RINGS OF URANUS: A REVIEW OF OCCULTATION RESULTS

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Since their discovery in 1977 (Elliot 1979), the dark, narrow rings of Uranus have intrigued dynamicists. The main enigma has been how the rings can remain so narrow - only a few km wide - when particle collisions and the Poynting-Robertson effect should cause the particles to disperse. The Uranian rings have posed other problems as well, and have proved to be a unique system for developing dynamical models of rings. The reason for this theoretical interest is the high precision and time coverage of the data available from occultation observations. With occultations we obtain a spatial resolution of 1 km in the position of ring segments and a resolution of 4 km in their structural details. These high-resolution data are available sufficiently often to be useful for dynamical purposes - at the rate of 1-2 events per year. This spatial resolution is somewhat better than that obtained by Voyager imaging of Jupiter's and Saturn's rings (Owen _et al_. 1979; Smith _et al_. 1981). Ground-based images of the Uranian rings, obtained by Matthews, Nicholson, and Neugebauer (1981), have a spatial resolution of ~50,000 km. Although unable to resolve individual rings, these data have established the mean geometric albedo of the rings at 0.030 ± 0.005.

At this conference Brahic has reviewed the relation of the Uranus rings to general models for rings and the ring systems of Jupiter and Saturn. For an earlier review, see Ip (1980a, b).

In this chapter we review the structure and orbits of the nine confirmed Uranian rings, as revealed by occultation observations from 10 March 1977 through 26 April 1981. We then compare the conclusions from these observations with current dynamical models. Finally we discuss what new information about the rings that we expect from the following observing opportunities: (i) future occultations, (ii) the Voyager encounter in 1986, and (iii) the Space Telescope.

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OBSERVATIONS

The main method for observing the Uranian rings has been stellar occultations (Elliot 1979). With this technique we measure the intensity of a star versus time during the passage of the ring system through our line of sight to the star. The result of this measurement is the optical depth versus distance along a particular track through the ring system. The precision of the measured optical depth depends on the signal-to-noise ratio of the photometry; the spatial resolution of the optical depth is limited by either Fresnel diffraction or the angular subtent of the occulted star. At the mean opposition distance of Uranus (18 au) and for the mean wavelength of the K band (2.2μ), Fresnel diffraction causes the minimum width of an occultation profile to be 4 km FWHM (full-width at half-maximum). This fundamental limit to the spatial resolution is equivalent to an angular resolution of 3×10^{-4} arcseconds. If the occulted star has an angular diameter comparable to or larger than this, then the spatial resolution of the ring occultation profiles becomes worse than 4 km. As an example, a KO star with an angular diameter of 3×10^{-4} arcseconds has $V = +9$ and $K = +7$. Some occulted stars are large enough so that their angular diameters can be determined from the ring occultation profiles (Millis _et al_. 1977).

The observation of a stellar occultation requires a prediction of when and where it will be visible. The first publicized prediction of an occultation by Uranus was made by Gordon Taylor (1973), who predicted the now famous occultation of SAO 158687 on 10 March 1977 when the Uranian rings were discovered (see Elliot 1979 for a review). To make this prediction, Taylor used the technique of comparing the Uranus ephemeris with star positions in the SAO catalog.

Since occultations of SAO stars by Uranus occur infrequently, just after the discovery it looked like years before we would be able to observe the Uranus rings again. This dismal forecast was radically changed by two developments: first, occultations of stars fainter than the SAO catalog limit were predicted by Klemola and Marsden (1977), who compared the ephemeris of Uranus for 1977-1980 with plates taken with the Lick double astrograph. Second, the Cal

TABLE I. OBSERVATIONS OF OCCULTATIONS BY THE URANIAN RINGS

Date	Star	Magnitude V	Magnitude K	Observatory	References
10 Mar 1977	SAO 158687	8.8	-	KAO[1]	Elliot, Dunham, and Mink (1977)
				Perth	Millis, Wasserman and Birch (1977) Hubbard and Zellner (1980)
				Cape Town	Churms (1977)
				Kavalur	Bhattacharyya and Kuppuswami (1977)
				Naini Tal	Mahra and Gupta (1977)
				Peking	Chen *et al.* (1978)
23 Dec 1977	KM 2[2]	10.4	-	Cabezón	Millis and Wasserman (1978)
10 Apr 1978	KM 5	11.6	10.1	Cerro Las Campanas	Nicholson *et al.* (1978)
10 Jun 1979	KM 9	-	11.5	Cerro Las Campanas	Nicholson, Matthews and Goldreich (1981a)
20 Mar 1980	KM 11	13.1	10.5	Cerro Tololo	Elliot *et al.* (1981a)
				Sutherland	" " "
15 Aug 1980	KM 12	-	8.7	Cerro Tololo	Elliot *et al.* (1981b)
				Cerro Las Campanas	Nicholson, Matthews and Goldreich (1981b)
				ESO[3]	Bouchet, Perrier and Sicardy (1980)
26 Apr 1981	KME 13[4]	-	7.5	See text	Not yet published

[1] Kuiper Airborne Observatory [2] KM 2 = BD-15°3969 [3] European Southern Observatory [4] KME 13 = BD-19°4222

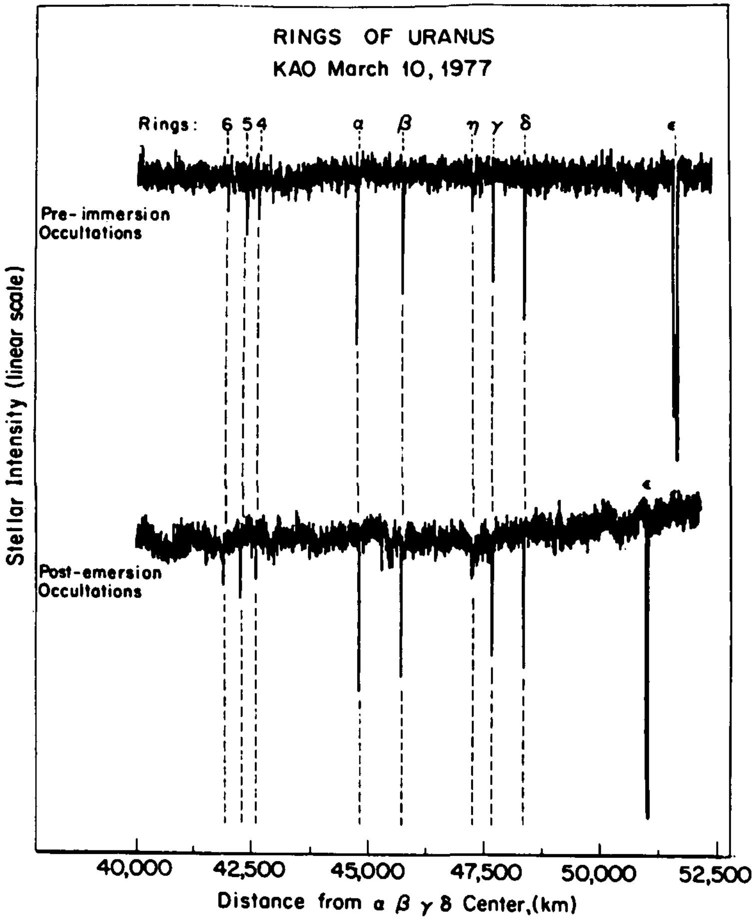
Tech group (Persson et al. 1978) realized that the occultations of most of Klemola and Marsden's stars could be observed with good signal-to-noise ratio in K wavelengths (2.2μ), where Uranus has a deep methane absorption band in its spectrum. In fact, the rings are brighter than Uranus at these wavelengths, with mean opposition K magnitudes of 12.0 and 13.1 respectively (Matthews, Nicholson, and Neugebauer 1981). The predictions of occultations by Uranus from Lick astrograph plates have been extended through 1984 by Klemola, Mink and Elliot (1981).

As a result of these predictions and infrared techniques, occultations have been observed regularly from the discovery in 1977 through the present. These observations are summarized in Table I. The most recent occultation, on 26 April 1981, was successfully observed from Siding Spring, Mount Stromlo, Kavalur and Naini Tal. At the time of this writing, the data have not been published.

What do the observations of Table I reveal as the components of the Uranian rings system? The only structures confirmed by all groups are nine narrow rings: 6, 5, 4, α, β, η, γ, δ and ε. The cumbersome notation arose, as is often the case in these matters, for historical reasons: see Elliot, Dunham and Mink (1977); Millis, Wasserman and Birch (1977); Elliot et al. (1978); and Nicholson et al. (1978). The occultation profiles of the nine rings are shown at low spatial resolution in Figure 1; the high-resolution structure of these rings will be discussed in the next section.

Other possible components of the ring system have been reported by several observers, but remain unconfirmed. The criteria for confirmation of ring structures are either (i) corresponding dips in signal can be identified in the data from two sites, or (ii) for a single site, corresponding dips having nearly identical structure are observed at equal distances from Uranus, when projected into its equatorial plane. Some latitude in the latter criterion would be acceptable to allow for elliptical rings. Reports of dips in signal that remain unexplained, have been given by Churms (1977), Tomita (1977), Bhattacharyya and Bappu (1977), Chen et al. (1978), Millis and Wasserman (1978), Bouchet, Perrier and Sicardy (1980), and Hubbard and Zellner (1980). These dips have not been confirmed as

Figure 1. Occultations by the rings of Uranus. The pre-immersion and post-emersion occultations by the rings of Uranus observed with the Kuiper Airborne Observatory (Elliot, Dunham and Mink 1977) have been plotted on the common scale of distance from the center of Uranus in the ring plane. Occultations corresponding to the nine confirmed rings are easily seen. Other possible occultation events are visible as shallow dips on the individual traces. Much (if not all) of the low frequency variations in the light curves are due to a variable amount of scattered moonlight on the telescope mirror. (After Elliot 1979).



ring structures, and it is doubtful that they could have been caused by small satellites, since none of the dips were deep enough to have been a total occultation of the star. To maintain the small satellite hypothesis, one would have to assume that these dips in signal were caused by grazing occultations or are due to diffraction effects. Most dips lasted too long for the lack of total occultation to be explained by diffraction, and it is highly unlikely that all were caused by grazing occultations. Although the causes of these dips in signal remain undetermined, mundane explanations are more probable and have not been ruled out: small clouds, telescope guiding errors, and starlight spilling out of the focal plane aperture due to seeing fluctuations.

A system of broad rings around Uranus, with an optical depth as great as 0.05, has been reported by Bhattacharyya and Bappu (1977) and Bhattacharyya et al. (1980). This system remains unconfirmed by other occultation data (Millis and Wasserman 1978; Nicholson et al. 1978), as well as the imaging data of Matthews, Nicholson and Neugebauer (1981). The latter authors conclude that any material composing such a system of broad rings must have an extremely low albedo to be consistent with their image contours.

STRUCTURE

The structural features of the rings that have been the most intriguing are their narrow widths and sharp edges. An example of these features is shown by the profile of the γ ring in Figure 2 (Elliot et al. 1981b). The points are the occultation data, which give the light transmission of the ring along the path probed by the star; the solid curve is a model occultation profile that would have been produced by an opaque ring, 3.4 kilometers wide. Although the model ring is opaque, with a "rectangular" optical depth profile, its occultation profile is not rectangular because of diffraction effects. In particular, the occultation profile does not reach zero intensity and diffraction fringes appear at the edge of the ring. Diffraction fringes occur also at the edges of some of the other rings - ε, for example - but the γ-ring profile has the largest fringes, relative to its depth, of the five main rings. Hence, it

Figure 2. Occultation profile of the γ ring. The points represent 20-ms averages of the data and the solid curve is a model profile for an occultation of a star 0.000 18 arcsec in diameter by an opaque ring 3.4 km wide. The peaks at the edges of the profile are due to Fresnel diffraction by the abrupt boundaries of the ring. (After Elliot et al. 1981b).

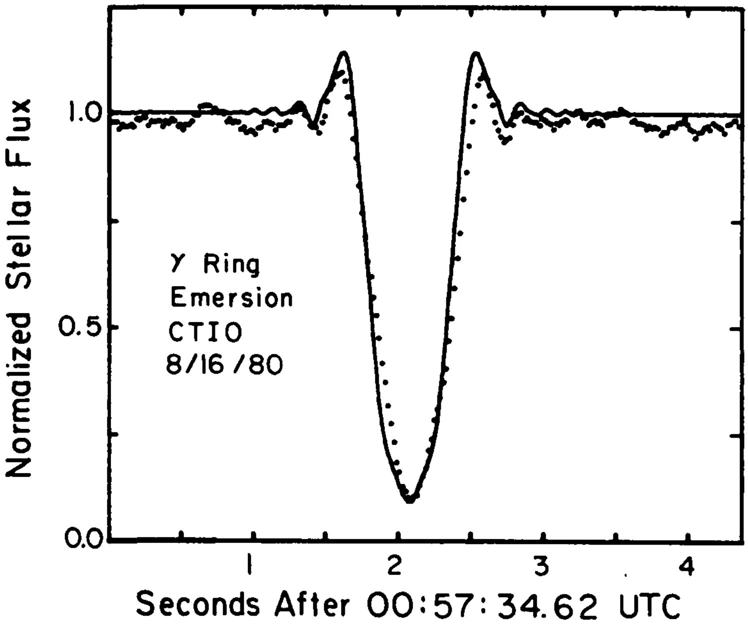
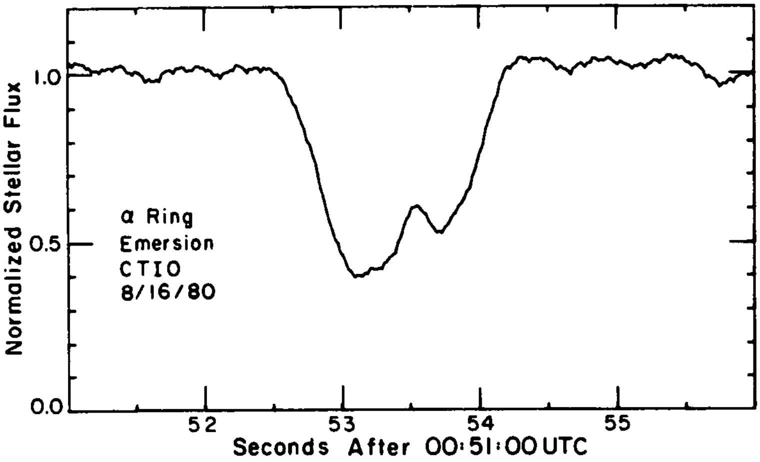


Figure 3. Occultation profile of the α ring. See text for possible interpretations of the "double-dip" structure. (After Elliot et al. 1981b).



has more abrupt edges than the α, β, δ and ε rings. Precise comparison with diffraction fringes produced by rings 6, 5, 4 and the core of the η ring is difficult because of the generally lower signal-to-noise ratio of these ring profiles.

Table II gives a summary of the observed ring structures. Rings 6, 5, 4, γ, δ and the core of the η ring are narrower than the resolution limit imposed by diffraction (4 km). The α ring sometimes shows a "double-dip" profile, an example of which can be seen in Figure 3. Resolution of the two peaks is barely above the diffraction limit, so we do not know whether the α ring is a single structured ring or two distinct rings, analogous to the "braided" F ring of Saturn (Smith et al. 1981).

The ε ring is the broadest ring, whose width varies between 20 and 100 km. Nicholson et al. (1978) showed that the width correlated linearly with the local radius of the ring, the broadest part occurring at apoapse and the narrowest part at periapse. This correlation implies that the ε ring precesses as a unit, which we shall discuss in the next section. The occultation profile of the ε ring shows an undulating structure (Millis, Wasserman and Birch 1977) that has remained the same over a period of years (Nicholson et al. 1978). This structure is evident in the broad sections of the ring, but is more difficult to discern in the narrow sections of the ring (for reasons discussed by Elliot et al. 1981a).

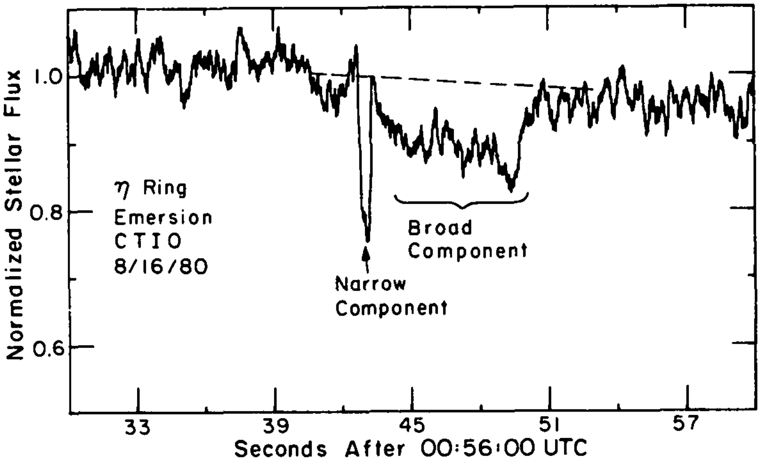
The most bizarre structure yet observed is that of the η ring (Figure 4). Originally, Elliot et al. (1978) reported it as a broad, circular ring, about 50 km wide. Later observations by Nicholson et al. (1978) indicated a narrow, circular ring of smaller radius. The apparent disagreement was resolved by data of higher signal-to-noise ratio obtained in August, 1980, which showed the η ring to be a broad ring with a narrow core at the inner edge of the broad component (Elliot 1979; Elliot et al. 1981b). The δ ring also shows a broad section of diffuse material adjacent to the main, narrow ring (Elliot et al. 1981b).

A simple model for the ring structure has been fitted to the ring profiles by Elliot et al. (1981a), who assume a trapezoidal shape for the ring profiles and include the effects of time constants

TABLE II. SUMMARY OF RING STRUCTURE

Ring	Mean Optical Depth	Mean Width (km)	Comments
6,5,4	≳0.2	<4	These rings have the lowest integrated optical depth and are the most difficult to detect.
α	0.8	7	Sometimes shows a "double-dip" structure (See Fig. 3); "braided" ring?
β	0.5	8	Occultation profile has flat bottom.
η	0.05	60	A broad ring containing an unresolved narrow core with mean optical depth ≳0.2.
γ	0.5	<4	Occultation profile shows the largest diffraction fringes, indicating sharper edges than the other rings.
δ	0.5	<4	Probable diffuse material adjacent to the main part of the ring.
ε	1 - 2	60	Width varies between 20 and 100 km; undulating structure in occultation profile.

Figure 4. Occultation profile of the η ring. The narrow component is unresolved and lies at the inner edge of the broad component, which is about 60 km wide. (After Elliot *et al.* 1981b).



in the data recording and the angular diameter of the occulted star. This model is adequate for obtaining ring widths and mid-occultation times, but a more sophisticated model should include diffraction effects and more realistic treatment of the α, ε and η rings.

RING ORBITS

Beginning with the original demonstration that narrow rings encircle Uranus (Elliot, Dunham and Mink, 1977), a series of improving kinematic models has been developed (Elliot et al. 1978; Nicholson et al. 1978; Elliot et al. 1981a, b; Nicholson, Matthews and Goldreich 1981a, b). The model of Elliot et al. (1981b) is fitted by least squares to the midtimes of the ring occultations and has the following free parameters: (i) the semi-major axis, a; orbital eccentricity, e; and references longitude of periapse, ω_0; for each ring; (ii) coefficients J_2 and J_4 that describe the zonal harmonics of the Uranian gravity field; (iii) α_p and δ_p, the RA and Decl. of the ring plane pole; (iv) corrections to the relative RA and Decl. of Uranus and the occulted star for each event. Altogether 41 parameters were fitted to 105 data points, which span nearly a four year interval.

The fitted parameters of interest are given in Table III, along with their formal errors from the fit. The main conclusions of the ring orbit solutions are (i) the rings fit the coplanar precession model with an rms precision of 0.3 sec in time (or 2.8 km in radius); (ii) the ring eccentricities, plotted against semi-major axis, show a decreasing trend (except for the ε ring); (iii) rings γ, δ and η possibly have "zero" eccentricity; and (iv) the semi-major axes of the rings do not align with three body resonances of known satellites (Dermott and Gold 1977; Goldreich and Nicholson 1977; Asknes 1977; Elliot et al. 1978).

Another result from the fit of the orbit model is that the rms error of the fit (0.3 sec) is much too large, since the occultation midtimes of the rings can be determined with an accuracy better than 0.1 sec. Hence, either (i) unidentified timing errors exist in the data set, or (ii) more effects should be included in the kinematic model. Orbital inclinations are obvious parameters to include, but

TABLE III

FITTED MODEL PARAMETERS[1]

(a) Orbital Elements

Ring	Semi-Major Axis, a (km)	Eccentricity $e \times 10^3$	Azimuth of Periapse ω_0 (degrees)[2]	Precession Rate From Fitted J_2 and J_4 (deg/day)	Precession Rate Fitted Individually (deg/day)
6	41863.8 ± 32.6	1.36 ± 0.07	235.9 ± 2.9	2.7600	2.7706 ± 0.0034
5	42270.3 ± 32.6	1.77 ± 0.06	181.8 ± 2.5	2.6678	2.6614 ± 0.0030
4	42598.3 ± 32.7	1.24 ± 0.09	120.1 ± 2.7	2.5963	2.5957 ± 0.0031
α	44750.5 ± 32.8	0.72 ± 0.03	331.4 ± 2.8	2.1832	2.1785 ± 0.0043
β	45693.8 ± 32.8	0.45 ± 0.03	231.3 ± 4.0	2.0288	2.0272 ± 0.0064
η	47207.1 ± 32.9	(0.03 ± 0.04)	(291.7 ± 88.3)	1.8094	. . .
γ	47655.4 ± 32.9	(0.04 ± 0.04)	(301.6 ± 49.1)	1.7503	. . .
δ	48332.0 ± 33.0	0.054 ± 0.035	139.0 ± 30.2	1.6657	. . .
ε	51179.7 ± 33.8	7.92 ± 0.04	215.6 ± 0.5	1.3625	1.3625 ± 0.0004

[1] For $M_u = 8.669 \times 10^{28}$ gm and $G = 6.670 \times 10^{-8}$ dyn cm^2 gm^{-2}

[2] At 20:00 UT on 10 March 1977

(b) Harmonic Coefficients of the Gravity Potential[3]

$J_2 = (3.352 \pm 0.006) \times 10^{-3}$

$J_4 = (-2.9 \pm 1.3) \times 10^{-5}$

(c) Pole of the Ring Plane

$\alpha_{1950.0} = 5^h\ 06^m\ 26^s.1 \pm 10^s.7$

$\delta_{1950.0} = +15°\ 13'\ 15'' \pm 3'3''$

[3] For a reference radius, R = 26,2000 km

This table was adapted from Elliot et al. (1981b).

are probably not the main effect causing the large residuals.

The final topic we discuss for the ring orbits is uniform precession, alluded to earlier in reference to the ε ring. Since the precession rate of a ring is a decreasing function of semi-major axis (see Eq. 1 of Elliot et al. 1981b), a ring of sufficient ellipticity would be disrupted by the different precession rates of the inner and outer particle orbits - unless the same precession rate for the entire ring is maintained by a force between ring particles in different orbits. By demonstrating the linear relation between width and radius for the ε ring, Nicholson et al. (1978) showed that ε ring precesses uniformly. The α and β rings have also been shown to be in uniform precession (Elliot et al. 1981a).

RESULTS FOR URANUS

From occultation observations, we obtain the following information about Uranus: (i) the coefficients J_2 and J_4 of the Uranian gravity potential; (ii) the coordinates (α_p, δ_p) of the ring plane pole; (iii) the equatorial radius, R_e, and ellipticity, ε; and (iv) the rotation period (from ε and J_2 under the assumption of hydrostatic equilibrium). The coefficients J_2 and J_4 are obtained directly from the ring orbit model (Table III) and can be used to constrain acceptable interior models for Uranus (MacFarlane and Hubbard, this conference; Podolak, this conference). Also obtained directly from the ring orbit model are the coordinates of the ring plane pole (Table III), which we can assume are also the coordinates of the Uranian north pole. For an unknown reason, these coordinates differ by several mean errors from the coordinates of the pole obtained from the satellite orbits (Dunham 1971, Elliot et al. 1981b).

The equatorial radius and ellipticity of Uranus are obtained from planetary occultation data, with the ring coordinate system as a reference. This allows chords from all occultations to be used in a single solution, which would not be possible without the rings. The values obtained by Elliot et al. (1981b), $R_e = 26{,}145 \pm 30$ km and $\varepsilon = 0.024 \pm 0.003$, refer to the occultation level ($\sim 8 \times 10^{13}$ cm^{-3} for an atmosphere of hydrogen and helium in their solar proportions).

These values supercede the original result of Elliot et al. (1980) and correct a systematic error in the earlier results. The occultation ellipticity agrees well with the value 0.022 ± 0.001 obtained by Franklin et al. (1980) from a reanalysis of the Stratoscope II images. The equatorial radius obtained from Stratoscope II by Danielson, Tomasko and Savage (1972), 25,900 ± 300 km, refers to the cloudtop level, which lies about 500 km below the occultation level. Hence, the cloudtop level implied by the occultation result is 25,650 km, which agrees with the Stratoscope II radius within its error.

The rotation period determined from ε and J_2 under the assumption of hydrostatic equilibrium (see Eq. 3 of Elliot et al. 1980) is 15.5 ± 1.3 hours. By the same method, the period obtained from the Stratoscope II ellipticity is 16.3 ± 0.5 hours (Franklin et al. 1980). One may question whether Uranus is sufficiently close to hydrostatic equilibrium for these estimates of the rotation period to be reliable. As a test of the method, we can use Jupiter because J_2, ε and its rotation period have each been measured independently. Jupiter's rotation period is $9^h\ 55^m$. This can be compared to $9^h\ 47^m$, the rotation period calculated from values of J_2 and ε given by Smoluchowski (1976) for the 1 bar pressure level. For Saturn, the period measured by Voyager 1 is $10^h\ 39^m$ (Desch and Kaiser 1981), which can be compared to the value $10^h\ 29^m$ that we calculated from ε and J_2 values measured by Pioneer (Gehrels et al. 1980, Anderson et al. 1980, Null et al. 1981). Hence, the assumption of hydrostatic equilibrium yields periods within 10^m of the correct ones for Jupiter and Saturn, and we can be optimistic about the success of this method for the rotation period of Uranus.

Periods of about 16 hours are obtained from some modern spectroscopic results (Munch and Hippelein 1979; Brown and Goody 1980), while other modern spectroscopic results (Hayes and Belton 1977; Trafton 1977) and unpublished photometric data (Smith and Slavsky 1979) favor longer periods. Our present knowledge of the rotation period has been reviewed by Goody at this conference.

RELATIONS TO DYNAMICAL MODELS

Several structural features and orbital properties of the rings have one or more proposed dynamical explanations. The sharp edges and narrow widths are apparently explained by small satellites that orbit nearby or within the rings. This idea has three possible scenarios. First, the model of Goldreich and Tremaine (1979a) postulates that each ring is constrained by two satellites, one with an orbit inside the ring and the other with an orbit outside the ring. Dermott, Gold and Sinclair (1979) have investigated a model that postulates a single constraining satellite within each ring. Since this model predicts an optical depth profile that is symmetrical about the mean radius of a ring cross-section, the model could not apply to the η ring (Figure 4). Finally, Cook and McIntosh (1981) propose that each ring was formed from a single satellite that is now dismembered into ring particles, so that each ring is held together by its own gravity. The gaseous model of the rings (Van Flandern 1979, 1980) is apparently untenable for reasons given by Hunten (1980), Fanale et al. (1980) and Gradie (1980).

Another effect requiring of a dynamical explanation is the uniform precession of the ϵ, β and α rings. After examining several mechanisms, Goldreich and Tremaine (1979b) conclude that self-gravity is the most likely cause. Their model, combined with the orbital parameters of the ϵ ring, implies a ring mass of 5×10^{18} gm. For the β ring, Elliot et al. (1981a) obtained a mass of 4×10^{16} gm, assuming the self-gravity model. The mass of the α ring is likely similar to that of the β ring (Elliot et al. 1981a).

On the basis of their dual satellite model, Goldreich and Tremaine (1981) have investigated what eccentricities would be expected for the ring orbits. They find that each ring would have a critical value of initial eccentricity, which would depend on the masses and distances of the constraining satellites. If the initial eccentricity is below the critical value, it would be damped to zero - forming a circular ring. Rings η, γ and δ might be examples. If the initial eccentricity is above the critical value, then it would increase as time goes on. So far, no explanation has been offered for the apparent decreasing trend (except for the ϵ ring) of ring eccentricities with increasing semi-major axis (see Figure 7 of Elliot et al. 1981b).

The unusual structure of the η ring (Figure 4) has been discussed at this conference by Cook and Dermott, but no models have yet been published.

PROSPECTS FOR THE FUTURE

For the next few years, we can expect new observations of the Uranian rings from three sources: occultations, Voyager and the Space Telescope.

Probably the most significant result that we can anticipate from further Earth-based occultation observations, would be the undisputed detection of a broad, diffuse component of the ring system. Such material must exist, at some level, as can be seen from the following argument. Relative to gravity, the magnitude of non-gravitational forces - such as the Poynting-Robertson effect and particle collisions - become greater for smaller particles. Hence, for some particle size, the non-gravitational forces will exceed the gravitational forces binding the rings, and the smaller particles will "leak out" from a narrow ring. These escaped particles will form a diffuse component of the ring system. The precise photometry required to detect this diffuse component is occasionally possible from the ground and can be routinely achieved with the Kuiper Airborne Observatory. Other knowledge to be gained from further ground-based occultation observations would be improved precision of ring orbits and optical depth profiles. Also, we need to find the reason for the unaccountably large residuals from the ring orbit solution, which might be caused by a yet unidentified dynamical effect.

Voyager's flyby of the Uranus system in 1986 will yield a variety of unique information. First, it should be able to locate satellites within the ring system and thereby tell us which (if any) of the constraining satellite models is correct. Also, Voyager imaging should be more sensitive than occultations to broad rings of low optical depth. Voyager images can resolve individual rings and yield the reflectance of each ring for a variety of wavelengths over a large range of phase angles. Although the resolution of the ring images will be only ~30 km due to smear, a stellar occultation observed with the photopolarimeter could achieve a spatial resolution of a few hundred meters (Stone, this conference). Because of constraints on the trajectory required to continue the mission to Neptune, values of J_2 and J_4 obtained by Voyager are expected to be much less precise than those that have been obtained from the ring precessions (see Table III and Stone, this conference).

The Space Telescope (ST), currently scheduled for launch in 1985 (Caldwell, this conference), will be a useful instrument for observation of the rings because of its access to far uv wavelengths and excellent resolution (about 0.1 arcsecond, which corresponds to 1000 km at the distance of Uranus). Hence, the ST should be able to obtain a reflection spectrum of the ε ring and perhaps several other rings as well. The resolution of the ST will also allow rejection of the background light from Uranus so that occultations can be observed in the far red and uv with much better signal-to-noise than can be achieved from the ground. On the ST, the High Speed Photometer (HSP) is being equipped with a red-sensitive photomultiplier (with a GaAs photocathode), particularly to observe stellar occultations by outer solar system bodies with methane absorption bands in their spectra. The occultation data in the uv will have three times better spatial resolution than the 2.2μ data because of the smaller size of Fresnel diffraction effects. The occultation profiles of the rings at uv and near ir wavelengths can be compared and will possibly yield information about the particle sizes in the rings. The superior resolution of the ST might also permit one of its cameras to detect small satellites within the ring system.

The ever more revealing observations of the Uranian rings through occultations, Voyager and the Space Telescope should continue to inspire progress in dynamical models for narrow rings and to improve our understanding of Uranus itself. And it is appropriate that these opportunities should help us celebrate the two-hundredth anniversary of Hershel's discovery.

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REFERENCES

Asknes, K. (1977). Quantitative analysis of the Dermott-Gold theory for Uranus's rings. Nature 269, 783.

Anderson, J.D., Null, G.W., Biller, E.D., Wong, S.K., Hubbard, W.B. and MacFarlane, J.J. (1980). Pioneer Saturn celestial mechanics experiment. Science 207, 449-452.

Bhattacharyya, J.C. and Bappu, M.K.V. (1977). Saturn-like ring system around Uranus. Nature 270, 503-506.

Bhattacharyya, J.C., Bappu, M.K.V., Mohin, S., Mahra, H.S. and Gupta, S.K. (1979). Extended ring system of Uranus. Moon and Planets 21, 393-404.

Bouchet, P., Perrier, C. and Sicardy, B. (1980). Occultation by Uranus. I.A.U. Circ. No. 3503.

Brown, R.A. and Goody, R.M. (1980). The rotation of Uranus. II. Astrophys. J. 235, 1066-1070.

Chen D.-H., Yang H.-Y., Wu C.-H., Wu Y.-C., Kiang S.-Y., Huang Y.-W., Yeh C.-T., Chai T.-S., Hsieh C.-C., Cheng C.-S. and Chang C. (1978). Photoelectric observation of the occultation of SAO 158687 by Uranian ring and the detection of Uranian ring signals from the light curve. Scientia Sinica XXI, 503-508.

Churms, J. (1977). Occultation of SAO 158687 by Uranian satellite belt. I.A.U. Circ. No. 3051.

Cook, A.F. and McIntosh, B.A. (1981). The rings of Uranus. Nature (submitted).

Danielson, R.E., Tomasko, M.G. and Savage, B.D. (1972). High resolution imagery of Uranus obtained from Stratoscope II. Astrophys J. 178, 887-900.

Dermott, S. and Gold T. (1977). The rings of Uranus: theory. Nature 267, 590-593.

Dermott, S.F., Gold, T. and Sinclair, A.T. (1979). The rings of Uranus: nature and origin. Astron. J. 84, 1225-1234.

Desch, M.D. and Kaiser, M.L. (1981). Voyager measurement of the rotation period of Saturn's magnetic field. Geophys. Res. Lett. (submitted).

Dunham, D.W. (1971). Motions of the satellites of Uranus. Ph.D. thesis, Yale University.

Elliot, J.L. (1979). Stellar occultation studies of the solar system. Ann. Rev. Astron. & Astrophys. 17, 445-475.

Elliot, J.L., Dunham. E.W. and Mink D.J. (1977). The rings of Uranus. Nature 267, 328-330.

Elliot, J.L., Dunham , E.W., Wasserman, L.H., Millis, R.L. and Churms, J. (1978). The radii of Uranian rings α, β, γ, δ, ε, η, 4, 5 and 6 from their occultation of SAO 158687. Astron. J. 83, 980-992.

Elliot, J.L., Dunham, E., Mink, D.J. and Churms, J. (1980). The radius and ellipticity of Uranus from its occultation of SAO 158687. Astrophys. J. 236, 1026-1030.

Elliot, J.L., Frogel, J.A., Elias, J.H., Glass, I.S., French, R.G., Mink, D.J. and Liller, W. (1981a). The 20 March 1980 occultation by the Uranian rings. Astron. J. 86, 127-134.

Elliot, J.L., French, R.G., Frogel, J.A., Elias, J.H., Mink, D.J. and Liller, W. (1981b). Orbits of nine Uranian rings. Astron. J. 86, 444-455.

Fanale, F.P., Veeder, G., Matson, D.L. and Johnson, T.V. (1980). Rings of Uranus: proposed model is unworkable. Science 208, 626.

Franklin, F.A., Avis, C.C., Columbo, G. and Shapiro, I.I. (1980). The geometric oblateness of Uranus. Astrophys. J. 236, 1031-1034.

Gehrels, T. et al. (1980). Imaging photopolarmeter on Pioneer Saturn. Science 207, 434-439.

Goldreich, P. and Nicholson, P.D. (1977). Revenge of tiny Miranda. Nature 269, 783-785.

Goldreich, P. and Tremaine, S. (1979a). Towards a theory for the Uranian rings. Nature 277, 97-99.

Goldreich, P. and Tremaine, S. (1979b). Precession of the ε ring of Uranus. Astron. J. 84, 1638-1641.

Goldreich, P. and Tremaine, S. (1981). The origin of the eccentricities of the rings of Uranus. Astrophys. J. 243, 1062-1075.

Gradie, J. (1980). Rings of Uranus: proposed model is unworkable. Science 207, 626-627.

Hayes, S.H. and Belton, M.J.S. (1977). The rotational periods of Uranus and Neptune. Icarus 32, 383-401.

Hubbard, W.B. and Zellner, B.H. (1980). Results from the 10 March 1977 occultation by the Uranus system. Astron. J. 85, 1663-1669.

Hunten, D.M. (1980). Rings of Uranus: proposed model is unworkable. Science 208, 625-626.

Ip, W.-H. (1980a). Physical studies of planetary rings. Space Sci. Rev. 26, 39-96.

Ip, W.-H. (1980b). New progress in the physical studies of planetary rings. Space Sci. Rev. 26, 97-109.

Klemola, A.R. and Marsden, B.G. (1977). Predicted occultations by the rings of Uranus 1977-1980. Astron. J. 82, 849-851.

Klemola, A.R., Mink, D.J. and Elliot, J.L. (1981). Predicted occultations by Uranus: 1981-1984. Astron. J. 86, 138-140.

Mahra, H.S. and Gupta, S.K. (1977). Occultation of SAO 158687 by Uranian rings. I.A.U. Circ. No. 3061.

Matthews, K., Nicholson, P.D. and Neugebauer, G. (1981). 2.2 Micron maps of the rings of Uranus. (preprint).

Millis, R.L., Wasserman, L.H., Elliot, J.L. and Dunham, E.W. (1977). The rings of Uranus: their widths and optical thicknesses. Bull. Amer. Astron. Soc. 9, 498.

Millis, R.L., Wasserman, L.H. and Birch, P. (1977). Detection of the rings of Uranus. Nature 267, 330-331.

Millis, R.L. and Wasserman, L.H. (1978). The occultation of BD-15°3969 by the rings of Uranus. Astron. J. 83, 993-998.

Münch, G. and Hippelein, H. (1979). The effects of seeing on the reflected spectrum of Uranus and Neptune. Astron. & Astrophys. 81, 189-197.

Nicholson, P.D., Matthews, K. and Goldreich, P. (1981a). The Uranus occultation of 10 June 1979. I. The rings. Astron. J. 86, 596-606.

Nicholson, P.D., Matthews, K. and Goldreich, P. (1981b). Radial widths, optical depths and eccentricities of the Uranian rings. Astron. J. (submitted).

Nicholson, P.D., Persson, S.E., Matthews, K., Goldreich, P. and Neugebauer, G. (1978). The rings of Uranus: results of the 1978 10 April occultation. Astron. J. 83, 1240-1248.

Null, G.W., Lau, E.L., Biller, E.D. and Anderson, J.D. (1981). Saturn gravity results obtained from Saturn Pioneer II tracking and Earth-based Saturn satellite data. Astron. J. 86, 456-468.

Owen, T., Danielson, G.E., Cook, A.F., Hansen, C., Hall, V. and Duxbury, T.C. (1979). Jupiter's rings. Nature 281, 442-446.

Persson, E., Nicholson, P., Matthews, K., Goldreich, P. and Neugebauer, G. (1978). Occultations by Uranian rings. I.A.U. Circ. No. 3215.

Smith, B.A. *et al*. (1981). Encounter with Saturn: Voyager imaging science results. Science 212, 163-190.

Smith, H.J. and Slavsky, D.B. (1979). Rotation period of Uranus. Bull. Amer. Astron. Soc. 11, 568.

Smoluchowski, R. (1976). Origin and structure of Jupiter and its satellites. In Jupiter (T. Gehrels, ed.), pp. 3-21. University of Arizona Press, Tucson.

Taylor, G.E. (1973). An occultation by Uranus. J. Brit. Astron. Assoc. 83, 352.

Tomita, K. (1977). Observation of occultation of the SAO 158687 star by Uranus at Dodaira Station. Tokyo Astr. Bull., Sec. Series, No. 250.

Trafton, L. (1977). Uranus' rotational period. Icarus 32, 402-412.

Van Flandern, T.C. (1979). Rings of Uranus: invisible and impossible? Science 204, 1076-1077.

Van Flandern, T.C. (1980) Rings of Uranus: proposed model is unworkable. Science 208, 627.