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THE D AND E RINGS OF SATURN

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ABSTRACT

CCD observations of Saturn Ring D, discovered by Guerin in 1969, confirm the existence of this inner ring and indicate that its surface brightness ranges from 0.03 (inner edge) to 0.05 (outer edge) relative to the maximum surface brightness of Ring B. If Ring D is composed of spherical, diffusely reflecting particles with average surface reflectivity equal to that of the particles in Ring B, the average normal optical thickness of Ring D is 0.02. Reanalysis of a photograph taken by Feibelman during the 1966 ring plane passage suggests a normal optical thickness for Ring E between 10^{-6} and 10^{-7}, depending upon the average reflectivity of the particles. No new observations of this outer ring will be possible until the earth passes through the Saturn ring plane in 1979–80.

I will discuss two rings of Saturn which cannot normally be seen; by that I mean rings which would be invisible to a visual observer using even the largest of telescopes. It must be said that, until quite recently, the very existence of both of these rings -- located interior to and exterior to the three bright rings -- was in serious question. Today we feel quite confident of the reality of the inner ring, while the outer ring probably still remains, in reality space, somewhere between Farrah Fawcett-Majors and Tinker Bell. The International Astronomical Union does recognize at least the hypothetical existence of both rings, however, and has designated the inner and outer as Rings D and E, respectively.

The outer ring has been reported by several visual observers since the turn of the century (Alexander, 1962), most notably by the famous French observer,

G. Fournier, and by the even more famous astrophysicist, Sir Arthur Stanley Eddington. Since we now know that the E ring is *much* too faint to be seen visually, it was perhaps an exercise of good judgement when Eddington decided to pursue a theoretical career. Ring E is in fact so faint that the only opportunity for detecting it at all happens during the time when the earth is passing through the Saturn ring plane. The most recent opportunity occurred in 1966 and we will have another chance in 1979-80.

The inner ring was first reported by Pierre Guérin after examining photographs that he had taken at Pic du Midi in 1969 (Guérin, 1970). Subsequent reexaminations of photographs by S. Larson at the Lunar and Planetary Laboratory of the University of Arizona and by myself at New Mexico State University tended to confirm the existence of Ring D, but the signal was buried uncomfortably far down in the noise of the light scattered by the bright rings and by Saturn itself. In 1975 JPL's Saturn Ring Study Team produced an impressive 150 page document entitled "The D Ring - Fact or Fiction" (JPL Document 760-134). The study concluded that the existence of the D ring could not be verified and that the maximum brightness of Ring D would have to be less than 0.01 of the maximum brightness of Ring B. However, recent studies by Larson (1978), using images obtained with a CCD camera, have provided quantitative confirmation of Ring D.

Looking more closely now at Ring E, the only quantitative data currently available (Smith *et al.*, 1975) are those which have been extracted from a single blue-light photographic image obtained during the 1966 opportunity by W.A. Feibelman at the Allegheny Observatory of the University of Pittsburgh (Feibelman, 1967). Although Feibelman had actually taken several dozen photographs of varying exposure with the Allegheny 76-cm refractor, only a single, 30-minute, overexposed image of Saturn showed a faint extension* of the visible rings. Fortunately, Feibelman's photograph also contains a dozen or so faint stars, thereby allowing a quantitative estimate of the brightness of the extended ring material. The only additional photographs known to show Ring E are several taken at the Catalina Observatory of the University of Arizona during the same opportunity in 1966 (Kuiper, 1974). Although the Arizona photographs tend to confirm the existence of the outer ring, the field of view was so small that no field stars were recorded and no quantitative brightness estimates are possible.

*The extension is most visible to the east of Saturn. The west side is cluttered by the overexposed images of Dione, Enceladus, Rhea and Titan

At the time that the Allegheny observation was made (15 November 1966), the ring plane was inclined 0°.233 to the line of sight. The projected width of Ring E would then be approximately 0.5 arc sec, considerably less than the 3.6 arc sec star images appearing on the same photograph. Thus, for photometric purposes, it is possible to treat the ring extension as a line source. The range over which the outer ring is seen extends from 3.3 to 6.5 Saturn radii (approximately 200,000 to 400,000 km) from the center of the planet. The inner limit is set by the core of the greatly overexposed image of Saturn itself, while the outer limit seems to be coincident with the edge of the annular halation area around the overexposed core. It seems likely that the faint ring extension is made visible by the photographic "inertia" provided by the halation annulus. If so, the ring may extend well beyond 6.5 Saturn radii. The uniformity over the observed range would also suggest that it probably extends inward to the outer edge of the visible rings.

Microdensitometry of the Feibelman image gives a line-source brightness of $m_B = 19.5 \pm 0.5$ magnitudes per linear arc sec. If we make the simplifying assumption that the ring is composed of diffusely reflecting, spherical particles, we can arrive at a normal optical thickness of the ring for any assumed average albedo of the individual ring particles. Assuming that the albedo extremes are bounded by granular, ice-covered surfaces (0.8) at one end and bare, carbonaceous-chrondritic material (0.05) at the other, we find the normal optical thickness to lie between $\tau = 1.0 \pm 0.5 \times 10^{-7}$ and $\tau = 1.6 \pm 0.7 \times 10^{-6}$.

The size distribution of particles in Ring E must be governed by the mechanisms of production and depletion. The Poynting-Robertson effect, for example, would have removed all primordial particles smaller than 7 cm over the age of the solar system. On the other hand, we might expect that new particles are being continuously created by meteoritic bombardment of larger particles near the outer edge of Ring A. Those spalled particles should then spiral outward under the influence of plasma drag. Such a mechanism would be increasingly effective with decreasing particle size and would tend, therefore, to populate the E ring with the smaller end of the spalled particle size-distribution range.

The hazard to spacecraft passing through Ring E depends, of course, on the distribution of particle size. As an example, if nearly all of the particles are very large, the separation between particles will be large compared to the size of the spacecraft and the probability of impact will be merely the normal optical thickness times a projection effect which is approximately the cosecant of the trajectory inclination. For even low inclination trajectories, this could hardly be considered a serious hazard. If the particles are very small, impacts are assured, but damage will likely be negligible. It is in the millimeter range of particle sizes that the hazard to spacecraft becomes greatest, but this may also be a range where primordial particles are depleted and steady-state production is relatively small.

Turning to the region inside the bright rings, our study of Ring D (Larson, 1978) has made use of CCD images of Saturn obtained in the 886-nm absorption band of methane. The absorption of reflected light within this band by methane in Saturn's atmosphere appreciably reduces one component of the scattered light which has made earlier attempts to detect this inner ring so difficult. Suppression of reflected light from Saturn is variable over the disk, as it depends upon height and scattering properties of the reflecting cloud layer. Averaged over the disk, however, the reduction in light reflected from the planet relative to that from the rings is about a factor of 10.

CCD images of Saturn and its rings were recorded in February and April 1977, using the University of Arizona 154-cm Catalina telescope. The phase angle was $0\overset{\circ}{.}14$ and $6\overset{\circ}{.}3$, respectively, and the ring plane was inclined 17° and 18° to the line of sight. Intensity profiles along the major axis of the rings were then compared with model intensity profiles convolved two-dimensionally with an appropriate point spread function (PSF). In order to provide a realistic PSF which would properly fit both the core and the wings of a smeared stellar image, we used a summed double gaussian. The model intensity profile for the three bright rings was based on microdensitometry of high-resolution photographic images obtained by Larson with the same telescope in 1974. The results are shown in Figure 1 which displays the observed profile along with both the convolved and unconvolved profiles of the model. It can be seen that the model requires a reflecting region interior to Ring C and that the surface brightness of the interior ring must decrease toward the planet. The surface brightness of Ring D at 886 nm varies between 0.03 and 0.05 that of Ring B.

If we again assume that Ring D is made up of spherical, diffusely reflecting particles, and that the average surface reflectivity is approximately equal to that of the particles in Ring B, the average normal optical thickness of the Ring D is 0.02. On the other hand, if the particles in Ring D are not ice covered, the normal optical thickness would be correspondingly higher. Larson (1978) further notes that the Ring D seems to follow the same opposition effect as that exhibited by the bright rings. The so called

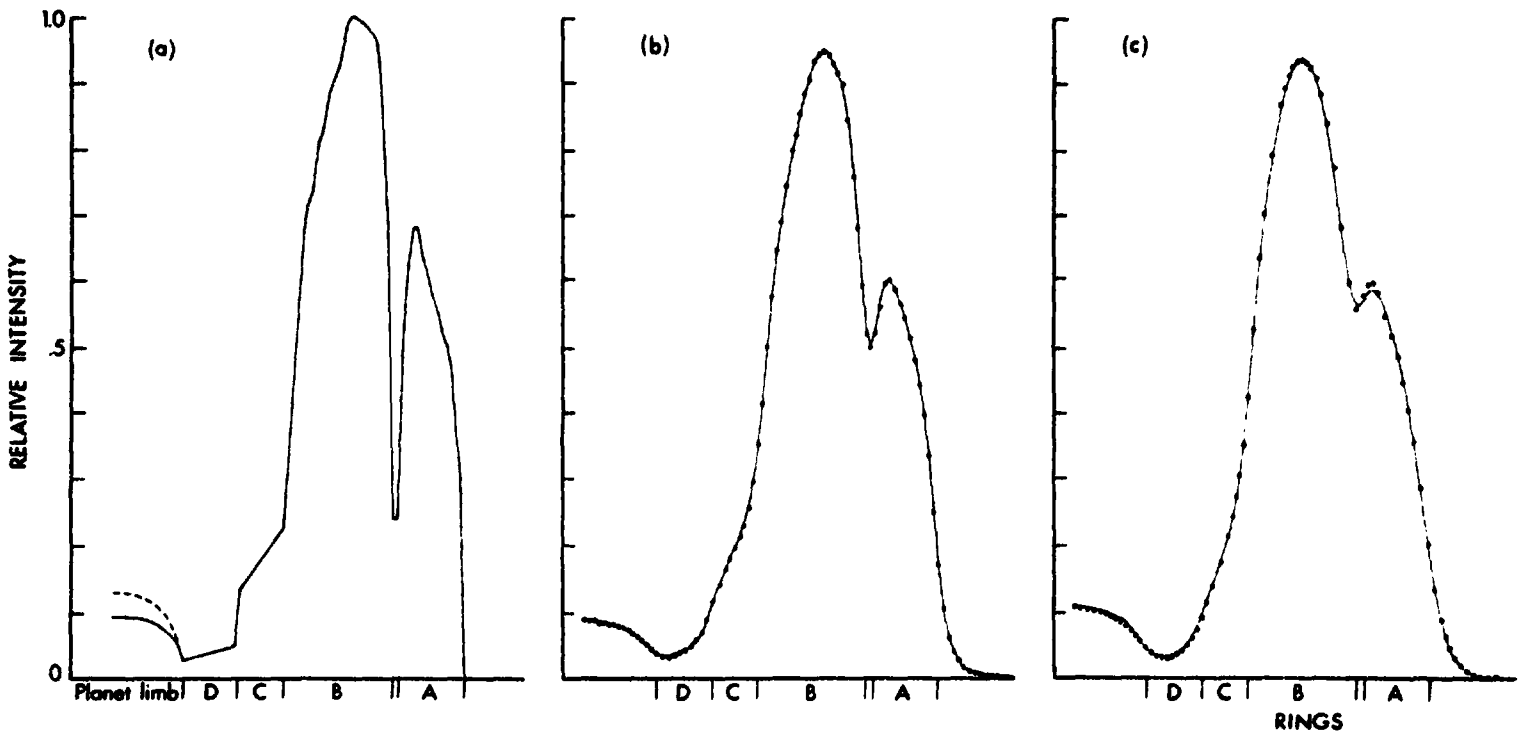

Figure 1. (a) Model intensity profiles of the rings. The solid and dashed lines represent the relative disk brightness at phase angles of 0.°14 and 6.°3 respectively. (b) Model convolved in two dimensions with a smearing function consisting of summed gaussians of 0.66 and 2.20 arc sec full width at half maximum. The dots are observational data from both ansae on 3 February 1977 at a phase angle of 0.°14. (c) Gaussians of 1.10 and 2.64 arcsec full width at half maximum. Dots are observational data from the east ansa on 22 April 1977 at a phase angle of 6.°3.

"Guérin Division" between Rings C and D was not observed, but this may be due to image quality which is somewhat inferior to that obtained by Guérin.

With regard to potential hazards to any future spacecraft attempting to fly through Ring D at any trajectory inclination, it is difficult to see any hope for survival unless all of the particles are large compared to the dimensions of the spacecraft itself.

As for future observations of these faint rings, I have already mentioned that 1979-80 will provide a good opportunity for groundbased telescopic studies of Ring E. Because of its very small optical thickness, it is unlikely that either Pioneer or Voyager will contribute anything new to our knowledge of the optical properties of this region. There is, however, the possibility that charged particle investigations will provide some new information, if indeed there is interaction between the trapped radiation and particulate material in the E Ring, as has been suggested by Van Allen (1976). The next good opportunity for ground-based studies of Ring D will not come until the mid to late 1980's. Long before that, Voyager should provide quantitative measurements of surface brightness, optical thickness and structure.

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DISCUSSION

J. CALDWELL: You said that Pioneer and Voyager wouldn't tell us much about the Ring E. But what about when Pioneer and Voyager actually go through the Ring E?

B. SMITH: The Voyager trajectory is such that it crosses the Saturn ring plane sometime shortly after leaving Jupiter and does not cross it again until it is very close to Saturn. So, as far as imaging is concerned, there's no hope of timing an exposure to look right in the plane. Yet, the optical thickness is so low you'd have to be exactly in the plane to be able to see it.

D. MORRISON: Perhaps one should note here that the first Voyager will not go that close to the rings, but both Pioneer 11 and the second Voyager, if it's on a Uranus trajectory, will go at about 2.37 Saturnian radii from the center of the planet.

D. WALLACE: Would you suggest that an Orbiter should be in the ring plane? You would discriminate then.

B. SMITH: Well, that might be discriminating the hard way. I don't recommend an orbiter in the ring plane.

J. POLLACK: Actually, from the point of view of other aspects of the ring, it probably would be useful to have the orbiter slightly inclined for two reasons: (1) You get a better ability to separate the ring mass from Saturn. (2) You have the ability to do some of the interesting bistatic radar experiments that I spoke about earlier.

D. HUNTEN: Not to mention imaging, which also requires being out of the ring plane.

D. MORRISON: This is an issue that we'll certainly want to come back to later, because if you are very far out of the plane of the rings, you may find that Titan is the only satellite that you can come close to, and there may be some trades that have to be made between multiple satellite encounters and getting a good look at the rings.