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The Jovian Ring

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The results of further measurements of the Jovian ring system are presented. The system has three major components: the bright ring, the faint sheet, and the out-of-plane halo. The bright ring has an outer radius of 1.81 ± 0.01 R_J, an inner radius 1.72 ± 0.01 R_J, an eccentricity not greater than 0.003 and a normal optical depth 3×10^{-5}. The faint sheet extends from the inner edge of the bright ring to the surface of Jupiter. Its optical depth is approximately 7×10^{-6}. Three arguments are presented to show that a halo of material envelops the above two rings and extends 10^4 km above the ring plane. A simple model is invoked to account for the halo by means of interactions between the Jovian magnetic field and charged ring particles less than 0.5 μm in diameter. The source of small particles is probably within the bright ring itself and may be due to micrometeorite impact into larger ring bodies. Small particles evolve in towards Jupiter under Poynting Robertson and other drag forces. The outer edge of the ring system is defined by the satellite 1979J1.

OBSERVATIONS

The ring of Jupiter comprises several distinct components [*Owen et al.*, 1979]. A bright ring about 6000 km in width has a relatively sharp outer boundary, now known to be coincident with the orbit of the small satellite 1979J1 [*Jewitt et al.*, 1979]. The inner edge is less distinct, and grades into a fainter component of roughly uniform brightness. The latter component appears to extend down to the atmosphere of Jupiter. A cloud of material envelops the above-mentioned components, forming a tenuous halo around them.

For simplicity in the discussion which follows, we refer to the above components of the ring as the bright ring, the faint sheet, and the halo, respectively, it being understood that the distinction is to some extent arbitrary, since the three components are all part of the one ring system. The components are identified in Figure 1.

The physical dimensions of the ring have been measured by several methods. The measurements presented here supercede previously reported values [*Smith et al.*, 1979*b*]. The radius of the outer edge of the bright ring has been determined from both inbound (small phase angle) and outbound (large phase angle) Voyager images. Results of the measurements are recorded in Table 1. With the exception of the measurement from the outbound image (FDS 20793.02) the measurements are mutually consistent and yield an outer radius of 1.81 ± 0.01 R_J (where 1 R_J is taken to be 71400 km). The ring radius obtained from the outbound frame FDS 20693.02 is 1.84 ± 0.01 R_J. The discrepancy between this value and the others may indicate a systematic error in the measurement. In this connection it should be noted that the method of measurement was necessarily different as a result of the absence of field stars in the outbound frame. Because of this the radius was determined by using spacecraft positional data alone. Alternatively, the discrepancy may be real and significant. Where the small phase angle observations reveal only the bright ring, those at high phase angle also show the other two components. The measurements at small phase angles probably refer to larger bodies in the ring, which are effective at backscattering sunlight. The appearance of the ring at large phase angles will be shown to be due to strong forward scattering by particles only an order of magnitude larger than the wavelength of visible light. Such particles may compose an extension from the bright ring, out to 1.84 R_J, which is not observable in the small phase angle images.

For convenience, the positions of other ring features have been measured with respect to the outer edge of the bright ring. The inner edge of the bright ring occurs at 1.72 ± 0.01 R_J. This measurement refers to the position at which the surface brightness of the ring falls to half its maximum value. The transition from the bright ring to the faint sheet occurs over a distance of approximately 0.02 R_J (1500 km). Hence the inner edge of the bright ring is less distinct than the outer edge, which decays over a distance of less than 0.01 R_J.

A search for detail in the bright ring has revealed only one unambiguous feature. This is a bright annulus at 1.79 R_J, with an apparent width of approximately 700 km. The annulus is about 10% brighter than the adjacent ring material. It is visible on outbound frames, and on the inbound Voyager 1 ring discovery image [*Owen et al.*, 1979, Figure 6]. Detection of other ring detail is limited by the smear motion present in the Voyager images. This motion approaches 0.01 R_J in many frames. Features substantially smaller than this cannot be observed in the Voyager images. Smear motion also limits the precision to which the gross dimensions of the Jupiter ring can be measured.

An attempt was made to determine the eccentricity of the outer edge of the bright ring. For this purpose, a least squares fit to the outer edge of the ring was made. However, owing to the combined effects of the image smear, the picture resolution, and the oblique viewing geometry (the spacecraft was only 2° above the ring plane), the fit was unable to significantly constrain the eccentricity.

Perhaps the best estimate of the eccentricity can be inferred from the ring radius measurements reported in Table 1. These measurements were made from photographs taken at widely different times and do not refer to similar azimuths in the ring. Neglecting the measurement from the outbound Voyager 2 frame (for reasons discussed above), the measurements suggest that the ring radius is independent of azimuth to within 0.01 R_J, so constraining the eccentricity of the outer edge of the bright ring to be less than about 0.003.

Estimates of the normal optical thickness τ of the bright ring were made using the relation $I = Fk\tau/\mu$, where I is the measured intensity of the ring, F the intensity of the incident solar radiation, k the geometric albedo of the individual ring particles, and μ the sine of the elevation angle of the space-

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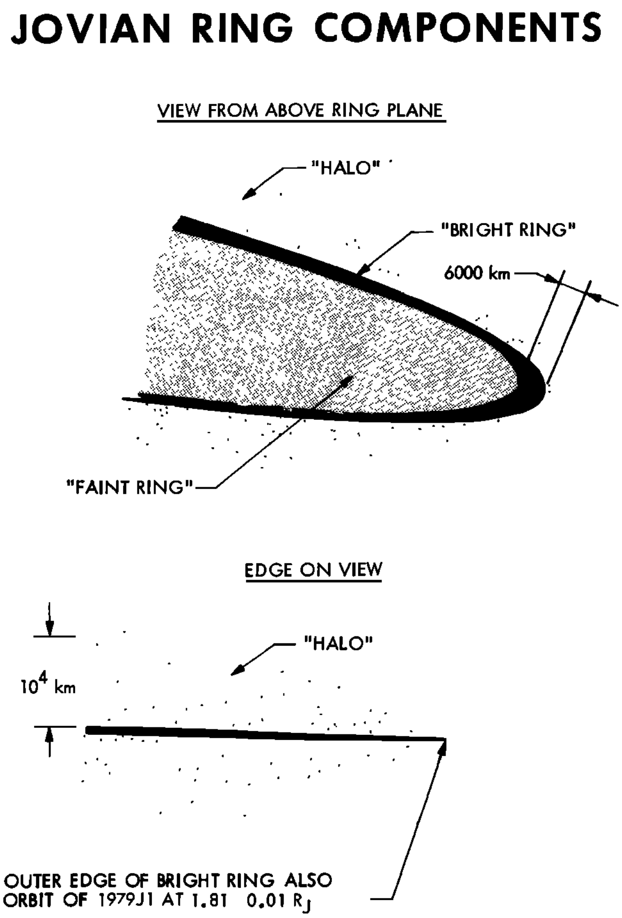

Fig. 1. This schematic drawing depicts the three major components of the Jovian ring.

craft above the ring plane. The relation is valid for small phase angles and assumes $\tau/\mu \ll 1$. Of the inbound images, only Voyager 1 frame FDS 16368.19 has sufficient signal to noise ratio to permit a significant measurement. Assuming that we can characterize the backscattering ring particles with an albedo $k = 0.04$ (representative of Amalthea [*Smith et al.*, 1979*a*], and of 1979J1 [*Jewitt et al.*, 1979], for example), we obtain $\tau = 3 \times 10^{-5}$ for the bright ring. The faint sheet is not visible in the Voyager 1 frame. In outbound Voyager 2 frames it has approximately one quarter of the brightness of the bright ring, possibly suggesting $\tau \sim 7 \times 10^{-6}$ for the faint sheet. The assumed albedo of 0.04 is characteristic of rock rather than ice particles. This assumption is justified later.

Similar optical depths are obtained from Pioneer 11 high-energy proton flux measurements made while the spacecraft passed under the ring in 1974 [*Acuna and Ness*, 1976]. The fluxes were observed to decrease at the locations of the known Jovian satellites and at the location of the (then unknown) ring. If we assume that the drift rate for high energy protons at the distance of the ring (1.8 R_J) is the same as the drift rate at Amalthea (2.5 R_J), the depths of the proton absorptions due to the two objects should be in proportion to their respective cross sections. The observed absorptions are in fact of similar depths. Hence the total solid cross section of the ring is comparable to that of Amalthea, namely, 1.1×10^{11} m^2. If spread uniformly over the bright ring, between radii of 1.81 and 1.72 R_J, this would give an optical depth of 2×10^{-5}. Considering the nature of the approximations made, the agreement between this and the value obtained from optical measurements is encouraging. The optical depths obtained are consistent with upper limits of about 3×10^{-4} imposed by IRIS observations at 25 μm wavelength [*Hanel et al.*, 1979].

TABLE 1. The Radius of the Bright Ring

Method of Determination	Frame Number*	Radius (R_J)
Star background	FDS 16368.19 (NA inbound)	1.81†
Star background	FDS 20630.53 (WA inbound)	1.81 ± 0.01
Star background	FDS 20630.52 (NA inbound)	1.81 ± 0.01
Picture geometry	FDS 20693.02 (WA outbound)	1.84 ± 0.01

*NA, narrow angle frame; WA, wide angle frame.

†Measurement obtained from Voyager 1 discovery image by T. Duxbury, JPL, no error quoted.

Figure 2 presents a scattering diagram for the bright ring. The variation of the phase angle around the ring was calculated from the known geometry of the Sun/Jupiter/spacecraft system, and from the measured dimensions of the Jovian ring. The above frame samples phase angles from approximately 174° to 176°. The variation of the scattering angle (the complement of the phase angle) is illustrated in Figure 3.

Assuming that the ring particles are all the same size, the scattering properties of the ring are consistent with those to be expected from Mie scatterers having a size parameter between 20 and 35 (the size parameter equals the ratio of the circumference of the particle to the wavelength). The scattering functions were obtained from the Mie scattering tabulations of *Gumprecht et al.* [1952].

The particle size determined from the scattering diagram is probably good to within a factor of 2. The calculations were made under the assumptions of negligible interparticle shadowing and negligible interparticle scattering, these assumptions being validated by the very low optical depths in the ring. The result states that the photometric properties of the bright ring in the clear filter (effective wavelength ~0.5 μm), in the phase angle range 174° to 176°, can be matched by perfect Mie scatterers, assumed spheroidal, with diameters of about 5 μm. It is unlikely that the ring particles are all the same size,

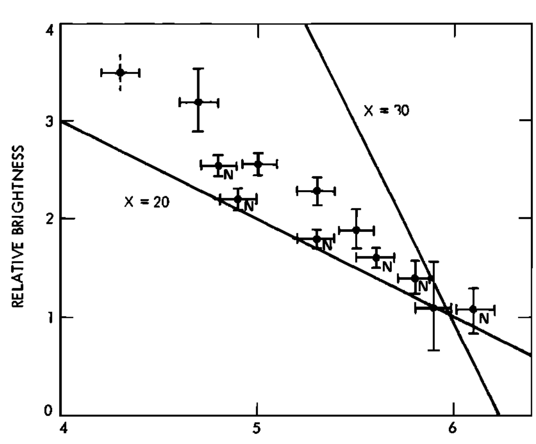

Fig. 2. This figure shows the scattered brightness from the Jovian ring, measured from the Voyager narrow angle picture sequence FDS 20692.37 to FDS 20692.57. The scattering angle, defined as 180° minus the phase angle, is plotted on the abscissa. The brightness measurements have been corrected for the variation of viewing angle around the ring and are normalized to unity at 6° scattering angle. The lines on the graph were taken from *Gumprecht et al.* [1952]. The measurements suggest a scattering parameter x ~ 30, i.e., a particle diameter of approximately 5 μm. Measurements from areas on the near arm are marked 'N.'

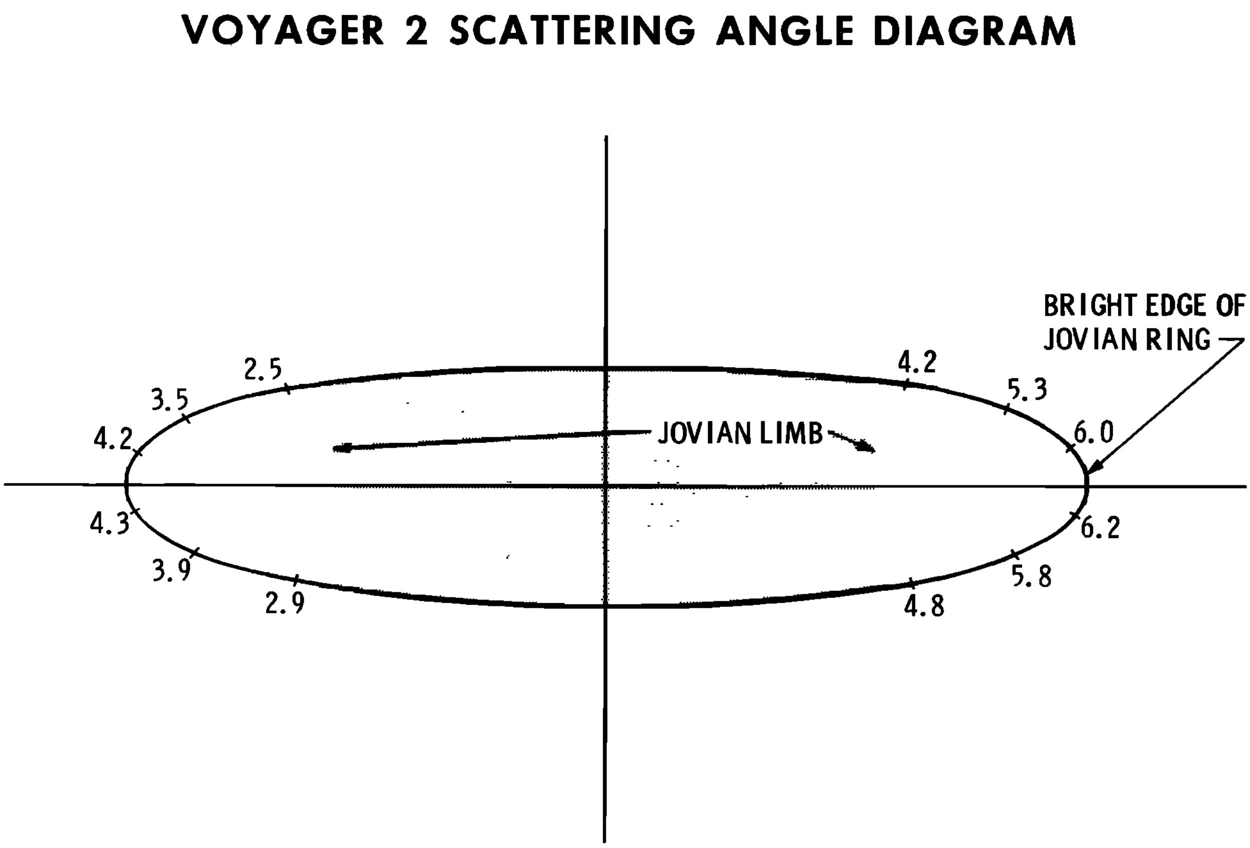

Fig. 3. This figure shows the variation of scattering angle around the Jovian ring as seen by Voyager 2 cameras 25 hours after closest approach to the planet. The calculations correspond approximately with the Voyager narrow angle ring picture sequence used to obtain Figure 2.

however. Most likely the ring comprises a distribution of particle sizes. At the very large phase angles sampled in frame FDS 20693.02 and in the other outbound Voyager frames, only particles with dimensions of a few microns would have sufficiently strong forward scattering to be detectable. Conversely, the small phase angle images might reveal those particles which have greater backscattering efficiency, probably those much larger than a few microns. There is some evidence for this interpretation. If the 5 μm particle size (as determined from large phase angle images) is used to predict the ring brightness at small phase angles, the result is unsatisfactory. The ring brightness at small phase angles is greater than would be expected if the ring comprised 5-μm particles only.

The detailed analysis of the photometric properties of the ring is complicated by ring material which evidently lies above the plane of the bright ring. Evidence for this 'halo material' is three-fold.

First, close examination of the shadow of the planet on the ring reveals an unexpected curvature (Figure 4). The curvature of the shadow edge persists when the 17 pixels of smear motion are removed from the image. If the ring material were entirely in the equatorial plane of the planet, the shadow edge would be straight and would lie along the intersection of the (roughly cylindrical) shadow of Jupiter with the ring plane. The observed curvature is consistent with the presence of out-of-plane material catching sunlight near the shadow edge.

Second, the material seen beyond the outer edge of the bright ring does not lie within an ellipse concentric with the bright ring but instead fades away at the ansa. This precludes the possibility that the material lies in the plane of the bright ring. The observation is consistent with the existence of out-of-plane material.

Third, the variation of phase angle with azimuth around the bright ring is such that some points on near and far arms of the ring possess the same phase angle. However, photometry of the bright ring demonstrates that the far arm is consistently brighter than the near arm, when areas with the same phase angle are compared (see Figure 3). This remains the case when various viewing geometry effects are taken into account, including the different values of spacecraft elevation angle as seen from points on near and far arms and the possible contribution of Jupiter-shine off particles in the far arm. The simplest way to account for this anomaly is by the introduction of material into the line of sight to the far arm. This material would add to the brightness of the far arm (again assuming $\tau \ll 1$ along the line of sight).

Taken together, it is believed that these three arguments indicate the existence of out-of-plane material beyond reasonable doubt. Direct measurement of high phase angle frames yields a characteristic halo dimension of 10^4 km, normal to the plane of the bright ring. The images, especially FDS 20693.02 and FDS 20691.28 suggest the out-of-plane material forms a broad lenslike halo, the outer limit being beyond 1.8 R_J (see Figure 5). There is a slight north/south asymmetry in the halo, with respect to the bright ring. This asymmetry could be removed by displacing the entire halo 300 km to the north.

DISCUSSION

The several characteristics of the Jovian ring which need to be accounted for by any model, include the following: (1) The

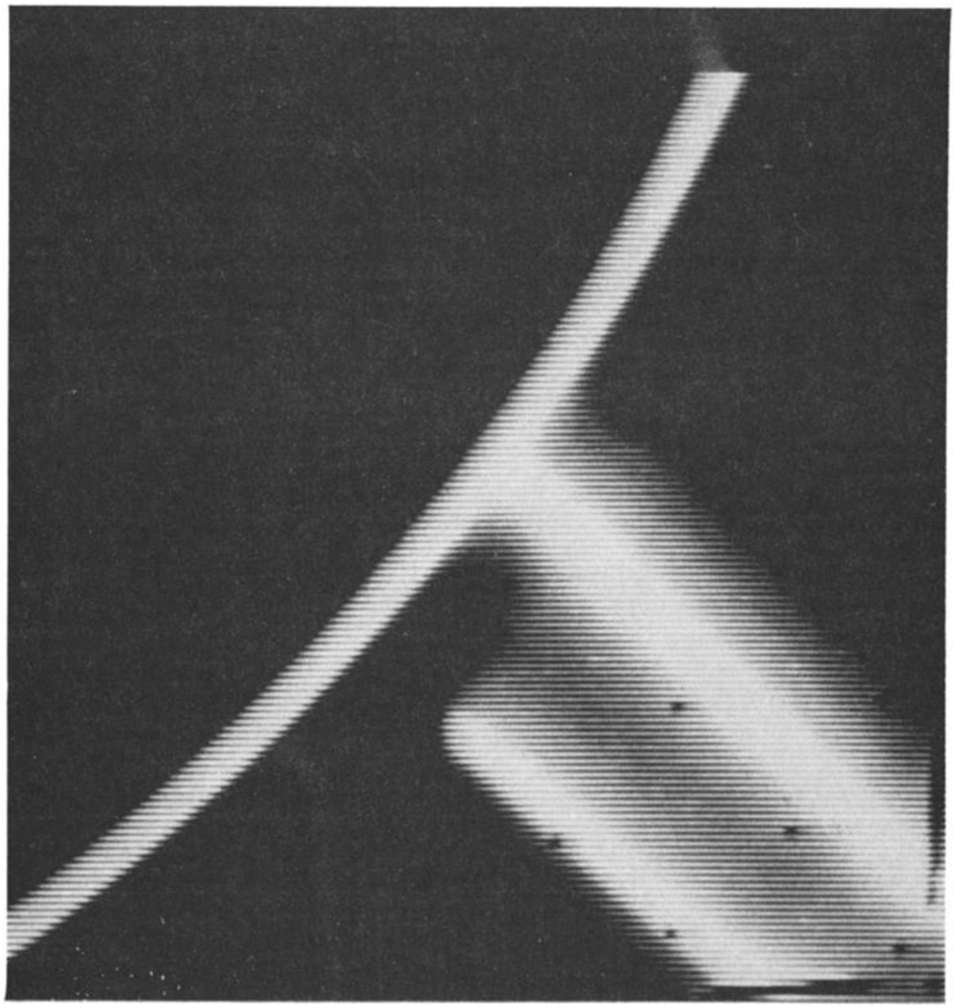

Fig. 4. The data in this picture has had a severe contrast enhancement to show the halo and Jupiter's shadow on the ring. The shadow is visible as a curved line which cuts across the near arm of the ring. The thin arc is the limb of the planet.

very sharp outer edge and less sharp, though still distinct, inner edge of the bright ring, (2) the narrow bright annulus at 1.79 R_J, (3) the faint sheet, (4) the broad halo which envelopes the other ring components, and (5) the photometric properties of the ring, including the very small optical depths. Important questions exist regarding the nature of the ring particles, including their composition and their source, and regarding the evolution of their orbits.

We begin by considering relevant time scales. The Poynting-Robertson orbital decay time for a particle of radius a is given by

$$t_p \sim \frac{\rho a c^2}{F_\odot} \ln \frac{r_i}{r_f}$$

where ρ is the particle density, c the speed of light, $F_\odot$ the flux of solar radiation falling on the particle, and r_i and r_f are the initial and final orbital radii of the particle. For a rock grain ($\rho = 3000$ kg m^{-3}), radius $a = 2.5 \times 10^{-6}$ m, with $F_\odot = 50$ W m^{-2}, the time scale for orbital collapse from $r_i = 1.8\ R_J$ to $r_f = 1.0\ R_J$ is $t_p \sim 2.5 \times 10^5$ years.

The lifetime set by sputtering is even shorter. The sputtering lifetime is $t_s \sim a/R$, where R is the sputtering loss rate (m/yr). Estimates of R for the Jovian environment vary, but values of order 10^{-7} m/yr seem likely [*Haff et al.*, 1979]. For a 5-μm grain, $t_s \sim 10^2$ years.

Clearly, the small particles in the Jovian ring must have been created recently. Plausible sources include micrometeorites from the interplanetary medium, micrometeorite impact erosion debris from Amalthea or 1979 JI, or even magnetically swept 'dust' from the plumes on Io [*Johnson et al.*, 1980]. These sources may contribute to the particles in the ring, though, for example, no transport mechanism for charged dust from Io has been demonstrated. However, the above mechanisms do not account for the larger ring particles which may be necessary to explain the backscatter images of the ring. We favor sources within the bright ring itself. Ring particles would collide on a time scale $t_c \sim 1/\Omega\tau$, where Ω is the Keplerian orbital motion appropriate for the bright ring and τ is the normal optical depth. Taking $\Omega = 2.5 \times 10^{-4}$ s^{-1} and $\tau = 3 \times 10^{-5}$, we find $t_c \sim 5$ years. At each collision, material might chip from larger bodies to maintain the small particle population. However, because of the large value of the collision time scale (5 years verses about 5 hours for Saturn's B ring), it is likely that micrometeorite erosion of larger bodies in the ring dominates collisions as a source of small particles.

It is of interest to estimate the possible dimensions of the inferred larger ring bodies. An absolute upper limit of approximately 1 km diameter is imposed by the Voyager images (bodies much larger than this would be individually visible in the ring pictures). In the lifetime of the solar system, the

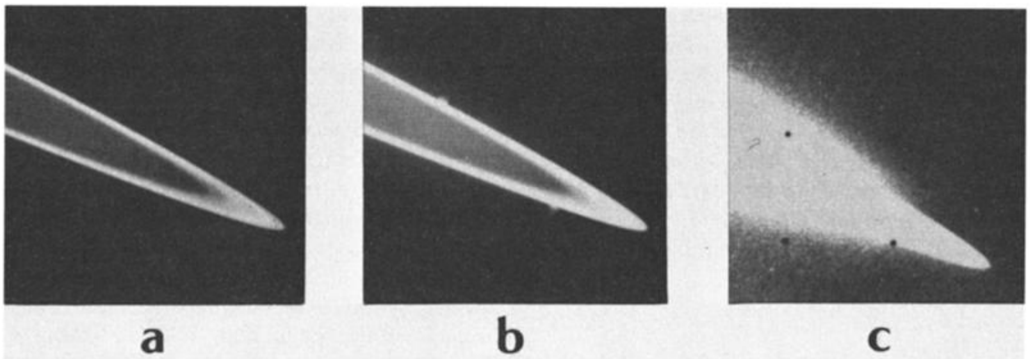

Fig. 5. The three images of the Jovian ring, all from FDS 20693.02, have been processed to show (*a*) the bright ring, (*b*) the interior faint ring, and (*c*) the out-of-plane halo.

Poynting-Robertson effect would have removed all bodies less than about 1 m diameter from the bright ring (however, there is no reason to believe the ring is as old as the solar system). Other constraints, imposed by the probable lifetimes of particles against sputtering or against micrometeorite erosion, are less significant, since erosion debris produced by these mechanisms may be almost entirely recaptured by the parent bodies.

Small particles produced by micrometeorite erosion or by other mechanisms may become subject to orbital decay by Poynting-Robertson drag forces. Such particles would evolve from the bright ring into the faint sheet over times of order t_p. Since we found $t_s < t_p$, we might expect to see a truncated inner edge to the faint sheet, corresponding to the removal of grains by sputtering. That we do not see such an edge may suggest that sputtered particles circulate around Jupiter and restick on grain surfaces, so that there is an equilibrium grain size. Alternatively, the sputtering rate R may be incorrect, or there may be an additional source of small particles in the faint sheet itself.

The composition of the ring particles cannot be deduced from the Voyager images alone. However, to first order we are concerned only to know whether the particles are of ice or of rock (metal particles are unlikely on cosmochemical grounds).

Water ice at the distance of Jupiter from the sun evaporates at a rate probably not greater than 10^{-6} m/yr [*Lebofsky*, 1975]. Evaporation of micron size ice grains would occur in only a year if this rate is applicable. Additionally, ice grains are more susceptible to sputtering erosion than are rock grains. For these reasons it seems more probable that the grains are rock rather than ice. Also, the two objects closest to the ring, 1979J1 and Amalthea, are known to be rocky by virtue of their low albedos. This too is suggestive of a rock ring rather than an ice ring, although the evidence is not compelling. Perhaps the strongest evidence for a nonicy composition is provided by the reflection spectrum of the ring, which cannot be matched by the spectra of H_2O, CH_4, or NH_3 ices [*Neugebauer et al.*, 1981].

The sharp outer edge of the bright ring suggests that it is not spreading outward. Interparticle collisions would normally be expected to cause such spreading. A similar situation exists with the Uranian rings, which are very narrow and have very sharp boundaries [*Nicholson et al.*, 1978]. To account for these boundaires, *Goldreich and Tremaine* [1979] have proposed that the rings are confined by tiny satellites. When ring particles approach the orbits of the satellites, oscillations build up in the particle orbits causing them to move in and out radially with respect to distant ring particles. Such oscillating particles may then undergo collisions with other ring particles, at which time their velocity vectors become reoriented. By this process, the satellites and rings effectively repel each other [*Lin and Papalouzou*, 1979]. The recently discovered satellite 1979J1 probably confines the Jupiter ring in this way. Its discovery provides strong evidence for the action of the above process.

The inner edge of the bright ring may suggest the presence of a guardian satellite at about 1.72 R_J. Alternatively, the spreading time for the bright ring may be long in comparison with the age of the ring in which case the bright ring may be unconfined on its inner edge and yet still possess a distinct boundary. A very careful search for a possible second guardian satellite has been conducted, with negative results. However, the Voyager images cover only two thirds of the ring, and such a satellite may have been missed.

It is of interest to estimate the mass of the Jupiter ring. This can be done from the knowledge that the total solid cross section presented by the ring is of order $C = 10^{11}$ m^2. If we assume that the ring particles are monodispersed, the total mass of the ring can be written $m \sim \rho a C$. An upper limit to a can be set equal to 1 km: such 'particles' would be individually visible in the Jupiter ring. Taking the density to be 3000 kg m^{-3}, as before, we obtain $m \sim 10^{17}$ kg as a rough upper limit to the ring mass. The radius of 1979J1 is approximately 15 km, which, assuming a similar value for the density, gives the satellite mass to be $\sim 4 \times 10^{16}$ kg. Hence, it is unlikely that the ring mass substantially exceeds the satellite mass.

The halo enveloping the main components of the ring indicates the action of out of plane forces on ring particles. A possible mechanism is outlined below.

In general, materials placed in the interplanetary environment acquire a net potential relative to the surrounding plasma. The magnitude and sign of the potential are determined by a balance between charging due to the photoelectric effect, electron and proton sticking, high-energy electron and proton induced seconary electron emission and possibly other effects [*Wyatt*, 1969]. A detailed balance calculation for Jupiter ring particles is at present impossible, but a plausible value for a dielectric in the ring environment might be -10 V [*Consolmagno*, 1980]. Such potential would render ring particles susceptible to interaction with the Jovian magnetic field via the Lorentz force. Because the Jovian best fit dipole is inclined to the spin axis of the planet by about 10°, the Lorentz force has an out-of-plane component. As seen from a ring particle, this component oscillates through the ring plane with a frequency Ω-ω, where Ω is the local orbital frequency and ω is the spinrate of the (corotational) magnetosphere. At the bright ring, the oscillation has a period of 23 hours. Small particles will be lifted out of the plane into the halo. The transition size between halo particles and those which remain in the ring plane may be found by comparing the gyration frequency ω_g with the orbital frequency. When $\omega_g \ll \Omega$, the motion is predominantly gravitational. When $\omega_g \gg \Omega$, a particle may make many gyrations in a single orbit and the motion is dominated by the Lorentz force. The transition between the two regimes occurs when $\omega_g \approx \Omega$.

We find

$$\frac{\omega_g}{\Omega} = \frac{3B\varepsilon V}{\rho \Omega a^2}$$

where B is the local magnetic flux density, ε is the permittivity of space, and V the potential on a grain of density ρ and radius a. We take $B = 10^{-4}$ T, $\varepsilon = 8.8 \times 10^{-12}$ F m^{-1}, and $\rho = 3000$ kg m^{-3} to find $\omega_g/\Omega = 3.5 \times 10^{-15}\ V/a^2$. For $V = 10$ V, the left-hand side equals unity for a particle radius $a = 2 \times 10^{-7}$ m. This is consistent with the observation that there are particles of 5-μm diameter in the bright ring.

If we make the further assumption that we can treat the motion of a charged grain to be independent of all other grains, it is possible to estimate the height z to which a charged grain may ascend from the plane. Considering only the component of the Lorentz force perpendicular to the ring plane acting on a particle at distance r from Jupiter, assuming $z/r \ll 1$, and further treating the Jovian magnetic field as an inclined dipole, we obtain

$$z = \frac{3B_x V\varepsilon}{\rho a^2} \frac{(\Omega - \omega)r}{\omega(2\Omega - \omega)}$$

where B_x is the component of the magnetic field in the ring plane, ($B_x \sim 10^{-5}$ T). We find $z \sim 2.7 \times 10^{-8}\ V/a^2$. For a potential of 10 V, particles with diameters 10^{-7} m may ascend to $z \sim 10^7$ m. Particles 100 times larger (such as those observed in the bright ring), rise to only 10^3 m from the equatorial plane. This value is consistent with the available upper limit to the bright ring thickness of 3×10^4 m [*Smith et al.*, 1979*b*].

The offset of the symmetry plane of the halo from the plane of the bright ring may be related to the offset of the best fit magnetic dipole from the center of Jupiter. However, the latter offset has not been determined unambiguously [*Smith and Gulkis*, 1979], so that a direct comparison is not possible.

Collected samples of interplanetary dust particles often show a complex aggregate structure [*Millman*, 1975]. Particles with dimensions 10^{-6} or 10^{-5} m may compose bound collections of much smaller grains (typically, 10^{-7} m). Electrostatic effects in the Jupiter ring may act to disrupt such aggregates or to prevent their formation.

SUMMARY

The physical properties of the Jovian ring are reported. The bright ring has an outer radius 1.81 ± 0.01 R_J and an inner radius 1.72 ± 0.01 R_J. A brighter region at 1.79 R_J suggests the presence of an enhanced concentration of ring particles at this distance. In addition to the faint sheet, which probably comprises small particles moving in towards Jupiter under the action of drag forces, there is a halo of particles which extends at least 10^4 km above the ring plane.

The satellite 1979J1 defines the outer edge of the bright ring by gravitationally scattering ring particles away from itself in a process already invoked by *Goldreich and Tremaine* [1980] to explain certain properties of the Uranian rings. Another satellite may exist at the location of the inner edge of the bright ring, though a search for it has proved negative.

The bright ring probably contains the source of the small particles seen in high phase angle pictures. Particles may be produced by micrometeorite erosion of larger ring bodies, probably between 1 m and 1 km in diameter, or of 1979J1.

Particles with diameters less than about 0.5 μm are strongly affected by the Jovian magnetic field and are swept out of the ring plane by it. Elementary calculations suggest that Lorentz forces, acting on particles charged to a potential of about 10 V, satisfactorily account for the halo.

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