with so many forces acting to spread it out and drive it from the ring plane, it is so neatly confined in dozens of bands, many of which are as sharp and narrow as the main rings seen in the same backlit view. Shepherding would not work well, depending as it does on collisions that would be infrequent between such widely spaced particles. One alternative would be to have an undetected ring of large particles shedding dust through collisions, micrometeorite impacts, and radiation spalling. That would make the otherwise invisible rings detectable when backlit, as is the case with the Jovian ring.

That explanation would add to the debris that Voyager 2 has already discovered in and about a ring system that from observations of Earth-based stellar occultations seemed to be nine narrow rings and mostly empty space. Voyager imaging added two faint new rings to those nine, a narrow one between the epsilon ring and the next most outermost ring (the delta ring) and a broad, 2600-kilometer-wide ring inside the innermost ring (ring 6). (The helter-skelter naming of the nine major rings came about before formal rules were developed for temporarily designating new rings. One group started naming from the inside out using the Greek alphabet while another started from the outside using numbers.) Frederick Scarf of TRW in Redondo Beach even reported that micrometer-size particles hit Vogager at a rate of 30 per second near ring-plane crossing all the way out near Miranda, 75,000 kilometers beyond epsilon.



The epsilon ring by starlight

The flickering of a star passing behind the ring, measured by Voyager's photopolarimeter, yields variations in optical depth or opacity across the ring, revealing sharp edges and internal structure. [*Source: L. Lane/JPL*]

The observation of the star Sigma Sagitarii passing behind the rings also turned up some unsuspected material, according to Lane. Just beyond the outer shepherd of the epsilon ring, the star repeatedly dimmed briefly, suggesting the presence of rings a few hundred meters to as little as 50 meters wide. And only 5 percent of the data from that occultation have been inspected. Confirmation as true rings will require their identification where the star passed that orbital distance on its way out of the ring system.

Images also revealed eight small satellites spread from outside the epsilon ring to half way to Miranda. Preliminary inspections of images in this area have not revealed any ring material being herded between these moonlets. By conventional reasoning, the tidal forces that act through Uranus's gravity to prevent ring particles from clumping into large moons are too weak at this distance to keep moonlets from growing at the expense of any rings present at the formation of the Uranian system.

Within the ring system, the search of Voyager images for more shepherds continues, but none as large as epsilon's are expected. In fact, none larger than the 5- to 10-kilometer limit of detection may ever be found. That would disappoint theorists who look for more ring-shepherd sets to refine their models, but it would not shake their faith in the existence of other Uranian shepherds. In the latest models, small shepherds, if close enough to rings, could be below the limit of detection and still be powerful enough to confine the major rings. Thus, says Goldreich, there is every reason to believe that more shepherds confine the rings inward of epsilon.

One predicted satellite will never be found. It is the 100-kilometer satellite that Richard French, Julie Kangas, and James Elliot of MIT suspected was perturbing the delta and gamma rings. They could predict the positions of the other rings with an accuracy of a few 100 meters on the basis of stellar occultations observed 2.7 billion kilometers from the planet. But the positions of delta and gamma could be predicted only to about 3 kilometers. A possible explanation was a satellite out toward Miranda that distorts the delta ring by creating a gravitational resonance near it.

Voyager found no such satellite, but its close passage by Uranus did allow a quarter-percent adjustment in the estimate of the mass of the planet, a crucial factor in the calculation of resonance positions. The mass had been thought to be more accurate than that, so the MIT group had discounted the possibility that the delta ring perturbations arose spontaneously as a resonance within the ring. Last year Nicole Borderies of the Observatory of Toulouse, Toulouse, France, Goldreich, and Tremaine suggested that instabilities within a ring of closely packed colliding particles could produce resonant pulsations like those reported by the MIT group. The adjustment in the mass makes the fit between the observed perturbations and internal instability predictions quite close. Apparently, waves of compressed particles bounce around within the ring, resonate, and amplify. The resulting ring pulsation might also help explain the changing radial position of some features in Saturn's B ring and the outer edge of the Cassini division.

Many more details of ring behavior should become apparent as the Voyager observations of the two stellar occultations come under close scrutiny. During the encounter Lane reported that the epsilon ring, whose circumference is eight times that of Earth's equator, is at most 25 to 30 meters thick. Its width as detected during stellar occultations observed from Earth varies from 12 to 60 kilometers, but its edges are so sharp that Voyager found the transition from apparently empty space to dense ring occurs over only 30 to 40 meters.

According to Larry Esposito of the University of Colorado, another photopolarimeter team member, the five broad variations in opacity across epsilon detected from Earth split into about two dozen features in the Voyager occultation data. Most of these features were stable enough to also be detected 120 degrees around the ring during the star's passage back to the outside of the rings. On the other hand, the single strand of the delta ring seen as the star crossed the ring inbound was split into three strands when the star crossed outbound. Some of the patterns of opacity variations in epsilon remind Esposito of the F ring or the edges of Saturn's Encke gap, which holds at least one shepherd. There is even a regular pattern of undulations that bears some resemblance to a spiral density wave, the watch spring–shaped wave of particle compression responsible for much of the structure in Saturn's A ring. ■

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ADDITIONAL READING

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Ubiquitin Moves to the Cell Surface

The varied activities of the protein ubiquitin now extend from the cell nucleus to the cytoplasm to the outer membrane

THE protein ubiquitin has two characteristics that are sure to draw the attention of cell biologists. Its distribution is . . . ubiquitous; it is found in all the cells of higher organisms and perhaps also in bacteria. Moreover, ubiquitin's structure has changed very little during the course of evolutionary history. Such characteristics generally indicate a protein that has a fundamental role in the life of the cell. "Ubiquitin is everywhere and is probably functional everywhere," says Alexander Varshavsky of the Massachusetts Institute of Technology.

Best established is its function as a marker for proteins that are destined for degradation. As such it helps to destroy the normally short-lived proteins of the cell, a category that is likely to include many of those involved in regulating gene expression and other cellular activities. Ubiquitin addition may also tag for destruction damaged or abnormal proteins, which could harm the cell if they accumulated. In this capacity, the ubiquitin system may be part of the cell's defenses against heat shock and other stresses.

All these activities take place in the nucleus and cytoplasm. New evidence now extends the possible sphere of ubiquitin's influence to the outer membrane of the cell. In two papers in this issue of *Science* (pp. 823 and 845), Irving Weissman and his colleagues at Stanford University School of Medicine present evidence suggesting that the protein is part of the receptor by which lymphocytes home in on and enter the lymph nodes, an activity that is necessary for normal immune responses.

Once lymphocytes, both of the T and B types, have reached a stage of maturity in which they are capable of responding to antigens, they begin shuttling around the body. During this time, they periodicially move into one or another of the lymphoid organs, which include the lymph nodes, the spleen, and the Peyer's patches found in and around the intestines. This system helps to ensure that a lymphocyte of appropriate specificity will be available no matter where a foreign antigen enters the body.

About 20 years ago, James Gowans, who was then at the University of Oxford in England, showed that lymphocytes enter the lymphoid organs through specialized blood vessels called postcapillary high endothelial venules. Results from Weissman and his Stanford colleagues Eugene Butcher and W. Michael Gallatin indicate that lymphocytes bind to the cells lining the vessels by means of specific receptors, which they call homing receptors. They find, among other things, that lymphocytes have a strong, although not absolute, preference for binding to venules from the lymph organ from which they were originally isolated.

Moreover, many lines of cloned lymphoma cells are extremely specific, binding either to lymph node or Peyer's patch venules, but not to both. By making monoclonal antibodies against the lymph-node specific lymphoma cells the Stanford workers were able to produce an antibody, which they called MEL-14, that recognizes the lymph node homing receptor.

Weissman, Thomas St. John, also of Stanford, and their colleagues then used the MEL-14 antibody in an attempt to identify the gene coding for the lymph node homing receptor protein. Three DNA clones yielded protein products that were recognized by the antibody. At this point the research took an unexpected turn. "We sequenced the genes and found they all encoded ubiquitin," Weissman says. "We were surprised and disappointed." Not only was ubiquitin not thought to occur on the cell surface, but the protein would not seem to provide any basis for the specificity required by a receptor.

For one, its structure is highly conserved, having the same sequence of 76 amino acids in species as diverse as the toad *Xenopus laevis*, the chicken, and the human. Even yeast ubiquitin differs in only three amino acids from the human version, according to Varshavsky and his MIT colleagues Daniel Finley and Engin Ozkaynak. "Currently it is the most conserved of all eukaryotic proteins," Varshavsky says.

For another, ubiquitin is made in all cells, not just the subgroup of lymphocytes that carry the lymph node homing receptor. Specificity could therefore not be attained by restricting production of ubiquitin to a particular cell type.

All this left Weissman and his colleagues