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The purpose of this short note is to present a heuristic discussion on the question of how the resonant oscillations of the earth's magnetic field are produced. Extensive theoretical studies have been made on the possible hydromagnetic resonance modes for the magnetosphere using various idealized models (e.g., Dungey, 1954; Radoski and Carovillano, 1966; Radoski and McClay, 1967; Troitskaya and Gul'elmi, 1967). Though there is little doubt that the solar wind is the ultimate source of stimulation of the magnetospheric resonance, the precise mechanism of the magnetosphere - solar wind interaction leading to this stimulation is not clear. The idea that the low-frequency pulsations observed on the earth's surface at high latitudes are caused by oscillations of the outer magnetosphere which in turn are engendered by a transfer of momentum from the solar wind can probably be said to have a connotation of a generation mechanism of a 'percussive' nature; namely, the solar wind beats the magnetosphere as if the latter is a percussive instrument in music. This was certainly true when Wilson and Sugiura (1961) attempted to explain hydromagnetic waves associated with sudden commencements of magnetic storms; the interplanetary shock wave responsible for a sudden commencement was the drumstick in this case.

Geomagnetic pulsations in the frequency range of Pc 2-4 are also considered to be due to hydromagnetic resonance of the magnetosphere (e.g., Saito, 1969; Troitskaya and Gul'elmi, 1969). However, the observation that coherent field oscillations can be sustained for such extended length of time as tens of minutes or several hours has been a puzzle to the present author if the generation of the magnetospheric resonance is essentially percussive. This question seems to be cleared, however, if one takes an analogy to the vibration of a string instrument, say, the violin. What follows below is a brief exposition of an idea that the magnetosphere resonates like a violin with the solar wind acting as the bow.

It is probably helpful first to review how the violin vibrates. From the violin a sustained tone is obtained by bowing, where the bowing is a process in which the bow, while being pressed against the string, is drawn in the direction transverse to the string either up or down. As the bow pulls the string, the tension of the string builds up until the frictional force from the bow can no longer pull the string, and when this happens the string slips back and overshoots its initial position. Then the bow catches the string again, and the above process is repeated; this sequence of events continues till the bowing is finished. The transverse displacement of the string is schematically illustrated in Figure 1 (C) in which the time axis is taken horizontally. Simple as it may appear macroscopically, there is a minute mechanical artifice to achieve a good bowing process.

Microphotographs of the surface structures of a string and a hair are shown in Figures 1 (A) and 1 (B), respectively. The string is an "A" string with a fundamental frequency of 440 Hz. The core of the string, made of sheep gut, is wrapped around with an aluminum strip, sections of which are seen as white stripes in the photograph (A). (Other metals may be used for the lower frequency strings, for instance, silver for the G string whose fundamental frequency is 198 Hz; obtaining a higher density appears to be the primary reason for using silver or other heavy metals.) The surface of the aluminum strip is threaded in the direction parallel to the axis of the string. The bow has a shank of about 150 (horse tail) hairs. One individual hair is magnified in the photograph (B), in which a scaly surface structure is revealed. The scales themselves, however, are not directly responsible for the friction in the bowing; instead, they hold rosin, which provides the required friction. It seems clear that the sticky rosin on the bow hair and the striae, or threads, on the metal strip around the string are the most important elements for creating the friction between the string and the bow. Mechanical actions of the violin, especially from the acoustic point of view, have been discussed in great detail, for instance, by Saunders (1937, 1940). However, since no references were available on the microscopic features of the string and the bow from readily accessible sources, the above investigation was made using a petrographic microscope.

In the case of the magnetosphere the solar wind acts as the bow continuously drawn as long as the solar wind lasts. The frictional force on the magnetopause assumed by Axford and Hines (1961) to produce a drag that drives the convection in the magnetosphere may be thought as the frictional force created by the solar wind bowing. An interesting point is that in this picture the magnetospheric resonance is produced by the same frictional force on the magnetopause as that responsible for the magnetospheric convection. Just as a violin can sound differently depending on the manner of bowing, namely, on the pressure with which the bow is pressed on the string and the speed with which the bow is moved, the magnetosphere will resonate differently depending on the solar wind pressure, speed, and other factors that are involved in the creation of the frictional force on the magnetopause. Relationships between the solar wind parameters and the intensities and/or predominant periods of geomagnetic pulsations have been shown in recent years (e.g., Saito, 1969; Troitskaya and Gul'elmi, 1967, 1969; Gringauz et al., 1971). It is suggested here that the 'bowing' process of the solar wind is the key linkage between the solar wind conditions and the magnetospheric oscillations.

In the violin the vibration of the string is transmitted to the belly, i.e. the top plate, through the bridge, and then to the back via the sound-post and to some extent, via the sides of the body; the air inside appears to resonate also at a low frequency. From a study of 'response curves' of violins, Saunders (1940) found that each tone of any one violin has a quality which is different from that of every other tone given by that instrument. Each response curve contains certain peaks and hollows. When a note is played, the peak corresponding to the frequency for the note becomes the fundamental tone. This is from a natural resonance of some part of the violin (usually of the belly) at this particular frequency. Even a simple flat, square metal plate (a Chladni plate) has complicated modes of resonant vibrations, making it possible to resonate to many different tones (Saunders, 1940). Each violin, having a complex structure with the bridge, the sound-post, the two f-shaped holes on the belly, etc., etc., has resonance modes that can only be investigated empirically. As to the magnetosphere, not only its size but its field configuration and plasma contents are highly variable even under magnetically quiet conditions (e.g., Sugiura et al., 1971). Thus the resonance of the magnetosphere must be extremely complicated. Probably only the very fundamental characteristics are predictable by theory, and empirical approaches are likely to be helpful.

Observations of low frequency waves in the magnetosphere have been made by Judge and Coleman (1962), Patel (1965), Cummings et al. (1969), and Heppner et al. (1970). The paper by Cummings et al. (1969) showed examples of waves observed by the synchronous satellite ATS 1 that can clearly be considered to be resonant oscillations, and the authors theoretically interpreted the waves as such. Heppner et al. (1970) gave a preliminary survey of the distribution of pulsations in the magnetosphere from OGO's 3 and 5. According to their analysis, waves in the Pc-3 band (10-45 sec periods) occur predominantly in the dayside magnetosphere; thus the diurnal variation in the occurrences of these waves resembles that of Pc-3 pulsations observed on the ground. (See, e.g., Saito, 1969, for statistics of ground pulsations.) According to Heppner et al. (1970), Pc-3 waves were observed a little over 30% of time between L = 5 and 8 near noon (their Figure 2). The results (a) that Pc-3 waves are found at all distances covered by the OGO observations, from the near-earth regions to the magnetopause, (b) that the diurnal variation in the frequency of occurrence has a maximum near noon, and (c) that the frequency of occurrence is high (~ 30% of time), namely that they are not rare events, are consistent with the violin model of the magnetosphere. The bowing is likely to be most effective in the subsolar area of the magnetopause, and the amplitudes of the resonant vibrations are expected to be largest near noon, diminishing toward the flanks and the tail. As to the point (c), for the model to be meaningful the resonant vibrations have to occur fairly frequently.

If the magnetosphere resonates as a whole, one would expect (or, hope), under favorable circumstances, to be able to observe field oscillations everywhere along one satellite pass from near its perigee to the magnetopause. Such an occasion was indeed encountered by OGO 5 on its outbound orbit on March 15, 1968. As oscillatory character of the field throughout the magnetosphere during this pass is evident in Figure 2. Power spectral analysis was made on the deviations, ΔB and ΔD, of the scalar field B and declination D from the respective quantities of a reference field, for the entire span of time for which data were available, namely from 0018 to 0400 UT. The results are given in Figure 3. The power spectrum for D has an outstanding peak at 384 seconds in period with two other less notable peaks at 115 seconds and 77 seconds. In the power spectrum for ΔB there is no trace of a peak in the vicinity of 384 seconds, meaning that this resonance involves only transverse oscillations. The same appears to be true with the other two peaks in ΔD. Conversely, the peaks at 117 and 45 seconds in the ΔB power spectrum have no counterparts in the power spectrum for D; thus these must be essentially longitudinal oscillations. It may be remarked that there is no definitive harmonic structures in these power spectra. The ratio of the frequencies for the two secondary peaks in ΔD (115 and 77 seconds in period) is approximately 2 to 3, but no spectral peak is found for the fundamental frequency. There have been found other passes on which field oscillations were observed over extended periods of time, sometimes with cleaner wave forms than in Figure 2 but more restricted in duration. A more detailed statistical study of power spectra will be reported later when the data analysis is further extended.

The magnetic field in the region just inside the dayside magnetopause usually exhibits regular or irregular fluctuations of time scales of the order of several minutes; Figure 2 is a good example showing irregular, large amplitude field fluctuations in this region. This feature can be found in nearly all figures giving the magnetospheric field near the dayside magnetopause. These fluctuations might be a direct effect of the solar wind 'bowing' on the magnetopause surface; namely, they may be the results of pulling and slipping of flux tubes from the bowing. In the dayside equatorial region the magnetospheric field immediately inside the magnetopause is nearly perpendicular to the bulk velocity of the solar wind. If the magnetopause surface has field-aligned striations, there would be even closer analogy to the violin string. What plays the role of rosin is not clear. Various theoretical models have been proposed such as: viscous stress (Axford, 1964; Faye-Petersen and Heckman, 1968), Kelvin-Helmholtz instability (Southwood, 1968), plasma instability (Eviator and Wolf, 1968), etc. To clarify this question, crucial observational factors appear to be still missing. However, the analogy of magnetospheric resonance to the violin playing is so intriguing that it seems worthwhile to pursue this line of approach further.

Acknowledgements

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CAPTIONS FOR FIGURES

Figure 1. A string and the bow of a violin: (A) a section of the string, showing the striated surface of an aluminum strip that wraps around the gut in the core; (B) scaly surface of a hair; the primary function of the scales is to hold rosin; (C) schematic illustration of the displacement (taken vertically) of the string plotted against time (the horizontal axis), indicating the repeated action of a pulling of the string by the bow followed by a slipping back. Photographs (A) and (B) were obtained using reflected light on a petrographic microscope; the length scales are given in units of microns.

Figure 2. ΔB (the observed scalar field minus the magnitude of a reference field), D (declination), and I (inclination) observed by the GSFC fluxgate magnetometer aboard OGO 5 along its outbound pass on March 15, 1968.

Figure 3. Power spectral densities for ΔB and ΔD for a four hour period covering geocentric distances from 2.3 to 9.6 R_e, taken from the magnetospheric portion of the orbit in Figure 2.

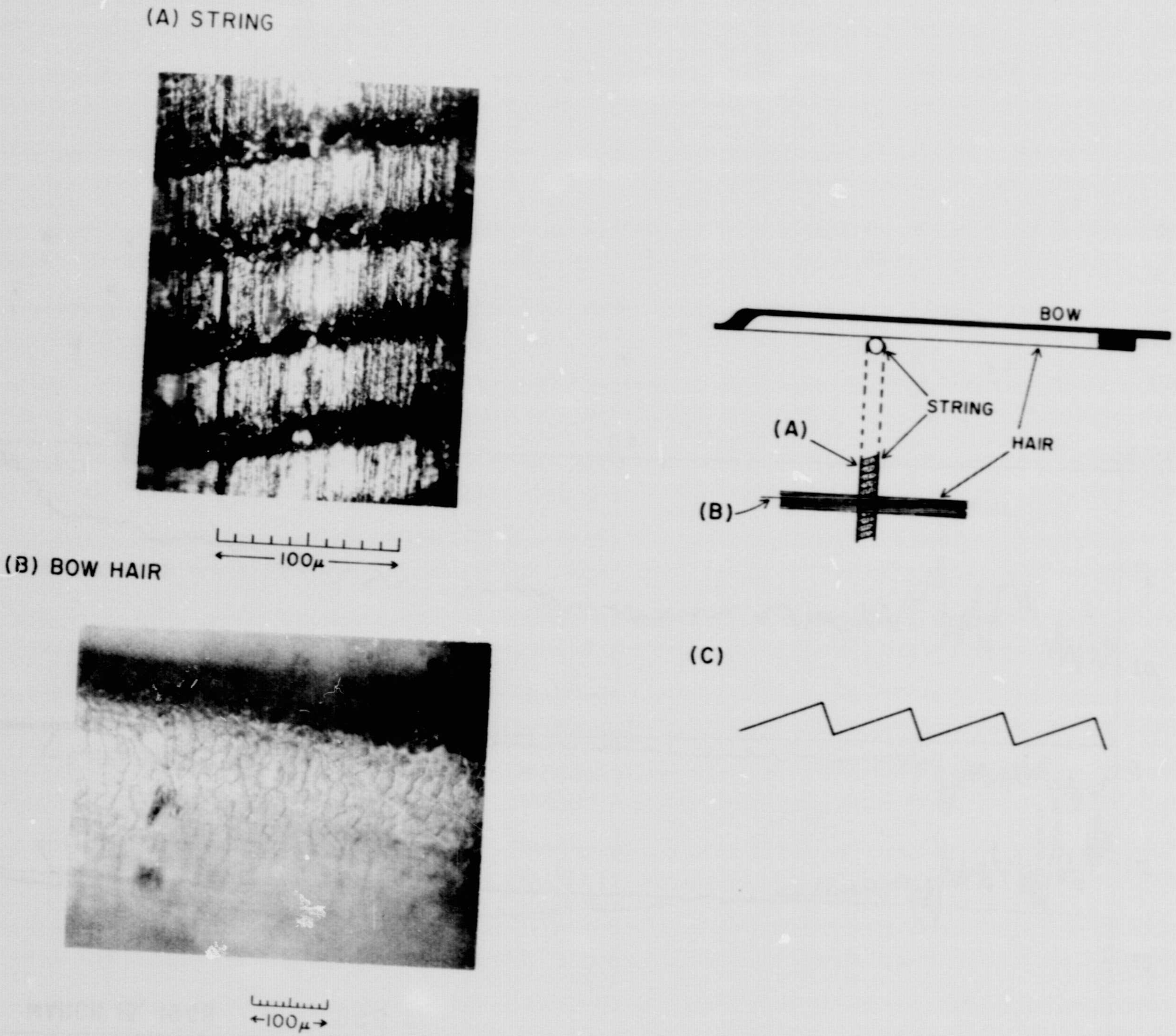

FIGURE 1

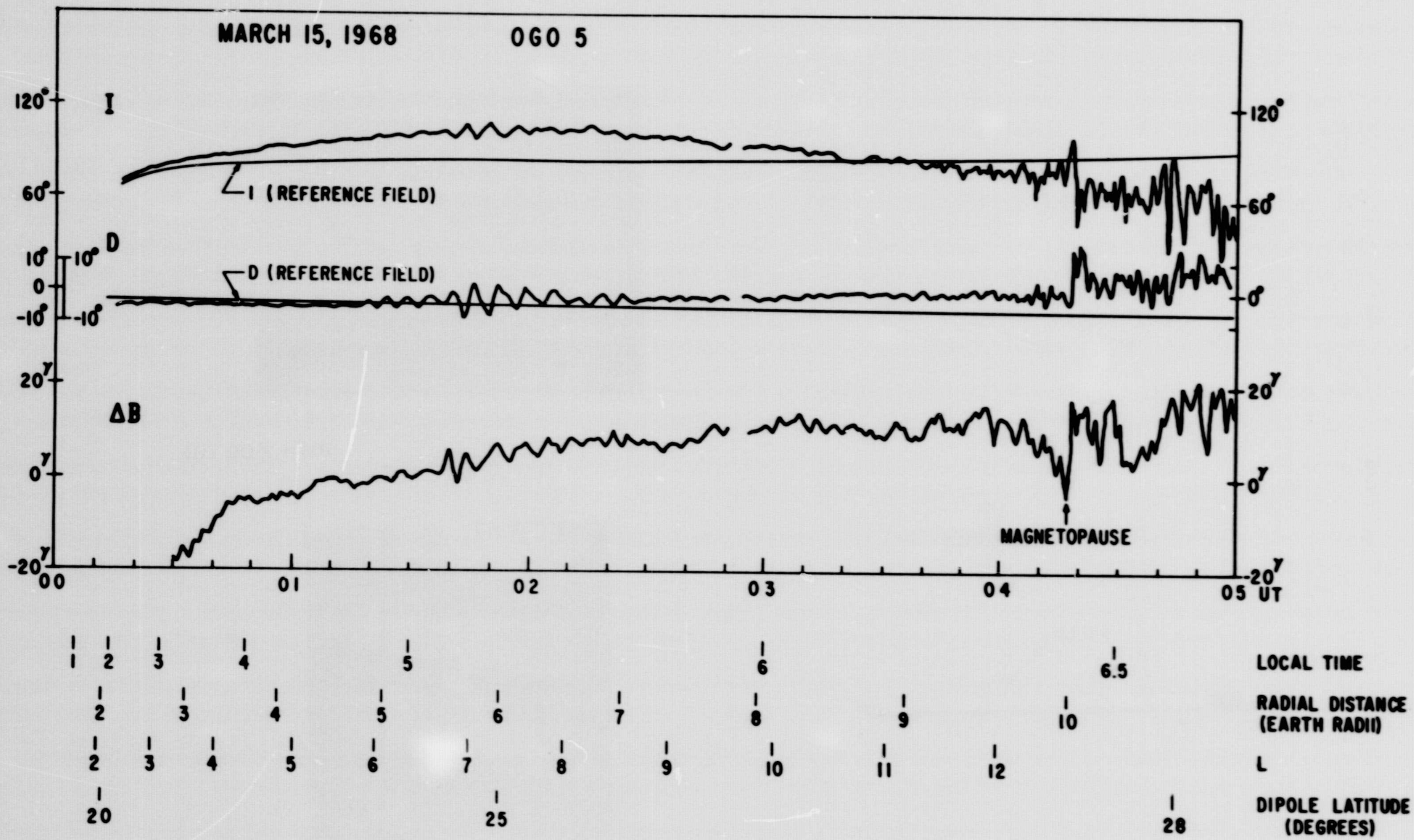
MARCH 15, 1968
OGO 5
I
I (REFERENCE FIELD)
D
D (REFERENCE FIELD)
ΔB
MAGNETOPAUSE
120°
60°
10°
0
-10°
20γ
0γ
-20γ
00
01
02
03
04
05 UT
LOCAL TIME
RADIAL DISTANCE (EARTH RADII)
L
DIPOLE LATITUDE (DEGREES)

FIGURE 2

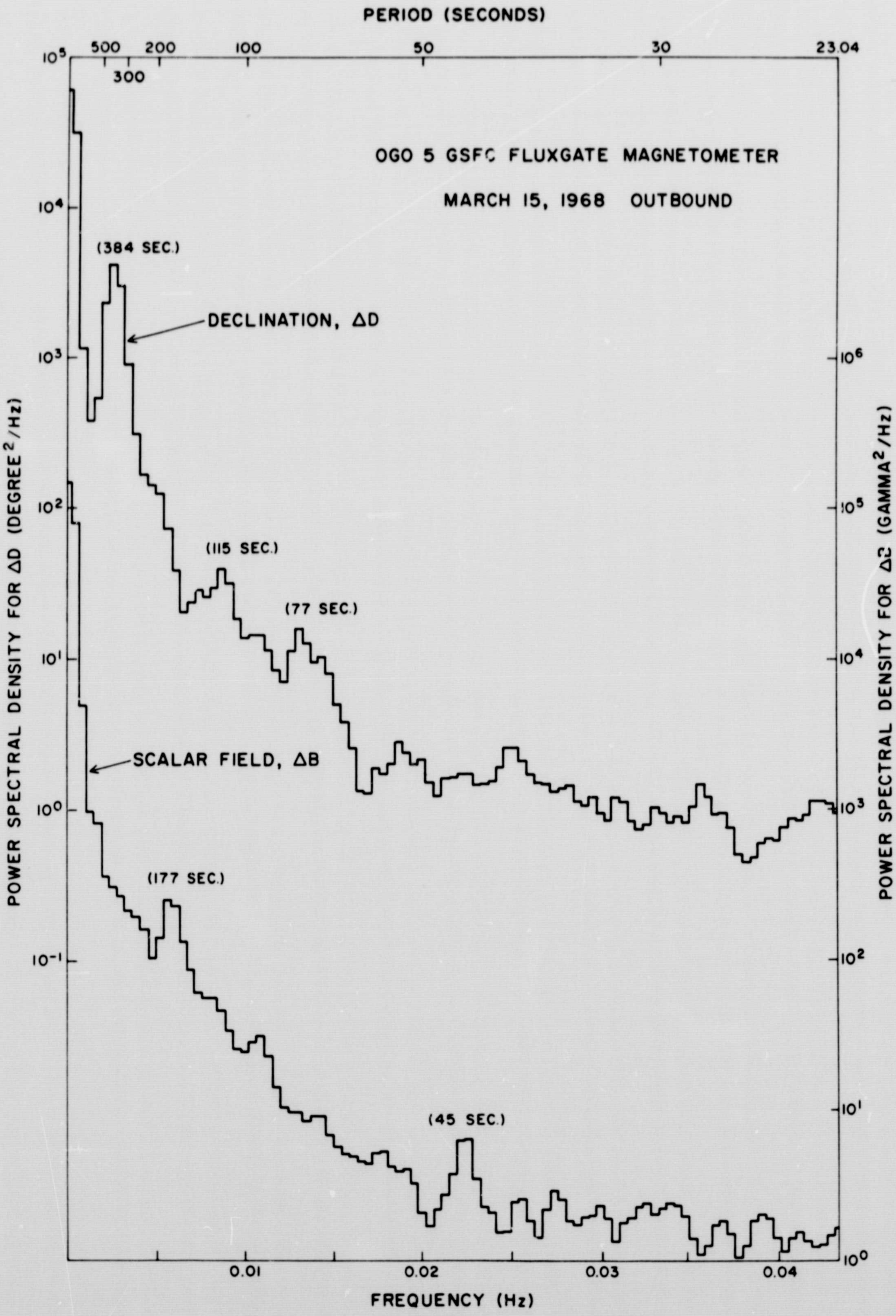
PERIOD (SECONDS)
500
200
100
50
30
23.04
300
OGO 5 GSFC FLUXGATE MAGNETOMETER
MARCH 15, 1968 OUTBOUND
(384 SEC.)
DECLINATION, ΔD
(115 SEC.)
(77 SEC.)
SCALAR FIELD, ΔB
(177 SEC.)
(45 SEC.)
POWER SPECTRAL DENSITY FOR ΔD (DEGREE²/Hz)
POWER SPECTRAL DENSITY FOR ΔB (GAMMA²/Hz)
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁶
0.01
0.02
0.03
0.04
FREQUENCY (Hz)

FIGURE 3