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NON-THERMAL RADIO EMISSION FROM SATURN

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ABSTRACT

Direct, strong evidence for non-thermal radio emission from Saturn exists in the hectometric data observed by Imp 6 and studied by L. W. Brown. With the approaches of the Voyager and Pioneer spacecraft, new and specific information on Saturn's magnetic field will become available by the end of 1979. The planet has been tentatively identified as a decametric source by several investigators, but the most sensitive and most recent data fail to confirm this. At metric or decimetric wavelengths Saturn has no non-thermal emission like Jupiter's synchrotron sources. Finally, a comparative study of earth and Jupiter radio emissions suggests what we may expect from giant planets in the way of evidence for lightning discharges.

Let T be source temperature in the usual thermodynamic sense (a measure of E_{av} per molecule); then, non-thermal radio emission occurs where the source is brighter than the radiance, $2E_{av}/\lambda^2$ $Wm^{-2}Hz^{-1}sr^{-1}$. λ is wavelength; $E_{av} = kT$ where $k = 1.38 \times 10^{-23}$ J per deg, and T = absolute temperature.

Hectometric radio emission from Saturn (at wavelengths of 100's of meters) has probably been observed from the Imp-6 Spacecraft by L. W. Brown (1975) (see Figure 1). At the peak, 300 m = λ, the flux density in this emission seen near the earth approximately equals the cosmic background radio flux, as well as the peak flux density of Jupiter's emission at 8 MHz (Brown, 1974). Its occurrence probability is less than 5% of that for Jupiter emission at 1 MHz. This may explain the lack of detection (Kaiser, 1977) of Saturn from the Radio Astronomy Explorer-2 spacecraft.

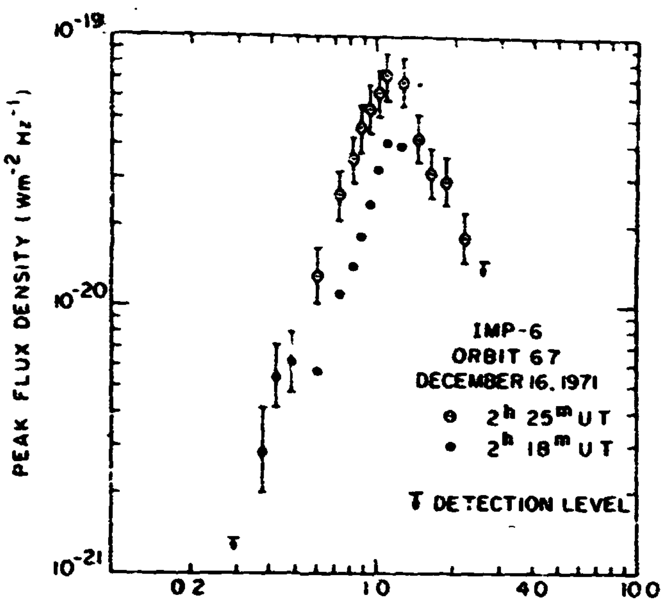

Figure 1. Hectometric Saturn burst (L. W. Brown, 1975). (Reproduced courtesy The Astrophysical Journal.)

Decametric radio emission from Saturn was tentatively detected by Smith and Douglas (1959), Carr *et al.* (1961), and Braude (1972). Further measurements to a very high sensitivity at 11.4 m (Shawhan *et al.*, 1973 and Mutel, 1974) indicate no continuous flux greater than about 1×10^{-26} flux units. Since the latter observations took place close to the maximum tilt of Saturn's southern pole towards the earth, it seems clear that there is little or no south pole emission. If Saturn is asymmetric, and favors its north pole, however, the Yale observations could have been consistent with northern emission, like Jupiter produces.

The possibility of Saturn synchrotron emission has generated many attempts to estimate and to measure polarization and spectral properties of Saturn's metric and decimetric radiations. This emission may well be significant only at metric wavelengths; measurements have not yet detected it (see Shawhan, 1978).

Phenomenologically distinct from these types of emission, there exists on the earth strong broadband impulsive radio emission associated with electrical discharges. It seems as though virtually all prognosticators believe that lightning also will occur in the giant planets' atmospheres near the water ice freezing levels (Lewis, 1969), and even in the atmosphere of Saturn's largest satellite, Titan (Sagan, 1974). My favorite magazine center-fold illustration is from *National Geographic* (February, 1975). It shows, I think, what we might all hope to record sometime aboard probes into the atmospheres of the giant planets and, perhaps, to Titan.

There are no measurements of Saturn's magnetic field as such. Brown's (1975) data represent indirect evidence for the field like (although it lacks polarization) the evidence on which Jupiter's field was inferred 20 years ago (Franklin and Burke, 1958). The inference that Saturn's polar surface field is 2 gauss follows from the comparison of the radio frequency of terrestrial kilometric radiation with that of Jupiter's decametric radiation. The one peaks at about 300 KHz, and the other, at about 8 MHz. The field strengths in the sources are directly proportional to these radio frequencies. This kind of agreement, as put forth by Kaiser and Stone (1975), is based on many different authors' theoretical and experimental results.

Theoretical inferences on Saturn's polar surface field cover an enormous range. Excluding predictions that it has no field at all (Smoluchowski, 1971), they range from 1/20 to 5 gauss (Stevenson, 1974; Warwick *et al.*, 1977), a factor of 100 Smoluchowski doubts the existence of the necessary liquid metallic core, Stevenson allows for only a small core (1/8 the planetary radius) and Warwick *et al.* use a physical scaling for magnetic theory, but do not discuss metallicity or conductivity of Saturn's interior. Many people (Luthey, Van Allen, Siscoe, Scarf, and others) adopt their own solutions to this problem of Saturn's internal fluidity and magnetism.

As I write (1 February, 1978), Brown's (1974) hectometric Jupiter signals would lie about 3 dB above cosmic noise at the Voyager spacecraft about 3 AU from Jupiter. The Voyager PRA experiment (Warwick *et al.*, 1977) at hectometric wavelengths uses a narrow bandwidth, only 1 kHz, and cannot detect the cosmic noise, both as a result of this bandwidth limitation, and also the presence of a small residual interference unsynchronized with the spacecraft clock. However, it has detected Jupiter in this range since 28 December 1977. The approach to Jupiter renders its signals much stronger than noise of Saturn. After Jupiter encounter, Saturn emission rapidly gains the advantage. At the time of the Pioneer 11 encounter in September, 1979, Voyager 1 should show Saturn signals comparable, at 1 MHz, to Jupiter signals and 10 dB stronger than the cosmic noise. At Titan's distance from Saturn, its signals will be 60 dB stronger than at Earth, and far above minimum detectable signals.

For more than one year before Voyager's Saturn encounter, and possibly as soon as Pioneer 11's Saturn encounter, the Voyagers will receive Saturn's hectometric radio emissions for measurements of spectrum, time variations, and polarization. If the emission is detected at all, and Brown's success in this respect is at the 95 percent confidence level, we can learn about Saturn the same things we learned about Jupiter from ground-based radio observations. These are: (1) rotation period of Saturn's internal magnetic field sources to a precision of a few seconds or better in 10 hours; (2) presence of satellite or ring interactions with Saturn's magnetospheric plasma; (3) asymmetries in the magnetic field on Saturn's surface; (4) strength and sense of the surface magnetic fields. In the latter data, we will, of course, perhaps only verify crudely what Pioneer 11 has already by then measured with considerable precision. However, it is comfortable to consider that whatever is Pioneer 11's fate almost two years from now, we can reasonably expect to learn something about Saturn's field just from Voyager data alone, and as soon as September, 1979. And finally, the radio period of rotation determined over a baseline of more than 10^3 rotations, will probably remain more precise than *in situ* field measures can provide over the 20 or 30 rotations of close encounter.

Electrical discharges from man-made sources, such as frictional electrification of synthetic fabrics, are a commonplace feature of everyday life. In their extreme natural form, they are dangerous, not common, and not understood. If the sole precondition for thunderstorm electrification in a planetary atmosphere is turbulent convection near the water freezing level, then we expect electrification in Saturn's and Titan's atmospheres, as well as Jupiter's.

Bar-Nun (1975) goes further, to compute the explicit intensity of thunderstorms like those on earth that would be required on Jupiter, according to his theory of the origin and chemical kinetics of ammonia and acetylene, to produce the observed acetylene. Many authors seek to explain the presumed existence of complex prebiotic chemistry in the giant planets, through laboratory experiments patterned after those of Miller and Urey (see Ponnamperuma, 1974) who sparked test tubes containing the cosmic mixture and analyzed the prebiotic products. No doubt, if lightning does occur out there, these reactions occur, whether or not their products are sufficiently abundant to produce the coloration visible in the giant planets' atmospheres. There is controversy on this point, which, to repeat, is whether there is evidence, from either chemistry, spectroscopy, or photometry, that lightning discharges take place on the giant planets.

What the space program might provide is *in situ* evidence for the occurrence of electrical discharges in giant planet atmospheres. The remainder of my report will discuss what evidence there may be from Earth-based data, and what evidence may be collected in the future from the Voyager spacecraft, as well as might have been already observed from the Pioneer spacecraft at the two Jupiter encounters.

Direct radio emission evidence, including the low-frequency phenomena of whistlers, is lacking from the Pioneers for the simple reason that neither of them carried a wave experiment at any frequency. These were energetic-particles-intensive spacecraft, and provided definitive evidence especially for engineering design of future spacecraft for flights around Jupiter.

On the other hand, optical experiments in the infrared and visual spectral regions showed Jupiter's atmosphere to be turbulent, on a scale no larger than a few hundred kilometers, everywhere, including polar regions. Furthermore the infrared experiment showed outward heat fluxes constant (Ingersoll *et al.*, 1976) over the entire planet accessible to observation, which implies that the forces driving convection are omnipresent. It is obviously not possible within the time scales of the Pioneer scanning photopolarimeter to record lightning flashes; this most direct of all methods does not work on those spacecraft.

Earth orbiting satellites can on the other hand detect nighttime lightning storms (Sparrow and Ney, 1971; Sizoo and Whalen, 1976). Signal levels from the Defense Meteorological Satellite Program (DMSP) satellites at just under 1000 km altitude easily detect city lights and squall lines, the latter through a unique streak of response by the scanning detector to intense flashes of lightning. From the Jupiter periapsis of Voyager 1 at more than 300 times the distance of DMSP from Earth's lightning strokes, the same effect must require about 50 dB greater lightning intensity. Success of the Voyager polarimeters must under these circumstances be doubted insofar as their detection of lightning is concerned, even though Bar-Nun (1975) requires essentially a thunderstorm on each element of area on Jupiter's surface measuring 10 x 10 km, each producing strokes once every 10 s, like a violent terrestrial storm.

In some particularly active centers, such as the Great Red Spot, he infers 10 x even that level, which is itself 10^4 x as active, per unit area averaged over Jupiter's surface, as is the level of terrestrial lightning.

It is well worth remembering that the earliest explanations of Jupiter's decametric emission were in terms of enormous lightning flashes requiring energies more than 10^8 x greater than those on Earth (Burke, 1961, and see below). This enormous enhancement is necessary if the fine time structure of the planetary emissions, fluctuations violent on a scale of 0.1 s to 10 s, represents individual flashes. Since, however, there are convincing reasons to believe this variability has more to do with scintillations produced in the solar wind plasma, than time variability in the sources on Jupiter, the early explanation is no longer accepted. Instead, Jupiter's radio sources today are understood in terms of magnetospheric physics, including the generation and precipitation of energetic electron streams into Jupiter's upper atmosphere.

Therefore we accept Bar-Nun's requirement of 10^4 enhancement in the average rate of occurrence of lightning flashes on Jupiter as compared with the Earth, rather than enormously enhanced individual flashes. Flashes are, by assumption, identical in physical structure on the two planets, and we will not discuss whether Bar-Nun's conclusion is, in its own terms, acceptable from a physical chemical point of view.

Thunderstorm activity on Earth produces radio emissions at all frequencies ranging from ELF to VHF. At high frequencies (HF), from 3 to 30 MHz, the emissions from individual flashes may escape the ionosphere of the earth and be recorded in space. Figure 2 shows a typical flash consisting of several return strokes, with coupled impulsive radio emissions at 15 kHz and 34 MHz, as well as quasi-continuous

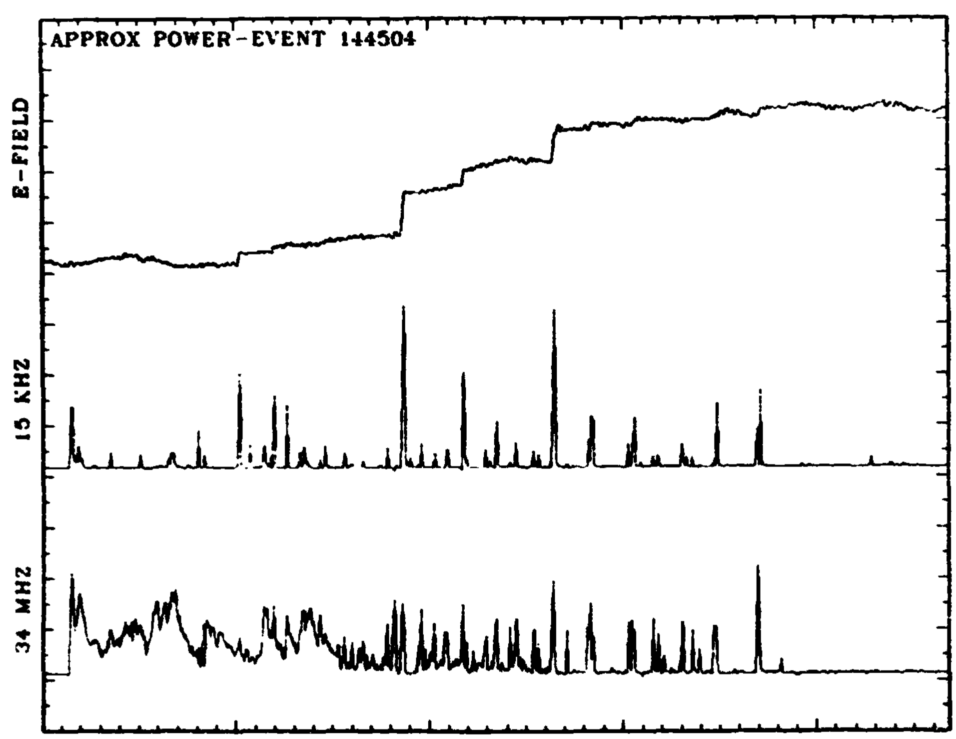

Figure 2. Electromagnetic fields in the lightning flash. The "E-field" curve is essentially the DC variations in the electrostatic field. The other two curves are, respectively, broadband emission centered on 15 KHz, and relatively narrow band emission centered on 34 MHz. The observations were made at the University of Colorado Radio Astronomy Observatory, near Nederland, Colorado, in September, 1977.

emission lasting for several tenths of one second at 34 MHz. Field strengths in an individual stroke at 34 MHz are typically a few millivolts per meter per root hundred kilohertz at ranges of a few kilometers (see Uman, 1969).

High frequency emission from a single, given, stroke seen from satellite altitudes, say, 1000 kilometers, about equals the cosmic background. To produce this much signal if its source were Jupiter, the stroke would have to be 120 dB more energetic, since Jupiter is about 10^6 x farther away (600,000,000 km at opposition). This is a much larger ratio than the one given by Gallet (1961), which was only a factor of 10^8 to 10^9 in energy.

Instead of individual flashes, observations of terrestrial discharges from space refer to the largest scale storm centers on Earth covering millions of square kilometers of tropical continents. These have been effectively observed by the Radio Astronomy Explorer-1 spacecraft at an altitude of 6000 km over the Amazon basin (Herman *et al.*, 1973). In southern winter, December, 1968, direct observations showed this particular terrestrial radio emission source to have a brightness about 50 dB above the cosmic noise level at 9 MHz. These are well calibrated results, by the spacecraft's Ryle-Vonberg comparison radiometer in 32 s averages. Furthermore, the lower Vee antenna of this spacecraft possesses a pattern 13° x 27° in dimensions, quite appropriate to a determination of the brightness variations over sources the size of Amazonia, seen from an altitude of 6000 km.

Thirty-four MHz stroke emission seen at 6000 km from a single stroke, should be 15 dB below the cosmic noise level. To enhance a single stroke by additional strokes sufficient to build the total emission 50 dB above the cosmic noise requires more than 3 x 10^6 strokes to occur simultaneously. Since only 10^3 storms are simultaneously present over the entire Earth, it may be that RAE-1's Amazonia observations are due to man-made interferences as well as to thunderstorms.

Our interest is, however, in Saturn, and to the extent it provides a model, also Jupiter. Taken at face value, that is, without allowance for man-made noise in the Amazonia data, the RAE-1 results suggest that thunderstorms on Jupiter, just like those on earth in stroke intensity and in rate of stroke occurrence per square km per s, are not far below the Earth-based detection level at 9 MHz. With the greater areal frequency of thunderstorms proposed by Bar-Nun, the radio emission should have already been recorded in Earth-based radio astronomical observations.

To demonstrate this we note that RAE-1's terrestrial "thunderstorm" levels at 9.1 MHz are 50 dB greater than the cosmic noise when the spacecraft is 6000 km above Amazonia. If the spacecraft were at Jupiter's distance 600,000,000 km instead, it would receive the signals from 10^5 x farther away, and therefore 100 dB weaker. This would result in the terrestrial signals there being 50 dB below the cosmic noise. Jupiter's area is 21 dB greater than the earth's, and as a result, if it is the source of thunderstorms exactly like those observed by RAE-1, but greater in number because of this greater area, Jupiter storms seen from the Earth should be just 29 dB below the cosmic noise at 9.1 MHz.

But Bar-Nun states that the normalized rate of occurrence of thunderstorm strokes on Jupiter needs for chemical reasons to be 10^4 x that of the Earth. Since there are no more than 10^3 storms in progress on the Earth at a given moment, the terrestrial areal occurrence frequency is no more than 1.96×10^{-6} km^{-2}, which requires one storm in each area measured 714 km on the sides over the entire Earth. Bar-Nun suggests that this figure on Jupiter would be, instead, 7.14 km on one side.

The total number of Jupiter storms visible at the Earth on Bar-Nun's hypothesis becomes 21 dB + 40 dB - 3 dB = 58 dB greater than are terrestrial storms visible from Jupiter. Since the latter are 50 dB below the cosmic noise, we conclude that in combination with the BAE-1 terrestrial data, Bar-Nun's theory predicts that terrestrial observations of Jupiter thunderstorms should lie 8 dB above the cosmic noise level at 9.1 MHz.

One caveat would be the possibility that at 9.1 MHz, Jupiter's ionosphere cuts off thunderstorm radio emissions. They are, of course less intense at higher VHF frequencies so that we would expect smaller signal to noise ratios there. And, in addition, decametric emissions will strongly cover thunderstorm emissions at higher frequencies. In any case, the Pioneer 10/11 ionosphere critical frequencies were only about 5 to 6 MHz (see Fjeldbo *et al.*, 1976). Finally, Bar-Nun suggests that the Great Red Spot, because of its obvious convective activity as well as strong color, should be an active thunderstorm region, 10 x more than other regions of Jupiter.

We have several years of high gain interferometer data recorded by the University of Colorado-High Altitude Observatory near Boulder, at 8.9 MHz. This should be an ideal base on which to investigate whether this effect occurs. These data have been scaled for Jupiter emissions, alongside similar data taken at 10.1 MHz (see Dulk and Clark, 1966) at the US Department of Commerce Observatory in Boulder. These authors analyzed their data for structures in the radio longitude system and in the Io longitude system. If, however, a putative atmospheric source contributes to these data the slower rotation rate of the GRS than the magnetic field of Jupiter might make it hard to observe. This smearing amounts to about 90° in only one observing season; while, at decametric wavelengths, features are much narrower than this value, it might be that in a few longitude ranges, say perhaps where GRS is located, a new peak would appear at the low frequency of 8.9 MHz.

Figure 3 shows the results of reanalyzing the 1964 apparition data at 8.9 MHz, and additional, unpublished material for the apparition of 1965. In essence, the new analyses, in radio longitude system III (1965) and as well, in temperature-altitude longitude system II, show as expected a very broadly distributed emission of almost global occurrence around the planet. The features are more consistent in system III, and shift backwards, towards smaller longitudes, in system II. This is precisely what should happen if the emission is totally dominated in these records by the familiar decametric emissions that relate to magnetospheric interactions. In particular, there is little evidence that a narrow new source appears at the LCM of the GRS, which is about 020° in system II at this time.

The upshot of all this is that it appears as though Bar-Nun's conclusion, alongside the RAE-1 data, together imply thunderstorm activity from Jupiter 8 dB above cosmic noise levels. The Jupiter decametric levels on these ground-based records are, although it has not been mentioned earlier, about 10 dB below the cosmic noise. Therefore, we conclude that our hypotheses are in error by 18 dB at least, and possibly some greater amount. If we conclude that our failure to find a system II connection is at the 10 dB level below the level of the Jupiter emissions themselves, we are probably safe in concluding that thunderstorm activity is at least 30 dB below the RAE-1-Bar-Nun prediction.

How should we understand this discrepancy? In the first place, suppose that the terrestrial thunderstorm data at 6000 km are 15 dB above cosmic noise instead of 50 dB. Herman *et al.* (1975) indicate, for United States thunderstorms, the levels are 6 to 12 dB higher than in the usual circumstances, when man-made noise dominates. This corresponds to the assumptions that there are 10^3 storms simultaneously in the antenna of RAE-1 over Brazil, and we know HF emission levels from strokes. In that case, we have made up the discrepancy vis-a-vis the 8.9 MHz observational data, and with only 5 dB required from Bar-Nun's theory (i.e., 35 dB enhancement over earth's thunderstorm activity, instead of 40 dB) to make it fit the data.

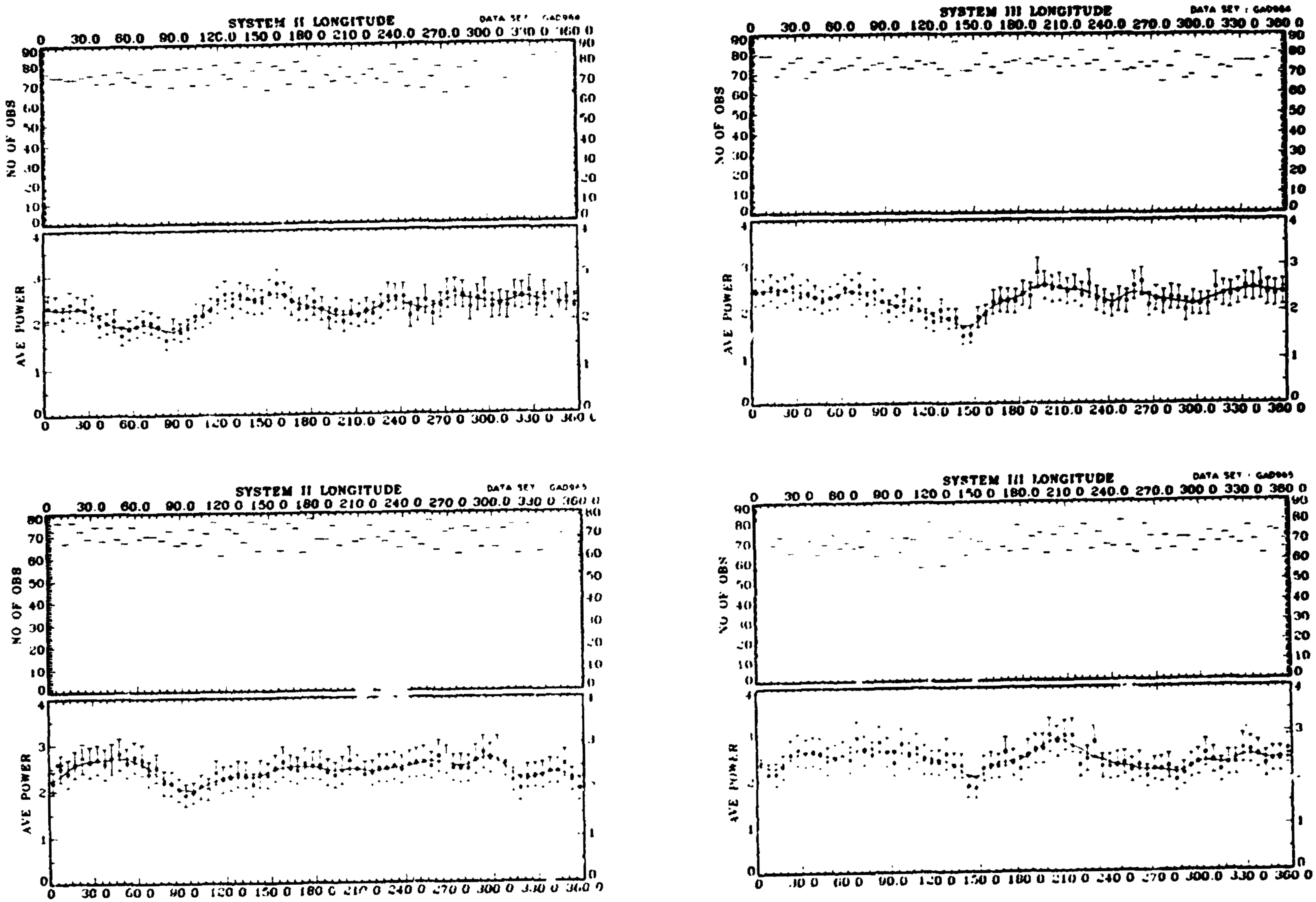

Figure 3 8.9 MHz radio emission from Jupiter in 1964 and 1965. The longitude systems are: system II, as defined in the American Ephemeris and Nautical Almanac (P_{II} = 9 hours 55 minutes 40.632 seconds), and system III (1965), as defined in Seidelmann and Divine (1977) (P_{III} = 9 hours 55 minutes 29.711 seconds).

Conversely, we might suggest that some Jupiter thunderstorm activity is indeed apparent in the Boulder 8.9 MHz data.

Voyager 1 passes by Jupiter at about 350,000 km distance, $(350)^2$ = 51 dB, away from the standard 1000 km distance at which a single stroke produces an equivalent radiation to the cosmic noise at decametric wavelengths. But there are 58 dB more storms there (if we accept Bar-Nun's hypothesis) than are visible from the earth, and the latter number is 30 dB more than one stroke. We expect to see thunderstorm activity, granted validity of Bar-Nun's conclusions, at a level 58 dB + 30 dB - 51 dB = 37 dB above the cosmic noise. This value exceeds the spacecraft interference levels at all frequencies, and suggests detectability of Bar-Nun's thunderstorms from both Voyagers.

The spacecraft are implemented so that observations on a time resolution of about 0.1 milliseconds are possible for a lot of observing time within the Jupiter system. The statistics of these data may reveal lightning storms on Jupiter, even if individual strokes are not distinguishable from the great bulk of emissions. In particular, enhancements associated with optical features such as the GRS are worth a careful search. Perhaps within a year or so, we can answer the vexing question of lightning occurrence on Jupiter, and then, within two and a half years, similar questions for Saturn and Titan.

ACKNOWLEDGEMENT

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DISCUSSION

B. SMITH: Jim, what is the hope that new observations will determine the radio rotation period (the equivalent of Jovian System III) for Saturn?

J. WARWICK: I believe that the possibility of observing non-thermal emission by Saturn from space remains for Voyager. Voyager I will be the first to detect Saturn, and that will be from a distance of about 4 AU in September of 1979. Until then, there won't be any more data than Brown's. To determine a Saturn rotation period will be a "first order of business" for us.

L. TYLER: What about the possibility of detecting lightning in other regions of the spectrum?

J. WARWICK: With a flyby of Jupiter, that's one of the things the plasma wave experiment would be looking for. The question is: Will there be any precursor events to identify the wave sources as lightning, such as the snap followed by the whistle? We may not be able to see the individual snap followed by the individual whistle. If there's as much activity as Bar-Nun thinks, we may not be able to see anything separately: just see a mishmash of noise comprising all the lightning strokes over the surface of Jupiter.