RADIO EMISSION FROM JUPITER[1]

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Introduction

Three reviews of radio emission from Jupiter have appeared recently (1, 2, 3) and at least one more is currently in press. The present review primarily covers work since 1961. It would be not too strong to suggest that explanations of Jupiter's emission now are in the second generation, with most observational phenomena fairly well established. The salient observed features are not widely known; this report will emphasize the author's evaluation of the relevant material. There is also presently a need to bring together the new material, for example, on conditions in the earth's magnetosphere, as they relate to Jupiter's radio emission.

At the time of its discovery in 1954 and 1955, Jupiter's nonthermal emission (then observed only in the decametric range) presented a deep puzzle, both because of its impulsive character (bursts of a fraction of one second up to a few seconds being commonly observed), and because of its strength, emanating from what had appeared to be a cold, albeit giant, planet. The explanations offered at that time centered around geophysical analogues, such as lightning in thunder storms or violent and frequent volcanic activity with consequent atmospheric shock waves. Inasmuch as nonthermal radio astronomy was then in birth, the perspective of these times is difficult for us, only eight years later. Solar bursts had not yet been given more than a tentative explanation; the sun was considered to produce cosmic rays very rarely, once or twice a spot cycle during the greatest of flares; the Van Allen belts were unknown; synchrotron radiation from the sun had not been observed, nor its existence in the Crab nebula definitively established; and the most remarkable objects of all, the quasi-stellar radio sources, such as a 3C273, were yet to be discovered. Had this range of phenomena been known in 1955, without a doubt, the discoverers of Jupiter's decametric emission would have turned to the types of explanations currently proposed, which rely heavily on nonthermal particles trapped in magnetic fields.

There are at least four competitive theories of Jupiter's decametric emission, all of which rely broadly on the existence at Jupiter of a magnetic field that traps fast particles which are involved with both decimetric and decametric emission. One group of theories, by Carr (4), Ellis (5, 6), Ellis & McCulloch (7), and Field (8) explains decametric phenomena in terms of coupling effects between fast particles and decametric radio waves; these effects do not necessarily occur close to the planet. In a broad sense, these

[1] The survey of literature for this review was concluded in November 1963.

explanations tend to associate the decametric emission with analogues of terrestrial VLF emission, which occurs at gyrofrequencies in the magnetosphere, at distances of the order of one earth's radius from the surface. A second class of theories, for example, the earlier explanations by Gallet (9), Zhelezniakov (10), and Sagan & Miller (11), require that the decametric emission orginate close to the surface of Jupiter, in order that the restriction of the emission to limited longitude ranges should have a natural explanation in the vignetting or occultation of emission from sources beyond the planet's limb, and so that energetic atmospheric processes might be involved. This class of theory receives its strongest advocacy from Warwick (12), who supposes the emission is generated near the gyrofrequency close to the surface of the planet. One objective of this review is to discuss the evidence that bears on the problem of the location of the decametric emission, in Jupiter's magnetosphere or ionosphere.

Another theory for the source of the radiation was proposed by Landovitz & Marshall (13), who discussed spin-flip transitions of electrons from the parallel (high energy) to antiparallel (low energy) states with respect to the magnetic field in Jupiter's magnetosphere. Hirshfield & Bekefi (14) proposed maserlike amplification of the synchrotron radiation from a non-Maxwellian electron energy distribution. Strom & Strom (15) suggested that Jupiter's ionosphere focuses a hypothetical backdrop of tiny decametric radio sources onto the earth. This suggestion met virtually unanimous disapproval (16, 17).

One of the features of the decametric emission that turned Warwick's attention (18) to external sources for the particles exciting the radiation was the apparent positive correlation of the emission with solar activity in 1960. Even then it was well known that Jupiter's decametric emission correlates inversely with the rise and fall of solar activity during the spot cycle. For example, in October 1963, Jupiter emitted detectable decametric radiation virtually every night, while in 1960, decametric events came only every sixth night, on the average. The increased activity in 1963 cannot be explained by improved ionospheric conditions since sunspot maximum, inasmuch as activity has increased by similar amounts at all frequencies above 20 Mc/s. Since virtually all theories of the decametric emission turn on magnetospheric phenomena of one kind or another, which are undoubtedly under control of the sun in the same manner as geomagnetic activity, we must confront the negative solar-Jupiter correlation. The existence of a parallel positive correlation to solar activity for the decimetric emission has been widely discussed; but it remains controversial, like the decametric correlation noted in 1960.

Even granting the enormous impact that the discovery of Jupiter's decametric emission had on astronomers, we still find it somewhat surprising that the more recent discovery of Jupiter's radiation belts has not equally impressed the astronomical world. Perhaps only because radiation belts are now a "popular" research topic, associated with the space effort, astronomers have been inclined to disregard trapping phenomena in the planets, the sun and stars, and in galaxies. Nevertheless Sloanaker's (19) nonthermal spectrum for Jupiter's decimetric emission, extended nearly to metric wavelengths by Drake & Hvatum and interpreted by them (20) as synchrotron emission from very energetic electrons in a strong dipole field, led directly to observations by Radhakrishnan & Roberts at the California Institute of Technology (21) of the large angular extent of the decimetric emission and its polarization; and finally, in work by Morris & Berge (22), to the determination of the obliquity of Jupiter's magnetic moment. First-generation observations of the decimetric emission are now nearly complete, with the careful determination by Komesaroff & Roberts (23) of the rotational profiles of intensity and degree and plane of polarization of the total 20-cm flux. Recent observations also extend many of these results to 10 cm (24–27).

Inferences on the magnetic field and electron spectrum and density follow from spectral, interferometric, and polarization measures of Jupiter's Van Allen belt radiation. Unfortunately, the problem remains extremely complex, particularly so in view of asymmetries in the decimetric flux that indicate either nonpoloidal, or perhaps merely noncentral, magnetic field sources. Unless high resolution observations are used to reduce the spatial integration effects, the shape of the magnetic field cannot be recovered from the spectrum and polarization measures.

The problem of electron acceleration confronts us directly in the decimetric emission and, also, in the decametric range, where probably lower energy electrons are involved. The number of electrons required, and their precipitation, suggest many parallels between Jupiter's and the earth's Van Allen belts. The attempts to define magnetospheric acceleration processes appear also relevant to Jupiter, where in an observational sense a more satisfactory perspective on spatial and temporal electron distributions can be maintained. We believe that high resolution ($\lesssim 5''$) radio studies of Jupiter in the decimetric range could provide vital data, otherwise unobtainable, relevant to the origin and storage of electrons in the terrestrial belts.

Jupiter, responding to the interplanetary plasma impinging on its magnetic field in much the same way as (but to a greater degree than) does the earth, measures this plasma five times farther from the sun, and often in radically different directions, from the earth's direction. Estimates of the strength, or even establishment of the mere presence of solar corpuscular influence there, represent plasma data unlikely to be matched by direct interplanetary rockets within the foreseeable future. The comet-tail method extends almost to the orbit of Jupiter, but interpretation of the results may still be ambiguous (28, 29). Conversion efficiency of solar wind into particle energies in our magnetosphere can be estimated, and allows extension of quantitative plasma observations to the orbit of Jupiter and perhaps beyond.

Jupiter, as a rapidly rotating planet, contains within itself the sources of its magnetic field, either a persistent remnant of the original electric current structure, frozen in by the high cosmic inductance and conductivity (8), or generated by convection currents in Jupiter's core acting as a self-excited dynamo (30). There is theoretical evidence that the red spot results from hydrodynamical flow phenomena over a topographic feature (31); it is a virtually stable rotational feature of the cloud structures that reflect sunlight. The magnetic field, as indicated by both high and low frequency radio sources, is, in this context, a unique cosmic feature, inasmuch as its rotation is decidedly faster than the red spot's. We may have to do with coupling phenomena between the mantle of a planet and its liquid core. To the best of the author's knowledge, at least, this is the first instance in astronomy where the distribution of angular momentum within a rotating cosmic body (perhaps even including the earth) manifests itself in observational effects measurable within a short time-scale.

In a discussion of nonthermal emission from Jupiter, we should not ignore the thermal emission of the planet, at centimetric wavelengths, and shortwards. Itself undoubtedly polarized (32), it permits studies on the structure and composition of Jupiter's outer atmosphere. Though not, in origin, associated closely with the magnetic field, centimetric thermal emission is superposed on the observed fluxes from the nonthermal source in the radiation belts. Finally, observations of the optical line spectrum are again alive, rejuvenated by recent researches into high dispersion spectra of the planet (33). What relation, if any, these data will bear to the nonthermal emission remains to be clarified.

Location of the Decametric Emission

One of the characteristics of Jupiter's decametric emission is that a "longitude" system can be defined on which emission events may be localized. In other words, emission tends to recur within limited ranges of longitude, defined by a rotation period of about $9^h55^m29^s.4$. Figure 1 shows such histograms, after Smith & Douglas (34), for data taken during the years 1961, 1962, and 1963 at Yale Observatory. The width at half frequency of the peak of the occurrence histogram at 230° [on the System III longitudes defined in (35)] is about 40° for these single frequency data. If the emission had gone from the source at Jupiter outwards into a hemisphere, no single peak like this one could have been as narrow as 40°. It follows that the emission goes into a narrow beam. An alternative interpretation might be a definite time-pattern of excitation of the emission, which would occur repetitively at the presentation of a given longitude range towards the earth. We shall adopt the simpler beaming hypothesis, with the more stringent beaming requirements that follow from dynamic spectral observations. The value found from these data is of the order of 10–20° between half-power points (12).

It seems necessary to associate the observed beaming of the radiation with the mechanism of generation. The alternative (9), in which an ionosphere lying above an initially isotropic radiator limits the escaping radiation to a narrow cone, fails to explain the fact that the emission covers a smaller range in longitude at high frequencies than at low. The longitude histogram of Jupiter emission above 35 Mc/s is limited to events in only two restricted

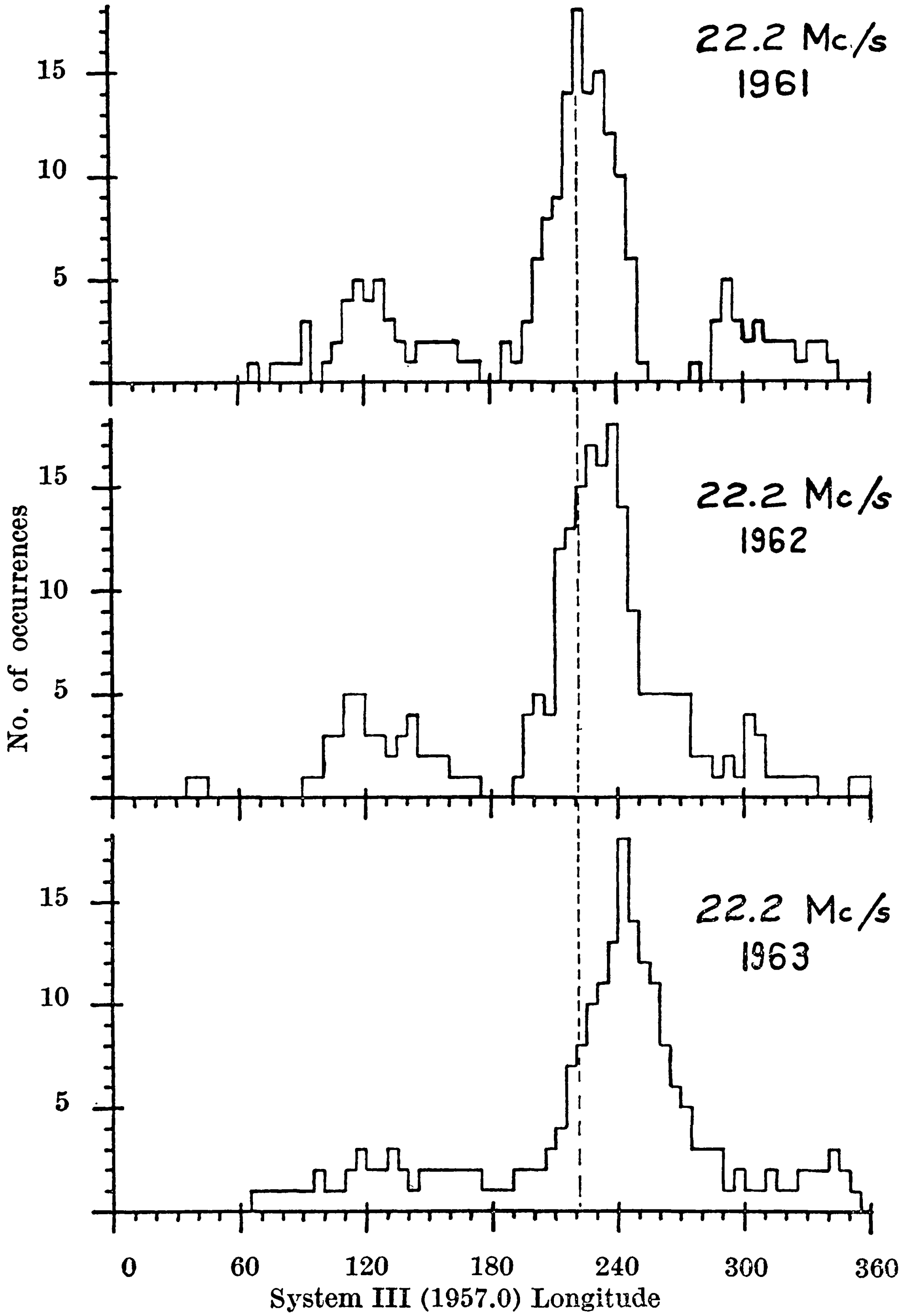

FIG. 1. Longitude histograms of Jupiter's decametric emission at 22.2 Mc/s in 1961, 1962, and 1963 [after Douglas & Smith (34)]. These illustrate the incidence of fixed-frequency occurrences of Jupiter emission as a function of longitude. On the basis of these data, Douglas & Smith concluded that a change in the System III period of rotation from $9^h55^m29^s.4$ to a rate of $9^h55^m30^s.2$ had occurred in the interval 1960–62. The evidence for "sources" is contained in such diagrams.

ranges, in the early source (100°–160°) and the main source (210°–270°); the emission falls into a narrower emission cone at high than at low frequencies.

A second important characteristic of the decametric emission is the recurrence of emission in definite frequency ranges as a function of longitude. Since the frequencies are different from one longitude to another, the dynamic spectrum of the emission tends to recur in a given longitude range. Excitation of a given frequency at a given longitude will not usually recur at every presentation of that longitude, but becomes clear in observations extending over thousands of rotations. This feature of the emission implies that the factors which control the radio frequency of the emission are constant when a certain meridian faces the earth, even over time spans of years (36). Furthermore, the general character of the dynamic spectrum is a drift from low to high frequencies (one octave in tens of minutes) in the early source, and in the contrary sense in the main and late sources.

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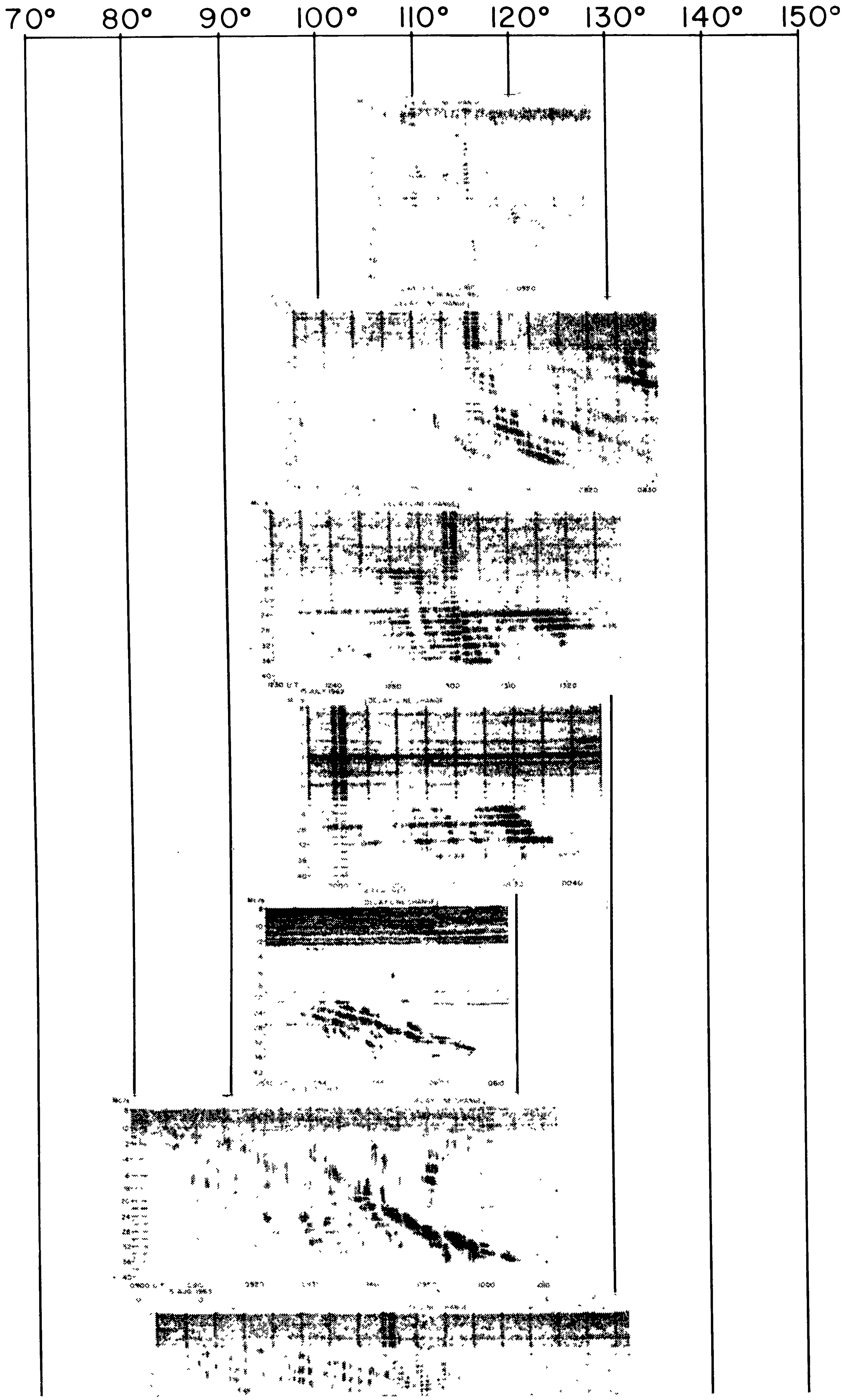
FIG. 2. Illustrating Jupiter's permanent dynamic spectrum, for the early source in the years 1962 and 1963. These data include virtually all Jupiter events recorded at the High Altitude Observatory that exceeded a frequency of 35 Mc/s in the longitude range 100° to 150° [λ_{III}(1957.0)] in those years. The great majority of all such high frequency events is also included here; i.e., very few events at such high frequencies have occurred elsewhere in longitude.

An attempt has been made to arrange the spectra in a series of morphological types. Note that each spectrum is modulated by diagonal, white interferometer fringes, which must be mentally ignored as you inspect the data. Over 150,000 individual radio spectra were obtained in the construction of these diagrams.

The typing of the spectra illustrates that "poor" events occur early and late in the longitude range from 65–205°, and rich, long-lived, and intense events occur in its center. Adjacent spectra, although often of startling similarity, do not necessarily occur even in the same year. However, several pairs of very similar spectra have occurred, each pair spanning about one month. Fine correspondences, so detailed as to make a complete description impractical here, exist in a great many of these events, which will reward the reader willing to spend considerable time inspecting the figure.

Note the wide differences in the character of the short duration bursts from one event to another. Boulder daylight hours lie roughly between 1300 and 0100 hours universal time; a number of these records, made in daylight, illustrate the considerably "softer," slower time variations in the bursts during that interval.

Finally, a number of the spectra exhibit Faraday effect in the frequency domain (6 IX 63, 5 VIII 63, 30 IV 62, 15 X 63, 13 IX 63, 12 VIII 63, 8 VI 62, 20 IX 63, and 22 X 63). This effect appears as intensity modulation running nearly parallel to the time axis. The modulation is widely spaced in frequency towards the high frequency end of the spectrum, but more closely spaced towards lower frequencies, in most cases merging and disappearing at a frequency in the low octave of our equipment. The Faraday effect is being studied here currently, and will, we hope, give us information on the absolute orientation in space of the polarization ellipse at the point of generation of the radiation in Jupiter. It is clear already that the total electron content of the earth's ionosphere and environs can account for virtually all of the observed effect; i.e., no significant amount of rotation need occur near Jupiter.


70°
80°
90°
100°
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130°
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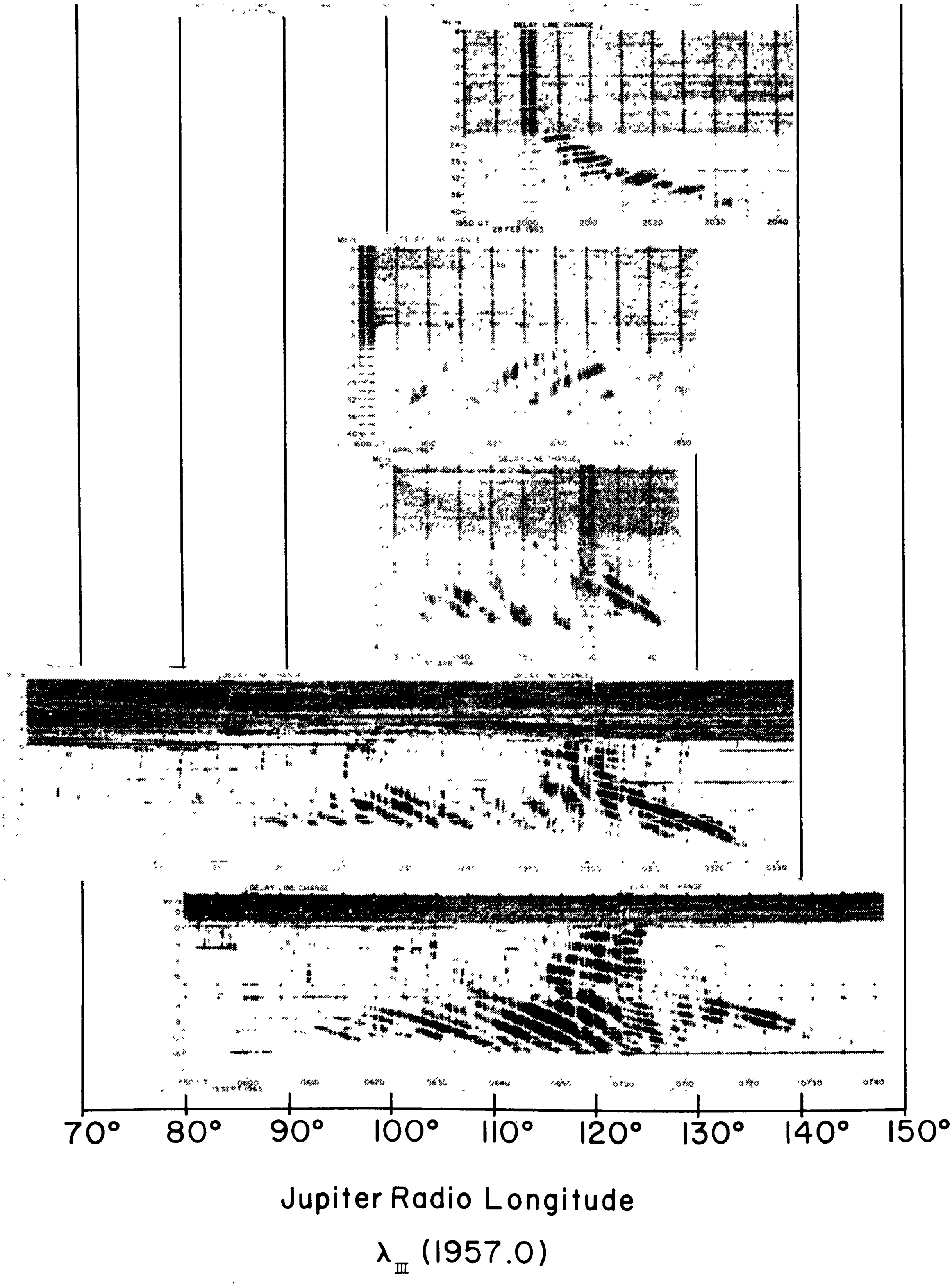
150°


70°
80°
90°
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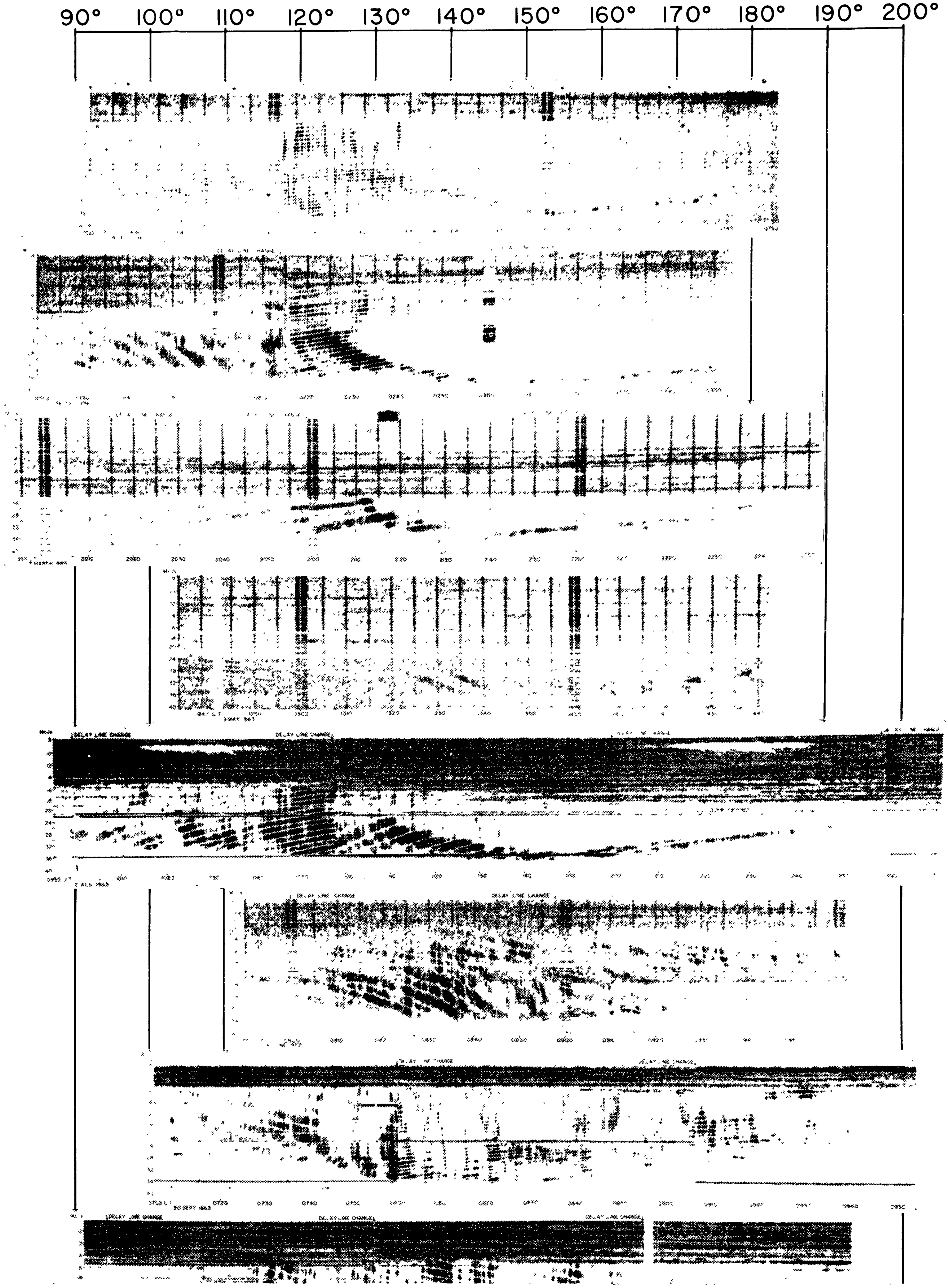
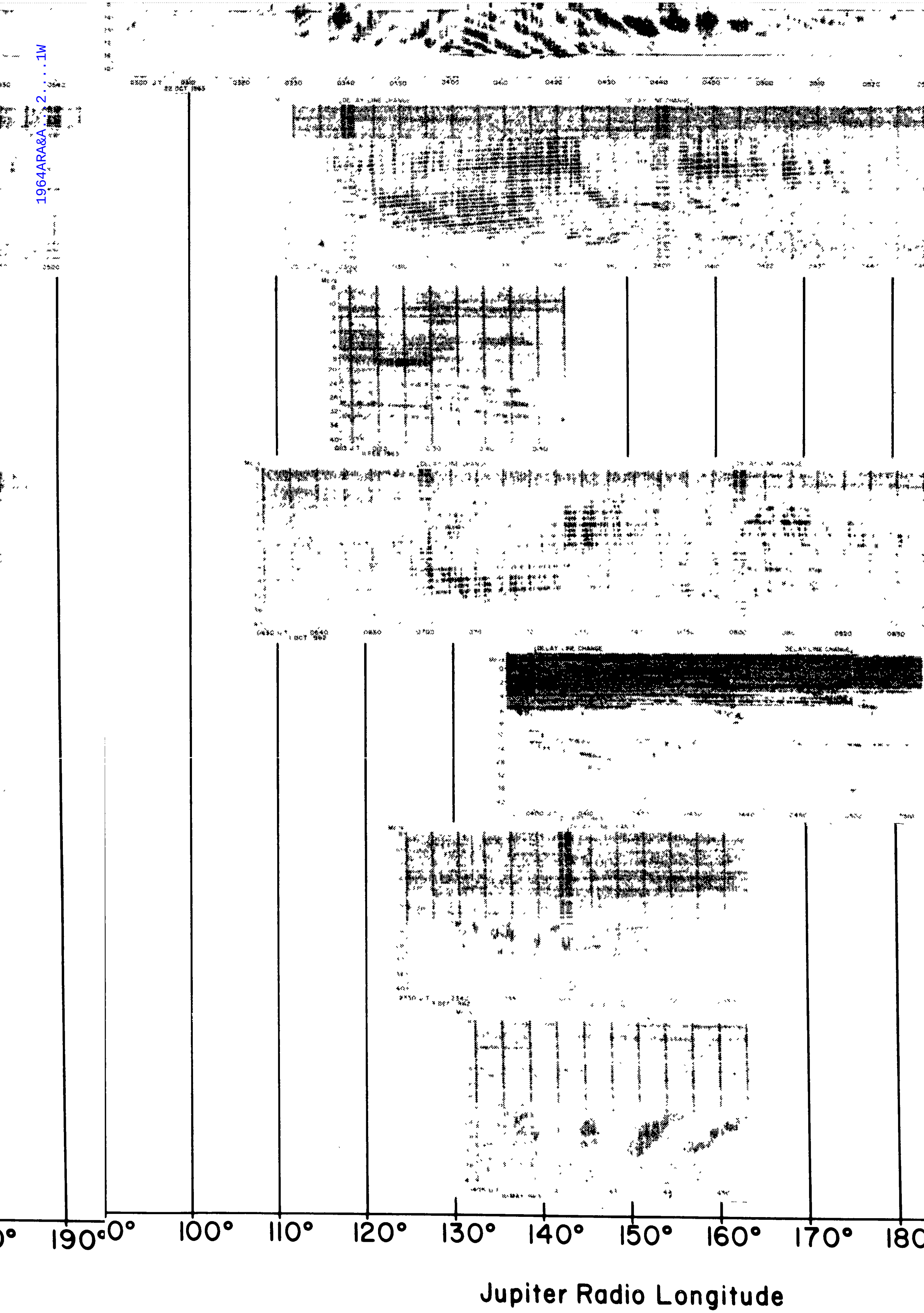
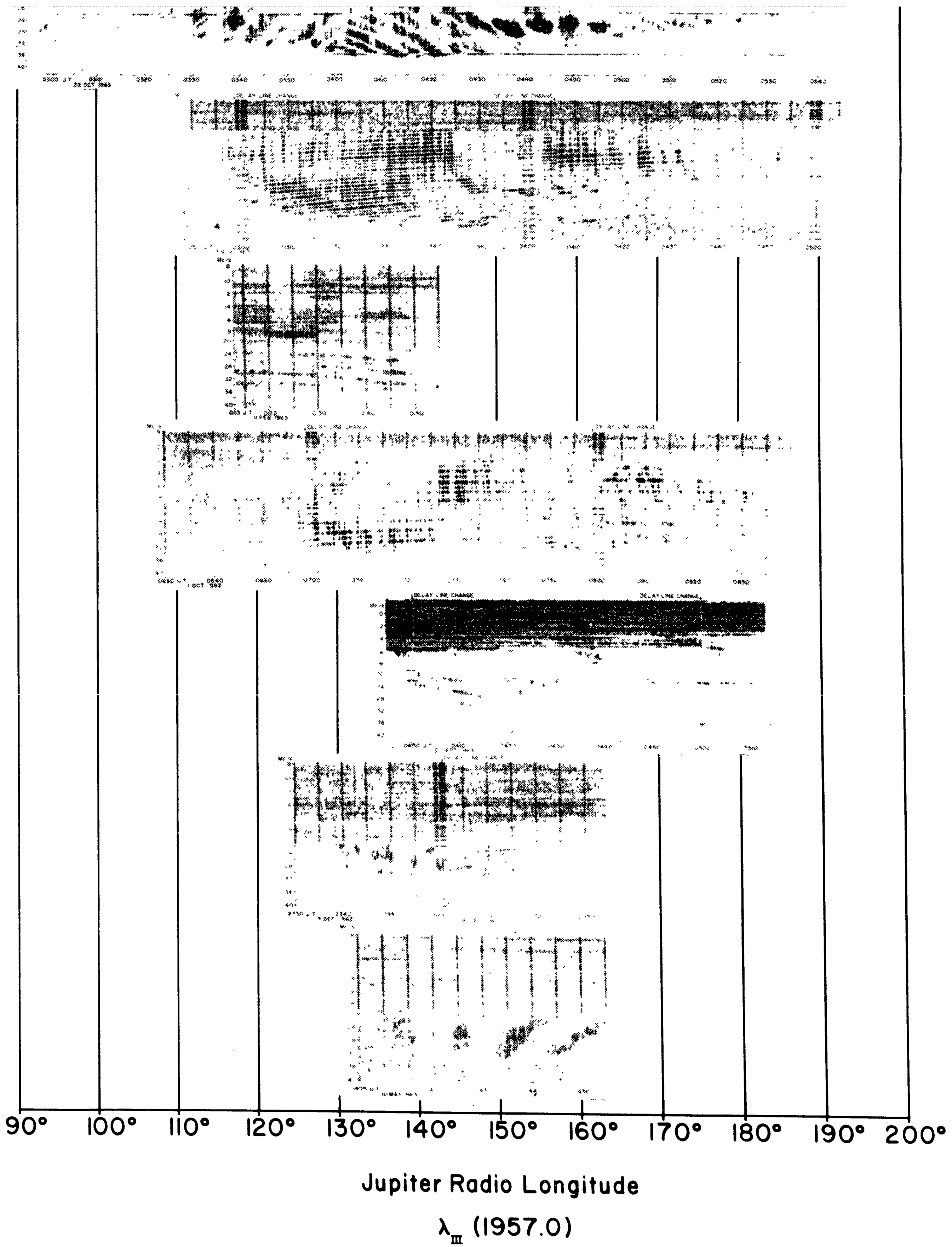
130°
140°
150°
Jupiter Radio Longitude
λ_{III} (1957.0)

FIG. 2a


90° 100° 110° 120° 130° 140° 150° 160° 170° 180° 190° 200°
DELAY LINE CHANGE
20 SEPT 1963


190°
100°
110°
120°
130°
140°
150°
160°
170°
Jupiter Radio Longitude
λ_{III} (1957.0)



90° 100° 110° 120° 130° 140° 150° 160° 170° 180° 190° 200°
Jupiter Radio Longitude
λ III (1957.0)

FIG. 2b

The stable character (see Fig. 2) of the radio frequency of emission implies that the radiation bears a close relation to the magnetic field strength and direction, although it need not occur precisely at the gyrofrequency. The narrow-band features of the permanent dynamic spectrum suggest that only very limited regions of the magnetic field are involved.

On the one hand, the frequency stability of the emission limits the range of field strengths involved in the emission, and on the other, the stability and narrowness of the longitude pattern limit the range of field directions.

The fact that the radio frequency of emission is a stable property of Jupiter's low frequency radiation is consistent with single frequency data, although these alone might be given different interpretation. By ignoring the difficulties in representing a complex spectrum by a simple power law in frequency, Smith et al. (16) have shown that the flux of the radiation varies with frequency more steeply than the minus fifth power. Observations at closely adjacent frequencies (within 1 or 2 Mc/s) have often been found to yield uncorrelated data. For years Jupiter observers concentrated on recordings in the 15–25 Mc/s range, the reason being the exceedingly sharp cutoff in the emission above these frequencies.

The fact that the emission is stable in both frequency and time implies that particular and very limited regions of Jupiter's magnetic field are singled out as the source of the emission. In general, it is difficult to see how mechanisms that do not isolate a single point along a given line of force can exhibit this dual stability. Note that along a given line of force through Jupiter's magnetosphere, the field strength must fall at least as fast as the inverse cube of the distance from the origin of Jupiter's magnetic dipole moment. For the case of the earth, for example, where the dipole lies near the center of the planet, field strengths along a typical VLF-involved line of force might vary from 0.3 gauss at the earth's surface, to 0.001 gauss at the highest point of the line of force five earth's radii over the equator. A range of 300:1 in gyrofrequency occurs along individual lines of force.

On the beaming hypothesis, in which the direction of emission must be identified with the direction of lines of force, only two widely separated locations on a given line of force point towards the earth at some time during Jupiter's rotation. The angular beaming of the emission, which is narrower than 10°, determines the path length along the segment of the line of force that lies within 5° of the direction of the earth. The range of field strengths along this segment of the line of force defines the minimum band-width of the emission. Along a given line of force, near its greatest distance from the magnetic equatorial plane, the variation of relative field strength is $\Delta H/H \sim (7\sqrt{3}/4)\Delta\gamma$, where $\Delta\gamma$ is the angular range in radians corresponding to $\Delta H/H$ along the line of force. Since bandwidths at any frequency within the range 15–40 Mc/s are often observed to be 10 percent or less, $\Delta H/H = 0.1$; but $\Delta\gamma$, as measured, exceeds 0.2 radians. The rapid variation of magnetic field strength along a line of force is inconsistent with the hypothesis that beaming of the emission defines that part of the line of force producing the emission. The beaming is too broad to define sufficiently narrow bandwidths.

We might argue that the particular mechanism (whatever it may be) of generation of the radiation singles out a point along the line of force. The singular feature related to, say, electron acceleration in the earth's magnetosphere has not yet been positively identified, so that it may be premature to form a conclusion on where the process occurs at Jupiter. Nevertheless, two regions of the lines of force might be singular: where the electron density and magnetic field are highest, at upper levels of the planet's atmosphere, and where the magnetic field is weakest and therefore subject to greatest fluctuation under the influence of solar plasma. The latter situation occurs in the equatorial plane of the dipole field. If the radiation originates there, it must be emitted in the directions transverse to the magnetic field direction. In this case there seems to be no plausible reason why the radio waves should be emitted into less than 180° of longitude, even though the frequency of emission might be as stable as suggested by the dynamic spectra. Furthermore, the field strength would have to reach tens of gauss far from the planet's surface. The alternative possibility suffers neither of these disadvantages.

We should emphasize the strong likelihood that more than one kind of mechanism is involved in the emission. At very low frequencies, below 10 Mc/s, where the longitude profile is nearly continuous, locations higher than the ionosphere may be involved. That this may be the case is indicated especially by Dowden's demonstration (37) that at 10 Mc/s, source one, and earlier ranges of longitude, show predominantly left-handed polarization, as though the opposite magnetic pole of the planet were involved. The Boulder data on the permanent dynamic spectrum relate primarily to frequencies above 15 Mc/s.

Radiation emitted outward along dipole lines of force near the planet propagates towards the earth only within a limited latitude range. Several workers have considered the possibility that the dipole field is strongly modified (7), close to the surface of the planet, by quadrupole, or more complex, fields. While remaining a distinct possibility, this model does not seem to explain the large longitude ranges within which stable, slowly drifting emission takes place (Fig. 2), nor the symmetry of drifts about the central meridian in the planet's magnetic field. Warwick (12) has discussed reflection of the radiation, emitted parallel to the lines of force, from the surface or ionosphere of the planet. Many features of the dynamic spectrum may be reproduced by a suitable choice of the location of the dipole in the reflection model. The origin of the dipole lies in the southern hemisphere of the planet. displaced by about 0.7 radii from the equatorial plane, and by a lesser amount from the axis of rotation. At 200° radio longitude [λ_{III}(1957.0)], the magnetic moment lies in a meridian plane to the east of the central meridian, with its northernmost end tipped towards the earth. Its northern end is a north-seeking magnetic pole (38).

Whether this asymmetric location of the dipole moment can be explained in terms of the dynamo mechanism of generation of planetary magnetic fields (30) remains to be seen. Further observational tests involving the decimetric emission are definitely feasible over the next ten years, so that checks of the theory should be close at hand. Meanwhile, we note that Jupiter's optical northern and southern hemispheres manifest strange asymmetries that might speculatively be associated with the proposed magnetic asymmetry. Jupiter's southern hemisphere, for example, contains the Great Red Spot and also is more active than the northern in other respects (39). Furthermore, Gehrels & Teska (40) report that the polarization of the continuum is stronger in the southern polar region than in the northern at short wavelengths, but conversely at long wavelengths. Of course, the optical data may be completely irrelevant in the final analysis, but they tend to establish precedent for asymmetries in the two hemispheres. By comparison with Jupiter, the earth's magnetic asymmetry is small, the displacement of the terrestrial dipole from the center being only a few hundred kilometers (41). Conversely, the sun was highly asymmetric during the crossover phase of the most recent sunspot maximum (42). Furthermore, solar activity during the recent maximum, as during several past maxima, fell predominantly in the northern hemisphere (43). Cosmic bodies evidently can become asymmetric for considerable periods of time, comparable to their periods of magnetic variability, and very long compared to their rotation periods.

A corollary to the "close-in" models of Jupiter's decametric emission is the prediction that the source should be small as seen from the earth (44). Considering that the beamwidth is 10° in longitude, we infer that a source covers only about 10 percent of the planet's diameter, that is, three to five seconds of arc. This is comparable to the angles subtended by artificial satellites. Extrapolating from ionospheric scintillation studies on radio stars, we anticipate severe amplitude fluctuations in Jupiter's emission, even had it left the planet without any time variations. The situation is akin to laboratory experiences with the unfamiliar but intense and highly collimated laser beams. When a piece of paper is illuminated by a laser, for example, fine structure of fibers within the paper jumps out with unexpected and startling clarity. Analogous phenomena have been known to occur on at least one occasion of solar radio emission from an extremely small source (as measured at metric wavelengths). Fluctuations of unprecedented amplitude and abruptness took place in the otherwise continuous solar emission, and were found to be uncorrelated over substantial terrestrial base lines. Most of the fluctuations in this solar event were due to structures near the earth, or in its ionosphere (45).

Extremely wide-based interferometry of Jupiter's decametric emission so far has yielded only the information that the waves come from sources subtending less than one-quarter minute of arc (46). The model of the emission suggests that fourfold greater spacing is required to resolve the source. One remarkable, and as yet unexplained, feature of these wide-based correlation studies (47) is the surprising degree of detailed correspondence, even down to emission features lasting 0.1 seconds or less, at stations separated by 100 km or so. Ionospheric limits on decametric phase stability are clearly far less restrictive than would have been predicted on the basis of standard models of the irregularities (48).

Morphology of the Decimetric Emission

The decimetric emission varies in polarization and intensity as Jupiter rotates. The variations of intensity are so steep a function of the earth's "declination" in Jupiter's magnetic system that they are essentially inconsistent with the rather small degree of polarization observed at 10 or 20 cm wavelength. Radiation beamed so narrowly about the planet's magnetic equator may be produced by electrons that are trapped in very flat helices, but the radiation should be more highly polarized than is observed. This circumstance suggested to Komesaroff & Roberts (23) that a two-component model, as proposed by Chang & Davis (49), is required. A belt of electrons moving in flat helices produces the sharp beaming and the observed polarization and its rocking as the planet rotates. A second, interior, belt of electrons moves with a very broad pitch—angle distribution. It has much lower polarization, but contributes a large measure to the observed total flux. This two-belt model accounts for the observed higher polarization in outer regions of the decimetric source. Multiple belt structure may also account for the several decametric sources (12).

Komesaroff & Roberts indicate (23) that the curve of polarization angle versus System III (1957.0) longitudes is asymmetric (see Fig. 3). This phenomenon cannot be explained in terms of differential Faraday effect between one part of the radiation belts and another. It may perhaps be explicable in terms of magnetic field configurations other than a simple dipole, but this kind of model opens up a wider range of possiblities than seems tractable today. The symmetry of decametric drifts suggests a poloidal field. Since the decimetric source corresponds to positions up to three Jupiter's radii away from the surface of the planet, any nonpoloidal components of the field should be very much smaller there than at the source of the decametric emission.

The suggestion again arises that the magnetic field, still poloidal, corresponds to that of an eccentric dipole within the planet, which occults or eclipses different parts of the radiation belts as it rotates (23, 24).

We can gain insight into the occultation effect by the following geometrical construction. Draw the locus of points in the dipole field where the lines of force lie perpendicular to the line of sight. This locus will be the main source of synchrotron radiation. Because trapped electrons spend most of their time at or near mirror points, and because the magnetic field there is at its strongest, most of the synchrotron emission may be expected to originate there. When the earth lies in the equatorial plane, the dipole field has two surfaces which constitute the desired locus: the entire equatorial plane, and the plane perpendicular to the line of sight. In another special case, when

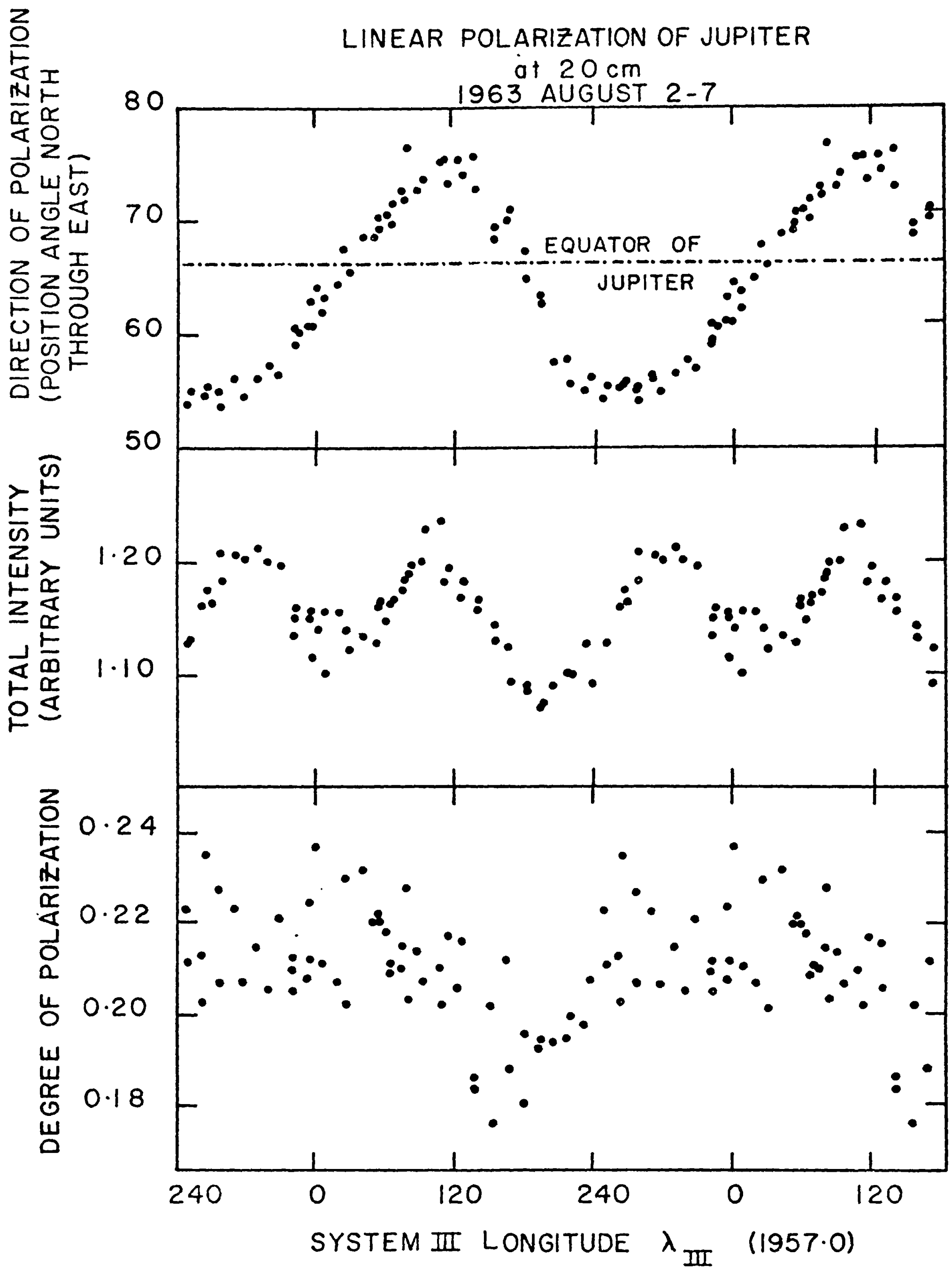


FIG. 3. Rotation profiles of polarization (top), total intensity (middle), and degree of polarization (bottom), after Komesaroff & Roberts (23). The total intensity is in units of the discrete source 3C17.

viewed along the magnetic dipole, the dipole-field orthogonal surfaces are two cones, at magnetic latitudes ±35.°3.

The intersection of a meridian plane, containing a line of force, with a certain plane perpendicular to the sightline, lies tangent to the line of force at two points. The locus, for all lines of force in the meridian plane, of the tangency points consists of two radial lines extending outward from the dipole. The angle between a reference direction lying in the perpendicular plane and the lines of force at the points of tangency is constant along a radial line.

Similar constructions are familiar (50) in geophysics where, for example, radar reflections from auroras occur at right angles to the lines of force. A difference between the two geometries occurs because the terrestrial radars, of course, lie within the magnetic field of the earth, but the Jupiter observations are made at essentially infinite distance from the planet.

Figure 4 illustrates the situation with plots of the contributing parts of a dipole field for a given inclination, 80°, of the dipole axis to the sightline. Shown is the direction of the electric vector of the synchrotron radiation from each point in space on the far side of the planet. The number of electrons which are present and the magnetic field strength at the corresponding point in space determine the intensity of the radiation. To interpret this figure, we imagine the planet covering up different parts of the field, which remains fixed. The limb of the planet is shown in its extreme positions according to (12). The shaded lunes indicate the areas of the radiation belts occulted at different phases of the rotation of the planet. In addition, the figure illustrates schematically the net electric vector contributed to the total polarization by each lune. The net emission from the lune labeled (A′) is polarized in a direction rotated slightly clockwise with respect to the equatorial plane of the magnetic dipole.

There are two "crossover" points in the rocking of the decimetric plane of polarization; when the magnetic pole in Jupiter's northern rotational hemis-

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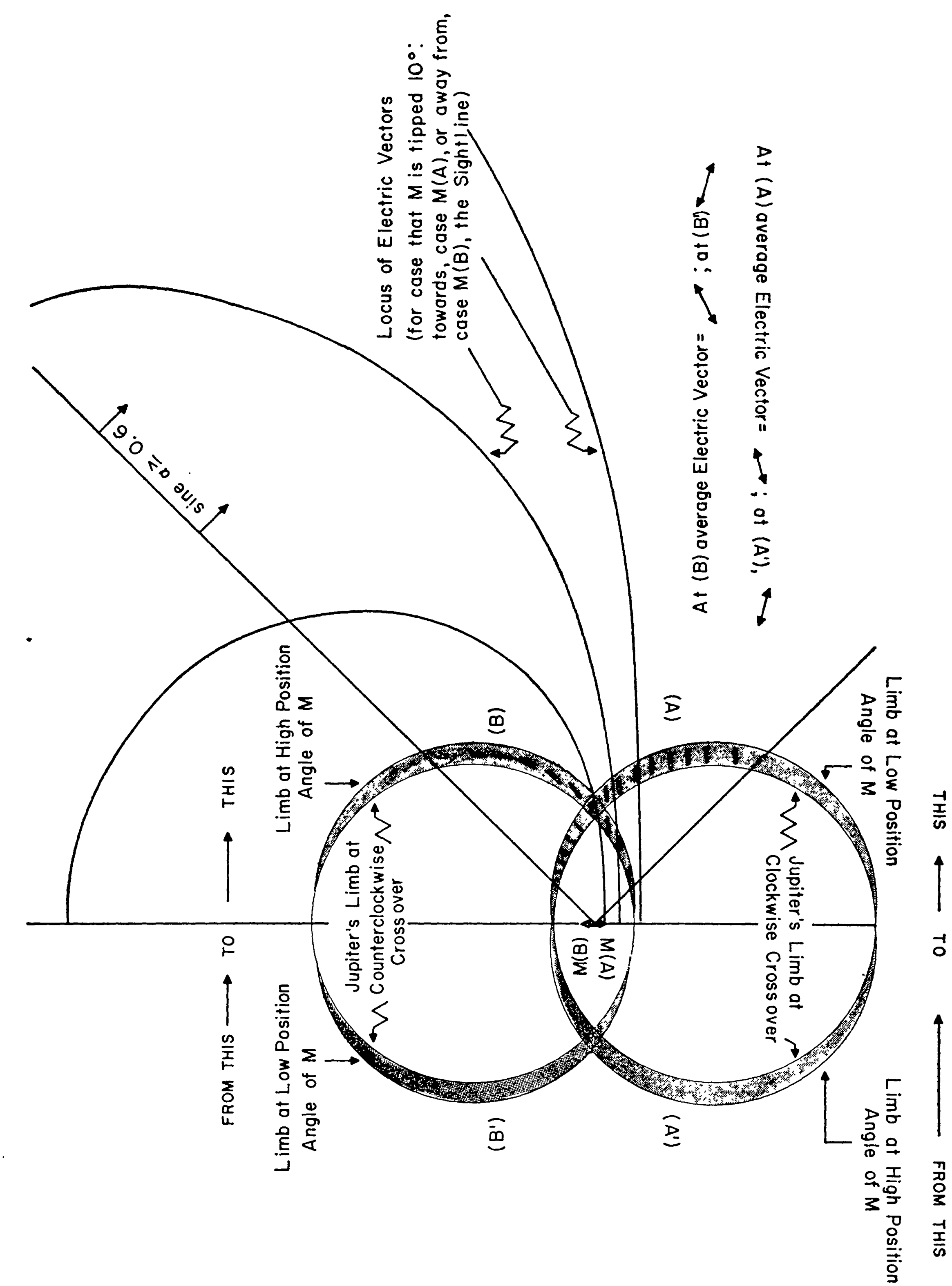
FIG. 4. Illustrating the geometry of the electric vector of synchrotron emission from electrons trapped in a dipole field. The dipole moment is either at M(A) or M(B), about three quarters of a planetary radius from the center of the planet. The loci of electric vectors are closed curves, with mirror symmetry in the two spatial regions from which the emission arrives at the earth, viz. from in front of, or behind the planet. Only the locus that lies in space behind the planet is shown. This locus encompasses the center of the planet at counterclockwise crossover, but lies below (to the south of) the planet at clockwise crossover. The limb is shown for longitudes 90° before and after each crossover, and at each crossover. The stippled lunes represent the portions of the synchrotron emission which are covered and uncovered in the course of Jupiter's rotation. Heavy lines within each lune represent the electric vector of the radiation from the lune, and typical averages of those vectors are shown on the figure. Two radial lines represent the projection of the region within which move electrons in a moderately flat pitch angle distribution sin $\alpha_L \leq 0.6$.


Locus of Electric Vectors
(for case that M is tipped 10°;
towards, case M(A), or away from,
case M(B), the Sight Line)
At (A) average Electric Vector= ; at (A'),
At (B) average Electric Vector= ; at (B')
Limb at High Position Angle of M
Limb at Low Position Angle of M
Jupiter's Limb at Counterclockwise Cross over
Jupiter's Limb at Clockwise Cross over
(A)
(A')
(B)
(B')
M(A)
M(B)
FROM THIS → TO → THIS
THIS ← TO ← FROM THIS

phere passes between us and the rotational pole, the plane of polarization lies perpendicular to the axis of rotation (except for a residual Faraday rotation that occurs within the earth's ionosphere). The plane rotates then in the clockwise sense. In the longitude range immediately preceding clockwise crossover, lune (A′) is uncovered, while the symmetrical lune at (A) is occulted. The net effect increases the angular rate of change of the plane of polarization through the time of clockwise crossover. For lunes (B′) and (B) a converse effect reduces the rate of change of the plane of polarization. If the moment lies in the northern hemisphere, the asymmetry of position angle variation near the crossovers would be reversed.

Short of the requisite extremely high resolution studies, one might hope for detailed theoretical calculations of synchrotron emission from asymmetric dipoles, in order to confirm the quantitative plausibility of this discussion.

Roberts & Komesaroff's measurements determine the inclination of the magnetic axis to Jupiter's rotation axis. At both the maximum and minimum position angle of the polarization, parts of the radiating regions are occulted; the measured position angle does not then correspond to the true position angle of the magnetic dipole axis. Figure 4 shows that near longitudes 90° before clockwise crossover (maximum deviation of the magnetic moment eastward from north), the position angle of the polarization will be somewhat greater than the position angle of the magnetic axis. Conversely, at 90° after clockwise crossover (maximum westward deviation of M), the position angle of the polarization will be somewhat less than the position angle of the magnetic axis. The effect should be roughly symmetrical at these two points, the degree of symmetry depending on the closeness of the magnetic dipole to the rotation axis. The total range of the position angle, which is between 20° and 21°, therefore is not exactly twice the inclination angle of the dipole axis to the axis of rotation, but is somewhat greater than twice, by an undetermined amount.

An alternative way to compute the inclination angle, for a symmetrical dipole located at the center of Jupiter, would start from the rate of change in position angle of the polarization as a function of the longitude of the central meridian. Expressed in degrees (of position angle) per degree [of longitude in System III (1957.0)], the position angle at the clockwise crossover has a rate of 0.156° per degree, and at the counterclockwise crossover, 0.133° per degree. If the position angle, P.A., depends on System III longitudes in the form P.A. $= A_0 \sin[(2\pi/360°)\,\lambda_{\mathrm{III}}(1957.0)$—constant], then we may find $A_0 = (360°/2\pi)\,(d/d\lambda_{\mathrm{III}})$ P.A. From the clockwise crossover, the value of A_0 is $-13.°0$, and from the counterclockwise crossover, $+7.°7$. These values would necessarily be equal numerically if the dipole were symmetrical.

In the absence of a definitive study of the brightness distribution of the decimetric radiation, we can only indicate approximately which of these values is the better, but it should be clear that the straight average of them is not appropriate. At clockwise crossover, the planet extends farther onto the equatorially polarized emission than at counterclockwise crossover; the occulted emission is then relatively stronger than the emission occulted at counterclockwise crossover. In other words, there is an absolute minimum of total intensity and degree of polarization at clockwise crossover. The occulted lunes shown in Figure 4 are less sensitive to the exact position of the planet, and the total polarization refers more precisely to the true variation of the position angle of the dipole axis, at the counterclockwise crossover. The derived inclination angle of the magnetic axis to the rotation axis is $\sim 8°$.

Roberts & Komesaroff noted the need for a belt with exceedingly restricted pitch angle distribution to produce the observed variations in degree of polarization and intensity as functions of longitude. In the absence of actual brightness distribution measurements, we note that the occulting mechanism may also contribute to the effect.

Supply of Energy to Jupiter's Magnetosphere

Although understanding of the manner in which energy is fed from solar corpuscular streams into the terrestrial magnetosphere is still in its infancy, observational data on the magnetosphere's energy content in the form of trapped fast particles on the one hand and on solar stream energy outside the magnetosphere, in interplanetary space, on the other are now available from direct probe measures. For decades, since Lindemann's and Chapman's pioneering investigations, solar-associated fluctuations in the earth's magnetic field have been interpreted in terms of the impact pressure of neutral, but ionized, solar plasma against the geomagnetic field a dozen or so earth's radii out in space.

In recent years, the previously mysterious mechanism of solar plasma emission has come to be understood in terms of the high coronal temperature and consequent coronal kinetic energy, relative to the solar gravitational potential, expressed in terms of energy per particle. The latter ratio, which increases outwards, leads to a hydrodynamic phenomenon similar to the flow of gas through a Venturi tube, where the speed of the wind increases as the cross section of the tube decreases. From the sun outwards to a few solar radii, gases flow at an accelerating velocity. From its maximum at that point the velocity drops, but remains high even at several astronomical units from the sun. This effect was called the "solar wind" by Parker and has been widely discussed since his original suggestion (51). Direct observations by the deep-space Venus probe Mariner II showed that the wind speed correlated positively with geomagnetic disturbance during the fall of 1962 (52). Furthermore, the usual wind speeds are the order of 500 km sec^{-1}, with typical particle densities of a few proton-electron pairs cm^{-3}.

If this plasma stream were isotropically emitted by the sun, total energy loss by the sun into all directions would be of the order of 10^{25} to 10^{26} ergs·sec^{-1}. Since the plasma undoubtedly flows into severely limited directions, the quoted range of energies lies near the upper limit.

The earth's magnetosphere presents a circle of radius roughly 10 $R_\oplus = 6 \times 10^9$ cm to the solar stream. The earth can therefore interact with a fraction, $\pi(10\ R_\oplus)^2/4\pi(1\ \text{a.u.})^2 = 5 \times 10^{-8}$, of the total solar wind power; e.g. 5×10^{16} ergs·sec^{-1} may be put into the magnetosphere at an upper limit. The total energy content of the earth's belts (in the form of the electrons with energies $\gtrsim$ 10 keV) is something like 3×10^{20} ergs. One measure of the influx of energy to the belts is that the belt electrons in effect must be capable of being replaced by the energy source in only 10^4 seconds (53). This implies 3×10^{16} ergs sec^{-1}, less than but quite comparable to the power available from the solar wind.

The boundary of Jupiter's magnetosphere is set by the requirement that magnetic pressure should there balance solar wind impact pressure. If the impact pressure falls, between earth and Jupiter, as the inverse square of the distance from the sun, then the magnetic field strength at the boundary of Jupiter's magnetosphere should be about 10 gammas. To scale this to the size of Jupiter's magnetosphere requires that we know the magnetic moment of Jupiter's field, which has been given as 4×10^{30} gauss cm^3 on the basis of the decametric data (12). With this value, the radius of Jupiter's magnetosphere is about 50 of Jupiter's equatorial radii, and the fraction of the total solar wind intercepted by Jupiter is about 5×10^{-6}. The power available from the wind is then about 10^{20} to 10^{21} ergs sec^{-1}, somewhat higher values than have been estimated by Roberts & Huguenin (54).

The total particle energy content of Jupiter's magnetosphere is extremely difficult to estimate accurately. If we assume the density of relativistic electrons to be 10^{-3}cm^{-3}, with an average energy of 30 MeV and extending over a volume 10 times the volume of the planet (49), we find a total energy of about 10^{24} ergs. The characteristic storage lifetime of this radiation is unknown, but it is presumably at least as long as similar storage in the earth's belts, of the order of 10^8 seconds. The decimetric power requirements then are no greater than 10^{16} ergs·sec^{-1} which is only a very small fraction of the total solar wind energy. The lower energy electrons responsible for the decametric emission represent about 3×10^{24} ergs. However, these electrons are stored for much shorter lifetimes, 10^3 sec, so that power requirements are about 3×10^{21} ergs·sec^{-1}. This exceeds, or at best is fully comparable with the energy available from the solar wind. The estimate of electron flux in the 10-keV range was based on a noncoherent emission theory for the decametric radio waves, as well as on the rather large emission cone of 20° total angle. It therefore represents an upper limit to decametric source power requirements. Note, however, that the total power for maintaining the earth's belts requires nearly as much of the available solar wind as do Jupiter's belts.

Acceleration of Electrons in Jupiter's Magnetosphere

Here again we must argue from closely comparable situations which arise in the earth's magnetosphere. The electrons and protons trapped in our magnetic field do not come as fast particles from the sun. The protons, indeed, may not come from the sun at all. A wide range of possible mechanisms has been proposed (55). They all involve magnetic field changes, except for the cosmic ray albedo hypothesis, which does not seem capable of explaining the broad distribution of electrons from heights of one earth's radius outwards.

A comprehensive description, based on Explorer 14 observations of the trapped radiation, has recently been presented by Van Allen and his co-workers (56). Explorer 14 swung in a highly eccentric orbit from the earth out to beyond the limit of the magnetosphere; as the earth revolved around the sun, the satellite's orbit took on varying orientations with respect to the earth-sun line and covered some 100° of longitude in the belts, from the day to the night hemisphere. The interior part of the magnetosphere, dominated by the quasidipolar geomagnetic field, terminates at 10 $R_{\oplus}$ at noon, and only 7 $R_{\oplus}$ at midnight. The boundary flares out from a semicircular form at a distance of 70° from the sun-earth line into an expanding conical shape. In the region of this skirt, particle fluxes remain high, but between the skirt and the interior magnetospheric region on the night side of the earth there are relatively few particles.

Outwards from the sunward boundary of the interior region of the magnetosphere, the abundance of trapped particles drops abruptly while the magnetic field and plasma become highly turbulent—essentially, according to Sonnett, a "disordered hydromagnetic medium in the collisionless limit" (57). In this part of the magnetosphere the residual and distorted magnetic field is, according to Spreiter & Jones (58), a remnant of the interplanetary field, modified as a result of impinging, along with the solar wind, against the earth's field. They emphasize the reversal of field direction observed by Explorer 12 in support of this contention. Freeman, Van Allen & Cahill (59) infer the existence there of a large flux, as high as 10^{10} cm^{-2} sec^{-1}, of electrons in the energy range of a few keV, extending outwards 10,000 km from the point of termination of the regular geomagnetic field at the time of mildly disturbed geomagnetic conditions. They believe the flux acts as the pressure transmitting agent from the solar wind to the geomagnetic field. The termination point of the regular field varies in distance, coming to within 50,000 km of the earth under disturbed conditions, and moving back out to 70,000 km or more under quiet conditions.

According to Sonnett (57), the energy density of the turbulent shocked region outwards from the termination of the regular field may be equated to the energy density carried by the solar wind at 1 proton cm^{-3} and 3×10^{7} cm·sec^{-1}. But the energy and lifetime of trapped electrons ($\sim$10 keV) already corresponds to the solar wind energy flux. It would seem, then, that the conversion of this energy into the acceleration of soft electrons in the electron Van Allen belt goes on with high efficiency virtually continuously on the daylight side of the earth. In support of this contention, we have O'Brien's observation (60) of large diurnal variations in the trapped radiation ($\gtrsim$40 keV), with their implication of a source of electrons steadily effective on the day side of the belts. He believes the source operates only in the equatorial plane within the regular part of the geomagnetic field. The turbulent interface region is itself unlikely to be the region of final injection into trapped orbits, although there would seem to be every reason that the electron acceleration processes might occur primarily there.

Again, following Sonnett & Abrams (61), we note that characteristic times for the irregularity structures are of the order of one second. If the speed of the structures past the satellite is given by the Alfvén velocity, $v_A \simeq B/\sqrt{4\pi\rho}$, where $B \sim 50$ gamma, and if the Alfvén velocity is of the order of 10^7 cm·sec^{-1}, then $\rho \sim 10^2$ proton-electron pairs cm^{-3} in the irregularity region. Since the solar wind velocity is much higher than v_A, the magnetopause is a shocked region, as Sonnett and others have asserted (52). The scale size of the structures is of the order of several hundred kilometers. The thickness of the region is of the order of several earth's radii, say 2×10^9 cm, within which there may exist several hundred irregularities along a given radius through the region.

Turning back to Jupiter, we noted that the magnetopause field strength there is smaller than the earth's, perhaps only 10 gammas. On the other hand, Jupiter's radiation belts contain 10^3 as many electrons as the earth's in the relativistic range, or precipitating towards the planet at low energies. It seems clear that the mere weakness of Jupiter's magnetic field in the magnetopause cannot be the decisive factor in establishing the character of the acceleration mechanism.

The boundaries of the turbulent region for the earth or Jupiter undoubtedly occur at the distance where the planetary magnetic field just begins to disturb the incident solar plasma, and the distance where it dominates the flow. If the stream energy density is E, and the magnetic field energy density is $H^2/8\pi = \text{constant} \times (1/R)^6$, the turbulent region will be limited to a small radial distance ΔR. Suppose that where $H^2/8\pi = (1/N)\ E$, field effects are first felt, and at NE, the field dominates. Then $6\Delta R/R = N^2$ or $\Delta R = (1/6)\ N^2 R$. Now for the earth, $(\Delta R/R) \simeq (1/4)$, so that $N \simeq 1.2$. Using the same N for Jupiter, we find $\Delta R = 12 R_{♃} = 8 \times 10^{10}$ cm. The thickness of Jupiter's magnetopause is 40 times as great as the earth's and, with the same scale size of turbulence as for the earth, must contain 10^4 irregularities along a given path radially through the magnetopause. In other words, an important difference between the accelerating regions of the magnetospheres of Jupiter and the earth appears to be the number of irregularity structures encountered along a radial line through the magnetopause. Field strengths and plasma densities at Jupiter are comparable to or less than those for the earth.

This situation suggests that some form of the Fermi mechanism (62) is operative for both the earth and Jupiter. It should be noted that this mechanism depends exponentially on the number of encounters between an accelerating particle and the irregularities in magnetic field. Particle energies near Jupiter should therefore far exceed those near the earth.

The question of acceleration in Jupiter's belts was also taken up briefly by Chang & Davis (49), who turned to a betatron mechanism to provide flat helices for the high energy electron component. The effect of this process in the earth's belts was discussed at some length by Coleman (63), who found that it leads to a modest acceleration there, as well.

Chang & Davis (49) also considered neutron albedo electrons as a source for the decimetric flux. The number of primary cosmic rays arriving at a latitude on Jupiter's surface where they can supply Jupiter's extensive radiation belts with its strong magnetic field is very much less than for the earth and seems to rule out, of itself, the possibility of this source.

Summary of Observed Properties of Jupiter's Nonthermal Radio Emission

Range of (observed) frequencies.—The reported extremes are 4.8–43 Mc/s. A frequency of 4.8 Mc/s was observed by Ellis in 1961 (64) and not since (private communication). At 43 Mc/s, an aural observation was reported by Kraus (65). The High Altitude Observatory's spectrograph on several occasions recorded emission as low as 7.6 Mc/s and as high as 39.5 Mc/s, but never higher.

Time variations.—Since its discovery, emission has been characteristically reported as "bursts," lasting from a fraction of one second to a few seconds or tens of seconds. Bursts vary in character from night to night even when the spectrum of emission is similar, while daytime observations frequently do not shows bursts (Fig. 2). The fine structure of 10's or 100's of milliseconds correlates over baselines of 50 to 100 km and perhaps longer. Interferometry over long path lengths suggests sources $\lesssim 15''$.

Polarization.—Between 20 Mc/s and 30 Mc/s, polarization was virtually always right-handed circular or elliptical, axial ratio 1.2 to 1 to 2 to 1, especially for early and late sources (66, 67); observations have not yet extended above about 30 Mc/s, but Warwick's theory (12) predicts right-handed polarization. Below 20 Mc/s, mixed events occur (67, 68), especially in the third source. At 10 Mc/s, the right-handed sense still predominates except in the early source which is left-handed. In mixed events, the sense can change from one second to the next. The role of the ionospheric structure is not yet clear.

Bandwidth.—The spectrograph indicates bandwidths near 1/2 Mc/s in some fine structures of the dynamic spectrum. Bandwidths tend to correlate with burst or burst-group durations, longer durations going with wider bandwidths, up to a few seconds and 5 or 10 Mc/s (12).

Frequency drifts.—Bursts lasting a few seconds often drift rapidly in frequency, 10 Mc/s in 10 seconds, for example. Drifts can be high frequency to low frequency or vice versa (see Fig. 2). Events lasting tens of minutes or hours drift slowly, 10 Mc/s in 10 minutes, and consist of many bursts and burst groups. The slower drifts during events strongly correlate with longitude, and in their totality comprise the permanent dynamic spectrum. Positive drifts occur in the range $50° - 180° = \lambda_{\text{III}}$ hr (1957.0), and negative drifts, $200° - 360°$.

Intensity.—Events with flux density of 10^{-20}w · m^{-2}(cps)$^{-1}$ are infrequent, occurring in perhaps 10 percent of all cases. Bursts lasting much shorter times exceed this level occasionally. Spectrum cannot be defined satisfactorily in terms of a power law, but flux in some rough sense parallels the increase of galactic flux towards lower frequencies.

Longitude profile as function of frequency.—Emission between 30–40 Mc/s occurs only in very restricted longitude ranges. "Sources" widen in longitude at lower frequencies. At 4.8 Mc/s, emission is constantly present, but varies in intensity as the planet rotates. This distinction between events and their intensity is not necessary at higher frequencies.

Correlation with solar activity.—Such correlation is certainly negative with the solar cycle; but perhaps there is a positive correlation between high-frequency decametric events (>30 Mc/s) and individual active solar regions.

Decimetric (Nonthermal)

Range of frequencies observed.—The extremes reported are 178 Mc/s −3200 Mc/s.

Time variations.—If any exist, they are slow, extending over weeks or months. Positive correlations with sunspot numbers have not yet been corroborated by all workers.

Polarization.—Polarization is linear plus random, 30 percent at 960 Mc/s, and decreasing towards higher frequencies. The direction of vibration of the linear component is only approximately parallel to Jupiter's equatorial plane; more exactly, it rocks back and forth through a total angle of about 20° in each Jupiter rotation. The period of rocking agrees with System III (35) within less than one second; the plane of vibration is perpendicular to the rotation axis at λ_{III} (1957.0) = 190° or 010°, and is then rocking in clockwise or counterclockwise sense, respectively. The tilt of the magnetic dipole to the rotation axis is about 8°.

Spectrum.—Observations suggest that the spectrum is flat between 3200 Mc/s and 178 Mc/s, with a flux (at a distance of 4.04 a.u.) equal to 6×10^{-26} w · m^{-2}(cps)$^{-1}$, over that entire range (69).

Source size and brightness distribution.—The source is elongated in the equatorial direction to three times the planet's diameter; in the polar direction, the source subtends about one planetary diameter. The source is more highly polarized in its outer equatorial portions.

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THE RR LYRAE STARS[1,2]

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For more than fifty years the RR Lyrae stars have played a prominent role in problems of galactic structure, first as distance indicators and more recently as population indicators. This has followed from the apparent homogeneity of the group, the large number present in the Galaxy, and their moderately high luminosities, which render them visible at large distances. However, in the past decade it has become clear that RR Lyrae stars are heterogeneous in many observable parameters. This heterogeneity limits their usefulness in some contexts and enhances their value in others. In addition to their applications in galactic research, the RR Lyrae stars are of current astrophysical interest on account of the line-doubling and emission that occur during rising light, the multiple periodicities found in many of them, and various other phase- and period-dependent phenomena that bear on the theory of stellar pulsation. In this review we summarize recent developments in these areas.

GROUP PROPERTIES

Absolute Magnitudes

The traditional value of $M_v = 0.0$ has been revised downwards in the past decade on the basis of several considerations. From a study of her own proper motion data and all available radial velocities, Pavlovskaya (1) derived a value $M_{pg} = +0.5$, or approximately $M_v = +0.2$. Other estimates have followed from consideration of the color-magnitude arrays of globular clusters. The assumption that all RR Lyrae stars have the same M_v led to a number of discrepancies in the location of cluster main sequences (2, 3, 4). While some of these discrepancies could be attributed to systematic errors in photometry of very faint stars, it was also recognized that the invariance of the absolute magnitudes of the RR Lyrae stars is an *ad hoc* assumption. Meanwhile Sandage & Eggen (5, 6) showed that all of the so-called subdwarfs lie on or near the Hyades main sequence when the differential blanketing effects of non-solar metals-to-hydrogen ratios are taken into account. For these reasons the problem has been inverted (7, 8). The absolute magnitudes of RR Lyrae stars have been estimated by fitting cluster main sequences, corrected for blanketing, to a standard main sequence, e.g. the Hyades main sequence. The result of this effort has been to reduce the absolute magnitudes and to introduce a dispersion in M_v of about ± 0.3 or 0.4 magnitudes. The same technique has been applied by Eggen & Sandage (9) to RR Lyrae stars considered by them to be members of moving groups with similar results. The

[1] The survey of literature for this review was concluded in October 1963.

[2] Contribution No. 158 from Lick Observatory.