QUIET-TIME OBSERVATION OF A COHERENT COMPRESSIONAL Pc-4 MICROPULSATION AT SYNCHRONOUS ALTITUDE

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ABSTRACT

During a magnetically quiet interval (1740-1850 UT), on February 14, 1967, the magnetic-field intensity and energetic electron fluxes ($E \approx 0.3$ - 2.0 MeV) at ATS 1 exhibited coherent modulations having a frequency of 33.8 cph (period $\approx$ 106.5 sec) and a duration of approximately 40 oscillations. The electron fluxes and the magnetic field oscillated in phase. The field perturbation reached 8γ (peak to peak) in the direction of the unperturbed geomagnetic field. The transverse component of the field perturbation was practically zero. The characteristics of the observed oscillations appear compatible with those of a compressional (magnetosonic) excitation of the outer magnetosphere. The substantially radial normal mode is perhaps driven by a bounce-resonant interaction with the 15-keV protons that populate the quiet-day ring current.

The work of Paulikas and Schulz was conducted under U. S. Air Force Space and Missile Systems Organization (SAMSO) Contract No. F04701-70-C-0059.

This communication reports the observation of an unusually periodic oscillation of the geomagnetic field intensity at synchronous altitude during the mid-morning hours (0740-0850 LT) of a geomagnetically quiet day (February 14, 1967; $\Sigma Kp = 9$). The peak-to-peak amplitude of the field oscillation remained $\sim 5\gamma$ and the oscillation frequency persisted at 33.8 cph (cycles per hour) for the duration of the event. Although apparently a rare occurrence, an oscillation that remains so coherent over an interval of ~ 40 oscillation periods should provide some insight, if properly exploited, into the underlying dynamics of the earth's magnetosphere.

The event was observed by three instruments aboard the ATS 1 satellite (150°W longitude; ATS LT = UT - 10 hours), the spin axis of which is approximately parallel to the earth's rotation axis and to the local magnetic field. The UCLA magnetometer consists of two orthogonal fluxgates with the axis of each inclined 45° to the satellite spin axis so as to permit a vector measurement of the magnetic field $\underset{\sim}{B}$ [Cummings and Coleman, 1968a, b]. The Bell Laboratories instrument consists of a six-element solid-state detector telescope with coincidence circuitry to identify particle species and energy. A 20° half-angle collimator looks out perpendicular to the satellite spin axis [Lanzerotti et al., 1967]. The Aerospace instrument consists of three shielded solid-state omnidirectional radiation directors with pulse-height circuitry to identify particle species and energy. This instrument provides integral flux measurements above four different electron-energy thresholds [Paulikas et al., 1968]. Because of poor statistics, data from the proton channels of both particle instruments are omitted from the study of this event.

The integral omnidirectional flux I_0 into each of the four Aerospace electron channels was sampled twice each 40.965 seconds. The two measurements were separated by 5.12 sec; for certain purposes their geometric mean is used as a single data point in this paper. A counting rate indicative of the differential undirectional flux J_1 into each of the seven BTL energy channels was measured three times at approximately equal intervals in a basic cycle of 81.930 sec. Data points for each of the seven channels, therefore, appear at intervals of 27.310 sec (on the average). Thus, the Nyquist frequencies associated with data sampling are only slightly larger than the oscillation frequency of the observed pulsations; Fourier analysis is required to establish the oscillation frequency precisely.

The magnetic-field oscillations and particle-flux modulations observed in representative electron channels are shown in Figure 1. The electron fluxes exhibit a modulation approximately in phase with the magnetic-field intensity. The oscillatory curves through the data points in Figure 1 serve solely to guide the reader's eye.

The magnetic-field data shown in Figure 1 are digitized at 15-sec intervals and represented in a field-oriented coordinate system. In this system, the unit vector $\hat{\zeta}$ points in the direction of the unperturbed magnetic field while $\hat{\rho}$ and $\hat{\varphi}$ lie in a plane orthogonal to $\hat{\zeta}$ and point approximately in the radial and azimuthal directions, respectively.

The field components in the $\rho\varphi\zeta$ coordinate system are obtained from original data expressed (for example) in the XYZ solar-ecliptic coordinate system. A low-pass square filter with a cut-off frequency

f_c = 14.4 cph (0.004 Hz) has been applied to the original data. The magnetic-field vector $\tilde{\mathbf{B}}$ that survives the low-pass filter defines the direction of $\hat{\boldsymbol{\zeta}}$. The outward-pointing unit vector $\hat{\boldsymbol{\rho}}$ is defined to lie in a geographic meridional plane and to be such that $\hat{\boldsymbol{\rho}} \cdot \hat{\boldsymbol{\zeta}} = 0$. The third unit vector is defined by $\hat{\boldsymbol{\varphi}} = \hat{\boldsymbol{\zeta}} \times \hat{\boldsymbol{\rho}}$.

Essentially all of the magnetic activity at 33.8 cph in Figure 1 resides in the ζ component, i.e., in the component parallel to the unperturbed $\mathbf{B}$-field. The oscillations are virtually absent from the ρ and φ components, which are perpendicular to the unperturbed field. Thus, the oscillations are purely compressional. Further, if the oscillations result from a traveling wave, the direction of propagation is perpendicular to $\mathbf{B}$ at the near-equatorial point of observation. The Fourier spectra of $\ln B_\zeta$ and of the logarithmic counting rate for a selected electron channel are shown in Figure 2 for an interval approximating 1700-1900 UT. The spectral densities of all eleven logarithmic electron fluxes and of $\ln B_\zeta$ distinctly exhibit the spectral peak at 33.8 cph with a full width of 1.4 cph at half maximum. This peak is virtually absent in comparable spectra of $B_\rho/\tilde{B}_\zeta$ and $B_\varphi/\tilde{B}_\zeta$, where $\tilde{B}_\zeta$ denotes the low-pass filtered B_ζ.

Close inspection of Figure 1 suggests that the particle and field (B_ζ) oscillations are approximately in phase. Cross-correlation spectra (not shown here) between $\ln J_1$ and $\ln B_\zeta$ confirm this visual impression and show phase agreement to within 5°. The degree of phase coherence is dramatically illustrated in Figure 3, where five minutes of data are plotted on an expanded time scale; each data point is located at the center of the applicable counting interval. The indicated sinusoids are selected to minimize the mean-square deviation from the logarithmic data obtained during the five-minute interval. The computed amplitudes and phases of the sinusoids for the four omnidirectional electron channels, relative to those of ln B_ζ, are indicated in Table 1. It is noteworthy that the degree of modulation in all four of these particle channels exceeds that of B_ζ. Further, the modulation is greater at the higher energies.

Similarly, it is found that the integrated content, or "power", under the spectral peak of ln $J_\perp$ invariably exceeds that of ln B_ζ. (As noted above, all these peaks have the same spectral width.) Table 2, obtained by comparing the spectral density of each logarithmic particle flux to that of ln B_ζ at the spectral peak (and taking the square root of the ratio), indicates the relative logarithmic modulation amplitudes characteristic of the two-hour interval as a whole. The values thereby obtained for the four omnidirectional channels compare favorably with those given in Table 1 for the five-minute interval. The energy dependence of the degree of modulation can in principle be used to infer the spatial structure of the locally observed field oscillation.

The quantitative procedure that makes this inference possible is greatly simplified in the case of equatorially mirroring electrons, for which $J_\perp/B_\zeta$ remains fixed along a particle trajectory [Nakada and Mead, 1965; Fälthammar, 1966; Lanzerotti et al., 1970]. This follows from Liouville's theorem. While the dynamical trajectory of a particle preserves the first invariant μ, the radiation detectors are sensitive to fixed energy intervals. For equatorially mirroring electrons of kinetic energy $E = (\gamma - 1)m_0c^2$, it is not difficult to show that

$$(\partial \ln J_\perp/\partial \ln B_\zeta)_E = \left\{1 - [(\gamma+1)/2\gamma]\ (\partial \ln J_\perp/\partial \ln E)_B\right\}(d \ln B_\mu/d \ln B_\zeta)$$
$$+ (\partial \ln J_\perp/\partial \ln B_\mu)_E\ [1 - (d \ln B_\mu/d \ln B_\zeta)] \qquad (1)$$

where B_μ is the field experienced by the representative particle's guiding center. In the event of a radial displacement, for example, the value of $d \ln B_\mu/d \ln B_\zeta$ should exceed unity; for an azimuthal displacement it should not. The formula stated above is of course valid only in the absence of drift-periodic echoes [Lanzerotti et al., 1967; Paulikas et al., 1968; Brewer et al., 1969; Lanzerotti et al., 1971], which indeed were not present on February 14.

The energy-spectral index $(-\partial \ln J_\perp/\partial \ln E)_B$ can be obtained by standard methods; i.e., by using the counting-efficiency functions obtained by instrument calibration [Lanzerotti et al., 1967], the observed channel-by-channel count rates typical of the time interval in question (filtered to suppress the oscillations), and a hypothesized functional form (with adjustable constants) for $J_\perp(E)$. On a sufficiently quiet day the "radial-gradient" factor $(\partial \ln J_\perp/\partial \ln B_\mu)_E$ can be estimated by observing the diurnal variation of $\ln J_\perp$ vs $\ln \tilde{B}_\zeta$, assuming that the magnetospheric configuration remains substantially constant in time.

Accumulative uncertainties associated with the various observational inputs to Equation (1) have prevented a quantitative understanding of Table 2. Certain qualitative inferences can be drawn from the analyses, however. The energy spectrum during and immediately preceding the micropulsation event has been found to resemble those previously obtained at the synchronous orbit [Lanzerotti et al., 1967], i.e., the spectral index $(-\partial \ln J_\perp/\partial \ln E)_B$ at the higher energies is ~ 5, and therefore is considerably larger in magnitude than the value ~ 1 found at the lower energies. In other words, the spectrum is quite steep at the higher energies ($E \gtrsim 1$ MeV) and quite flat at the lower energies ($E \lesssim 500$ keV). This property would tend to make the modulation more intense in the higher-energy channels, as observed. However, several values of $(\partial \ln J_{\perp} / \partial \ln B_{\zeta})_E$ in Table 2 would require spectral indices ~ 10 in the event that $d \ln B_{\mu}/d \ln B_{\zeta} = 1$. Since this requirement is not satisfied by the observed energy spectrum, it must be concluded that the February 14 micropulsation is not a wave that propagates purely in the direction of azimuthal drift.

Thus, it seems appropriate to consider a likely alternative, i.e., a substantially radial oscillation of the magnetosphere in a compressional mode. Frequency selection might then reside in the resonant properties of the magnetosphere. Cummings et al. [1969] have appealed to the idea of Alfvénic eigenmodes of the magnetosphere to account for spectrally pure transverse (noncompressional) oscillations having periods ~ 100 sec. Those oscillations were also observed at synchronous altitude during quiet times, but (being noncompressional) exhibited magnetic activity in the $\rho\varphi$ plane rather than in the ζ direction. The present observations suggest that perhaps in this case the magnetosphere (or that portion of it that lies beyond the plasmapause) has acted as a magnetosonic resonant cavity.

Except for the implications of Equation (1), the observations would have been compatible with the occurrence of a compressional drift wave carried by 15-keV protons, which have a total velocity $v \approx 1700$ km/sec. A wavelength of 2π gyroradii and a phase velocity comparable to the azimuthal drift velocity of these protons at $L = 6.6$ would have produced a wave frequency $\omega/2\pi \sim 3v/4\pi La \sim 10^{-2}$ Hz, as observed, where $\underline{a}$ is the radius of the earth. The estimated wavelength ($\sim 10^3$ km) would have substantially exceeded the gyroradius of a 1-MeV electron (~ 40 km), thereby accounting for the apparently adiabatic response of relativistic electrons to the field oscillations.

In view of the greater-than-expected degree of modulation in several of the electron channels, however, the drift-wave interpretation must be rejected in favor of a substantially radial magnetosonic oscillation, for which $d \ln B_\mu / d \ln B_\zeta$ in Equation (1) can significantly exceed unity. In this case the observed frequency can be accounted for by postulating a wavelength of roughly twenty earth radii, an ambient field $\sim 100\gamma$, and a plasma density ~ 3 protons/cm^3. The gradual growth of wave amplitude with time (Figure 1) suggests a convective plasma instability within the magnetosphere rather than an externally applied impulse. In this context it is interesting that the <u>bounce</u> frequency of a 15-keV proton is comparable in magnitude to the oscillation frequency observed. Bounce-resonant (15-keV) protons should be present in the magnetosphere as a major constituent of the quiet-day ring current. Either an inward radial gradient in their spatial distribution or an off-equatorial peak in their mirror-point distribution at constant μ (first invariant) might be an adequate source of free energy to initiate the field oscillation. Unfortunately the available instrumentation on ATS 1 did not provide for observation of protons in this relevant energy range.

Evidence for the magnetospheric scale of the February 14 event is provided by the magnetic-field data recorded during the same time period by the ground-based station at College, Alaska. College lies close to the foot of the field line passing through ATS 1. The rapid-run magnetogram shows a perceptible oscillation having a period ~ 2 min throughout the time interval 1740-1900 UT. Events having this character, however, are quite commonly observed at College, and coincidence with a compressional wave at synchronous altitude is apparently quite rare.

Indeed, the present observation at synchronous altitude appears unique among compressional waves in that it occurred during a magnetically quiet period. The three hours preceding the event (1500-1800 UT) exhibited Kp = 0, and the three hours following onset (1800-2100) showed Kp = 1^+ [Lincoln, 1967]. Hourly Dst values during this period were +2, +1, +0, +3, -0, and -2 gammas, respectively [Sugiura and Cain, 1969].

The oscillations observed at this time were quite different from any magnetic oscillations previously reported at synchronous altitude; e.g., storm-associated Pc-5 wave events [Barfield and Coleman, 1970], substorm-associated irregular pulsations [McPherron and Coleman, 1970], quiet-time transverse magnetic oscillations [Cummings et al., 1969], and band-limited pulsations [McPherron and Coleman, 1971]. Of the previously reported oscillations, only the transverse oscillations described by Cummings et al. [1969] occur during magnetically quiet periods. The storm-associated Pc-5 wave events are distinct from the event of February 14, 1967, in that they have a large transverse component. The substorm-associated irregular pulsations and band-limited pulsations mentioned above are quite irregular and occur only during magnetospheric substorms.

Moreover, the present radial oscillation differs in almost every respect from the azimuthally propagating drift wave detected by Brown et al. [1968] at $L \approx 5$ on April 18, 1965, and attributed to the drift mirror instability [Hasegawa, 1969; Lanzerotti et al., 1969]. That wave occurred during a geomagnetic storm, exhibited a much larger oscillation amplitude ($\sim 40\gamma$ peak-to-peak) than the present wave, and broke up into turbulence after only a few oscillations. Relativistic electrons were apparently heated non-adiabatically in the process. Further, the onset of the April 18 wave was preceded by a pronounced diamagnetic decrease of the field strength, clearly indicating that β (defined as the ratio of plasma pressure to magnetic pressure) was then of order unity. Accordingly, it was possible in that case to invoke a fluid-like instability (limited by gyroradius effects) rather than one involving 15-keV protons acting as resonant particles. Although observations by Frank [1967] suggest that $\beta \sim 1$ at the center of the ring current even during quiet periods, it would be unrealistic to invoke a fluid-like instability to explain the present observation because no apparent diamagnetic impulse precedes the onset of oscillation (Figure 1). A low-β condition among particles distributed unfavorably for wave growth could perhaps account for the unusual duration of phase coherence in the February 14 event.

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Table 1. Amplitudes and phases of log $I_0(E)$ relative to log B_ζ, 1759-1804 UT, as illustrated in Figure 3.

Omnidirectional Electron Channel Designation	Relative Amplitude	Relative Phase
$I_1 \equiv I_0(E > 0.30 \text{ MeV})$	2.11	$+1.9^\circ$
$I_2 \equiv I_0(E > 0.45 \text{ MeV})$	4.34	-6.7°
$I_3 \equiv I_0(E > 1.05 \text{ MeV})$	6.21	$+2.0^\circ$
$I_4 \equiv I_0(E > 1.90 \text{ MeV})$	6.44	$+2.2^\circ$

Table 2. Observed ratio of logarithmic modulation amplitudes, electron flux vs magnetic field, as deduced from Fourier spectra (1700-1900 UT).

Flux Type	Energy (MeV)	Relative Amplitude $(\partial \ln \text{Flux}/\partial \ln B_\zeta)_E$
$J_\perp$	0.4	4.74
$J_\perp$	0.6	6.45
$J_\perp$	0.8	8.14
$J_\perp$	1.1	8.74
$J_\perp$	1.3	8.12
$J_\perp$	1.5	6.71
$J_\perp$	1.9	6.49
I_0	0.30	2.53
I_0	0.45	4.85
I_0	1.05	6.55
I_0	1.90	5.62

FIGURE CAPTIONS

Fig. 1: Observations of electron-flux and magnetic-field oscillations at synchronous altitude. Absence of magnetic activity at 33.8 ± 0.7 cph in the $\rho\varphi$ plane identifies the oscillation as compressional. Logarithms (LOG) refer to base 10.

Fig. 2: Fourier spectra of representative logarithmic particle and field measurements, approximately 1700-1900 UT. Logarithms (LN) refer to base e. For computational convenience, the analyzed time interval has a length of 7209.840 sec (= 264 × 27.310 sec). The computed point nearest the spectral peak therefore corresponds to a frequency of 33.9536 cph (= 68 × 0.4993176 cph). The subsidiary peak at 22 cph arises from an instrumental effect contained in the particle data. Spectral behavior at $f < f_c = 14.4$ cph is influenced by application of a numerical filter to the field data, as required for defining $\hat{\underset{\sim}{\zeta}}$.

Fig. 3: Five-minute detail of logarithmic particle (I_0) and field (B_ζ) measurements, indicating phase coherence and relative amplitudes of best-fitting sinusoids. Logarithms (LOG) refer to base 10. Scale for log B_ζ is expanded by a factor of two (relative to the logarithmic electron-flux scales) for clarity.

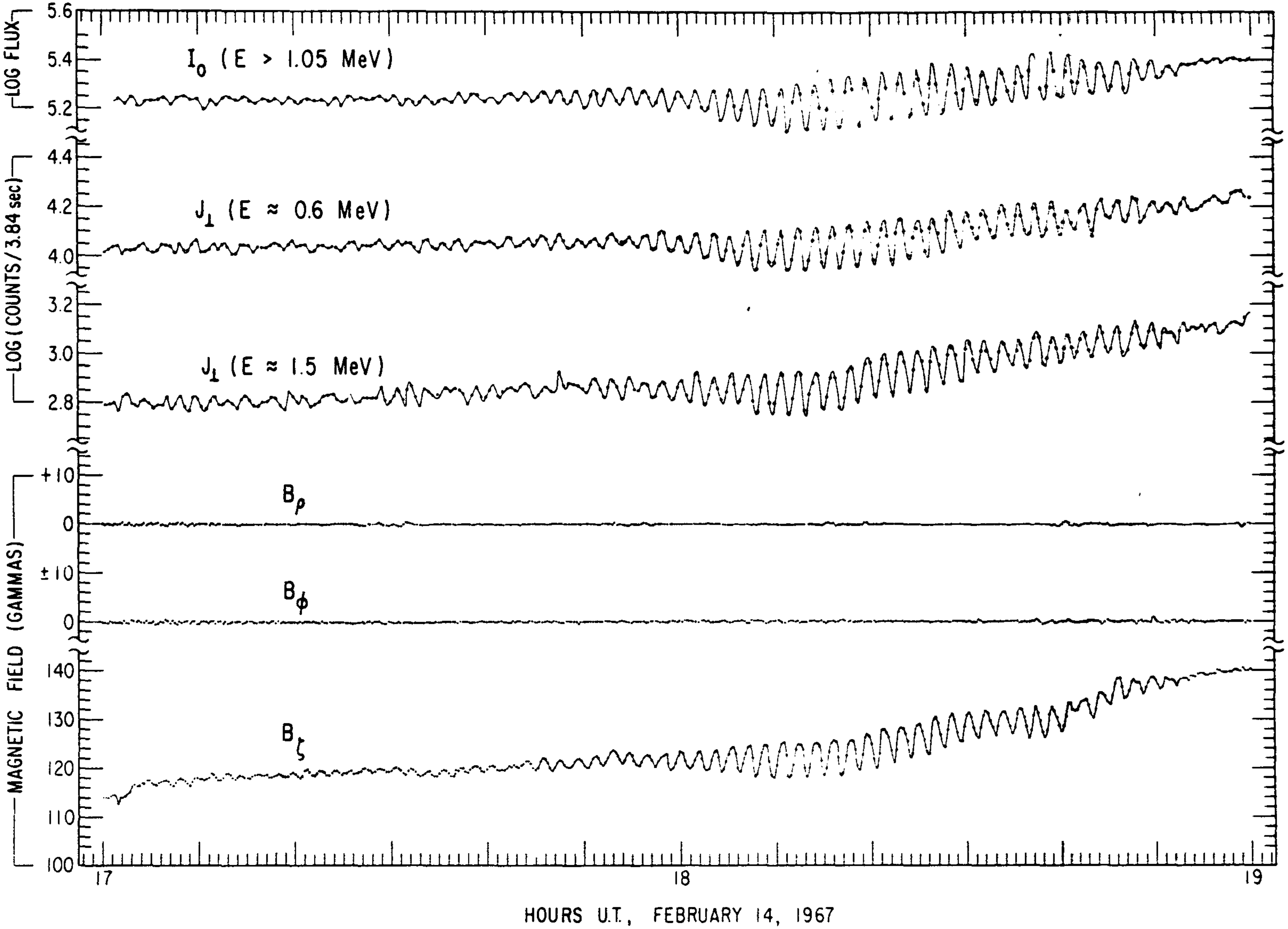
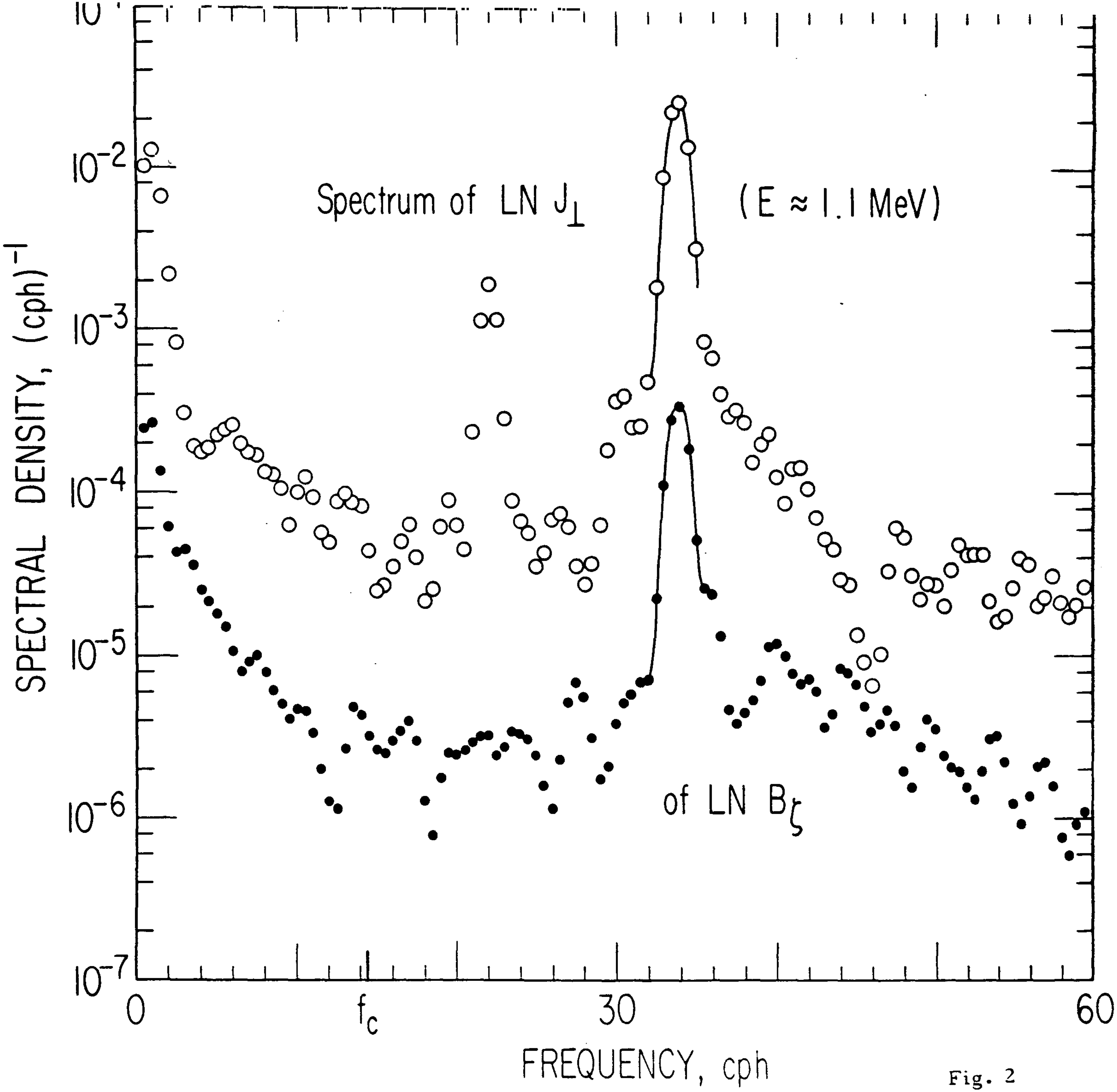
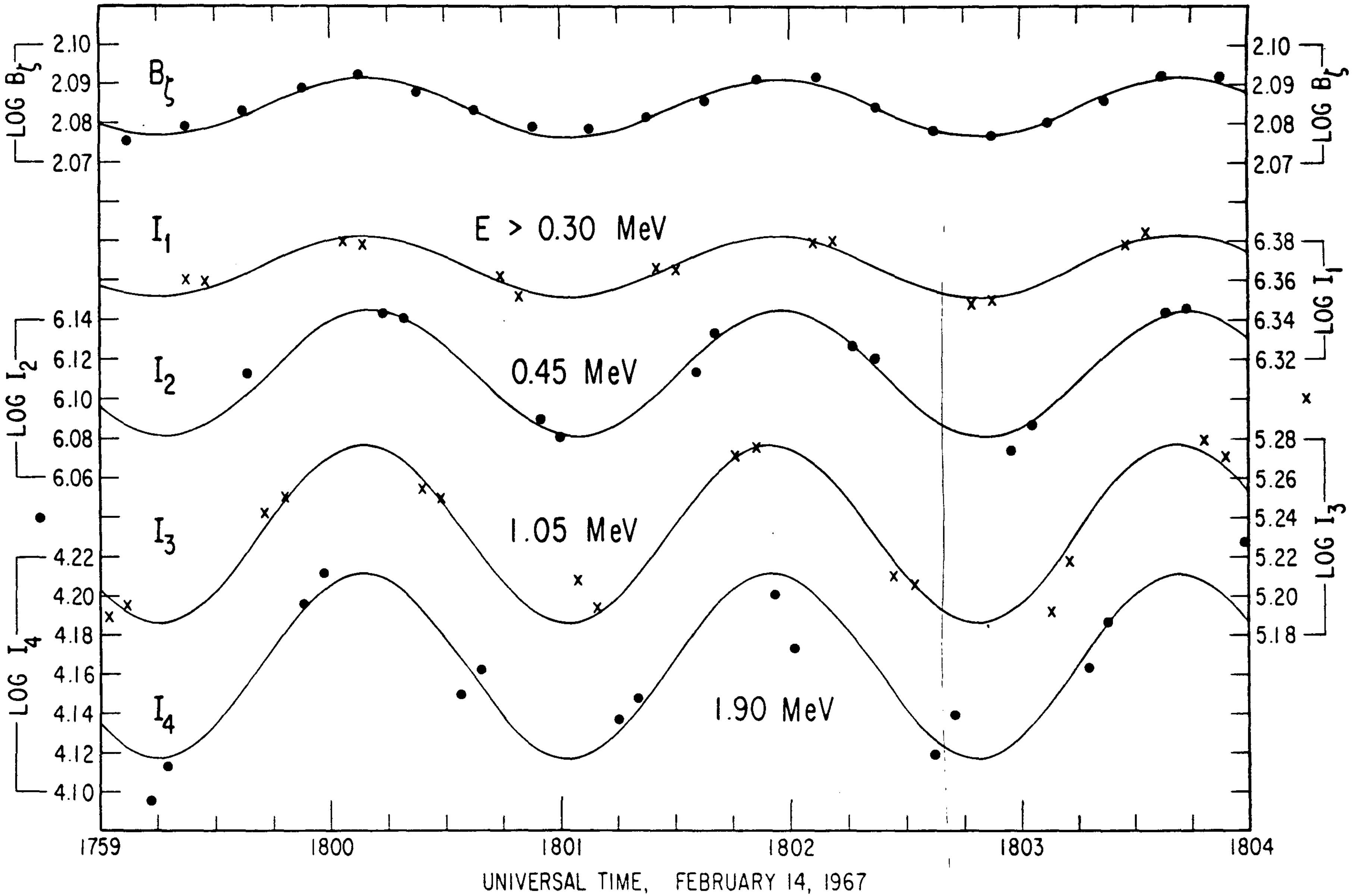

LOG FLUX
LOG (COUNTS / 3.84 sec)
MAGNETIC FIELD (GAMMAS)
5.6
5.4
5.2
4.4
4.2
4.0
3.2
3.0
2.8
+10
0
±10
0
140
130
120
110
100
I_0 (E > 1.05 MeV)
$J_\perp$ (E ≈ 0.6 MeV)
$J_\perp$ (E ≈ 1.5 MeV)
B_ρ
B_ϕ
B_ζ
17
18
19
HOURS U.T., FEBRUARY 14, 1967

Fig. 1



Spectrum of LN $J_\perp$
$(E \approx 1.1\ \mathrm{MeV})$
of LN B_ζ
SPECTRAL DENSITY, $(\mathrm{cph})^{-1}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
f_c
30
60
FREQUENCY, cph

Fig. 2



B_ζ
I_1
E > 0.30 MeV
I_2
0.45 MeV
I_3
1.05 MeV
I_4
1.90 MeV
LOG B_ζ
LOG I_1
LOG I_2
LOG I_3
LOG I_4
2.10
2.09
2.08
2.07
6.38
6.36
6.34
6.32
6.14
6.12
6.10
6.08
6.06
5.28
5.26
5.24
5.22
5.20
5.18
4.22
4.20
4.18
4.16
4.14
4.12
4.10
1759
1800
1801
1802
1803
1804
UNIVERSAL TIME, FEBRUARY 14, 1967

Fig. 3