Reports

Rings of Uranus: Invisible and Impossible?

Abstract. *Neither the dynamical nor the optical properties of the rings of Uranus are easily understood, unless it is assumed that they are not rings in the ordinary sense but simply volatile material in the orbits of several individual small satellites. It is possible that other natural satellites may also leave such rings in their wakes.*

The mystery of the "rings" of Uranus continues to grow. There are apparently about nine roughly circular rings, all in or near the plane of the uranian equator (*1*). All but the outermost or ϵ ring are very thin and very narrow, perhaps only a few kilometers wide. It is not known how this condition could be maintained for ordinary rings, since perturbations experienced by individual ring particles should cause radial spreading of the rings in just a few decades. The ϵ ring varies in width from 20 to 100 km and is either elliptical or inclined to the equator of Uranus. Either condition is very difficult to explain. If the ϵ ring is elliptical, then differential perturbations of the pericenters of the individual bodies (arising from the oblateness of Uranus) should cause them to spread out into wider but circular rings in about 20 years. If the ϵ ring is inclined to the equator of Uranus, perturbations on the nodes would have a similar effect, producing thicker but circular rings symmetric about the equator of Uranus. Even solid rings, if such were conceivable, would be dynamically unstable and would collapse into Uranus in short order (*2*).

Another mysterious aspect is that the rings are apparently invisible. Two sensitive measurements of the albedo of the rings yielded results of 3 ± 3 percent and less than 1 percent of the corresponding albedo of Saturn's rings (*3*). No known material in space meets this albedo constraint. It implies material reflecting less light than the blackest coal dust. In view of the evidence, exotic explanations are being considered (*4*).

The following is a possible partial model of the ring system, consistent with these observations and yet not too exotic. Consider that there may be a single body orbiting in each of the observed ring locations, which sheds gaseous material as it orbits. There are three known types of situations that are analogous: comets, which sublimate material under the influence of solar radiation; the jovian satellite Io, which is immersed in a cloud of sodium and hydrogen spread out into a torus around its orbit, formed by molecules removed from the surface of Io by the bombardment of intense energetic particles in Jupiter's magnetosphere (*5*); and Saturn's satellite Titan, which has insufficient gravitation to retain the hydrogen in its atmosphere and continually diffuses it into its orbit. The mechanism for Uranus may or may not be similar to one of these three cases. The key features of the model are that the gaseous material shed by each orbiting body diffuses rapidly (within a few years, at most) and that it is continuously renewed in each part of the orbit by each passage of the satellite. This hypothesis enables us to circumvent the dynamical problems entirely, since only the stable orbits of individual satellites need be considered. The recently emitted gaseous material will necessarily lie close to the satellite's current orbit, wherever that may be.

Presumably, the satellite giving rise to the ϵ ring is considerably larger or more volatile than the others. This assumption, combined with the satellite's longer orbital period (about 8 hours), gives the ring more chance to spread out before dissipating completely. It is not obvious whether the dissipation can be sufficiently rapid to account for the apparently well defined edges of the ϵ ring. (Perhaps this feature is an indication that the satellites are massive enough to prevent dissipation and instead cause the ring material to librate in the satellite's orbit.) But, because the time interval since the last passage of the satellite is a factor in ring density, it can be readily understood in this model why some of the ring densities seemed to change between March and December 1977 (*6*), and why the "optical depths" at different points in the ϵ ring were inversely proportional to the ring widths (this result suggests that there is the same amount of material in the rings at each place but that it is spread out by varying amounts, as in a "wake") (*7*).

Such satellites would be too small and too close to Uranus to be detectable optically. The uranian satellite Miranda, which is a few hundred kilometers in diameter and more than twice as far from Uranus as the outermost ring, is extremely difficult to observe. The rings might remain invisible because their optical depths would presumably be too slight to reflect very much sunlight. How, then, can they occult the light of a star? The mechanism of occultation is presumed to be refractive defocusing of the star's light, rather than the optical depth of the gaseous medium, by analogy with what happens when a star is occulted by a planetary atmosphere (*8*). It is this defocusing effect which causes the umbra of Earth's shadow cast on the moon during a lunar eclipse to be more than 100 km larger in radius than Earth's solid body. Even the tenuous atmosphere above 100 km, although it cannot absorb or scatter significant sunlight (nor be seen by astronauts), can still effectively defocus sunlight.

The defocusing causes the light of the background star to diminish by different amounts in each ring, depending on the density and refractive properties of the gaseous material in that ring. In no case did the occulted star completely disappear when the rings were discovered. Generally, the gas densities required to produce the observed dimmings would be too small to reflect detectable light, except possibly for the ϵ ring (*8*). However, it is consistent with this model that the suspected detection of the shadow of the rings on the planet (*9*) is real, since defocused sunlight can cast a shadow just as easily as absorbed or reflected sunlight.

If this model of the uranian rings is essentially correct, then it is interesting to contemplate their possible uniqueness. I am unaware of any observations of the passage of a background star across the orbit of any known natural satellite in the outer solar system, with the exception of Beta Scorpii C near Io in 1971, when unexplained irregularities in the light curve of the star were observed (*10*) (Io is known to have such gaseous material in its orbit). It is therefore possible that we may discover many such rings in the outer solar system, corresponding to many of the known natural satellites of Jupiter, Saturn, Uranus, and Neptune, and perhaps rings of some as yet undiscovered satellites. Indeed, the example of Uranus suggests that even quite small

0036-8075/79/0608-1076$00.50/0

bodies, a few kilometers in diameter (the width of several of the rings), may produce detectable variations in the brightness of background stars.

Occulations of stars by the orbits of Jupiter's galilean satellites are rare because of the slight angle of tilt of those orbits to our line of sight, resulting in a small occultation cross section; but, if the relatively high inclination outer satellites produced such rings, the potential for discovering more outer jovian satellites would be great indeed. Moreover, the considerable gap between Miranda and the ϵ ring is likely to contain additional satellites.

On the other hand, the satellite system of Neptune seems to have been disrupted in the remote past; the chances of finding any surviving ring-producing satellites around this planet, other than Triton and Nereid, seem minimal. As for Saturn's many satellites, the probability of the existence of a ring in each orbit depends primarily upon the nature of the mechanism for producing the gaseous material, since Saturn seems to have only perhaps 10 percent of Jupiter's magnetic field. Titan, which is known to be losing the hydrogen in its atmosphere into space, would be a good candidate for a possible ring.

The model presented here reinterprets the rings of Uranus as gaseous material shed by single orbiting satellites into their orbits, which spreads and dissipates rapidly. The primary advantage of this model is that it provides a simple visualization for understanding the puzzling dynamical properties of the rings as well as their apparent failure to reflect a reasonable amount of sunlight. Moreover, it leads to the interesting and easily testable speculation that some other satellites in the solar system may likewise produce rings.

Note added in proof: (i) The reported "pictures" of the rings of Uranus (*11*) should be interpreted with caution, and may represent only scattered light from material near Uranus. The direction of intensity maximum in the pictures differed from the predicted direction for the rings; and 2 percent albedo material is still very difficult to explain physically. (ii) Observations of material in satellite orbits have now been reported for Europa and possibly Amalthea, in addition to Io (*12*). (iii) A model equivalent to the one proposed here would consist of material everywhere in near-Uranus space except for tunnels continuously cleared out by a few satellites.

THOMAS C. VAN FLANDERN
U.S. Naval Observatory, Washington, D.C. 20390

References and Notes

1. J. L. Elliot, E. Dunham, L. H. Wasserman, R. L. Millis, J. Churms, *Astron J.* **83**, 980 (1978).
2. More detail about dynamical constraints on these and other ring models was provided by P. Nicholson (paper presented at the American Astronomical Society Division for Planetary Sciences meeting, Boston, 27 October 1977). Much of this information is summarized in P. D. Nicholson, S. E. Persson, K. Matthews, P. Goldreich, G. Neugebauer, *Astron. J.* **83**, 1240 (1978).
3. W. A. Bau, B. Thomsen, B. L. Mortan, paper presented at the American Astronomical Society Division for Planetary Sciences meeting, Boston, 27 October 1977; B. A. Smith, H. J. Reitsema, D. E. Weistrop, *ibid.* [preliminary abstracts for both of these papers may be found in *Bull. Am. Astron. Soc.* **9**, 499 (1977)]; see also W. M. Sinton, *Science* **198**, 503 (1977).
4. For example, J. C. Bhattacharyya and M. K. V. Bappu, *Nature (London)* **270**, 503 (1977).
5. *Sky Telescope* **54**, 479 (1977).
6. *Sci. News* **113**, 37 (1978).
7. R. L. Lucke, *Nature (London)* **272**, 148 (1978).
8. W. A. Baum and A. D. Code, *Astron. J.* **58**, 108 (1953).
9. G. Columbo, *Sky Telescope* **54**, 188 (1977).
10. T. C. Van Flandern and P. Espenschied, *Astrophys. J.* **200**, 61 (1975).
11. K. Matthews, G. Neugebauer, P. Nicholson, *Sky Telescope* **56**, 497 (1978).
12. W. H. Smyth, *Bull. Am. Astron. Soc.* **10**, 577 (1978); in preparation.

11 September 1978

Chesterton Soil Concretions: Ilmenite and Not Iron-Manganese Cementing Matrix

Abstract. *Dark reddish-brown spherules are common in soils of the Chesterton soil series of a high marine terrace in southern California. The spherules are concretionary in structure and are bound by ilmenite rather than by an iron-manganese complex. The spherules have been mislabeled both with respect to structure and mineralogy.*

The Chesterton soil series is found primarily in San Diego County, California. The series occurs on the Linda Vista terrace, an old marine terrace, and is comprised of sandy materials derived from what appear to be ancestral beach ridges. Reddish-brown spherules ranging in size from pinheads to 3 cm occur within the surface horizons (A11 and A12) and in some cases on the surface. The A horizon is commonly 20 to 25 percent spherules (by weight). There has been much speculation about the true nature of these spherules, whether they are pebbles, nodules, or concretions (*1*). Pebbles are the product of physical rounding from some larger original specimen. Nodules are basically heterogeneous throughout. Concretions display concentric growth binding (*2*). There is also a question about the nature of the cementing agent. Are the quartz, sand-sized grains held in a matrix of largely ferromagnesium minerals or in some other iron-rich mineral assemblage?

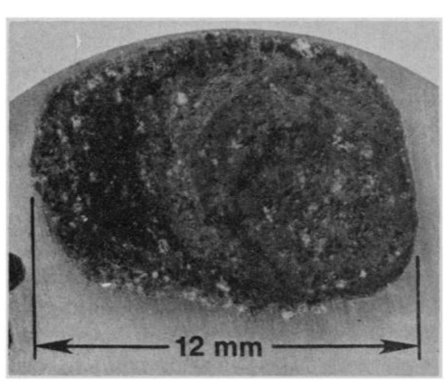

Fig. 1. Slice of one of the reddish-brown spherules in the Chesterton soil series.

I prepared spherules for macro- and microscopic examination by impregnating the samples with low-viscosity plastic under vacuum and slicing them upon polymerization with a diamond saw. The resultant slices display concentric bands to the naked eye (Fig. 1). I coated several samples with a thin layer (20 nm) of gold-palladium prior to examination in a scanning electron microscope (SEM) (JEOL JSMU-3) equipped with an energy-dispersive system (EDS).

No magnesium or manganese was detected in any samples examined by x-ray microanalysis. Silicon was detected in dense discrete concentrations which match the locations of the quartz grains. Iron was found in relatively lower concentrations than silicon. Both elements, when displayed in elemental dot maps, reflect a roughly concentric pattern. Using the same system and frame locations, I analyzed for titanium. The titanium clusters were of a lower concentration than the iron. The map, however, still displayed discrete clusters of titanium which closely overlie the iron concentrations. The failure to detect magnesium and manganese could possibly be due to the detection limits of the EDS system. Therefore, I used destructive chemical analysis with three different procedures (*3*). All procedures yielded results indicating less than 0.5 percent manganese and 1 percent magnesium on the basis of MnO and MgO. Both of these oxides are found in the lattice work of minerals which occur in low concentrations within the spherule. Thus the manganese and magnesium should not be considered part of the cementing matrix of the sphe-