Reports

Io-Related Radio Emission from Jupiter

Abstract. *As evidenced by spectra of Jupiter's decametric radio emissions from 1960 through 1964, Jupiter's satellite Io acts to induce much of the emission and influences the spectral character of the emission. The emission pattern of Io-related emission is derived, and possible interaction mechanisms to explain the Io effect are discussed.*

Bigg (*1*) discovered that Jupiter's satellite Io exerts a strong influence on Jupiter's decametric radio emission. In making his discovery, Bigg analyzed data obtained on the Boulder (Colorado) spectrograph in the years 1961 through 1963. This report is an extension of Bigg's work to the years 1960 and 1964. It shows that Io affects both the probability of emission and the character of the emission spectrum and that the emission probability approaches 1.0 when Io's position and the Jupiter longitude are simultaneously favorable, and deduce that "early-source" and Io-related "main-source" emission are simultaneously emitted into two cones once every 12.9 hours when the plane of Jupiter's magnetic axis swings past Io.

The estimated emission probability for the apparitions of 1960–1964 as a function of ϕ_{Io}, Io's departure from superior conjunction, is shown in Fig. 1. Superior conjunction occurs when Io is directly behind Jupiter as seen from the earth. All emissions recorded on the Boulder spectrograph are included. The spectrograph has a range from 7.6 to 41 Mc/sec, but the highest-frequency Jupiter emission ever recorded was 39.5 Mc/sec. Because of limitations of the equipment in 1960, there were only 57 Jupiter events recorded in that year. An emission-probability curve based on so few events would not be meaningful, so the number of events was plotted instead. From Fig. 1, the curves for all five apparitions are similar and have prominent peaks and troughs at the same Io phase. Bigg (*1*) obtained curves similar to those in Fig. 1, having plotted the number of emissions weighted by the emission intensity for each of the calendar years 1961–1963. In Fig. 1 no weighting was used, and the curves are based on apparitions of the years 1960–1964.

The emission probability is not solely dependent on Io's position, but is equally dependent on the System III (1957.0) central meridian longitude of Jupiter (denoted LCM). Much of the main source emission (200° < LCM < 280°) occurs regardless of Io's position, but the emission probability is considerably enhanced if Io's position is near 240°. Early source emission (80° < LCM < 200°) occurs only rarely if ϕ_{Io} is not close to 90°. When the central meridian longitude and Io's position are simultaneously favorable, the probability of emission approaches 1.0 (Table 1). The highest emission probability occurs in two configurations: $\phi_{Io} \simeq 90°$ when 100° < LCM <170° (early source) and $\phi_{Io} \simeq 240°$ when 200° < LCM < 270° (main source). There were 83 occasions in the years 1961–1964 when these two configurations existed and Jupiter was within the beam of our antennas. On 78 occasions, emission was definitely recorded. On five occasions, emission was either very weak or absent. These five occasions occurred when Jupiter was within 50° of superior conjunction. Therefore, the emission probability in favorable circumstances was at least 94 percent in the years 1961–1964.

The character of Jupiter's decametric emission spectrum has been discussed by Warwick (*2, 3*). He has shown that the spectrum depends on the central meridian longitude at the time of emission, and that many details of the spectra have from time to time reappeared over several years. Figure 2 shows six early source spectra obtained in 1962 and 1963. The intensity of the received radiation is proportional to the blackening on the record. If the interference by terrestrial sources at low frequencies and the diagonal white streaks which are interferometer fringes are ignored, there is striking similarity among the top five spectra. Of special importance is the fact that there is a drift from low- to high-frequency emission over the longitude range 90° < LCM < 130°, the prominent stub of high-intensity radiation occurring when LCM ≃ 130° to 140°, and the very long, narrow-band tail on the second and third spectra. The tail seems to become the high-frequency edge of the broad-band emission in the later phases of the fourth and fifth spectra. These are but five examples out of more than fifty which are strikingly similar and which were obtained in the past few years.

It was surprising to find that Io was at 90° ± 20° at the time of each and every one of the more than 50 emissions which clearly have the character of the spectra of the top

Table 1. Emissions when the Io position was most favorable, 1961–1964. All figures are number of times.

Recordings	1961	1962	1963	1964
Early source. ϕ_{Io}=90° when 110° < LCM < 170°				
Favorable circumstances	22	20	21	23
Jupiter in antenna beam	9	8	13	13
Emission definitely recorded	9	7	13	12
Weak emission probably recorded	0	0	0	1
No emission recorded	0	1	0	0
Main source. ϕ_{Io}=240° when 210° < LCM < 270°				
Favorable circumstances	20	22	22	20
Jupiter in antenna beam	8	7	14	11
Emission definitely recorded	7	6	14	10
Weak emission probably recorded	1	0	0	0
No emission recorded	0	1	0	1

five of Fig. 2. Of the rare early source emissions which occurred when Io was not close to 90°, the spectrum at the bottom of Fig. 2 is one with a character most nearly resembling the Io-related events exemplified by the top five. Even so, this spectrum is not strikingly similar to the Io-related spectra. Furthermore, no emission with a spectrum similar to the Io-related spectra of Fig. 2 has been recorded when the central meridian longitude was outside the range of 90° to 190°.

The details of the spectrum of the early-source emission appear to depend on the exact position of Io within its effective range. Below each of the spectra in Fig. 2 there is an arrow indicating the point where Io reached 90°. The emission started at "early" Jupiter longitudes if Io reached 90° "early." The prominent stub of the topmost spectrum occurs at LCM $\simeq$ 120° and seems to be heading toward a frequency higher than 41 Mc/sec, but some mechanism seems to cut off the emission at about 39 Mc/sec. The second spectrum shows a stub at LCM $\simeq$ 130°, and a tail which reaches 39.5 Mc/sec. The third spectrum has a prominent stub at LCM $\simeq$ 140° and a tail reaching 37 Mc/sec, whereas the stub of the fourth spectrum occurs at LCM $\simeq$ 150° and the tail is less prominent, reaching only 32 Mc/sec. The factor which seems to determine the highest frequencies in the tails and the longitude ranges of the stubs is the position of Io at the time of emission. All of the 50 early-source spectra with similar characteristics fall in this sequence according to the Io position at the time of emission.

The spectra of the main source are not as rich in identifiable details, but the overall structure and a few details of main peak emissions are related to the exact position of Io in the range 225° < ϕ_{Io} < 255°. Some of the third-source spectra (280° < LCM < 360°) are Io-related and occur when $\phi_{\mathrm{Io}} \simeq$ 240°. These spectra show a drift from high to low frequency (25 Mc/sec to less than 10 Mc/sec) over an interval of about 2 hours. Similarly, most fourth-source spectra (0° < LCM < 100°) are Io-related and occur when $\phi_{\mathrm{Io}} \simeq$ 100°. These spectra are narrow-band (about 2 to 3 Mc/sec), and drift from low to high frequency (8 to 18 Mc/sec) over a time span of about 90 minutes.

The earliest spectrum recorded by the Boulder spectrograph which definitely is Io-related was the early source event on 8 May 1960.

The plane containing Jupiter's rotational and magnetic axis is here referred to as the "magnetic axis plane" (Fig. 3). It intersects the earth when the LCM $\simeq$ 190° to 200° (*4, 5*). I will use the value 200° and denote that longitude by λ_{III} = 200° to indicate it independently of the earth's position (Fig. 3). In Fig. 3, a diagram of Io's position and Jupiter's magnetic axis plane when emission is most probable, Io is shown near Jupiter's magnetic axis plane for both early-source and main-source emission and is on the far side of the earth-Jupiter line in both cases.

The two parts of Fig. 3 can be used to obtain the pattern of the Io-related emission. Suppose that in the "main source" diagram in Fig. 3, there is an observer in the direction *E'*. To such an observer, the geometry is that at the start of early-source emission. However, as already mentioned, Io-related emission can be observed if Io is within a range of about ± 20° of its most favorable position, indicating an emission cone of about 40°. From these combined results, the emission pattern shown in Fig. 4 is obtained. From Table 1, both early-source and main-source emission having occurred on at least 94 percent of the occasions when the geometry was favorable, we can conclude that main-source and early-source emission occur once every 12.9 hours, near the time when Jupiter's magnetic axis sweeps past Io. Emission is observed on the earth only if the earth is situated in one of the cones shown in Fig. 4.

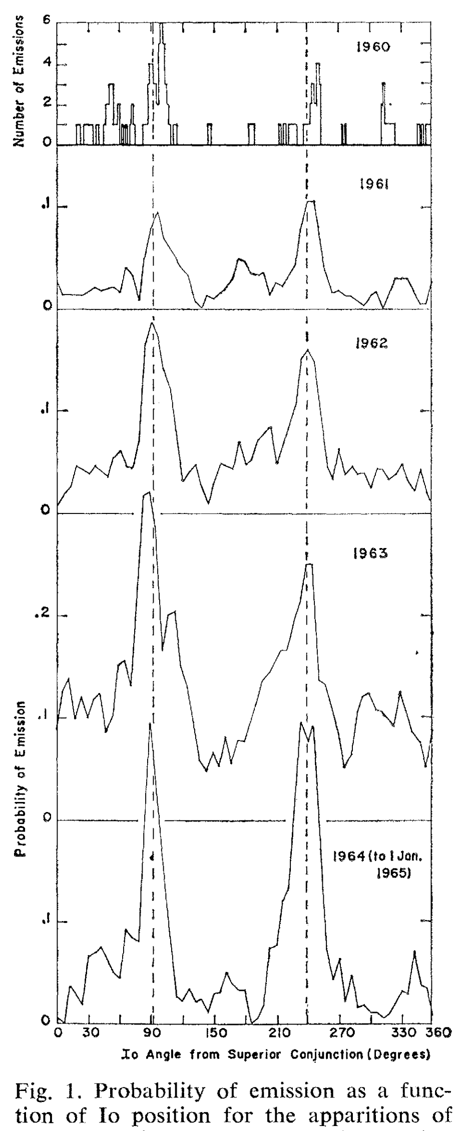

Fig. 1. Probability of emission as a function of Io position for the apparitions of 1960 through most of 1964. The number of Jupiter events included: 243 in 1961, 353 in 1962, 429 in 1963, and 181 in 1964 (to 1 January 1965).

The sequence of early-source spectra (Fig. 2) and analogous sequences of spectra characteristic of the other sources show that the spectra received on the earth are very sensitive to the exact position of Io when Jupiter's magnetic axis plane sweeps by. Features of the spectra appearing with Io at one position may not appear if Io is but 10° away. Thus the type of spectrum received depends critically on the position of the earth within the emission cones shown in Fig. 4, and the emission producing the details of the spectrum is highly directive. The maximum frequency recorded also depends on the position of the earth in the cones. For instance, the maximum frequency received if the earth is located near the left side of the early source cone (Fig. 4) is about 39 Mc/sec, whereas the maximum frequency is about 32 Mc/sec if the earth is to the right of the cone center. This implies that high-frequency emissions are directed into narrower cones than low frequency emissions are.

Emission into the main-source cone occurs as the magnetic axis plane swings from 60° ahead of Io to about 20° past Io. Emission into the early-source cone occurs as the magnetic axis plane swings from 20° ahead of Io to about 70° past Io. Thus, providing the emission pattern is independent of the sun's position, there is an overlap of about 40° when radiation is simultaneously emitted into the early-source cone and the main-source cone. This range of magnetic axis position is shaded on Fig. 4. Thus, the regions on Jupiter which are responsible for early-source emission and Io-related main-source emission are close together (within about 40° of longitude), or are overlapping. These source regions are near $\lambda_{III} \sim 200°$, and may be on opposite sides of $\lambda_{III} = 200°$. This is perhaps the first evidence of the position of the source regions on Jupiter, and since they are close together, one might consider them a single source region. A single source region has been postulated before (6).

Figure 4 shows the Io-related emission pattern in the ecliptic plane. (Jupiter is always close to the ecliptic, its rotational axis is nearly perpendicular to the ecliptic, and Io's orbital plane is nearly parallel to the ecliptic.) There

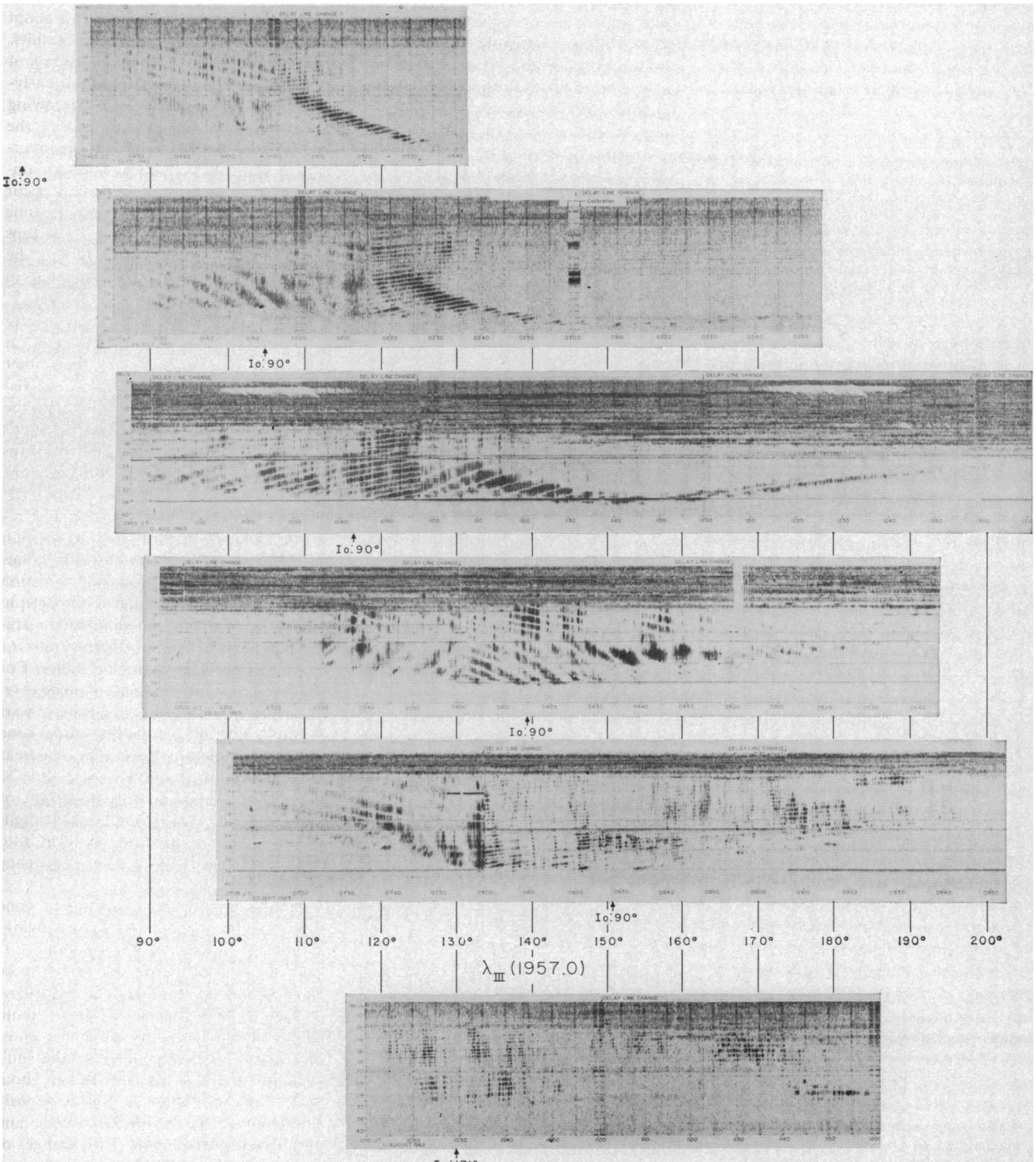

Fig. 2. Spectra of the "early source" showing the relative position of Io. In each of the spectra, the abscissa is time (or, equivalently, LCM at the time of emission) and the ordinate is frequency, from 7.6 Mc/sec at the top to 41 Mc/sec at the bottom.

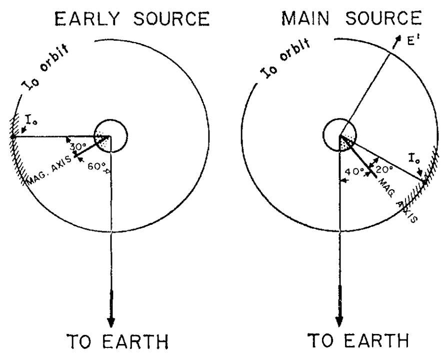

Fig. 3. Relative positions of Io and the plane of Jupiter's rotational and magnetic axes at the time of "early-source" and "main-source" emission. The position of Io and the plane of the magnetic axis at times of most probable emission are shown by the dot and line, respectively. Cross hatching and shading show range of Io position and magnetic axis position when there is Io-induced emission.

is no observation of the emission pattern in other directions, but the emission is unlikely to be confined to a region near the ecliptic; probably the pattern is some kind of conical sheet. The conical sheet intersecting the ecliptic plane gives the emission cones shown in Fig. 4. We will probably have to await a space probe to the vicinity of Jupiter before the total emission pattern can be determined.

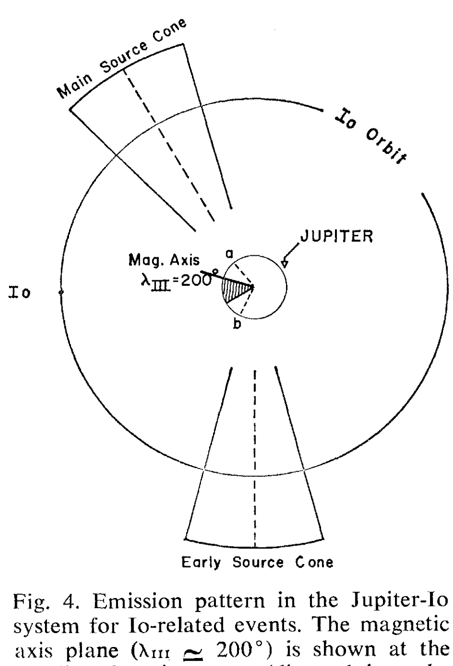

Fig. 4. Emission pattern in the Jupiter-Io system for Io-related events. The magnetic axis plane ($\lambda_{III} \simeq 200°$) is shown at the middle of main-source (directed into the "main-source cone") and at the start of early-source emission (directed into the "early-source cone"). The limits of the magnetic axis position are depicted, *a* at the start of main-source emission, and *b* at the end of early-source emission. The range of simultaneous early- and main-source emission is shown by the shading.

The most probable explanation for the Io effect on Jupiter's radio emission is that Io disturbs the orbits of particles trapped on nearby field lines of Jupiter's magnetosphere, causing them to precipitate into Jupiter's atmosphere or ionosphere where they generate the radio emission. The emission is highly directive, and is received on the earth only if the earth is within the emission pattern. The narrow-band features of the emission are consistent with the hypothesis that a small group of field lines in Io's vicinity are disturbed; however, the broad-band emission often present implies that field lines are disturbed over a fairly wide longitude range, a fairly thick L-shell, or both. The implications of Fig. 4, together with similar implications from third-source and fourth-source emissions, are that Io can induce emission into the ecliptic plane when Io is over the hemisphere $110° < \lambda_{III} < 290°$. No emission is induced into the ecliptic when Io is over the other hemisphere, an implication that any emission induced by Io when it is over that hemisphere ($290° < \lambda_{III} < 110°$) goes into a sheet which does not intersect the ecliptic. Together with the observation that Jupiter's dipole is tilted toward the earth when the LCM ~ 200° (*5*), this implies that Jupiter's dipole is also displaced; for otherwise we should observe emission with characteristics similar to the early source (for example) when Io is symmetrically situated over the other hemisphere. A displaced dipole has previously been postulated by Warwick (*3*), and observed by Berge and Morris (*7*).

The relation between Io-related and Io-independent emissions is not clear. Since both types of emission have many characteristics in common, it is unlikely that they are generated by different emission processes. Perhaps Io-independent emissions are due to particles disturbed by a different mechanism, are generated on a different L-shell, or are generated on field lines leading to a different longitude region on Jupiter. Warwick (*8*) has suggested that so-called Io-independent events may be generated by Io, but that there is much broader beaming of the resultant emission. Alternatively, the longitude range affected by the Io disturbance may occasionally be large, perhaps because the disturbance at a given longitude decays with a time constant of several hours.

It is difficult to understand how Io's influence can extend to a large distance from its surface. Its gravitational force is small compared to Jupiter's only 0.1 of Jupiter's radius (R_J) from Io. Its motion through Jupiter's field lines is sub-Alfvenic, so that an ordinary Mach-type shock wave will not exist. A possible agent to extend Io's influence is a magnetic field. If Io has a magnetic moment equal to the earth's magnetic moment, Io's field will be confined by Jupiter's field to about 0.2 R_J of Io's, although Jupiter's field lines will be distorted at a distance several times greater than 0.2 R_J, on the assumption that Jupiter's magnetic moment is about 4×10^{30} gauss cm^3 (*3*). Io need not have an internal magnetic field source to have a magnetic moment; it may contain a quantity of highly permeable material to interact with Jupiter's field. Or a magnetospheric tail may be formed near Io in a manner similar to that suggested by Gold (*9*) for the moon, where the motion of the body through a plasma and magnetic field induces the magnetospheric tail.

Even if Io influences only a small region near its position, it will still affect particles in a fairly thick L-shell if Jupiter's magnetic dipole is displaced horizontally (perpendicular to the rotational axis). For instance, if Jupiter's dipole is displaced 0.3 R_J away from the rotational axis, in the course of one Jupiter rotation Io will affect particles in the shell $5.6 < L < 6.2$. Berge and Morris' (*7*) observations indicate the dipole is displaced 0.5 R_J along the rotational axis and about 0.4 R_J horizontally. Warwick (*3*), by a different line of reasoning, derived a vertical displacement of 0.7 R_J and a horizontal displacement of about 0.2 R_J. Therefore, a horizontal displacement of 0.3 R_J is not unreasonable, and the affected L-shell would be 0.6 R_J thick.

Though such a displaced dipole may help explain some of the narrow-band, drifting features of the spectra, it does not explain the Io-related broad-band emission or the simultaneous emission of early- and main-source spectra with largely different character. I suggest that the broad-band emission provides evidence that Io's influence is not confined to its near vicinity, but influences a region a few tenths of a Jupiter radius in thickness or perhaps 40° wide in longitude. A magnetic field or magnetospheric tail at Io is the probable agent to extend the influence.

The Io effect enables us to predict when most of the major radio events will occur, the duration and highest frequency of emission, and even the character of the emission spectrum. Quiet times can also be predicted. There is some evidence for year to year changes in the character of the emission and Io effect. Emission in 1964 was more patchy, weaker, and less frequent than in 1963 or 1962, and the Io effect (Fig. 1) was stronger in 1964. The significance of these changes has yet to be determined.

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Phase Relations in the System $Na_2Si_2O_5$–SiO_2

Abstract. *A new compound, $Na_6Si_8O_{19}$, is shown to be a thermodynamically stable phase in the Na_2O–SiO_2 system at 1 atmosphere. The new compound melts incongruently to SiO_2 (quartz) and liquid at 808° ± 2°C, and it disproportionates to $\beta Na_2Si_2O_5$ and quartz at 700° ± 10°C.*

The Na_2O–SiO_2 system has been studied by Kracek (*1*) who found $Na_2Si_2O_5$ as the only crystalline phase coexisting stably with quartz (SiO_2). Because of the thoroughness of this study it has usually been accepted as definitive. However, another silica-rich phase, $Na_2Si_3O_7$, has been reported (*2*). It was obtained by prolonged crystallization of a Na_2O–SiO_2 glass containing 75 percent SiO_2 (all percentages are mol percent). The reported x-ray powder diffraction data are certainly sufficient to establish that the mixture is distinctly different from any of the known polymorphs of SiO_2 and $Na_2Si_2O_5$. However, no proof of its formula or thermodynamic stability can be adduced from the data.

In our study, a compound which fitted Matveev's description (*2*) was readily prepared by devitrification of Na_2O–SiO_2 glasses containing 75 percent SiO_2. A few representative runs are shown in Table 1. Our glasses, like Kracek's, were prepared from reagent-grade laboratory chemicals, fused several times in platinum crucibles and checked for homogeneity. If random samples taken from a given preparation had a constant refractive index (± 0.001), the preparation was accepted as homogeneous. The composition of homogeneous glasses was checked by comparison of their refractive indexes with the values given in a critical compilation (*3*). The composition of crystalline starting materials was checked by chemical analysis for sodium as well as by fusing portions to a glass and measuring their refractive indexes. The two independent means of checking the composition agreed to within 0.5 percent Na_2O of the Na_2O composition stated in Table 1.

Small samples of the glasses and crystalline starting materials were crystallized in controlled temperature furnaces for periods ranging from several hours to 30 days (Table 1). At temperatures just below the solidus, the crystalline starting materials reacted rapidly and completely, giving relatively coarse-grained crystalline aggregates. Petrographic and x-ray powder diffraction examination showed that glass starting materials gave persistent metastable phase assemblages; $Na_6Si_8O_{19}$ was only one of the crystalline products encountered. However, crystalline starting materials containing 73 percent SiO_2 yielded a single homogeneous crystalline phase. Crystalline starting materials containing 75 percent SiO_2 gave considerable quartz as a second crystalline phase; those containing 72 percent SiO_2 gave a small amount of sodium disilicate ($Na_2Si_2O_5$) as a second crystalline phase. This fixes the composition of the phase as approximately 73.0 ± 1 percent SiO_2 and suggests that the phase must have a virtually constant composition in the temperature range 780 to 800°C. Matveev's proposed $Na_2Si_3O_7$ formula (75 percent SiO_2) is thus incorrect.

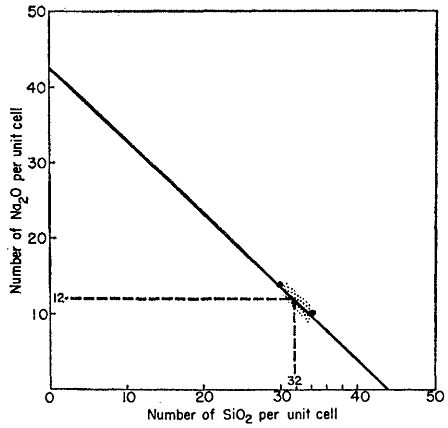

Fig. 1. Unit-cell contents of some hypothetical sodium silicates having a density of 2.50 and a unit-cell volume of 1768Å³. The stippled area is bounded top and bottom by limits representing a possible error in the density of +0.05 and −0.05, respectively. Cell contents which are consistent with space group requirements and also lie in the stippled area include the $12Na_2O \cdot 32SiO_2$ formula whose intercepts are shown by dashed lines and two other compositions shown by solid dots. These have as intercepts $14Na_2O \cdot 30SiO_2$ and $10Na_2O \cdot 34SiO_2$ and have SiO_2 contents of ~ 68 and ~ 77 percent respectively. The $12Na_2O \cdot 32SiO_2$ formula is thus the only ratio fitting all the data (see text for discussion).

The formula was determined more exactly as follows. Single crystals were grown by cooling a 72.5 percent SiO_2 liquid through the interval between liquidus and solidus. Comparison of

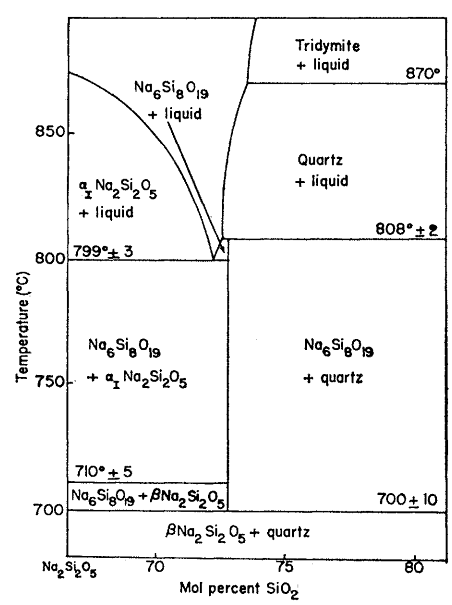

Fig. 2. A portion of the equilibrium phase diagram for the system $Na_2Si_2O_5$–SiO_2, showing a stability field of the $Na_6Si_8O_{19}$ phase. Liquidus data for runs that do not appear in Table 1 are taken mainly from Kracek (*1*).