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Plasma Wave Interactions with Energetic Ions Near the Magnetic Equator

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Near the Magnetic Equator+

by

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Abstract

An intense band of electromagnetic noise is frequently observed near the magnetic equatorial plane at radial distance from about 2 to 5 R_e. Recent wideband wave-form measurements with the IMP-6 and Hawkeye-1 satellites have shown that the equatorial noise consists of a complex superposition of many harmonically spaced lines. Several distinctly different frequency spacings are often evident in the same spectrum. The frequency spacing typically ranges from a few Hz to a few tens of Hz. The purpose of this paper is to suggest that these waves are interacting with energetic protons, alpha particles and other heavy ions trapped near the magnetic equator. The possible role these waves play in controlling the distribution of the energetic ions is considered.

I. Introduction

For several years it has been known (Russell *et al.*, 1969) that an unusual band of electromagnetic noise is present near the magnetic equator at frequencies from about ten to several hundred Hz. These waves are propagating perpendicular to the magnetic field and are only observed inside of the plasmasphere at radial distances from about 2 to 5 R_e. Both the origin of this noise and the role these waves play in their interaction with the surrounding plasma have remained essentially unknown.

Recent wideband electric and magnetic field measurements with the IMP-6 and Hawkeye-1 satellites have shown that the equatorial noise consists of a complex superposition of harmonically spaced lines with frequency spacings ranging from a few Hz to a few tens of Hz. The occurrence of sharp lines in the frequency spectrum indicates that this noise is involved in resonant interactions with some component of the energetic particle population which exists in the region near the magnetic equator. The purpose of this paper is to suggest that these waves are involved in gyrofrequency harmonic interactions with energetic ring current protons, alpha particles and other heavy ions of the type detected by Krimigis and Van Allen (1967) and Shelley *et al.* (1972).

II. Characteristic of the Equatorial Noise

An example of the equatorial noise detected by the Hawkeye-1 spacecraft is shown in Figure 1. Because of the highly eccentric polar orbit of Hawkeye-1 this spacecraft provides a particularly clear illustration of the confinement of this noise to the magnetic equatorial plane. Details of the Hawkeye-1 plasma wave experiment are given by Kurth et al. (1973). The data in Figure 1 show the electric and magnetic field intensity in six frequency channels from 1.78 Hz to 562 Hz. The ordinate for each channel is proportional to the logarithm of the field strength with a range from the baseline of one channel to the baseline of the next higher channel of 100 db. Several types of noise are evident during this pass. In the low frequency, 1.78 Hz to 56.2 Hz, channels an abrupt increase in the electric field noise level is evident at the plasmapause in both the northern and southern hemispheres. This noise is similar to the electrostatic noise previously reported by Anderson and Gurnett (1973) near the plasmapause using measurements from the S^3-A satellite. Inside of the plasmapause plasmaspheric hiss is evident in both the electric and magnetic field channels at 178 Hz and 562 Hz. As the spacecraft crosses the magnetic equatorial plane at about 2216 UT a pronounced peak is evident in the 17.8 and 56.2 Hz electric and magnetic field channels. This distinct peak in the low frequency electric and magnetic field intensities as the spacecraft crosses the magnetic equator is the characteristic signature of the equatorial noise being considered in this paper.

To provide a better determination of the spatial region in which the equatorial noise is found we have performed a survey of all of the available IMP-6 and

Hawkeye-1 data, totaling about 3 years of inflight observations, to identify all of the equatorial noise events observed during this period. The magnetic latitude and radial distance coordinates of the spacecraft for each time interval over which an event was detected are shown in Figure 2. The end points correspond to times when the intensity is approximately one half of the peak intensity for that pass. Also shown in Figure 2 are the coordinates given by Russell et al. (1969) for some of the equatorial noise events observed by the OGO-3 spacecraft. The apparent difference in the radial distance at which IMP-6 and Hawkeye-1 have observed this noise, compared to OGO-3, is believed to be entirely due to the different radial distances at which these satellites cross the equator. Most of the IMP-6 equator crossings tend to occur at radial distances from about 2 to 3.5 R_e, whereas the OGO-3 equator crossings all occur at radial distances greater than 3 R_e. For the data currently available Hawkeye-1 always crosses the magnetic equator at about 2.5 ± 0.5 R_e.

From Figure 2 it can be seen that the equatorial noise is confined within a latitudinal range of about $\pm 10^{o}$ from the magnetic equator. Because of the small number of events available and the difficulty in properly accounting for the region sampled by each satellite no attempt has been made to determine a properly normalized frequency of occurrence. It is, however, our impression that both the intensity and frequency of occurrence are largest in the radial distance range from about 2.5 to 3.5 R_e. Although the equatorial noise was observed on only about 10 % of the total number of orbits the actual frequency of occurrence is probably considerably larger because many of the orbits did not have adequate telemetry coverage near the magnetic equator. Frequently events have been observed on several successive orbits of IMP-6 indicating that when the noise occurs it persists fo period of several weeks. A brief survey of the local time at which these events were observed also shows no marked dependence on local time. Similar events have been observed in all four local time quadrants. Typical broad band amplitudes of the equatorial noise at the peak intensity are 20 milligammas for the magnetic field strength and 200 μV m^{-1} for the electric field strength.

Wide-band waveform measurements from both IMP-6 and Hawkeye-1 show that the frequency spectrum of the equatorial noise consists of a very complex superposition of bands with frequency spacings ranging from a few Hz to several tens of Hz. A typical frequency-time spectrogram of this noise is shown in Figure 3. The spectrum in this case is of the electric field, however comparable spectra are also observed for the magnetic field. Two different frequency scales are shown in Figure 3 for the same event to provide better resolution of the fine structure. The spectrum is seen to consist of many fine lines with bandwidths of only a few Hz or less. In some regions of the spectrogram these lines show a very clear harmonic structure. Several distinctly different frequency spacings are evident. At frequencies above about 100 Hz the bottom spectrogram shows a very clear harmonic structure with a frequency spacing of about 16 Hz. At frequencies below 100 Hz, from about 0310 to 0320 UT, another series of lines, also with a distinct harmonic structure, is evident with a frequency spacing of about 4 to 5 Hz. Lines with spacings of about 8 Hz are also evident in this same region (see the top spectrogram). In the upper right hand corner of the top spectrogram lines with an even smaller frequency spacing of ~ 2 Hz are also evident, superimposed on the coarse 16 Hz harmonics. The characteristic frequency of the entire band structure increases slowly as the spacecraft passes through the region where the noise is observed. Detailed comparisons show that the largest frequency spacing, 16 Hz, is close to, but not exactly equal to, the local proton gyrofrequency. For comparison the proton gyrofrequency is 15.7 Hz and 13.1 Hz at 0300 and 0330 UT, respectively.

The frequency spectrum of another equatorial noise event detected by IMP-6 is shown in Figure 4. Again a complex line structure is evident with a very distinct harmonic relationship between the lines. The primary frequency spacing is about 2.2 Hz, although a less distinct spacing of about 3 Hz is evident at frequencies above about 80 Hz. In this case the local proton gyrofrequency is 17.3 Hz at 2215 UT. The frequency spacings therefore correspond to approximately one-eight and one-half of the local proton gyrofrequency.

III. Discussion

The occurrence of distinct harmonics in the spectrum of the equatorial noise indicates that this noise is interacting at some characteristic resonance frequency of the plasma in the region near the magnetic equator. Only two types of resonances are known which are in the correct frequency range to account for the observed frequency spacings: (1) the electron bounce-resonance and (2) the ion gyrofrequency harmonic resonances.

For electrons trapped near the magnetic equator the bounce-resonance frequency given by Roberts (1968) is

$$f_o = 15.9 \left(\frac{\beta \sin \alpha_o}{L}\right) , \tag{1}$$

where $\beta = v/c$ (v is the electron velocity and c is the speed of light), α_o is the equatorial pitch angle and L is the magnetic L-shell parameter. Russell *et al.* (1969) have suggested that the equatorial noise acts to scatter energetic electrons trapped near the magnetic equator by bounce-resonance interactions. Although the equatorial noise may be involved in bounce-resonance interactions with energetic electrons we do not believe that this resonance can account for the discrete lines in the emission spectrum. As shown earlier some of the emission lines are extremely narrow, with $\Delta f/f$ less than 1 %. Since the bounce-resonance frequency depends on the velocity and pitch angle of the particle at the equator (via the β and α_o dependence in equation 1) the bounce-resonance frequency is different for each particle. For a continuous distribution of electron velocities and pitch angles the bounce-resonance cannot produce discrete lines in the plasma wave spectrum. Also, the bounce-resonance frequency is too small ($f_o \leq 5.3$ Hz at L = 3) to account for the observed frequency spacings (compare with Figure 3, where one of primary harmonic spacings is 16 Hz).

Ion gyrofrequency harmonic resonances provide a much more satisfactory explanation of the harmonic structure of the equatorial noise. The occurrence of bands at harmonics of the electron and ion gyrofrequencies is a well-known characteristic of hot plasmas, both in the laboratory (Crawford and Weiss, 1966) and in space (Kennel et al., 1970). The interactions near harmonics of the gyrofrequency arise from terms of the following form

$$\sum_n \int \frac{\omega_p^2 \left(K_\parallel \frac{\partial F}{\partial v_\parallel} + \frac{n\omega_g}{v_\perp}\frac{\partial F}{\partial v_\perp}\right) J_n^2 \left(R_\perp K_\perp\right)}{\omega + K_\parallel v_\parallel + n\omega_g} d^3v \qquad (2)$$

which occur in the dispersion relation for a hot plasma (Stix, 1962). The symbols $\parallel$ and $\perp$ refer to components parallel and perpendicular to the magnetic field, K is the wave number, v is the particle velocity and ω_p and ω_g are the plasma frequency and gyrofrequency, respectively. The interaction at each gyrofrequency harmonic is controlled by the Bessel function $J_n(K_\perp R_\perp)$, where $R_\perp$ is the gyroradius of the particle. For large perpendicular wavelengths and/or low temperatures, where $R_\perp K_\perp \ll 1$, the harmonic effects disappear completely and resonance occurs only at the fundamental (n = 1) of the gyrofrequency. Only when the gyroradii are comparable to, or larger than the perpendicular wavelength do the harmonic interactions become important. Gyrofrequency harmonic interactions occur for both electrostatic and electromagnetic waves. Although the gyrofrequency harmonic effects have been studied extensively for the electrostatic modes (Harris, 1959; Young <u>et al.</u>, 1973; Ashour-Abdalla and Kennel, 1976) much less is known about the properties and characteristics of the electromagnetic gyrofrequency harmonic modes which can occur in a hot plasma.

Quantitatively, the observed frequency spacing of the harmonic bands agrees very well with the gyrofrequencies expected for energetic protons, alpha particles and other heavy ions which have been observed in the magnetosphere. At L = 3 for example, the gyrofrequencies for protons and alpha particles, both of which are present in the magnetosphere with significant energies and intensities (Davis and Williamson, 1963; Krimigis and Van Allen, 1965; Frank, 1967), are about 16 Hz and 8 Hz, respectively. The corresponding gyrofrequencies for He^+ and O^+ ions, which have also been observed in the magnetosphere, (Shelley <u>et al.</u>, 1972), are 4 Hz and 1 Hz, respectively. Although the frequency spacing between the bands is in the general range of the gyrofrequencies expected for these ions, careful comparisons show that the frequency spacing of the lines in the spectrum of the equatorial noise do not correspond in detail with the local gyrofrequency at the spacecraft. However, since these waves can propagate a considerable distance from the region where the gyrofrequency harmonic interaction is occurring it is not expected that the observed frequency spacing would necessarily correspond with local conditions at the spacecraft.

Near the magnetic equator, and in the same region where the equatorial noise is observed, Fritz and Williams (1973) have reported the occurrence of large fluxes of alpha particles and other $Z \geq 2$ heavy ions with energies of ~ 1 MeV. It is easily shown that these energetic alpha particles and $Z \geq 2$ heavy ions, as well as the energetic protons observed in this same region, should interact strongly with the equatorial noise at harmonics of the gyrofrequency. Russell et al. (1969) have shown that the wave normal direction of the equatorial noise is perpendicular to the magnetic field. Using typical plasma parameters for $L = 3$ and the whistler-mode dispersion relation for propagation perpendicular to the magnetic field the wavelength is estimated to be about $\lambda = 60$ km at 100 Hz. For a 1.0 MeV alpha particle at $L = 3$ the gyroradius is $R_{\perp} = 190$ km. The gyroradius is therefore considerably larger than the perpendicular wavelength, which shows that the high order gyrofrequency harmonic terms in the dispersion relation will be quite important (i.e. $R_{\perp}K_{\perp} \gg 1$) for these particles. For the ~ 10 keV H^{+} and O^{+} ions reported by Shelley et al. (1972) it is easily shown that these particlas should also experience strong gyrofrequency harmonic interactions with the equatorial noise.

Although it is virtually certain that the equatorial noise must interact with these energetic ions in the region near the magnetic equator it is not clear whether these ions are in any way involved in the generation of this noise. The close similarity of the regions in which the energetic ions and equatorial noise are observed and the highly anisotropic pitch angle distribution of the ions strongly indicate that these particles play an essential role in the generation of this noise. Regardless of the origin of the noise it is of interest to speculate on the consequences of the interaction of these waves with the ion distribution. Because the direction of propagation is perpendicular to the magnetic field, with the wave magnetic field parallel and the wave electric field perpendicular to the static magnetic field, the first order effect is to modify the energy of the ions rather than cause pitch angle scattering. Whether a given ion species is energized or de-energized depends in detail on whether these ions are contributing to the growth or damping of the waves.

Because of the radial gradient in the ion gyrofrequencies it is possible that a significant transfer of energy may take place from one species to another by the emission and subsequent absorption of these waves at the gyrofrequency harmonics. That such emission and subsequent absorption may be taking place is supported by the fact that the equatorial noise apparently does not escape from the region near the equatorial plane, since the noise is never observed outside of the plasmasphere or at low altitudes in the ionosphere. Recently Brice and Lucas (1975) have suggested that a similar energy exchange process can occur via ion cyclotron wave interactions with the ring current ions. Since the equatorial noise occurs at frequencies above the proton gyrofrequency this noise cannot correspond to the waves postulated by Brice and Lucas. In over a year of inflight operation no ion cyclotron waves have yet been detected by Hawkeye-1 near the equatorial plane. The magnetic field sensitivity of Hawkeye-1 is about 70 milligammas and 6.9 milligammas at 1.78 Hz and 5.62 Hz, respectively.

Whether the equatorial noise can produce a significant transfer of energy between the energetic ions can be estimated from the power flux of the waves compared to the total particle energy. For a typical magnetic and electric field amplitude of 20 mγ and 200 μV m^{-1} the total power crossing an L-shell (assuming radial propagation at L = 3.0) is estimated to be about 1.5×10^{13} ergs sec^{-1}. From the data given by Fritz and Williams (1973) the total energy of the energetic alpha particles trapped near the equatorial plane is estimated to be about 3.0×10^{19} ergs. It would be possible then for these waves to significantly modify the energy distribution of the energetic alpha particles on a time scale of about 2×10^{6} sec ($\sim$23 days). This rough estimate shows that the equatorial noise cannot account for abrupt (a few hours) changes in the alpha particle population which occur during magnetic storms but that these waves could be important for determining the long term equilibrium distribution.

For gyrofrequency harmonic interactions the energy gained by the particles is quite different for particles with different charge to mass ratios and depends in great detail on the wave spectrum. The ratio of the intensities of the various ions is therefore not expected to be conserved during such interactions. If the equatorial noise is interacting strongly with the equatorial proton and alpha particle distribution then the alpha to proton intensity ratio cannot be used to determine whether these particles originate from the ionosphere or from the solar wind, as has been frequently suggested. Large unexplained variations in this ratio are in fact observed (see Fritz and Williams, 1973).

Acknowledgements

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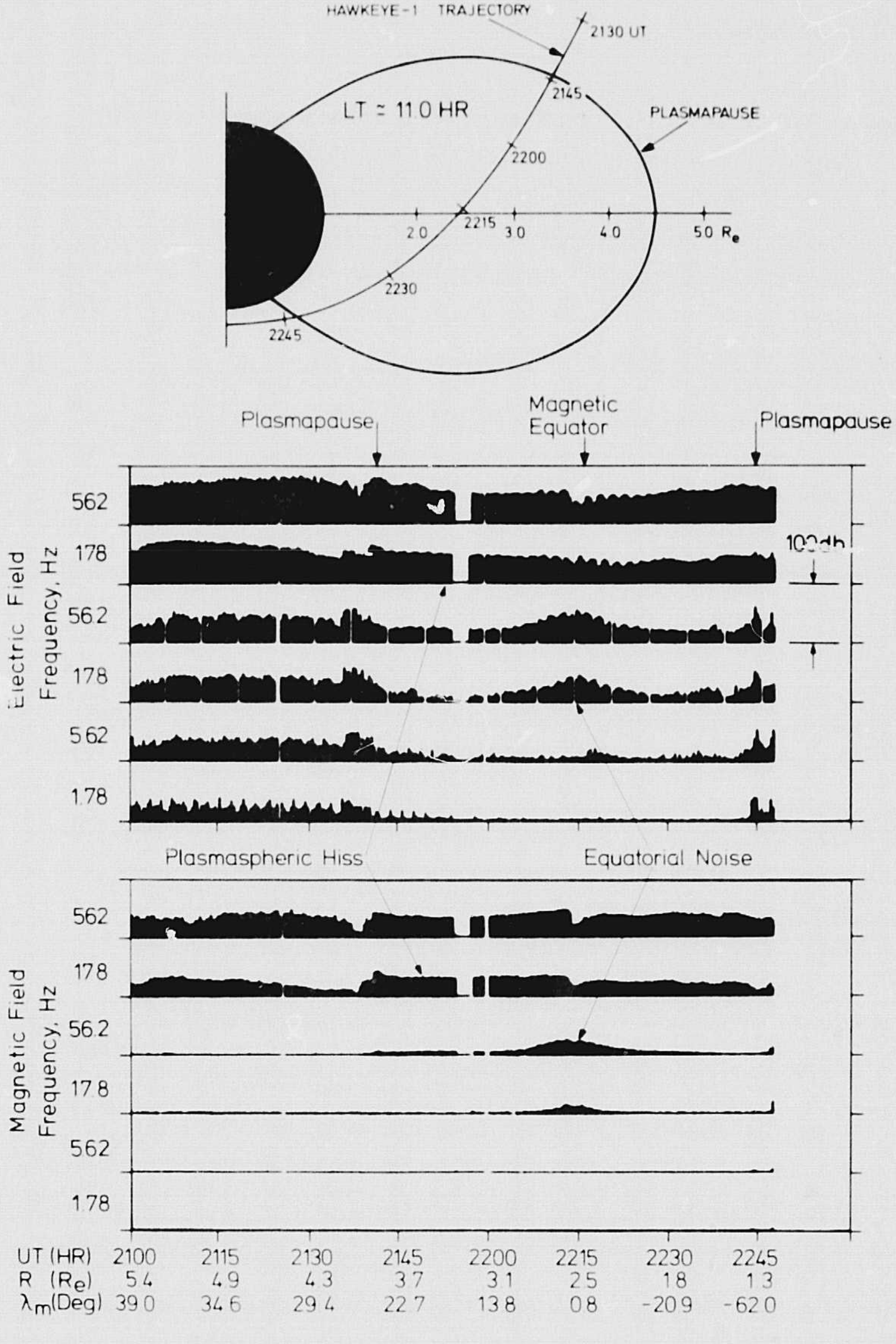
Figure Captions

Figure 1. A typical Hawkeye-1 pass across the magnetic equator. The equatorial noise is evident in the 17.8 Hz and 56.2 Hz electric and magnetic field channels as the spacecraft crosses the magnetic equator. The proton gyrofrequency at the equator is 21.7 Hz. The equatorial noise extends to frequencies well above the local proton gyrofrequency.

Figure 2. A magnetic meridian plane projection of all of the equatorial noise events observed by IMP-6 and Hawkeye-1. Additional events from Russell et al. (1970) are shown to illustrate the range of radial distances over which this noise is observed. The noise has never been observed outside of the plasmasphere or at low altitudes in the ionosphere.

Figure 3. Frequency-time spectrograms of the equatorial noise showing the occurrence of many lines in the frequency spectrum. These lines are harmonically related, however several different frequency spacings, ranging from ~ 2 Hz to about 16 Hz are present. The local proton gyrofrequencies at 0300 and 0330 are 15.7 Hz and 13.1 Hz, respectively.

Figure 4. Another example showing the occurrence of distinct harmonically related lines in the spectrum of the equatorial noise. The dominant frequency spacing in this case is about 2.7 Hz at low frequencies and about 8 Hz at frequencies above about 80 Hz. The local proton gyrofrequency is 17.3 Hz at 2215 UT.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LT ≃ 11.0 HR
PLASMAPAUSE
2200
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5.0 R_e
2230
2245
Plasmapause
Magnetic Equator
Plasmapause
Electric Field Frequency, Hz
562
178
56.2
17.8
5.62
1.78
100db
Plasmaspheric Hiss
Equatorial Noise
Magnetic Field Frequency, Hz
562
178
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1.78
UT (HR) 2100 2115 2130 2145 2200 2215 2230 2245
R (R_e) 5.4 4.9 4.3 3.7 3.1 2.5 1.8 1.3
λ_m(Deg) 39.0 34.6 29.4 22.7 13.8 0.8 -20.9 -62.0

Fig. 1

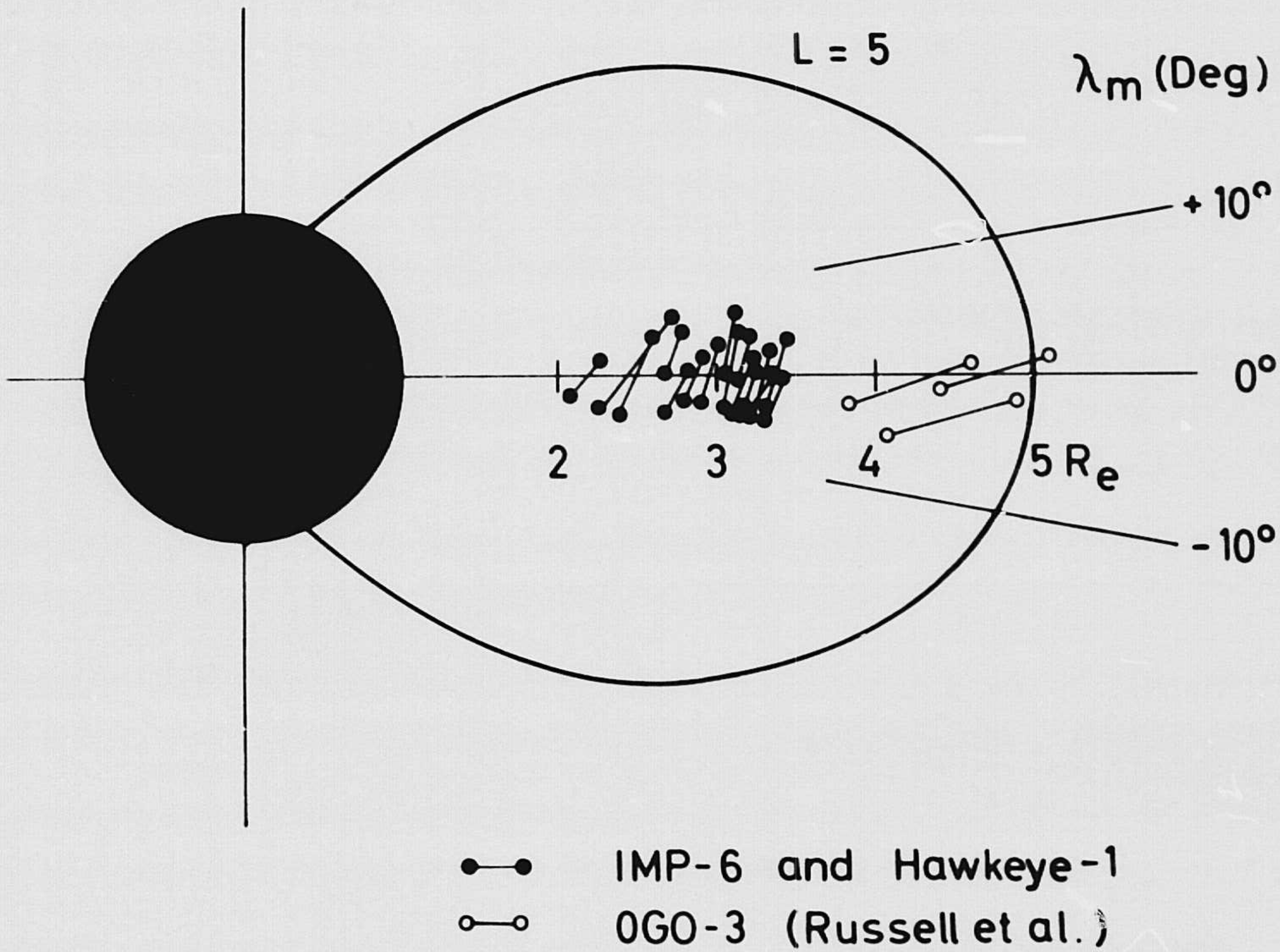

Fig. 2

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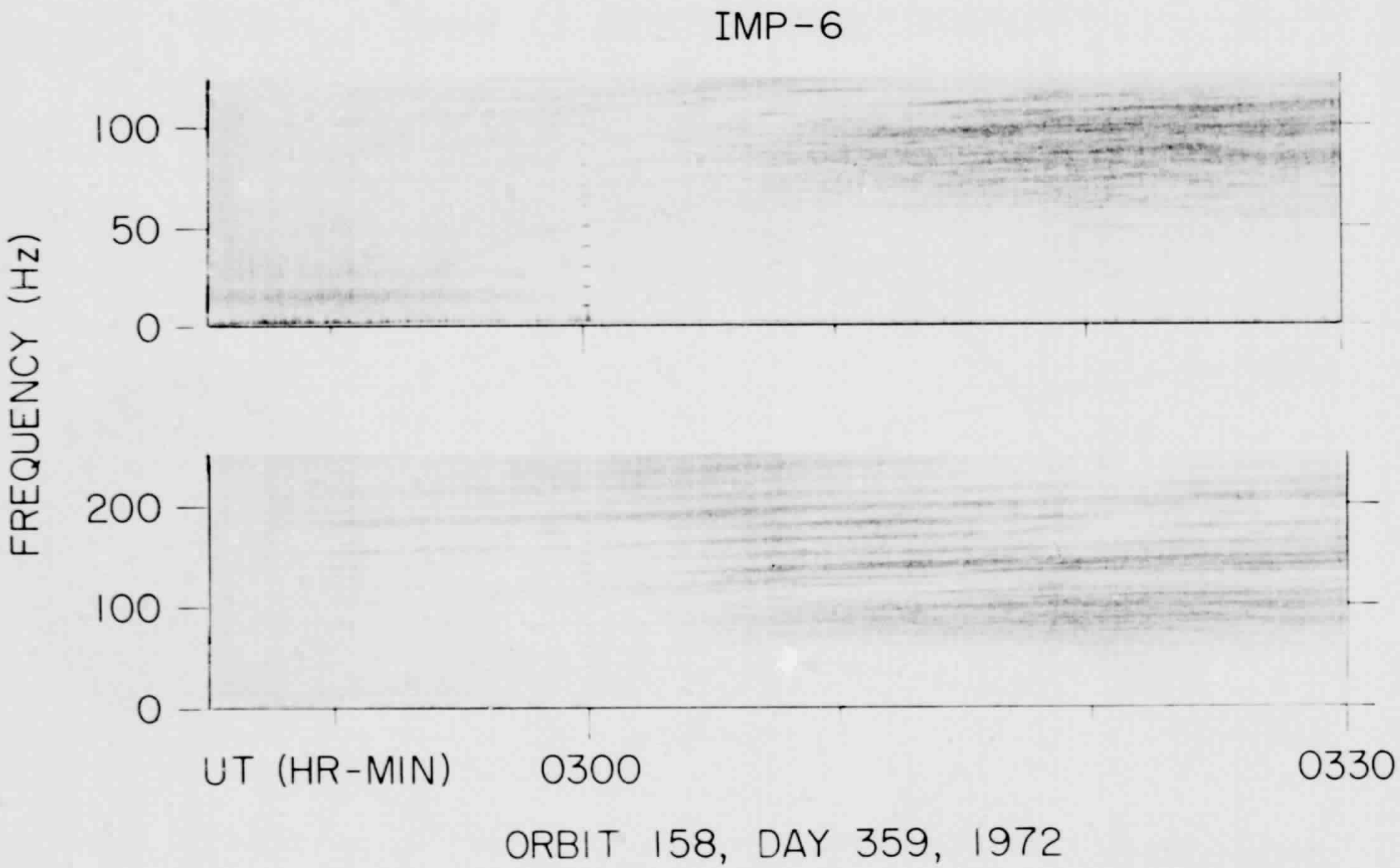
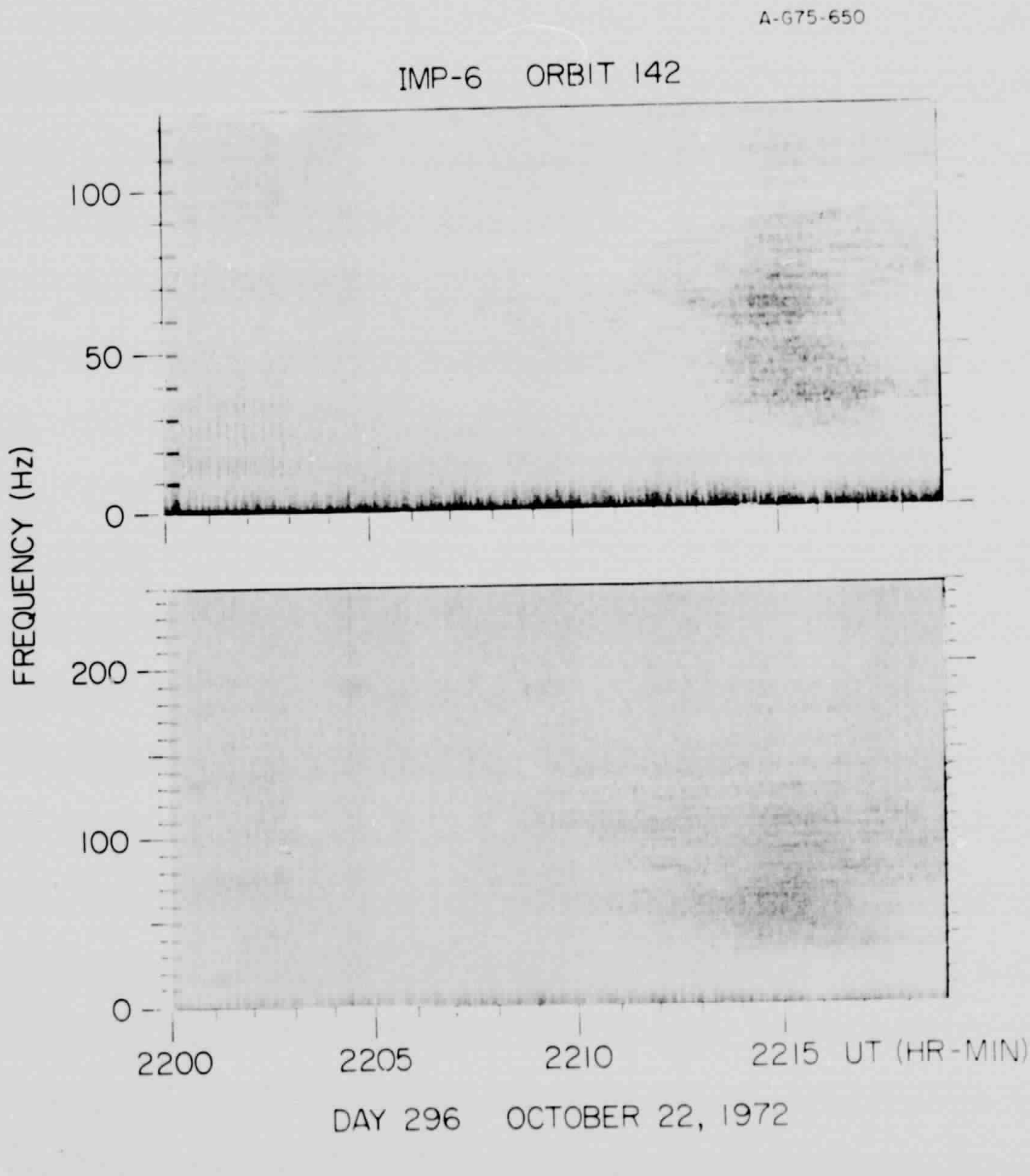


Fig. 3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DAY 296 OCTOBER 22, 1972

Fig. 4