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ABSTRACT

Jupiter's low-frequency radio emissions have been detected by the planetary radio astronomy instruments onboard the two Voyager spacecraft. The emission is surprisingly similar in morphology but opposite in polarization to the high-frequency Jovian radio noise that has been observed with ground-based telescopes for more than two decades. Several possible explanations for the behavior of the low-frequency emisssion are examined, but none of them is completely satisfactory.

Introduction

The two Voyager spacecraft launched in August and September, 1977, carry identical planetary radio astronomy (PRA) receivers designed to measure left-hand (LH) circular and right-hand (RH) circular polarized power over the frequency range 1 kHz to 40 MHz in 198 steps (Warwick et al., 1977). Below 1326 kHz the PRA receivers tune to 70 discrete frequency steps or channels with bandwidths of 1 kHz. In this low frequency band we have identified Jupiter emissions over the range from about 500 to 1326 kHz on several hundred occasions from mid-November, 1977, until late June, 1978, at which time both spacecraft were commanded into a very low data rate. (In the 200 kHz bandwidth region from 1228 kHz to 40 MHz, spacecraft-generated interference prevented detection of Jupiter until late 1978.) This report will summarize our low-frequency results from this seven-month period and will compare them with the more than two decades of higher-frequency ground-based Jovian observations.

Ground Based Observations

Virtually all prior studies of Jupiter's radio emission are dependent on ground-based observations made at frequencies corresponding to wavelengths in the *decametric* (DAM) range or still shorter wavelengths. A few ground-based studies have been made at frequencies from 2 to 5 MHz, but the statistics are poor due to ionospheric opacity and to high background interference. The Radio Astronomy Explorers and the IMP-6 spacecraft (neither of which were capable of measuring polarization) detected Jupiter in the range from about 500 kHz to 9 MHz, the hectometric (HOM) and long DAM range. These results have been reviewed by Carr and Desch (1976).

DAM consists of noise storms lasting some tens of minutes which are in turn made up of individual bursts with time scales from milliseconds to seconds. The noise storms may be limited at any instant to a narrow bandwidth and the center frequency of the band often drifts slowly upward or downward with time.

A striking feature of the DAM emission, illustrated here at 22 MHz (Figure 1, lower panel) is its strong asymmetry in occurrence as a function of Jupiter's CML-central meridian longitude (Seidelmann and Devine, 1977). As Jupiter rotates, two prominent peaks of DAM emission activity occur -50° and $+40^{\circ}$ on either side of the "inferior conjunction" of the planet's northern dipole tip with the earth (that is, when the northern dipole tip is tilted at its maximum angle towards the earth, near 200° CML). The emission from these two longitudes is strongly right-hand polarized. A third, less prominent "source" whose emission occurrence peaks at $\sim 130^{\circ}$ after northern dipole tip inferior conjunction tends to be left-hand polarized at low frequencies (at and below 16 MHz), although even it is predominantly right-hand polarized at 22 MHz and above.

At frequencies near 8 to 10 MHz, Jupiter's emission seems to occur quite uniformly at all CML (Dulk and Clark, 1966). Its polarization there is balanced between right-hand and left-hand states, with right-hand at northern dipole tip inferior conjunction and left-hand at southern dipole tip inferior conjunction 180° away in CML (Kennedy, 1969).

At 15 MHz and above, the Jovian emissions are strongly modulated by the innermost Galilean satellite Io. In the upper panel of Figure 1 the same data as in the lower panel are displayed as a function of Io phase angle, which is the departure of Io from superior conjunction as seen by the observer. Again the data show unmistakable asymmetries with major peaks in occurrence at Io phases of 90^{o} and 240^{o}. At lower frequencies the Io effect is less evident although for strong flux density events Io control persists down to at least 2.2 MHz (Desch and Carr, 1978).

These persistent CML and Io-related features are widely interpreted (Smith, 1976) to indicate that the emission is generated close to the surface of Jupiter in its ionosphere. The complex magnetic field shape and the looming presence of the nearby planet itself combine to produce radio emissions that have complicated, non-sinusoidal occurrence probability at all CML. In one model, Io's effect is communicated through the magnetic flux tube which connects Io with the ionosphere. Flux tube currents generate strongly beamed radio emission at the foot of the flux tube where particles precipitate into the atmosphere. The observer records Io-controlled emissions only when his line-of-sight intercepts the beam.

Voyager Observations

The first recognized Jupiter event in the Voyager data is shown in Figure 2a. The event is LH polarized and displays a clear frequency drift. Other typical events are shown in panels b thru e. Like DAM events, the HOM events consist of noise storms lasting some tens of minutes. Within these storms there is evidence for considerable temporal variation at the 6-second level. (One receiver frequency sweep requires 6 sec to complete.) Variations in emission polarization sense are sometimes apparent on a time scale of tens of minutes. There is also evidence of structure at the tens of milliseconds level although this tentative finding requires further analysis. The instantaneous bandwidth of HOM is often as small as $\sim$100 kHz and frequency-drifting like that shown in Figure 2a, b, c is evident on approximately one third of the events detected to date.

The remaining events such as shown in Figure 2d and 2e show no discernable drift. The characteristics of the HOM dynamic spectra are described more fully by Lecacheux et al. (1979).

Perhaps the most surprising result from the Voyager HOM observations is the relatively high percentage of LH events. Approximately 80% of all events detected in the first seven months were LH. This is in direct contrast with DAM where, at 22 MHz, at least 90% of all events are RH (Kennedy, 1969).

The variation of HOM emission frequency of occurrence and polarization with CML and Io phase are shown in Figure 3a for Voyager-1 and 3b for Voyager-2. The data for the two Voyagers have some obvious differences. These differences we attribute to an extremely narrow emission beam width at Jupiter coupled with a small ($\sim 3^{\circ}$) jovigraphic latitude separation between the two spacecraft (Alexander et al., 1979). We believe that for the purposes of comparison with DAM, only the Voyager-1 observations should be used since excursions in jovigraphic latitude experienced by Voyager-1 are similar to those that a ground-based observer might experience. Voyager-2 is well outside the range of jovigraphic latitudes obtainable from Earth.

With only minor qualifications, neither Voyager shows an Io control of HOM. The emission does, however, seem to be well organized in CML. Indeed, the Voyager-1 CML profile appears to be generally similar to the DAM profile. The major difference, may lie just in the relative amplitudes of the three major peaks. Table 1 compares the gross properties of DAM and HOM.

Discussion and Summary

At this early stage in the analysis of PRA data, we are thus chiefly impressed with two aspects of the results when we view them in the context of the DAM morphology. First, the CML profile derived from the Voyager observations (Figure 3) exhibits pronounced modulation, similar to the higher-frequency ($\gtrsim 18$ MHz) DAM results shown in

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Figure 1, but unlike the uniform CML profiles observed in the 8-10 MHz range. At DAM frequencies above 15 MHz, it is widely believed that proximity of sources to Jupiter's surface provides the modulation. At 8-10 MHz, where this modulation weakens, it is widely believed that the sources lie farther above the Jovian surface. At HOM it was expected that the sources would be farther yet above surface and thus be still more symmetric. This is evidently not the case. Either the modulation of HOM in planetary rotation phase depends on other factors than just the proximity of the source region to Jupiter's surface; or, the low-frequency emission radiates from source regions relatively close to the planet. The observation of well-defined HOM dynamic spectra carries with it the same implications.

Further evidence possibly bearing on this problem is provided by the second surprising result to come from the PRA observations, namely the dominance at all longitudes of LH polarized emission in HOM, opposite in sense to the polarized emission which dominates in DAM and again in marked contrast to symmetrical polarization variations seen at 8-10 MHz. These results appear to be very fundamental elements of the overall DAM-HOM morphology.

Toward this end, we examine below in a very qualitative way a few possible interpretations of our initial results. The discussion serves primarily to help place the observations within the framework of plausible radio emission theories, but it may also provide working hypotheses for future work. Since the DAM and HOM phenomenology is rich in detail, we will order the discussion primarily according to the polarization results alone.

We consider one dual-source model and two single-source models. We follow most authors in assuming that at high DAM frequencies the radiation leaves the source in the extraordinary (x) magnetoionic mode. In this mode, the radiating electrons and wave electric vector in a fixed plane have the same rotational sense about the local magnetic field line, B. A right-hand polarized wave propagating parallel to B, that is, <u>out</u> of Jupiter's northern magnetic hemisphere, is in the x-mode [see "Standards on Radio Wave Propagation", Proc. IRE (suppl.), 30 (1942)], provided $f > f_{pe}$. (The following magnetoionic notation is employed: f is the emission frequency, f_{pe}, f_{pi}, f_{ge}, f_{gi} are the electron and ion plasma frequencies, and electron and ion gyrofrequencies, respectively.)

Conceptually, the simplest model is based on the dual-source hypothesis in which RH (LH) polarized emission is beamed from a source region located in Jupiter's northern (southern) magnetic hemisphere (Dowden, 1963 and Carr et al., 1965). According to this view, the northern- and southern-hemisphere sources have visibilities which are strongly dependent on observing frequency. The observed north-south asymmetry in the magnetic field structure of Jupiter (Acuna and Ness, 1976), although it is an extrapolation in so far as the surface is concerned, lends support to this model. The vast difference in frequency between the RH and LH polarized emission regimes appears to be greater than the north-south field asymmetry inferred for surface fields. Perhaps more importantly, single-frequency observations of reversals in polarization sense on a time scale of tens of minutes suggests a more complex situation than can be supported by this model, one in which a single radiation region is probably required to produce both polarization states.

In fact, several single-source models are capable of producing both senses of polarization with each sense dominant over either different frequency regimes or different viewing geometries (beaming angles). In each model, let us consider for simplicity only the northern hemisphere as the source location (the predicted polarization sense is reversed if the southern hemisphere is used). In the first case, we obtain dual polarization by requiring that emission take place at two frequencies, one above and one below f_{pe}. At both frequencies, x-mode emission from the same near-surface source region is assumed. The lower hybrid resonance frequency ($f^2_{LH} = f_{gi} f_{ge} (f_{gi} f_{ge} + f^2_{pe})/(f^2_{pe} + f^2_{ge})$) and upper hybrid resonance frequency ($f^2_{UH} = f^2_{pe} + f^2_{ge}$), for which the polarization senses are LH and RH respectively, are likely places for wave growth to occur. This model makes some progress toward explaining not only the polarization reversal with frequency but also the pronounced modulation in CML and well-defined dynamic spectra evidenced by HOM. The latter is true because, as mentioned previously, locating the source of both DAM and HOM within Jupiter's complex, near-surface field simplifies the problem of explaining such morphology. This model has the serious drawback, however, of predicting a lower frequency range for the LH (HOM) component than presently observed if we accept the Pioneer occultation data (Fjeldbo et al., 1976) on ionospheric electron density as applicable to the DAM-HOM source region. That is, the measured f_{pe}/f_{ge} does not exceed 0.20 in Jupiter's inner magnetosphere (which yields $f_{LH}/f_{UH} \sim 1/200$). The peak LH polarized emission frequency is thus predicted to be $\sim$ 40 MHz x (f_{LH}/f_{UH}) or 200 kHz. This model has the further disadvantage in that, under the uniform plasma conditions described here, emission at $f = f_{LH}$ is not in a free-escape mode and so should remain trapped within the source region.

Single-source models which do not rely so heavily on propagation effects have recently been offered as explanations for terrestrial kilometric radiation. The theories predict that electrostatic waves at 2 f_{pe} (Maggs, 1978) or at 2 f_{UH} (Barbosa, 1976) couple to both the o and x electromagnetic modes, thus producing both LH and RH polarized emission at the same frequency. In the context of Jovian emission, the latter mechanism has the advantage in that, since the emission frequency is tied to the magnetic field intensity, it is better able to account for both high-frequency (20 - 40 MHz) DAM and repeatable dynamic spectral features (Warwick, 1967). However, it is not clear how one can explain the observed frequency morphology of the predominant polarization sense in the context of these models.

In summary, primarily because we observe variations in polarization sense both as functions of frequency and of time, none of the scenarios described here is, by itself, completely satisfactory, and it is conceivable that some combination of single-source and dual-source models which incorporate propagation effects needs to be

TABLE 1

COMPARISON BETWEEN DAM AND HOM JOVIAN RADIO EMISSION

CHARACTERISTIC	DAM (15-40 MHz)	HOM ($\lesssim$ 1.3 MHz)
Frequency of occurrence vs CML	similar profiles for same jovigraphic latitude	
Polarization	predominately right-handed	predominately left-handed
Burstiness	much on a time scale of sec also some on msec scale	same as DAM
Dynamic spectra	distinct drifting structure on tens of minutes time scale	
Satellite effects	strong for Io	none (or weak)
jovigraphic latitude effect	yes	Yes

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Figure Captions

Fig. 1. The relative occurrence of Jupiter's 22.2 MHz radio emission as a function of central meridian longitude seen by the observer at the time of the observation (bottom panel) and departure of the satellite Io from superior conjunction (top panel).

Fig. 2. Examples of frequency versus time profiles characteristic of the Voyager data. Increasing intensity is proportional to increasing darkness. Panel a shows, near 21 hr, the first Jovian event that was recognized. Panel b at 22 hr, panel c at 16 hr, panel d at 11 hr, 16 hr, and 20 hr and panel e at 03 hr, 07 hr and 17 hr show the range of profiles typical of the Jovian HOM emission. Also evident in these displays are many fast-drift solar bursts (e.g., 03-14 hr in panel a and 09 hr in panel c), however, no confusion with Jovian emission occurs because the solar bursts are not polarized. The occasional horizontal streaks are cases of spacecraft-generated interference.

Fig. 3. The relative occurrence of HOM emission detected by the Voyagers displayed in a format similar to Figure 1 except that RH and LH components are shown separately.

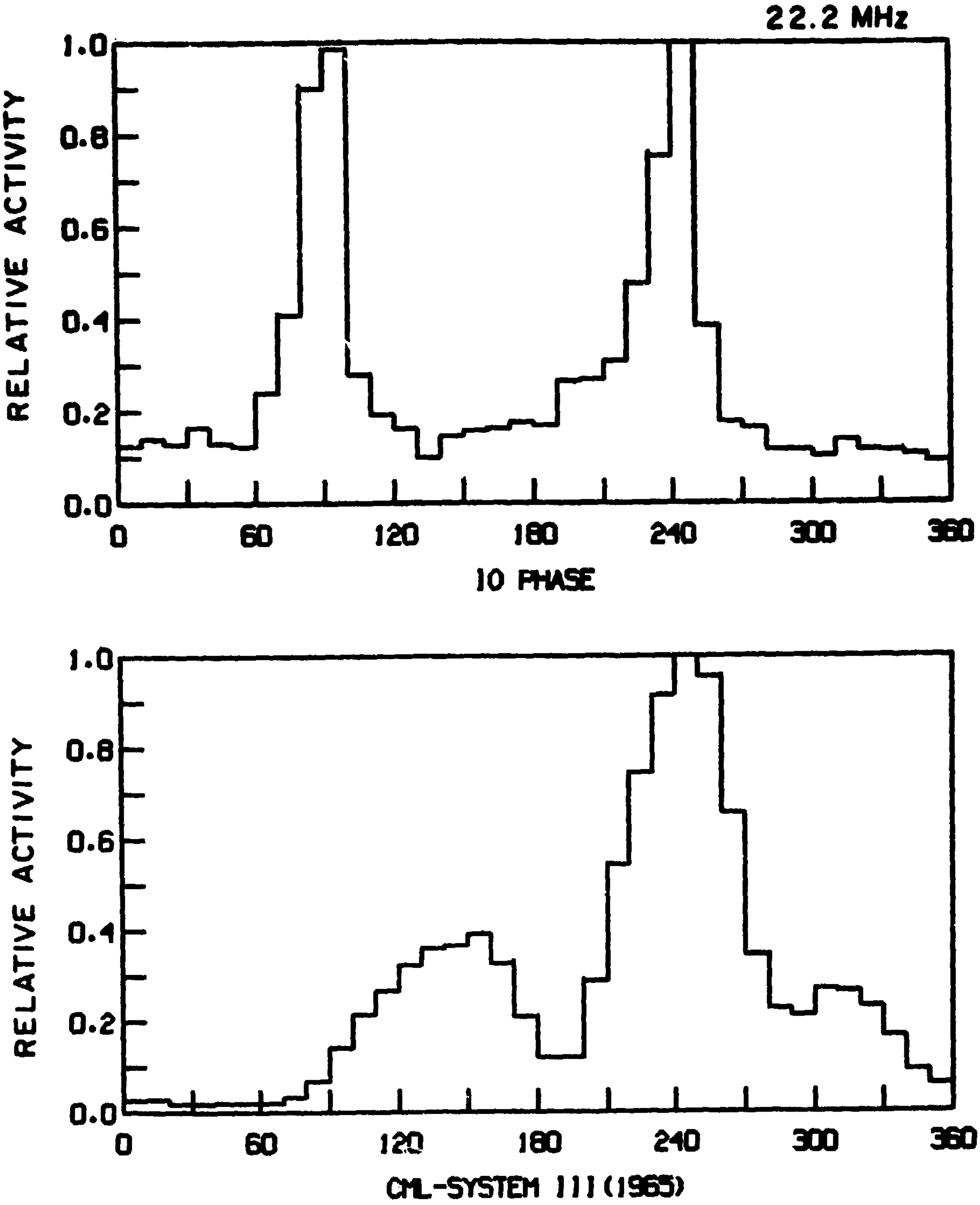

Figure 1

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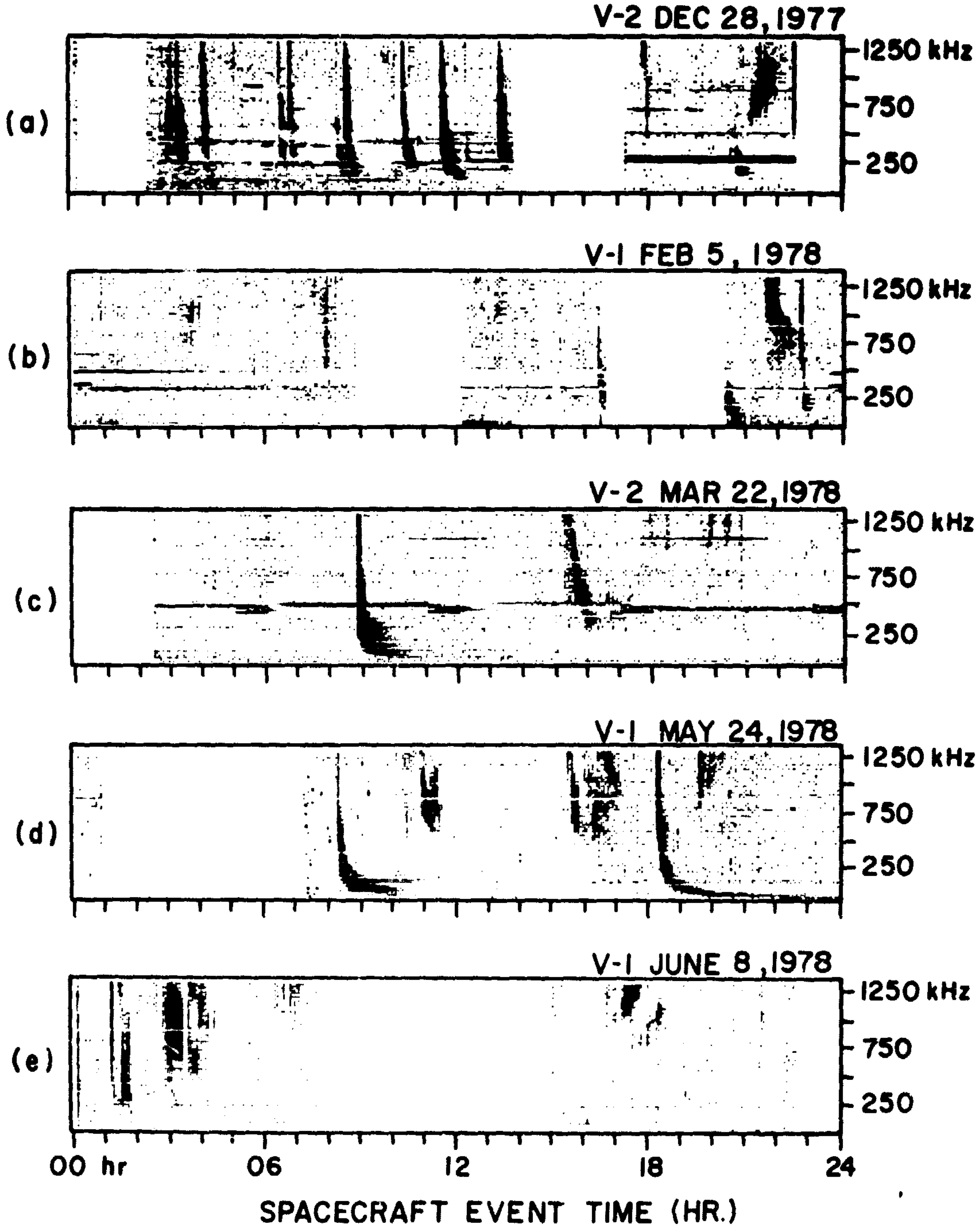
V-2 DEC 28, 1977
(a)
V-1 FEB 5, 1978
(b)
V-2 MAR 22, 1978
(c)
V-1 MAY 24, 1978
(d)
V-1 JUNE 8, 1978
(e)
1250 kHz
750
250
00 hr
06
12
18
24
SPACECRAFT EVENT TIME (HR.)

Figure 2

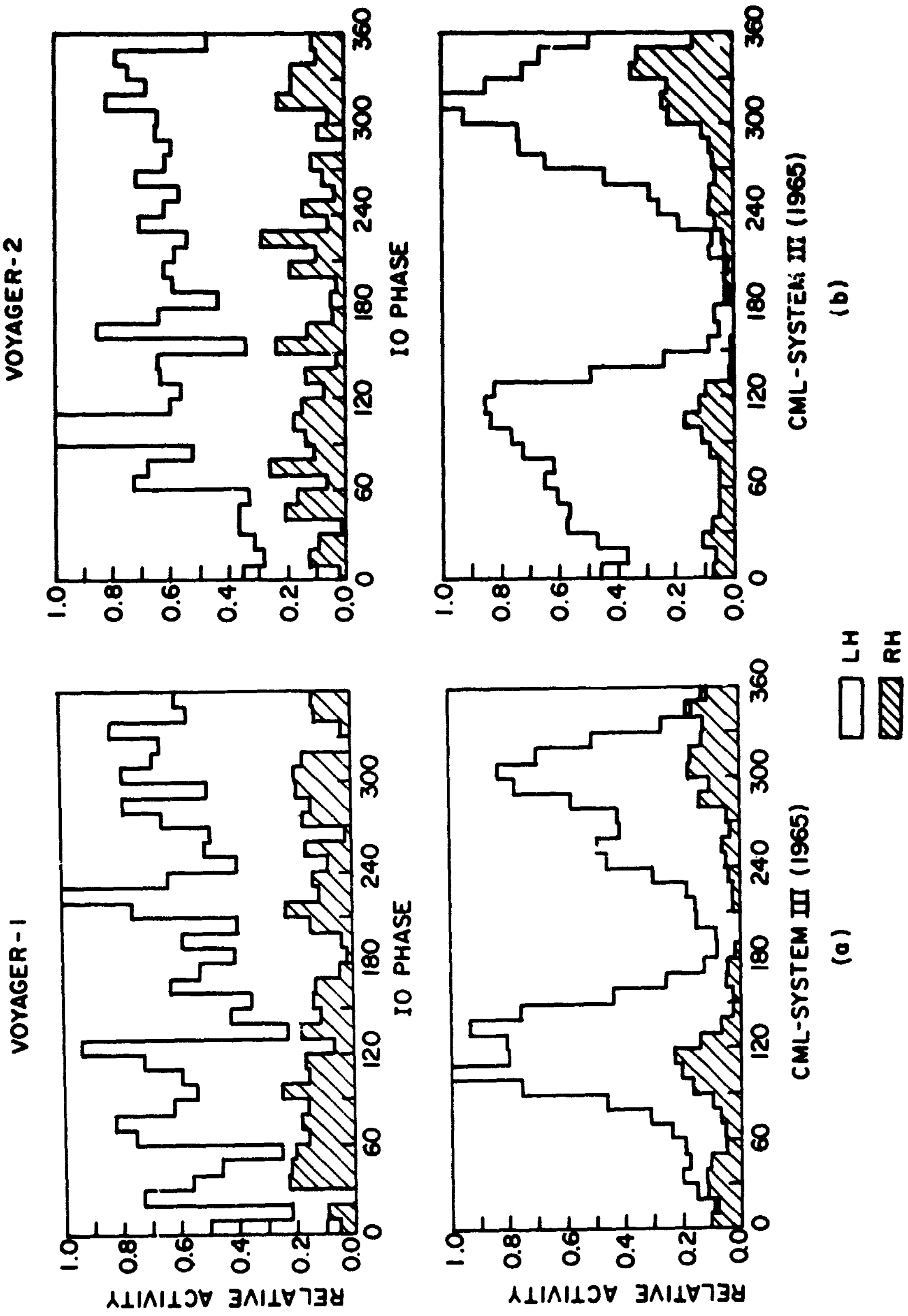
VOYAGER-1
VOYAGER-2
RELATIVE ACTIVITY
1.0
0.8
0.6
0.4
0.2
0.0
0
60
120
180
240
300
360
IO PHASE
CML-SYSTEM III (1965)
(a)
(b)
LH
RH

Figure 3

BIBLIOGRAPHIC DATA SHEET

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16. Abstract

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