POLARIZATION OF JUPITER'S DECAMETRIC RADIO BURSTS

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Abstract

Polarization measurements of Jupiter's decametric radio bursts were made by using the spectro–polarimeter at a frequency above 20 MHz. In the analysis of axial ratio (γ), the effect of reflected waves from ground was evaluated as a factor which modulated original γ. 20 Io–related and 2 non–Io radio storms show following polarization characteristics:
1) Right–handed (RH) elliptical polarization is dominant in Io–related storms and the mean value of the AR for RH storms is -0.31 ± 0.09 (standard deviation). 2) Io–A and Io–B storms indicate a significant difference in their γs; i.e. -0.35 ± 0.08 and -0.26 ± 0.06 for RH Io–A and RH Io–B storms, respectively. 3) Non–Io–A storms indicate somewhat more circular polarization than Io–related storms.

It is not enough to explain the origin of elliptical polarization by the simple combination of present Jupiter's magnetic field models and an oblique emission from the region where the local cyclotron frequency is close to the wave frequency, nor is mutual coupling between R–X and L–O mode waves during the propagation. It is necessary to make further investigations for magnetic field configurations and/or wave coupling conditions along ray paths.

1 Introduction

Polarization of Jupiter's decametric radio bursts is one of the important characteristics to clarify the unknown generation mechanisms and poorly known plasma properties in and near the source regions. Many observations have been tried to reveal the polarization characteristics since the early period after the discovery of the bursts [Carr et al., 1983]. Recently well developed analyses by using the complete Stokes polarimetry were reported by Lecacheux et al. [1991] and Dulk et al. [1994]. Their major findings are as follows: 1) The polarization fraction m is quite large. 2) The polarization is always elliptical. The absolute values of the axial ratio $|\gamma|$ are generally less than 0.6. 3) Io–A storms show more circular polarization than Io–B storms. 4) Almost all events show nearly constant

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polarization as a function of frequency and time, even in the storms which last for a few hours.

The purpose of this paper is to report an investigation of polarization characteristics which were made as quantitatively as possible with ground–based measurements. For the purpose, we particularly took account of a factor which was expected to modulate the original polarization; i.e. the interference caused by reflected waves from ground. In section 2, the observation system is introduced. We show the effect of the interference by reflected waves in our observation system and the estimation method of γ under the effect in section 3. The observational results and brief interpretation for the origin of elliptical polarization are given in section 4 and 5, respectively.

2 Spectro–polarimeter

Polarization measurements were made by using the spectro–polarimeter at the Zao site of Tohoku University (E 140°34', N 38°6', H 420m). The front–end consists of orthogonally crossed log–periodic dipole antennas and a hybrid circuit for dividing a received signal into right–handed (RH) and left–handed (LH) circular polarized components. The antennas are steerable and mounted on a tower at the height of 15 m. The half power beam widths of one antenna are 65° and 130° in horizontal and vertical planes, respectively. The back–end consists of a 2–stage super–heterodyne receiver and an exclusive video tape recorder of 2 MHz band width to recode RH and LH signals alternately every 1/60 sec. The center frequency is tunable at a frequency range of 20 $\sim$ 40 MHz by changing the 1st local frequency of the receiver. The recoded signals are detected with a spectrum analyzer at a frequency resolution of 30 kHz and at the maximum sweep rate of 2 MHz/2msec. The detected signals are digitized with a 8 bits A/D converter and finally used for calculating the axial ratio γ. The resolutions of the γ in this study are 30 kHz at a frequency domain and 100msec at a time domain. The error of γ caused by the instrumental specifications is expected to be $-0.08 \sim +0.03$ in case of $|\gamma| = 0.3$ for the worst.

3 Axial ratio and the modulation caused by reflected waves

In this study, observed γs were calculated on an assumption that the polarization fractions (m) of the observed radio bursts were always equal to 1. The assumption is based on the observational result studied by Dulk et al. [1994]; i.e., the m of Jupiter's radio bursts is generally a large value. An observed γ was actually calculated by

$$\gamma = \frac{(L_J - L_{background}) - (R_J - R_{background})}{(L_J - L_{background}) + (R_J - R_{background})} ,$$

where L and R are the amplitude of LH and RH signals, respectively, and the suffix J denotes Jupiter's radio bursts.

There is no signal which was sampled just simultaneously at RH and LH channels, because the spectro–polarimeter recorded RH and LH signals alternately. In order to minimize the

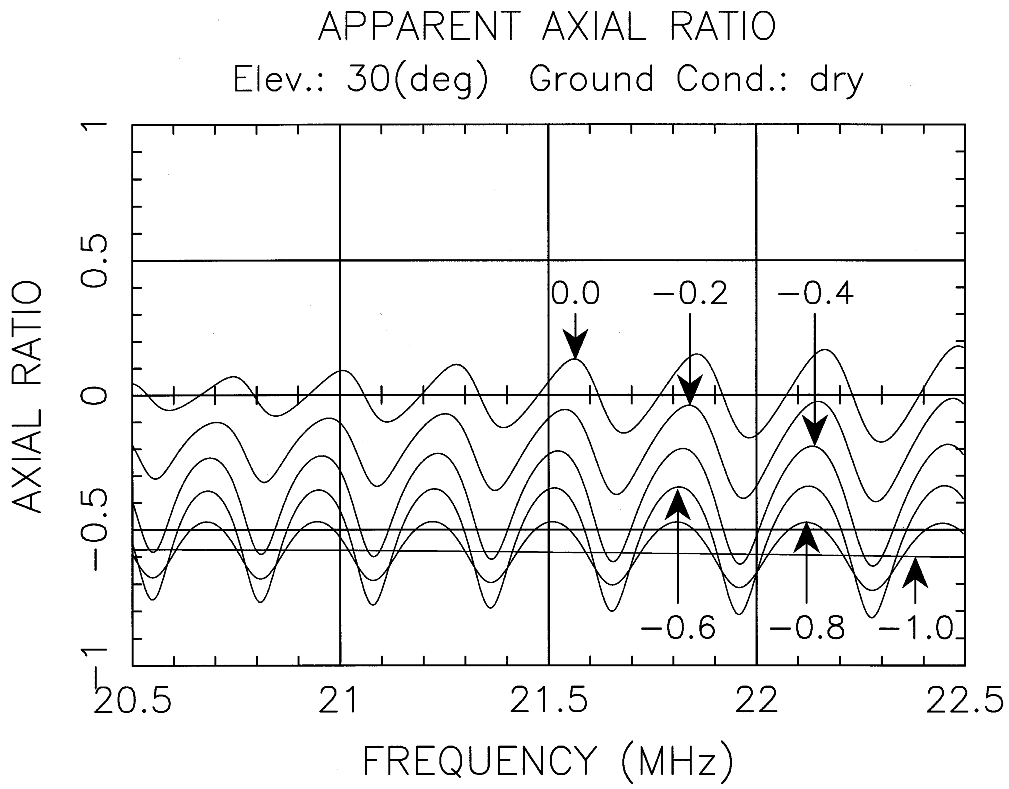

Figure 1: Modulation pattern of axial ratios caused by the Faraday rotation. The actual axial ratios are set from −1.0 to 0.0 at every 0.2 step. The total Faraday rotation angle is set at 7π for the 2 MHz bandwidth.

effect in the estimation of γs, we selected the bursts which showed no significant change in their polarization characteristics for at least 100 msec.

Our antennas have some sensitivities for a reflected wave from ground besides a direct–coming wave because of their broad beam widths. This leads to the modulation of observed γs. The reflection coefficients for vertical and horizontal components of radio waves differ in both the phase and the amplitude. The degree of the modulation depends on how a direct–coming wave consists of horizontal and vertical components, that is, depends on the value of the γ and the direction of the axes of the polarization ellipse. Since Faraday rotation generally occurs in Jupiter's radio bursts because of their elliptical polarities, the degree of the modulation changes quasi–periodically as the Faraday rotation angle changes with the frequency. In our measurements, this leads to a quasi–periodical variation of observed γs. In Figure 1, we show an example of the modulation which is calculated for several values of γs under the conditions of actual observations. The degree of the modulation also depends on the elevation angle of Jupiter.

An original γ is derived by comparing the observed γ with modeled γs which are calculated from the synthesis of direct–coming waves and reflected waves, and by selecting the fittest γ as the original one. We show an example of the reduction of γ for an Io–A radio storm in Figure 2. In this case, the derived γ is -0.35.

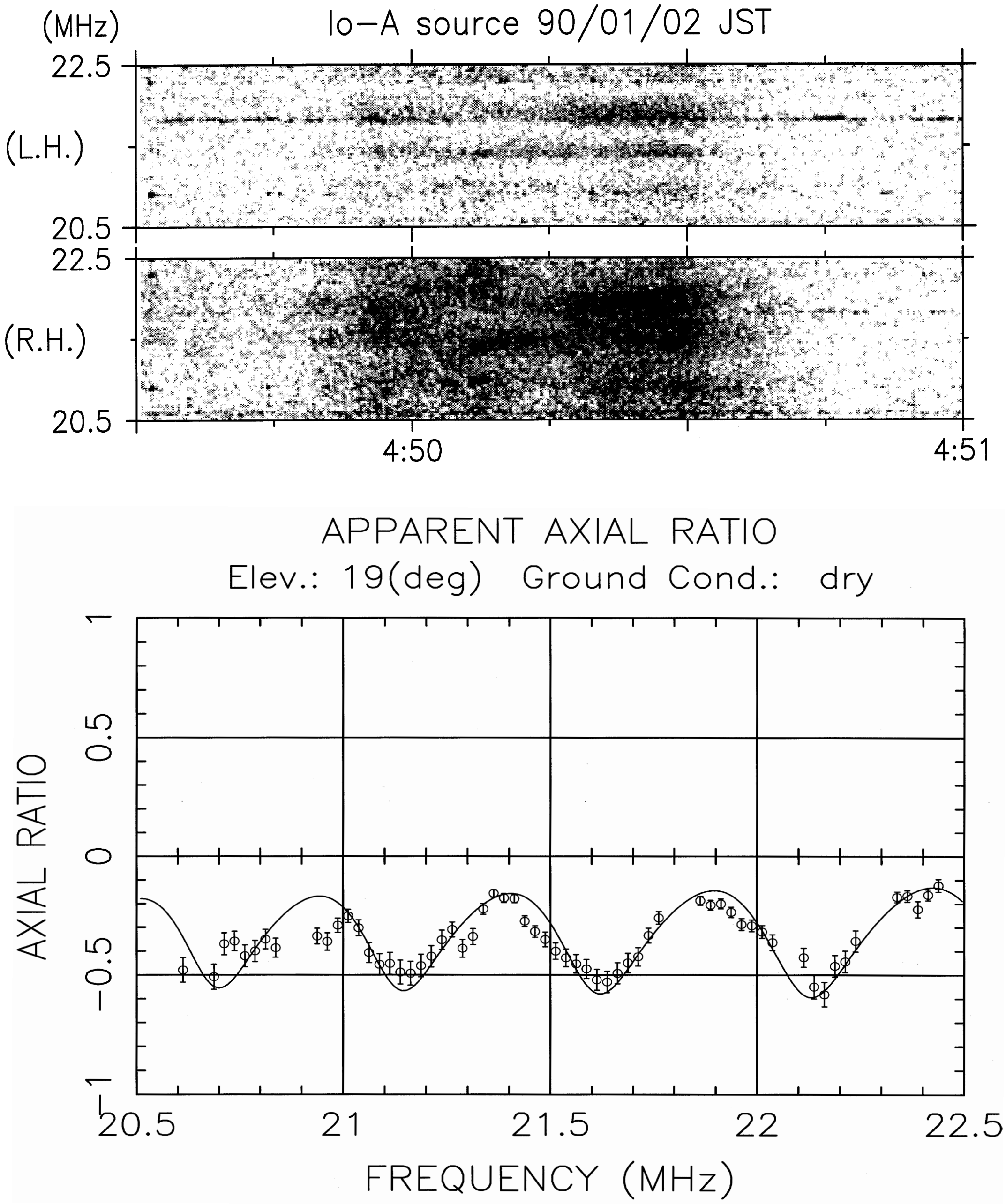

Figure 2: Upper panel: Dynamic spectra of the Io–A radio storm observed on Jan. 2, 1990. Bottom panel: Observed axial ratios (open circle) and fitted axial ratios (solid line). The observed axial ratios are indicated with vertical bars of twice the standard deviations.

4 Observational results

Polarization measurements were made for 20 Io–related and 2 non–Io–A radio storms during November 1987 $\sim$ February 1990 at a frequency of 20.5 $\sim$ 25.5 MHz. The summary plot of analyzed γs of 39 events in 22 radio storms is shown in Figure 3. Each γ was estimated with the same procedure as mentioned in the previous section and on the assumption of $m = 1$. 34 events in 36 Io–related events and all of 3 non–Io–A events showed RH elliptical polarization. The mean value of γs for RH Io–related events is -0.31 ± 0.09 (standard deviation), while, that of non–Io–A events is -0.43 ± 0.04. There is a significant difference in the mean value of γs for RH Io–A and RH Io–B events; i.e. -0.35 ± 0.08 and -0.26 ± 0.06 for Io–A and Io–B events, respectively. The similar difference of γs between RH Io–A and RH Io–B events is reported by Green and Sherrill [1969], Lecacheux et al., [1991], and Dulk et al., [1994].

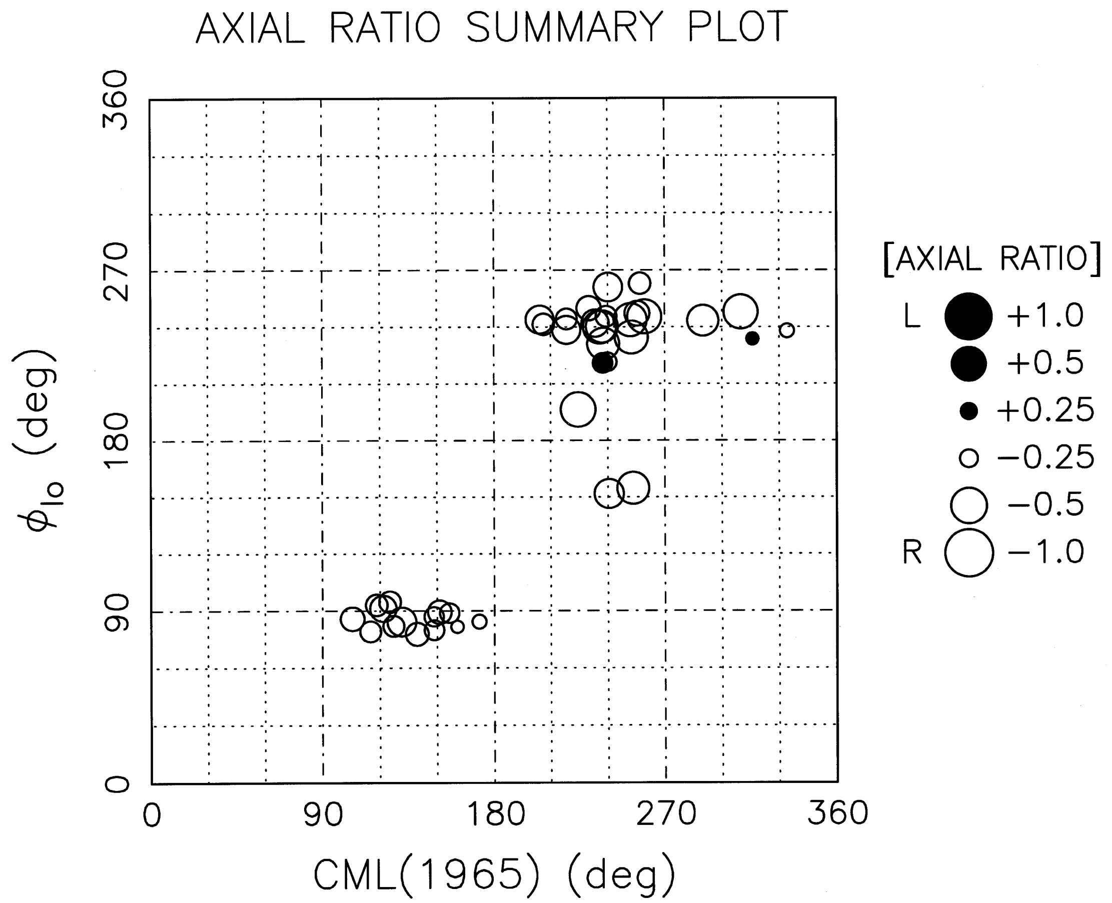

Figure 3: Summary plot of observed axial ratios. Open and solid circles denote the axial ratios of RH polarization storms and those of LH polarization storms, respectively.

5 Origin of the elliptical polarization

As mentioned by Lecacheux [1988], the elliptical polarization of Jupiter's decametric radio storms is a unique characteristic in planetary radio emissions. In order to investigate the origin of the elliptical polarization, we examined two possibilities. One is a mutual coupling of R–X and L–O mode waves during the propagation to an observer, the other is an oblique emission at the source region.

Mutual coupling during the propagation

If there is large mutual coupling between one free–space mode wave and another free–space mode wave during the propagation, the observed γ is different from the original one at Jupiter.

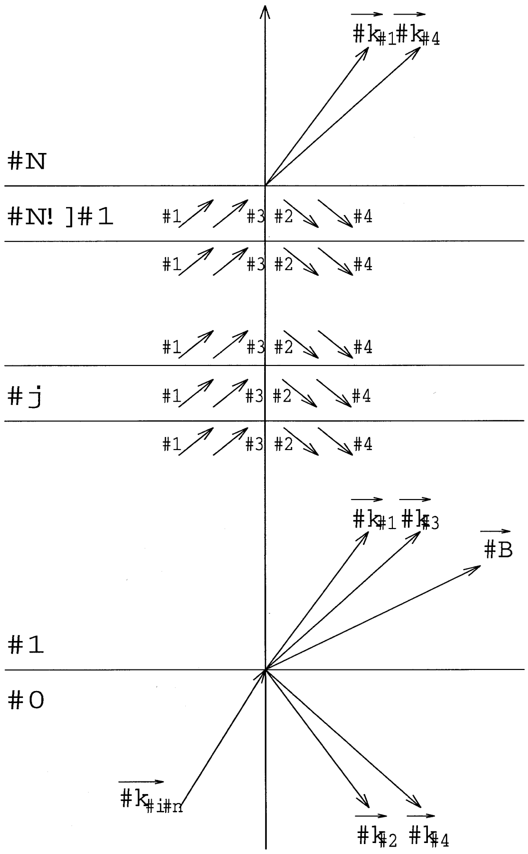

Figure 4: Multi–layer model of a plasma space. The suffix numbers $1 \sim 4$ of $\vec{k}$ denote transmitted R–X, reflected R–X, transmitted L–O, and reflected L–O mode waves, respectively.

The degree of the mutual coupling was evaluated by using the full wave analysis for incidence of R–X and L–O mode waves to multi–layered static magnetized plasma space which was modeled after actual plasma conditions along the propagation to an observer (Figure 4). We divided the path into three regions; i.e. the Jovian plasma space, the interplanetary plasma space and the terrestrial plasma space, and calculated energy conversion rates from an incident wave to transmitted waves and reflected waves in each region. Parameters of the full wave analysis are summarized in Table 1. An example of the results of the full wave analysis is shown in Figure 5. The largest mutual coupling from an R–X mode wave to an L–O mode wave is expected to occur in the terrestrial plasma space, however, the energy conversion rate from an R–X mode wave to an L–O mode wave is at most 10^{-5}. The value corresponds to ~ 0.01 in an axial ratio. The result is nearly the same as the case of the incidence of an L–O mode wave. The mutual coupling has, therefore, little effect on the original polarization at Jupiter. There should be the origin of the elliptical polarization in and/or near the source region.

Oblique emission at the source region

An explanation of the origin of the Io–related RH elliptical polarization was proposed by Lecacheux et al. [1991] and Melrose and Dulk [1991] as follows; i.e. 1) radio bursts are

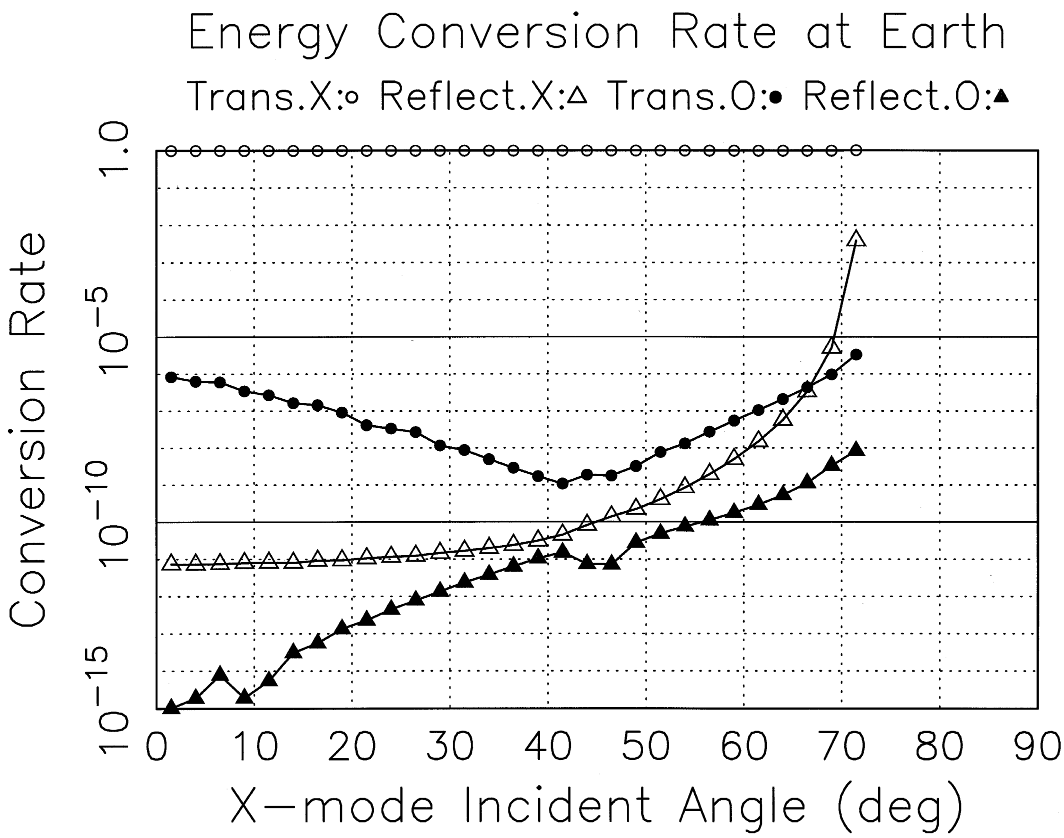

Figure 5: Energy conversion rates calculated with the full wave analysis for the terrestrial plasma space model. The incident wave is an R–X mode wave at a frequency of 20 MHz. Open circles, solid circles, open triangles and solid triangles denote calculated energy conversion rates for transmitted R–X, transmitted L–O, reflected R–X, and reflected L–O mode waves, respectively. The angle between the local magnetic field direction and the normal of multi–layers is set at 45°.

radiated as R–X mode waves from the northern hemisphere of Jupiter, 2) each burst is originally generated as elliptical polarization state, and 3) the plasma density in and near source regions is quite low, therefore, the original polarization is maintained throughout the propagation to observers. Following their explanation, γ equals to $\cos\theta$, where θ is

Table 1: Parameters of the full wave analysis.

plasma space	parameter (maximum value on ray paths)	
	magnetic field strength	electron density
Jovian plasma space	8G	2×10^5cm^{-3}
Interplanetary plasma space	5γ	5cm^{-3}
Terrestrial plasma space	0.4G	5×10^5cm^{-3}
Segment length for every calculation step	$1/5\cdot\lambda$	
Accuracy in an energy conversion rate	10^{-9}(typical)	

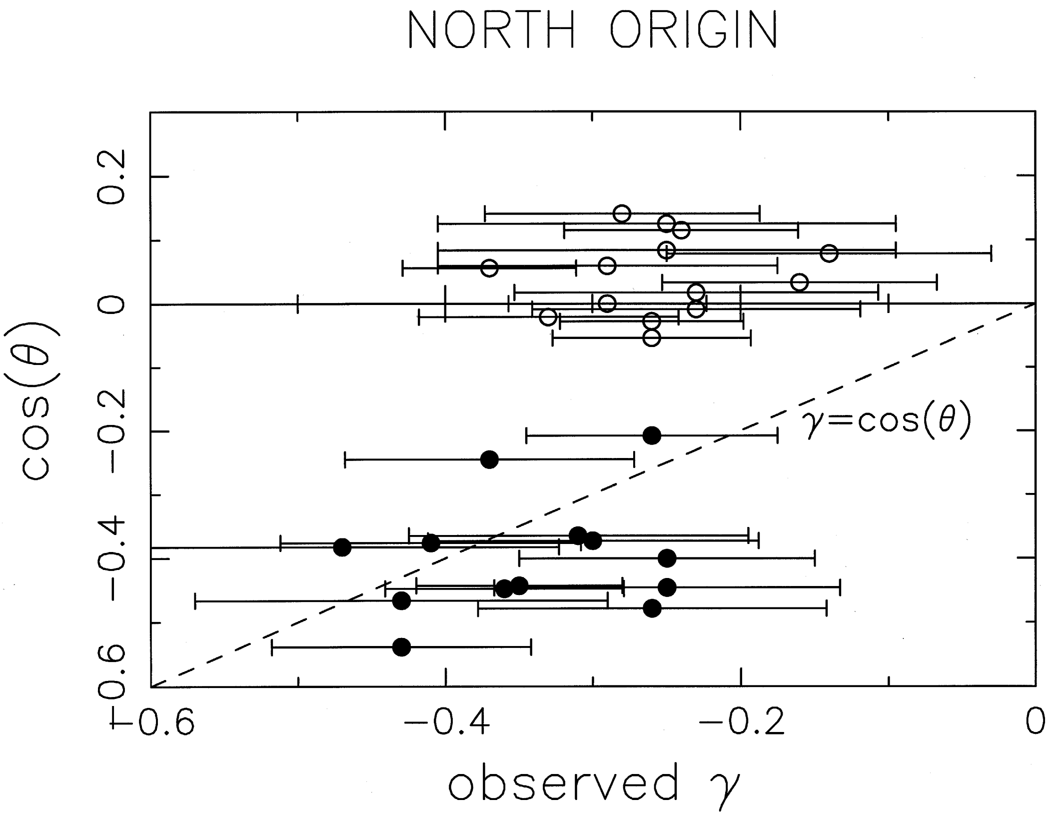

Figure 6: Relation of $\cos\theta$ *vs. observed axial ratios* γ*. Open and solid circles denote* $\cos\theta$*s for Io–A events and those for Io–B events, respectively. Horizontal bars denote twice the standard deviations.*

the angle between the direction to the earth and the local magnetic field direction in the source region.

We compared our observational result of γs with $\cos\theta$ to examine the explanation. The plots of $\cos\theta$ to the observed γ relation are shown in Figure 6, where θ is calculated by using the GSFC–O_4 model [Acuña and Ness, 1976b] and on the assumption that the source locates at the position of $f = f_g$ in the northern Io flux tube (IFT). Here f_g is a local gyro–frequency. We took into account of the delay angle between the predicted IFT and the apparent source field line caused by one way propagation time of Alfvén wave from Io to the source region and by the refraction of Alfvén wave in the Io plasma torus

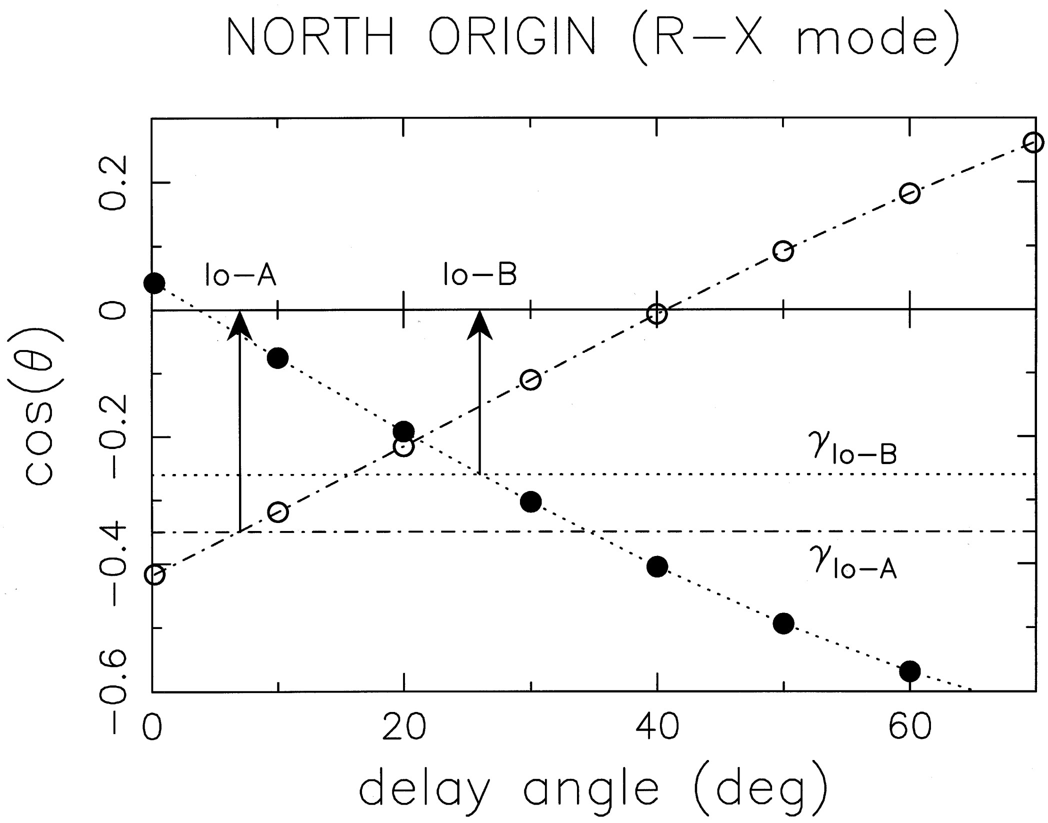

Figure 7: Plot of $\cos\theta$ *as a function of the delay angles. The symbols are the same as in Figure 6.*

[Bagenal, 1983]. The data of Io–A events (∘) indicate some correlation with $\gamma = \cos\theta$ (dashed line), however, that of Io–B events (•) indicate little correlation.

This result shows that it is hard to accept their explanation just as they mentioned, and suggests other possibilities as inferred by Melrose and Dulk [1991]. One is related to the ambiguity of source locations of Io–related radio bursts which is caused by uncertainties in Jupiter's magnetic field models and/or in paths of energy injection from Io to source regions. Genova and Aubier [1985] and Genova and Calvert [1988] showed that there were apparent angle delays up to 70° between the apparent source field line of Io–related radio bursts and the IFT predicted with the O_4 model. We calculated $\cos\theta$ as a function of the delay angle (Figure 7). The source positions and the θs were calculated by using the previous hypotheses; i.e. 1) through 3). The $\cos\theta$s are equal to observed mean γs in case that delay angles are about 7° and 26° for Io–A and Io–B radio storms, respectively. This result requires further investigations to explain the reasons why the delay angles are different between Io–A and Io–B radio bursts, and between our result and the results of Genova and Aubier [1985] and Genova and Calvert [1988].

There is another possibility based on a hypothesis that the wave mode coupling is weak in and near the source regions instead of the strongly coupled condition as discussed above. Cohen [1960] derived a "transitional" frequency, f_t, as a critical value which divided the degree of mode coupling condition; i.e., when a wave frequency f is much greater than f_t, the modes are strongly coupled, while, they are weakly coupled when $f \ll f_t$. Hashimoto and Goldstein [1983] studied the occurrence probability of Io–related radio bursts by using a ray–tracing method, and showed that the radio bursts were radiated quasi–perpendicular to the local magnetic field. In case of such a "quasi–transverse" propagation, the f_t [Hz] is defined as

$$f_t^4 = 10^{17} NSB^3 \ ,$$

where N, S, B are the number density of electrons $[cm^{-3}]$, the scale of the field $[cm]$, and magnetic field $[Gauss]$, respectively. When we consider the order of magnitude of f_t for the source region of 20 MHz radio bursts, the S and B might be taken as $1R_J = 7.1 \times 10^9 \, [cm]$, $7 \, [Gauss]$, respectively. Here we think that the N is low, but not quite a low case, say, $N = 500 \, [cm^{-3}]$. The plasma frequency to the gyro frequency ratio is 0.01:1 in this case, which is suitable for the wave generation condition by the cyclotron maser mechanism. These parameters give $f_t \simeq 100$ [MHz], which is greater than f=20 MHz. Although it is necessary to investigate the degree of mode coupling more precisely along ray paths, this order estimation suggests that there is a possibility of weak coupling condition in and near source regions, and of the polarization state changing from quasi–linear to elliptical during the propagation.