The turn-up in the differential GCR proton energy spectrum below 100 MeV

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Abstract — The high energy portion of galactic cosmic ray proton spectrum in the vicinity of Earth, above about 500 MeV per nucleon, can be well approximated by the "force field" model, whose only formal parameter is the modulation potential. Here I show that the entire spectrum can be well approximated by the force field model, when the force field is treated as an electric field. The analysis also explains the origin of the anomalously energetic ions in the low energy tail of the solar wind.

Index terms—Heliosphere, electric field, GCR proton spectrum, turn-up, solar wind, suprathermal ions, energetic ions.

I. INTRODUCTION

I have previously pointed out [1, 2] that the modulation potential used in force field models of solar modulation of galactic cosmic rays (GCRs) is, in fact, an electric potential. The electric field is created and sustained by the diffusion-like behavior of GCR protons which penetrate deeply inside the heliosphere leaving behind their accompanying GCR electrons, having lost all but a tiny fraction of their kinetic energy to the field. Some of these protons become trapped for a time because of their diffusive behavior, delaying their neutralization by electrons. The resulting separation of charges is what creates and sustains the pervasive quasi-static electric field. This paper describes a mechanism which can account for the diffusion-like behavior of certain of the highly modulated GCR protons.

In this paper I show that the heliospheric electric field is not only responsible for the shape of the GCR proton spectrum at high energies (above 500 MeV), but is also responsible for its features below 500 MeV, all the way to its abrupt termination at 2 MeV. The model described here also accounts for the suprathermal and energetic ions observed in the solar wind, the origins of which are not understood.

II. THE GCR PROTON SPECTRUM

Many spectra of GCR protons and ions have been measured over the years and described in the literature. The spectra from data collected during solar minimum conditions generally cover the range from above 10^{14} MeV down to about 2 MeV, per nucleon. For this analysis the differential GCR proton flux intensity spectrum of Meyer et al. [3] was chosen (curve labeled LS in Fig. 1).

Most or all of the data for this spectrum were collected near Earth during solar minimum conditions, probably at the end of Solar Cycle 19 in the 1963–1965 timeframe. This spectrum appears to indicate a heliospheric electric potential of about 1 GV, whereas in previous analyses [1, 2] the potential was assumed to be 800 ± 400 MV, based on the results of force field studies, using a different data set [4]. Note that, for simplicity and clarification of what is to follow, the electric potential associated with the spectrum shown in Fig. 1 will be assumed to be exactly 1 GV, and constant in time.

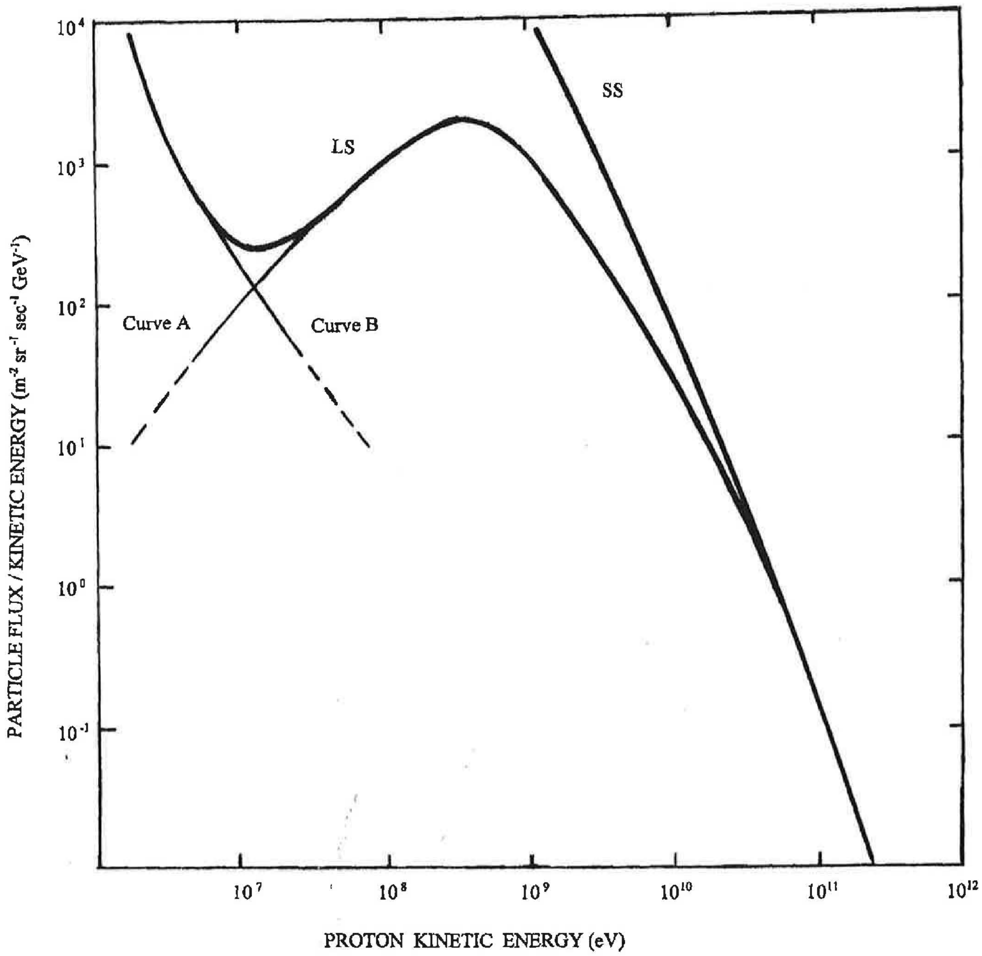

Figure 1. Proton flux intensity during solar activity minimum conditions. Heavy lines are the galactic cosmic ray proton source spectrum (SS) extrapolated by the author, and the local spectrum (LS) measured near Earth. Light lines are Curves A and B (see text) and broken lines are uncertain extrapolations. The local spectrum was taken from Figure 6 of Meyer at al. [3].

A. Proton energy above 500 MeV

We begin our interpretation of the general features of this spectrum proceeding from right to left on Fig. 1, from higher to lower proton kinetic energy. Above 100 GeV, the spectrum follows a power law with index of about -2.6. Since solar modulation is negligible at those energies, this is presumed to represent the spectral index of the primary proton spectrum (outside the influence of the solar system). At about 50 GeV the local spectrum (labeled LS on Fig. 1) begins to turn down gradually, reaching a maximum flux at about 500 MeV.

The portion of the energy spectrum above 500 MeV can be approximated by applying the solar modulation equation developed by Parker [5], although a better fit can be achieve using the "force field" model originated by Gleeson and Axford [6], which has been further developed and refined during the intervening 40 odd years [4]. In the force field model this portion of the curve, LS, is produced by subtracting the energy lost to the modulation potential from each point on the primary GCR spectrum (or source spectrum, labeled SS on Fig. 1) until the maximum of the LS spectrum is reached at 500 MeV.

B. GCR proton diffusion

Before proceeding to describe the behavior of GCR protons at lower energies it is necessary to understand a key assumption that has been made. An electric field of the kind described in [2] will bring a 1 GeV proton to a complete stop if the proton arrives at the centroid of the heliosphere, where the electric field vanishes. Protons with initial energy higher than 1 GeV will go past the centroid and out of the heliosphere, whereas protons with less energy will not be able to reach the centroid before their energy is exhausted. The assumption that has been made is that there is a "trapping" region surrounding the centroid which behaves similarly, except that the angle of arriving protons determines how much energy the proton will lose, on average. The trapping region is that region surrounding the centroid, where the electric field vanishes and the sun's magnetic field is most intense and variable, i.e., a region conducive to causing low energy protons to move in a manner similar to diffusion, except that the motions are collisionless. Trapping ends when a proton happens to diffuse away from the trapping region into a region where the electric field is greater and the magnetic field is less intense and variable. Beyond that distance diffusion becomes more and more biased to move the proton outward by electrodynamic repulsion from the field.

Most of the high energy GCR protons which impact the trapping region toward its center will lose the full 1 GeV of energy, and most of those arriving at grazing angles will lose little or no energy at the trapping region. At angles between those limits there will be a gradation of energy losses. Protons which lose all of their energy except for a few hundreds of keV will be swept up promptly by the solar wind and carried out of the heliosphere, whereas those left with more energy will behave diffusively so will spend more time in the trapping region before eventually diffusing out and merging with the solar wind. Thus the angle of impact produces two populations of protons; one comprised of protons which avoid the trapping region, and one comprised of protons which undergo diffusion-like behavior in the trapping region. The spectra of these proton populations are labeled on Fig. 1 as Curve A and Curve B, respectively. Since some of the protons which impact near the center of the trapping region will promptly escape, and some which impact away from the center will become trapped, Curves A and B will overlap, as shown.

C. Proton energy between 15 and 500 MeV

Below the flux maximum at 500 MeV on the LS curve the spectrum transitions downward (curve A on Fig. 1), which is extrapolated to lower energies. This population of protons derives from the GCR protons with energy greater than 1.015 GeV. The local spectrum then turns back up to arrive at a minimum flux intensity at 15 MeV before it begins to rise again. The flattening of the flux intensity above 15 MeV is due to the contribution from the high energy portion of Curve B protons. At the 15 MeV flux minimum of 300 m^{-2} sr^{--1} sec^{-1} GeV^{-1}, the contributions from Curve A protons and Curve B protons are each 50% of the flux intensity.

D. Proton energy below 15 MeV (the turn-up)

The rise of the flux intensity below 15 MeV is also due to the contribution from the higher energy portion of the Curve B protons. Below 15 MeV the local spectrum transitions gradually to a straight line, with index of about -2.6, then terminates at 2 MeV. Accounting for the turn-up has been a serious problem for theorists because GCR protons with energy in this range are known to be completely excluded from entering the heliosphere, and protons with such high energy are almost completely collisionless. However, if the modulation potential is in fact an electric potential as described in [1, 2], then the explanation becomes clear. It is evident from the "turn-up" portion of Curve LS that almost all of those primary GCR protons with energy greater than about 1.015 GeV have enough energy to pass through the trapping region and out of the heliosphere without ever losing enough energy to cause them to move diffusively.

Virtually all of the GCR protons with initial energy less than 1.010 GeV but greater than 1.002 which arrive very nearby the centroid will become trapped for a period of time in the trapping region, and move in a diffusion-like manner. Such trapping results because the electric field is minimum there [2] and also the solar magnetic field is maximum both in intensity and variability.

Protons with kinetic energy less than about 1.002 GeV are unable to arrive at the centroid of the heliosphere because they lose so much of their energy to the field before arriving there, and most are promptly swept back out of the heliosphere by the solar wind. If the end of the data set at 2 MeV is not due to detection instrument limitations, the abruptness of this termination seems to provide strong support of the "trapping region" concept.

The electric field model described in [1, 2] is supported by the features of this portion of the spectrum, that is, between 2 MeV and 8 MeV, which has a spectral index of -2.6. The protons with these energies evidently are the same ones that were originally a part of the primary GCR spectrum with energy in the range 1.002 GeV to 1.008 GeV which have lost 1 GeV to the electric field. This population of protons would retain their original spectral index of -2.6, as can be seen from the following:

When the differential flux intensity of a population of protons has a simple power law distribution D of the form

$$D(E) = AE^{\gamma}, \qquad (1)$$

and the protons all undergo a uniform energy loss C by passing through a common electric potential, then the new distribution will have the form

$$D(E - C) = A(E - C)^{\gamma}, \qquad (2)$$

where E is the proton kinetic energy and A and C are constants. So the new spectrum (Eq. 2) will have the same power law index γ as the original spectrum (Eq. 1), as observed. The similarity of the spectral index between 2 MeV and about 8 MeV, and that above 50 GeV, has been noted in the literature, but a causal connection between the two was not proposed.

III. SOLAR WIND ENERGETIC IONS

Observations of the quiet solar wind persistently reveal an interplanetary suprathermal ion population extending to ~1 MeV per nucleon, and an overlapping population of energetic ions having energies as high as about 100 MeV, and the origin of these ions is not understood . The suspected sources of these energetic protons [7] are one or even a combination of the following:

1. Planetary bow shocks & magnetospheres
2. Inner-source and interstellar pick-up ions
3. Cometary ions
4. Fast & slow solar wind
5. Solar energetic particles
6. Corotating interaction regions
7. Energetic storm particles

Most of these suspected sources are impulsive or transient in nature, whereas a significant portion of the energetic ions is always observed to be present in the solar wind even in unusually quiet conditions. In the model presented here, it seems likely that these anomalously energetic protons are the same ones that are in the trapping reservoir of protons and ions that behave diffusively and continuously leak out of the reservoir and merge with the solar wind. This source of energetic protons would be expected to be continuous, as observed, and would be in the energy range 2 MeV < E < 15 MeV.

It seems likely that ions in the solar wind having energy less than 2 MeV originate from primary GCRs with energy extending all the way down to exactly 1 GeV (which produce protons at rest), most of which can arrive very near to the boundary of the trapping region but cannot penetrate it because they lack enough energy to do so. Such protons, along with heavier GCR ions, would be promptly swept up by the solar wind, and comprise the population of ions which are observed as suprathermal ions.

IV. CONCLUSIONS

This paper describes a model which accounts for anomalously energetic ions in the low energy tail of the solar wind, based on a previous conclusion [1, 2] that the so-called "solar" modulation is, in fact, caused almost entirely by a positive, quasi-static electric field which pervades the heliosphere. Because of spherical symmetry, the electric field vanishes near the centroid of the heliosphere. This is important to creating and sustaining the field, by providing conditions favorable to maintaining a reservoir of diffusive GCR protons which are restrained for a time from rejoining their companion GCR electrons in or near the termination shock.

The population of diffusive protons leaks out of the reservoir and merges with the solar wind, and these protons (and other ions which behave similarly) are observed as energetic solar wind ions. The great majority of the energetic protons have kinetic energy near 2 MeV, and take about 3 days to arrive at the termination shock. During this time interval the protons remain separated from their companion GCR electrons, with the result that the population of unpaired protons in the heliosphere tends toward a homogeneous distribution. Since a homogeneous distribution was assumed in [1, 2], this model supports the concept of a pervasive, quasi-static electric field in the heliosphere which vanishes at the centroid of the heliosphere, and increases linearly to + 120 mV/km near the termination shock.

Suprathermal protons originate from primary GCR protons having initial energies between 1.000 and 1.002 GeV, which produce modulated protons near the center of the heliosphere which have kinetic energies which range between 0 and 2 MeV.

REFERENCES

[1] H. D. May, "A pervasive electric field in the heliosphere", (Part I), *IEEE Trans. Plasma Phys.* vol. 36, no. 5, pp. 2876-2879, Oct. 2008.
[2] H. D. May, "A pervasive electric field in the heliosphere (Part II)", o*nline journal viXra*, http://vixra.org/abs/1005.0090 , May, 2010.
[3] P. Meyer, R. Ramaty, and W. R Webber, Cosmic Rays: Astronomy with energetic particles", *Phys. Today*, vol. 27, no. 10, pp. 23-32, Oct., 1974.
[4] I. G. Usoskin, K. Alanko-Houtari, G. A. Kovaltsov, and K. Mursala, "Heliospheric modulation of cosmic rays: Monthly reconstruction for 1951 – 2004", *J. Geophys. Res*,vol. 110, no. A12, pp. 1 – 10, Dec. 2005.
[5] E. N. Parker, *Planet. and Space Sci*., vol. 13, pp. 9-49, 1965.
[6] L. J. Gleeson and W. I. Axford, "Cosmic rays in the interplanetary medium", *Astrophys. J.*, vol. 149, pp. L115-L118m 1967.
[7] G. M. Mason and G. Gloeckler, "Power law distributions of suprathermal ions in the quiet solar wind", *Space Sci. Rev.*, DOI 10.1007/s11214-010-9741-0, published online by Springer, 10 Feb. 2011.

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