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Direct Evidence for Solar Wind Control of Jupiter's Hectometer-Wavelength Radio Emission

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DIRECT EVIDENCE FOR SOLAR WIND CONTROL OF JUPITER'S HECTOMETER-WAVELENGTH RADIO EMISSION

by

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ABSTRACT

Observations of the solar wind close to Jupiter, by the Voyager 1 and Voyager 2 spacecraft in 1978 and 1979, are compared with the hectometer-wavelength radio emission from the planet. A significant positive correlation is found between variations in the solar wind plasma density at Jupiter and the level of Jovian radio emission output. During the 173-day interval studied for the Voyager 2 data, the radio emission displayed a long-term periodicity of about 13 days, identical to that shown by the solar wind density at Jupiter and consistent with the magnetic sector structure association already proposed for groundbased observations of the decameter-wavelength emission.

I. INTRODUCTION

Observations with the Voyager Planetary Radio Astronomy (PRA) experiment have shown that the low-frequency radio spectrum of Jupiter contains four distinct components: a decameter-wavelength emission (DAM), a hectometer-wavelength emission (HOM), and two components at kilometer wavelength (bKOM and nKOM). The characteristics of each of these have been investigated by several authors [see, e.g., Carr et al., 1983 and Alexander et al., 1981 for reviews]. The HOM, which is the subject of the present study, extends from about 3 MHz down to 100 kHz. It has been suggested [Lecacheux et al., 1980] that HOM is a low-frequency extension of DAM. However, HOM has a distinct spectral peak near 1 MHz [Brown, 1974] and the occurrence probability of HOM as a function of jovian System III central meridian longitude (CML) differs from that of the DAM. This argues for an independent HOM emission component. In addition, unlike the DAM, the HOM intensity variations show no evidence for control by Io. Thus the HOM is almost certainly distinct from the Io-modulated DAM and very probably distinct from the Io-independent component of DAM. This raises questions as to the source of the strong intensity fluctuations apparent in the HOM.

It is well known that the principal intensity modulation of the DAM is that due to Io; however, a number of papers have demonstrated, from ground-based observations, that the DAM is additionally related to solar activity through the solar wind, although the exact nature of the relationship has yet to be established [see, e.g., Pokorny, 1976 and 1982, Terasawa et al., 1978, Levitski and Vladimirski 1979, and Barrow 1978 and 1979]. Relative to this, Desch [1982], and Desch and Rucker [1983] have shown that Saturn's kilometric radiation (SKR) is strongly correlated with a number of solar wind parameters, notably the solar wind ram pressure and the density. Also, Gallagher and D'Angelo [1981] have demonstrated that the terrestrial (auroral) kilometric emission (AKR) is strongly controlled by the solar wind.

In a recent investigation by Zarka and Genova [1983] the HOM power spectrum was found to contain a spectral peak attributable to solar influence. The present paper further examines the evidence that the jovian HOM is controlled by the solar wind. Specifically, following Desch and Rucker [1983], we investigate the linear cross correlations between variations in the HOM energy output and the solar wind density and speed profiles at Jupiter. We also examine the autocorrelation function of these quantities for evidence of any significant long-term periodicities that they might have in common. Finally, we inter-compare the degrees to which the solar wind drives the low-frequency radio output of the known radio planets: earth, Jupiter and Saturn. We use observations made by experiments on board the Voyager 1 (V1) and Voyager 2 (V2) spacecraft as they approached Jupiter from distances of less than 1 AU. The solar wind measurements were collected by the Plasma Science (PLS) experiment [Bridge et al., 1977] and the radio emission data by the PRA experiment [Warwick et al., 1977].

II. OBSERVATIONS

A typical 24-hr dynamic spectrum from the Voyager 2 PRA experiment is shown in Figure 1. The figure covers both bands in which the receiver operates, that is, high band (from 1.3 to 40 MHz) and low band (from 1.2 to 1300 kHz). The spectrum demonstrates the distinctive nature and appearance of the HOM relative to the other major jovian emission components, namely, DAM and KOM. Three periods of HOM activity can be seen. In this spectrum they are centered in time and frequency at approximately 04, 14, and 23 hr SCET (spacecraft event time) and 750 kHz. The broadband kilometer-wavelength (bKOM) emission episodes are centered between the HOM episodes but are lower in frequency, at about 200 kHz. The DAM emission is represented here by the Io-related source C event that extends from near 35 MHz at 22 hr SCET down to about 1100 kHz at 23 hr. The low frequency extent of this Io-controlled DAM emission is marked by the pointer, and it is important to note the failure of this emission to extend far into the HOM band. In previous studies [Desch and Carr, 1978; Kaiser et al., 1979] no long-term statistical evidence for Io control of the HOM was found. This figure supports these earlier studies by graphically illustrating the extremely small degree to which Io-controlled emission contributes to the overall HOM energy output. The absence of any significant modulation by Io of the HOM intensity vastly simplifies the search for relatively weak modulations that might be due to the solar wind.

Although it is not immediately evident in Figure 1 because of a severe sensitivity change between the PRA low and high bands, some of the HOM emission extends to higher frequencies, into high band. This is true, not only in the spectrum shown, but in general. Carr et al., [1983], for example, have demonstrated that the HOM spectral peak is near 1 MHz and has a high-frequency shoulder that extends to 3 or 4 MHz before merging with the DAM spectrum. In this study, however, we examined only the PRA low-band detections of HOM, because only these observations have sufficient sensitivity to yield the several months long analysis intervals necessary to investigate long-term intensity changes. It is doubtful, however, that this restricted frequency coverage compromises the analysis because the PRA low band encompasses not only the spectral peak of the emission, but also all of the low frequency shoulder, and some of the high-frequency shoulder. Therefore it adequately represents relative HOM intensity changes even if less than 100% of the total emission output is sampled.

In Figures 2 and 3, time histories of the HOM intensity variations are compared with the solar wind density at Jupiter for the V1 and V2 observations, respectively. The analysis intervals lasted 74 days and 173 days, corresponding to the following dates: December 18, 1978 (day 352) through March 1, 1979 (day 60) for Voyager 1 and from January 9 (day 9) through June 30, 1979 (day 182) for Voyager 2. During these intervals the spacecraft were approaching Jupiter from distances of between 7.9×10^7 km to 5.4×10^6 km (V1) and 1.3×10^8 km to 8.0×10^6 km (V2).

The radio data, shown by the solid line, are 1 Jupiter rotation (10-hr) averages of the total emitted HOM energy. The energy was computed by integrating the measured HOM flux densities over the (variable) emission bandwidth (usually 500 to 1000 kHz) and summing the resultant spectral density over 1 jovian rotation. Only events exceeding a flux density threshold (10^{-20} W/m^2/Hz) easily detectable at the beginning of the analysis intervals were included in the 10-hr averages. This procedure avoids possible bias by weak events that are detectable close to the planet. An isotropically emitting source was assumed in the conversion to total radiated power.

The solar wind density variations, shown by the shaded curves in Figures 2 and 3, are also 10-hr averages and are shown as they would be observed at Jupiter. The solar wind was ballistically projected from the spacecraft to the planet as described by Desch and Rucker [1983]. The projections were almost entirely in the radial (sun-Jupiter) direction and corresponded to radial propagation delays of between about 51 hr and 3 hr for the V1 solar wind data and between 90 hr and 7 hr for the V2 data. By comparison, the sun-centered angular separation between Voyager 1 and Jupiter and Voyager 2 and Jupiter never exceeded 2.0° and 5.3°, corresponding to only 3.4 hr and 8.9 hr of angular separation delay, respectively. The ballistic projections do not take the interaction of low and high speed solar wind streams into account. However, Desch and Rucker showed that projections of solar wind speed and density are between 80% and 95% reliable if 10-hr averaged quantities are used and if the projections are nearly in the radial direction. They also showed that arrival times of solar wind features were predictable to within ±10 hr.

That there might be a significant correlation between the quantities plotted in Figures 2 and 3 is not obvious. The clearest visual evidence for an association between the solar wind density and the HOM is in the strong tendency for the radio output to reach minimum values when the density at Jupiter is also extremely low. Note, for example, intervals centered near days 2, 10, 20, and 46 in Figure 1 and days 73, 105, 125, and 136 in Figure 2. In fact, in both data sets, 80 to 90% of the time that the density is below average value, the HOM is simultaneously below normal intensity levels. The converse situation is not nearly so common. That is, there is not a strong tendency for the HOM energy output to be high when the density is high, although there are some dramatic examples of these occurrences also. Overall, there is enough evidence of a visual correlation between these two quantities to investigate the matter more thoroughly.

III. RESULTS

In Figure 4 we show the results of a linear cross correlation analysis of the time histories shown in Figures 2 and 3. We have also correlated the HOM energies as shown in these two figures with the solar wind speed, since the speed was found to be a good predictor of terrestrial (AKR) radio emission intensities [Gallagher and D'Angelo, 1981]. The solar wind value was chosen that corresponded in time to that closest to the beginning of the HOM occurrence probability cycle, i.e., near 260° CML. The V1 results for density and speed are shown in the top two panels of Figure 4 and the V2 results in the bottom two. Each time series was randomized before being cross correlated [Jenkins and Watts, 1968]. This eliminates the tendency, in all data sets, for adjacent points in the same set to be highly correlated, which if uncorrected could result in artificially large cross correlations. This procedure also permits expression of the cross correlations in terms of standard deviations (sigma) as shown.

It can be seen that the solar wind density correlation is statistically significant, with levels above 3 sigma for both V1 and V2 data sets. The corresponding lag times for peak correlations are at 0 and -1 rotations, respectively. In our definition, negative time lags violate causality in that radio fluctuations precede corresponding fluctuations in the solar wind. However, the V1 and V2 lag times are actually compatible and are consistent with zero time lag since there is a ±10 hr uncertainty in the analysis due to the 10 hr averaging intervals and the uncertainty, as mentioned above, in the exact arrival time of the solar wind at Jupiter. Both V1 and V2 data sets show no evidence of a significant correlation with the solar wind speed, as is evident from the two panels on the right in Figure 4.

The magnitudes of the linear cross correlation coefficients for the density peaks shown in Figure 4 are 37% (V1) and 26% (V2). While these values are significant at the 0.2% significance level for the number of data point pairs being correlated, they are not as high as the correlations found to exist in the saturnian and terrestrial cases. For example, the equivalent solar wind-AKR correlation coefficient was 78%

[Gallagher and D'Angelo, 1981] and for solar wind-SKR as high as 71% [Desch and Rucker, 1983]. The implications of this result are discussed in more detail below.

As a further test of the validity of the cross-correlation results, the original (unrandomized) HOM, solar wind density and solar wind speed profiles were each autocorrelated to search for periodicities that the quantities might have in common. The results are shown in Figure 5. Curves are for Voyager 2 data only as the corresponding Voyager 1 data are not available for a sufficiently long period to allow a lag of more than about 9 days. It can be seen in Figure 5 that the HOM and the solar wind density both show similar shapes, at least up to about 18 days lag. Both have a peak at about 13 days and nearly identical 'persistence' times of about 3 days. We define the persistence time in terms of the width of the main peak from 0 days lag to the first zero crossing. It is an indication of the typical time scale between intensity changes in the time series being autocorrelated. Thus the HOM and the solar wind density at Jupiter fluctuate on time scales that are very similar, consistent with the fluctuations shown by the time histories in Figures 2 and 3. This is at least a necessary condition for there to be a good correlation between the two quantities. On the other hand, the HOM autocorrelation curve does not match the speed autocorrelation in either periodicity or persistence, supporting the conclusion that the solar wind speed is not an important factor in controlling HOM.

The 13-day periodicity apparent in Figure 4 was anticipated by previous studies. The solar wind density tends to increase along the leading edge of high speed streams, which are in turn related to the interplanetary magnetic sector structure. Since the sector structure is periodic, our observations complement the already proposed [Barrow, 1979] association between sector structure and the Io-independent DAM. As mentioned previously, a more recent investigation by Zarka and Genova [1983] of the HOM power spectrum revealed a number of spectral peaks. One near 14.5 days they attributed to magnetic sector structure effects at Jupiter.

IV. DISCUSSION

We have shown, based on two independent data sets, both visual and statistical evidence that the Jovian HOM is controlled to some extent by the solar wind. Of the two solar wind quantities investigated, the density is by far the better predictor of HOM energy. In this way the Jovian emission is more like Saturn's SKR than like the earth's AKR in that the solar wind density and not the speed yields the better correlation. We are thus in a position to make inter-planetary comparisons in the degree to which the solar wind drives planetary radio output. Both the SKR and AKR show evidence of an effective one-to-one correspondence between solar wind input and radio output. This is clearly not the case for the jovian HOM, where, as was mentioned above, the correlation is significant but smaller.

We have considered the possibility that differences between the present analysis and that of Gallagher and D'Angelo [1981] of the AKR and that of Desch and Rucker [1983] of the SKR might account for the different degrees of solar wind control obtained. Gallagher and D'Angelo used 3-day (rather than 1-rotation) averages of the correlated quantities, which has the effect of inflating the correlations slightly relative to the present analysis. But this is not enough to account for the large differences observed. In the SKR study, Desch and Rucker used analytical techniques that were nearly identical to those used here. Therefore there seems to be a real difference between the moderate degree to which the solar wind modulates the radio output of Jupiter as compared with the strong degree to which it modulates the radio emissions of earth and Saturn. It is possible, but not likely, that some solar wind quantity other than density is a better predictor of HOM intensities, and this possibility is being investigated. At present, it is known that Io is not effective in modulating HOM, although Io or the Io plasma torus may play an as yet unspecified role in controlling the generation of HOM. It is clear from the results of the present analysis that all of the factors involved in the long-term modulation of the HOM have yet to be uncovered.

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FIGURE CAPTIONS

Figure 1. 24-hr frequency-time dynamic spectrum from the Voyager 2 PRA experiment comparing HOM emission with DAM and KOM activity on June 20, 1979. Note that the Io-controlled event does not contribute significantly to the HOM emission.

Figure 2. Variation in the HOM energy level compared with the solar wind density for the period December 18, 1978 (day 352) through March 1, 1979 (day 60) as observed by Voyager 1. The solar wind profiles are shown as they would appear at Jupiter, following propagation from Voyager 1 to the planet. Both the solar wind and the HOM radio data are 10-hr averages.

Figure 3. Same as Figure 2 but for Voyager 2 data for the period January 9, 1979 (day 9) through June 30, 1979 (day 181).

Figure 4. Cross correlation coefficient, expressed in terms of standard deviation, versus time lag in increments of jovian rotation for HOM energy correlated with solar wind density and with solar wind speed for both Voyager 1 and Voyager 2 data sets.

Figure 5. Autocorrelation coefficient versus time lag in days for HOM energy, solar wind density and solar wind speed observed by Voyager 2.

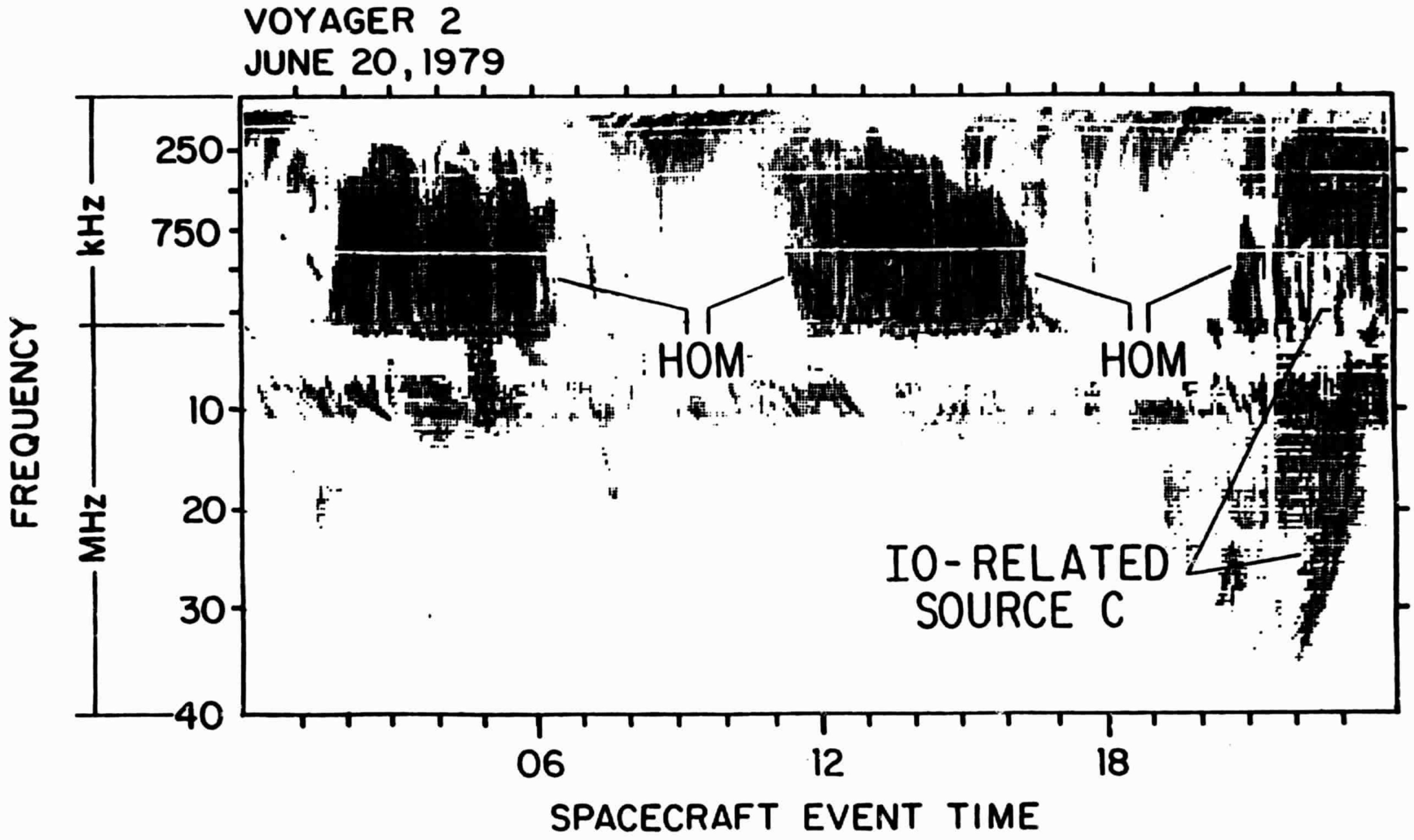

VOYAGER 2
JUNE 20, 1979
FREQUENCY
kHz
MHz
250
750
10
20
30
40
HOM
HOM
IO-RELATED
SOURCE C
06
12
18
SPACECRAFT EVENT TIME

FIGURE 1

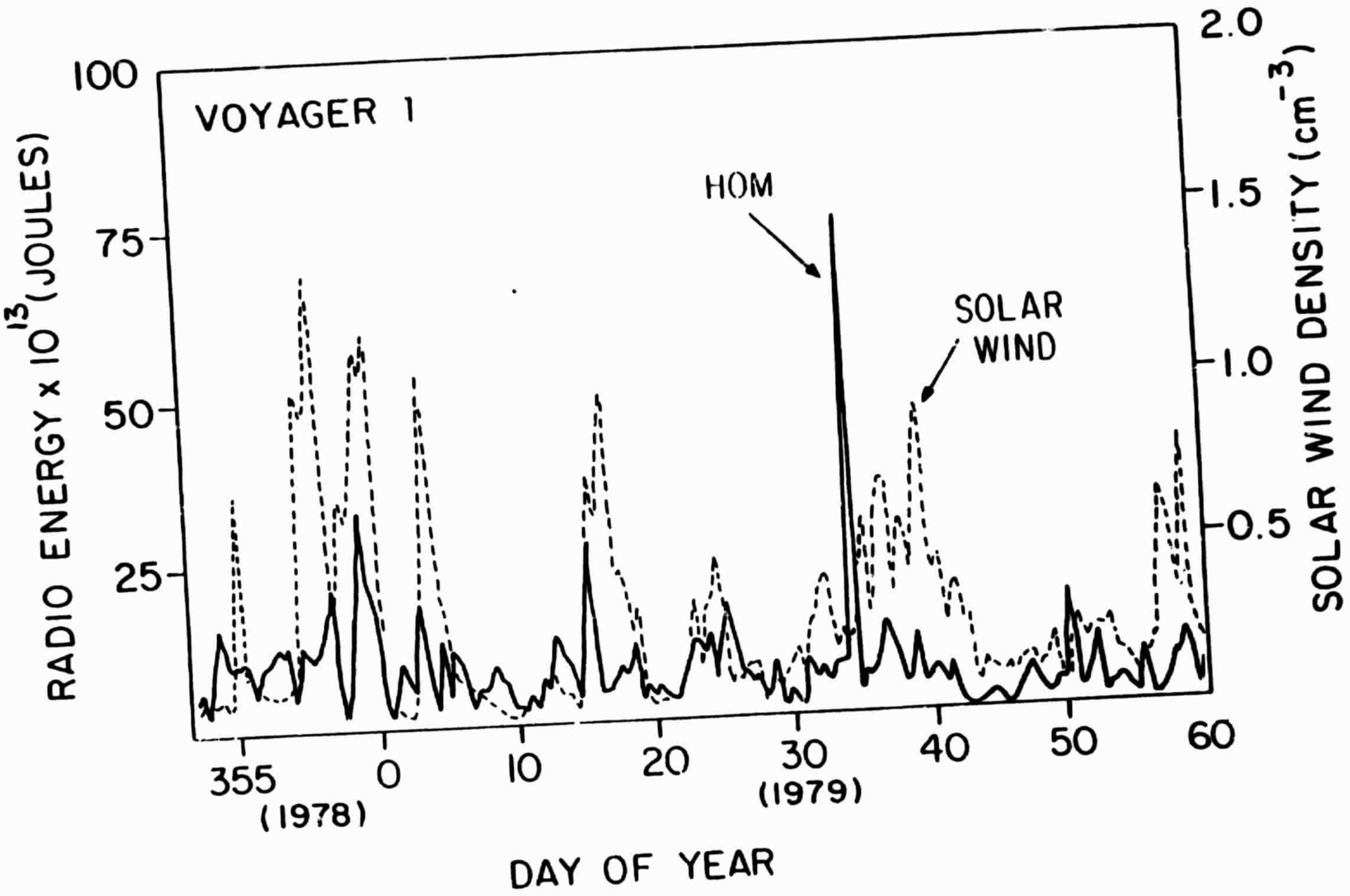
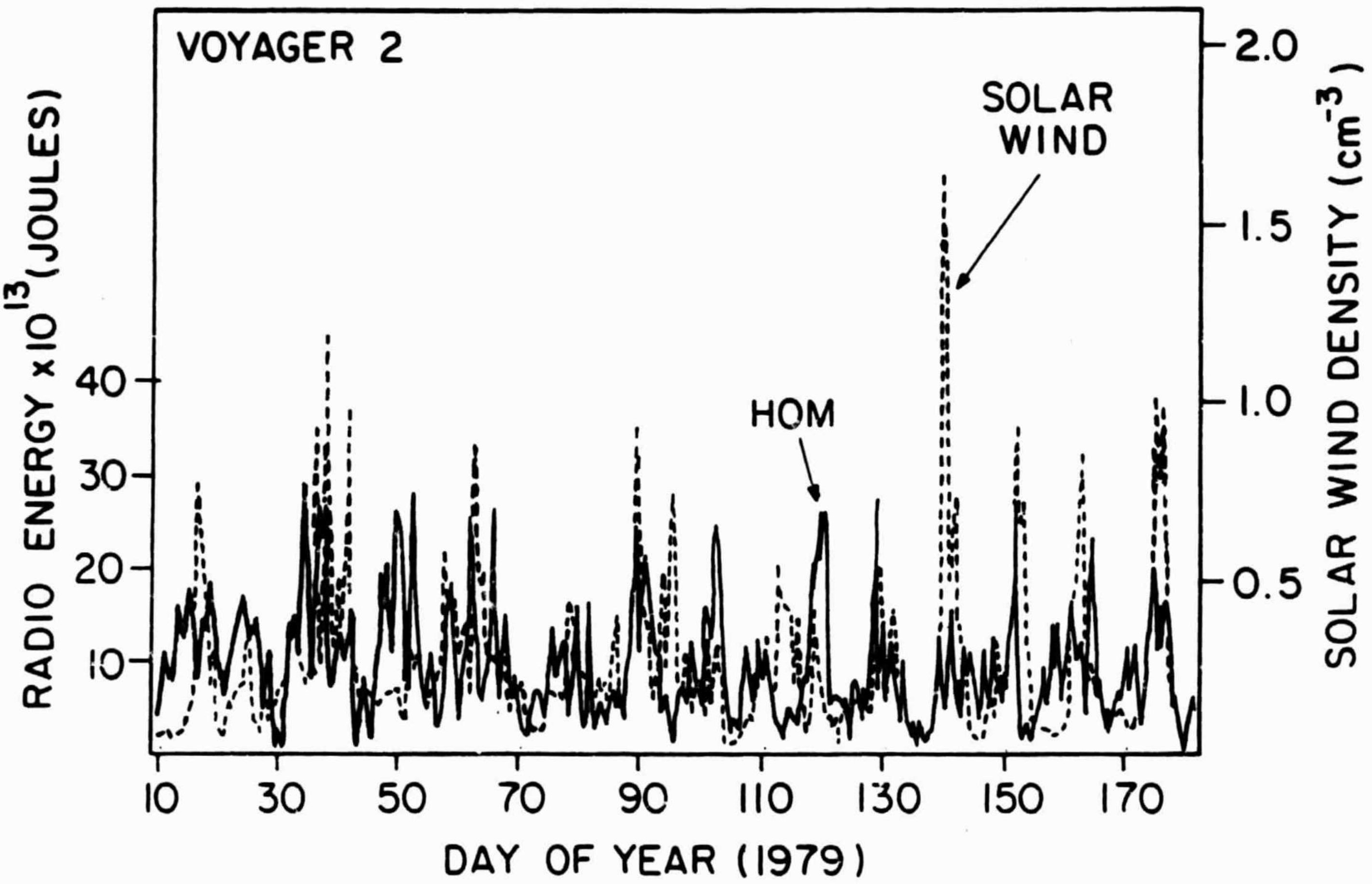

VOYAGER 1
HOM
SOLAR WIND
RADIO ENERGY x 10^{13} (JOULES)
100
75
50
25
SOLAR WIND DENSITY (cm^{-3})
2.0
1.5
1.0
0.5
355
(1978)
0
10
20
30
(1979)
40
50
60
DAY OF YEAR

FIGURE 2


VOYAGER 2
SOLAR WIND
HOM
RADIO ENERGY x 10^{13} (JOULES)
SOLAR WIND DENSITY (cm^{-3})
DAY OF YEAR (1979)
10
20
30
40
0.5
1.0
1.5
2.0
10
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50
70
90
110
130
150
170

FIGURE 3

ORIGINAL PAGE IS
OF POOR QUALITY

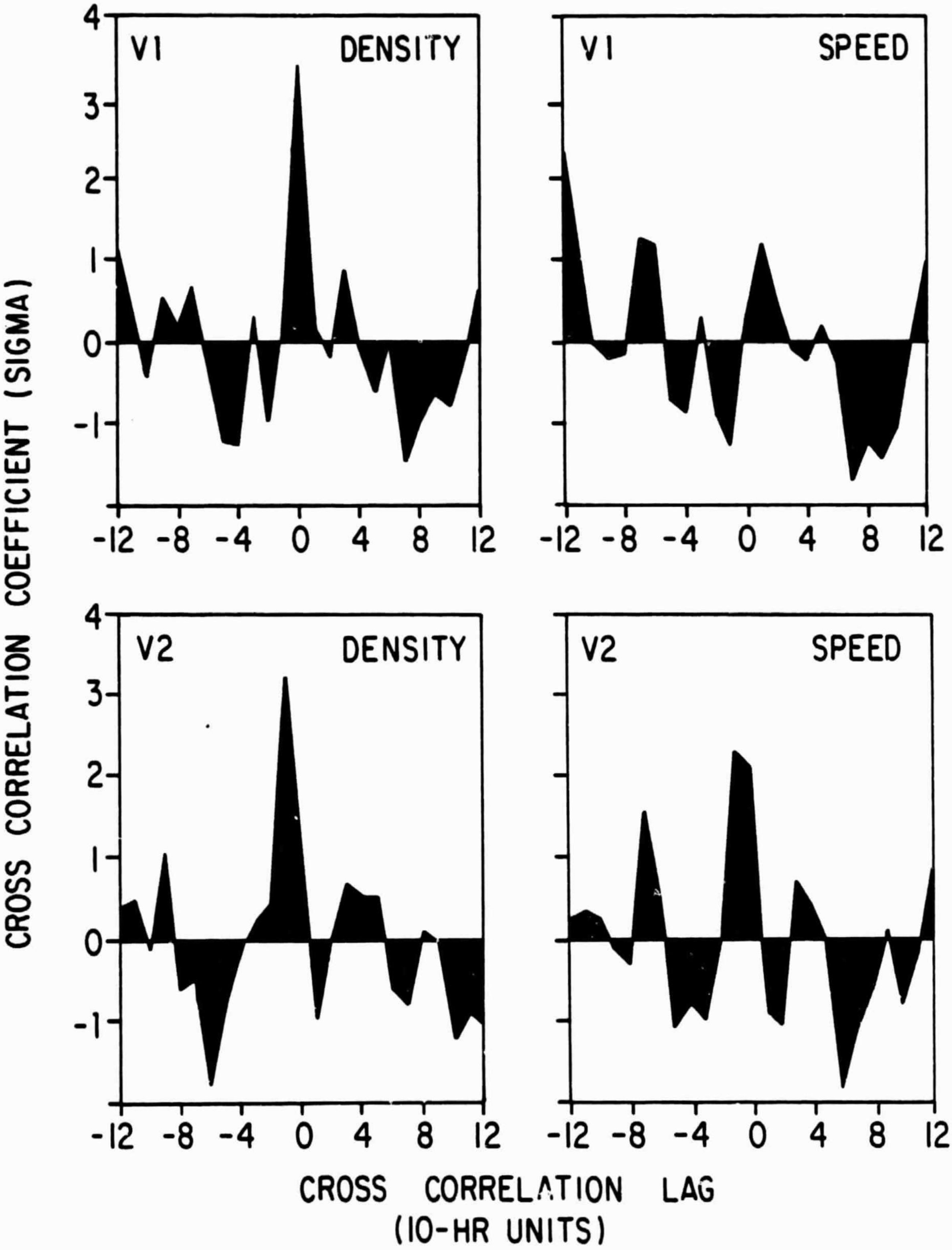
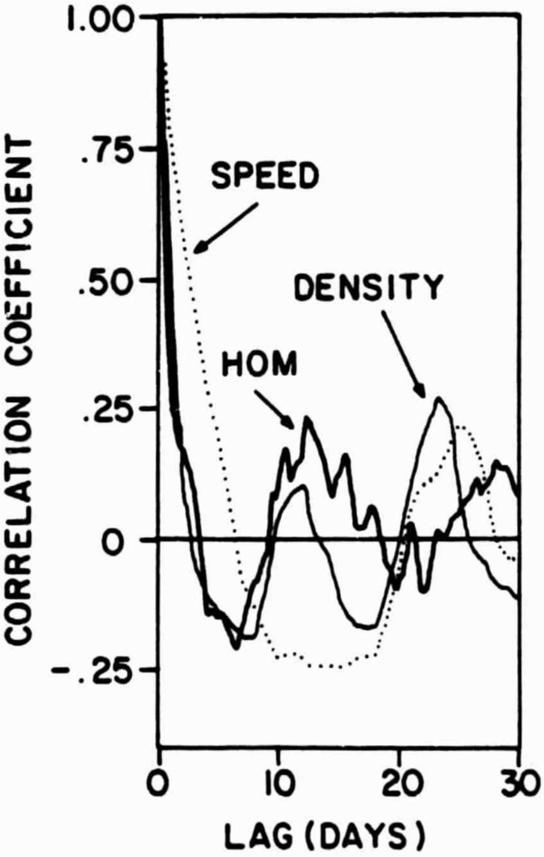


FIGURE 4


1.00
.75
.50
.25
0
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CORRELATION COEFFICIENT
SPEED
DENSITY
HOM
0
10
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30
LAG (DAYS)

FIGURE 5

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16. Abstract

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