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ON A SUSPECTED RING EXTERNAL TO THE VISIBLE RINGS OF SATURN

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# ABSTRACT

Reexamination of a photograph of Saturn taken on 15 November 1966 when the earth was nearly in the ring plane indicates that ring material does exist outside the visible rings, extending to more than 6 Saturnian radii. The observed brightness in blue light was estimated to be  $m_B = 19.5 \pm 0.5$  per linear arc second, implying a normal optical thickness,  $\tau \approx 10^{-7}$  for ice-covered particles. For spacecraft passing through this region, the hazards are found to be minimal.

The potential hazards encountered by spacecraft approaching Saturn's ring plane, as well as the inherent scientific significance of particles located outside of Ring A, has caused us to re-examine in greater detail the possible existence of an extensive external ring as reported previously by one of us (Feibelman 1967).

During the 1966 edge-on presentation of the Saturnian ring plane to the earth, several dozen photographs of varying length were taken with the 76 cm f/18.5 photographic refractor at the Allegheny Observatory of the University of Pittsburgh. The plate scale of the refractor is 14.6 arcsec/mm for the 380 nm to 500 nm spectral region. Throughout the 1966-67 opportunity, observations were made on 28 Oct, 15 Nov, 22 Nov, 13 Dec, 10 Jan and 17 Jan. Except for a few exposures on 28 Oct taken in the red region through a Corning 2403 filter, all others were obtained on Eastman 103a-0 antihalation-backed spectroscopic film without filters to avoid any possibility of internal reflections giving rise to ghost images.

Exposures ranged from a few seconds (for satellite identification) to 30 minutes duration, yielding a greatly overexposed image of the planet. A 30-minute exposure taken on 15 November 1966 showing a very faint extension of the nearly edge-on ring plane to a distance of approximately 6.5 Saturnian radii forms the basis for the following discussion.

A ring of particles external to Ring A has been referred to in the literature both as the D ring and the D' ring. In order to avoid confusion with the suspected ring internal to Ring C, we will refer to the external ring as the Z ring. If its existence is confirmed during the earth's next ring-plane passage in 1980, a permanent name will be given by the IAU Working Group for Planetary System Nomenclature.

The 15 November Allegheny photograph consists of a swollen, overexposed, high-density image of Saturn with a radius of 3.3 Saturnian radii ( $3.3 R_S$ ) and an annular photographic halation area with a radius of approximately  $6.5 R_S$ . Images of the satellites Enceladus, Dione, Rhea, Titan, Hyperion and Iapetus along with a dozen or so stars are recorded. The satellite Mimas was behind the globe of Saturn at the time, Tethys is invisible within the dense overexposed image of Saturn and Phoebe was outside of the 9.3 by 6.1 arc-minute field of view. Of particular interest is an apparent brightening in the ring plane, coincident with the hypothetical Z ring and extending from the outer edge of the overexposed core ( $3.3 R_S$ ) to the outer edge of the annular halation area ( $6.5 R_S$ ) on the east side of Saturn. There seems to be a very slight diminution in intensity with increasing distance from the planet. Although its appearance is certainly suggestive of being a real feature, the contrast is marginal and the possibility of a chance alignment of grain clumps or a developed linear "pressure mark" cannot be excluded completely. No such brightening is seen in the ring plane on the west side of Saturn, but this region is cluttered by the overexposed images of Dione, Enceladus, Rhea and Titan.

Only one additional photograph had an exposure time as long as 30 minutes, a blue-light exposure made on 13 December 1966. On this image, bright satellites dominate the ring plane on both sides of Saturn and a special technique employed by Feibelman eliminated the halation annulus around the planet. No sign of the Z ring is evident but, under the circumstances, this might be expected. We proceed with the assumption that the Z ring is real and that it is optically thin.

In an effort to improve a severe signal-to-noise problem, the D' ring was scanned with a Jarrell-Ash strip-chart recording microdensitometer using a large area-integrating slit, 10  $\mu\text{m}$  wide by 1000  $\mu\text{m}$  ( $1.6 R_S$ ) long, with the long axis parallel to the ring plane. The Z ring could just be seen through the noise, having a smeared intensity only two percent brighter than the scattered light around the planet. Such data do not lend themselves to quantitative analysis. There is, however, another method for estimating the brightness of the Z ring on the 15 November 1966 Allegheny photograph, for it lies just above the detection threshold of the photograph and thus can be compared with images of field stars which also lie just at or above the detection threshold. Because the density of the halation annulus (1.0) is greater than the density of the sky background (0.65), and because both are located below the linear portion of the characteristic curve of the photographic emulsion, the contrast of the Z ring image is greater than that of the stellar images, resulting in superior discrimination for the Z ring. The estimated brightness of the Z ring based on comparison with the field stars, therefore, would tend to be an overestimate. The field of the Allegheny photograph was located on Palomar Sky Survey chart number  $-6^{\circ}23^{\text{h}}36^{\text{m}}$  (blue) and the threshold stars identified. Unfortunately, no useable standard stars could be located on this particular PSS chart. Another PSS chart ( $+12^{\circ}8^{\text{h}}38^{\text{m}}$ , blue), containing the cluster M67 and taken through approximately the same air mass, was used to estimate the blue magnitudes of the stars on PSS  $-6^{\circ}23^{\text{h}}36^{\text{m}}$ . The diameters of the fainter stars on both PSS charts is the same, approximately 80 micrometers. The visual magnitudes of stars in M67 and their corresponding color indices (B-V) are taken from Racine (1971). Using

the Palomar Sky Survey charts, the threshold field stars on the Feibelman photograph are estimated to be  $m_B = 18.1 \pm 0.3$ .

Measurements of faint field stars on the Allegheny photograph give an average image diameter of 250 micrometers. This spreading of a point source caused by atmospheric "seeing" can be converted to an angular value of 3.6 arc-seconds, using the telescope plate scale of 14.6 arcsec/mm. If the Z ring is assumed to have a geometric thickness which is negligible compared to its diameter (as is the case for the three bright rings), the projected width of the Z ring at an inclination of  $0^\circ 23'$  would be 0.5 arc-seconds. Since this is much smaller than the atmospherically smeared images of the field stars, the Z ring can be treated as being nearly equivalent to a line source which also was smeared by atmospheric "seeing" to an apparent thickness of 3.6 arc-seconds. To a first approximation, the line-source Z ring is equivalent to a linear sequence of  $m_B = 18.1$  stars spaced at intervals of 3.6 arc-seconds. Allowing 0.2 magnitudes additional uncertainty in transferring from one PSS chart to the other, we estimate that the Z ring had a line-source brightness of  $m_B = 19.5 \pm 0.5$  per linear arc-second on 15 November 1966.

The lack of any conspicuous decrease in brightness of the projection of the suspected Z ring with increasing radius would suggest that the Z ring, if real, must extend beyond  $6.5 R_S$ . In the absence of any knowledge of its total extent, the projected width will be assumed to be a uniform 0.5 arc-seconds throughout the region of visibility within the halation annulus. At the distance of Saturn on 15 November 1966 (9.00 au), 0.5 arc-seconds corresponds to 3300 km.

Taking  $m_B = -26.16$  as the brightness of the sun in blue light at 1 au, the brightness of a normally illuminated perfectly diffusing surface of unit albedo at the heliocentric distance of Saturn on 15 November 1966 would be  $m_B = 6.55$  per square arc-second. A simplifying assumption is made that the suspected Z ring contains spherical, diffusely reflecting particles. Reasonable extremes for the normal albedos of the reflecting surfaces in blue light are 0.8 for a granular ice-covered surface and 0.05 for carbonaceous chondritic material. Taking the brightness of a 0.5 by 1.0 arc-second reflecting element to be  $m_B = 19.5 \pm 0.5$ , and the brightness of an identical element in a normally illuminated, perfectly diffusing, unit albedo surface to be  $m_B = 7.3$ , the two extreme models would give optical thicknesses of  $\tau = 2.5 \pm 1.2 \times 10^{-5}$  and  $\tau = 4 \pm 2 \times 10^{-4}$  for the icy and carbonaceous chondritic surfaces respectively. This, of course, is the optical thickness as seen from a viewing position  $0^\circ 233$  above the ring plane. The normal optical thicknesses would then be  $\tau = 1.0 \pm 0.5 \times 10^{-7}$  and  $\tau = 1.6 \pm 0.7 \times 10^{-6}$  for ice-covered and carbonaceous chondritic spherical particles respectively. The assumption made earlier that the Z ring is optically thin has been fully justified.

The particles in the Z ring may well be primordial, i.e., left behind after the formation of the Saturnian system. A plausible upper limit for the size of these particles would be the logarithmic mean of the visible-ring thicknesses deduced by Focas and Dollfus (1969) and Kiladze (1969) which is  $1.6 \pm 0.8$  km. An extreme lower limit of about 7 cm is imposed by the requirement that the Poynting-Robertson effect not be capable of removing the particles from the region over the age of the solar system. We use a density of

$0.6 \text{ gm cm}^{-3}$  as for the particles in Rings A and B (Cook and Franklin, 1974). This may be compared with the lower limit of 6 cm imposed by current observational data for particles in Rings A and B (Cook and Franklin, these proceedings).

Alternatively, the particles in the Z Ring may be ice crystals spalled by meteoritic bombardment from the outer rim of Ring A and subsequently dragged outward by plasma attached to Saturn's magnetic field. In that case the characteristic radius may be taken at about  $30 \text{ }\mu\text{m}$  (Cook and Franklin, these proceedings).

We now examine the spacecraft hazard by using a perpendicular optical thickness of  $10^{-7}$  and large-particle radii of 0.8 km and 7 cm for the two cases given above and finally by using a perpendicular optical thickness of  $10^{-6}$  and a small-particle radius of  $30 \text{ }\mu\text{m}$ .

For the very largest particles the spacecraft is small compared to the particle dimension and the probability of encountering a ring particle on a perpendicular passage through the rings (as seen in the frame of reference of the local circularly orbiting particles) is simply the optical thickness. Passage at an inclination of 0.1 radians to the ring plane would raise this probability from  $10^{-7}$  to  $10^{-6}$ . Both are entirely negligible.

For the small end of the range of large particles, the particles are much smaller than the spacecraft and we are required to know their area number density within the ring plane. The cross-section of the individual particle is  $150 \text{ cm}^2$  and, after division by the optical thickness, we have an area of  $15 \times 10^9 \text{ cm}^2$  occupied by each particle, i.e.,  $7 \times 10^{-10}$  particles  $\text{cm}^{-2}$ . Even for passage through the ring plane at an inclination of

0.1 radians this leads to an impact probability of only  $7 \times 10^{-4}$  for a spacecraft with  $10 \text{ m}^2$  of cross-section.

For the very small particles we have a cross-section of  $3 \times 10^{-5} \text{ cm}^2$  and an area number density of  $3 \times 10^{-2} \text{ particles cm}^{-2}$ , or about  $3 \times 10^3$  particles per  $10 \text{ m}^2$ . The masses of such particles, however, are only about  $10^{-7} \text{ gm}$  so that their impacts would result only in a slight etching of the surface of the spacecraft.

It is apparent that if the particles could be shown to have radii in the millimeter range a great hazard would exist. Primordial particles in this size range would have been swept into Rings A and B long ago by Poynting-Robertson effect alone. They may also have been swept outward to be ejected from the ring plane by encounter with satellites. In that case plasma drag would have been dominant. If plasma drag is strong enough at present to release any particles of this size spalled from the outer part of Ring A it would be much more effective for smaller sizes which we would expect to dominate the distribution of initially spalled sizes in the first place. The mechanism thus operates as a filter especially favoring the smallest sizes, in this case the smallest structural elements required by the infrared reflection spectrum of Rings A and B (see the review by Cook and Franklin in these proceedings).

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