22-year variation pattern of cosmic ray intensity and solar activity

Tohru NOSAKA

Abstract

It is well known that cosmic ray intensity variation present flat peak at sunspot minimum in one solar cycle(11year), and following next solar cycle present sharp peak at same phase of sunspot cycle. Flat peaks apear in positive state and sharp peaks in negative state. The relation between peak type of cosmic ray maximum and magnetic polarity pattern in heliosphere is a problem taken into account to reveal 22-year variation mechanism of cosmic ray intensity. To explain the peak pattern of 22-year cycle qualitatively, physical process can be presented in consideration of inward or outward motion of cosmic ray particle on the magnetic field structure of polarty pattern in heliosphere. In this paper, a simple process is proposed by introducing two factors, one is "capacity" of cosmic ray particles in heliocphere and the other is migration which changes trajectry of cosmic ray particles depending on the solar magnetic polarity (negative state or positive state). That is expected to make a contribution to understand the two type peak of cosmic ray intensity in the solar cycle dependence. Another problem is correlation with cosmic ray intensity and sunspot number which is established as inverse correlation. Indeed, maximum of cosmic ray intensity is well coincident with minimum of sunspot number, whereas minimum of cosmic ray intensity and corresponding maximum of sunspot number has some delay time of 1～3 year. Especialy, time delay is long in odd cycle. Magnetic field structure of polarity pattern in heliosphere changes in odd or even cycle which affects propagation of cosmic ray.

1. Introduction

Long-term variation of cosmic ray intensity has well inverse correlation with sunspot number. In generally, this relation is established as a foundermental knowledge by many researchers. (e. g., Nagashima and Morishita, 1979; Webber and Lockwood, 1988) Nevertheless, physical process between the cosmic ray intensity variation and the sunnspot number is not revealed completely. Convection by the solar wind, diffusion inward to the heliosphere from interstellar space, and drift motion in heliosphere are accepted as main process of cosmic ray modulation (Parker, 1965). Possibility for explaining the relation between the cosmic ray and the sunspot number is expected to the behaviour of solar wind and magnetic field which have the origin on the solar atmosphere (that means surface of the sun) and constructs electromagnetic environment in heliosphere. Unfortunately, solar wind parameters which can be affected to cosmic ray propagation, for example solar wind velocity, plasma density, magnetic field irregularity do not show the 11-year periodicity correlated with sunspot number. These features pointed out by several researchers (Nosaka and Maezawa, 1988; Stozhkov, et al, 2000 ; Ahluwalia, H. S., 2003). Fig.1 shows the comparison between the solar wind parameters and sunspot number. Using the data of NSSDC, irregularity of magnetic field magnitude and direction, solar wind velocity and magnitude of magnetic field are compared with sunspot number from 1964 to 2002. Symple relation is not recognized between the sunspot number and solar wind parameters. It is expected that physical interaction or relation has existed among solar activity (moniterd with sunspot number), solar wind plasma parameter and cosmic ray intensity. Problem is the existence of correlation between solar activity and cosmic ray intensity in spite of less correlation with solar wind plasma parameter.

In this paper, re-examination of the correlation between cosmic ray intensity variation and sunspot number from 1964 to 2000. As some previous works revealed, macroscopic property shows well correlation inversely, even if irreguler relation exists microscopically (Usoskin et al., 1999). It takes us unknown physical process and introducing a concept to give our attention to microscopic disorder.

2. Two type of recovering cosmic ray intensity

Fig.2 is an example for re-investigation of long-term variation and relation between the cosmic ray intensity and sunspot number. Upper panel Fig.2 (a) is monthly average of sunspot number, and Fig.2 (b) is monthly average of cosmic ray intensity (neutron monitor data in Oulu). Following features can be pointed out. First, inverse correlation is well recognized except for some detail. This feature indicates that cosmic ray intensity in heliosphere is well controled by the solar activity, which is monitored with sunspot number. Second, sunspot minimum is occured in late 1964, early 1976, late 1985, and 1996. These minimum positions are coincident with cosmic ray maximum, where time delay is less than 1 year. On the other hand, sunspot maximum is occured in late 1968, late 1979, and 1989. Compeared with corresponding cosmic ray minimum which occured in late 1969, 1982, 1991, time delay is 1~3 year. Systematic disorder (time delay) can be recognized between the maximum time of sunspot number and corresponding minimum time of cosmic ray intensity.

Although cosmic ray intensity increases during the decreasing period of sunspot number, two types of recovering pattern can be recognized in cosmic ray intensity variation. One is begining with rapid increase from cosmic ray minimum, and change the increasing rate for time, then make flat peak. In Fig.2 (b) this type of variation can be seen from late 1969 to early 1979, and from 1991 to 1996. Another type of recovering pattern presents "normal" increase with constantly increasing rate for time, and make sharp peak. In Fig.2 (b) this type of variation can be seen from 1982 to late 1985.

For three solar cycle (from cycle 20 to cycle22), two type of recovering pattern of cosmic ray intensity can be seen systematically construct 22-year cycle pattern. These feature can be recognized in Fig.3 which shows the data from 1953.

It seems to be important relation that the rapid increase and following flat peak in cosmic ray variation correspond to the declining phase of the solar activity in even cycle, and the normal increase and following sharp peak correspond to the same phase in odd cycle. Recovering process of cosmic ray intensity in heliosphere depends on not only the convection by the solar wind containing magnetic irregularity and diffusion by the radial gradient of cosmic ray particles, but also the structure of magnetic field in heliosphere. Especialy propagation route of cosmic ray particles is different between near or far from the magnetic neutral sheet. Basic mechanism is presented in Fig.5. At the region of boundery between away field and toward field, cosmic ray particle drifts perpendicular to the field line, along the boundary resion (Levy, 1976). Migration in the neutral sheet changes route which provides rapid motion of inward and outward flow, and that seems to be results as the systematic disorder of correlation between cosmic ray intensity and sunspot number. Magnetic polarity controles direction of particle migration, inward or outward, and according to the solar rotation, magnetic field originating to the sun, expand rdially and sweep in the interplanetary space. These two factor, particle migration velocity and sweeping velocity are taken into consideration, so that the type of recovering pattern of cosmic ray intensity may be explain with migration.

It is normal idea that rapid increase results large peak compeared with the case of normal increase in cosmic ray intensity. In Fig.2 (b), maximum value of every peaks in cosmic ray intensity variation present nearly equal level. Considering the sunspot number which shows large or small value in each maximum. To understand the result desclibed above, we must introduce the concept that upper limit of cosmic ray particles existes in heliosphere.

3. Dependence of cosmic ray 11-year variation on the solar magnetic polarity

In previous section, it was pointed out that anti-correlation between sunspot number and cosmic ray intensity is slightly broken systematically in the same phase of solar cycle, and also that increasing rate for time of cosmic ray intensity shows rapid increase in positive polarity and "normal" increase in negative polarity. These features are clear in Fig.4, which compared cosmic ray intensity variation in solar cycle 20, 21, 22 with time relation for minimum phase of cosmic ray intensity, and for the position of sunspot maximum, and minimum. In this figure, upper panel Fig.4 (a), middle panel Fig.4 (b), and lower panel Fig.4 (c) show the variation of monthly mean cosmic ray intensity in sunspot cycle 20, 21, and 22, respectivly. Minimum of cosmic ray intensity has time delay from sunspot maximum (marked▼) about 1~3 year. In cycle 21 (odd cycle) of Fig.4 (b), the time delay is large compared with other cycle. Recovery phase from minimum intensity shows neary linear incerease ("normal" increase descrived above) in Fig.4 (b). On the other hand, Increasing rapidly with following curved line and nearly flat is shown in Fig.4 (a), and (c). The important relation can be pointed out in the cosmic ray intensity variation for 3 solar cycle 20, 21 and 22 shown in Fig.4. Solar magnetic polarity changes from negative state to positive state within the period 1~2 year from sunspot maximum to declining phase in the even solar cycle 20, 22 (Fig.4 (a), (c)) and changes from positive state to negative state within the same phase in the odd solar cycle 21 (Fig.4 (b)). Cosmic ray particle propagation is affected by magnetic field and the structure. Especialy, along the neutral sheet, migration process of cosmic ray particles contribute to change the recovery time of cosmic ray intensity. Fig.5 showes the relation between the magnetic polarity pattern and the direction of particle propagation with migration process (Levy, 1976, modified figuare)

Parker spiral structure of the magnetic field is characteristic in the direction of magnetic field vector, that is almost azimuthal direction at large radial distance from the sun (here,called outer heliosphere), and increasing radial compoent according to near the sun, so that the magnetic field vector is almost radial direction (here, called inner heliosphere). Considering drift motion through the neutral sheet where the magnetic field polarity reversal, particles which migrate perpendicular to the magnetic field, along magnetic neutral sheet inward in heliosphere propagate rapidly almost radial to the sun at outer heliospere, but direction of propagation changes to rotate around the sun at inner heliosphere. Pitch angle of interplanetary magnetic field direction depend on not only angular velosity of solar rotation, but also solar wind velosity. Under the Parker spiral field chacacterised above, radial profile of cosmic ray intensity variation expected to be different between in outer heliosphere and in inner helosphere. For example, cosmic ray particles introduced inner heliosphere are stable within this region because of rotational motion around the sun, whereas in outer heliosphere radial motion (inward or outward) is dominant, which results sudden change of trend in the radial gradient of cosmic ray intensity.

4. Discussion

Basic idea is to explain two type peak pattern of cosmic ray intensity variation of 22-year cycle that means rapid increase followed by flat peak and normal increase followed by sharp peak, with considering migration effect near the magnetic neutral sheet. This idea has the origin in the relation between the direction of particle migration and magnetic polarity pattern. In the two hemisphere model of the magnetic polarity, charged particle migration is inward for negative state, and outward for positve state. Particle migration has some contribution to the intensity distribution of cosmic ray.

Averaged intensity distribution of galactic cosmic ray is increasing with radial distance from the Sun. In the positive state, migration effect is outward, so that in the outer heliosphere radial gradient of comic ray intensity is smaller than the average gradient. On the other hand, inner heliosphere cosmic ray intensity is little changed because migration is almost azimuthal direction around the Sun, which result almost constant in cosmic ray intensity, so that near the solar magnetic neutral sheet, density of cosmic ray particles is lower than the other region where migration dose not take place due to the latitudinal distance far from the magnetic neutral sheet in heliosphere. Therefore in the latitudinal distribution of cosmic ray, north-south symmetric component of cosmic ray distribution is higher density with higher distance from the neutral sheet.

In the negative state, migration effect is inward. Near the magnetic neutral sheet, cosmic ray density is higher than the other region where migration dose not take place due to the latitudinal distance far from the magnetic neutral sheet in heliosphere. Therefore in the latitudinal distribution of cosmic ray, north-south symmetric component is lower with higher distance from the neutral sheet. (Antonucci et al, 1978; Antonucci et al, 1981; Nosaka et al, 1984) These discussion relates two types of cosmic ray recovering pattern, that mean rapid increase and normal increase, to migration effect. North-south symmetric component of cosmic ray latitudinal distribution is shown derived from drift model (Munakata, et. al, 2002)

Another problem that correlation with cosmic ray minimum and sunspot maximum slightly broken with time delay 1~3year, may be explained by the solar cycle variation of the mean free path (Cummings and Stone, 2003). Cummings and Stone research the mean free path at 1.5GV inferred from the gradient of cosmic rays observed by Voyager 1 and 2. The mean free path is a factor of 10 or more larger at solar minimum than at solar maximum. Therefore, change of cosmic ray particles distribution can be performed rapidly at solar minimum. Whereas, at solar maximum must be required many time.

5. Conclusion

Cosmic ray intensity distribution was investigated with relation to the solar activity and to the solar magnetic polariy in heliosphere. Long-term change of cosmic ray intensity shows the two type patterns can be recognized. One is rapid increase from cosmic ray minimum following flat peak, and the other is normal increase from cosmic ray minimum following sharp peak. At the rapid increase, period from.. minimum to maximum of cosmic ray intensity is about one year, whereas at the normal increase, that period is about three years.

Flat peak appears in positive state, so that migration effect near the magnetic neutral sheet is outward from the Sun. On the other hand, sharp peak appeas in negative state, so that migration effect near the manetic neutral sheet is inward to the Sun.

Inverse correlation between sunspot number and cosmic ray intensity is foundermental property. This relation, however, is slightly broken systematically. Sunspot minimum is well coincident with cosmic ray maximum, but cosmic ray minimum has some time delay with sunspot maximum which is 1 to 3 year. These results indicate that solar poler magnetic polarity dose not change at sunspot minimum, then magetic structure dose not change, but at sunspot maximum, solar poler magnetic polarity reversal takes place, then the change of magnetic polarity pattern in heliosphere affects particle migration. Migration affects motion of cosmic ray particle, which contribute the change of cosmic ray distribution.

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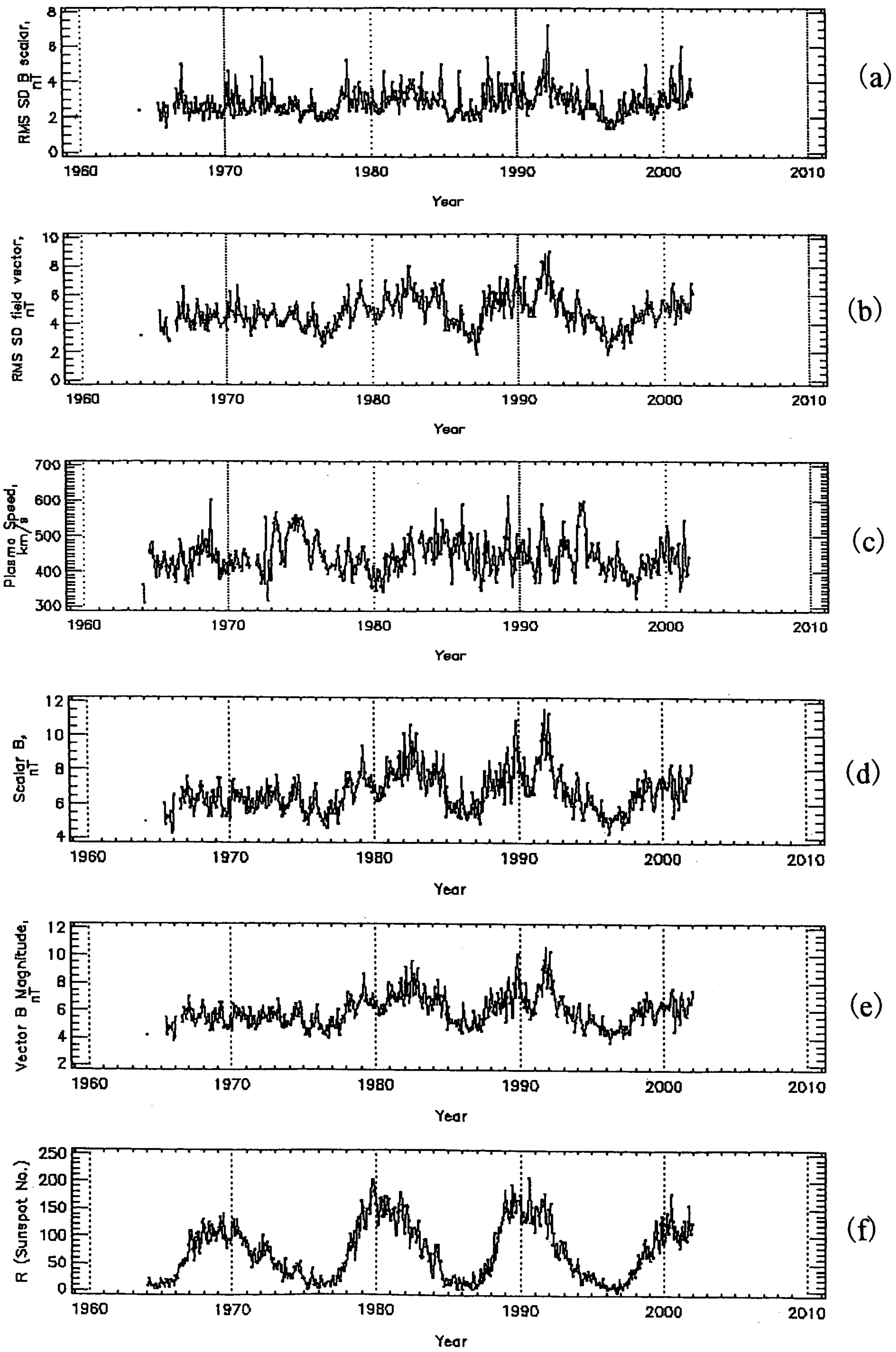


Figure 1 Comparison between solar wind parameters and sunspot number.
(a) irregularity of magnetic field magnitude, (b) irregularity of magnetic field direction(vector), (c) solar wind velocity, (d) magnetic field magnitude, (e) magnitude of magnetic field vector, (f) sunspot number.

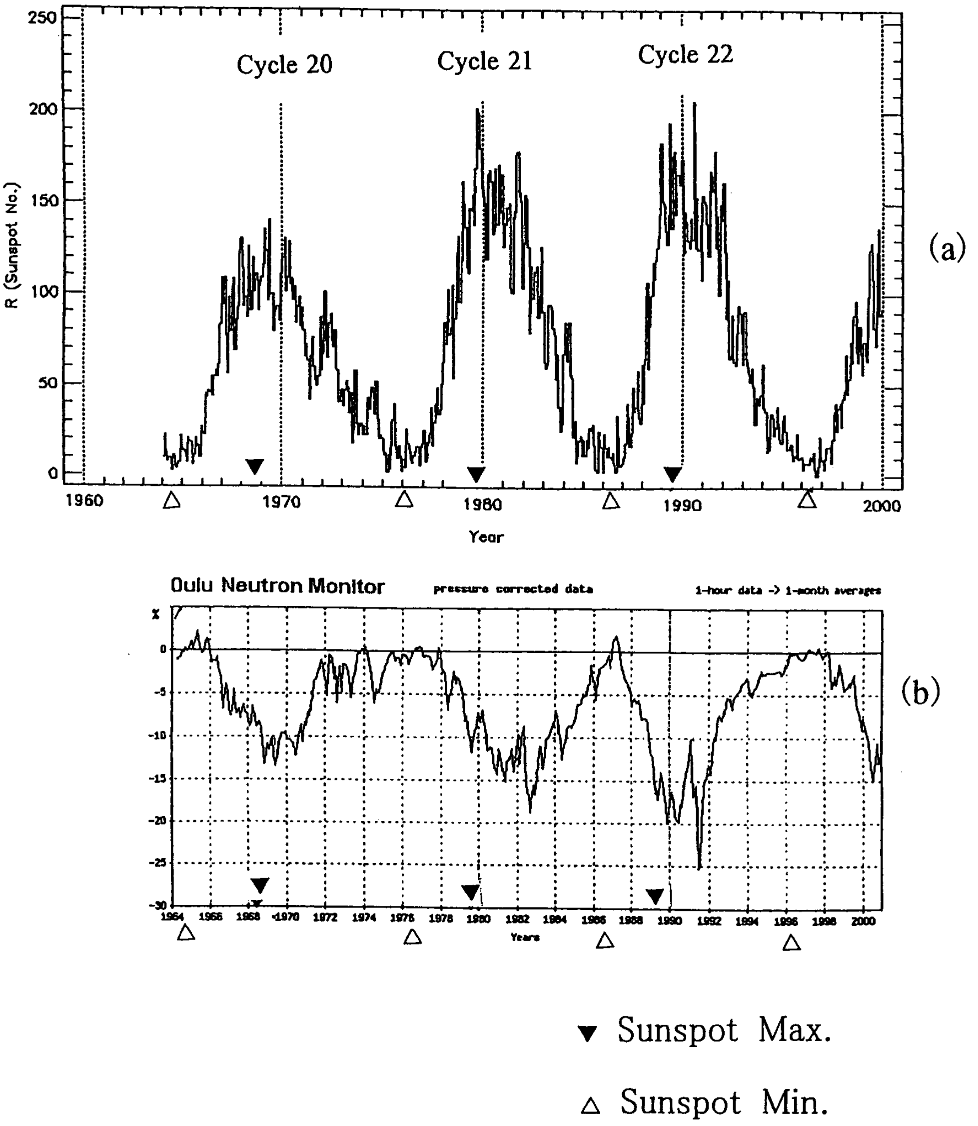


Figure 2

(a) sunspot number (monthly average).

(b) cosmic ray intensity (monthly average :Oulu neutron monitor). From 1964 to 2000. Marked▼denotes maximum of sunspot number, and marked△denotes minimum of sunspot number.

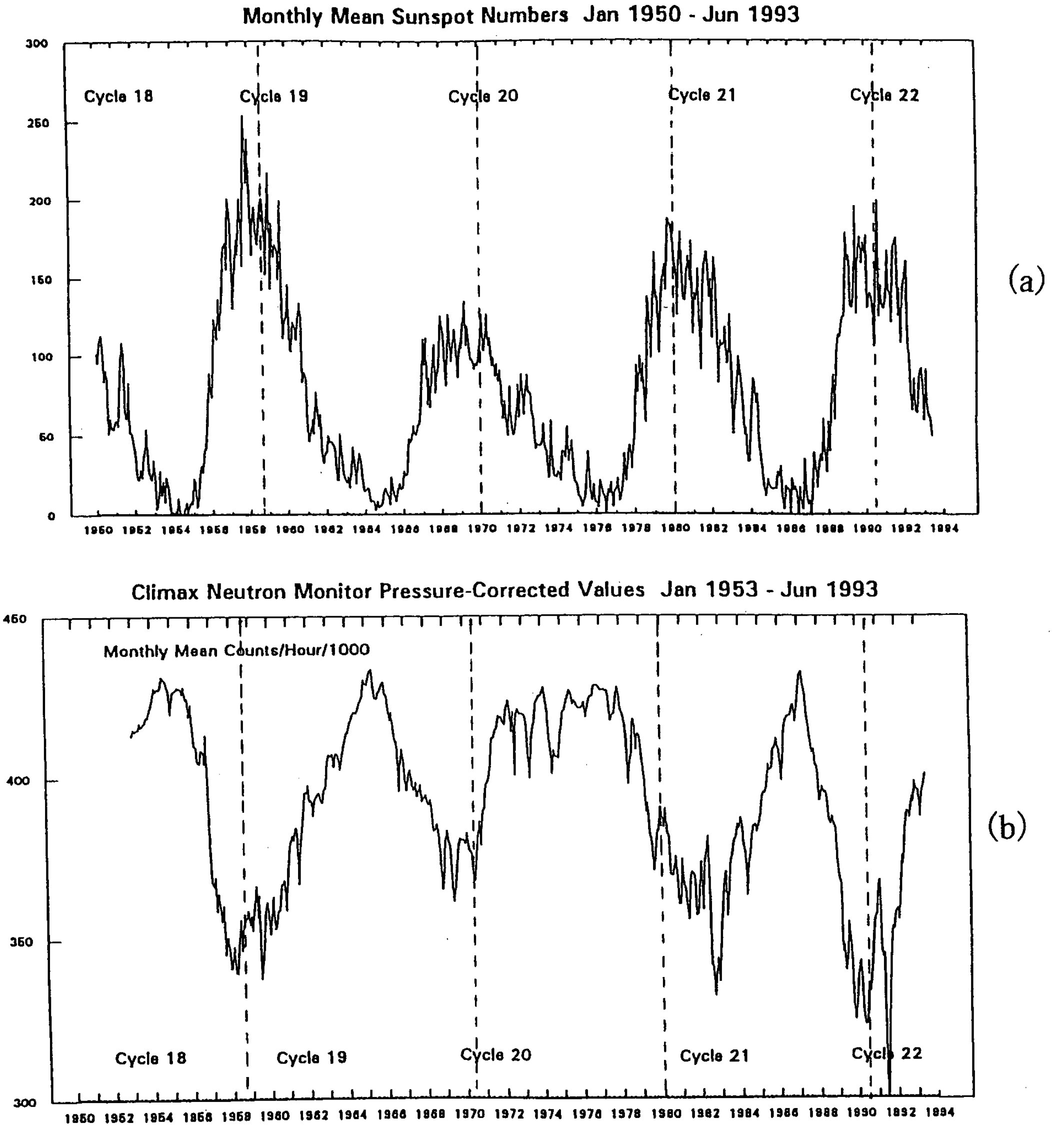


Figure 3

(a) sunspot number (b) cosmic ray intensity of Climax neutron monitor

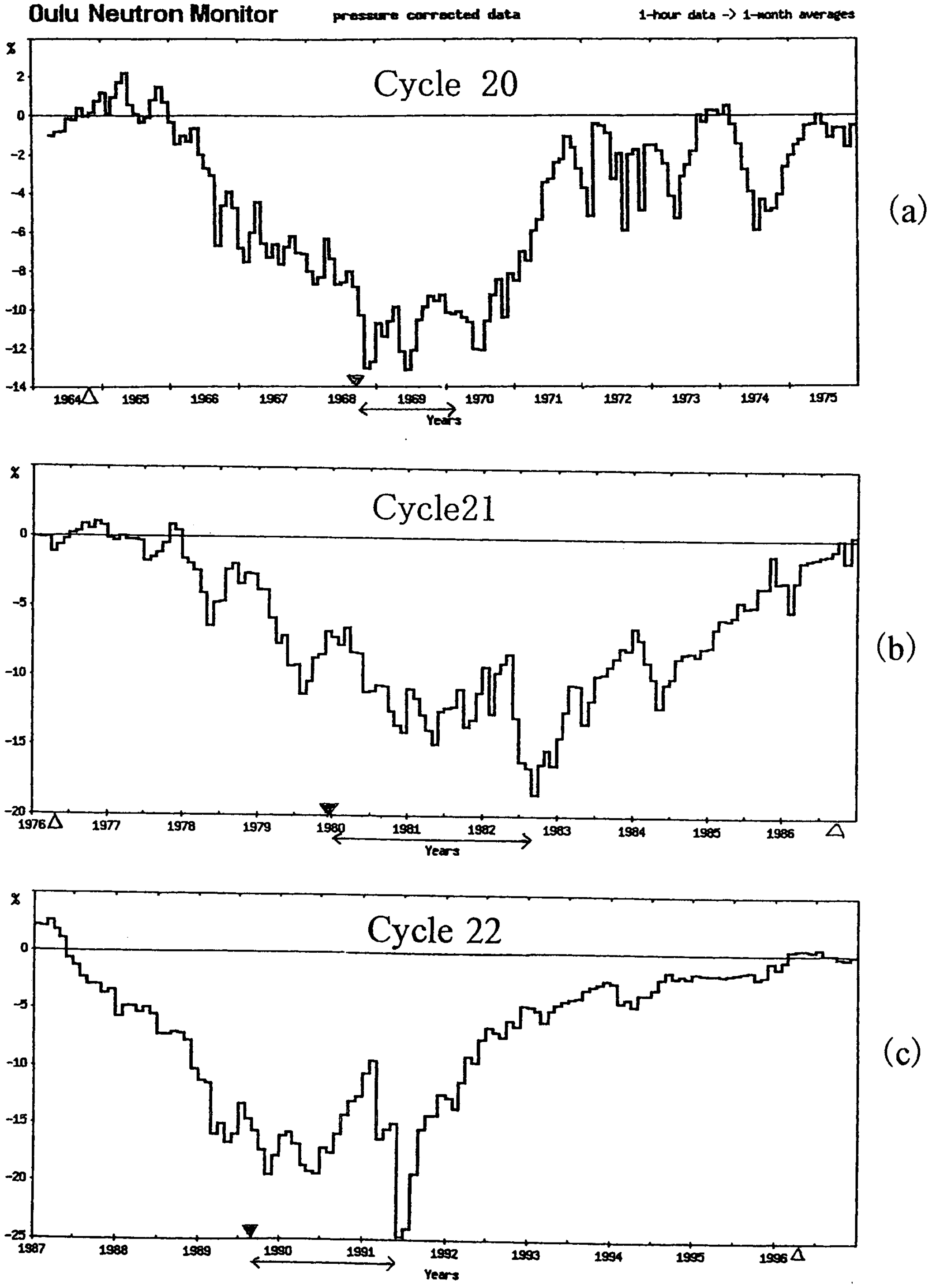


Figure 4 Cosmic ray intensity variation (monthly average: Oulu neutron monitor) for each solar cycle.

(a) solar cycle 20 (1964-1975)

(b) solar cycle 21 (1976-1986)

(c) solar cycle 22 (1987-1996)

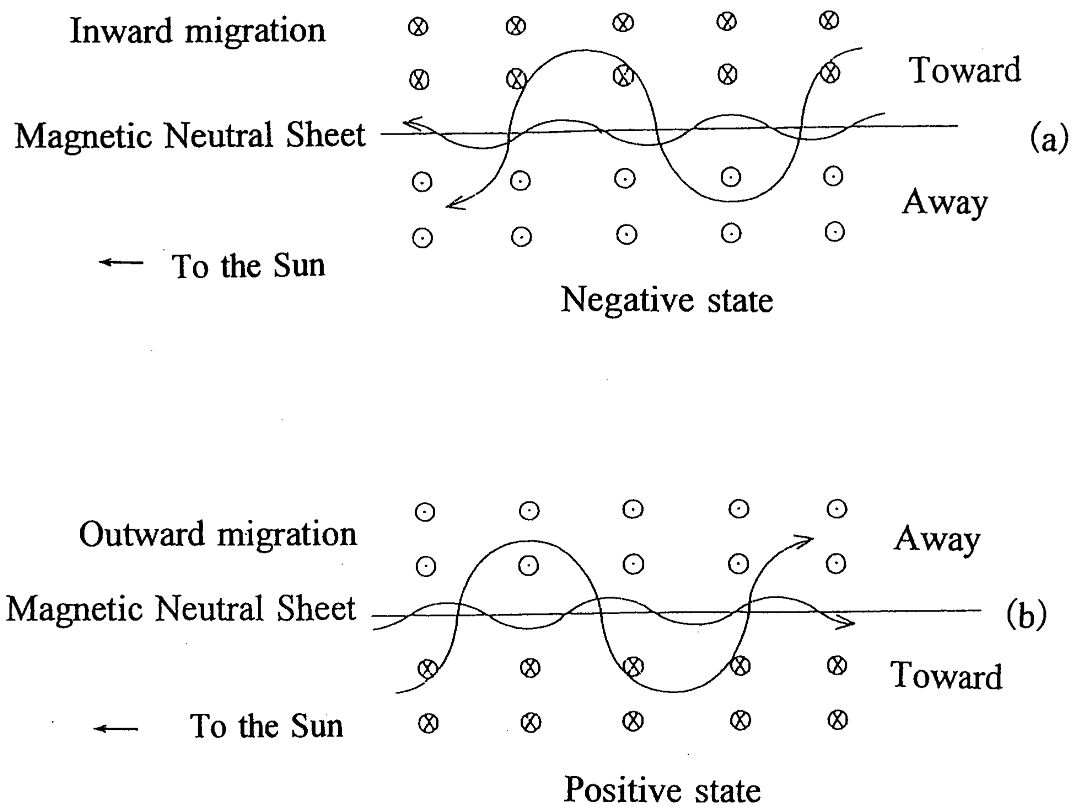
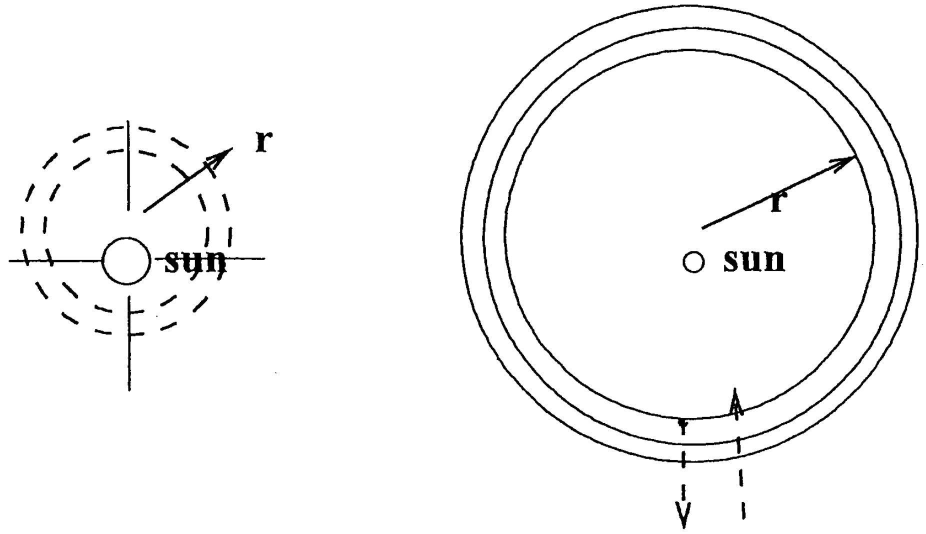


Figure 5 Relation between magnetic polarity pattern and the direction of the migration.
(a) Inward migration for negative state.
(b) Outward migration for positive state (Modified from the figure in (Levy, 1976))

Characteristic structure of Parker spiral magnetic field



r : near the sun

Inner heliosphere

(a)

r : far from the sun

Outer heliosphere

(b)

- - - ➤ direction of particle motion

——➤ direction of magnetic field

r **radial ditannce**

Figure.6 Charactoristic structure of Parker spiral magnetic field.

(a) Magnetic field vector is almost radial near the sun in the small radial distance from the sun (called inner heliosphere).

(b) Magnetic field vector is almost azimuthal far from the sun at the large radial distance (called outer heliosphere). Dotted line denotes particle motion, and rigid line denotes direction of magnetic field vector.