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# Solar modulation of charged particle oscillations in the heliosphere (f$\sim$ 5 $\mu$Hz)

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**Abstract.** Time series analysis of low energy electron and high energy proton cosmic ray fluxes, both measured on the Ulysses spacecraft, shows that they are coherent in some frequency bands in the energy range 0–6 $\mu$Hz, especially near 5 $\mu$Hz. Interplanetary particle fluxes with very different kinematic properties (e.g., gyrofrequencies) are modulated coherently in the heliosphere at discrete frequencies; one specific example, discussed here, has a period of $\sim$2.2 days. The analyzed data spans the interval 1 January 1993 to 20 April 1994 when Ulysses traveled between $22^\circ$ and $60^\circ$ south heliographic latitude and was about 4 AU from the Sun. The frequency at $5.26$ $\mu$Hz is tentatively identified as a zonal harmonic mode with $l = 2$, $m = 0$.

## 1 Introduction

The nature of the interplanetary medium has long been a topic of considerable significance in space plasma physics (e.g., Parker, 1963). The propagation and transport of solar and galactic charged particles within the medium have also been continuing subjects of intense theoretical and observational investigations. It is well recognized that large scale structures in the interplanetary medium, especially corotating (with the Sun) interaction regions (CIRs), modulate the interplanetary charged particle population over a wide range of energies (and thus a wide range in kinematic parameter space; Wibberenz *et al.*, 1998). The co-rotating interaction regions, with periods of the order of a solar rotation, are identified with complicated magnetic structures on the Sun, including the boundaries that delineate coronal holes (e.g., Simnett *et al.*, 1998). The interactions can change the energies of solar and heliospheric particles. Recently, Thomson *et al.* (1995, hereafter TML; see also Thomson *et al.*, 2000) reported that the Sun also appears to modulate the interplanetary medium at periods in the range of days to minutes. If so, there should be coherent variations in particle fluxes at frequencies considerably higher than that corresponding to the solar rotation.

Blake *et al.* (1997) in fact have reported evidence for some higher frequency variations in galactic cosmic rays (protons $E > 230$ MeV). Neugebauer *et al.* (1995) reported variations in interplanetary magnetic fields with a period in a broad band around 2–3 days. Thomson *et al.* (1997) reported that spectral analysis of low energy ($\sim$0.5–2 MeV/nuc) protons, helium, and oxygen ions exhibited periods in the range 5 days to $< 26$ days that did not correspond to the expected harmonics of the solar rotation period. Thus, there is evidence that frequencies of a few days exist, at least at some times, in the interplanetary medium.

In this paper, the coherence of time variations of $\gtrsim 50$ keV electrons with high-energy protons (125–250 MeV; 250 MeV–2 GeV; $>$ 2 GeV) measured with the HI-SCALE (Lanzerotti *et al.*, 1992) and KET (Simpson *et al.*, 1992) instruments, respectively, on the Ulysses spacecraft is investigated (Thomson *et al.*, 2001). Particles of these energies are used since they have quite different kinematic properties. In particular, the gyrofrequencies of the electrons and protons in a 1 nT field are $\sim 200$ Hz and $\sim 200$ mHz, respectively, both much higher than the frequencies studied here. The electron velocity $v_e$ is approximately $v_p$/2. Data in the interval 1 January 1993 through 20 April 1994 are investigated. During this interval Ulysses traveled over the latitude range from $\sim 22^\circ$ S to $\sim 60^\circ$ S, and from 5.05 to 3.23 AU.

Shown in the upper panels of Figure 1 are the time series of 38–53 keV electrons and $> 2$ GeV protons for the interval studied. The bottom panel shows the same two particle flux time series filtered in a narrow band around 5.2 $\mu$Hz (4.92–5.23 $\mu$Hz; $\sim$2.2 day period). The amplitudes and phases of the two time series track quite well in this band, particularly after about mid-1993. This suggests the existence of large scale modulation in the heliosphere that can affect particles with very different kinematic properties.

Examination of the statistical characteristics of these data shows that logarithms of the electron fluxes are closer to Gaussian than the original data samples. Hence, the series

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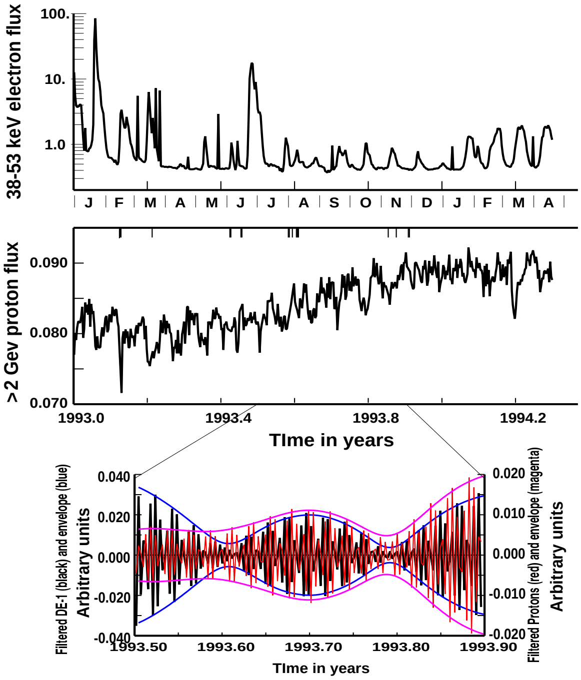


**Fig. 1.** Upper panels: Daily spin-averaged 38–53 keV electrons (DE1) and KET $>$ 2 GeV protons (upper and center panels, respectively), 1 January 1993 to 20 April 1994. Lower panel: 150 days of data from the top panels filtered in the narrow band 4.92–5.23$\mu$Hz. The red (dark) traces correspond to the ions (electrons).

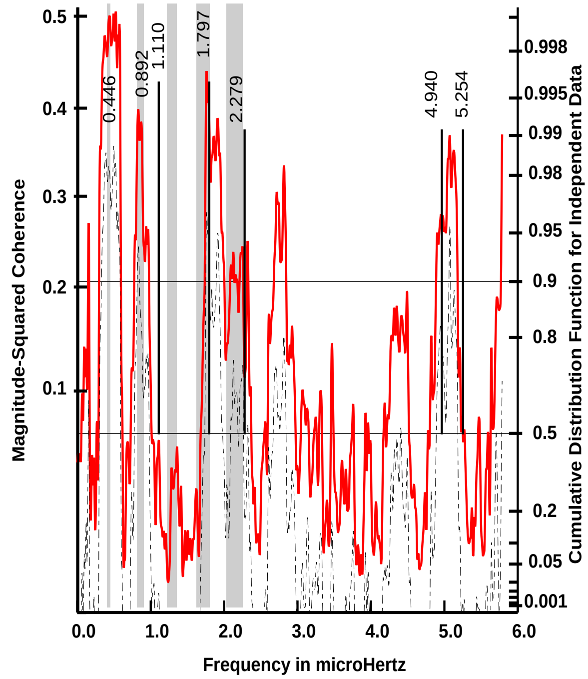


**Fig. 2.** Smoothed multitaper magnitude-squared coherence (MSC) between DE1 and $>$ 2 GeV protons. The left-hand scale is in units of MSC. The right-hand scale is the cumulative distribution function for two independent series. The solid (red) curve is the estimated MSC, the dotted curve is one standard deviation below it. The grey bands show the range of solar rotation frequencies, 452.4 to 407.5 nHz for the latitudes covered plus the first four "harmonics." The labeled frequencies (some with solid vertical lines) mark frequencies from TML Table 2.

of the logarithms are less dominated by rare large peaks, and their statistics are more characteristic of the majority of the data. Lanzerotti *et al.* (1991) give additional information on the distribution of interplanetary particle fluxes and argue that, because of the product terms occurring during acceleration of the particles, the logarithmic transformation gives physically more meaningful results. The resulting power spectra are much more reliable when logarithms of the electron fluxes are used. Because cosmic ray flux is generally negatively correlated with solar activity, we used the negative proton fluxes. Averages were subtracted from the transformed data before further processing.

## 2 Results

The magnitude-squared coherence (MSC) between the 50 keV DE1 electrons and the $>$ 2 GeV protons for the time interval of the upper panels of Figure 1 is shown by the solid curve in Figure 2 as a function of frequency from 0 to 6 $\mu$Hz. Coherences were calculated between each time series using multiple-windows (or tapers) (Thomson, 1982, 1990, 2001, summarized also in Thomson *et al.*, 2001). The dotted curve is one standard deviation below it. The cumulative probability distribution (confidence levels), calculated for independent data sets, is shown on the right axis. Several peaks where the coherence exceeds the 98% significance level are evident, with 24% of the estimates above the 90% level. Generally, the standard deviations are close to those expected for Gaussian processes, implying that the significance levels should be reliable. The labeled frequencies (some with solid vertical lines) mark frequencies from TML, Table 2. This table lists 35 frequencies between 0.446 and 131.989 $\mu$Hz ($\sim$2.1h to $\sim$26d period) where TML reported at least 4 coincident spectral peaks in 9 data sets that did not include the cosmic ray proton data analyzed here. Analyses presented in Thomson *et al.* (2001) demonstrate that the 5.2 $\mu$Hz peak is not a harmonic of the solar rotation.

The phase between the electron and proton time series was investigated. The dark solid line in Figure 3 shows the phase of the coherency for the DE1 and the $>$2 GeV proton fluxes for the same frequency range as in Figure 2. The light dashed lines are $\pm$1 standard deviations from this phase, computed as for Figure 2. Where the coherences in Figure 2 are low, the standard deviations of the phase values tend to be large (e.g., between 1 and 1.8 $\mu$Hz and 3 and 4.8 $\mu$Hz). The lower dashed straight line was fit to the phases at frequencies where the MSC had a local maximum in the band around 5 $\mu$Hz. At the frequency of 5 $\mu$Hz, the phase is $\sim 81^\circ$, with the low-energy electrons leading the relativistic protons by about 0.56 day. This is not understood.

The robustness of the phase determination at $\sim$ 5 $\mu$Hz was checked by sliding the 50 keV electron data by three days relative to the $>$2 GeV protons. The result of this phase cal-

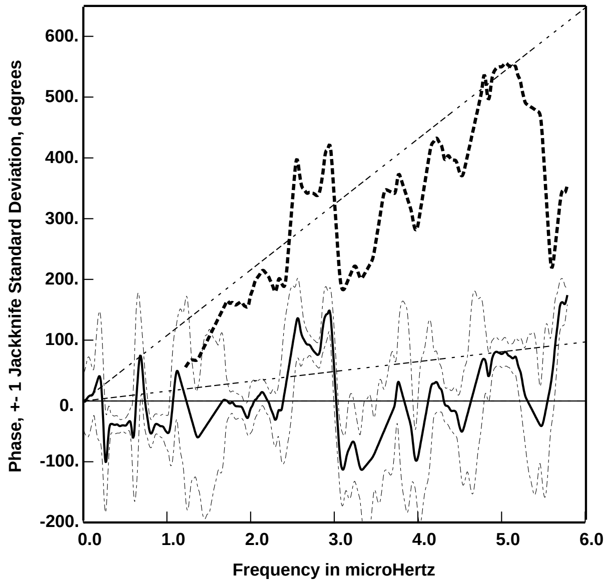


**Fig. 3.** The phase of the coherence between the DE1 electrons and $>$2 GeV protons (heavy solid line). The lighter dashed lines are $\pm1$ standard deviation from the phase estimate. In regions where the coherence is high the phase is determined to within about $\pm10$ or 15 degrees. The lower straight dashed line is a linear fit between 0 frequency and the phases at the high coherency frequencies around 5 $\mu$Hz; the upper dashed line is the result of advancing the electron data by three days.

culation is shown by the upper thick dotted line in Figure 3. (Sample $n = 0$ was the electron data for 4 Jan 1993, and the $>$2 GeV data for 1 Jan 1993.) The upper straight dashed line is not a fit but rather is the lower dashed line fit plus an additional slope of $3 \times 360 \times 86400 \times 10^{-6\circ}$ $/\mu$Hz. This is the phase shift between the two quantities that would be expected if there were a real physical process in the interplanetary medium that was modulating both particle species at the frequency identified. Indeed, in the band near 5 $\mu$Hz, the agreement is excellent.

## 3 Discussion

The results above, which are greatly elaborated upon in Thomson *et al.* (2001), demonstrate that charged particle fluxes in the interplanetary medium are modulated at a period that corresponds to $\sim$2.2 days ($\sim 5.2\mu$Hz). This period can not readily be ascribed to a high harmonic of the basic solar rotation period, especially since many of the lower harmonics are not evident in the coherence results. The two particle species have very different physical properties. They would not be expected to have coherent modulations at such a frequency if the only influences upon the particles were scattering by fluctuating magnetic fields at the particle gyro frequencies and large-scale modulations by the heliospheric current sheet (Jokipii, 1966; Bieber and Matthaeus, 1997). The large-scale, solar rotation-related modulation of each species by the heliospheric current sheet arises from the controlling solar source: that is, by the complex magnetic topology of the streamer belt that gives rise to the current sheet.

We conclude that there must be a controlling solar source that is producing a large-scale modulation of the heliosphere particle fluxes at a period of $\sim$2.2 days. Furthermore, this periodicity must be present at the solar photosphere, probably produced by fundamental oscillations in the solar interior, as proposed previously by TML. These oscillations at the photosphere propagate to the solar corona and then into the interplanetary medium as hydromagnetic waves. The dynamics of the interplanetary medium does not destroy such a fundamental period generated by the Sun. It would be expected that this period should also be present in the fluxes of interplanetary plasmas and magnetic fields, and Neugebauer *et al.* (1995) have presented some evidence for this. From their analyses, Thomson *et al.* (2001) tentatively identify the frequency at $\sim 5.26\,\mu$Hz as a solar zonal harmonic mode with $l = 2$, $m = 0$.

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