Dual Periodicity of the Jovian Magnetosphere

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Jupiter's magnetic field, like that of the Sun, and perhaps Saturn, exhibits a clear, persistent dual periodicity, the two Jovian periods differing by almost exactly 3%. We offer a provisional definition of a new Jovian longitude system (which we call system IV) to organize magnetospheric data that are not stationary in system III. We show that available, independent data sets, covering a time interval of 4 years, which either drift in system III or show no particular organization in system III, fit mutually consistent patterns in system IV. All of the data sets covering several rotations of the planet that are presently available to us, including Voyager observations of ultraviolet and narrow-band kilometric emissions and ground-based optical observations, are organized in either system III, system IV, or both. Using these data, we derive provisional values for a transformation between systems III and IV: $\omega_{IV} = \omega_{III} + 338 - 25.486(t - 2443874.5)$ where $t$ is the Julian day and fractional day of the observation. There are pronounced 14.1-day variations in a number of Jovian magnetospheric phenomena. One possible interpretation of the system IV modulation is that it is a sideband resulting from the 14.1-day amplitude modulation of system III phenomena. Alternatively, the 14.1-day period could be explained if we assume the existence of an active sector that is fixed in system IV but drifts approximately 25.5°/d relative to the active sector in system III. When the system III and system IV activity maxima are aligned, magnetospheric activity, such as radio emissions and torus asymmetries, is enhanced, and when the activity maxima are anti-aligned, magnetospheric activity is subdued. The interval between alignments (or anti-alignments) is 14.1 days. Finally, we note that, in developing system IV, we have utilized only a small number of data sets. System IV needs to be tested against additional data before its durability is assured.

1. INTRODUCTION

Magnetospheric phenomena are commonly organized into one of two longitude coordinate systems: either a system that remains fixed relative to the Sun (e.g., local time coordinates), or a system that rotates with the planet and utilizes a planetary coordinate grid (e.g., universal time coordinates). Mighty Jupiter is different. It was early recognized that two rotating longitude systems were required to conveniently describe cloud motions (system I for low latitudes and system II for high latitudes). Later, an additional rotating longitude system was added to track magnetospheric radio phenomena (system III). It now appears that, as with the problem of tracking clouds that move with one of two angular velocities, system III is not enough to track various magnetospheric phenomena. An additional longitude grid that rotates with an angular velocity different from system III is needed.

The first magnetospheric phenomenon found to have a period different from system III was the Jovian narrow-band kilometric radio emission [Kaiser and Desch, 1980], which they concluded rotated 3% to 5% slower than system III. Then, Roesler et al. [1984] discovered that the brightness of the Io plasma torus varies with a periodicity having a component that is 3 ± 1% longer than the system III period. Persistent system III longitudinal variations in brightness had been reported earlier [Trafter, 1980; Pilcher and Morgan, 1980; Trauger et al., 1980], so the existence of a second distinct periodicity in torus brightness was new and unexpected. The observation of Roesler et al. was confirmed by Sandel [1983], who also noted the presence of a system III periodicity in the brightness of the torus. Finally, Pilcher and Morgan [1985] and Pilcher et al. [1985] present observations that they interpret as requiring plasma sources in the Io torus rotating with system III or at a 1% slower rate.

The two magnetospheric periods cannot be described in terms of a single, broadband period that encompasses both of the observed periods. The periods are distinct, separate, and persistent. Three concepts have been advanced to account for the presence of these two periodicities in the magnetosphere of Jupiter.


2. W. Horton and R. A. Smith (Solitary vortices in the Io plasma torus, submitted to Journal of Geophysical Research, 1987) propose a localised, long-lived vortex within the torus, the vortex being energised by the radial gradient in plasma slippage. They argue that the vortex will lag system III corotation, and it is this vortex that accounts for the longer periodicity.

3. Dessler [1985] suggests that Jupiter's magnetic field, like the Sun's, possesses more than one rotation period. He postulates a high-latitude, magnetospherically significant magnetic feature in Jupiter's internal field that has a rotation period $3\%$ longer than the system III period, and it is this feature that determines the new, longer periodicity.
TABLE 1. Comparison of Systems IV(1979) and III(1965)

<table>
<thead>
<tr>
<th></th>
<th>System IV</th>
<th>System III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidereal rotation rate*</td>
<td>845.05 ± 0.09</td>
<td>870.536 ± 0.001</td>
</tr>
<tr>
<td>(deg/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CML at 0000 UT on</td>
<td>126.</td>
<td>148.0</td>
</tr>
<tr>
<td>Jan. 1, 1979, deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(JD 2443874.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidereal period†</td>
<td>1013.27 (10.224 hours)</td>
<td>0955.29.71 (9.0249 hours)</td>
</tr>
</tbody>
</table>

* The rotation rates are to be regarded as exact by definition. The stated uncertainty is an indication of how much they might be changed in some future revision.
† Approximate values derived from rotation rates.

Our purpose in this paper is to provide a more extensive analysis concerning the nature of the second magnetospheric periodicity and to define a matching coordinate system, which we refer to as system IV. We use principally data from the 1979 Voyager flybys of Jupiter. In order to lengthen the time base and thereby improve the determination of the system IV rotation rate, we also utilize two available sets of ground-based observations of the Io torus. The data used are from (1) the Voyager 2 ultraviolet spectrometer (UVS), covering 100 rotations of Jupiter between April 26 and June 7, 1979, (2) the Voyager 1 and 2 Planetary Radio Astronomy experiments, covering nearly a full calendar year, January 2 to December 31, 1979, (3) ground-based observations by Brown and Shemansky, data obtained between February 23 and April 27, 1981, and (4) ground-based observations by Roesler et al. between April 12 and 30, 1982. The data base, with interruptions, spans a period of just 3.3 years, and we have used only the three time intervals listed in sets 2 through 4 above. We do not regard the following analysis as definitely establishing system IV. The reality of the proposed system IV must be verified by demonstrations of its persistence outside of the 1979–1982 interval.

We will not present the data in the iterative manner in which we worked. Rather, we begin by introducing system IV, which was developed to fit the data described in sections 3–5.

2. SYSTEM IV

In order to be able to conveniently intercompare various relevant magnetospheric observations, we provisionally define a coordinate system (called system IV(1979)) that parallels systems I, II, and III, but whose rotation rate is chosen to match the apparent angular motion of the magnetospheric phenomena that seem to share the new, longer periodicity as described in the introduction. We follow the precedent of the establishment of systems I and II by placing the zero or prime meridian so that the phenomena being observed is conveniently placed [Marth, 1888, p. 367]. Specifically, the rotation rate and initial rotational phase are chosen to keep the maximum brightness of the torus in the vicinity of \( \lambda_{IV} = 180^\circ \).

The basic system IV rotation rate is obtained from Voyager 1 and 2 narrow-band kilometric (nKOM) radio data and Voyager 2 UV spectrometer data and refined with ground-based data. As shown in section 5, the system IV(1979) sidereal rotation rate that best fits all the data is \( \Omega_{IV} = 845.05^\circ/d \), as compared with the system III(1965) sidereal rotation rate \( \Omega_{III} = 870.536^\circ/d \). (By "day," we mean the ordinary 24-hour terrestrial day.) The rotation rate \( \Omega_{IV} \) is assumed to be exact by definition (as is the value for \( \Omega_{III} \)). Zero time (\( t_0 \)) for the starting of the system is arbitrarily set to be 0000 UT on the first day of the year of closest approach of the Voyagers to Jupiter (January 1, 1979, Julian day 2443874.5). In order that the bright portion of the torus be at a system IV longitude of \( \lambda_{IV} \sim 180^\circ \), the system IV Central Meridian Longitude (CML) at 0000 UT on January 1, 1979 is set at \( \lambda_{IV} = 126^\circ \). The conversion between system III and system IV is presented in the form

\[
\lambda_{IV}(1979) = \lambda_{III}(1965) + 338. - 25.486(t - t_0)
\]

where \( \Delta \Omega = -25.486 \) is the difference between \( \Omega_{III} \) and \( \Omega_{IV} \), and \( t \) is the Julian day and decimal day for the day and time corresponding to the value of \( \lambda_{III} \). The two coordinate systems are compared in Table 1.

The rotation rate for system IV is, at this time, not determined well enough to assure that phenomena will not drift in longitude by as much as about \( 35^\circ \)/year. Fortunately, observations of system IV torus periodicity can be made from the Earth [e.g., Roesler et al., 1984]. If the various phenomena associated with system IV do share a common, identical rotation period that is durable over time intervals of years, as we explicitly assume, improvements in the value of \( \Omega_{IV} \) and the initial CML will be forthcoming. In that case, we should follow the example of Marth [1888, p. 88] and reset the rotation rate and move the prime meridian as necessary to keep the phenomena of interest from drifting in an improperly defined coordinate system and to keep the phenomena in a convenient part of the longitude scale. If, on the other hand, other observations show the bright portion of the torus moves about erratically in system IV, or if the data do not show order as in the cases we have examined, system IV will be of little utility, and the present values defining system IV will be adequate.

3. EUV OBSERVATIONS AND ANALYSIS

The Voyager 2 UVS is an objective-grating spectrometer covering the wavelength range from about 50 to 170 nm with 126 contiguous channels [Broadfoot et al., 1977, 1981]. The data used in this investigation were obtained from scans of Jupiter's satellite system between days 116 and 158 of 1979, or between 75 and 33 days prior to encounter. These scans, made with the 0.1° × 0.86° UVS slit approximately perpendicular to the satellite plane, produced measurements of the intensity of the plasma torus over a period covering 100 rotations of Jupiter. The brightness used here refers to the most intense feature of the EUV spectrum at 68.5 nm, which includes emission from one O III and three S III multiplets. These data have already been reported by Sandel and Broadfoot [1982a], but they are analyzed here from a different perspective.

The basic data consist of 235 scans across the torus, which measured the brightness of the approaching (east) and receding (west) ansae. The interval between measurements was nonuniform. The observational sets usually consisted of a sequence of seven or eight samples of both ansae separated by approximately 2 hours followed by a gap of 12 or 10 hours, repeated once per day. This sampling does not suit the data to analysis by the powerful techniques developed for searching for periodic modulation of a signal that is
sampled at equal intervals. In the appendix we summarize two techniques that are useful in the analysis of nonuniformly sampled data such as these. The first is based on the classical periodogram, with modifications and extensions by Scargle [1982], permitting a straightforward statistical interpretation of the results. The second technique described in the appendix, essentially a superposed-epoch analysis, is useful as a cross check.

The strongest feature in periodograms computed by Scargle's [1982] method for the approaching and receding ansae of the torus is a component at Io's orbital frequency (Figures 1a (approaching) and 2a (receding)). This is simply the Io-related modulation of the torus brightness described by Sandel and Broadfoot [1982b]. Because we wish to focus on periods near the system III period, it is helpful to remove this component from the data before proceeding further. Subtraction of the third-order Fourier-series approximations to the Io modulation in Figure 2 of Sandel and Broadfoot [1982b] leaves the substantially simplified periodograms in Figures 1b and 2b. Dominant in the receding ansa is a component at 14.75 rad/d, and in the approaching ansa are strong components both at this angular rate and at 15.19 rad/d. Several prominent yet spurious features marked in the plot were identified by analyzing control samples of synthetic data. The spurious features are not statistically significant according to Scargle's criteria. Some of the nonspurious features are harmonics or beat frequencies between systems III and IV and a 14.1-day modulation period.

To concentrate on components near the system III rotation rate, it is convenient to replott the portion of the periodogram marked by the bars in Figures 1 and 2 in units of $P_{III}$, the system III period (Figure 3). Modulation of the EUV brightness at the system III period has not been reported prior to this investigation [Sandel and Broadfoot, 1982a; Shemanskii and Sandel, 1982], but ground-based measurements of visible emissions show persistent correlation with system III longitude [e.g., Fuller and Morgan, 1985]. Therefore we examine the periodograms for evidence of power at $P_{III}$, the system III rotation period. At the receding ansa, the amplitude of the periodogram is low near the system III rotation period, but the approaching ansa shows a small peak at $(1.000 \pm 0.002) \times P_{III}$. We must estimate the noise power $\sigma_0^2$ to calculate confidence levels. Because the measurement error and periodic variations are small compared with (apparently) aperiodic fluctuations in brightness, we find $\sigma$ directly from the scatter of the data points about their mean, after the Io modulation is subtracted. This is consistent with the procedure described by Horne and Baliunas [1986] and with their admonition regarding the interpretation of the variance of the data. We find $\sigma^2$ (approaching) = 0.11 and $\sigma^2$ (receding) = 0.17. Analysis of synthetic data that were generated using these values has verified that they are appropriate. Using (5) from the appendix, we find a probability of 0.003 that the observed power of 0.631 at the null at $(1.005 \times P_{III})$ (nearest the peak) is present by chance at this preselected frequency. This is evidence for modulation of the brightness of the approaching ansa at the system III period.

Periodograms for both ansae have peaks near 1.03 $P_{III}$. Optical observations have revealed brightness variations near this period, but the period was not precisely determined [Roester et al., 1984]. Therefore in evaluating our confidence in these peaks, we make the most cautious es-
The best estimate of the period of the modulation is the peak in the oversampled periodogram. These peaks are at 1.000 $P_{III}$ and 1.030 $P_{III}$ at the approaching ansa and at 1.030 $P_{III}$ at the receding ansa. Using (14) of Horne and Baliunas [1986], we estimate a two-sigma uncertainty of 0.001 $P_{III}$ in the period. However, our analysis of synthetic data has shown that the location of the peak in the periodogram is sensitive to the random noise component and more weakly sensitive to the starting point for the computation of the periodogram. Many synthesis and analysis cycles with different random noise sequences (but the same amplitude $A$ in (8)), and with different starting points for computation of the periodogram have shown that a two-sigma uncertainty of 0.002 $P_{III}$ is a better estimate. This is the uncertainty we have adopted in Table 2.

The amplitudes of the modulation estimated from (7) are shown in the first line of Table 2. The quoted uncertainties were derived using Groth's [1975] Figure 1 as described in the appendix. As a consistency check, the data synthesis technique can be applied by adjusting the amplitudes until the synthetic periodogram is acceptably similar to the periodogram computed from the data. A potential pitfall in this approach is that it may underestimate the uncertainty in the amplitude. This is because small variations in the random noise component can materially affect the amplitude of the periodogram, even for a prominent and statistically significant feature. To avoid this difficulty, we have computed periodograms from data synthesized using several sequences of random numbers to describe the noise in the data. The uncertainties quoted with the amplitudes in the second line of Table 2 reflect the results of this investigation.

Plots of the brightness at the approaching and receding ansae as a function of system IV longitude (Figure 4) show an obvious modulation of the brightness of the receding ansa, and a weaker but nonetheless detectable modulation at the approaching ansa. Fitting low-order Fourier series to these data gives an objective measure of amplitude and phase. The amplitudes of the modulations estimated in this way are included in the third line of Table 2. We have assigned no uncertainties because there is no obvious analytical procedure to estimate uncertainties by this technique. Instead, we rely on the other techniques.
Fig. 3. Periodograms of UVS measurements at approaching and receding ansae expanded from the regions marked by the bars in Figures 1 and 2. These have been replotted in terms of period rather than frequency to ease later references. The circles mark the amplitude of the periodogram at nulls in the spectral window, the set of natural periods for evaluation of the periodogram. The smooth curve is the highly oversampled periodogram. Significant modulation at 1.03 $P_{III}$ is present at both ansae, and the brightness of the approaching ansa is modulated at the system III period as well.

Because the modulation at the approaching ansa is difficult to detect by eye, we have investigated means of making it more obvious. We have found that the EUV brightness, like the nKOM emission probability, is modulated more strongly when the system III and IV peaks in the nKOM probability are near alignment. An example is shown in Figure 5, where we have plotted EUV brightness of the two ansae as a function of $\lambda_{IV}$, having selected those observations within 3.5 days of the times of alignment and of anti-alignment as described in section 4. In Figure 5a the modulation at the receding ansa is more prominent than in Figure 4, and modulation at the approaching ansa is apparent as well.

Figures 4 and 5 show that the brightness of an ansa is greatest when the ansa is near $\lambda_{IV} = 180^\circ$, that is, the brightness curves of the two ansae are about 180$^\circ$ out of phase. At least two physical phenomena are consistent with this behavior. The first involves a region of enhanced EUV emission that is fixed near $\lambda_{IV} = 180^\circ$, and that rotates through one ansa and then the other as system IV rotates. The second involves periodic out-of-phase brightening and dimming of the ansae, driven by a mechanism other than a bright spot fixed in system IV. We cannot choose between these two possibilities solely on the basis of the EUV observations, because time coverage and spatial resolution do not permit us to follow a putative enhancement in EUV emission as it moves with the torus. Thus we can neither confirm nor rule out an EUV enhancement that rotates with system IV to drive the observed modulation. Although a rotating bright spot such as implied by S II images may seem to be the most natural interpretation of the EUV variations as well, we note in section 6 that variations in the dawn-dusk electric field that have the system IV period could account for the observations in an equally natural way.

The curves of brightness versus $\lambda_{IV}$ in Figure 4 have a characteristic shape. The brightness of the receding ansa gradually increases to a maximum, then decreases more rapidly. This shape is similar to the shape that Sandel and

![Periodogram](image)

**Table 2. Amplitude of the Modulation**

<table>
<thead>
<tr>
<th>Method</th>
<th>Approaching Ansa $1.00 \times P_{III}^*$</th>
<th>Approaching Ansa $1.03 \times P_{III}$</th>
<th>Receding Ansa $1.03 \times P_{III}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation (7)</td>
<td>$0.148^{+0.05}_{-0.06}$†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthesis</td>
<td>0.23†</td>
<td>0.16†</td>
<td>0.382$^{+0.05}_{-0.06}$†</td>
</tr>
<tr>
<td>Phase plots</td>
<td>0.24†</td>
<td>0.15†</td>
<td>0.375†</td>
</tr>
</tbody>
</table>

* $P_{III}$ is the system III period, 0955:29.71
† Uncertainties represent 95% confidence.
‡ Fourier fit (with component at 1.03 $P_{III}$ removed).
$\frac{1}{2}(\text{max} - \text{min})$ (with component at 1.03 $P_{III}$ removed).
Fig. 4. Relative brightness of the (top) approaching and (bottom) receding ansae of the plasma torus from UVS data as a function of system IV longitude. We show the brightness of the S III 685-Å feature, the brightest in the EUV spectrum of the torus. The abscissa refers to the system IV longitude of the observed ansae. The solid curves below the data points are sliding averages of the data displaced downward by two units. The brightness at both ansae is modulated at the system IV period, with the modulation at the receding ansa stronger than at the approaching, where the modulation is barely apparent in this figure. The dashed curve in the bottom panel is a scaled and phase-shifted plot of nKOM probability from Figure 8a. The EUV brightness and the nKOM probability change with system IV in qualitatively the same way.

Broadfoot [1982b] found for the Io-correlated brightness enhancement, when brightness is plotted against the orbital phase of Io. In spite of the similarity in the shapes, the mechanism described by Sandel and Broadfoot is not applicable to the system IV modulation described here. Their mechanism involves heating of the plasma electrons as they are swept past Io. Subsequent cooling of the plasma by EUV radiation as the plasma is carried further downstream from Io leads to the observed dependence of brightness on the azimuthal separation from Io. The key to the success of the model is the relationship between the radiative cooling rate and the angular velocity of the plasma relative to the energy source at Io, about 28°/h. The difference in angular velocities between systems III and IV is only about 1°/h, so cooling would take place near a source fixed in system IV. Furthermore, if the concept of plasma slippage is considered [Hill, 1980], the torus plasma should be virtually stationary in system IV. We would therefore expect a brightness curve more symmetrical than observed if the curve represented heating and radiative cooling versus time.

The shape of the azimuthal variation in the S III EUV emissions that we infer here is similar to that reported by Pitcher and Morgan [1985] for the S III 953-nm brightness. Both sets of observations show a steeper brightness gradient toward the high-longitude side of the peak. This behavior may also be characteristic of the S III 953-nm observations.

Fig. 5a. Relative brightness of the ansae as a function of system IV longitude. These observations from the half-periods about (a) alignment and (b) anti-alignment of the probability peaks in systems III and IV show that modulation of the EUV is enhanced near times of alignment, particularly in the receding ansa. Near alignment, modulation is apparent in the approaching ansa, with peaks in each ansa near Δυ/2 = 180°. The solid curves are sliding averages of the data displaced downward for clarity.

Fig. 5b. Relative brightness of the (top) approaching and (bottom) receding ansae as a function of system IV longitude. We show the brightness of the S III 685-Å feature, the brightest in the EUV spectrum of the torus. The abscissa refers to the system IV longitude of the observed ansae. The solid curves below the data points are sliding averages of the data displaced downward by two units. The brightness at both ansae is modulated at the system IV period, with the modulation at the receding ansa stronger than at the approaching, where the modulation is barely apparent in this figure. The dashed curve in the bottom panel is a scaled and phase-shifted plot of nKOM probability from Figure 8a. The EUV brightness and the nKOM probability change with system IV in qualitatively the same way.
of Roessler et al. [1984], but there is certainly less pronounced (see section 5). Pilcher and Morgan suggest that this structure may arise from a plasma source that lags corotation.

Comparison of the EUV spectra from times of maximum and minimum brightness shows that the brightness variation is consistent with the inferred change in electron temperature. This analysis is based on the ratio of the SIII 68.5-nm and 102.0-nm features, as described by Shemansky and Sandel [1982], for the case of the dawn-dusk EUV asymmetry. Changes in electron temperature are also responsible for the Io-related enhancement in EUV emission [Sandel and Broadfoot, 1982].

The azimuthal extent of the enhancement in EUV brightness is difficult to determine from these data. Because we are limited in this data set to samples at the ansa, this extent can be determined only in the case of a bright spot that revolves at the system IV period, and is therefore carried through the ansa. By using simple models of azimuthal variations in brightness [Sandel and Broadfoot, 1982], we estimate that such a bright region probably would have a width between 60° and 150° in azimuth.

To investigate the system III modulation at the approaching ansa, it is desirable to remove the effects of the modulation in system IV. This can be done in first order by subtracting from each data point the Fourier fit derived from the phase curve calculated for the system IV variation. The plot so derived (Figure 6) shows strong grouping of the points in phase because the observing sequence was closely synchronized with Jupiter's rotation rate. Nevertheless a weak modulation in the brightness of the approaching ansa in system III is apparent. The mean and standard deviation for each of the groups are indicated by the bars to the right of each group. All the groups overlap at the one sigma level, so this particular presentation of the data does not demonstrate that significant modulation is present at

the system III period at the approaching ansa. However, this modulation has already been demonstrated to a high degree of confidence by the periodogram analysis. We use this plot rather to learn the phase of the modulation and to verify that the amplitude inferred from the other techniques is reasonable. The plot shows that the minimum brightness occurs when the approaching ansa is near 5°. The phase curve is again asymmetric, with the maximum when the approaching ansa is near 80°. Because of the discontinuous phase grouping, the amplitude is best defined as half the difference of maximum and minimum group means, or 0.24 as shown in the last line of Table 2.

For both ansae, the amplitudes of the modulation at 1.03 PIII determined by the three methods and shown in Table 2 are in excellent agreement. For the modulation at 1.00 PIII, (7) gives a value significantly lower than that derived from the other two methods, which are in agreement with each other. This inconsistency may be related to the asymmetry in the brightness variation. But, in any case, it is the existence of the modulation, rather than its exact amplitude, that is of central importance in this paper.

The amplitude of the periodogram at PIII is not an artifact of the sampling sequence, even though the sequence leads to phase grouping at a period of PIII. This possibility is ruled out on several grounds. First, no significant amplitude is present in the receding ansa at 1.00 PIII, even though the sampling sequence was exactly the same. Second, periodograms computed from data synthesized including realistic random noise (but no periodic components) have no significant amplitudes near PIII. As a control, we have examined plots of brightness versus phase for periods at which the periodograms have no significant amplitude and found no indication of modulation.

4. NARROW-BAND KILOMETRIC RADIATION

Here we consider observations of the narrow-band kilometric radiation in the context of system IV and of the EUV measurements. Using catalogs of Voyager nKOM observations kindly supplied to us by M. L. Kaiser and Y. Leblanc, we have investigated the nKOM periodicity reported by Kaiser and Desch [1980] and Daigne and Leblanc [1986] to help in establishing the system IV longitude system and to determine the phase relationship of the EUV and nKOM modulations. We have also verified the system III modulation reported by Daigne and Leblanc [1986].

The nKOM data used here are the recorded times of the narrow-band kilometric radiation in the context of system IV and of the EUV measurements. Using catalogs of Voyager nKOM observations kindly supplied to us by M. L. Kaiser and Y. Leblanc, we have investigated the nKOM periodicity reported by Kaiser and Desch [1980] and Daigne and Leblanc [1986] to help in establishing the system IV longitude system and to determine the phase relationship of the EUV and nKOM modulations. We have also verified the system III modulation reported by Daigne and Leblanc [1986].

The nKOM data used here are the recorded times of the beginning and end of intervals during which nKOM emissions were detected. The polarization of the radiation was recorded as well, but has not been included in this analysis. Near closest approach to Jupiter, nKOM was detected almost continuously. Therefore nKOM observations from these times are not helpful in defining periods, and nKOM observations within two days of closest approach have been omitted from consideration. The remaining 381 separate episodes of nKOM detected by both Voyagers 1 and 2 span a full year, from January 2, 1979, to December 31, 1979.

We use a simple modification of superposed epoch analysis to study the data. The nKOM catalog does not include explicit information on the detected signal strength, so that the usual techniques are not directly applicable. Instead, we plot the probability of detecting nKOM as a function of the system IV longitude of the central meridian of Jupiter as seen from Voyager. To compute this probability, we record the number of times nKOM is detected in 360 azimuth bins,
Fig. 7. The ordinate measures the degree of organization in plots of the probability of detecting nKOM as a function of azimuth, when azimuth is computed using the value $\Delta \Omega$ on the abscissa. The range of $\Delta \Omega$ in the lower panel corresponds to periods from 1% less than the system III period to 7% greater. The smaller plots show the two dominant peaks near $\Delta \Omega = 0.0$ and $-25.4^\circ$/d at higher resolution. Compare with Figure 99 of Daigne and Leblanc [1986].

Each $1^\circ$ wide in $\lambda_{IV}$. For the plots shown here, we have summed these bins in groups of five to 10 for smoothing. Using a similar technique, we have also computed the probability of finding the center of an nKOM episode in a particular range of $\lambda_{IV}$. The two procedures yield consistent results. Because the first procedure preserves information about the duration of each episode while the second does not, we prefer the first and rely on it here.

This technique can reveal periodicities in the occurrence of nKOM. If the nKOM is modulated at the trial period used to compute the azimuthal binning, then the probability distribution will vary markedly in azimuth. To define periodicities in the nKOM, we have searched a number of trial periods near the system III period and near a period 3% greater that is consistent with earlier determinations of the nKOM period and with the EUV period determined here.

Figure 7 shows the results. In each panel, the ordinate measures the degree of modulation found when the probability of detecting nKOM is computed at the value of $\Delta \Omega$ along the abscissa. Maxima are clearly defined at periods corresponding to $\Delta \Omega = 0.0$ (that is, the system III period) and at $\Delta \Omega = -25.4^\circ$/d, corresponding to a period about 3% greater than the system III period. The latter is in close agreement with the period inferred from the analysis of the EUV data. The peaks are rather broad because of scatter in the nKOM episodes about their mean, because at least two periods are present, and because many of the nKOM episodes are lengthy. Figure 7 also shows peaks near $\Delta \Omega = -23.3$ and $-27.5^\circ$/d. Although the peak at $\Delta \Omega = -23.3^\circ$/d is quite strong, both it and the one at $-27.5^\circ$/d are outside the range of periods that is acceptable, based on the EUV analysis. For this and other reasons discussed in section 5, we rule out these periods and focus on the values of $\Delta \Omega$ near $-25.4^\circ$/d for system IV.

Figure 8 shows the probability of observing nKOM as a function of longitude for system III and for system IV. In computing the latter, we have used the definition of system IV in section 2. Modulation at a period compatible with system IV has already been demonstrated by Kaiser and Desch [1980]. Daigne and Leblanc [1986] showed that the emissions are also modulated at the system III period. Figure 8 is therefore a verification of these earlier findings. Daigne and Leblanc point out that considering the polarization of the signal resolves the structure in Figure 8a into two separate peaks. The stronger, which is in right-hand polarized emission, falls near $\lambda_{III} = 40^\circ$ and is the main contributor to the maximum in Figure 8a.

There is no significant modulation if other periods are randomly selected. For example, Figure 9 shows the same probability plotted in a system defined by a value of $\Delta \Omega$ for which only weak modulation is expected on the basis of Figure 7. The striking differences in modulation with azimuth between Figure 9 and Figure 8 show that the periods used in Figures 8 (i.e., the system III and IV periods) do in fact organize the nKOM probability better than do other periods.

The shapes of the probability curves in the two coordinate systems are similarly asymmetric, with maxima separated from minima by about $130^\circ$, measuring in the direction of increasing longitude. That is, as seen from Voyager, the time from maximum probability of detecting nKOM to minimum probability is about 3.6 hours, while the time from minimum to maximum is about 6.4 hours. Also, the nKOM probability curve has the same asymmetry as the EUV brightness curve as shown in Figure 4.

The presence of modulation at these two similar periods suggests that some aspect of the nKOM should vary as these two systems rotate relative to one another. Ev-
Fig. 8. Relative probability of observing nKOM as a function of the longitude of the central meridian of Jupiter as seen from Voyager. (a) Probability in system III. (b) Probability in system IV. In both systems the probability has well-defined peaks and varies by more than a factor of 2 with longitude. In this and the following three figures, the radial coordinate is only a rough estimate of the absolute probability. This coordinate properly represents changes in the relative probability under the different conditions of the four figures.

Figures 11a and 11b illustrate these effects more dramatically. These plots include nKOM episodes within one day of alignment and anti-alignment. The most striking difference is in the number of episodes detected during the two windows: 71 in the window near alignment, and only 34 in the window about anti-alignment. In contrast, there is no significant difference in the average durations of episodes in the two windows. This nKOM modulation has been pointed out by Daigne and Leblanc [1986], who note the existence of long-term fluctuations with a period of 30-40 Jovian rotations. The 14-day periodicity in (3) corresponds to 34.2 rotations of system III. In summary, the duration of a typical nKOM event does not depend on the relative alignment of the system III and IV longitude grids, but the probability of detecting nKOM at all is strongly dependent on this alignment, and hence exhibits a period of approximately 14 days.

Kurth et al. [1980] described a 14-day separation between several minima in the bKOM emission (which originates from a different part of the magnetosphere than the nKOM), but they attributed this periodicity to changes in the sector structure of the magnetic field of the solar wind. The minima reported by Kurth et al. were at days 162, 176, 188, and 204 of 1979. Using (3) for times of anti-alignment, we find that expected minima in nKOM activity in systems III and IV fall at days 161.5, 175.6, 189.8, and 203.9 of 1979, in agreement with the times reported by Kurth et al. We
suggest that their observations are most naturally explained as a beat period between system III and system IV.

As a consistency check we have used two other techniques, computation of the Fourier power spectrum and Scargle's periodogram, to search for periodicities in the nKOM. We find results that are in accord with those already described. Both of these techniques are intended to look for periodic structure in the amplitude of a signal that depends on time. Because the nKOM data available to us include no explicit measure of signal amplitude, it was necessary to provide amplitude information in some way. For the Fourier analysis, we divided the time spanned by the data into 10-min intervals, corresponding approximately to the time resolution of the nKOM catalog. To each of these intervals we assigned an amplitude of 1 or 0, depending on whether nKOM was or was not detected during that interval. These data were used to compute the Fourier power spectrum. To compute the Scargle periodogram, times were taken as the center of each nKOM episode, and the corresponding amplitude was taken to be the duration of the episode. This is physically reasonable because the duration of the event is measured between the times at which the nKOM amplitude exceeds and falls below the detection threshold. Thus the duration of the episode may be expected to be related to the amplitude of the detected signal. With both methods, the two strongest peaks lie near $\Delta \Omega = 0$ and $\Delta \Omega = -25.5^\circ/d$, with

![Fig. 10. Relative nKOM probability as a function of the system IV longitude of the central meridian. The observations have been divided into two portions, (a) the 7-day half-period around the time of alignment of the peaks in systems III and IV shown in Figure 8, and (b) the other half-period about anti-alignment of the peaks. The probability is more strongly modulated at times near alignment of the peaks in systems III and IV.](image)

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The relative probability of detecting nKOM as a function of the system IV longitude of the observer's central meridian. This figure is similar to Figure 10, except that only data from 2-day periods about (a) alignment and (b) anti-alignment of the peaks in systems III and IV have been included. Detection of nKOM is more likely during times of alignment.

The modulation in the EUV and the nKOM probability have a fixed relationship in system IV. The system IV phase has been chosen to place the EUV bright spot near $\lambda_{IV} = 180^\circ$, as shown in Figure 4. The source of the nKOM is believed to lie near the central meridian plane at the times when the nKOM is detected [Kaiser and Desch, 1980]. The minimum in nKOM probability (near central meridian $\lambda_{IV} = 180^\circ$) is approximately the system IV longitude of the EUV bright spot. Details of the shape of the nKOM probability curve and of the EUV brightness enhancement are similar, as shown in Figure 4.

Other evidence argues that the nKOM and EUV phenomena that we describe here are related in a fundamental way. Figures 5a and 5b show the result of dividing the EUV data into two groups, one including data near times of alignment as given by (2), and the other near times of anti-alignment as given by (3). Modulation of the EUV brightness at both anaeae is more pronounced near alignment. We have also searched for the time of alignment that yields the strongest modulation of the EUV brightness of the receding anaeae. We find a time that agrees with the time given in (2) within 0.5 day, which is near the resolution of the determination. The EUV and nKOM modulations are therefore related not only in having the same 10.2-hour period, but also the amplitude of their modulations varies synchronously with a 14-day period.

5. GROUND-BASED OBSERVATIONS

The EUV and nKOM observations show that both phenomena are modulated at a period of about 10.2 hours, but from these data alone the period cannot be determined precisely enough to permit comparisons of observations several years apart. The fractional uncertainty of 0.002 in the period inferred from the EUV measurements corresponds to a drift of $1.74^\circ$/d, or $180^\circ$ in about 100 days. The nKOM observations help to reduce this uncertainty because they span a longer period of time. However, we can define this quantity more accurately if we turn to ground-based observations of the torus that do not share the limited temporal coverage inherent in the Voyager observations. To be most useful in this context, observations should span a number of rotations of the planet, should have time resolution better than...

Fig. 11. Relative probability of detecting nKOM as a function of the system IV longitude of the observer's central meridian. This figure is similar to Figure 10, except that only data from 2-day periods about (a) alignment and (b) anti-alignment of the peaks in systems III and IV have been included. Detection of nKOM is more likely during times of alignment.

Fig. 12. Ranges of values of $\Delta\Omega$ that are acceptable on the basis of several subsets of the data. The ranges determined from the EUV and nKOM observations are independent. Neither the data of Roesler et al. nor of Brown and Shemansky limit $\Delta\Omega$ within the range of the abscissa. The ranges shown for those sets of observations were inferred by combining them with the EUV and nKOM measurements.
1 hour, and should show modulation at a period consistent with those determined from the Voyager observations.

Such observations have been reported by Roesler et al. [1984]. These authors measured the brightness of the [S III] 953-nm emission from the receding ansa of the plasma torus, accumulating 71 observations in the time period of April 12 to 30, 1982. They identified a modulation in the brightness of the ansa that had a period of 10.2 ± 0.1 hours, corresponding to \( \Delta \Omega = -23 \pm 8^\circ/d \). The extent of the bright region was about 90° in azimuth, and the amplitude of the modulation was a factor of about 2.

The observations of Roesler et al. relate to the same species, S III, as the EUV measurements and, within the uncertainty, show the same periodicity. Therefore we explicitly assume that the two sets of data are manifestations of the same underlying physical mechanism, and we further assume that the bright regions at the two wavelengths would have been coincident had the two sets of measurements been performed at the same epoch. We adjust the value of \( \Delta \Omega \) and \( \lambda IV \) so that the region of enhanced [S III] 953-nm emission falls at \( \lambda IV = 180^\circ \).

In Figure 13 we have used our preferred value for \( \Delta \Omega \) of -25.486°/d to plot the data of Roesler et al. in system IV. These data were kindly supplied to us in a form useful for this investigation by F. Scherb. This figure, which is analogous to Figure 2 of Roesler et al., shows an unmistakable modulation at the system IV period, with a peak at \( \lambda IV = 180^\circ \). The 953-nm observations span a time interval that includes periods of both alignment and anti-alignment of the sectors of maximum activity in systems III and IV. We find that the amplitude of the azimuthal variation in the 953-nm brightness tends to be greater at times near alignment than at times near anti-alignment. The data are not extensive enough to permit an unambiguous identification of this trend, but we note that such behavior is common to the EUV and nKOM emissions as well. Such commonality suggests a close relationship among the sources of the emissions.

Several values of \( \Delta \Omega \) are consistent with the nKOM, the EUV, and the 953-nm observations, because of the ambiguity introduced by the possibility of increasing or decreasing the rotation of system IV relative to system III by an integral number of complete rotations in the 1000 days between the Voyager and the ground-based observations. Discrete ranges of periods are acceptable, and the centers of these ranges fall at \( \Delta \Omega = -25.486 \pm 0.337^\circ/d \). The width of the range is determined from our estimate of the uncertainty in the location of the peak 953-nm brightness in system IV, ±45°. These ranges are shown in Figure 12. Four of them are at least marginally consistent with the full data set examined so far, with the two at -25.149 and -25.486°/d being preferable to the two more extreme values.

To discriminate among these possible periods, we add the observations of the plasma torus reported by Brown and Shemansky [1982]. They measured dramatic variations in the brightness of S II 673-nm emission from both ansae of the torus in February and April of 1981. They reported that their search for a dependence of brightness in system III revealed none, although system III variations are reported by others [e.g., Pilcher et al., 1985]. However, we find that their data are organized in system IV. We have added their S II 673-nm brightnesses plotted against \( \lambda IV \), as computed from the definition given in section 2, to those of Roesler et al. The results are shown in Figure 14. The brightest points fall in the range \( \lambda IV = 180^\circ \pm 90^\circ \), with most of them closer to 180°. The ambiguity in \( \Delta \Omega \) described for the 953-nm observations is present in this case as well, and the acceptable values of \( \Delta \Omega \) are shown in Figure 12. The spacing of the values is different because 673-nm observations were made about 700 days after the Voyager measurements, and the uncertainty is larger because of the larger scatter in the 637-nm brightness values.

Taking all these data into account, we find that one of the discrete ranges of \( \Delta \Omega \) fits better than any of the others. The center of this range is \( \Delta \Omega = -25.486^\circ/d \), and this is the value that we have adopted in section 2. This selection hinges on the weight given to the 673-nm observations. Relaxing the requirement for compatibility with these measurements would leave the \( \Delta \Omega = -25.149^\circ/d \) an acceptable alternative to -25.486°/d. Nevertheless, we believe that \( \Delta \Omega = -25.486 \) is the correct choice because it is closer to...
the value preferred on the basis of the nKOM and the other phenomena that fit naturally into the system IV so defined.

Other ground-based observations of S II emissions have shown azimuthal asymmetries that are consistently fixed in system III [Pilcher et al., 1985; Morgan, 1985; Trafton, 1986]. Sampling of a structure correlated with system IV at different times when, by chance, the relationship between the two systems is nearly constant would cause the structure to appear fixed in system III as well. This is apparently not the case with the S II observations. For the two nights’ observations shown in Figures 12 and 13 of Pilcher et al. [1985], the offset between systems III and IV changed by only 20°, so any structure would be stable in both systems. However, Figure 6 of Morgan [1985] shows the same structure in system III at a time when the offset between the two systems differed by about 180° from that of the earlier measurements. We conclude that these variations are well organized in system III, but not in system IV.

Pilcher and Morgan’s [1985] observed peaks in the brightness of both S III and S II emissions drift toward higher \( \lambda_{1II} \) by 25° in about 50 hours. This drift is in the correct sense for a phenomenon fixed in system IV, but the rate is a factor of about 2 smaller than our preferred value of \( \Delta \Omega \). However, our rate is a time-averaged value of \( \Delta \Omega \), and each of the data sets used in defining it is compatible with intermittent departures by a factor of 2 from this average value. Thus the short-term drift rate observed by Pilcher and Morgan may be consistent with other system IV phenomena.

Pilcher and Morgan’s Figure 3 suggests that peaks in the brightness of both S II and S III emissions shifted by roughly the same amount in 2 days. If this correlation is typical, then we face a difficulty in understanding the relationship of the 953-nm S III measurements of Roesler et al. (which are organized in system IV), to the 673-nm S II emissions (which show persistent organization in system III). However, we note that the S III 953-nm peak in Pilcher and Morgan’s Figure 3 falls at \( \lambda_{1II} \sim 230° \), near its expected position in system IV. More information on the conditions under which the S II and S III emissions are correlated is needed.

All the phenomena used in the definition of system IV show a 14-day modulation, with maximum amplitude at times near alignment of the sectors of maximum activity in systems III and IV. We find a suggestion of this behavior in the S II emissions as well. All the data plotted in the figures of Pilcher and Morgan [1985] were obtained near times of alignment, and show pronounced azimuthal variations. Morgan [1985] shows data acquired near alignment (his run 1, Figure 4), midway between alignment and anti-alignment (run 3, Figure 5), and near anti-alignment (runs 2 and 4, Figure 4, 5, and 6). Run 1 (aligned) shows the strongest and best organized modulation in both S II emissions of all four data sets. This is similar to the behavior of the 953-nm emissions described earlier, the EUV, and the nKOM emissions. Near anti-alignment (runs 2 and 4, particularly Figure 6) the brightness is more uniform in azimuth than the data from his run 1 and in Figures 1, 2, and 3 of Pilcher and Morgan, especially in view of the point near \( \lambda_{1II} = 10° \) in his Figure 6. Although we cannot draw firm conclusions from this limited sampling, it seems plausible that the azimuthal asymmetry in the S II emissions is modulated in a way analogous to the EUV, the nKOM, and the S III 953-nm brightness measured by Roesler et al.

### 6. THEORETICAL IMPLICATIONS

#### 6.1. General Considerations

The principal finding of two persistent, discrete periodicities in the Jovian magnetosphere can be addressed in several ways. We are aware of the three listed in the introduction: (1) plasma slippage in the Io torus, (2) a localized vortex within the torus, and (3) a differential rotation within Jupiter’s magnetic field.

Suggestion 1 is the most conspicuous possibility. Unfortunately, it has no obvious merit. As pointed out by Dessler [1985], “To get a distinctly different period utilizing the slippage of magnetospheric plasma, one would have to suppose the existence of a physically unrealistic, longitudinally confined, long-lived blob that (a) slips relative to corotation, (b) does not change its Jovicentric distance, and (c) is continually resupplied with either plasma or energy.” The period of a magnetospheric phenomenon is determined by the periodicity of the source that powers that phenomenon. Simple plasma slippage shifts the phase of a spin-modulated phenomenon, but it cannot change the period. For example, although the solar wind slips rather excessively relative to solar rotation, the period of solar wind activity remains the nominal 27-day rotation period of the Sun. There is a phase shift, however, as receding (west) limb activity at the Sun is often more important terrestrially than approaching (east) limb activity.

Suggestion 2, the formation of a vortex within the torus, is a clever and sophisticated variant of suggestion 1. W. Horton and R. A. Smith (Solitary vortices in the Io plasma torus, submitted to Journal of Geophysical Research, 1987) propose that the velocity shear in the torus that is caused by the predicted and observed increase of plasma slippage with increasing radial distance [Hill, 1979; McNutt et al., 1979] can provide a continuous source of power to a vortex (or soliton) within the torus. This suggestion immediately overcomes difficulties (a) and (c) quoted in the previous paragraph. The lifetime of a soliton in the torus is not addressed. However, we can see that this is an important issue. The rotation period of a soliton must remain constant within rather narrow limits for months to account for, say, the nKOM data, which requires, presumably, that the Jovicentric distance of a soliton cannot change (difficulty (b)). Also, because there is no evidence for two or more sources within the torus, the birthrate of solitons in the torus must be low so that only one soliton is present at any time. Another potential difficulty for the soliton model is that it does not seem to explain the observed 14-day periodicity in magnetospheric activity. Finally, the soliton model is specific to Jupiter and the Io plasma torus. As pointed out by Dessler [1985], dual periodicity may be a common feature of gaseous planets. A model with wider applicability would be preferable.

Suggestion 3 is the most complex, and it has the broadest applicability. We begin by calling the reader’s attention to the observations of the Sun’s magnetic field, showing that its dipole field rotates with two discrete periods that are present simultaneously [Hoekema and Scherrer, 1987]. The two periods, 26.9 days and 28.1 days, differ by 4.5%. There is indirect evidence that Saturn exhibits the same sort of dual periodicity behavior in the rotation of its magnetic field. For Saturn, if we accept the commonly held view that the forma-
tion of spokes in its rings is somehow a magnetospheric phenomenon, then the discovery by Porco and Danielson [1984] of a dual periodicity in spoke activity leads us to suspect a phenomenon, then the discovery by Porto and Danielson, [1984] recent more extensive analysis (C. Porco, private communication, 1987). Porco and Danielson point out that the two periodicities of spoke activity are approximately coincident with the SKR (Saturn kilometric radiation) period and the periodicities of spoke activity are approximately coincident with Hockstetters and Scherrer [1987] present compelling evidence for two periodicities, Howard et al. [1984] show that the phenomenon being observed. For example, the EUV (Figure 6), the ground-based data of Brown and Shemansky [1982], and of Roesler et al. [1984] (Figure 15) are not well ordered in system III. The organization of the nKOM in system III (Figure 8) may be due in part to the wobbling of the torus caused by its 7° tilt relative to Jupiter's spin axis. The nKOM shows beaming in magnetic latitude [Daigne and Leblanc, 1986]. Thus the λIII dependence of the nKOM may be to some unknown degree a viewing angle effect and not solely a system III longitudinal asymmetry.

If we assume for the moment that there are two active sectors, one in each coordinate system, that drift relative to one another, we could well expect a modulation of the strength of the corotating convection pattern. The period of the modulation would be 14 days, as shown in (2) and (3). We have already noted the coincidence between the nulling of the kilometric radio emissions from Jupiter reported by Kurth et al. [1980] and the times of minimum magnetospheric convection that we would predict using (3).

Also, we find in data presented by several observers that Jupiter's decametric radio emission is modulated with a 14-day periodicity [e.g., Barlow, 1979; Carr et al. 1983, p. 256]. Although these modulations are usually attributed to a two-sector structure in the solar wind, we note several difficulties with the solar wind interpretation. First, a quantitative mismatch lies in the synodic period of solar rotation, which as seen from Jupiter is approximately 25 days, not the 27-day period seen from Earth. Thus if a two-sector structure in the solar wind were to produce a modulation at Jupiter, it would have periods centered on 12 to 13 days, not the observed 14-day period. Second, we are not aware of a mechanism that would connect the solar wind to the deep interior of a magnetosphere such as Jupiter's, which is dominated by plasma processes related to the rapid spin of the planet and the Io torus. Finally, we remind the reader that (3), which was derived from other data sets, and is not related to solar wind phenomena, successfully accounts for the times of the four nulling events observed at 56.2 kHz [Kurth et al., 1980].

6.2. Modulated Corotating Convection

Corotating convection, as originally suggested by Vasylkina [1978], is driven by the effect of centrifugal stress on an azimuthal mass imbalance in the inner portion of the torus. (See Hill et al. [1983, pp. 392-393] and Vasylkina [1983, pp. 450-451] for a description of this particular view of corotating convection.) The system III longitude range from which the convection is expected to be outward is the active sector. The longitude range of the active sector (from about λIII = 150° to 320°) contains nearly all the Jovian magnetospheric phenomena that show a gross azimuthal asymmetry (see Figure 10.10 of Hill et al. [1983]).

To account for the system IV longitudinal asymmetries that have been described in this paper, we propose a second active sector, this one fixed in system IV. This active sector appears to influence the outer part of the torus where there is organization in system III and system IV, depending on the phenomenon being observed. For example, the EUV (Figure 6), the ground-based data of Brown and Shemansky [1982], and of Roesler et al. [1984] (Figure 15) are not well ordered in system III. The organization of the nKOM in system III (Figure 8) may be due in part to the wobbling of the torus caused by its 7° tilt relative to Jupiter's spin axis. The nKOM shows beaming in magnetic latitude [Daigne and Leblanc, 1986]. Thus the λIII dependence of the nKOM may be to some unknown degree a viewing angle effect and not solely a system III longitudinal asymmetry.

Fig. 15. The same data as in Figure 14, except plotted in system III coordinates. The data are not ordered as they are in Figure 14, although persistent system III ordering is reported by Trauton [1980], Fletcher and Morgan [1980], and Trunet et al. [1980].
6.3. Dusk Quadrant Modulation

The convection electric field across the Earth's magnetotail is uniform to first order, and except for substorm intervals, it is rather smoothly impressed across the polar cap ionosphere, from whence global convection effects are transmitted to lower latitudes. But again, mighty Jupiter is different. Vaslunus [1983] has pointed out that the neutral x-line (which, for the Earth at magnetically quiet times, extends the full width of the tail) in Jupiter's case is likely to cross only part of the tail. This is illustrated in Figure 16. We propose that the flow of plasma from the Io torus into the outflow region on the dusk side is modulated at the system IV period. A consequence of this unsymmetrical outflow is seen in Figure 4, where only the receding ansa (which is on the dusk side for Voyager 2 inbound) shows a clear spin-modulation signature.

Another demonstration of the difference in character of the modulation on the dusk side is shown in Figure 17. We see a large range of motion of the dusk (receding) ansa—nearly a full Jupiter radius—while the dawn (approaching) ansa, except for the singular point at 5.25 RJ which we discuss below, is normally restricted to a movement of 0.3 RJ, or just 1/3 of the motion of the dusk ansa.

The radial position of each ansa is determined in part by plasma drift in the local convection electric field [Goertz and Ip, 1984; Ip and Goertz, 1983; Barbosa and Kivelson, 1983]. Because this electric field is modulated at the system IV period on the dusk side, the UVS instrument on Voyager 2 inbound saw large radial motions and brightness variations in the receding ansa and correspondingly small effects in the approaching ansa where the electric field shows little spin modulation.

The case marked by the triangle in Figure 17 is an interesting exception. At the time that measurement was made (1979, day 41, 13 hours), the size of the magnetosphere was expanding from about 62 RJ on day 39 to 114 RJ on day 46 [Goodrich et al., 1980]. Using (2), we find the system III and IV active sectors were aligned at the time of the observation, and from the Voyager log and (1), the active sectors were in the sunlit hemisphere (Jupiter's subsolar longitude was \( \lambda_{III} \approx 200^\circ \), and \( \lambda_{IV} \approx 230^\circ \)). Outward plasma flow on the dayside is normally inhibited by solar wind pressure, as is suggested in Figure 16. However, this is not the case on 1979 day 41 when the magnetosphere was expanding at an average rate of 7.4 RJ/d, with sporadic intervals of faster (and slower) expansion. We believe that at this time there was transient sunward flow out of the aligned active sectors. The convection electric field was reversed and impressed across the approaching ansa. Thus the approaching ansa moved inward and brightened, while the receding ansa was located at approximately the radial distance one usually finds the approaching ansa. The normal dawn to dusk brightening was observed to reverse. We conclude therefore that the point plotted as a triangle in Figure 17 is a special case wherein the plasma flow from the active sectors was not as shown in Figure 16, but instead was temporarily directed sunward instead of anti-sunward.

7. Conclusion

We have shown that a number of separate phenomena can be fit into a new Jovian longitude grid (system IV) having a presently defined rotation rate of 845.05°/d. However, until more independent data are obtained, it is not established that all the phenomena we have plotted will remain fixed in system IV. In a sense, we have forced a fit among three data sets. Study of Figure 12 should show that, with two independent, adjustable constants in (1), namely, \( \omega_0 \) and \( \Delta \), we would have found an acceptable fit even if, contrary to our explicit assumption, the phase of the 1981 and 1982 points were not fixed in a rigidly rotating longitude system. The test of the validity and utility of system IV will be to place more independently acquired data from different times into this system.

The question of beat frequencies and sidebands has not been investigated. At this point it is possible that the sys-
system IV variations reported here are a result of a 14.1-day amplitude modulation of system III phenomena. Similarly, as explained in section 6, the 14.1-day modulation could follow from the beating of the system III and system IV periods. Additional analysis is necessary.

If system IV should prove to be a duraible description of a significant portion of the time-dependent behavior of a certain class of Jovian phenomena, a new theoretical challenge will be to find a description of Jupiter’s magnetic field that allows for this sort of dual periodicity and to relate this theory to other objects exhibiting dual magnetic periodicities such as the Sun, and possibly Saturn, and certain pulsars.

APPENDIX: ANALYSIS TECHNIQUES

The brightness of the ansae of the Io torus undergo large, apparently aperiodic, fluctuations in the extreme ultraviolet that exceed the measurement uncertainty. These fluctuations mask any periodic structure in a simple plot of brightness versus time. To reveal possible periodic structure, we must rely on detection techniques suited to finding modulations that are weak compared with random fluctuations and that may be applied to unevenly sampled data. One such technique is based on periodogram analysis. Scargle [1982] has developed a useful formulation of the statistical properties of a slightly modified form of the classical periodogram, including simple expressions for the reliability of detections and for the power at a particular frequency. We have computed periodograms from our data using Scargle’s equations 10 and 11:

$$P_s(\omega) = \frac{1}{2} \left\{ \sum_j X_j \cos(\omega(t_j - \tau)) \right\}^2 \left\{ \sum_j \cos^2 \omega(t_j - \tau) + \sum_j \sin^2 \omega(t_j - \tau) \right\}$$

where \( \tau \) is defined by

$$\tan(2\omega \tau) = \sum_j \sin 2\omega t_j$$

and \( X_j \) is the signal measured at time \( t_j \) (see also Scargle’s Appendix B). For evenly sampled data, the periodogram is usually evaluated at a set of frequencies \( \omega_n \) given by

$$\omega_n = \frac{2\pi n}{T}$$

where \( T \) is the total time spanned by the observations, and \( n = 0, 1, 2, \ldots, N_0/2 \) (\( N_0 \) is the number of observations). For unevenly sampled data, the analogous set of natural frequencies is the set of nulls in the spectral window function. Although no closed-form expression for this window exists under the definition of the modified periodogram, a satisfactory approximation can be derived by computing the periodogram of a high-frequency sine wave (see Scargle’s Appendix D) or of a dc signal [Black and Scargle, 1982]. At the set of frequencies determined in this way, the amplitudes of the periodogram are independent of each other, and the statistical properties of the periodogram are well understood. If we wish to evaluate the evidence of modulation at a preselected frequency, the expression to use is

$$Pr(Z > z) = \exp(-z)$$

where \( \nu \) is the number of independent frequencies examined. As \( \nu \) is increased by testing more frequencies for significant power, the probability of finding by chance a physically unreal, but apparently significant, \( Z > z \) is increased. This is taken into account by the exponent \( \nu \) in (6).

The best estimates for the signal frequency and power come not from evaluating the periodogram at the frequencies defined by the nulls in the spectral window, but by over-sampling to find the true peak in the periodogram [Black and Scargle, 1982]. The best estimate for the signal frequency is simply the frequency of the peak in the periodogram. The amplitude of the modulation \( X_0 \) is Scargle’s equation 7:

$$X_0 = 2 \sqrt{\frac{P}{N_0}}$$

where \( P \) is the amplitude of the periodogram at the peak and \( N_0 \) is the number of observations.

The amplitude of the modulation obtained in this way is only an estimate, but it is useful to know, at a specified level of confidence, the range of amplitudes consistent with the observations. This range, which depends on the ratio of signal power to noise power, may be found for several confidence levels using curves in Groth’s [1975] Figure 1 in conjunction with (7).

A second method of searching for periodic modulations, sometimes called superposed epoch analysis, is based on the idea that a plot of brightness versus phase will group points of similar phase close together when the correct frequency is chosen. Similar techniques have been used by Belton et al. [1980] and by Lafler and Kinman [1964]. To calculate a quality-of-fit discriminant, a measure of the grouping of the data points, we have averaged brightness as a function of phase over a number of bins, typically 10. The discriminant is the sum of the squared deviation of each brightness from the mean in its phase bin. A plot of the discriminant versus frequency has a minimum at a frequency present in the signal.

Although the two techniques yield consistent results when applied to our data, most of our discussion is based on periodogram analysis because its statistical behavior is well known and because it permits an explicit estimate of the power at a particular frequency. On the other hand, the superposed epoch analysis is conceptually simpler and leads to an intuitively more satisfying result. The signal power can be estimated by generating and analyzing synthetic data, keeping in mind the dangers mentioned in section 3.

Analysis of synthetic data has also proven to be a useful adjunct to the more direct methods described above. Generation and reduction of synthetic data is a sensitive test of the functioning of the analysis program, and it helps to iden-
ify spurious features resulting from the sampling scheme or leakage from other frequencies. Synthetic data were generated for the times of the observations from

$$S(t_i) = AG_i + \sum_j B_j \sin(\omega_j t_i) \tag{8}$$

Noise is included through the term $AG_i$, where $G_i$ is a Gaussian random variable having variance 1.0. Measurement error makes a small contribution to the total "noise," but real, aperiodic brightness variations dominate the EUV data. Therefore the amplitude $A$ cannot be determined from the measurement error alone. In practice, it is adjusted to match the random component of the observed brightness variations as measured by the two analysis techniques already described.

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