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Multiple Alfven Wave Reflections Excited by Io: Origin of the Jovian Decametric Arcs

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The recent Voyager radio astronomy measurements near Jupiter show that the Jovian decametric radiation consists of numerous discrete features called decametric arcs which are observed at all Jovian longitudes. It is generally believed that these arcs are produced by an interaction of Io with the Jovian magnetosphere. In this paper we propose that the large number of decametric arcs is caused by multiple reflections of a standing Alfven wave current system excited by Io. Estimates of the reflection coefficient at the ionosphere and other damping processes show that a large number of reflections can occur, with the Alfven wave current system possibly extending completely around Jupiter. This source geometry can account for a number of otherwise puzzling characteristics of the Jovian decametric radiation.

1. INTRODUCTION

Ever since Bigg [1964] made the remarkable discovery that Jovian decametric radio emissions are modulated by the orbital position of Jupiter's satellite Io, considerable theoretical attention has been given to the possible explanations of this interaction. In the intervening years, numerous mechanisms have been proposed to account for the observed effects. These mechanisms include the excitation of large-amplitude MHD waves by the passage of Io through the Jovian magnetosphere [*Warwick,* 1967; *Goertz and Deift,* 1973], the generation of field-aligned currents and particle beams due to the emf induced by the motion of Io through the Jovian magnetic field [*Goldreich and Lynden-Bell,* 1969] and the formation of unstable charged particle distribution functions by the absorption of trapped radiation belt particles by Io [*Wu,* 1973]. For a review of these interaction mechanisms and various radio emission processes which have been proposed, see *Smith* [1976].

The recent Voyager 1 and 2 encounters with Jupiter have provided many new observations which significantly alter our views of the basic Io interaction and the decametric emission process. The Voyager 1 pass by the Io flux tube, for example, now strongly indicates that the Io interaction consists of the generation of large-amplitude standing Alfven waves which propagate northward and southward along the magnetic field lines from Io [*Ness et al.,* 1979; *Neubauer,* 1980; *Goertz,* 1980]. Each Alfven wave is associated with a pair of oppositely directed currents which flow along the Alfven characteristics between Io and the Jovian ionosphere. Although this current loop is almost certainly the ultimate energy source of the decametric radiation, the unexpectedly high plasma density and low Alfven velocity in the Io plasma torus invalidates the simple dc circuit model used by *Goldreich and Lynden-Bell* [1969] and others. The high plasma density also makes it unlikely that large sheath electric fields, such as proposed by *Gurnett* [1972] and others, can occur in the vicinity of Io. The radio astronomy measurements on Voyager also provided the first close up high-resolution measurements of radio emissions from Jupiter. The decametric radiation observations are remarkable in that they show that the Io-modulated decametric radiation consists of many closely spaced narrow-band emissions called decametric arcs which have a distinctive arclike appearance on a frequency-time spectrogram [*Warwick et al.,* 1979*a*, *b*].

The purpose of this paper is to investigate the possibility that the multiple-decametric arc structure is produced by multiple reflections of the standing Alfven wave system generated by the motion of Io through the plasma torus. As will be shown, estimates of the reflection coefficient of Alfven waves at the Jovian ionosphere indicate that possibly up to a hundred or more reflections could occur, with the Alfven wave system extending completely around Jupiter. Estimates of the geometrical spacing of the standing Alfven waves are shown to be in reasonable agreement with the typical longitudinal spacing of the decametric arc structure. Possible mechanisms whereby the Io orbital position could modulate the intensity of the decametric radiation are also considered.

2. SURVEY OF DECAMETRIC ARC CHARACTERISTICS

Before considering the possible role of Alfven wave reflections in the generation of Jovian decametric radiation, we first review the basic characteristics and interpretation of the decametric arc structure. From ground-based observations [*Warwick,* 1967; *Carr and Desch,* 1976] it is known that the Jovian decametric radiation often consists of narrow-band emissions drifting either upward or downward in frequency. It was also found that the Io control of the emission intensity is almost completely confined to high frequencies, above about 20 MHz. Because of the much better sensitivity and frequency range the Voyager measurements now show that the decametric radiation consists almost entirely of discrete narrow-band arc structures extending from a few MHz up to about 40 MHz. Two examples of the decametric arc structure observed by Voyager 1 during the approach to Jupiter are shown in Figure 1. Typically, the arcs occur in a nested pattern with the curvature of the arcs changing slowly over a period of a few

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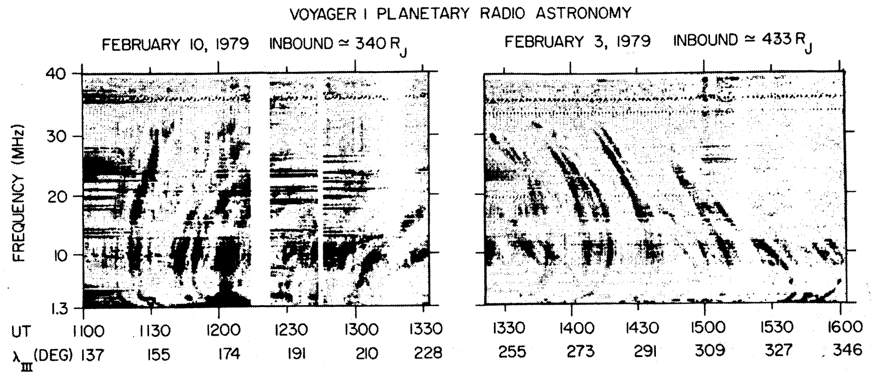

Fig. 1. Representative frequency-time spectrograms of decametric arcs observed by Voyager 1 during the approach to Jupiter (data provided by J. Warwick). Note the complex structure with arc spacings ranging from only a few minutes up to about a half an hour.

hours [*Warwick et al.,* 1979*b*]. The arcs can curve either to the right or to the left. The arcs associated with the early source around $\lambda_{\rm III} \simeq 140^\circ$ open toward increasing time (vertex-early) and the arcs associated with the main (or late) source around $\lambda_{\rm III} \simeq 280^\circ$ open toward decreasing time (vertex-late). At low frequencies, below about 12 MHz, arcs can be seen at essentially all Jovian longitudes. During one rotation of Jupiter as many as 100 separate arcs can sometimes be distinguished. The arc spacing is clearly not random but shows an underlying systematic structure, often consisting of closely spaced pairs or groups separated by time intervals ranging from a few minutes to 30 min. The February 3, 1979, event in Figure 1, for example, shows a major spacing between the groups of arcs of about 25 min. A somewhat similar spacing can be identified in the February 10, 1979, event. The width of an individual arc is typically very small, only about 3min, and appears to be nearly independent of frequency.

As pointed out by *Warwick et al.* [1979*b*] the repeatability of the arc pattern argues strongly that the shape of the arc structure is geometrical in origin. According to their discussion, each arc consists of radiation from a continuous distribution of frequencies along a single magnetic field line, with the radiation being emitted in a conical emission pattern as shown in Figure 2. Only when the geometrical orientation is such that the observer is located on or near the emission cone will the radiation be detected. Measurements of the polarization and upper cutoff frequency strongly indicate that the radiation is emitted in the right-hand mode at a frequency slightly above the electron gyrofrequency. Since the emission frequency is thereby uniquely determined by the position along the magnetic field line, the frequency detected by an observer will correspond to the point along the field line which has an emission cone intersecting the observer's position. For an observer near the equatorial plane it can be shown that there are two frequencies, f_3 near the planet and f_1 farther out along the field line, which can be detected at any given time. As illustrated in Figure 2, this double-valued solution coupled with the longitudinal motion of the source field line accounts for the basic arc structure. In general, the vertex-early arcs arise from source field lines to the right of the planet as viewed by the observer, and the vertex-late arcs arise from field lines to the left of the planet. Using a simple dipole field model and straight-line ray paths, we have demonstrated that reasonable fits can be obtained if the emission cone angle α generally decreases with increasing altitude, varying from about 85° at 1 R_J to about 60° at 3 R_J.

Although the emission-cone model accounts for the basic arc structure, we must still explain why so many arcs are observed. Because of the strong Io control at high frequencies, it has been widely accepted that the decametric radiation must be generated within the Io flux tube by a current system between Io and the Jovian ionosphere. This viewpoint is given further support by the Voyager 1 observation of a current system near the Io flux tube with more than enough power, $\sim 10^{12}$ W, to account for the decametric radiation, which has a total power of about 10^8 W [*Warwick,* 1967]. Furthermore, the very narrow width of the arcs, corresponding to a source with a longitudinal width of about (3 min/Io's rotation period) 360° = 0.42°, is in very good agreement with the longitudinal scale size of the Io flux tube, which is approximately (Io's diameter/2π times the radius of Io's orbit) 360° = 0.45°. Thus all of the essential requirements for identifying the decametric radiation source with the Io flux tube appear to be satisfied, with the exception of the number of arcs. If only a single current loop exists between Io and the ionosphere, then only two arcs should be observed, one when Io is approximately 75° to the right of Jupiter, as in Figure 2, and the other when Io is approximately 75° to the left of Jupiter. Instead, up to 100 or more arcs are observed distributed more or less uniformly over all Jovian longitudes, seemingly independent of Io's position.

3. EVIDENCE OF MULTIPLE ALFVEN WAVE REFLECTIONS

To understand the origin of the multiple decametric arc structure, we must first recognize that because of the unexpectedly high plasma density in the Io torus, the current system generated by Io can no longer be regarded as a simple

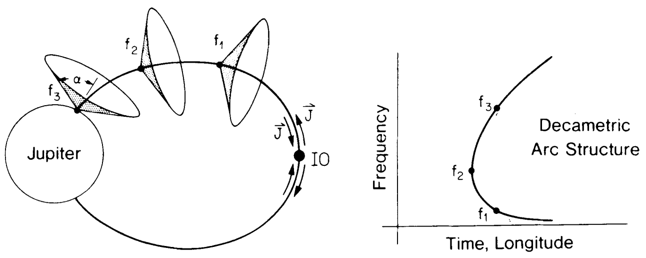

Fig. 2. The basic explanation of the decametric arc structure. Radiation is detected only if the observer lies on the surface of one of the conical emission cones. The frequency dependence implied by this geometric constraint accounts for the frequency-time structure of the arc.

field-aligned dc current loop between Io and the Jovian ionosphere. Instead, as has been pointed out by *Neubauer* [1980] and *Goertz* [1980], the current system must be regarded as a slow (shear) Alfven wave, with the current and energy flow determined by the Alfven wave impedance rather than the ionospheric resistivity. Because of the slow Alfven propagation velocity through the torus, the reflected Alfven wave from the ionosphere is not expected to arrive back at the orbit of Io in time to close the dc current circuit, in the sense described by Goldreich and Lynden-Bell. The possibility therefore arises that many reflections of the Alfven wave could occur from one hemisphere to the other, thereby producing an extended standing wave current system, downstream of Io. The geometry of this current system is illustrated in Figure 3, which shows the Alfven wave structure projected onto the Io L shell with the Io torus in the middle and the Northern and Southern hemispheres at the top and bottom. The abrupt change in slope of the Alfven wave trajectory at the torus boundary is caused by the much lower plasma density outside of the torus, compared to the plasma density inside of the torus. Since the reflected Alfven waves essentially produce a series of mirror images of the original Alfven wave current system extending all the way around the Io L shell, this system of multiple reflections provides a simple explanation for the large number of decametric arcs observed in the radio emission spectrum. A three-dimensional representation of the Alfven wave current system and the associated radiation sources predicted by this model are illustrated in Figure 4.

Before considering the implications of this model for the decametric radiation structure, we first estimate the number of reflections which could be expected. As suggested by *Neubauer* [1980], reflections can occur at both the torus and ionospheric boundaries. If Alfven waves are responsible for the decametric radiation, then a substantial amount of energy must be transmitted across the torus boundary, otherwise it would not be possible to account for the generation of the decametric radiation close to Jupiter. Furthermore, because the scale size of the Alfven wave disturbance (a few times the radius of Io) is small compared to the north-south thickness of the torus, there is good reason to believe that the reflection coefficient at the torus boundary should be small [*Goertz,* 1980]. Therefore in estimating the number of reflections which could occur, we will ignore reflections at the torus boundary.

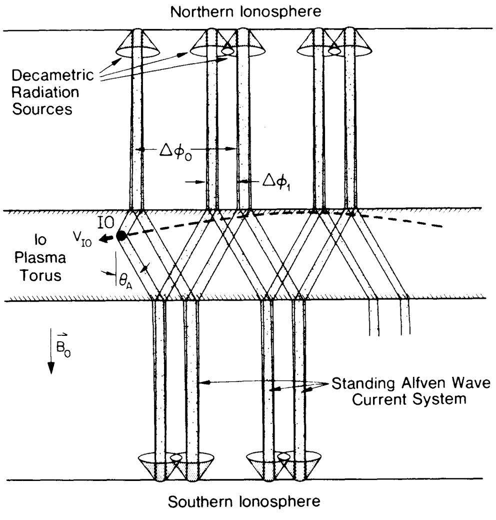

Fig. 3. The standing wave pattern formed by Alfven waves excited by the motion of Io through the plasma torus, shown projected onto the Io L shell.

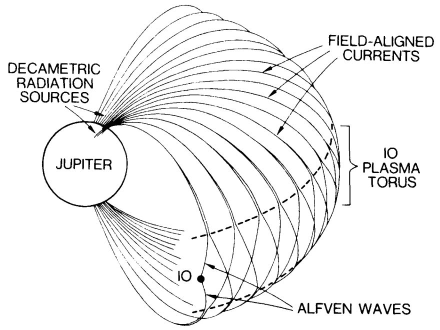

Fig. 4. A three-dimensional representation of the standing Alfven wave excited by Io.

To estimate the damping rate, both collisional and collisionless processes must be considered. The only collisional damping which should occur is due to absorption at the ionospheric boundary. As shown by *Scholer* [1970], the reflection coefficient for long wavelength Alfven waves incident on the ionospheric boundary is

$$r = \frac{\Sigma_J - \Sigma_A}{\Sigma_J + \Sigma_A} \tag{1}$$

where Σ_J is the height-integrated Pedersen conductivity, Σ_A is the Alfven wave conductance, $\Sigma_A = 1/\mu_0 V_A$, and V_A is the Alven speed. It is relatively easy to show that the number of reflections, N, required for the Alfven wave amplitude to decrease to e^{-1} of the original amplitude is $N = \Sigma_J/2\Sigma_A$, where we have assumed that Σ_A is much less than Σ_J. Using a representative ionospheric electron density of 5×10^4 cm^{-3} [*Fjeldbo et al.,* 1976] and a magnetic field strength of 14 G, the Alfven wave conductance in the ionosphere is approximately $\Sigma_A = 5.7 \times 10^3$ mhos. The height-integrated conductivity of the Jovian ionosphere is more difficult to estimate. Based on solar UV ionization profiles, *Goldreich and Lynden-Bell* [1969] and *Brice and Ioannidis* [1970] give values for Σ_J of 0.57 mho and 2–20 mhos. These ionospheric conductivities would allow a total of 49 and 172–1720 reflections, respectively. More recently, using the Pioneer atmospheric and ionospheric density measurements, *Dessler and Hill* [1979] have estimated a value for Σ_J of 0.1 mho, which would allow about nine reflections. All of these estimates indicate that the reflection coefficient at the ionosphere is close to unity and that many reflections should occur. It should also be noted that any increase in the charged particle precipitation will increase Σ_J and further increase the number of reflections.

At least three types of collisionless damping mechanisms must be considered, (1) resonant wave-particle interactions, (2) energy conversion due to charged particle acceleration by parallel electric fields, and (3) nonlinear wave-wave coupling. The damping of the Alfven wave due to resonant-wave-particle interactions is mainly due to electrons and can be estimated from the ratio of the damping rate γ, to frequency, ω, given by *Fejer and Kan* [1969]:

$$\frac{\gamma}{\omega} = -\pi^{1/2}\left(\frac{m_e}{m_i}\right)\left(\frac{V_A}{V_e}\right)^3\left(\frac{\omega}{\Omega_i}\right)^2\left(\frac{k_\perp}{k_\parallel}\right)^2 \exp\left[-\left(\frac{V_A}{V_e}\right)^2\right] \tag{2}$$

where m_e and m_i are the electron and ion mass, V_e is the electron thermal speed, Ω_i is the ion gyrofrequency, and $k_\perp$ and $k_\parallel$

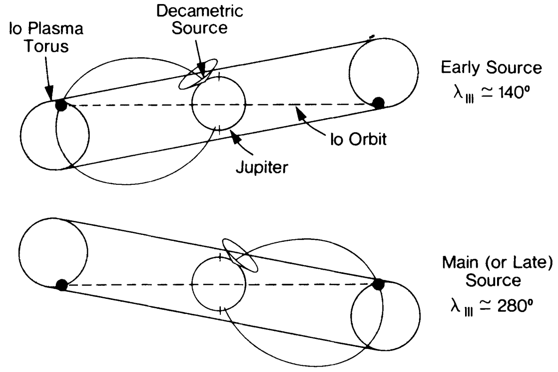

Fig. 5. The geometry of the torus and Io's orbit at times corresponding to the early and main (or late) Io-independent source. These sources lie on field lines for which Io passes close to the edge of the torus.

are the perpendicular and parallel wave number. For the shear Alfven mode the frequency is given by $\omega = V_A k_{\|}$, which eliminates the dependence on $k_{\|}$ in equation (2). For the perpendicular wave number we use the largest possible value which is $k_{\perp} H_{\mathrm{Io}} = \pi$, where H_{Io} is the scale height of Io's ionosphere. Using parameters typical of the plasma torus, with $V_A = 230$ km/s, $\Omega_i = 1.7$ Hz, and an electron temperature of 8 eV [see *Goertz,* 1980; *Southwood et al.,* 1980], the damping rate due to resonant wave particle interactions is $\gamma/\omega \simeq 10^{-5}$, which would permit over 10^3 reflections. Compared to other loss mechanisms, wave-particle interactions do not appear to be a significant source of damping.

Damping due to charged particle acceleration by parallel electric fields is more difficult to estimate. As discussed by *Goertz and Boswell* [1979], a parallel electric field is expected to form in the leading edge of an Alfven wave disturbance because of finite ion gyroradius effects. This electric field is potentially very important because it can act to accelerate some of the plasma particles up to high energies, thereby producing charged particle beams and other effects commonly associated with auroral charged particle precipitation. Charged particle acceleration effects of this type must, of course, be present to account for the decametric radio emission, since currents by themselves cannot produce radio emissions. Since any charged particle acceleration represents an energy loss, it will lead to damping of the Alfven wave. At the present time it is very difficult to make a reliable theoretical estimate of this damping rate, since parallel electric field processes of this type are only now beginning to be understood in the earth's magnetosphere and are virtually unexplored at Jupiter. About the only estimates which can be made are on the basis of overall energetics and analogies with the earth's auroral kilometric radiation, which is thought to be comparable to the Jovian decametric radiation [*Gurnett,* 1974]. If we assume, for example, that on the average 100 arcs are active and that the total power radiated in the decametric radiation is 10^8 W [*Warwick,* 1967], then the total power radiated per arc is about 10^6 W. If we furthermore assume that the ratio of the radiated energy to the total energy in the accelerated particle distribution is comparable to the power ratio of the earth's auroral kilometric radiation and inverted-V precipitation, which is typically about 10^{-3}–10^{-4} [*Green et al.,* 1979], then the total power of the accelerated particles in a given arc would be about 10^9–10^{10} W. Compared to the 10^{12} W available in the Alfven wave current system, this loss would allow from 100 to 1000 reflections. On the basis of all of these estimates it appears that a large number of Alfven wave reflections could be excited by the Io torus interaction.

Damping due to nonlinear wave-wave interactions is the most difficult loss mechanism to evaluate. Since only the shear Alfven mode results in an energy flow directed exactly along the magnetic field line [*Stix,* 1962], coupling to the compressional Alfven mode, which radiates isotropically, will lead to a decay of the Alfven wave energy. Because of the complexity of the possible nonlinear interactions involved, we are not able at the present time to give a reliable estimate of this decay rate. It is, however, worth noting that of the three possible MHD modes in a hot plasma, the shear Alfven wave is the least likely to be affected by nonlinear interactions, since for the case of field-aligned propagation ($k_{\perp} = 0$) the shear Alfven wave is an exact solution of the fully nonlinear MHD equations [*Schmidt,* 1966]. If significant nonlinear interactions occur, it is expected that the loss rate will be a strong function of wave amplitude, and that after an initial rapid decay the amplitude will approach a level below which nonlinear effects are negligible.

4. DISCUSSION

Since a large number of Alfven wave reflections are evidently possible, we now consider the implications for the structure and phenomenology of the decametric arcs. First, we compare the basic longitudinal separation between the Alfven waves with the temporal separation between successive decametric arcs. Since the Alfven velocity outside of the torus is very large, the angular separation between successive reflections of the same wave, $\Delta\phi_0$ in Figure 3, is mainly determined by the Alfven Mach number, $M_A = \tan\theta_A$, in the torus and the north-south thickness, l, of the torus. From simple geometric considerations it can be shown that $\Delta\phi_0 = (360°)(2l \tan\theta_A)/2\pi(5.9\ R_J)$. The current best estimate of the Alfven Mach number near the Io flux tube is $\tan\theta_A \simeq 0.15$ [*Acuna et al.,* 1980; *Southwood et al.,* 1980]. The north-south thickness of the torus as determined from the ultraviolet spectrometer [*Broadfoot et al.,* 1979] is about $2.0 \pm 0.6\ R_J$. Using these parameters the longitudinal separation between successive reflections is $\Delta\phi_0 \simeq 5.8°$, which would require 123 reflections to extend completely around Jupiter. If the dipole axis of Jupiter were perfectly aligned with the rotational axis, then the temporal separation would be solely determined by Io's orbital period, $\tau_{\mathrm{Io}} = 1.77$ days. The basic periodicity would then be $T_0 = (\Delta\phi_0/360°)\ \tau_{\mathrm{Io}} \simeq 40$ min. In addition, as can be seen from

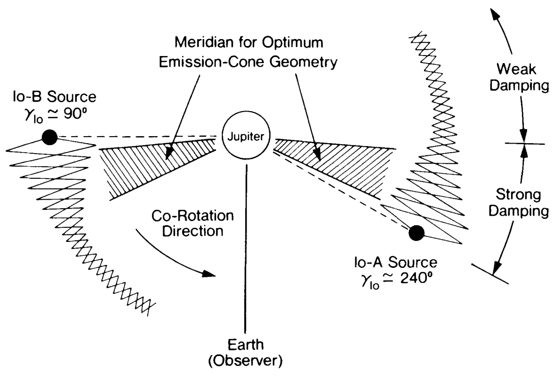

Fig. 6. The Io-controlled sources at $\gamma_{\mathrm{Io}} \simeq 90°$ and 240° can be explained if the Alfven wave damping is nonlinear, with strong damping for the first few reflections followed by weak damping.

Figure 3, a minor period $T_1 = (\Delta\phi_1/\Delta\phi_0)\ T_0$ is also introduced by the out-of-phase wave propagating the opposite direction away from Io. This period is modulated by the north-south position of Io in the torus. The temporal separations between successive arcs would therefore range from about 0 to 40 min., with an average of about 20 min. These estimates are probably accurate to only about a factor of 2 because of the uncertainties in the Alfven Mach number and the thickness of the torus.

Although spectrograms such as Figure 1 show certain features which have approximately the right separation times, they usually do not show the very regular periodic structure suggested by the idealized reflection model in Figure 3. Numerous effects, however, can be identified which would lead to a much more complex longitudinal structure. For example, if more than about 120 reflections occur then the Alfven wave system will start to overlap the waves generated during the previous rotation of Jupiter. This overlap effect would then give a superposition of arcs from successive rotations, some with lower intensities than others because of damping effects. Many of the decametric radiation spectrograms give one the strong impression that such superposition effects are present (see Figure 1). In fact, if the decametric arcs do originate from Io as indicated by the Io control at high frequencies, then such an overlap must be occurring since at low frequencies the decametric arcs are observed essentially continuously for all Jovian longitudes. Other effects which tend to produce a more complex structure include longitudinal variations in the density and thickness of the torus, reflections at the torus boundary, latitudinal changes in the emission-cone geometry caused by Jupiter's rotation, and higher-order multipole distortions of the magnetic field over the polar regions.

The Alfven wave reflection model also has some interesting implications for the interpretation of the well-known Jovian λ_{III} longitude and Io control of the decametric radiation intensity [*Carr and Desch,* 1976]. These effects are generally believed to be caused by variations in the strength of the Io interaction at certain points along the Io orbit. Although the Alfven reflection model does not address the cause of these variations, it does provide a new perspective for analyzing these interaction effects. Since the energy flow for the shear Alfven wave is always exactly parallel to the magnetic field, it is evident that any enhancement which occurs in the amplitude of the Alfven wave current system will remain in the same meridian plane as the wave bounces from one hemisphere to the other. Later, perhaps well after the interaction actually occurred, the meridian of enhanced Alfven wave intensity may rotate into the observers 'field-of-view' as determined by the emission-cone geometry. Thus any analysis of variations in the Io interaction must take into account this 'memory' effect in addition to the emission-cone geometry. For example, Figure 5 shows the torus geometry in relation to the Io orbit for the Io-independent early source at $\lambda_{III} \simeq 140°$, and the main (or late) source at $\lambda_{III} \simeq 280°$. It is immediately apparent that both the early and main sources occur in a longitude range where Io passes close to the edge of the torus, which indicates that the strongest interaction occurs near the edge of the torus. Note, however, that Io need not be passing through the edge of the torus at the actual time of observation. It is only necessary that Io pass by the edge of the torus at this longitude some time earlier, which of course occurs once during every rotation of Jupiter. Thus if the Io interaction is strongest near the edge of the torus, then the Alfven reflection model provides a simple explanation for the basic λ_{III} longitude control of the Io-independent decametric radiation.

In addition to the λ_{III} longitude control, the enhancements in the decametric radiation which occur when the departure of Io from superior geocentric conjunction (γ_{Io}) is near 90° or 240° can also be explained if the Alfven wave damping is nonlinear, with the first few reflections decaying more rapidly than subsequent reflections, as illustrated in Figure 6. Nonlinear effects of this type could occur, for example, if a threshold current exists above which rapid dissipation occurs. Such current dependent threshold effects could occur, for example, if regions of anomalous resistivity or electrostatic double layers form in the current system outside of the torus.

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