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High Resolution Measurements of Density Structures in the Jovian Plasma Sheet

by

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Abstract. A recent effort to digitize the plasma density by using the low frequency cutoff of trapped continuum radiation in the vicinity of the Jovian plasma sheet has revealed the existence of sharply defined density structures in the plasma sheet. These structures typically have a plasma density which is relatively constant but of order 50% greater or less than in the surrounding plasma. At the boundaries of these structures, the transitions from low to high density occur on time scales of about ten seconds, which correspond to spatial dimensions on the order of a few ion Larmor radii. The structures themselves last for intervals from less than a minute to more than five minutes, corresponding to size scales from a fraction of a Jovian radius to more than a Jovian radius, depending on the velocity of the structure relative to the spacecraft. In view of the importance of near corotational plasma flows, these structures are likely to be limited in both the longitudinal and radial dimensions and, therefore, could represent flux tubes with greatly varying plasma content. We present these observations as among the first to directly address the theoretically proposed interchange instability.

INTRODUCTION: DETERMINATION OF DENSITY FROM PLASMA WAVE OBSERVATIONS

In planetary magnetospheres, nonthermal continuum radiation in the form of ordinary mode radio waves is trapped at frequencies above the local electron plasma frequency. Gurnett and Shaw [1973] used this property to locate the electron plasma frequency from the low frequency cutoff of continuum radiation trapped in the Earth's magnetosphere [Gurnett, 1975].

Once measured, the plasma frequency can be straightforwardly used to calculate the electron density. The electron plasma frequency is related to the electron density by Equation (1) :

$$f_p = 8.98\sqrt{n_e}\ \text{kHz}. \tag{1}$$

The technique of finding the electron density from continuum radiation cutoff was employed at Jupiter by Gurnett et al. [1979, 1981] using data from the Plasma Wave (PWS) Instrument on board the Voyager 2 spacecraft. For more information concerning the Plasma Wave Instrument, see Scarf and Gurnett [1977].

The Voyager 1 and 2 wideband waveform observations provide high resolution spectra from which the cutoff frequency, and hence the electron density can be determined. The wideband spectrograms, as shown in Figure 1, have a basic resolution of 60 ms, from which we make four-second average spectra. This represents a highly improved temporal resolution in comparison to the 96-second resolution in situ measurements of electron density made by the Voyager Plasma Science (PLS) Instrument [Bridge et al., 1977, 1979]. The four-second averaged spectra are individually examined to determine the cutoff frequency, which subsequently gives the electron density.

The method described works only when the Voyager wideband data are available and when the continuum radiation is present; a significant portion of the two Jupiter encounters. Once the density is determined, a data file is created detailing the cutoff frequency, the density, the spacecraft event time, and a data quality flag for each point. The quality flag is necessary to distinguish points in which we have high confidence from points in which we have less confidence due to: 1) lack of continuum radiation in that particular four-second average, 2) confusion with interference from the spacecraft power supply, or 3) a poorly defined cutoff. Once complete, the data set will be submitted to the Planetary Data System (PDS) as the highest resolution density information available at Jupiter.

DATA: STRUCTURES IN THE JOVIAN PLASMA SHEET

In preparation of the data set for submission to the PDS, one particular thirty-minute segment of data from Voyager 1 contained unusual variations and warranted further examination. The segment, from 0200 to 0230 SCET on March 7, 1979, illustrated in Figure 2, shows density fluctuations in an outbound plasma sheet crossing at about three hours local time at a radial distance of about 33 Jovian radii. The same structure was evident but not resolved with the 96-second resolution PLS data. Detailed observation revealed variations characterized by density changes on the order of 50% with sharp gradients on time scales of about ten seconds. These gradients likely correspond to spatial scales on the order of a few ion gyroradii. This half-hour segment has proven to be the best example of small scale structures in the plasma sheet, as it has the highest percentage of continuous frames with clear, well-defined cutoffs.

Inspection of other processed data, including some dayside data from March 3 and 4, 1979, revealed similar structures at slightly larger distances of about 42 Jovian radii. The density variations on the dayside are typically greater, on the order of several hundred percent, and last significantly longer; several minutes as compared with 1-2 minutes or less for the nightside data from March 7.

In an attempt to gain an initial understanding of the spatial characteristics of these structures, an estimate of the spacecraft velocity relative to the surrounding plasma can be made based on corotation of the plasma with the planet. At 33 R_J, the plasma corotates at about 400 km/s, much faster than the spacecraft's velocity. Using this approximation, the longitudinal width of the structures can be estimated to be between 0.1 and 2.5 R_J, with the largest ones, again, being typically observed further out and on the dayside.

The structures that were observed in the plasma sheet at 33 R_J on March 7 typically had density variations on the order of 50%. The plasma outside of the density increases had an average electron density of approximately 0.13 cm^{-3} while the density inside the structures was nearly 0.2 cm^{-3}. These differences were fairly common, though many of the variations were slightly smaller, such as density increases from 0.08 to 0.13 cm^{-3}. It is important to note that similar 'reverse' transitions occurred from higher densities back down to lower levels. These transitions were of the same magnitude, around 50%, and the density often decreased to nearly the same value that existed before the structure was entered by the spacecraft. A few isolated cases which were observed on the dayside had density differences on the order of several hundred percent, rising from 0.03 cm^{-3} to nearly 0.13 cm^{-3}. Other cases showed significantly less variation, but still larger than 50%.

The transitions for these variations (both increases and decreases) are defined by two or three data points, typically, which correspond to 8 to 12 seconds in our four-second resolution. This rather sharp gradient likely corresponds to several ion gyroradii at the boundary of the phenomena. Assuming rigid plasma corotation at 33 R_J, the transitions have size scales on the order of 4000 km. Oxygen and sulfur ions with energies near 1 keV (determined by Pioneer 10 and Pioneer 11 measurements [McNutt et al., 1981]) have gyroradii of around 1300 km and 3600 km, respectively. The gradient is the same when entering or exiting the structures. This was true of cases both for March 7, and for the earlier cases on March 3 and 4.

This preliminary analysis, though promising, is gleaned from a relatively small fraction of the data. Further production of high resolution density data will provide more structures for detailed examination. Problems with some of the data include the fact that the PWS frames were often transmitted intermittently with the imaging data, such that only every fourth 48-second frame is available for PWS measurements. Additionally, there is a significant number of frames for which the cutoff of the trapped continuum is either absent, or at frequencies above the passband of the wideband receiver (i.e., greater than 12 kHz).

IMPLICATIONS FOR PLASMA TRANSPORT

These density measurements are believed to be important for the theory of centrifugally driven interchange instabilities [Gold, 1959]. A key problem of Jovian magnetospheric physics is the mechanism by which plasma is transported throughout the Jovian system from the source, which is volcanic gas emissions from the moon, Io. Centrifugally driven radial diffusion of plasma from Io has been examined since before the Voyager encounters with Jupiter [Chen, 1977], and has been more closely studied since in situ measurements were received from spacecraft flybys of Jupiter [Richardson et al., 1980; Froidevaux, 1980; Siscoe and Summers, 1981]. One mechanism for this diffusion involves radial flux tube interchange [Sonnerup and Laird, 1963; Melrose, 1967; Michel and Sturrock, 1974]. Flux tubes of higher density plasma than the surrounding plasma are centrifugally driven in a radially outward direction, while low density flux tubes move inward. The azimuthal and radial extent of the tubes that are slung outward is not well known and difficult to predict theoretically, however some recent models for transport have been devised [Pontius et al., 1986; Pontius and Hill, 1989].

It was mentioned previously that corotation with the planet was used as a model for the motion of the plasma sheet past the spacecraft. This corotation at approximately 400 km/s implies that the structures are constrained in the azimuthal direction, allowing the possibility that the structures the spacecraft encountered could in fact be flux tubes of different density plasma being transported through the plasma sheet according to the theory of interchange instability.

DISCUSSION

The primary importance of these structures lies in the fact that they may represent the flux tubes involved in the radial transport of plasma. For the first time this high resolution data enabled us to resolve small structures in the plasma sheet and to characterize the density structures on scales comparable to the ion cyclotron radii. Though the presence of these structures is established, there is little understanding of their origin, dynamics, or longevity. There is also the possibility of other causes for these structures besides the suggested radial transport of flux tubes. One such possibility is a wave-like motion of the plasma sheet boundary past the spacecraft. Future analyses and comparisons with other data should allow us to determine whether the structures occur most often during a crossing of the plasma sheet or at the edges of the plasma disk.

Several studies were conducted with regard to the nature of the structures. The scale lengths of the density structures were examined to determine if a Kolmogorov spectrum (indicative of fully developed turbulence) was present. Figure 3 shows a Fourier transform of the density data from approximately 0200 to 0245 SCET on March 7, 1979. This spectrum contains the same thirty-minute segment that was shown in Figure 2. It can be seen that the frequency spectrum falls off rather smoothly with a slope close to -1. A line with slope -5/3 has been drawn into the figure for comparison. A smooth decrease near -5/3 would have been indicative of a Kolmogorov relation, but such a relation is not present in this plasma sheet crossing. The absence of any characteristic scale lengths in the structures, however, implies that the spectrum is not compatible with a local instability. There is more power in the low frequency (or long wavelength) components, which does not agree with the theory of interchange instability which predicts faster growth for the smaller wavelengths.

The magnetometer data for the same period of time are shown in Figure 4. There is at best a general correlation between the density and the magnetic field. In the theory of interchange instability, it is assumed that the flux tube plasma content is constant which would imply that n/B remains nearly constant, but there is little evidence to support such a relationship in this segment of data. One can see some fluctuations of the magnetic field strength and magnetic field rotations at some of the boundaries between high and low densities, but these correlations are weak and not persistent. The weak correlation between density and magnetic field may be explained by an anticorrelation between cold and hot plasma. Such an anticorrelation is to be expected if the source of the cold plasma is the inner magnetosphere (e.g. the Io torus) and the source of the hot plasma is in the outer magnetosphere (e.g. the solar wind or energized plasma in the outer magnetosphere). Flux tubes moving outwards should thus contain denser but colder plasma than flux tubes moving inwards. Thus the variation of pressure could be small, and therefore not affect a significant change in the magnetic field strength. The lack of correlation could also be attributed to a motion of the density gradient in the z-direction instead of the assumed azimuthal spatial density variations. The structures are apparent throughout the plasma sheet crossing which is indicated by the reversal of B_r, and not only at the boundaries. Motions in the z-direction could be due to a surface wave on the plasma sheet, and it could be these 'grooves' that are passing the spacecraft as it moves near the top and bottom boundaries of the plasma sheet.

SUMMARY AND CONCLUSIONS

By examining the cutoff of trapped continuum radiation, the electron density in the Jovian plasma sheet can be calculated and examined with a high temporal resolution. This high resolution revealed detailed small structure yet unseen in the plasma sheet. The implications these small structures have in the theories of plasma transport and interchange instability is expected to motivate further analysis. Based on available data, the structures appear to have durations varying from less than a minute up to nearly ten minutes, corresponding to longitudinal widths ranging from a tenth up to about two R_J if it is assumed that azimuthal gradients corotate past the spacecraft. The density variations at the boundaries have been measured at between 50% and 450%, with the majority being on the order of 50%, although this depends on radial distance from the planet. There is a tendency toward more structure in the plasma sheet crossing near 0300 local time than 1100 local time for Voyager 1 data, but there is more structure at an 1100 local time crossing for the Voyager 2 data. This new data set gives the first solid evidence for small scale structures in the Jovian plasma sheet, which are of potential importance in models of plasma transport. The structures seen are similar to the density perturbations predicted by the theory of interchange instability. First attempts at analysis, however, do not seem to be compatible with a local instability. A Fourier analysis, marked by the absence of a Kolmogorov relation, did not indicate the presence of fully developed two-dimensional turbulence. Additionally, the density data show little correlation with magnetometer data.

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FIGURE CAPTIONS

Figure 1. Wideband spectrogram from the Voyager 1 Plasma Wave Instrument. The darker areas correspond to more intense waves. The sharp boundary between the dark continuum radiation and the lighter region is the cutoff frequency which identifies the local electron plasma frequency during this plasma sheet crossing. Interference is from the power supply of the spacecraft.

Figure 2. Thirty-minute segment of data showing the cutoff frequency for each four-second average of the wideband data, and the electron density calculated using Equation (1). Overlaid on the density are the in situ measurements of electron density made by the Plasma Science Instrument on board Voyager 1.

Figure 3. Fourier transform of 46 minutes of density data including the thirty-minute segment in Figure 2. The point at 3.6×10^{-4} Hz corresponds to a period of the entire 46-minute interval, while the point near 0.125 Hz approaches the sampling rate of four seconds. The line with slope -5/3 is drawn in for comparison.

Figure 4. The same 46-minute segment of data as in Figure 3 is plotted with the magnetic field strength and vector components. Little correlation is evident between electron density and magnetic field strength in this plasma sheet crossing.

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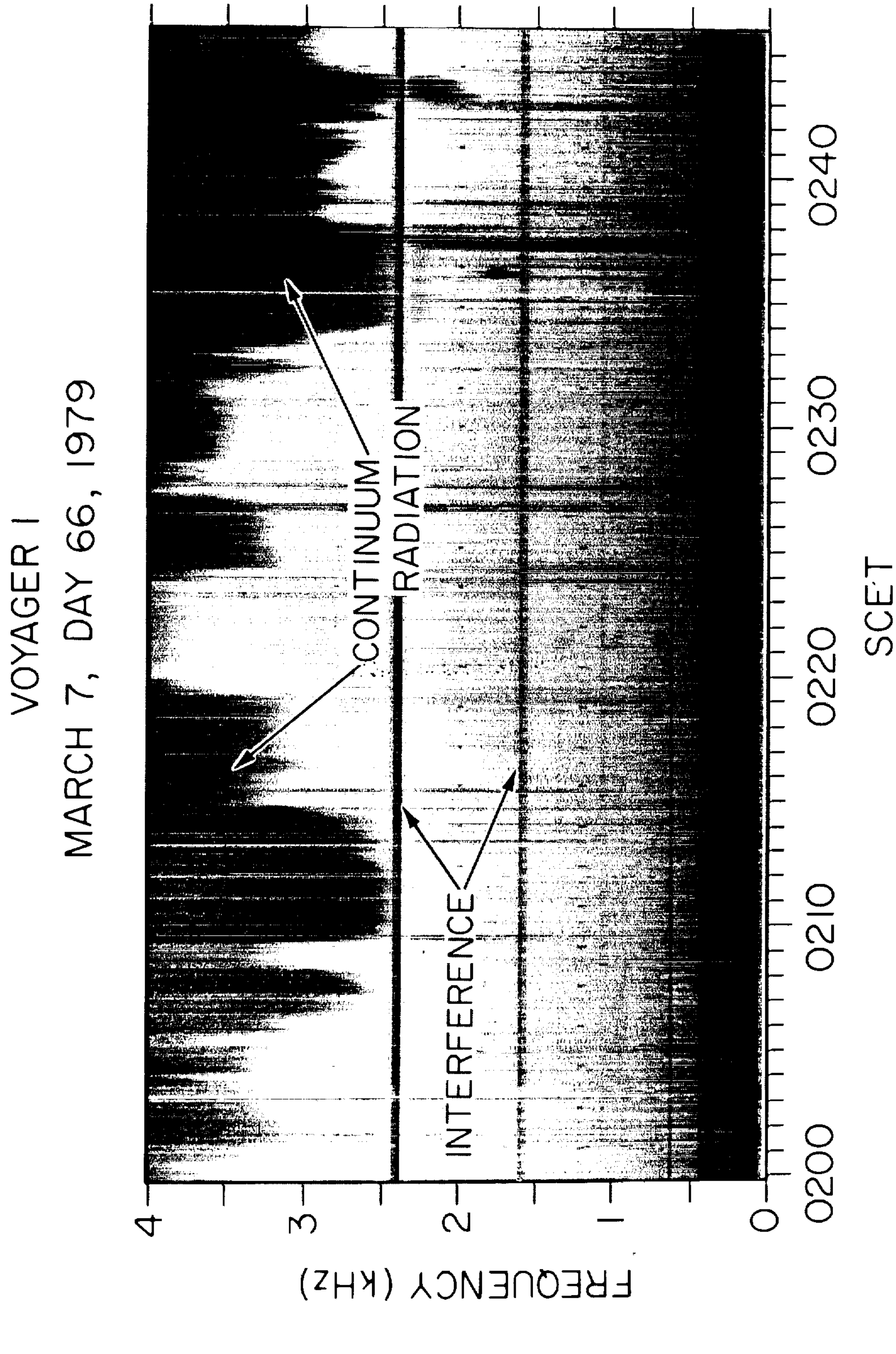
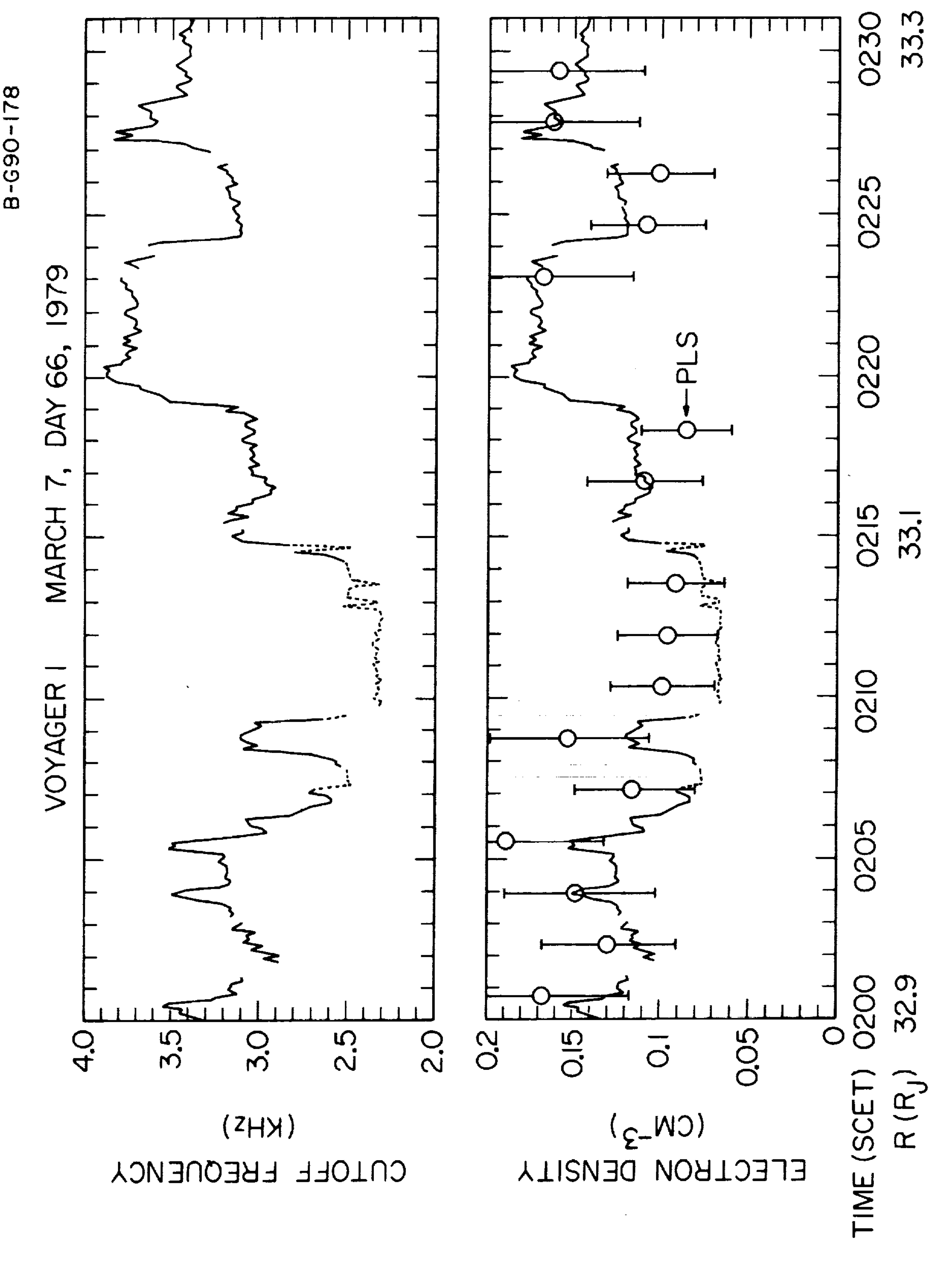


Figure 1



B-G90-178
VOYAGER I MARCH 7, DAY 66, 1979
CUTOFF FREQUENCY (KHz)
4.0
3.5
3.0
2.5
2.0
ELECTRON DENSITY (CM^{-3})
0.2
0.15
0.1
0.05
0
PLS
TIME (SCET) 0200 0205 0210 0215 0220 0225 0230
R (R_J) 32.9 33.1 33.3

Figure 2

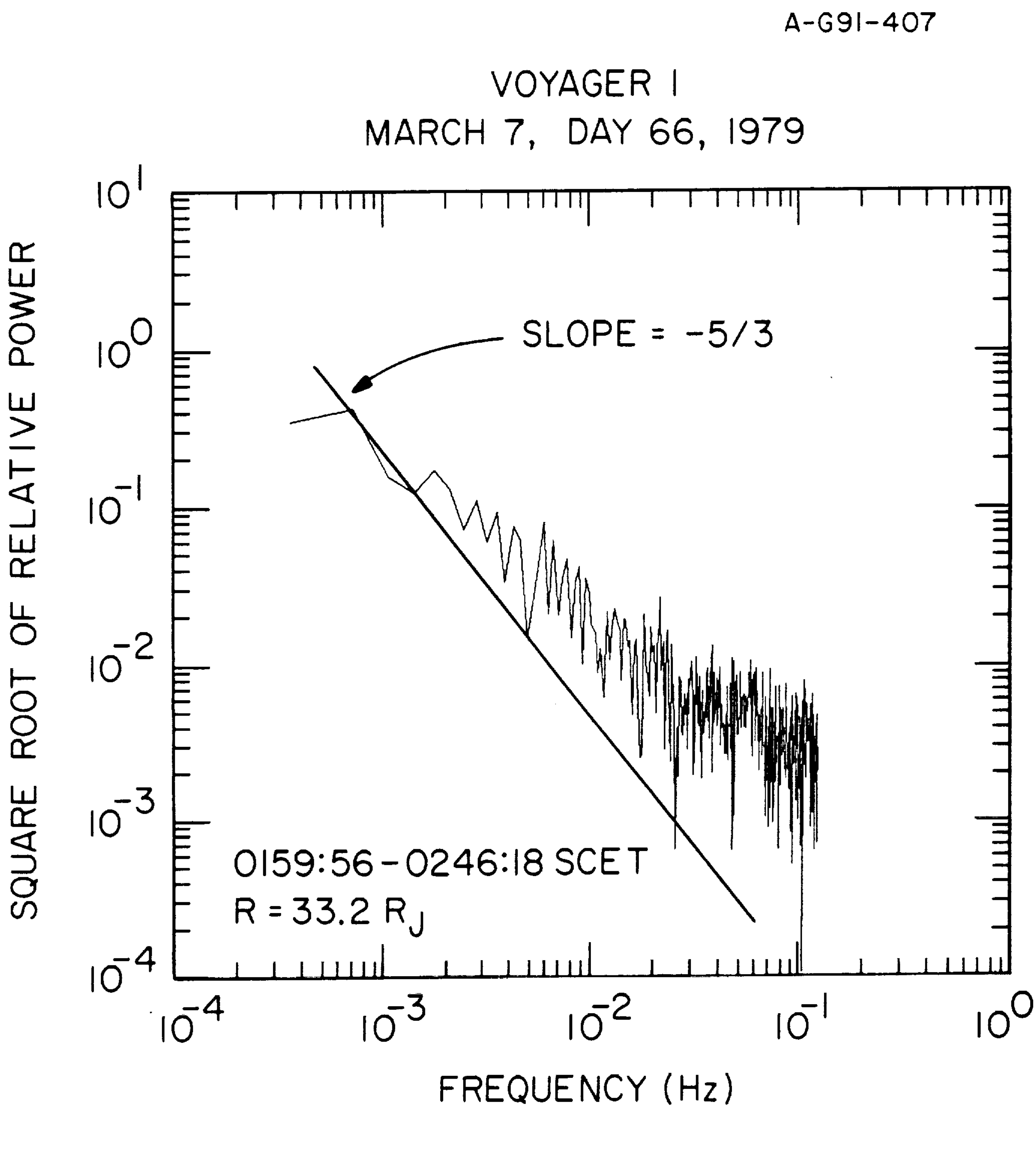

A-G91-407
VOYAGER I
MARCH 7, DAY 66, 1979
SLOPE = -5/3
0159:56-0246:18 SCET
R = 33.2 R
J
SQUARE ROOT OF RELATIVE POWER
FREQUENCY (Hz)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-4
10^-3
10^-2
10^-1
10^0

Figure 3

A-G91-337

VOYAGER I
MARCH 7, DAY 66, 1979