SOLAR POLAR FIELD REVERSALS AND SECULAR VARIATION OF COSMIC RAY INTENSITY

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The profile of the well-known 11-year variation of the cosmic ray intensity appears to depend upon the emerging solar polar magnetic field regime in a very characteristic manner. During the solar activity cycle 19, the cosmic ray intensity takes about seven years to recover to its solar activity minimum level. But during the solar activity cycle 20, the recovery takes place in only about two years. It appears that these characteristic recovery modes are obtainable every other solar activity cycle. We are led to suggest two model configurations for the heliosphere. We believe that an "open" heliosphere model applies to solar activity cycles 18 and 20. A "closed" heliosphere model is obtainable during solar activity cycles 17 and 19. Our results are discussed.

1. INTRODUCTION

The variation of the annual mean cosmic ray intensity, at a given site, with the sunspot activity cycle has been known for many years (Forbush, 1966). It is referred to as the eleven-year variation of the cosmic ray intensity in the literature. Perhaps several causes contribute to the observed modulation of the cosmic ray intensity. Over the last three decades many brave hypotheses have been suggested to identify and to describe the contributory causes. These attempts have only helped us in developing some interesting "insights", but have not yet resulted in a satisfactory theory. Somehow the lower energy cosmic rays are prevented from reaching the earth, as the solar activity increases. The "obstruction" gradually disappears with the decline in the solar activity. There is probably a general agreement, however, that a major underlying physical process which contributes to the "obstruction" is the scattering of the cosmic rays by the inhomogenieties in the interplanetary magnetic field. This idea was first suggested by Morrison (1956) and developed by Parker (1958). The present status of this approach to the problem is given by Forman (1975) and by Quenby (1977).

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2. ELEVEN YEAR VARIATION OVER FOUR SOLAR ACTIVITY CYCLES

Figure 1(a) shows a plot of the annual mean Zurich sunspot numbers over the period 1937-78. The data are represented by crosses (x). The epochs of the minima and the maxima in the solar activity are indicated by arrows. The data cover four solar activity cycles; namely, 17, 18, 19, and 20.

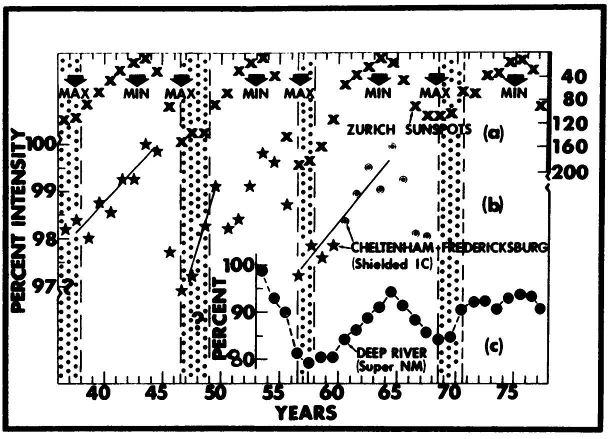

Figure 1(a), (b), (c)

Figure 1(b) depicts the annual mean muon intensity measured with a shielded ion-chamber at Cheltenham-Fredericksburg by Forbush's group (Lange and Forbush, 1957; Beach and Forbush, 1969). The data cover the period 1937-68 and are indicated by: * and ⊙. One can recognize the 11-year variation of the cosmic ray intensity. Note that the intensity of the muons is the highest when the sunspot activity is the lowest and vice versa. Solid lines are eye-fit estimates to the muon data for the periods 1938-45, 1947-50, and 1957-64. These lines represent recovery of the cosmic ray intensity during solar activity cycles 17, 18, and 19 respectively. One can see that the recovery of the cosmic ray intensity occurs more rapidly in 1947-50 period than during the other two epochs. The significance of this will become clear as you read on!

Figure 1(c) gives a plot of the annual mean hourly counting rate of the neutron monitors at Ottawa for 1954-59 and at Deep River for 1960-78. The counting rates of the two monitors are normalized for the month of December 1959. The neutron monitors respond to lower energy cosmic rays (median primary energy of response is ∿7 GeV) and the shielded ion-chambers respond to higher energy cosmic rays (median primary energy of response is ∿50 GeV). So a comparison of the amplitudes of the 11-year variations recorded by the two detectors gives us an estimate of the energy dependence of the solar modulation processes. I might also mention that the median primary energy of response of the neutron monitor at Deep River is slightly higher than that of the Ottawa neutron monitor.

The epochs of the solar polar field reversals for 1957-58 (Babcock, 1959) and 1969-71 (Howard, 1974) are indicated by the vertical shaded areas. The shaded areas with question marks (?) are our estimate of the earlier epochs of solar polar field reversals during 1947-49 and 1937-38. These estimates are made from the study of the recovery modes of the 11-year variation of the cosmic ray intensity. The basis of these predictions will become clear from the discussion presented in the following section.

I wish to draw the attention of the reader to the following salient features present in the data that are summarized in the Figures 1(a), (b), and (c).

(1) Eleven year variation of the cosmic ray intensity is clearly seen in the data of the neutron monitors as well as that of the shielded ion-chamber. As expected, the amplitude of the effect is larger in the neutron monitor data than in the muon data. The amplitude for the neutron data is nearly 7 times larger than muons in the 1954-58 and about 3 times larger in 1965-68 periods.

(2) Cosmic ray muon intensity recovers completely near each solar activity minimum. This is not true of the neutron monitor data. The latter intensity is still depressed about 6% below 1954 level in 1965 as well as in 1976. A part of this difference is undoubtedly due to the fact that the neutron monitor at Ottawa has a slightly lower median primary energy of response than does the super neutron monitor at Deep River. This does not account for the entire difference, however.

(3) A very remarkable effect manifests itself in the recovery mode of the neutron intensity as well as in the recovery of the muon intensity. Neutrons take about 7 years to recover to a level nearly 6% below the 1954 level in the solar activity cycle 19 and only about 2 years to attain the same level in the solar activity cycle 20. In both cases the recovery follows the epochs of the solar polar field reversals. The latter recovery has been called anomalous by some research workers.

3. MODELS OF THE HELIOSPHERE

Long recovery times characterize recovery by diffusion whereas short recovery times imply almost a direct connection to the source. We also note here that after solar polar field reversal in 1969-71 the solar dipole is oriented in a direction opposite to that of the geomagnetic dipole. The large-scale interplanetary magnetic field, away from the ecliptic plane, corresponds to this new orientation (Smith and Tsurutani, 1978). Keeping these facts in mind, if we now recall the rapid recovery of muon intensity in 1947-49 period compared to the recovery of muon in 1937-45 and 1957-65 periods, we realize that the solar polar field configuration after the reversal in 1947-49 must be the same as that obtainable after the reversal in 1969-71; if indeed the anomalous recovery is to be ascribed to a particular configuration of the solar polar field.

The above line of reasoning demands that the most recent solar polar field reversal must connect the heliosphere to the interstellar medium in such a manner as to make it easier for the interstellar cosmic rays to enter the heliosphere in more or less unrestricted manner. This leads us to suggest an open heliosphere model shown in Figure 2(b). The model is inspired by the work of Alfven (1954), Dungey (1961, 1963), and Levy et al (1964), who have invoked similar models to understand the responses

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of the comets and the magnetosphere to the super-sonic solar wind.

The main rationale for the indicated shape of the heliosphere is that our solar system is moving with a velocity of about 20 km/sec, with respect to the interstellar medium, in the direction of the constellation Hercules. Reliable parameters pertaining to the local interstellar medium are not available at present. Sparse data (Heiles, 1976) seem to indicate that magnetosonic mach number may not exceed unity. So a bow shock may not form. An important requirement for the models is that there must exist a significant component of the interstellar magnetic field oriented in the manner shown in Figure 2(b). If this is granted then the "anomalous" recovery of the cosmic ray intensity, during even solar activity cycles, may be readily understood. The given magnetic configuration of the heliosphere enables the interstellar cosmic rays to reach locations at fairly low heliolatitudes. This inference also provides a very natural explanation for the results reported by McKibben et al (1979). They find large latitudinal gradients for the anomalous helium as well as for the protons. Also our inference provides a strong support for the assumption made by Fisk et al (1974) that the anomalous components are of interstellar origin. In this scheme of things gradient and curvature drifts (Jokipii et al, 1977) play only a secondary role in the transport of the interstellar cosmic rays.

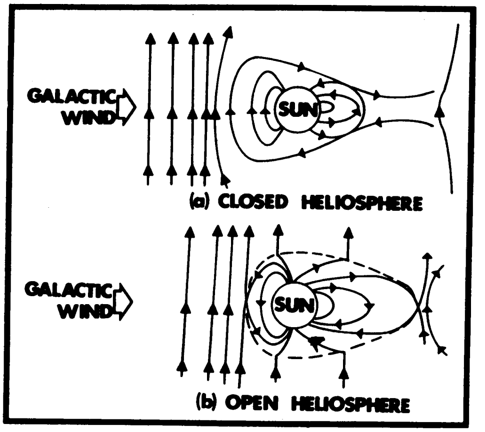

Figure 2(a), (b)

Quite naturally one expects that during odd solar activity cycles a closed heliosphere configuration, shown in Figure 2(a), must be obtainable in the nature. Diffusion plays a major role in the transport of the interstellar cosmic rays to earth. So we expect recovery for the 11-year variation of the cosmic ray intensity to occur over a longer period, as is indeed observed.

The fact that the neutron intensity in 1965 and 1976 is below 1954 level might be due to the fact that there is some residual modulation of the lower energy cosmic rays still present during these years. We note that the solar activity during 1954 was extremely low. The point is that if our ideas are correct then we expect the cosmic ray particle density gradient to undergo characteristic time variations over a Hale cycle. We intend to examine this question further in our study of the observed long-term changes in the parameters of the solar anisotropy of cosmic rays (Ahluwalia, 1977a, b).

It is quite interesting to note that heliosphere is not really "closed" at any time due to the presence of the neutral points on the

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heliopause. The observed modulation is therefore likely to be different in different regions of the heliosphere. For example, one would expect to observe very dynamic modulation of cosmic rays at high heliolatitudes. We have to wait for the solar polar missions to make this discovery.

These models may also have some implications for the solar wind and the origin of the coronal holes. During odd solar activity cycles the closed heliosphere configuration permits an almost radial expansion for the solar wind. On the other hand, non-radial expansion of the solar wind is perhaps to be expected during the open heliosphere regime, if the polar wind is deflected towards lower heliolatitudes, at the heliopause. More work is clearly necessary to examine this question in detail. One may also note here that the connection of the solar polar field lines with the interstellar magnetic field might encourage the formation of the polar coronal holes. Moreover, the charged particles precipitating in the solar polar regions might constitute an additional nontrivial source of energy needed to heat the solar wind in the outer solar corona (Zirker, 1977). This question also needs to be examined in more detail. We expect to do this in the future.

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REFERENCES

Ahluwalia, H.S.: 1977a, 15th Intern. Cosmic Ray Conf., Plovdiv. Conference Papers (Bulgarian Academy of Sciences), 11, 298.
Ahluwalia, H.S.: 1977b, 15th Intern. Cosmic Ray Conf., Plovdiv. Conference Papers (Bulgarian Academy of Sciences), 11, 304.
Alfven, H.: 1957, Tellus, 9, 92.
Babcock, H.D., 1959, Astrophys. J., 130, 364.
Beach, L., and Forbush, S.E.: 1969, Cosmic-ray Results, Carnegie Inst. Wash., Publ. 175, Vol. 22.
Dungey, J.W.: 1961, Phys. Rev. Letters, 6, 47.
Dungey, J.W.: 1963, Geophysics: The Earth's Environment. Lectures given at Les Houches during 1962 Summer School of Theoretical Physics of the Univ. of Grenoble, Gordon and Breach Science Publishers, New York.
Fisk, L.A., Koslovsky, B., and Ramaty, R.: 1974, Astrophys. J., 190, L39.
Forbush, S.E.: 1967, J. Geophys. Res., 72, 4937.
Forbush, S.E.: 1966, in S. Flugge (ed), Handbuch der Physik, Springer-Verlag, New York, 49/1, 159.
Forman, M.A.: 1975, Rapporteur Paper at the 14th Intern. Cosmic Ray Conf., Munich, Conference Papers (Max-Planck-Institut fur Estraterrestrische Physik), 11, 3820.
Howard, R.: 1974, Solar Phys., 38, 283.

Heiles, C.: 1976, Ann. Rev. Astron. Astrophys., 14, 1.
Jokippi, J.R., Levy, E.H., and Hubbard, W.B.: 1977, Astrophys. J., 213, 861.
Knapp, G.R., Tremaine, S.D., and Gunn, J.E.: 1978, Astron. J., 83, 1585.
Lange, I., and Forbush, S.E.: 1957, Cosmic-ray Results, Carnegie Inst. Wash., Publ. 175, Vol. 20.
Levy, R.H., Petschek, H.E., and Siscoe, G.L.: 1964, A.I.A.A. Jour., 2, 2065.
McKibben, R.B., Pyle, K.R., and Simpson, J.A.: 1979, Astrophys. J., 277, L147.
Morrison, P.: 1956, Phys. Rev., 101, 1397.
Nagashima, K.: 1977, Rapporteur paper at the 15th Intern. Cosmic Ray Conf., Plovdiv. Conference papers (Bulgarian Academy of Sciences), 10, 380.
Parker, E.N.: 1958, Phys. Rev., 110, 1445.
Quenby, J.J.: 1977, Rapporteur paper at the 15th Intern. Cosmic Ray Conf., Plovdiv, Conference Papers (Bulgarian Academy of Sciences), 10, 364.
Schatten, K.H., and Wilcox, J.M.: 1969, J. Geophys. Res., 74, 4157.
Smith, E.J., and Tsurutani, B.T.: 1978, Astrophys. J., 83, 717.
Wagner, W.J.: 1976, Astrophys. J., 206, 583.
Zirker, J.B.: 1977, Rev. Geophys. and Space Phys., 15, 257.

DISCUSSION

Datlowe: The magnetic configuration shown in Figure 2 is of a type, like the earth, in which the magnetic field dominates the plasma pressure. But the interplanetary situation has the solar wind plasma dominating the magnetic field. Is this figure a useful model for understanding cosmic ray propagation?

Ahluwalia: Let me answer the first part of your question first. I wish to emphasize that I do not suggest that the interplanetary magnetic field dominates the solar wind, inside the heliosphere. Far from it! Figures 2(a), (b) are drawn for the case of a non-rotating sun. In the real world the field lines would be bent into Archimedian spirals due to the rotation of the sun. However, in the open heliosphere model, the field at the heliopause may be strong enough to deflect the polar solar wind towards lower helioaltitudes. Since the magnetic field is frozen into the wind, it would follow the wind. In this manner we are able to understand the result of Wagner (1975) that much of the interplanetary magnetic field sampled at earth, during 1972-73 period, originates at high heliolatitudes. This inference is probably valid for much of the even solar activity cycles when an open heliosphere regime is obtainable.

Now let me attempt to answer the second part of your question. As I said in my talk the models do explain the recovery modes of the 11-year cosmic ray intensity variation, during odd and even solar activity cycles. They also explain the presence of the anomalous components of the energetic particles measured by McKibben et al. (1979), during solar activity cycle 20. Schatten and Wilcox (1969) have invoked a similar idea, but with a spherical heliosphere, to explain the 20-year wave in the solar diurnal variation of cosmic rays reported by Forbush (1967). Schatten-Wilcox model is invoked by Nagashima (1977) to explain a variety of energetic particle measurements reported in the literature. Our models explain everything that Schatten-Wilcox model does. But they are more general. They imply that the traditional concept of a spherical symmetry, so often invoked by the theoreticians to explain the observed solar modulations, is at best obtainable only during odd solar activity cycles. The models also imply that one must drastically revise the concept of a modulation region surrounding the sun. During even cycles the modulation is much more dynamic. I am satisfied that we are on the right track. However, one can see that the models are in a skeletal form. In the future we have to build-in more details by confronting the models with a variety of observations. At this point in time I am quite optimistic!

Stix: High altitude solar prominences and faculae also indicate polar field reversals. Using them one could thus infer the epochs of the two earlier reversals of your Figure 2.

Ahluwalia: I thank you for your suggestion. My motive in coming to this meeting was to invite comments from my solar colleagues that would help me refine my hypothesis. I will certainly compare the two results.

Newkirk: Your model appears to require that you identify the increase of galactic cosmic ray flux after each sunspot maximum as the result of diffusion in the heliosphere with a characteristic time of about 5 years. This would require an unusually low diffusion coefficient. Would it not be simpler to view the recovery of galactic cosmic ray flux as the response to the evolution of the heliosphere over the $\sim$ 6 years of declining activity?

Ahluwalia: Gordon, the models that I have attempted to describe are much more dynamic than you seem to think. We are just now beginning to appreciate how solar modulation of cosmic rays comes about. Probably the following causes contribute to the observed modulation:

(a) Solar active regions. Details of how they contribute are still obscure.
(b) Fast streams and stream interaction regions.
(c) Solar flare initiated shocks in the interplanetary medium.
(d) Large scale organization of the interplanetary magnetic field.
(e) State of magnetic connection of the heliosphere with the interstellar medium.

I must emphasize that it is not yet clear what fraction of the observed modulation is contributed by each of the above causes. We can not rule out the possibility that there might exist another set of contributing mechanisms which are unidentified yet. The point is that during the period when (a), (b) and (c) do not contribute, the cosmic ray intensity at earth must attempt to rise to the level obtainable in the interstellar medium. Under closed-heliosphere regime this is brought about, primarily, by cosmic ray entry into the heliosphere through neutral points. Under open-heliosphere regime, rise in intensity level is brought about by 'unrestricted' flow of interstellar cosmic rays into the heliosphere. Since all solar disturbances propagate radially outwards, recovery is much more rapid under the open-heliosphere regime, since the interstellar cosmic rays have almost direct access to the 'depletion' region surrounding the earth. This is how the 'anomalous recovery' of the eleven-year variation of cosmic ray intensity comes about in EVEN solar activity cycles. Contributions from (a), (b) and (c) described above are controlled by the level of activity in each solar cycle but recovery mode at earth depends upon which of the two heliospheric regimes is obtainable, at a given point in time.

Levine: For the recovery of the mean counting rates beginning about 1947, you draw a line through the data indicating a much shorter time scale than for the even-numbered solar cycles. Because your conclusions are strongly dependent on this faster recovery, can you explain why you ignored the points after 1950, which would give a slope the same as for the other cycles?

Ahluwalia: The line representing the recovery of the 11-year cosmic ray variation, during solar activity cycle 18, is obtained by joining three consecutive data points after cosmic ray intensity minimum in 1947. As you point out there is a depression in the cosmic ray intensity for the period 1951-52. This is probably due to the Forbush decreases. They occur all the time. They are seen more clearly in the monthly averages of the data. Figure 3 shows a plot of the monthly mean intensity of cosmic rays recorded by the neutron monitors at Huancayo and Chimax, for the solar activity cycles 18, and 19. The reported epochs of the solar polar field reversals are indicated by vertical shaded areas. The features discussed in reference to the neutron monitor data at Deep River (Figure 2(c)) are also seen in these data. But you also see sharp, temporary depressions of the intensity due to the Forbush decreases, during both cycles. Some of these depressions are quite large. But the point is that when the Forbush event is over, the long-term recovery is resumed uninterrupted. This is true of muon data also for 1952-54 period. The eye-fit line joining these data points is parallel to the line that I have drawn for the recovery during 1947-1950.

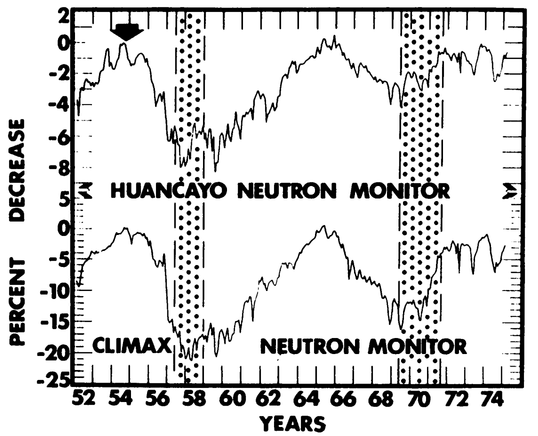

Figure 3

I take this opportunity to point out that the large fluctuations of the cosmic ray intensity observed after 1971 is referred to as a "mini" solar activity cycle. Fast streams play a dominant role in producing the observed modulation. Probably a similar situation is available in 1951-52 period. We intend to investigate this further.

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