Proceedings of ICRC 2001: 3592 © Copernicus Gesellschaft 2001

ICRC 2001

Wavelet analysis of the 26 days recurrent component in the outer heliosphere

C. Kato[1], **F. Mcdonald**[2], **and S. Yasue**[1]

[1]Fac. of Science, Shinshu University, JAPAN
[1]IPST, University of Maryland, USA

Abstract. It has been reported in previous studies that the 26-day recurrent phenomena exist in the data of intensity variations of solar wind, interplanetary magnetic field and cosmic rays observed in the outer Heliosphere. In recent paper by Zhang (1994), a liner correlation between mean amplitude of those recurrent phenomena and latitudinal gradient of cosmic rays has been reported based on the data from Ulysses. We analyse this phenomena at larger heliospheric distances using observations from the cycle 21 solar minimum period by applying a wavelet transform technique to the data from Voyager-1 &-2 and Pioneer-11. The average amplitudes as derived for Ions (>70 MeV/n) or H (>80 MeV), are 1.78+0.47 (%), 0.69+0.25 (%) and 5.64+1.05 (%) at the location of Voyager-1, -2 and Pioneer-11, respectively.

1 Introduction

The passage of Co-rotating Interaction Regions (CIRs) is usually thought to change particle diffusion properties and create recurrent variations observed at low and middle heliospheric latitude (Kóta and Jokipii, 1991). The latitude gradient of cosmic ray flux may be caused by large scale magnetic structure in the heliosphere. It has been thought that these two are independent of each other because magnetic fields of two different scales play a role for those two cosmic ray variations. However, Zhang (1997) has shown that a linear relation does exist between those two phenomena in the inner heliosphere using data from Ulysses and IMP.

It is useful to investigate these relations in the outer heliosphere. The 26 days recurrent phenomena in the outer heliosphere have been reported previously (c.f. Decker, et.al,1999). Co-rotating shocks are weakening in this region (≥15 AU). In this paper we probe the amplitude of 26 days recurrent component in the outer heliosphere by applying wavelet transform thecnique.

Correspondence to: C. KATO (ckato@corona.shinshu-u.ac.jp)

Table 1. Location of the spacecrafts

Space crafts	Radial diatance (AU)	Heliospheric latitude (deg.)
Voyager-1	26-36	30N
Voyager-2	20-30	4N
Pioneer11	21-29	15N

2 Observations

This study is based on the data from Voyager-1, -2 and Pioneer-11 observed at 20-36 AU in the minimum period of 1986 to 1988. During this period, the spacecrafts were at various heliographic latitudes. Voyager-1 made observation at about 30 degrees north and Voyager-2 observed at nearly equatorial plane. Pioneer-11 was located between Voyager-1 and -2, at about 15 degrees north. Positions of space crafts are summarized in Table 1.

The daily averaged counting rate of ions > 70 - 80 MeV/n, have been analysed. Ions > 80 MeV observed at IMP-8 are also used as a reference at 1 AU.

Figure 1 shows the counting rate of ions > 70 MeV/n observed at Voyager-1, 2 and of H (> 80 MeV, including electrons with energy of > 31 MeV) by GTT on board Pioneer-11 as function of time. 10days running averaged data are shown. Spiky solar events are eliminated from the data.

The intensity of charged particle at Voyager-2 and IMP-8 has a maximum in 1987. On the other hands, high intensity is continuing to the end of 1988 at Voyager-1 as reported previously (ex. McDonald et al, 1993). It seems that yearly variation exist on the data from Pioneer11. Unfortunately, there is significant absence of particle data for the first half year of 1998 at Poneer-11. The data is interpolated by linear function for that period.

In figure 1, the intensity variation of ions with energy of >80 MeV observed at IMP-8 is also shown as a 1 AU reference. To focus on 26 days periodicity, the general trend has been removed from the data by subtracting from the 26 days running average. Data filtered by 26 days running aver-

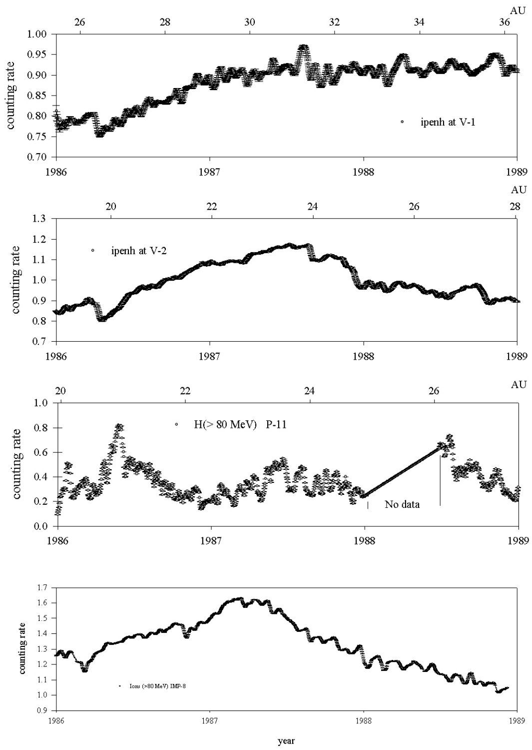

Fig. 1. Counting rate of cosmic ray in 1986-1988. From top to bottom panels, 10 days running averaged data at Voyager-1 (ions > 70 MeV), Voyager-2 (ions > 70 MeV), Pioneer11 (H > 80 MeV) and IMP-8 (ions > 80 MeV) are plotted. Effects of Spiky solar events are rejected.

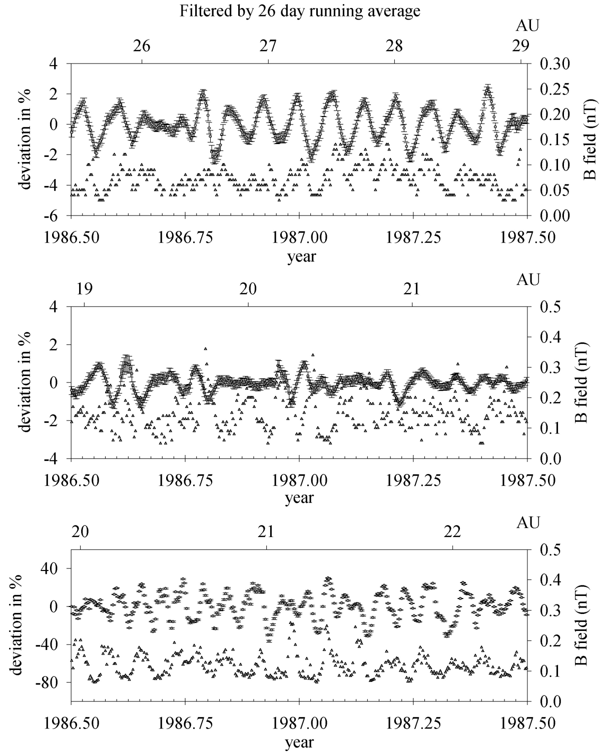

Fig. 2. Deviation from 26 days running average observed at Voyager-1(top), Voyager-2(middle) and Pioneer11(bottom). Data is filtered by 26 days running average. About 26 days recurrent component can be seen clearly in the data of Voyager-1 and Pioneer-11. The data are from the Voyager-1 and -2 magnetometer experiments(N.F. Ness,P.I.) and the Pioneer-11 magnetometer exp. (E.J.Smith, P.I.)

age of ions for the period of solar minimum (1986.5-1987.5) are shown in figure 2. Three panels, from the top, show the data of Voyager-1, -2 and Pioneer-11, respectively. B-field data (NOT filtered) are also shown in figure 2 with solid triangle. Recurrent phenomena can be seen clearly. We applied wavelet transform technique to the data after removing general trends.

3 Wavelet analysis

Most of the cases to which wavelets are applied are in fields of engineering such as image reconstruction and data compression or mathematics. But it is also applied to periodic analysis of data in physics. For time dependent signal, $f(t)$, the information about the frequency is derived by Fourier transform, $f(\omega)$. But the Fourier transform does not give us "t" and "ω" representation simultaneously. With the wavelet transform, it can describe the behavior of the signal in $t-\omega$ phase space.

Many books, which are describing mathematical detail of wavelet transform, have been published. So, we briefly describe some of the basic transform equations here.

The basic wavelet transform equation is describing as following,

$$\Psi(\tau,\lambda) = \frac{1}{\sqrt{\mid\lambda\mid}}\int f(t)\varphi(\frac{t-\tau}{\lambda})dt \qquad (1)$$

Where $f(t)$ is time dependent data, which is based on daily value of observation in our analysis. Two parameters of transformed function Ψ, namely τ and λ are the translation and scale parameter, which are corresponding to time and wavelength (i.e. frequency) in $t-\omega$ phase space, respectively. A wavelet module, $\Psi(\tau,\lambda)$, describes the intensity of signal in $t-\omega$ phase space. Transforming function φ, which is called mother wavelet, is localized in t and ω coordinate. There is also an inverse wavelet transform by which it is possible to reconstruct the signal. The inverse wavelet transform

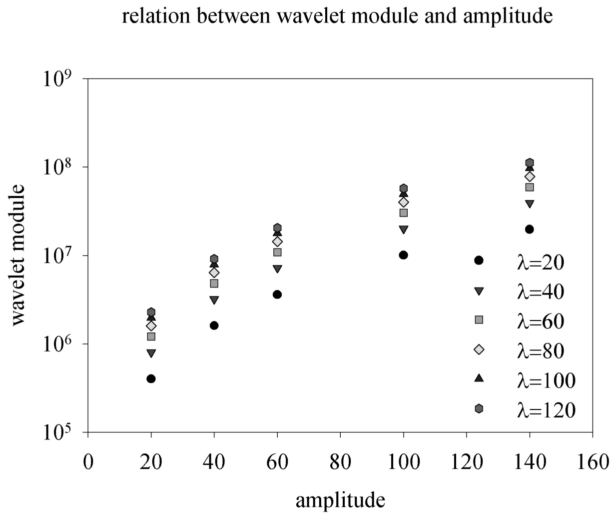

Fig. 3. Relation between amplitude and wavelet module for several waves, which have different wavelength, λ.

is defined as

$$f(t) = \frac{1}{C_\nu} \int \int \Psi(\tau,\lambda) \frac{1}{\sqrt{\mid \lambda \mid}} \varphi(\frac{t-\tau}{\lambda}) \frac{d\lambda d\tau}{a^2} \qquad (2)$$

An admissible condition has to be satisfied to define the function above. That is,

$$C_\nu = \int_{-\infty}^{\infty} \frac{\mid \widehat{\varphi}(\omega) \mid^2}{\mid \omega \mid} d\omega < \infty \qquad (3)$$

Where $\widehat{\varphi}$ is a Fourier transform of φ. In general, the following condition is used instead of admissible condition.

$$\int_{-\infty}^{\infty} \varphi(t) dt = 0 \qquad (4)$$

This equation means that the mother wavelet is oscillatory. In this analysis, the following mother wavelet is selected.

$$\varphi(x) = \exp(-\frac{x^2}{8^2}) \exp(ix) \qquad (5)$$

This mother wavelet is a kind of "Gabor wavelet", which is known to be suitable for probing frequency of signal. In general, it is normal to discuss about wave component with wavelet module. But we need to compare the amplitude reported previously.

When we are interested in average amplitude of wavelet components, there is another way to estimate it by finding the relation between wavelet module and amplitude instead of using an inverse transform. This relation has been checked by analysis of artificial wave data. Figure 3 shows the relation between $\Psi(\tau,\lambda)$ and amplitude of the signal when a monochromatic wave with known amplitude and frequency has been transformed. 3000 data points created by cosine function have been used to derive this figure. A λ dependence is also seen in this figure. These characteristics make it difficult to compare the wavelet module among several wavelengths quantitatively. The data points have been fitted by Least Square method. Fitting error is 4.3 %.

4 Results

Table 2. Average amplitude of 26day recurrent component in solar minimum 1986.6 - 1987.5.

S/C	wavelet	Zhang's method
V-1 (ions>70 MeV/n)	1.78 ± 0.50	0.60 ± 0.09
V-2 (ions>70 MeV/n)	0.69 ± 0.31	0.13 ± 0.07
P11 (ions>80 MeV/n)	5.64 ± 1.05	6.23 ± 1.65
IMP-8 (ions>80 MeV)	0.63 ± 0.11	0.12 ± 0.04

We selected the period of 1986.5 - 1987.5 as solar minimum. Average amplitudes of 26 days periodic components are summarized in Table 2. It is evident that the component at Pioneer-11 (middle latitude) has the maximum amplitude that is almost one order larger than Voyager-2 and IMP-8 (heliospheric equator). The amplitude at Voyager-1 (30N) is larger than that of equator by factor of $\sim$2.

Cummings and Stone (1988) had reported large recurrent components in the data of ions $>$70 MeV and anomalous oxygen at Voyager-1, which did not exist at Voyager-2. Our results is consistent with their reports but maximum amplitude are observed at Pioneer-11 at mediate latitudes.

The amplitude derived by following Zhang's(1997) method are also listed on Table 2. In this method, filtered data have been summed up every 26 days and fitted by a sine function. Smaller amplitude is caused by different phase of recurrent phenomena. That is, amplitude has been canceled in summing by different phase. It is clear that the largest amplitude is also at Pioneer-11.

Figure 5 shows locations of Corona Holes (CH). CHs exist at the latitude of 10 - 20 degrees north and greater than $\pm$40 degrees for 1770 - 1780 in carrington rotation.

The period, which we selected as solar minimum, is roughly corresponding to the Carrington rotation of 1774 - 1786. Considering that high speed solar wind with 700 km/s take $\sim$50 - 80 days to reach at the distances of Pioneer-11, CHs observed at carrington rotations from 1770 to 1780 are thought to be related to the largest amplitude at middle heliospheric latitude.

It is needed to probe the energetic ion data in detail and compare with models of cosmic ray transport.

5 Summary

We found that 26 days recurrent components in the outer heliosphere have the maximum amplitude at Pioneer-11 in the solar minimum period of 1986.5-1987.5. The magnitude of average amplitude at 17$\deg$N is nearly one order larger than that of equator. It seems that CHs on the sun are related to large amplitude at middle latitude.

Burlaga et.al(1993) found that over the solar minimum period of cycle 21 that the changes in cosmic ray intensity ob-

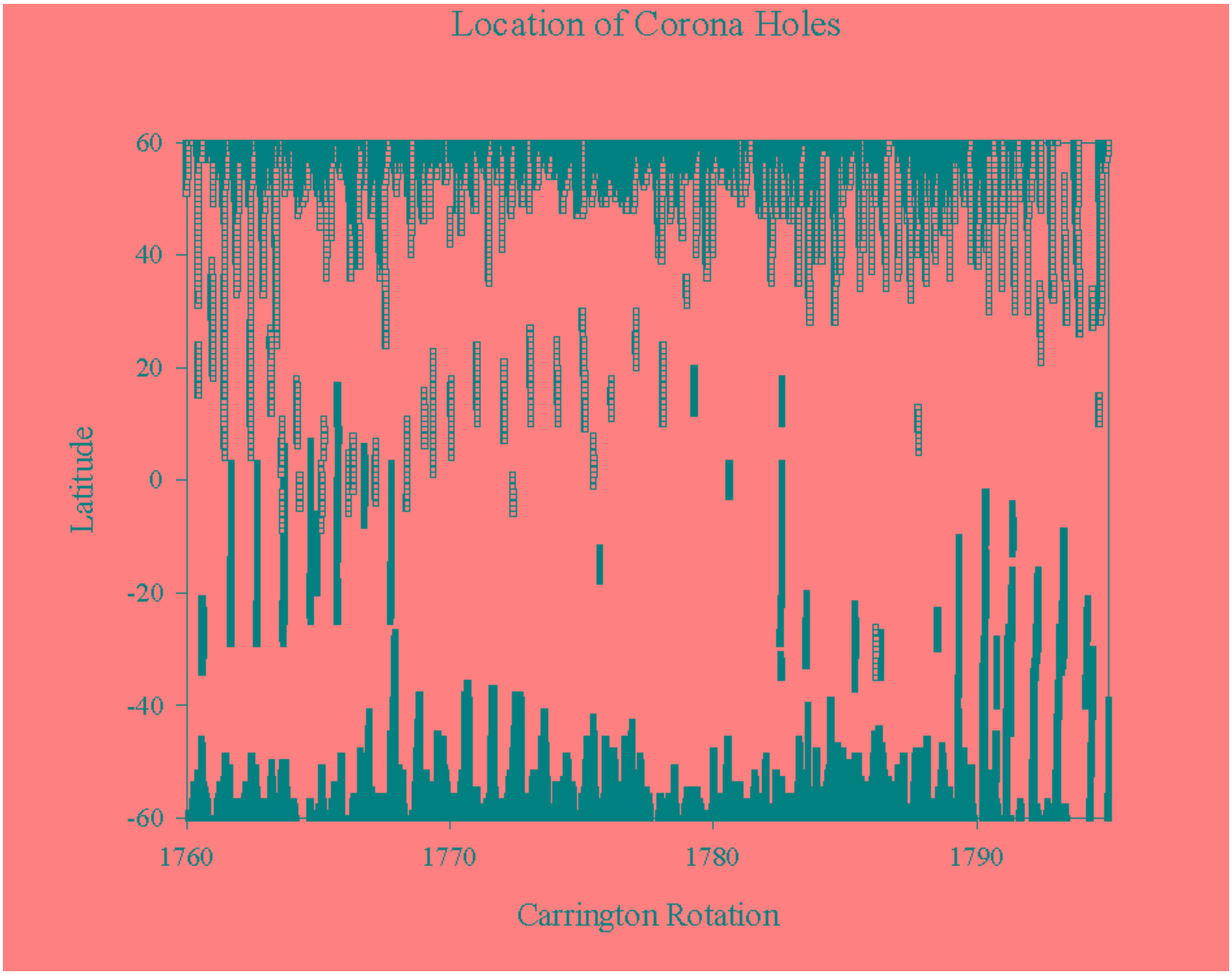

Fig. 4. Location of Corona Hole from 1760 to 1800 in carrington rotation.

served at Voyager-1 from 1986 through 1988 were closely related and anti-correlated to the large-scale fluctuation in the interplanetary magnetic field strength (B). The one exception they noted was from day 45 to day 110, 1987 when the periodicity of both the intensity and B appear to be in phase. This is in the middle of the interval (fig.2) where the periodicities are best defined in the Voyager-1 data. This is also the time latitudinal gradients of Galactic Cosmic Rays at Voyager-2 approach their maximum negative value (McDonald, et.al, 1992).

References

Burlaga, L.F., et.al., Pickup protons and pressure-balanced structures: Voyager 2 observations in Marged Interaction Regions near 35 AU, JGR, 99, 21511-, 1994.

Cummings, A.C. and Stone, E.C., Composition gradients and temporal variations of the Anomalous Cosmic Ray components, in V.J.Pizzo, T.E.Holzer and D.G.Sime(*eds.*), Proc. 6th Intern. Solar Wind Conf.,Thec. Note NCARR/TN-306,Natl. Cent. for Atmos. Res. Estes Park, Colo.,599-,1988

Decker, R.B.,et.al., Behavior of Energetic Particles and Cosmic Rays, Space Sci. Rev., 89, 278-, 1999.

Gazis, P.R. and McDonald, F.B., et.al., Corotating Interaction Regions in the Outer Heliosphere, Space Sci. Rev., 89, 269-305, 1999.

McDonald, F.B., et.al., The Cosmic Radiation in the Heliosphere at Successive Solar Minima, J, Geophys. Res., 97, A2, 1557-, 1992.

McDonald, F.B., et.al., Role of Drifts and Global Merged Interaction Regions in the Long-Term Modulation of COsmic Rays, J, Geophys. Res., 98, A2, 1243-, 1993.

Zhang, M., A linear relationship between the latitude gradient and 26 day recurrent variation in the flux of galactic cosmic rays and anomalous nuclear components. I. Observations, ApJ, 488, 841-853, 1997.