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North-south asymmetry in cosmic rays in 1990–1998

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Abstract. The data on the north-south (N-S) asymmetry in cosmic ray fluxes obtained in stratospheric measurements at high-latitude stations Murmansk and Mirny (Antarctic) in 1970–1998 are considered. Monthly averaged and averaged over an 11-year cycle data on the N-S asymmetry are shown. The main N-S asymmetry features and their relation to the velocity of solar wind and the sign of the interplanetary magnetic field (IMF) are discussed. The N-S asymmetry dependence on the cutoff rigidity of cosmic rays is shown as well as its annual wave due to the season temperature variations. In the 1990s, the sign of the north-south asymmetry was opposite to that observed in the 1970s. Earlier, a hypothesis was put forward that the value and sign of the N-S asymmetry can be determined by the difference in the solar wind velocities above and under the heliospheric current sheet (HCS), which is consistent with a large positive N-S asymmetry in 1973. To test the validity of this hypothesis, it is important to see whether it is confirmed by the data on the asymmetry obtained in 1990–1998. The results of this checking are presented in this paper. On the basis of this checking, one can make the conclusion that the difference in the solar wind velocities above and under the HCS can be one of the factors responsible for the N-S asymmetry but is not the only source of it.

1. Introduction

The north-south asymmetry in cosmic ray fluxes in the lower atmosphere established on the basis of long-term sonde measurements at the high-latitude stations Murmansk and Mirny (Antarctic) has been discussed by many authors [*Charakhchyan*, 1986a, 1986b; *Charakhchyan and Charakhchyan*, 1979; *Charakhchyan and Stozhkov*, 1983; *Stozhkov et al.*, 1996; *Svirzhevskaya et al.*, 1997]. Nevertheless, the physical mechanism responsible for different particle fluxes in the Northern and Southern hemispheres incident at large angles to the ecliptic is still unclear. The attempts to find a parameter in the solar wind or interplanetary magnetic field (IMF) that would correlate with the asymmetry in the particle fluxes for a long time period have also failed.

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Probably, there are several causes for the N-S asymmetry. Any north-south asymmetry in the solar wind and IMF parameters can lead to asymmetry in the particle fluxes. Various scenarios for development of asymmetry also are in favor of the fact that there are different sources of the asymmetry. Most often, the asymmetry arises when time variations in the particle fluxes in the north and south are in phase, but somewhat shifted in time and differ in magnitude. However, sometimes the particle fluxes at the two stations are observed to be in antiphase, as, for instance, in February–June 1973.

Charakhchyan [1986b] put forward the hypothesis that properties of the N-S asymmetry are determined by the sign of the total magnetic field of the Sun and, hence, can experience 22-year variations. At first glance, this hypothesis was not confirmed because a large positive N-S asymmetry (like in the 1970s) was expected to take place after the solar magnetic field polarity reversal in 1991, when the IMF direction became the same as in 1971–1979. In 1991–1998, the north-south asymmetry was indeed large, but it changed the sign [*Svirzhevskaya et al.*, 1997]. Probably, the 22-year periodicity is manifested only in the magnitude of the asymmetry. So it was nearly zero under negative IMF in the Northern hemisphere of the heliosphere (N^-S^+) in 1963–

1970 and 1980–1988 and large under the IMF of opposite sign (N^+S^-) in 1971–1979 and 1991–1998.

Svirzhevskaya et al. [1997] showed, using a large positive asymmetry of 1973 as an example, that the magnitude of the N-S asymmetry A_{NS} does not change the sign when the Earth passes from one IMF sector to another. The parameter, which is related to the interplanetary plasma and IMF and behaves in a similar manner at that time, is the difference between the solar wind velocities in neighboring sectors, dV_{sw}. There was an evident anticorrelation between A_{NS} and dV_{sw} in the first half of 1973. *Svirzhevskaya et al.* [1997] proposed a possible scheme for formation of the N-S asymmetry involving the diffusion current of particles which has the same direction in neighboring sectors. In case of different solar wind velocities at opposite sides of the HCS, an asymmetric convective particle outflow takes place. It leads to a lower density of particles in the sector with a higher wind velocity. In this case a density gradient of cosmic rays perpendicular to the HCS and the diffusion current associated with this gradient arise. The current flows from the sector with a lower V_{sw} to the higher-velocity sector and does not change its direction at the sector boundary. The diffusion current supports the asymmetry as long as the difference between the solar wind velocities dV_{sw} in neighboring sectors remains sufficiently large. It is quite clear what sign the asymmetry has in this situation: the additional particle flux is directed from the sector with a low solar wind velocity toward the higher-velocity sector. The verification of the ascribed above scheme with the data on the N-S asymmetry obtained in 1990–1998 when its sign was changed is the main goal of the present work.

We have also wanted to describe some characteristics of the N-S asymmetry in the particle fluxes in the Earth's atmosphere. These characteristics are the next: (1) the N-S asymmetry in the particle fluxes does not change its sign when the Earth crosses the boundary of the IMF sector; (2) the averaged over an 11-year cycle N-S asymmetry is large in magnitude under the positive IMF in the Northern hemisphere of the heliosphere (N^+S^- or $A > 0$) and it is nearly zero under the IMF of opposite sign (N^-S^+ or $A < 0$), while the sign of the N-S asymmetry does not depend on the sign of the IMF; (3) the magnitude of the N-S asymmetry A_{NS} is within the limits of errors at the cutoff rigidity $R < 2$ GV, while at $R =$ 3–6 GV A_{NS} equals 5–8% sometimes; (4) the part of the N-S asymmetry in the particle fluxes in the atmosphere arises from the season temperature variations in antiphase at the polar stations in the south and north hemispheres.

The characteristic feature of the N-S asymmetry in the particle fluxes observed in the measurements in the atmosphere is its large magnitude in comparison with that obtained from the high-latitude neutron monitor data [*Pomerantz and Bieber*, 1984; *Belov and Oleneva*, 1997]. We would like to note that in the last time the data on the N-S asymmetry in the atmosphere were experimentally confirmed by *Gorchakov et al.* [1995], where the N-S asymmetries of the proton and helium fluxes with $R > 2$ GV measured on Kosmos 600 satellite deep in the polar caps were defined. In some periods in 1973–1978 the magnitude of the N-S asymmetry $A_{NS} =$ 4–6% that agrees with our data. The magnitude of the N-S asymmetry $A_{NS} =$ 0.05–0.2% obtained from the neutron monitor data can be explained by the drift mechanism proposed by *Swinson* [1969]. *Pomerantz and Bieber* [1984] and *Belov and Oleneva* [1997] derived the quite reasonable radial gradients of the galactic cosmic rays (GCR) from the data on the N-S asymmetry. It is obvious that the N-S asymmetry of the cosmic ray fluxes observed in the atmosphere which by the order of magnitude exceeds that for the neutron monitors cannot be explained by drift mechanism and can not be consistent with the GCR radial gradients. We think that the sources of the N-S asymmetry in the cosmic ray fluxes in the atmosphere are the asymmetries of the basic parameters of the solar plasma (the solar wind velocity, and the values and disturbances of the IMF) with respect to the HCS as well as the asymmetric position of the HCS itself in the heliosphere.

2. Experimental Data on the N-S Asymmetry

2.1. Monthly Averages

To quantitatively characterize the asymmetry, the parameter $A_{NS} = 100 \times (N_{Murm} - N_{Mirn})/(N_{Murm} + N_{Mirn})$ is typically used. Here, N_{Murm} and N_{Mirn} are the fluxes of charged particles at Murmansk and Mirny, respectively. The temporal behavior of the N-S asymmetry in 1970–1998 for fluxes of charged particles measured by Geiger counters is shown in Figure 1. A_{NS} is given for four intervals of atmospheric pressure: 200–300, 300–400, 400–500, and 500–600 g cm^{-2}. Temporal variations in A_{NS} are synchronous in all pressure intervals, and the value of asymmetry depends on pressure x so that the lowest A_{NS} magnitudes correspond to $x =$ 200–300 g cm^{-2} and the highest A_{NS} magnitudes correspond to $x =$ 500–600 g cm^{-2}. It is likely that in 1980–1988 the asymmetry was suppressed, while in the 1970s and 1990s it was sometimes as large as 10–12%. Beginning from 1989, A_{NS} became, on the average, negative, and, in addition, a pseudoannual wave with a minimum approximately in the middle of the year appeared. The asymmetry for vertical particle intensity in the atmosphere measured by telescopes involving Geiger counters in the pressure intervals 300–400, 400–500, and 500–600 g cm^{-2} confirms that the picture is stable (Figure 2).

2.2. Asymmetry in Fluxes Averaged Over an 11-Year Cycle

The N-S asymmetry manifests itself also in the particle fluxes averaged over an 11-year cycle (Figure 3). In the 1970s and 1990s, the value of the asymmetry A_{NS} was 2–4%. On the average, in the 1970s the particle fluxes from the northern direction of the heliosphere were larger than from the southern direction. In the 1990s, the opposite situation took place. It can be expected that some physical parameters on the Sun or in the heliosphere varied in a similar fashion. The

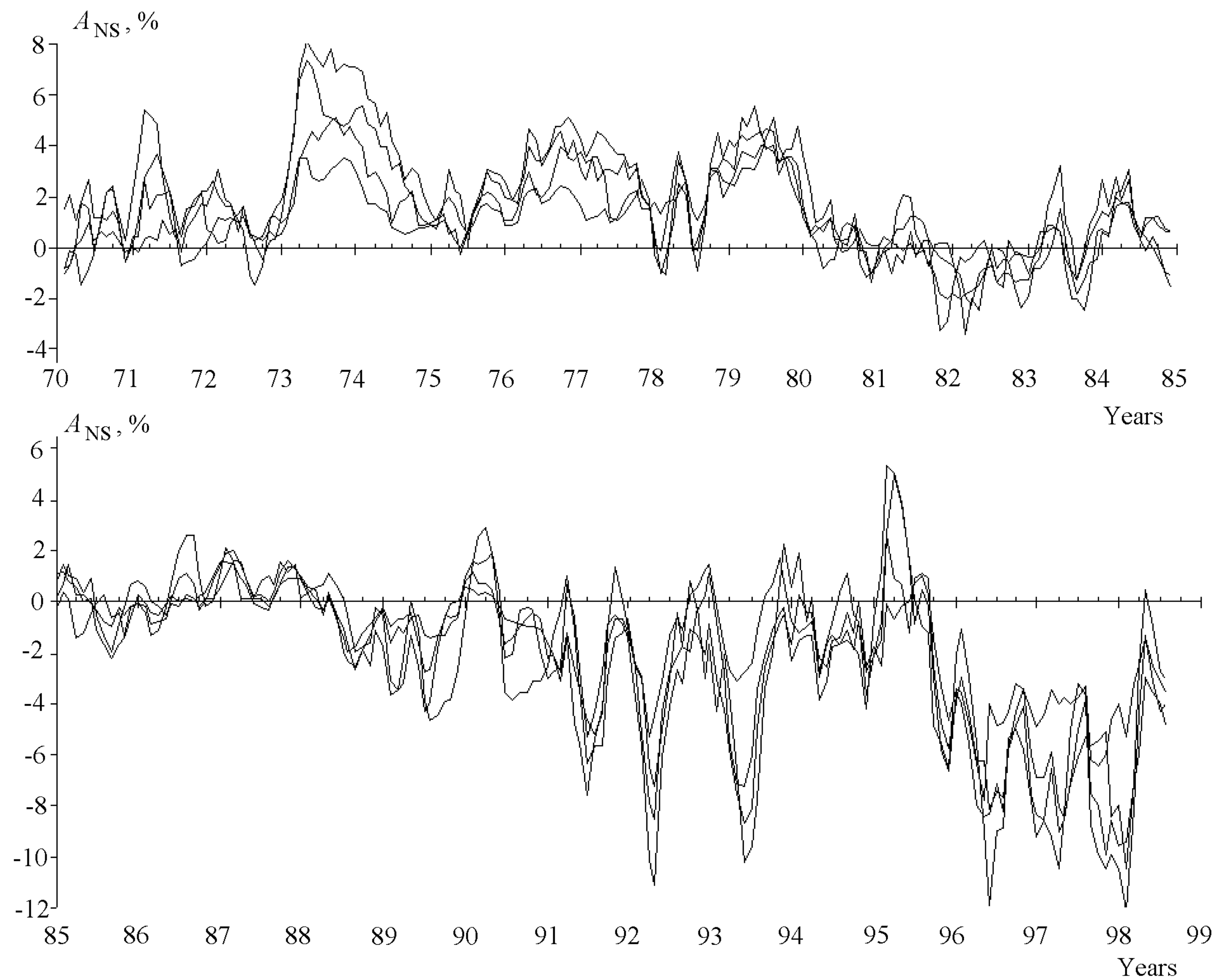

Figure 1. North-south asymmetry for the omnidirectional particle flux for atmospheric pressures 200–300, 300–400, 400–500, and 500–600 g cm^{-2} as a function of time.

value of the asymmetry A_{NS} in the 1980s was by an order of magnitude lower than in the 1970s and 1990s. Note that there is no pronounced correlation between the solar wind velocity and the asymmetry averaged over an 11-year cycle. The average solar wind velocity V_{sw} near the Earth in the 1970s, 1980s, and 1990s was 443.6, 443.3, and 438.9 km s^{-1}, respectively.

3. Solar Wind and the N-S Asymmetry in 1990–1997

As it was shown earlier the A_{NS} does not change the sign when the Earth passes from one IMF sector to another [*Svirzhevskaya et al.*, 1997]. The parameter, which is related to the interplanetary plasma and IMF and behaves in a similar manner, is the difference between the solar wind velocities in neighboring sectors, $dV_{sw} = V_+ - V_-$. In this work the value A_{NS} and sign of the N-S asymmetry are compared with the dV_{sw} in 1990–1998. The OMNI files were used as initial data on the IMF and solar wind [*NASA*, 1998]. The magnetic field in the Northern hemisphere of the heliosphere directed away from the Sun forms a positive sector near the helioequator if the azimuthal IMF component B_φ falls into the longitudinal interval $45^\circ - 225^\circ$ with the average value of 135° in the ecliptic (right-handed) coordinate system with the Ox axis pointed from the Earth's center toward the Sun. The field in the Southern hemisphere directed toward the Sun forms a negative sector near the helioequator in the longitudinal interval $225^\circ - 45deg$ with the average value of 315°. For the positive and negative sectors, monthly average velocities V_+ and V_- were derived, and then dV_{sw} was calculated.

The magnitude of the N-S asymmetry A_{NS} and the difference between the solar wind velocities dV_{sw} in 1990–1998 are shown in Figure 4. One can see that the A_{NS} and dV_{sw} values vary in antiphase during two and a half years in succession (1992–1994), in the early 1995, and in 1996. During these periods, the relation between A_{NS} and dV_{sw} is the same (anticorrelation) as in February–June 1973. During

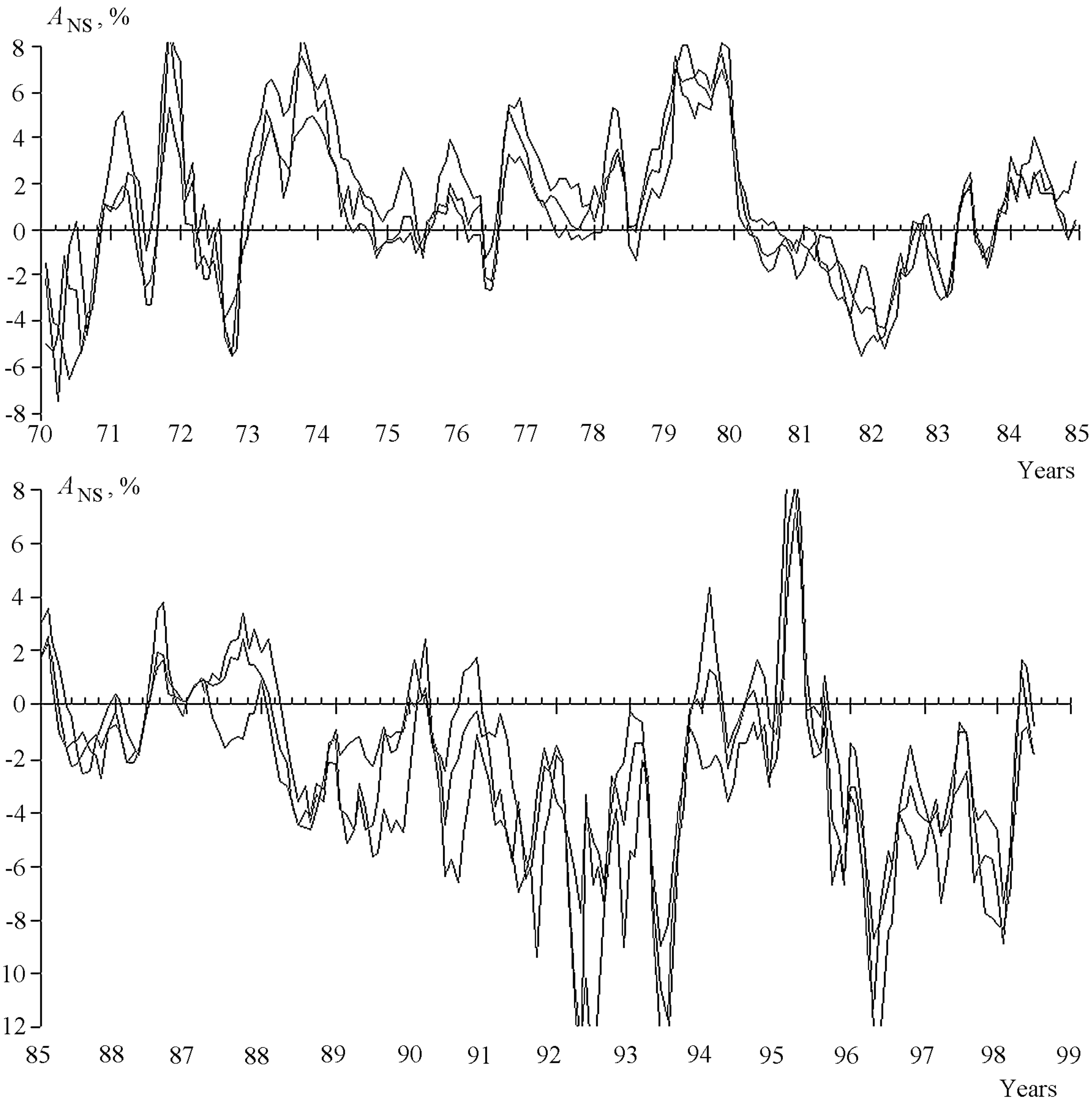

Figure 2. North-south asymmetry for the vertical particle intensity for atmospheric pressures 300–400, 400–500, and 500–600 g cm^{-2} as a function of time.

some periods (1991, the second half of 1994 and of 1995) the anticorrelation is disturbed. The correlation coefficient between two data series for the whole period 1990–1997 is low and equals -0.33. This leads to the conclusion that the difference between the solar wind velocities above and below the heliospheric current sheet $dV_{\rm sw}$ can be one of the factors controlling the N-S asymmetry. However, it is not the only source of the N-S asymmetry.

In 1991–1997 (with the exception of 1995), the annual wave was observed in the N-S asymmetry. The oscillations in $A_{\rm NS}$ were not symmetric with respect to zero, they were shifted toward negative values. During this period, the annual wave was also observed in the velocity difference $dV_{\rm sw}$. In 1994–1997, it was probably associated with the change in the Earth's heliolatitude. In March, the Earth occupies the extreme southern position in heliolatitude and the solar wind velocity $V_{\rm sw}$ in the southern sectors is considerably higher than in the northern ones. In half a year, in early September, the Earth's heliolatitude is $\sim 7°$N, and $V_{\rm sw}$ is higher in the northern sectors than in the southern ones. In 1992–1993, the annual wave in $dV_{\rm sw}$ had a different phase. Note also the asymmetry of $dV_{\rm sw}$ with respect to its zero value. The solar wind velocity to the south of the HCS in 1994, 1995, and 1996 was higher than to the north of the sheet, as if the Earth moved to greater distances from the heliospheric current sheet in the negative (southern) sector than in the positive (northern) sector. This could happen if the HCS extended northward from the helioequator. The northward extension of the HCS was confirmed by the Ulysses data in 1996 [*Forsyth et al.*, 1997] but there are reasons to believe that in 1994 the HCS extended southward from the helioequator by approximately 10° [*Simpson*, 1996].

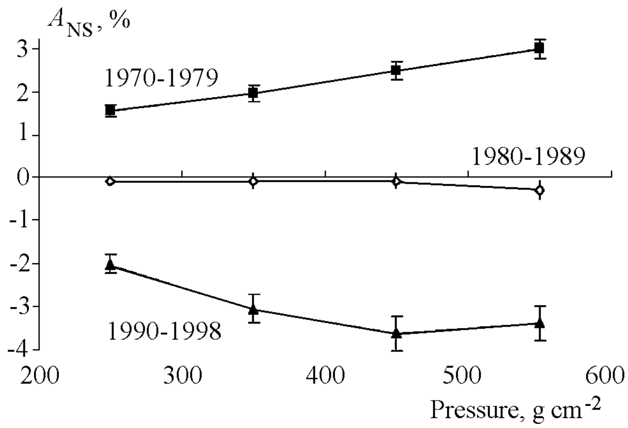

Figure 3. A_{NS} as a function of atmospheric pressure for the 1970s, 1980s, and 1990s.

4. Discussion

Below we discuss some properties of the N-S asymmetry in charged particle fluxes in the lower atmosphere. The source of secondary radiation in the lower atmosphere (under atmospheric pressure $x > 300$ g cm^{-2}) are the galactic cosmic rays, mainly protons with a threshold rigidity greater than 4 GV and the median rigidity of spectra ~15–20 GV.

4.1. The N-S Asymmetry Does Not Change Its Sign at Crossing of the HCS by the Earth

The N-S asymmetry is typically described by invoking the drift currents $\mathbf{B}\times(\text{grad } n)_r$, where $\mathbf{B}$ is the IMF strength and $(\text{grad } n)_r$ is the radial component of gradient of the distribution function of cosmic ray density n [*Pomerantz and Bieber*, 1984]. These currents reverse the sign when the Earth crosses the sector boundary. The fact that the N-S asymmetry does not change its sign when the Earth traverses the HCS means that the drift currents of the $\mathbf{B}\times(\text{grad } n)_r$ type do not give a significant contribution to A_{NS} in our case.

Svirzhevskaya et al. [1997] discussed a possible scheme for formation of the N-S asymmetry involving the diffusion current of particles which has the same direction in neighboring sectors. In case of different solar wind velocities at opposite sides of the HCS, an asymmetric convective particle outflow takes place that leads to a lower density of particles in the sector with a higher wind velocity. As a consequence of that, the diffusion current flows from the sector with a lower V_{sw} to the higher-velocity sector. The diffusion current supports the asymmetry as long as the difference between the solar wind velocities dV_{sw} in neighboring sectors remains sufficiently large. This scheme describes well the large asymmetry in February–June 1973. When high-velocity solar wind fluxes were observed in the Southern hemisphere of the heliosphere, dV_{sw} was negative and A_{NS} was positive. One can see from Figure 4 that this scheme correctly predicts the asymmetry sign for the greater part of the 1990s, but during some periods (1991, the second half of 1994 and of 1995)

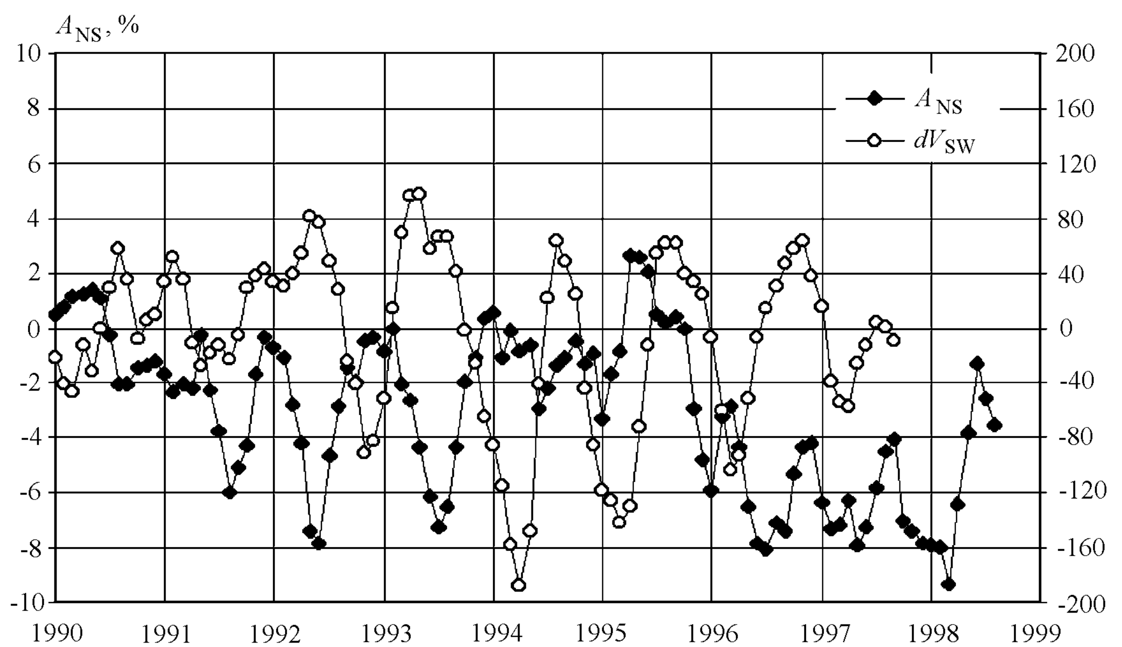

Figure 4. North-south asymmetry (average values for the pressure interval 200–600 g cm^{-2}) and the difference in the solar wind velocities in the positive and negative IMF sectors near the Earth.

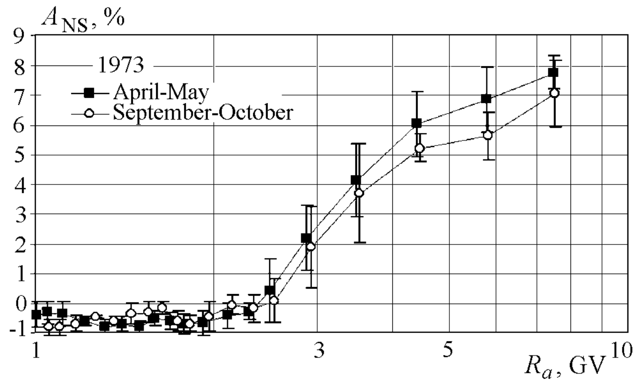

Figure 5. Asymmetry value as a function of the atmospheric threshold in 1973.

the anticorrelation is violated. The condition $dV_{sw} > 0$ (or $dV_{sw} < 0$) is not sufficient for the onset of negative or positive asymmetry in these cases.

A large stable asymmetry during two years (1996–1997) should be noted. In the first half of 1996 the sector structure at the Earth's orbit was nearly absent: for the most part of the period the Earth was in the southern sector, that is, in the magnetic field of the same sign. The asymmetry in this case could be caused by the equatorward drift of particles from the South pole. The drift current in this case could be detected only at Mirny where asymptotic reception cones pointed southward.

4.2. The Asymmetry Value A_{NS} is Large for the (N^+S^-) IMF (1970s and 1990s) and Nearly Zero for the Opposite Directed IMF (1980s)

As follows from the drift theories of modulation, in the 1970s and 1990s the drift currents were directed from the heliosphere poles toward the equator and further, along the HCS, to the heliosphere boundary [*Potgieter and Moraal,* 1985]. In the 1980s, the drift currents flew along the HCS toward the Sun and then to the poles. The longitudes of the asymptotic directions for particles with a rigidity of 10 GV for Murmansk and Mirny stations during the whole year were within the angle of $\sim 90°$ directed from the Earth toward the Sun. Therefore, detectors in the lower atmosphere at these stations can efficiently detect particles only in case of the (N^+S^-) IMF orientation when particles move from the poles toward the helioequator. For the opposite IMF, detectors were pointed in the drift direction, and, hence, were not sensitive to particles.

Thus the mutual orientation of asymptotic directions of Murmansk and Mirny stations and drift currents depends on the IMF direction. In the 1970s and 1990s, drift particle fluxes were efficiently detected in the lower atmosphere. The conditions for development of asymmetry were, therefore, favorable, and A_{NS} (by modulus) was indeed large during those years. In the 1980s, detectors in the lower atmosphere were not sensitive to the drift particle fluxes, and $A_{NS} \cong 0$.

4.3. The Rigidity Dependence of the N-S Asymmetry Magnitude A_{NS}

The major difference between estimates of the N-S asymmetry from neutron monitor data and atmospheric measurements is that it is calculated for different threshold GCR rigidities. The N-S asymmetry in the atmosphere is observed in a wide range of pressures, 200–700 g cm^{-2}. For each pressure x in the atmosphere there is a definite cutoff threshold R_a of the primary GCR spectrum. It is such that the secondary radiation from particles with rigidity $R < R_a$ does not reach the level of observation of x due to absorption in the atmosphere. Therefore, the dependence of the asymmetry value A_{NS} on pressure x can be recalculated into the dependence of A_{NS} on R_a, and the N-S asymmetry can be estimated for different atmospheric thresholds, from 1.5 to 6 GV. The dependence of A_{NS} on R_a for 1973 is shown in Figure 5. It is evident from Figure 5 that the N-S asymmetry exhibits a strong dependence on energy. For instance, in the pressure interval 150–200 g cm^{-2} which corresponds to atmospheric thresholds of 1.5–2.5 GV, the asymmetry is by 5–10 times smaller than for pressure 400–600 g cm^{-2} where atmospheric thresholds are 4–6 GV. The rigidity thresholds of high-latitude neutron monitors determined by the atmospheric cutoff are of the order of 1.5 GV. Therefore, in the A_{NS} calculations a small asymmetry (by the number of particles) in the energy region ≅5 GeV superimposes on large "symmetric" fluxes of particles with lower energy, and the resulting asymmetry is underestimated. Carefull calculations of the N-S asymmetry made in [*Pomerantz and Bieber*, 1984; *Belov and Oleneva*, 1997] have shown that the A_{NS} obtained from the neutron monitor data is 0.05–0.2%. Thus it can be concluded that stratospheric measurements are better suited for observations of the N-S asymmetry than are neutron monitors.

4.4. Annual Wave in the N-S Asymmetry

Figure 6 shows an annual wave in the north-south asymmetry of cosmic rays. It is caused by meteorological effects in the atmosphere. Seasonal variations in temperature and heights of barometric levels at stratospheric stations in different hemispheres of the Earth are in antiphase. The maximum A_{NS} is in July-August. Numerically, the annual variation is $A_{NS} \cong 1.5\%$.

5. Conclusion

The basic objective of present work was to test the assumption about the association of the north-south asymmetry of cosmic rays with the difference dV_{sw} in the solar wind velocities above and under the heliospheric current sheet near the Earth. In the suggested simple scheme of the possible origin of north-south asymmetry its magnitude A_{NS} and sign are predicted by the magnitude and sign of the velocities difference dV_{sw}. The crucial test of this scheme was made

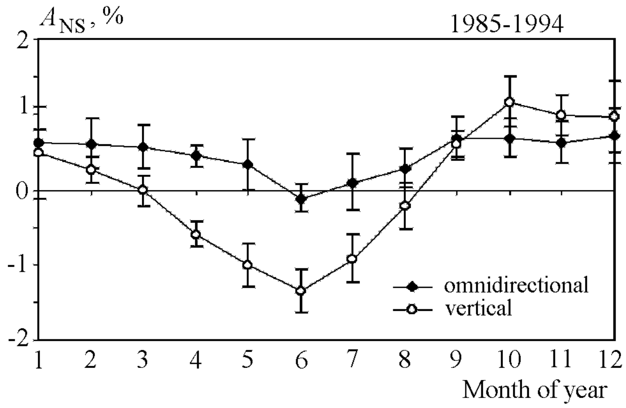

Figure 6. The annual wave in the -asymmetry for the vertical intensity and omnidirectional flux of the cosmic rays (data for the time period 1965–1994 averaged over pressure interval 300–600 g cm^{-2}).

with the data on the N-S asymmetry obtained in 1990–1998 when its sign was changed on the opposite one. The definitive evidence of the dependence of the magnitude $A_{\rm NS}$ and the sign of the north-south asymmetry on the $dV_{\rm sw}$ was not found.

It is believed that the cause of the N-S asymmetry observed in the Earth's atmosphere is the GCR anisotropic distribution beyond the magnetosphere. As noted above, the attempts to find one characteristic in the solar wind or IMF that would correlate with the N-S asymmetry in the particle fluxes in the atmosphere for a sufficiently long period of time have failed. Any asymmetry in basic characteristics of the solar plasma (solar wind velocity responsible for convection and also the IMF strengths and disturbances causing particle drift and diffusion) must lead to asymmetry in particle fluxes. Therefore, to quantitatively describe the asymmetry, the transport equation of the GCR for distributions of the solar wind velocities and IMF characteristics in the Northern and Southern hemispheres of the heliosphere should be solved for specific time periods.

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