MODULATION AND ANISOTROPY OF GALACTIC COSMIC RAYS IN THE HELIOSPHERE

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This rapporteur paper is intended to review sessions SH-4, which were devoted to the study of solar modulation of galactic cosmic rays. Two of the seven sessions, SH-4.6 (anomalous component) and SH-4.7 (radial gradients based on multi-spacecraft measurements) were covered by Dr. Ng in the preceding rapporteur talk. Though these sessions constitute a most important part of the recent developments in modulation studies, they will not be repeatedly reviewed here. The five sessions to be reported on contained 82 contributed papers, among which about 50 were presented at the Conference. Due to the limited scope of this paper, many excellent contributions cannot be quoted here. This report is inevitably biased, reflecting my personal views and approach. The main line of the review shall follow the classification used by the Program Committee. First, modulation models will be discussed with more time spent on two current ideas: episodic modulation and drift models, then the various types of anisotropies will be addressed. Finally, other time variations and correlation studies will briefly be reviewed.

1. INTRODUCTION

Having entered the heliosphere cosmic rays are subject to solar modulation. Charged particles are convected outward by the magnetic fields frozen in the radially expanding solar wind and also undergo adiabatic deceleration due to the expansion of the solar wind plasma. The intensity reduction and energy loss of cosmic rays are very closely connected. At a given energy, an observer inside the heliosphere sees the unmodulated galactic spectrum at higher energies, a falling spectrum should thus result in a decrease of flux. In fact, most of the modulation can be related to energy loss. In a lesser extent, an absorbing boundary near the sun may also give rise to an intensity reduction of cosmic rays without any change of energy.

By now, it is well established that, as long as the diffusion approximation applies, the transport of charged particles in the heliosphere is governed by the equation:

$$\partial f/\partial t = \mathrm{div}(\underline{\kappa}\,\mathrm{grad}\, f) - \underline{V}.\mathrm{grad} f + (\mathrm{div}\underline{V}/3).\partial f/\partial \ln p \qquad (1)$$

where $f(r,p)$ stands for the isotropic part of the cosmic ray distribution in the 6-dimensional $(\underline{r},\underline{p})$ phase-space; the momentum-spectrum, $U_p(\underline{r},p)$ can be expressed as $U_p=4\pi p^2 f$. $\underline{V}$ is the solar wind speed. The diffusion-tensor, $\underline{\kappa}$, has different values along and across the magnetic field, respectively, while its antisymmetric component accounts for the effects of the regular magnetic field. The anisotropy-vector, ξ, is the sum of the diffusive and convective components.

2. MODULATION MODELS

The multi-spacecraft measurements of cosmic ray intensity pose a serious challenge to modulation theories. The 2-4 %/AU value of the radial gradient of >60 MeV particles remained surprisingly stable from solar minimum to solar maximum, while the level of modulation changed considerably (Webber and Lockwood SH 4.7-1). At lower energies, there was virtually no observable gradient between 1 AU and 30 AU during solar activity maximum (McKibben, Pyle, and Simpson 1985; SH 4.7-5). For a detailed review of the radial gradients the reader is referred to the report of Ng in this volume. All these results imply that a very large part of modulation should take place at heliographic distances beyond 30 AU. It seems that either the region of modulation should be larger than believed, or modulation should be fairly effective at large heliographic distances.

There may be several possibilities to resolve this problem. In a pair of papers Gold and Venkatesan (SH 4.1-14) and Roelof (SH 4.1-24) suggested that the shocked plasma may form a buffer at large distances (>10 AU) from the sun. By reaching the distance of 10 AU, practically all the plasma must have gone through a shock: the shocked plasma is expected to be turbulent with a small diffusion coefficient. The unshocked plasma, on the other hand, is assumed to be virtually scatterfree. The authors presented an indication in favour of this hypothesis: at 1 AU a higher cosmic ray intensity was found when the connecting field line reached the shocked region at larger distances, and intensity minima were observed when this assumed shocked region happened to be near the earth.

Another possibility is the presence of a boundary effect as it was proposed by Krainev, Stozhkov, and Charakchyan (SH 4.2-19). So far, very little is known about the transition between the interstellar space and the heliospheric magnetic field. One cannot even rule out that the location of the outer boundary changes during a solar cycle. The study of the outer boundary, which has been a largely neglected subject so far, is one of the topics which should be addressed to in the next years. It would not be too surprising if the region of solar wind termination turned out to have profound effects in the transport of cosmic rays.

In the paper SH 4.1-6, Garcia-Munoz, Pyle, and Simpson demonstrated that the observed modulation of proton, helium, and carbon spectra can be explained in terms of a simple 1-dimensional force-field model. They used the helium spectrum as an input to estimate the radial diffusion coefficient, κ_{rr}, which was allowed to vary from year to year. Then the thus adjusted diffusion coefficients (Figure 1) gave a good fit for the other species, too. The force-field solution (Gleeson and Axford 1968) represents the most widely usable analytical approximation to the time-independent form of the transport-equation (1). It does,

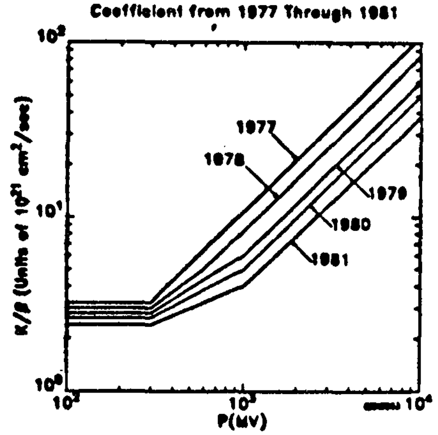


FIG. 1. - Inferred diffusion coefficients at 1 AU (SH 4.1-16)

however, rely upon the assumption of κ_{rr}>>r.V which is violated at larger distances if, as assumed, κ_{rr} changes slowly between 1 AU and 30 AU. It remains to be determined whether the force-field solution still gives a reasonable approximation for the case of $\kappa_{rr} \approx rV$. One may expect a certain breakdown of the force-field theory, and a dramatic increase of modulation if $rV/\kappa_{rr} \gg 1$. Most probably, employing a numerical method instead of the force-field approximation would result in somewhat modified diffusion coefficients at low energies but would not alter the overall picture. The results of SH 4.1-6, however, do not necessarily prove that cosmic ray transport is indeed 1-dimensional, they may show only that, at the present stage, we have still too much freedom in adjusting the values of diffusion coefficient.

2.1. Episodic modulation

It has been noted by McDonald et.al. (1981) that cosmic ray intensity shows sudden step-like decreases followed by slow, but not full, recoveries. These events, in most cases, can be associated with disturbances travelling outward in the solar system. The step-like decreases can be identified in the records of various spacecraft, the time lags correspond to a propagation speed of roughly the solar wind velocity. This led to the hypothesis that the long-term modulation is a cumulative effect of many episodic decreases. The immediate cause of the sudden decreases has not yet been clearly established, it may be, for instance, either the shock itself or the enhanced scattering in the disturbed region. Perko and Fisk (1983) assume narrow shells of enhanced scattering propagating together with the solar wind. The emission of these shells is supposed to be more frequent at high solar activity. This treatment calls for the solution of the time dependent transport equation (1). In return for the more numerical computation required, this method is also able to account for time lag between the variation of the cosmic ray intensity and the solar activity.

Venkatesan et. al. (1984) found that the phase of solar modulation propagated considerably faster than the speed of the solar wind. This seemingly surprising finding was explained by Forman, Jones, and Perko (SH 4.1-12) in an elegant way. As these authors pointed out, modulation is sensitive to the integrated effects between the observer and the outer boundary. Crudely, the integral is maximum, and intensity is at minimum, when the maximum of disturbances is halfway between the observer and the boundary. As a result, the phase of modulation may travel about twice as fast as the solar wind. The more accurate numerical work gave a value of 1.85 times the speed of the individual decraeses. It should be borne in mind, as the authors emphasized, that this derivation applies only if modulation is indeed a cumulative effect of many events. In the case of one single event or decaying disturbanceswhich do not travel to large distances, the phase of modulation should obviously propagate with the velocity of individual decreases.

There have been arguments brought forward indicating that "merged interaction regions" are responsible for the sudden intensity decreases. Burlaga, Goldstein, and McDonald (SH 4.1-11) found a most impressive agreement between the occurence of decreases in the intensity of >75 MeV/n nuclei and the passage of regions of enhanced magnetic field at the Voyager spacecraft (Figure 2). The regions of strong magnetic field are interpreted as "merged interaction regions" with turbulent fields which are formed as a result of interaction of shocks and streams. Now it is

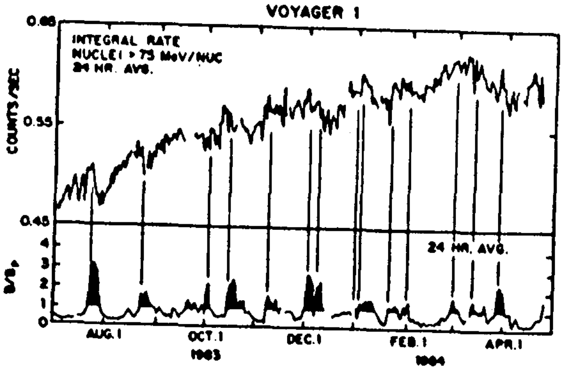


FIG. 2. - Itensity of cosmic rays)75 MeV/n vs. time (top) and magnetic field strength w.r.t. the spiral field (SH 4.1-11)

the turn of theory to provide a solid basis to the originally phenomenological description: a yet unpublished paper of Chic and Lee (1985) claims to give this theoretical support. Thus, research in this field seems to be vigorous and progress is rapid. The theoretical model permits an estimation of the diffusion tensor, the thus inferred value turns out close to the value of Perko and Fisk (1983).

At higher rigidities (1-2 GV), the effect of a sequence of shocks was investigated by Gall, Thomas, and Durand (SH 4.1-7) who applied a method based on calculating the intensity reduction from the spectrum of energy loss. The remarkable feature of this work is that it permits acceleration and decelaration at the same time. One single shock will give rise to a sharp Forbush-like decrease. If, however, there is a sequence of shocks then particles trapped between two shocks may also gain energy, and this may give rise to a slower variation of intensity. In this context it is important that shocks are assumed to widen while traveling outward otherwise div$\underline{V}$, which is responsible for energy gain or loss, could not be negative. In the overall balance deceleration is the dominant process leading to a net decrease of particle flux. The most important parameter of modulation appears to be the frequency of the shocks emitted. This work also included drift-effects which can be important at the energies considered. Indeed, a marked difference was found between the results obtained for the two opposite magnetic configurations.

In recent years, there has been a great deal of misunderstanding concerning calculations relating the modulation of cosmic ray intensity to the spectrum of energy loss. The subject of controversy is the applicability of the Liouville's theorem for diffusive processes like cosmic ray transport in the heliosphere. It can be shown, however, that the "method of energy loss" is mathematically equivalent to the use of the adjoint Green-function developed by Webb and Gleeson (1977) (see Kóta 1984). Intensity modulation and energy loss stem from the same basic physical process and there is a close and deep relation between them. Energy loss is not an extra process, but, in a sense, is rather tantamount to intensity change.

Obviously, the study of Forbush-decreases may allow a better insight into the process of modulation. An extensive statistical study of the recovery time was presented by Lockwood, Webber, and Jokipii (SH 4.1-9). They conclude that the average recovery time is fairly stable throughout the solar cycle, including the polarity reversal of the sun. It also turns out independent of particle energy, but it does depend on the heliographic distance. The longer recovery time at large radii may lead to a more effective modulation in the outer heliosphere. By analyzing the rigidity spectra of long-term modulation and Forbush-decreases at neutron monitor energies, Fenton, Fenton, and Humble (SH 4.4-10), on the other hand, arrived at different spectral exponents, which might be considered as an indication against interpreting long term modulation as superimposed Forbush-decreases, at least at these energies.

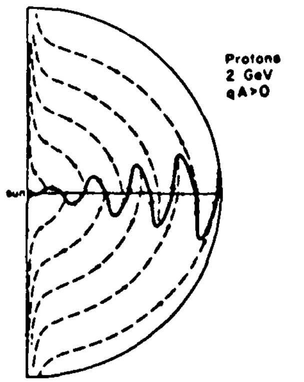
Earl (SH 4.1-3) and Earl and Jokipii (SH 4.1-3) presented a couple of works on numerical techniques for solving time-dependent transport equations. These papers are more relevant to the propagation of solar particles where time variations are faster and numerical subtleties are more delicate. Nevertheless, they have a message to the modulation workers, too. First, the grids should be chosen carefully. One should add that in a realistic case the coefficients of the transport equation are not constant, thus the construction of an appropriate grid is not at all trivial. The main lesson, in my judgement, is that one should first understand the qualitative behaviour of the solution and then employ the numerical code.

2.2. Drift models

Drift still remained a most controversial subject, there were numerous arguments both pro and contra drift. Drift models seem to have been attracting critics ever since the pioneering work of Jokipii, Levy and Hubbard (1977). This stems from the fact that drift theories come up with very specific predictions. Curvature and gradient drifts are the only known process in cosmic ray transport which is sensitive to the electric charge. Thus, a charge dependence in the modulation should be a unique signature of drift. A charge asymmetry may appear in two obvious indirect forms. First, two consecutive 11-year cycles may be different or, in other words, the two halves of the 22-year magnetic cycle are different. Second, the location of the interplanetray neutral sheet can be important. My classification in this section (i.e. 22-year cycle, charge-asymmetry, neutral sheet effects) is largely artificial, all these result from a common origin, namely charge-dependence.

Conceptual developments

For a near isotropic distribution the particle drift velocity in a magnetic field, $\underline{B}$, is $\underline{v}_d = (pc/3q)\nabla\times(\underline{B}/B^2)$, which is also the divergence of the antisymmetric part of the diffusion tensor, provided the scattering mean free path, λ, is sufficiently larger than the Larmour radius, ρ. Positively charged particles drift (Figure 3) from the poles toward the neutral sheet in the magnetic configuration prevailing in the years 1970-1980, when field lines point away from the sun above the neutral sheet and sunward below the sheet (A>0). For the opposite configuration (A<0) the sense of drift reverses. The δ-like singularity of the drift appearing at the neutral sheet may cause some concern. The velocity of the guiding center is indeed infinite at the crossing of the neutral sheet, the average drift of a particle during a gyro-period, however, obviously remains less than the particle speed. Burger, Moraal, and Webb (SH 4.2-3) refined the concept of drift by evaluating the average (and finite, of course) drifts near the neutral sheet. Since drift velocity is divergence-free, it immediately follows that the two approaches must give the same net drift in the $(-2\rho,+2\rho)$ vicinity of the neutral sheet. The δ-singularity can also be avoided in the original derivation, its emerge is connected with the well-known inaccuracy of the diffusion picture near a boundary.



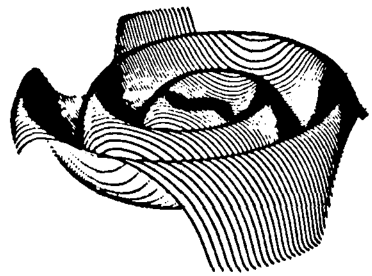


FIG. 3. - Drift velocities (left) and the wavy neutral sheet (right)

22-year cycle

The presence of a 22-year cycle first appeared in the earth-based anisotropy measurements: in the periods of A>0, the phase of the solar daily variation was observed to shift toward earlier hours with respect to the 18 hr phase of corotation. This effect can be accounted for in a natural way in terms of drift. In fact, the renaissance of drift theory started when Levy (1976) invoked drift to explain this phase shift in the solar daily wave of cosmic ray intensity variation. Anisotropies will be discussed in more detail in a later paragraph.

In an extensive numerical work Potgieter (SH 4.2-4, SH 4.2-5, see also Potgieter and Moraal 1985) was able to describe the proton and electron spectra for two consecutive solar minima (1965 and 1977) with one single set of parameters. Figure 4 shows the good agreement between the observed and calculated proton and electron ratios (1977 relative to 1965) in the 50 MeV - 1 GeV range. The predicted radial gradient of protons turns out considerably smaller for the magnetic configuration of 1977 (A>0), in accord with other drift calculations (see Kóta and Jokipii 1983, and references therein). Observations, on the other hand, seem to indicate a stable gradient or a decrease of gradient for A<0, (see the

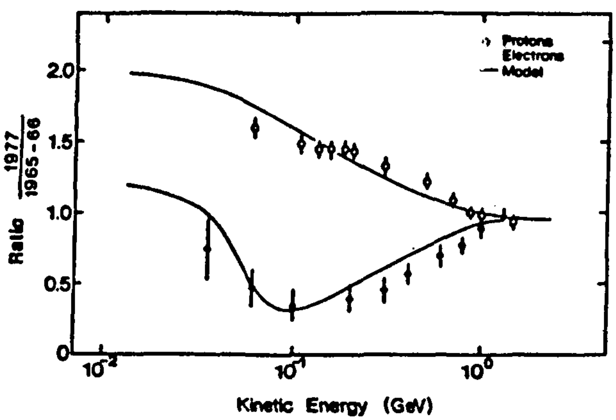


FIG. 4. - Calculated proton and electron ratios for 1977 relative to 1965 + 1966 (SH 4.2-4)

review of Ng, this volume). The radial gradient is certainly an exciting and controversial subject. The smaller radial gradient for A>0 seems to be essential in explaining the observed phase-shift of the anisotropy at GeV energies. Conversely, the smaller azimuthal streaming obtained by anisotropy measurements in the seventies implies a smaller radial gradient, at least for the GeV energies, where direct data on the gradient are scarce. The small radial gradient in the case of A>0 is a common feature of drift models. Kóta (1981) has derived a 3-D force-field solution including drift which gives a charge independent radial gradient, this model, however, relies upon specific assumptions. At low energies, the nature and extent of drift effects are not fully understood yet, the exploration of these is an important and urgent task.

Neutron monitor intensities exhibit different time evolution in the two 11-year cycles. Shea and Smart (SH 4.2-24) presented an updated statistical analysis of the correlation between cosmic ray intensity and the geomagnetic aa index. It is apparent from Figure 5 that, in the sixties, cosmic ray intensity was peaked at solar minimum, while the period of the seventies was characterized by a long plateau. This is just what one would expect from a drift model incorporating a wavy neutral sheet, with the tilt angle varying from small to larger angles as solar

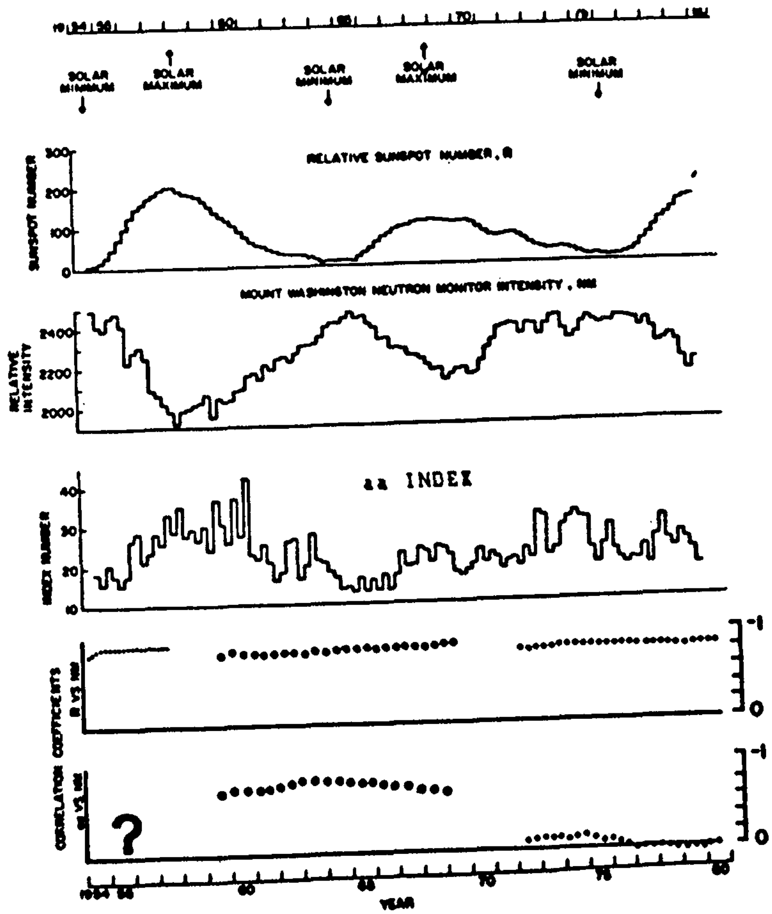


FIG. 5. - The sunspot numbers, cosmic ray flux, and aa index vs. time from 1954 to 1979. Lower panels show correlation coefficients. For details see SH 4.2-24.

activity increases (Kóta and Jokipii 1983). The correlation between the cosmic ray intensity and the geomagnetic aa index was found to be good for A<0 and poor for A>0. This, again, is in accord with the predictions of drift models. In this context, it is not crucially important that the modulation is ascribed to the wavy neutral sheet, it could be substituted by any other phenomenon which affects cosmic rays primarily in the helioequatorial region. In contrast to these results, Otaola, Perez-Enriquez, and Valdes-Galicia (SH 4.2-22) and Chirkov (SH 4.2-21) find a good correlation between the aa index and cosmic ray intensity for A>0, too. According to these authors, the aa index itself has a 22-year cycle and this is solely responsible for the asymmetry in cosmic ray counts. Similar conclusion is reached by Krivoshapkin et.al. (SH 4.4-22) at high rigidities. More studies are required to resolve the discrepancy between these works.

I also would like to mention two works here, which were presented in other sessions but bear importance in the topic of my report, too. Moraal and Mulder (SH 5.1-2) presented a statistical analysis of Forbush-decreases in the two different magnetic cycles. They find an evidence indicating that, at neutron monitor energies, the recovery is faster in the A>0 configuration. This may be interpreted as a result of drift: particles drifting down from higher latitudes (A>0) can refill the earth's vicinity more rapidly than particles coming through the equatorial region (A<0). It would be interesting to see if there is a difference between the anisotropies during the time of recovery.

One of the most interesting developments at the Conference was the reappearence of the anomalous component. The spectrum of the anomalous component has been found to shift toward higher energies with respect to the last cycle (Cummings, Stone, and Webber SH 4.6-1). This can be interpreted in terms of drift (Jokipii 1985). The anomalous component has very important implications, these will not be discussed here (for details on the anomalous component, see the report of Ng, this volume).

Charge-asymmetry

Recently Evenson and Meyer (1984) found that after the last solar maximum electron intensity recovered faster than protons while the opposite happened following the previous (1970) maximum. This is in agreement with the prediction of Kóta and Jokipii (1983), and can be interpreted as strong indication of drift effect. At this conference, Garcia-Munoz et. al. (SH 4.2-23) presented a thorough study of the helium to electron ratio from 1965 to 1985. The investigated energy ranges correspond to roughly the same rigidities, the difference in velocities is not expected to introduce a significant effect. The relative content of 70-95 MeV/n helium increased by about a factor of 2 around the polarity reversal of the sun in 1970, and decreased to its earlier (1968) level around 1980 (Figure 6). Since observations refer to the same time period, there can be little doubt that this finding should be interpreted as a clear sign of a charge dependence in the modulation of cosmic rays. It would be , however, too early to celebrate for those who believe in drift. Electrons fail to show the peaked 11-year cycle in the years of seventies, which would be a major prediction of the model of Kóta and Jokipii (1983). Instead, the time evolution of electron and helium intensities turn out rather similar (Figure 7). Certainly, further theoretical and experimental efforts are needed to clarify this subtle problem. Unfortunately, simultaneous electron and helium data are avail-

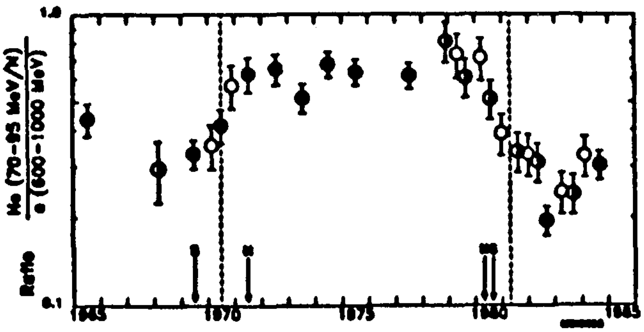


FIG. 6. - Helium to electron ratio versus time. The dashed vertical lines refer to solar polarity reversals. For details see SH 4.2-23.

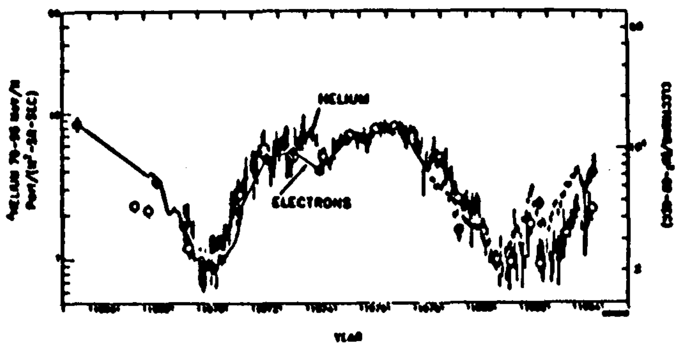


FIG. 7. - Modulation of helium and electrons in the 1970-80 cycle. Note that shapes are near the same. (SH 4.2-23)

able for one cycle only, the status of experiments will improve as the present cycle proceeds. From the theoretical side, the implications of drift should be studied more thoroughly at lower energies. Furthermore, it should be kept in mind that the model of Kóta and Jokipii (1983) does not claim to describe the period of solar maximum. The present model is certainly too simplified for that case. Unfortunately, a more sophisticated model will encounter new numerical, and also conceptual, difficulties.

<u>Neutral sheet effects</u>

The structure and location of the neutral sheet may affect cosmic ray transport in either a direct way via drift or an indirect way via the increase of the solar wind speed away from the neutral sheet.

A drift-model incorporating a wavy neutral sheet obviously needs a 3-dimensional calculation. The numerical studies of Kóta and Jokipii (1983, see also SH 4.2-10) represent the only full 3-D treatment available so far. Figure 8 shows the intensity contours obtained on a 1 AU sphere for both A>0 and A<0. The 3-dimensional character of the solutions is apparent. The intensity contours are best organized by the neutral sheet. It should also be kept in mind, however, that there is no obvious single parameter to fully organize the contours.

As a rule, cosmic ray intensity is predicted to rise toward the poles for A>0, and fall away from the neutral sheet for A<0. The difference in the latitudinal gradients, if observed, would be an evidence in favour of drift. Earth-based measurements give azimuthal sections in a narrow band around the heliographic equator. The 7.5° excursion of the earth about

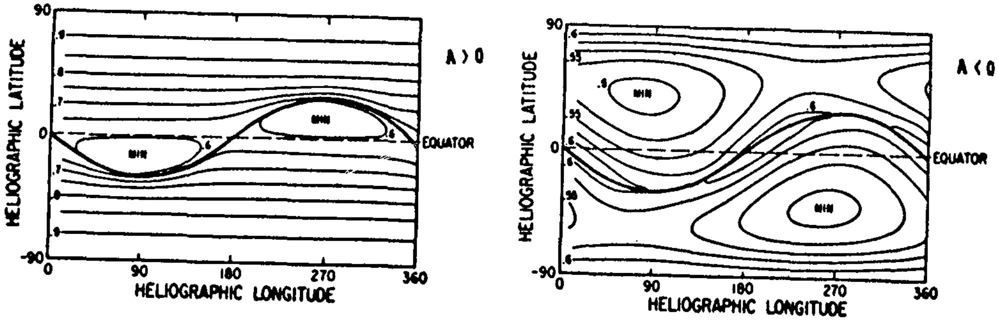


FIG. 8. - Computed contours of equal cosmic ray intensity at 1 AU, for 2.36 GeV protons, for A>0 (left) and A<0 (right). The inclination of the neutral sheet is 30 degree (Kota and Jokipii 1983).

the helioequatorial plane permits the study of the latitudinal gradient. By exploiting this, Kóta, Merényi, and Erdős (1985) arrived at a polarity dependent gradient of high rigidity (~70 GV) cosmic rays rising away from the neutral sheet in the period of 1974-79, in accord with the predictions.

When the earth-based intensities are organized according to the "heliomagnetic latitude" of the earth (i.e. distance from the neutral sheet), a negative correlation is obtained between cosmic ray intensity and heliomagnetic latitude (Figure 9) for both configurations (Newkirk and Fisk 1985; Newkirk et.al. SH 4.2-16). This result is seemingly surprising for A>0. With a numerical simulation of the experimental situation, Jokipii and Kóta (SH 4.2-10) demonstrated that a 3-D model does predict such a negative correlation (Figure 10) thus experimental results do not disprove drift. Newkirk et.al. (SH 4.2-16) have also pointed out that the model calculations of Kóta and Jokipii (1983) would give a much larger gradient for A<0, while the measurements do not show any significant difference (Figure 11). This challenge has not been answered yet. The A<0 solutions are sensitive to perpendicular diffusion, thus it is conceivable that adjusting the parameters could cure the discrepancy. Another, perhaps more probable, possibility is that calculations employed a too simplified, and too regular model.

$U = a_0 + a_1 \sin^2\lambda_{mg}$,

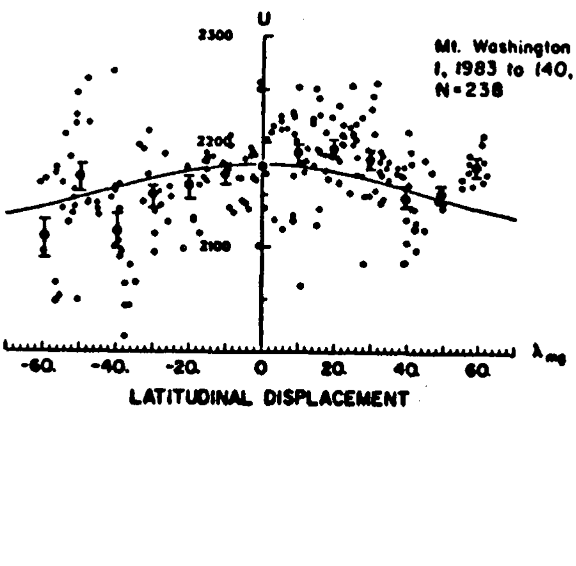


FIG. 9. - An example of the variation of cosmic ray flux vs. heliomagnetic latitude during 1983-84 (A<0) (SH 4.2-16). A very similar picture is obtained for A>0 (Newkirk and Fisk 1985).

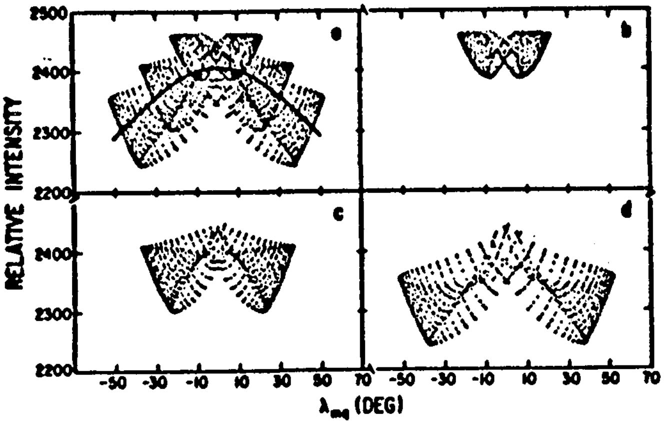


FIG. 10. - a total scatter plot of intensity versus heliomagnetic latitude, λ_{mg}, summed over three inclinations: 15 (b), 30 (c), and 45 (d) degrees (SH 4.1-10)

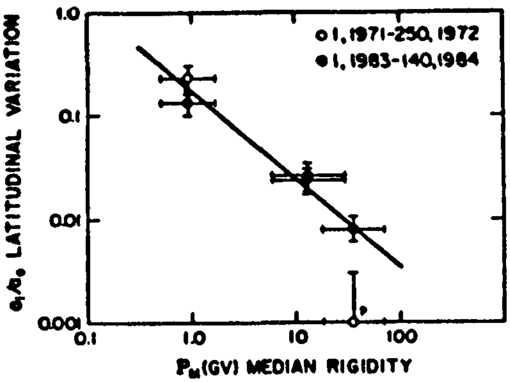


FIG. 11. - The rigidity dependence of the relative latitudinal gradients. Note the lack of a significant difference between the 1971-72 and 1983-84 intervals (SH 4.22-16).

Christon et.al. (SH 4.2-9) used the data of Voyagers to derive the latitudinal gradient of >75 MeV protons from two-point measurements in the period of 1981-83 (A<0). They found that a negative gradient became significant when a selecting restriction was employed. Crudely, this restriction selected the configurations when both spacecraft were on the same side of the sheet (say above) and, furthermore, the one at higher latitude (Voyager 1) was also more distant from the sheet. This selection enabled the authors to filter out real latitudinal effects and suppress the noise from azimuthal effects. The result is in good agreement with the predictions of drift.

Saito and Swinson (SH 4.2-8) pointed out that, in the period of 1971-74, two remarkable decreases in the counts of the Mt. Washington Neutron Monitor coincided with high inclinations of the tilt angle of the neutral sheet, just as expected from drift models. Badruddin and Yadav (SH 4.2-12) also find a negative correlation between the tilt angle and the intensity of cosmic rays, which, however, they attribute to the increase of the solar wind speed.

In a numerical study including a wavy neutral sheet, Alaniya et.al. (SH 4.2-18) confirm that cosmic ray intensity decreases as the tilt angle of the sheet is increased. This work, however, employs a 2-D code assuming azimuthal symmetry. Conceptually, the neutral sheet cannot be azimuthally symmetric, it would violate the div$\underline{B}$=0 condition. The azimuthal asymmetry, in my judgement, is essential in the case of a wavy sheet. These authors also make an ambitious attempt to derive some interesting quantities from the anisotropies obtained in different magnetic sectors. In doing so, however, they seem to assume a constant latitudinal gradient, which appears to be unjustified: the latitudinal gradient is bound to change at sector crossings.

2.3. Concluding Remarks

It seems that progress has been made since the last Conference. The field of episodic modulation is flourishing. Drift still remained a controversial subject and attracted much attention: there were new experimental and theoretical works presented both in favour of drift and challenging it. Being personally biased I would be inclined to giving more credit to the pro arguments. Drift models were successful in explaining some basic phenomena, the difficulties encountered may be connected with the simple, overly regular field models employed in the calculations. Often, the question is set in the form: is modulation caused by drift or something else? It should be remembered, that drift does not exclude other effects superimposed on it. In particular, drift models in their present form do not claim to describe the period of solar maximum when the heliospheric field should be more complex.

Spacecraft measurements in the outer heliosphere brought puzzling results which will certainly inspire theoretical research. By the time of the next Conference we reach solar minimum which then can be compared with the last minimum. We will be ahead of the exploration of high latitudes by the Ulysses mission, which makes 3-D predictions to become increasingly important. To promote the credit of model-calculations we need a better understanding of the scattering-process. Unfortunately, theory has advanced little in this field in the last years. At the Conference, there was only one theoretical paper addressing this problem: Dorman et.al. (SH 4.1-20) attempted to separate the scattering effects of "small-scale" and "large-scale" magnetic inhomogenities.

3. ANISOTROPIES

Anisotropies will be divided into three convenient groups. First, I discuss the so-called $\underline{B} \times \underline{\nabla} n$ anisotropy which is closely related to the local gradients. Then sidereal anisotropies will be reviewed, which aim to the search of a galactic signal. Finally, the term of solar anisotropies will include all solar induced anisotropies which do not fall into either of the first two categories.

3.1. $\underline{B} \times \underline{\nabla} n$ anisotropy, local gradients

The $\underline{B} \times \underline{\nabla} n$ anisotropy arises as a result of the antisymmetric term of the diffusion tensor. This streaming is connected with the regular spiralling motion in the magnetic field. It is not directly connected to particle drift: without density gradient, drift will not produce any anisotropy, while a density gradient does lead to a streaming in a homogeneous magnetic field, too. The magnitude of the resulting anisotropy is $\rho . \nabla_{\perp} n/n$, where $\nabla_{\perp} n$ is the density gradient in the direction normal to the field. Being polarity-dependent this anisotropy can be disentangled from other terms of the anisotropy, and then, knowing the Larmour radius, ρ, the gradient can be determined (Bercovitch 1970).

Fillius et.al. (SH 4.3-7) employed this method to estimate the radial gradient from the >500 MeV/n channel of Pioneer 10 (median rigidity $\sim$5 GV) in the period of 1973-75, during which the spacecraft traveled from 3 AU to $\sim$7 AU. The analysis gave a fairly stable gradient between 1 - 2 %/AU which is also comparable with the values of the global gradient between the earth and the spacecraft derived from the total counts. Unfortunately, the global gradient is not available for the same channel (see SH 4.7-2) during this period.

At higher rigidities ($\sim$10 GV), Bieber and Pomerantz (SH 4.2-6) convincingly demonstrate the presence of a $\underline{B} \times \underline{\nabla}n$ anisotropy, which produces a North-Shouth asymmetry in the counting rates of the neutron monitors at Thule and McMurdo, respectively (Figure 12). The inferred

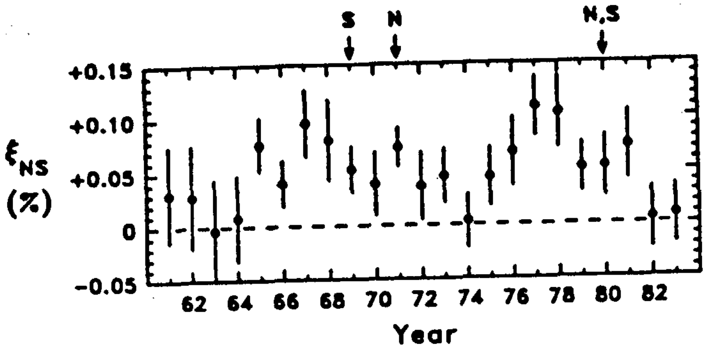


FIG. 12. - The cosmic ray North-South anisotropy, as obtained from the Thule and McMurdo NM records (SH 4.2-6)

radial gradient seems to show an 11-year cycle around a mean of 1.7 per cent/AU, and fails to show any noticeable dependence on the polarity of the solar field. The mean value of gradient agrees with that of Fillius et.al. It is intriguing that the radial gradient appears fairly stable over a wide range of energy: the values are barely larger for the >60 MeV particles (see Webber and Lockwood SH 4.7-1), despite the anticipated change of κ_{rr} in this range (c.f. Figure 1). At the lowest energies, the decrease of the Compton-Getting factor may explain the low value of the gradient, but it is hard to see a similar effect above 200 MeV.

The presence of the $\underline{B} \times \underline{\nabla}n$ streaming was also demonstrated in the work of Takahashi, Yahagi, and Chiba (SH 4.3-13) who deduced the first zonal harmonic from the data of the worldwide neutron monitor network, and showed that it undergoes sudden jumps at sector-crossings. A good correlation was found between the anisotropy and the components of the magnetic field by Xue, Zhang, and Xao (SH 4.3-15).

In a theoretical work Kóta and Jokipii (SH 4.2-11) argue that the $\underline{B} \times \underline{\nabla}n$ anisotropy may not appear in its full form. The latitudinal gradient may depend on magnetic polarity and, in this case, diffusion across the field lines will also give a polarity-dependent streaming, which may reduce the net N-S anisotropy. This effect can be important in the drift-models where latitudinal gradients are not negligible. In this case, the commonly used quantitative relation between the polarity dependent N-S anisotropy and the radial gradient may be inaccurate (the value of perpendicular diffusion coefficient should be crucial). It is also pointed out in this work that, in contrast to 2-D models, a 3-D model is able to reproduce the correct sense of this anisotropy.

The $\underline{B} \times \underline{\nabla}n$ anisotropy can also be applied to detect a steady North-South gradient as it has been shown by Swinson, Shea, and Humble (SH 4.2-7). The $\underline{B} \times \underline{\nabla}n$ streaming, in this case, adds a polarity-dependent component to the daily variation in solar time. This study yielded a significant gradient rising toward the south for A<0, while a symmetrically rising gradient was obtained for the opposite polarity state (A>0, i.e. 1970-80). The authors attribute the asymmetric gradient to the N-S asymmetry of the sun: the northern hemisphere was observed to be more active during 1960-70, then this asymmetry disappeared after 1970. The symmetric gradient may be interpreted in terms of drift.

Significant N-S gradient has been found by other workers, too. By making use of the 7.5^{o} inclination of the earth's orbit, Pathak et.al. (SH 4.3-14) infer an about 0.2 %/degree gradient pointing toward the south and no observable symmetric gradient during 1978-83. Since this study gives a mean variation averaged over polarities, the lack of a symmetric gradient does not deny the predictions of drift models. From the analysis of isotropic intensity waves, Duldig, Jacklyn and Pomerantz (SH 4.3-8) arrived at the conclusion that these may have resulted from a higher intensity of cosmic rays below the sheet. This is only one possible interpretation, the origin of the observed intensity waves is not yet well understood.

The presence of a small asymmetry of the heliosphere would bear some implications. For sake of simplicity, most of the theoretical works adopt simple symmetric models. One would anticipate small changes in the intensity distribution due to small asymmetries. The impact, however, would be more severe on the anisotropies which depend on a delicate balance.

3.2. Sidereal variations, galactic anisotropy

A major objective of studying sidereal daily variations is the search for a genuine galactic anisotropy. Beside a true galactic signal, there are other known effects which may also give rise to an intensity variation in sidereal time. An asymmetric heliosphere could easily produce a net stream of particles which could not be distinguished from a galactic signal. Even a symmetric heliosphere may, and does, produce 'spurious signal': the second spherical harmonics of the heliospheric anisotropy can also contribute to the sidereal daily variation. This was discussed in detail in the Highlight Talk of Mori (this volume). To eliminate this effect, most of the presented works employed the 'Nagashima-correction' (Nagashima et.al. 1983) inferring the spurious sidereal daily wave from the observed antisidereal wave. I shall return to this correction in the next paragraph.

Another difficulty in detecting a galactic anisotropy is posed by the 'magnetic optics' of the interplanetary field: the deflection of particle trajectories will distort and attenuate the original signal, random scattering will further impair the conditions of observation. An extensive study of these effects (Nagashima, Morishita, and Yasue, 1982) predicted a large dependence on the polarity of the heliospheric field. Bercovitch (1984, and also SH 4.4-1) compared these predictions with the experimental results of the Ottawa Horizontal Muon Array, and found that the expected displacements of the sidereal vectors failed to show up at the last polarity reversal. The discrepancy could not be resolved by changing the rate of scattering. This finding might imply that our model of the heliospheric magnetic field is inaccurate. It is an attractive feature cf the several hundred GV particles that they may prove to be quite powerful in exploring the large-scale interplanetary field. Of course, the way of exploration is not straightforward, and these hopes may be excessively optimistic.

Galactic anisotropy was searched for in a wide range of energies. Some of the reported first harmonics are summarized in Table 1. The lowest energies were represented in the work of Ishida et.al. (SH 4.4-2) who analyzed an impressive amount of data from the worldwide network of neutron monitors, and obtained somewhat different phases for the two polarity states. The 30 year record of the Yakutsk ionization chamber gave very small amplitude (Kuzmin et.al. SH 4.4-8). Ueno et.al. (SH 4.4-3) presented a comprehensive study of Nagoya, Misato, and Sakashita muon telescopes. Table 1 shows the results of the vertical telescopes, and also a high-energy point from the Sakashita South 60° inclined telescope is added. A similar analysis has been carried out by Swinson and Nagashima (SH 4.4-7) including the Bolivia, Embudo, and Soccoro stations. The deep-underground results of Matsushiro (Yasue, Mori, and Sagisaka SH 4.4-9) are already barely influenced by solar effects. All the quoted results are corrected for solar effects with Nagashima's method.

Paper	Station		P_m(GV)	amp $\times 10^4$	phase	
SH 4.4-2	NM network			2.0 ± 0.2	6.1 hr	A<0
				2.1 ± 0.2	8.6 hr	A>0
SH 4.4-8	ion ch. Yakutsk			< 0.5		
SH 4.4-3	muon	Nagoya (V)	60	2.1 ± 1.1	4.4 hr	
		Misato (V)	145	1.2 ± 0.8	0.9 hr	
		Sakash.(V)	331	2.8 ± 0.4	4.2 hr	
		--- (SS)	540	7.2 ± 0.6	2.4 hr	
SH 4.4-7	muon	Bolivia(V)	125	1.7 ± 0.5	9 hr	
		Embudo (V)	132	0.9 ± 0.3	1 hr	
		Soccoro(V)	305	2.7 ± 0.4	4 hr	
SH 4.4-9	muon	Matsushiro	700	3.1 ± 0.5	2.3 hr	
SH 4.4-4	muon	Poatina	1200	8.1 ± 2.5	2.4 hr	

Table 1.

Finally, the highest energy point is given by the Poatina measurement reported by Humble, Fenton, and Fenton (SH 4.4-4). The lack of significant variation in solar and anti-sidereal time confirms that the observed sidereal variation is due to a true galactic signal, and solar contamination is indeed negligible. Their first harmonic is in a good agreement with the well established galactic anisotropy obtained at somewhat still higher energies by the Musala, Norikura, and Baksan experiments, which, in a consensus, agree in a first harmonic of 0.057 percent and phase around 1.4 hr (c.f. Gombosi et.al. 1975, Sakakibara et. al. 1984, Alexeenko et.al. 1981). There is no compelling reason to expect the same anisotropy at the Northern and Southern hemispheres, respectively. The close agreement of the first harmonics is reassuring, as it implies that the structure of the anisotropy is reasonably smooth and relatively simple.

Inspection of Table 1 shows that the high-energy points tend to have a phase close to the 'expected' 1-2 hr. Measurements of median rigidities above 500 GV (Matsushiro, Sakashita SS) yield phases of 2-3 hr, the 300-500 GV range tends to shift toward later hours (around 4 hr). I would feel tempted to draw the conclusion that going down below 300 GV it is increasingly difficult to eliminate solar effects. In particular, I would like to call attention to the possible asymmetries of the heliosphere (see previous paragraph) which are largely unkown. Experimental accuracy has vastly improved in the last decade. Our knowledge of the heliospheric field, however, may not live up to this accuracy. Now, we are able to see tiny effects which cannot be accounted for on the basis of our present knowledge. The traditional way of approach may need to be reversed: instead of taking the field model granted, we may use the anisotropy measurements to extract more information on the large scale structure of the heliosphere.

The second harmonic of the sidereal variation remains an intriguing problem. All of the Norikura, Baksan and Musala measurements show a significant second harmonic with phases around 5-6 hr, Norikura even claims a third harmonic around 7 hr (Sakakibara et.al. 1984), implying that the galactic anisotropy cannot be ascribed to a simple streaming. The Poatina results, on the other hand, do not show any noticeable second harmonic. This might be due to the limited statistics, but may as well indicate a true North-South difference. The discussion of the nature of a galactic anisotropy falls beyond the scope of this review. Yet, I feel tempted to make a remark, which stems from heliospheric background. It was proposed by Kóta (1979) that anisotropic pitch-angle scattering might be responsible for the rise of higher harmonics in the galactic anisotropy. Recently, Bieber and Pomerantz (1983) has worked out a similar, more advanced, theory including adiabatic focusing, to explain the higher harmonics of solar anisotropies. It would be interesting to see if the observed sidereal harmonics could be interpreted within the frame of the unified theory of Bieber and Pomerantz (1983).

A puzzling observation was presented by Jacklyn and Duldig (SH 4.4-6). During the years of sixties, a significant sidereal semi-diurnal wave was seen by both the Hobart and Mawson experiments. This wave disappeared after 1970 and failed to reappear after 1980. It seems hard to think of a plausible interpretation of this finding.

3.3. Solar anisotropies, higher harmonics

This paragraph is divided into two major parts. First, results on the solar daily wave will be reviewed then the higher harmonics and their effects will be considered. Among the various components of the anisotropy, the solar daily vector is the most robust, and also has the longest and most extensive history. Recently, higher harmonics seem to attract more and more attention, this can be attributed to developments in both theoretical and experimental research.

Solar daily variation

As for the very first approximation, the solar diurnal wave of intensity variation of cosmic rays was believed to be a result of a pure corotation with the sun. Corotation could be simply interpreted in the classic diffusion-convection theory if diffusion was permitted in the field's direction only. Forbush (1969) was the first to notice that the solar diurnal vector shows a 22-year wave, a phase shift occurs in association with the polarity reversal of the sun. The effect has been proved beyond doubt by numerous subsequent works: during the periods of seventies, fifties, etc., the daily vector moves toward earlier hours from the 18hr phase of corotation. This phase shift was first explained by Levy (1976) invoking drift.

The conventional wisdom of phase shift is also apparent in the works presented at this Conference (Ahluwalia and Riker SH 4.5-7, Takahashi et.al. SH 4.5-13; Chuang, Kusunose, and Wada SH 4.5-14). Now, the main objective of the research is to find the rigidity spectrum, and find the solar parameters responsible for the year-to-year changes of the solar daily vector. Figure 13 shows the long-term variations of the amplitudes and phases as obtained by neutron monitors and muon telescopes during 1962-1979. Neutron monitor amplitudes tend to remain relatively stable while muon results undergo drastic variations. This is usually interpreted as a result of a changing cut-off rigidity.

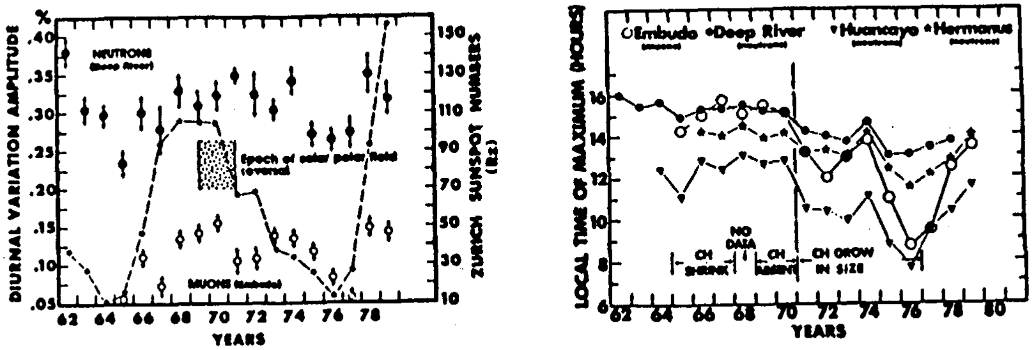


FIG. 13. - The annual mean amplitudes (left) and phases (right) of the solar daily waves, as obtained from neutron monitor and muon measurements. The dashed line shows the Zurich sunspot number (SH 4.5-7).

From the side of theory, the diffusive transport-equation (1) is applicable for neutron monitor energies. The major effect i.e. phase-shift has been reproduced by many independent numerical works incorporating drift (Potgieter and Moraal 1985; Potgieter SH 4.2-4; Kóta and Jokipii SH 4.2-11; Munakata and Nagashima SH 4.5-1; Kadokura and Nishida 1984). This consensus of the numerical results, and also our understanding of the physics involved should convince one that drift indeed gives rise to a phase shift. The quantitative features, on the other hand, are not yet all understood. Figure 14 shows the predictions of Potgieter (SH 4.2-4) together with experimental results. The agreement

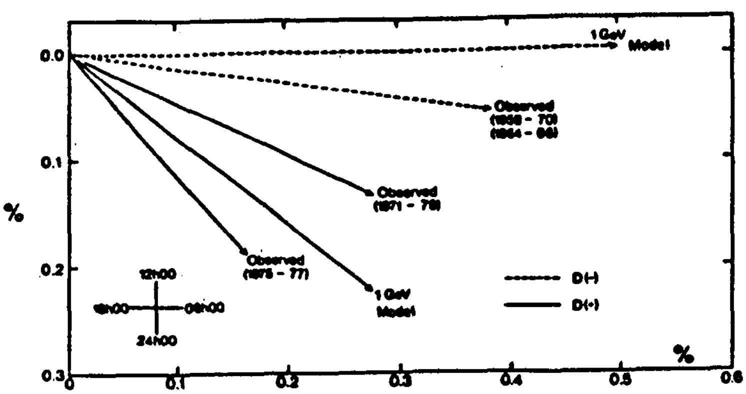


FIG. 14. - Observed (Hermanus, 4.5 GV) and computed solar diurnal vectors (SH 4.2-4)

is fairly close if we consider that model calculations are bound to be overly simplified. One might try to achieve a better fit by adjusting the input parameters. This, however, may not be very meaningful. The real solution would be the inclusion of a more realistic model of the heliosphere, which, if available, would require enormous amount of computing. At present, however, the full complexity of the heliosphere is not yet well modelled. Further studies may help to explore which features of the interplanetary field are primarily responsible for the long-term changes of the solar daily vector.

An important but conceptually obscure quantity is the upper the cut-off rigidity where solar effects cease. The upper cut-off undergoes a large variation during a 22-year cycle. It had a very low value in 1976 when virtually no anisotropy was detected by the muon telescopes (see Figure 13). On the other hand, Ueno et.al. (SH 4.5-18) reported on obtaining an anomalous large value during 1982, when the amplitude doubled at high rigidities (Sakashita, P_m=330 GV) while it remained the same at lower rigidities (Misato, Nagoya). The authors estimate a cut-off around 270 GV.

Ahluwalia (SH 4.5-4, SH 4.5-7) questioned the principle of cut-off. It is indeed a crude approximation expressing the common wisdom that solar effects should diminish at high rigidities. The Japanese groups use a 'power-exponential' formula which permits a power law at low rigidities and an exponential decrease above the cut-off. This should be a better approximation than the use of a flat spectrum with a sharp cut-off. However, both approaches are phenomenological and have little theoretical support. Admittedly, theory has been offering little help so far. At high rigidities (just around the cut-off), the whole concept of diffusive propagation breaks down, and the transport equation (1) is no more applicable. This is not only a matter of knowing the relevant parameters and solving the equation numerically. The cause of breakdown can be formulated in different ways. Physically, diffusion picture assumes the scattering mean free path to be small with respect to other distances involved. Taking a mathematical approach, one neglects higher harmonics in deriving the transport equation (1). At high rigidities, however, the spatial variation of the second harmonic becomes comparable to that of the density.

The method of Erdős and Kóta (SH 4.5-5, and references therein) may provide one part of the solution. These authors calculate energy losses along regular trajectories, disregarding scattering and retaining only the large-scale structure of the heliospheric field, including a wavy neutral sheet. This model can successfully reproduce many major aspects of the anisotropies observed at high rigidities. The predictions are similar to those of the drift models at lower energies. This is not at all surprising, since both models emphasize the effect of the regular field. The trajectory model could easily accommodate other large-scale structures, too. The inclusion of scattering would be a major step toward understanding the nature of cut-off.

In the paper SH 4.5-5, Erdős, Kóta, and Merényi predict rather gradual declines in the rigidity-spectra of solar and sidereal daily variations. For the 22-year cycle of the solar diurnal vector, they obtain a horseshoe shape, fairly similar to the loop inferred from experimental observations by Chuang, Kusunose, and Wada (SH 4.5-14) (Figure 15).

An alternative explanation of the phase shift of anisotropy was put forward by Kravtsov et.al. (SH 4.5-20) suggesting that this phase shift

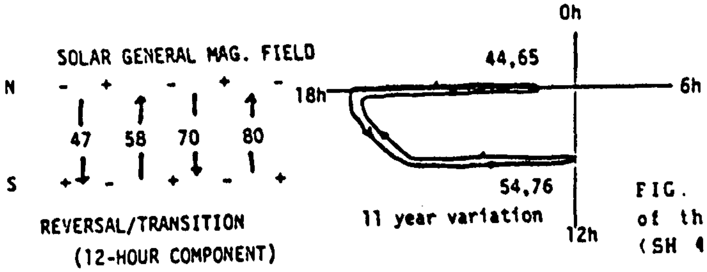


FIG. 15. - The 22 yr. loop of the solar daily vector (SH 4.5-14)

originates in the different connections of the heliospheric and interstellar magnetic fields. These 'open' and 'closed' configurations proposed by Ahluwalia (1979) deserve further study. At the present stage, however, this model is rather speculative. Drift models, on the other hand, firmly predict the observed phase shift and offer a more plausible explanation.

Higher harmonics

In general, the directional distribution of cosmic rays cannot be described with a single vector but it also contains higher spherical harmonics. As a rule, the n-th spherical harmonic may produce various daily harmonics (from n-th down to 1st, together with sidebands) in earth-based measurements. These indirect, sometimes so-called spurious, effects are still fairly tractable for the second harmonic and become increasingly complicated for the higher order terms.

The second order anisotropy has five independent components corresponding to the five spherical harmonics or, in an equivalent description, to the components of a symmetric and traceless tensor (Kota 1975). Assuming an azimuthal symmetry around the rotational axis of the sun, the resulting daily variations can be evaluated in a straightforward way. The following major terms will emerge:

semidiurnal :	solar 2nd	solar+sidereal	sidereal 2nd
diurnal :	antisidereal	solar	sidereal
zonal harmonic:	semiannual	annual	constant

Table 2

The classification is intended to express the geometrical relations. The variations in the same row have the same dependence on geographical latitude. Variations in one column arise from the same component(s) of the anisotropy, therefore there is a purely geometrical relation between them (Kóta 1975). At this Conference, Tatsuoka and Nagashima (SH 4.5-2) presented an extensive geometrical study giving all the coupling coefficients of the transformation of the second order anisotropy into earth-based intensity variations.

The direct geometrical relation between the solar semidiurnal and the antisidereal diurnal waves has been convincingly demonstrated by Swinson and Nagashima (SH 4.4-7). If the 2nd order anisotropy results from a pure pitch-angle distribution around the direction of the magnetic field, then it can be described with one single parameter, and a strict relation will hold between the sidereal and antisidereal daily waves. This constitutes the basis of the Nagashima-correction (see in paragraph 3.2.). It should be borne in mind that the Nagashima correction involves the physical assumption of a pitch-angle distribution, while the relation between the solar semidiurnal and the antisidereal waves is purely geometrical. Of course, there are physical grounds to expect a pitch-angle distribution. The Nagashima correction has been successful in organizing the worldwide observations of the sidereal daily variations into a coherent and transparent pattern (Nagashima, Tatsuoka, and Matsuzaki 1983). The results of the Hobart underground telescope could best be interpreted by employing this correction (Humble and Fenton SH 4.4-5), giving further credit to this method.

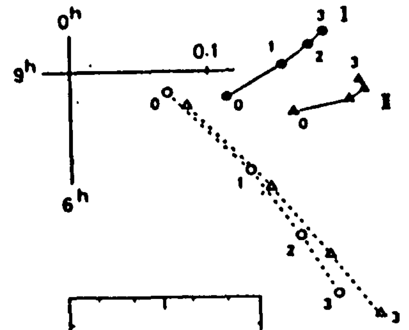
There may also be deviations from the pitch-angle picture, at high rigidities in particular. Several works at the conference were devoted to the study of the structure of the 2nd order anisotropy. Takahashi and Yahagi (SH 4.3-12) investigated the 2nd order zonal harmonic (bottom row in Table 2) on the basis of data from the worldwide network of neutron monitors. From a pitch-angle distribution, one would expect a *constant* value with a semiannual wave superimposed. It would deserve a more detailed study to see if observations are in agreement with the predictions of the pitch-angle concept. The magnitude of the observed semiannual wave seems surprisingly large (about 5%) at the cut-off energy, unless the upper cut-off is overestimated. Similarly large, puzzling diurnal effect was reported by Asatryan, Babayan, and Stozhkov (SH 4.5-8) on the basis of stratospheric measurements. At present, it seems hard to think of any process leading to such huge anisotropies.

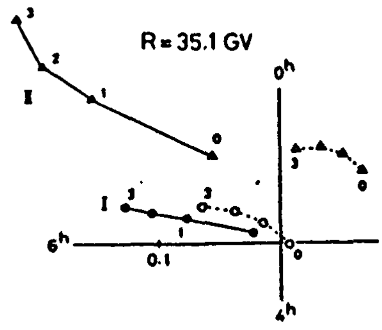
On the grounds of symmetry, Nagashima, Munakata, and Tatsuoka (SH 4.3-9) pointed out that the two components responsible for the second column of Table 2 should be polarity dependent. Analyzing the data of the multi-directional muon telescope at Nagoya, they could extricate the expected effects: a semidiurnal wave with the frequency between the solar and sidereal semidiurnal frequencies, and also a polarity-dependent contribution to the solar daily wave. This result implies that the anisotropy is not entirely axially symmetric.

Munakata and Nagashima (SH 4.5-1) endeavoured to compute the first three harmonics of the cosmic ray anisotropy. It is reassuring to see the self-consistency of the calculation, they start with computing the density distribution and then continue to proceed step by step upward in the hierarchy of the harmonics. The resulting free-space 2nd and 3rd harmonics are shown in Figure 16, together with their dependence on rigidity. A remarkable feature of the calculated 2nd harmonic is the marked deviation from the 'conventional' phase of 3 hr for the case of $A<0$. This seems somewhat surprising, and the underlying physics is not yet clear. The deviation from the 3hr phase, again, would indicate that the pitch-angle distribution is violated, and the Nagashima-correction may not perfectly eliminate the sidereal wave of heliospheric origin.

The 3rd harmonics also show different phases for $A>0$ and $A<0$, respectively. The consistently 7 hr phase for $A>0$ is not compatible with a pitch angle distribution which would predict either 1 hr or 5 hr.

Recently, Bieber and Pomerantz (1983) proposed a unified theory of the higher harmonics. The model includes adiabatic focusing and also anisotropic pith-angle scattering. The former is primarily responsible for the second harmonic, the basic process being the same as that in the loss-cone model of Fujii et.al (1971). The anisotropic scattering has more effect on the third harmonic, earlier this process was suggested to account for the higher harmonics of the galactic anisotropy (Kóta 1979).





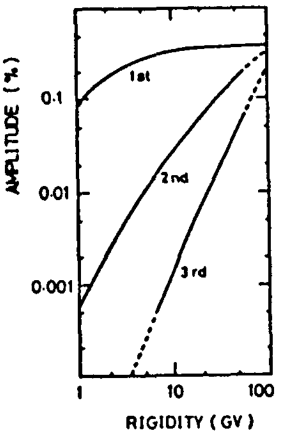


FIG. 16. - Calculated 2nd (upper left) and 3rd (right) harmonics of the solar anisotropy. The lower left panel shows the rigidity dependence of the first three harmonics. Full symbols refer to A>0, open symbols refer to A<0. For details see SH 4.5-1.

The unified theory of Bieber and Pomerantz should yield a pitch-angle distribution from the diffusive streaming, which ultimately predicts that all the higher harmonics must have either maximum or minimum at 9 hr (and 21 hr); for the first harmonic the contribution of convection should first be removed.

The unified theory predicts the relative magnitude of the second harmonic to be roughly proportional to the scattering mean free path. Bieber and Pomerantz (SH 4.5-21) used this principle to check their model. In Figure 17, the amplitudes and phases of the first three harmonics observed at Swarthmore are plotted as a function of the relative variance of the interplanetary magnetic field. The second harmonic tends to decrease with increasing field fluctuation, which also should mean increasing scattering i.e. smaller mean free path. However, this decrease seems slower than that expected from the theory.

The predictions of the unified model of Bieber and Pomerantz seem to be irreconcilable with the results of Munakata and Nagashima (SH 4.5-1). Yet, we may not need to ask which of them is correct. The model of Bieber and Pomerantz is particularly attractive to a theoretician. It is based on a firm prediction of the theory of scattering, and one would most welcome to see that the expected effect is indeed there. On the other hand, the unified model of anisotropy strongly relies on the assumption of 1-dimensional propagation. Any perpendicular diffusion or drift should modify the picture. This seems to be a plausible reason why the the model of Bieber and Pomerantz works well at lower rigidities, and may become incorrect at high rigidities where cross-field transport is much easier. This would also be in accord with the rigidity spectra shown in Figure

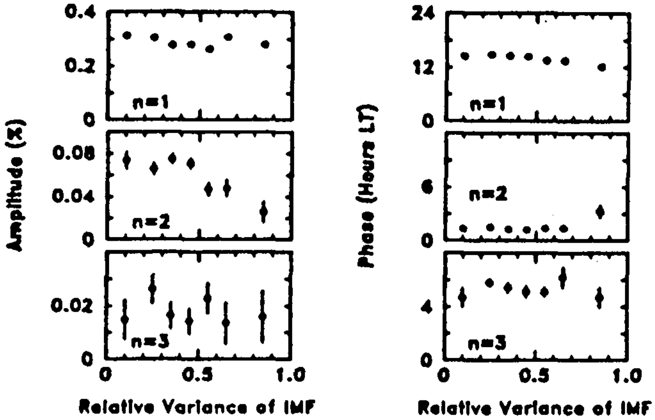


FIG. 17. - Amplitudes and phases of the first three solar harmonics observed at Swarthmore plotted vs. the relative variance of the interplanetray magnetic field. Note the decrease of the amplitude of the 2nd harmonic (SH 4.5-21)

16, which predict the relative magnitude of the 'non pitch-angle' higher harmonics to increase rapidly toward higher rigidities.

The solar tri-diurnal variation was experimentally investigated by Mori et.al. (SH 4.5-3) on the basis of the Nagoya, Misato, and Sakashita muon telescopes. The results are shown in Figure 18. The authors conclude that the best value of the phase is near 7 hr, in fair agreement with the results of Munakata and Nagashima (SH 4.5-1). Inspection of Figure 18 may also suggest the occurence of a phase shift from 1981 to 1982. It is also my impression that, in the period of 1970-80 (A>0), all the high-rigidity harmonics tend to have a phase close to 15 hr. Speaking in terms of regular motion, the ecliptic 15 hr direction represents the trajectory which has a maximum access to the neutral sheet. It is not inconceivable that this may prove to be a preferential direction.

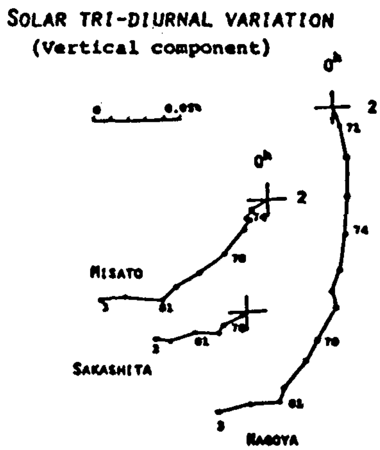


FIG. 18. - Solar tri-diurnal waves observed at Sakashita, Misato, and Nagoya (SH 4.5-3)

4. OTHER TIME VARIATIONS, CORRELATIONS

In this last, loosely organized, section, I would like to report on some interesting new developments which did not fit into the line of the previous two sections. The topics to be covered here can be summarized as time variations other than 11-year cycle or periodic variations due to the motion of the earth. For most of these variations, there is no firm theoretical prediction available. In cases such as this, when the underlying physical processes are largely unknown, the study of correlations might give an insight with helping to explore possible connections between various quantities. When doing correlation analyses, one should exercise caution, a correlation does not necessarily imply a close physical connection.

Attolini, Cecchini, and Galli (SH 4.4-14) endeavoured to discover correlations between the sunspot number, cosmic ray flux, aa index, and solar flares in narrow frequency bands. They worked out a method specifically designed for the study of narrow frequency bands. Several periodicities were found, among these the most significant is the 154 day period found in the cross-correlation of cosmic rays vs. solar flares. The method is promising even if the results are not always easy to interpret. One may hope that this new technique will be added to the already existing arsenal of the matemathical tools of correlation studies.

Analyzing variations close the 27-day rotational period of the sun, Shatashvili et.al. (SH 4.4-20) found that the period of cosmic ray recurrency increased to about 30 days between 1973 and 1975. The authors interpret this as an effect of drift. During this period, particles reached the earth through the polar regions, thus they experienced a longer period because of the differential rotation of the sun. No similar finding is apparent in the power spectrum analysis of Agrawal (SH 4.4-16).

On the basis of a large amount of observational data from 1958 to 1975. Bazilevskaya, Tyaso, and Vernova (SH 4.4-19) attempted to establish a relation between the cosmic ray flux at the earth and the longitudinal distribution of solar activity on the sun. This latter was found to undergo profoundly larger variations during the periods of solar polarity reversals. The study of correlation led to a puzzling result, which the authors find difficult to accept. The maximum correlation was obtained with a time shift of about 80 days, in the 'unexpected', implausible direction: the variation in cosmic ray flux seemed to preceed that in the distribution of solar activity. It seems incomprehensible that cosmic ray should affect solar activity in any way. An indirect effect through the solar wind is highly improbable, too. This example shows that the interpretation of a correlation is not always straightforward. The other possibilities are either an unlikely coincidence or a subtle artifact.

An interesting finding was reported by Kavlakov and Georgiev (SH 4.5-16): days of magnetic storms were observed to be preceded by enhanced daily waves in the cosmic ray counts at the Musala multi-directional telescope. This kind of 'forecast' is not inconceiveble since cosmic ray particles may experience interplanetary disturbances between the earth and the sun.

A warning came from Pandley et.al (SH 4.4-1) to those who use the solar flare index (SFI), provided by different publications. A simple correlation study gave significantly different results for the SFI-s from different sources. To avoid unwanted artifacts, correlation studies are strongly recommended to use the same source, at least within one work. This acute problem calls for an clarification of the discrepancies since the SFI is a widely used parameter of modulation research (see Agrawal, Mishra, and Jain SH 4.1-10).

Finally, the subject of biannual variation deserves attention. At this Conference, Charakchyan et.al. (SH 4.4-21) demonstrated that the 2-year variation seen earlier in stratospheric measurements is not a geophysical effect but it can clearly be observed in satellite data, too. Cosmic ray fluxes were shown to be in a quite sharp anti-phase with the geomagnetic Ap index, suggesting that a relatively local effect is responsible for the biannual variation of cosmic rays. Though the magnitude of this variation undergoes considerable changes, a closer look seems to rule out a close connection with solar activity. The interpretation of this phenomenon is still an open question.

ACKNOWLEDGEMENTS

I am grateful to the General Organizing Committee for inviting me to be a rapporteur. I greatly benefited from the helpful and stimulating discussions with many authors and other participants at the Conference. Special thanks are due to Dr. Ng for taking the burden of the sessions SH 4.6 and SH 4.7. This work was supported by the National Science Foundation under the Grants ATM-220-18 and INT-8400591.

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