GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 10, PAGES 1745-1748, SEPTEMBER 1990

OBSERVATIONS OF NEPTUNIAN RINGS BY VOYAGER PHOTOPOLARIMETER EXPERIMENT

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Abstract. The Voyager photopolarimeter experiment detected the Neptunian rings 1989N1R and possibly 1989N2R. These rings were also photographed by the Voyager imaging cameras in August 1989. Our firm detection of 1989N1R has an equivalent depth (the product of the radial width and mean normal optical depth) of 0.77 +/- 0.13 km, while a less certain detection of 1989N2R has an equivalent depth of 0.7 km +/- 0.2 km. Several statistical techniques were used to search for additional material in the Neptune ring system and none was identified at a high confidence level.

Introduction

Earth-based stellar occultation measurements obtained during the last decade indicated the existence of partial rings (called ring arcs) orbiting Neptune rather than azimuthally complete rings like those orbiting Saturn and Uranus. Around 50 stellar occultations of the Neptune ring system had been observed before the August 1989 Voyager flyby and only about 20% of the observations provided any ring arc detections (Nicholson et al., 1990). The ring arcs were found at several different apparent radial distances from Neptune. Post-Voyager knowledge of the Neptune pole has allowed most detections in favor of 1989N1R (Nicholson et al., 1990).

Convincing evidence for material in orbit about Neptune was provided in at least five stellar occultations (Couvalt et al., 1986; Hubbard et al., 1986 and Reitsema et al., 1982). Several of the detections were simultaneously observed from more than one telescope. All ground-based detections indicated incomplete rings, with detections occuring on either side of the planet, but never both sides during the same occultation.

Voyager images of the Neptune ring system showed that the arcs detected in ground-based occultations were probably three azimuthally confined regions of relatively high optical depth embedded in the narrow, continuous low optical depth ring, 1989N1R (Smith et al., 1989).

The Voyager photopolarimeter (PPS) observed the star σ Sagittarii as it was occulted by Neptune's rings (Lane et al., 1989). Best estimates indicate that this stellar occultation grazed the leading edge of the leading arc seen in the Voyager images (Smith et al., 1989). The PPS observations, in all probability, penetrated the same arc material as seen from the ground (Nicholson et al., 1990), and not just the thinner azimuthally continuous material comprising the bulk of the ring. The Neptune system was examined over the radial range from 42,000 to 75,000 km. This range also included all of the rings detected in Voyager images and from the ground. The data were acquired with the ultraviolet 0.26 micron filter. Light from the star was sampled at 10 millisecond intervals using the same techniques successfully applied at both Saturn and Uranus (Lane et al., 1982; Lane et al., 1986; Colwell et al., 1990). Assuming that the material resides in Neptune's equatorial plane, the radial resolution during the occultation ranged from 80 meters at a radial distance of 75,000 km to 10 meters at the end of the occultation as the radial velocity component along the occultation path slowed. The Neptune viewing geometry was 70.69 degrees from the ring plane normal. At this oblique viewing geometry, observed optical depths are a factor of 3.02 greater than normal optical depths, making it easier to detect low optical depth material.

Paper number 90GL01471
0094-8276/90/90GL-01471$03.00

Statistical Techniques

Several statistical techniques were used on the Voyager PPS σ Sagittarii data in an effort to identify material in the Neptune ring system. These techniques were developed and employed by Horn (1983) and Graps et al. (1984) on the PPS Saturn ring data and similar techniques were recently used by Colwell et al. (1990) on the PPS Uranus ring data. In this section the behavior of the star calibration data is examined. It is followed by an analysis of the Neptune ring occultation data.

Normal Distribution of Star Calibration Data

The occultation star, σ Sagittarii, was observed for calibration purposes well away from Neptune. About six hours of observations in long-term blocks were obtained on the star both before and after the Neptune flyby. Photon statistics follow a Poisson distribution with the population variance equal to the population mean. When the Poisson mean exceeds about 30 the normal distribution is a good approximation for the Poisson distribution (Mendenhall, 1975). Typical σ Sagittarii star counts were about 42 counts per sample.

Both star calibration data sets were examined to verify that they indeed followed normal distributions. The data sets were divided into groups of 6000 data points and histograms were generated for each set. Both normal and Poisson distributions were fitted to each set and a χ^2 test was performed to check each fit. In all cases, the normal distribution fitted the data with a confidence level greater than 99% although the Poisson distribution provided a slightly better overall fit. The data set was subdivided for the χ^2 test in order to offset possible spurious effects from detector non-uniformity as the Voyager spacecraft limit cycle motion slowly moved the star from one position to another in the PPS field-of-view. The Neptune ring system contains only low optical depth material and, after including the effects of scattered light from Neptune, the photon statistics for the occultation data should behave much like those for the star calibrations.

Variation of the Mean

One method employed in searching for new ring material involves evaluating the statistical significance of the mean of a small subset of data when compared to the mean of nearby data. The Student's t test is one procedure for comparing small subsets of data to the larger population when the parent (or total) data set follows a normal distribution.

The t statistic for samples taken from a single data set is given by (Mendenhall, 1975):

$$t = \frac{y_1 - \mu_1}{s_1 \left(\frac{1}{n_1}\right)^{1/2}} \qquad (1)$$

For comparing the means of two independent pieces of data, the t statistic is given by (Mendenhall, 1975):

$$t = \frac{(y_1 - y_2) - (\mu_1 - \mu_2)}{S_p \left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{1/2}} \qquad (2)$$

where y_1 and y_2 are the means for the subset of data and for a nearby section of data, μ_1 and μ_2 are the total data set means, n_1 and n_2 are the number of points in each selected section of data, and S_p is the pooled estimator of the standard deviation (see Mendenhall, 1975).

The stellar data sets represent two-tailed distributions. The critical values of t are found in standard math tables. These tests were used to identify regions of low optical depth material in the outer part of Saturn's ring system (Graps et al., 1984, Graps and Lane 1986) and to search for low optical depth material in Saturn's ring gaps (Horn, 1983).

Another statistical test applied to the occultation and calibration data is based on the cumulative sum of the Poisson distribution which also describes the PPS data. This test calculates the m-statistic for events of unusually low or high counting rates at different bin sizes and was used by Colwell et al. (1990) to search for tenuous material at Uranus. In this test the data sets are searched at different bin sizes for low values of the cumulative sum of the Poisson distribution, given by:

$$P(C,\mu) = \sum_{x=0}^{C} \frac{e^{-\mu} \mu^x}{x!} \qquad (3)$$

When low values of $P(C,\mu)$ are multiplied by n, the number of samples in data set, we obtain m, an estimate of the number of such events (i.e. with that value of $P(C,\mu)$ or lower) we would expect to occur simply due to random fluctuations in the data (Colwell et al., 1990).

Results

Two automated methods were used to perform the t test. The first method compared the mean of a large section of data to the means of small segments of data internal to the larger section using Equation 1. 1989N1R was easily identified using this method.

The second method compared a small segment mean to the means of larger regions of data both preceding the time series and just after the time series of the small segment using Equation 2. This method evaluates local deviations in the mean and allows some fine tuning in regions whose means are slightly different locally (i.e. limit cycle effects) from the mean of a more extended region of data.

These tests were performed first on the Neptune star calibration data. Small data segments ranging from 50 to 1000 data points were examined. The larger regions were anywhere from 6 to 10 times greater than the small segments. No statistically significant events fell above 4.3σ in either of the star calibration data sets.

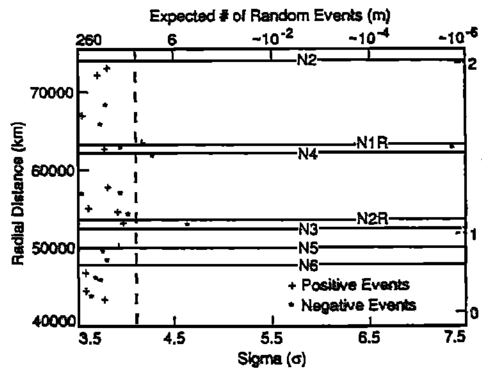

Figure 1: Statistics of Neptune Stellar Occultation Data. Events with statistical significance greater than 3.5σ are shown. Data are averaged in bins ranging from 50 to 1000 data points (roughly 0.5 km to 80 km radial resolution; resolution increases by factor of 8 during occultation). The +'s represent positive σ events and the *'s represent negative σ events. Horizontal lines indicate positions of satellite and ring orbits given in Smith et al., 1989. Dashed line at 4.3σ is shown for reference to calculated statistical limit from star calibration data. Upper x-axis indicates number of expected events (m value) given 540,000 data points.

The results for the PPS stellar occultation data set are shown in Figure 1. Only a small number of events exceed the 4.3σ limit (dashed verical line) set by the star calibration statistics. The +'s represent positive events where the mean of the small segment is greater than the means of the adjacent, larger segments by the indicated number of standard deviations. The *'s represent nega-

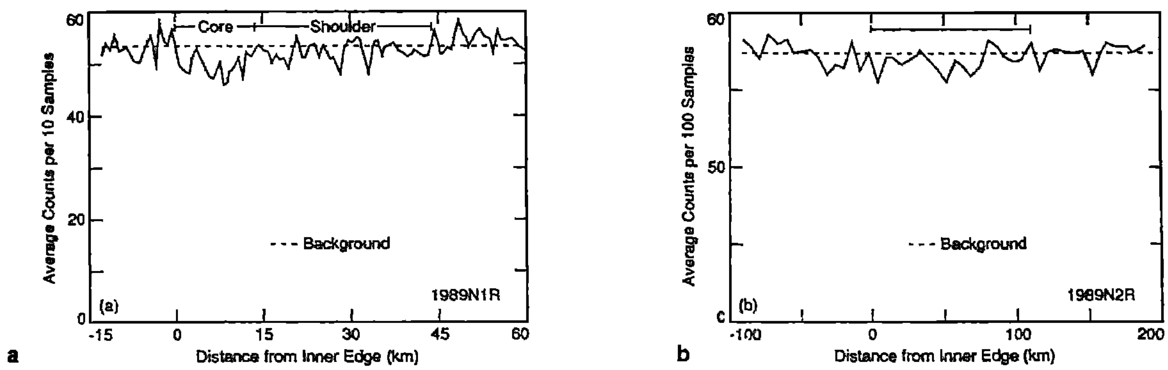

Figure 2: a) Profile of 1989N1R. Ten-point averages of raw PPS photon counts are plotted versus radial distance from inner edge of ring. A 14 km wide "core" at inner edge of ring has a normal optical depth of 0.34 +/- 0.005, roughly three times normal optical depth of broad outer "shoulder". The dashed line shows the level of the unocculted star plus background signal. The entire ring is at $Z>8\sigma$. b) Profile of possible 1989N2R Detection. One hundred-point averages of raw PPS photon counts are plotted versus radial distance from inner edge of ring. Edges were picked to maximize statistical significance of feature. With edges as indicated, $Z= 5\sigma$, normal optical depth is 0.0062 +/- 0.0015, and feature is 113 km wide.

tive events where the mean of the small segment is less than the means of the adjacent, larger segments. Negative events can be produced by ring material which blocks some of the starlight and lowers the local mean. Only one detection is unambiguously identified in the PPS occultation data. An event with this confidence level will occur by chance in a data set of this size with a probability of only 3×10^{-8}. This detection corresponds to the imaging location of 1989N1R (Smith et al., 1989).

An automated search of the data was also carried out with the m-statistic at bin sizes of 10, 50, 200, 600, and 1200 points. Ten-point record subsets (6000 points) were used to determine the local mean of the data. This test identified 1989N1R at all bin sizes except the 10 point bin with $m<<1$. The only other event with $m<1$ found in the occultation data had an m value of 0.6. In the calibration data, the smallest value of m at any bin size was 1.2. Based on this blind test of the data, 1989N1R is the only unambiguous ring. No other statistically unusual events were found at these bin sizes. This test is not capable of detecting very broad and shallow statistically significant events, however, and bin sizes the order of 1989N2R have not been studied.

The PPS data of 1989N1R are plotted in ten-point averages in Figure 2a. The midpoint occultation time was DOY 236/23:24:44.693 Spacecraft Event Time (SCET) and FDS 11384:37:757. The ring, or arc, has 2 components in the PPS data: an inner core with mean normal optical depth of 0.034 +/- 0.005 and a broad outer shoulder with a normal optical depth of 0.011 +/- 0.003. The radial resolution at the location of 1989N1R was about 73 m/sample and the data in Figure 2a are at 730 m/point. If the shoulder occurred by itself in the PPS data it would be a 4σ event, and an event of its size would be expected to occur roughly 80 times by chance in the data set (i.e. m=80). Just from considering the length of the data set (n=540,000 points) it is unlikely that such an event would occur right next to 1989N1R by chance. The core alone has $Z=5\sigma$, and when the shoulder is included $Z=8.3\sigma$ for the entire arc. The core width identified in Figure 2a is 14.3 km, calculated on the assumption that it lies in Neptune's equatorial plane. The shoulder is 28.6 km wide. The mean normal optical depth of the entire arc along the PPS occultation chord is 0.018 +/- 0.003. The arc equivalent depth is thus 0.77 +/- 0.13 km. The widths, normal optical depths, equivalent depths, and the errors associated with each are treated identically to those in Colwell et al. (1990).

The Voyager ultraviolet spectrometer (UVS) experiment simultaneously observed the σ Sagittarii occultation with PPS. 1989N1R was detected in their data set also (Broadfoot et al., 1989). In the UVS data set it is roughly 35 km in radial width with a mean normal optical depth of 0.02 and an equivalent depth of 0.66 +/- 0.12. These values are in good agreement with the PPS numbers. Key ground-based occultations of Neptune's ring arcs, most probably in 1989N1R (Nicholson et al., 1990), provide radial widths ranging from 9 km to 26 km, normal optical depths from 0.07 to 0.18 and equivalent depths from 1.25 km to 2.15 km. These normal optical depths and equivalent depths are at least a factor of two larger than the Voyager PPS and UVS values, which make all of the data sets consistent. The ground-based optical depths and equivalent depths are expected to be twice the Voyager PPS and UVS values from geometric effects (see Cuzzi, 1985).

A second event occurs near the location of 1989N2R centered on DOY 236/23:49:04.911 SCET (FDS 11385:08:294). In the Voyager images, 1989N2R appears to be a complete but tenuous ring (Smith et al., 1989). In this data set an event with this confidence level will occur by chance four times (m=4). However, the probability that a statistically significant event will fall so close to the actual location of 1989N2R by chance alone is very small. Figure 2b shows a profile of 1989N2R. The edges of 1989N2R were selected to maximize the statistical significance of the event. Because the data are close to the background signal, the uncertainty in the width of the feature does not strongly affect the equivalent depth reported below (Colwell et al., 1990). It is 113 km in width (again assuming that the ring lies in Neptune's equatorial plane) with an average normal optical depth of 0.0062 +/- 0.0015 and an equivalent depth of 0.7 +/- 0.2 km. This feature has no narrow, high optical depth component comparable to what the Voyager cameras observed for 1989N1R.

Other events may also be indicative of real ring material but it is not possible with the PPS data set alone to identify which events are real and which are random fluctuations.

Conclusions

Rings 1989N1R and possibly 1989N2R were detected during the Voyager photopolarimeter stellar occultation of the Neptune ring system. PPS values for the width, normal optical depth and equivalent depth of 1989N1R are consistent with values reported by the Voyager UVS and with ground-based numbers. Other statistical events may be real as well, but from the PPS data set alone none of them are of sufficient statistical significance to be convincing. Other rings imaged by the Voyager cameras were not detected in the PPS data. These rings may have extremely low optical depths or may exhibit azimuthal asymmetries similar to the Uranus η, γ and λ (1986U1R) rings (Lane et al., 1986) and 1989N1R. Small, undetected moonlets may orbit in the broad sheet of diffuse material (called the plateau in Smith et al., 1989) in the Neptune ring system. These satellites would create gaps in the material that may be time variable. Their signatures in the stellar occultation data could be statistically positive events. Large positive as well as negative fluctuations should be carefully examined. Future work could include a comparison of the locations of statistically significant events in both the UVS and PPS stellar occultation data sets since both were recorded simultaneously.

Acknowledgements. We thank J.B. Holberg, C.T. Russell and an anonymous referee for their helpful comments and suggestions. We also thank Ron Hungerford for his timely assistance. The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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(Received April 2, 1990
revised June 13, 1990
accepted June 16, 1990)