Vol. 4, No. 1 Geophysical Research Letters January 1977

PERSISTENT SUNWARD FLOW OF ~ 1.6 MeV PROTONS at 1 AU

F. E. Marshall and E. C. Stone

California Institute of Technology, Pasadena, California 91125

Abstract. It has been found that except during the onset of prompt solar particle events the diffusive flow of 1.3 to 2.3 MeV protons at 1 AU is predominantly sunward. The anisotropy of the proton intensity has been measured with the Caltech Electron/Isotope Spectrometer aboard IMP-7 for periods between prompt solar particle events from 72/273 to 74/2. The diffusive anisotropy, which has been determined by subtracting the independently determined convective anisotropy from the observed anisotropy, is predominantly directed toward the sun with a mean radial component of 14%. This sunward diffusion is typical of intensities from 0.012 to 1.2 $(cm^2\ sec\ sr\ MeV)^{-1}$ for 1.3 - 2.3 MeV protons and indicates that a positive radial gradient is characteristic of these modestly enhanced fluxes. The direction of the flow is opposite to that which would be produced by previously proposed models which involve a continuous solar source for the observed particles. A steady-state propagation model which includes adiabatic energy loss with particle injection beyond 1 AU produces the average observed anisotropy for $\kappa_{rr} \sim 4 \times 10^{20}\ cm^2\ sec^{-1}$.

Introduction

The flux of low energy protons at 1 AU varies over several orders of magnitude even during the periods between prompt solar particle flares. Individual increases, or events, have been studied by several authors including Bryant et al. (1965), Fan et al. (1968), Anderson (1969), McDonald and Desai (1971), Krimigis et al.(1971) and Roelof and Krimigis (1973). These events are distinguished from the prompt flare-associated events by their slower rise times, more symmetric time development and lack of velocity dispersion. These increases have been modeled as streams of energetic particles corotating with the sun whose source is either continuous solar acceleration or intermittent solar acceleration with near-sun storage. A more comprehensive study by Kinsey (1970) extended this model to that of the sun as a continuous, but variable, source of low energy protons.

Of these studies, only Krimigis et al.(1971) (whose data were subsequently analyzed by Roelof and Krimigis (1973)) reported measurements of extended periods with continuous streaming from the sun to support the proposed solar source. The observations of Krimigis et al. (1971) are at lower energies (≥ 0.3 MeV) than those reported in this letter.

Evidence of a different source for corotating streams at ≥ 3 AU has been reported by McDonald et al. (1975), who found that the average size of such events seen by Pioneer 11 near 3 AU is ~ 10 times as large as the average events seen at Earth by IMP-7 during the same time period. The authors suggested interplanetary acceleration as the most likely source of the streams seen near 3 AU.

In this letter we report the anisotropy of 1.3 to 2.3 MeV protons during 317 6-hour periods from 72/273 to 74/2, excluding periods when prompt solar particle events are observed. It is found that the diffusive streaming is predominantly toward the sun, indicating a predominantly positive radial gradient in the particle density.

Data Analysis

The energetic particle data are from the Caltech Electron/Isotope Spectrometer (EIS) on IMP-7. Anisotropies are determined for nucleons which stop in a 47 µm solid-state detector D2 (the instrument has been described by Hurford et al. (1974)). The analyzed nucleons are primarily 1.3 to 2.3 MeV protons, but heavier nuclei contribute ~ 5%.

Each analyzed event is labeled to indicate in which of 8 sectors in the ecliptic plane it was observed. The anisotropy ξ is determined by fitting the function $A_o\{1 + \xi \cos(\phi_i - \phi_o)\}$ to the sectored events accumulated in each 6-hour period, where ϕ_i is the average direction of sector i. The anisotropy direction, which is the direction toward which the particles are flowing, is defined to be $\phi_o + 180^o$, and the anisotropy amplitude ξ_{OBS} is $1.08\ \xi$. The factor 1.08 corrects for the smoothing effect of the finite sector width and finite instrumental opening angle. The solar ecliptic (SE) coordinate system, in which the x-axis points toward the sun and the z-axis points toward the North Ecliptic Pole, has been used.

Jokipii and Parker (1970) have shown that the observed anisotropy is given by:

$$\vec{\xi}_{OBS} = \vec{\xi}_{CON} + \vec{\xi}_{DIF} = \frac{3}{w}\left[C\vec{V} - (\underline{\kappa} \cdot \vec{\nabla} U)/U \right] \quad (1)$$

in which U = particle density = $4\pi j/w$
$\vec{V}$ = solar wind velocity
$\underline{\kappa}$ = diffusion tensor
w = particle velocity
C = Compton-Getting Factor $= (2-\alpha\gamma)/3$
$\alpha = (T + 2mc^2)/(T + mc^2)$
$\gamma = \partial \ln j/\partial \ln T$
j = particle intensity
T = particle kinetic energy

The spectral index γ is determined by fitting the energy spectrum observed by the Caltech EIS experiment. The solar wind speed has been obtained from the MIT plasma experiment on IMP-7 (J.D. Sullivan and H. S. Bridge, private communication) and is assumed to be radial. For this preliminary study

Paper number 6L0711.

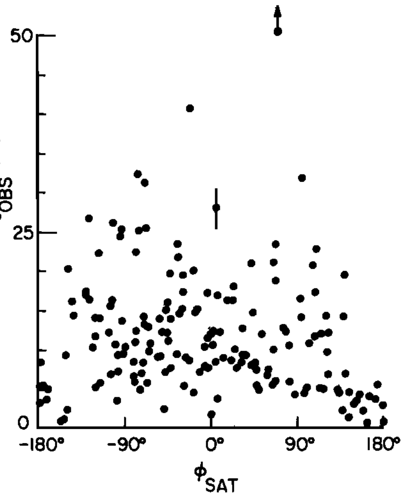

Figure 1. The amplitude of the observed anisotropy, $\vec{\xi}_{OBS}$, as a function of the longitude ϕ_{SAT} of the IMP-7 satellite in GSE coordinates. Each dot represents one 6-hour period. A typical $\pm 1\sigma$ error bar is indicated. Since solar wind data are not needed for this figure, the data set has been extended from 72/273 to 75/18 to increase the sample size. Only periods when the flux of 1.2 to 2.4 MeV protons is between 0.12 and 1.2 $(cm^2\ sec\ sr\ MeV)^{-1}$ are included. Periods when the flux of ~0.2 to ~1.0 MeV electrons exceeds 2 $(cm^2\ sec\ sr)^{-1}$ are not included. Periods dominated by prompt solar particle events have been rejected using the criteria discussed in the text.

only periods with speeds less than 700 km sec^{-1} have been used. Thus $\vec{\xi}_{CON}$ can be computed, and $\vec{\xi}_{DIF}$ thereby determined from Eq. 1.

Selection

Not all of the 6-hour periods from 72/273 to 74/2 are included in this study. Periods dominated by prompt solar particle events have been eliminated by two methods. First, periods when the PLO rate (which monitors nucleons stopping in D2) exceeds 0.3 sec^{-1} (corresponding to a flux of 1.2 $(cm^2\ sec\ sr\ MeV)^{-1}$) are not included. This criterion also means that the measured anisotropies are negligibly affected by the high rate effects discussed by Roelof (1974). Second, 25 individual prompt solar particle events have been identified by their characteristically rapid onsets. The day preceding, the day of, and the two days following the onset are eliminated. This criterion eliminates small events and the beginnings of large events even if the PLO rate is not larger than 0.3 sec^{-1}.

Periods are included only when IMP-7 is sunward of the earth, i.e., in interplanetary space. The dependence of the $\vec{\xi}_{OBS}$ on the position of IMP-7 has been examined to determine any remaining magnetospheric influence. For example, any blockage of particle flow by the magnetosphere should be more pronounced when IMP-7 is on the dawn side of earth than on the dusk side of earth. Figure 1 shows the observed anisotropy amplitude as a function of the Geocentric Solar Ecliptic (GSE) longitude of IMP-7. The outstanding feature of this figure is the small anisotropies found when the longitude of IMP-7 is near 180°, i.e. when IMP-7 is in the magnetotail. There is no apparent difference between the dawn and dusk side of earth while the spacecraft is sunward of the earth. The difference in the mean anisotropy amplitude for the sunward quadrants is 0.9% ± 2.0%. Differences in the mean anisotropy direction for the two quadrants are also not statistically significant. Thus we have no evidence of magnetospheric influence on anisotropies for these periods when IMP-7 is sunward of the earth. In particular, we have seen no evidence that the earth is a source of protons as has been observed at lower energies (Krimigis et al., 1975).

Results

Figure 2a shows $\vec{\xi}_{OBS}$ for the 112 6-hour periods meeting the above requirements and also having a PLO rate between 0.03 sec^{-1} and 0.3 sec^{-1}. Somewhat more than half these periods (57%) have a decreasing PLO rate. The mean x and y components of the anisotropy are:

$$\langle \vec{\xi}_{OBS} \rangle = (-7.2\% \pm 1.2\%, -1.8\% \pm 1.1\%)$$

For each of these 112 periods, the measured spectral index γ and solar wind speed V have been used in Eq. 1 to determine $\vec{\xi}_{DIF}$, which has been plotted in Figure 2b. The mean x and y components of the diffusive anisotropy are:

$$\langle \vec{\xi}_{DIF} \rangle = (13.6\% \pm 1.2\%, -3.2\% \pm 1.1\%)$$

Thus although the mean observed streaming is from the sun, the mean diffusive streaming is toward the sun. The difference in the y-components is due to the earth's velocity.

As shown in Eq. 1, the spatial gradients implied by $\vec{\xi}_{DIF}$ depend on the form of $\underline{\kappa}$. However, a predominantly positive radial gradient is indicated for either isotropic or anisotropic diffusion. For isotropic diffusion, $\vec{\xi}_{DIF}$ is proportional to $\vec{\nabla}U$, so the fact that 88% of the periods shown in Figure 2b have a positive x-component indicates that 88% of the periods have a positive radial gradient. If diffusion is preferentially along the magnetic field rather than across the field, then $\vec{\xi}_{DIF} \cdot \vec{B}$ should be used to determine whether the particle density U is increasing along the field toward or away from the sun. Using this technique, it has been found that 80% of the periods have a positive gradient along the field away from the sun. Thus for either isotropic or anisotropic diffusion, $\vec{\xi}_{DIF}$ indicates that U is typically larger outside 1 AU than inside.

This diffusive flow back toward the sun was found to be typical of all flux levels used in this study (0.012 to 1.2 $(cm^2\ sec\ sr\ MeV)^{-1}$) and of both increasing and decreasing intensities. Lower intensities were not included because of large statistical uncertainties in the measured anisotropy when determined over a 6-hour period.

Jokipii and Parker (1970) have shown that the anisotropy following individual particles, that is particles with the same T in the rest frame of the solar wind, is

$$\vec{\xi}_{Part} = \frac{3}{w} \left[\vec{V} - \underline{\kappa} \cdot \vec{\nabla} U / U \right] . \quad (2)$$

The average radial component of $\vec{\xi}_{Part}$ is 5% ± 1% toward the sun. Thus the individual particles are

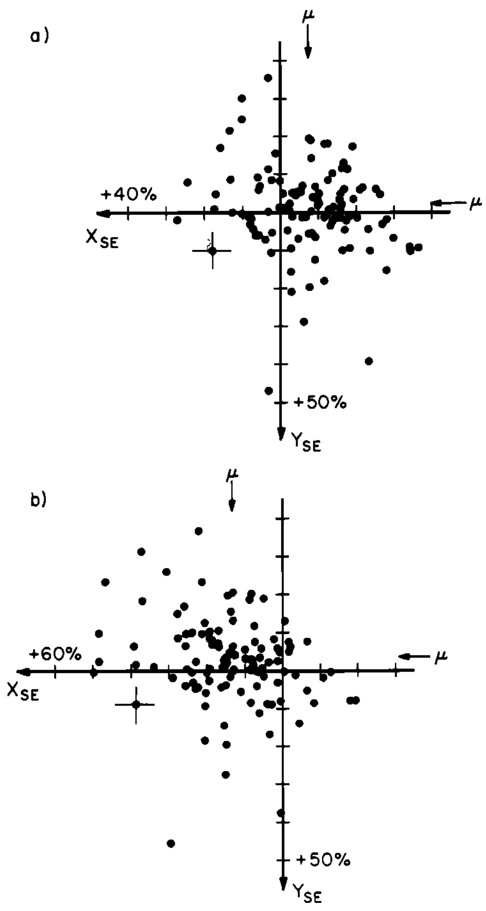

Figure 2. a) Six-hour averages of the observed anisotropy, $\vec{\xi}_{OBS}$. A typical ± 1σ error bar is shown. The means (μ) of the x and y components of the anisotropy are indicated by arrows. Only periods from 72/273 to 74/2 when IMP-7 is sunward of Earth and the flux of 1.2 to 2.4 MeV protons is between 0.12 and 1.2 (cm^2 sec sr $MeV)^{-1}$ are included. Periods dominated by prompt solar particle events have been rejected.

b) Six-hour averages of the diffusive anisotropy, $\vec{\xi}_{DIF}$.

diffusing toward the sun faster than they are convected away from the sun. Such a sunward flow indicates a sink for 1.3 to 2.3 MeV particles inside 1 AU.

The earlier observations established the recurrent character of the intensity increases. This long-term coherence suggests consideration of a simple steady-state propagation model in which adiabatic energy loss is the sink of 1.6 MeV protons inside 1 AU. The steady-state propagation equation:

$$\vec{\nabla}\cdot(\underline{\kappa}\cdot\vec{\nabla}U) - \vec{\nabla}\cdot(U\vec{V}) + \frac{1}{3}\,\vec{\nabla}\cdot\vec{V}\,\frac{\partial}{\partial T}(\alpha(T)\;TU) = 0 \quad (3)$$

has been simplified by assuming a power-law energy spectrum, azimuthal symmetry, κ_{rr} independent of radius and energy, $\vec{V}$ radial and independent of r, U finite at r = 0, and a source of particles at some r > 1 AU. The same assumptions about $\underline{\kappa}$, $\vec{V}$, and U have been used by Lupton and Stone (1973) in a time-dependent model to fit successfully the time development of prompt solar particle events. The solution is of the form

$$U(r)=U_K(-2C + 2;2;-\frac{V}{\kappa_{rr}}r)e^{Vr/\kappa_{rr}}$$

in which U_K is a solution to Kummer's equation. U increases approximately exponentially away from r = 0 with a scale length of $\sim \kappa_{rr}/V$. This solution was included in a discussion of the modulation of galactic cosmic rays by Fisk and Axford (1969).

The model predicts an increasing radial component of $\vec{\xi}_{DIF}$ with increasing solar wind speed. The observed dependence is consistent with the model calculations as shown in Figure 3. The data points are averages for 4 sets of data grouped by solar wind speed.

Using the mean observed γ of -3.15 and V of 440 km sec^{-1}, the model produces diffusive anisotropies ranging from 10% to 17% for κ_{rr} from 10^{20} to 10^{21} cm^2 sec^{-1}. The mean observed radial diffusive anisotropy is 14% ± 1%. A κ_{rr} of 10^{21} cm^2 sec^{-1} produces an intensity ratio of 13 between 1 and 3 AU, comparable to that inferred from Pioneer 11 data, and a ratio of 3 between 0.3 and 1 AU. Smaller values of κ_{rr} produce larger gradients. However, if particles are injected over a range of radii around 3 AU or if κ_{rr} increases with radius, smaller values of κ_{rr} at 1 AU would also produce a ratio of ~ 10 between 1 and 3 AU.

Conclusion

The diffusive streaming of low energy protons has been found to be predominantly toward the sun during periods between prompt solar particle events. The long-term average radial component (14%) of this anisotropy and its dependence on the solar wind speed are consistent with the anisotropy calculated using a steady-state propagation model including adiabatic energy loss for $\kappa_{rr} \sim 4 \times 10^{20}$ cm^2 sec^{-1}. More sophisticated models will be needed to account for the detailed time variations in the anisotropy and to investigate the possibility that the particle sink inside 1 AU results from propagation to and eventual outflow from higher solar latitudes.

Previous observations at 1 AU during periods between prompt events have been interpreted as indicating the sun to be a continuous source of MeV protons. The new observations of predominantly sunward diffusive flow show that such a direct solar source is rare during 1973 and suggest the possibility that some of the previously observed increases may not be due to such a source.

At the present stage of analysis it is not possible to specify the source mechanism(s) for these particles. Although no direct association has been established, the observations are consistent with the increases near 3 AU reported by McDonald et al. (1975). Thus, interplanetary acceleration mechanisms such as transit-time damping (Fisk, 1976) which have been suggested to produce the increases seen by McDonald et al. (1975) may be relevant to the new observations at 1 AU. However, Fermi acceleration throughout the heliosphere, which would result in ~ 1% diffusive anisotropy (Fisk, 1976), is inconsistent with the large diffusive anisotropy observed at 1 AU. Other possibilities may include stream-stream interactions, out-of-the-ecliptic propagation, or stor-

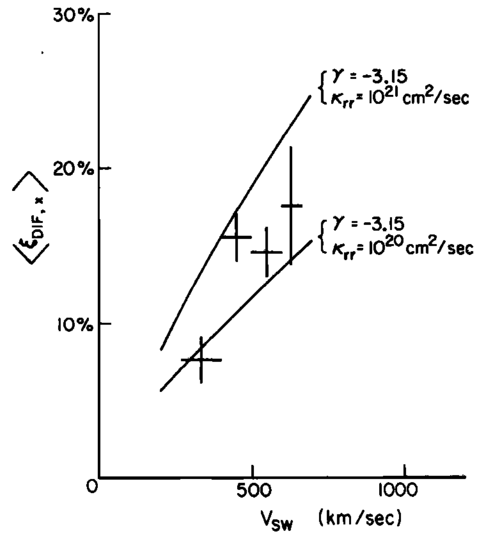

Figure 3. The average x-component of $\vec{\xi}_{DIF}$ as a function of the solar wind speed. Only periods from 72/273 to 74/2 when IMP-7 is sunward of Earth and the flux of 1.2 to 2.4 MeV protons is from 0.04 and 1.2 (cm^2 sec sr MeV)$^{-1}$are included. Periods dominated by prompt solar particle events have been rejected.

age beyond 1 AU of particles from solar flares not observed as prompt events at Earth.

Acknowledgments. We are grateful to H. S. Bridge and J. D. Sullivan for providing IMP-7 plasma data prior to publication. We are also grateful to R. E. Vogt who has been intimately involved throughout the IMP-7 program. Significant contributions to this project have also been made by W. E. Althouse, G. J.Hurford, and R. A. Mewaldt. This work was supported in part by the National Aeronautics and Space Administration under Contract NAS5-11066 and Grant NGR 05-002-160. F. E. Marshall has received valuable support from an NDEA Fellowship.

References

Anderson, K.A., Electrons and Protons in Long-Lived Streams of Energetic Solar Particles, Solar Physics, 6, 111, 1969.

Bryant, D.A., T.L. Cline, U.D. Desai, and F.B. McDonald, Continual Acceleration of Solar Protons in the MeV Range, Phys. Rev. Lett., 14, 481, 1965.

Fan, C.Y., M. Pick, R. Pyle, J.A. Simpson, and D.R. Smith, Protons Associated with Centers of Solar Activity and Their Propagation in Interplanetary Magnetic Field Regions Corotating with the Sun, J. Geophys. Res., 73, 1555, 1968.

Fisk, L.A., On the Acceleration of Energetic Particles in the Interplanetary Medium, GSFC Preprint X-660-76-25, 1976.

Fisk, L.A. and W.I. Axford, Solar Modulation of Galactic Cosmic Rays, 1, J. Geophys.Res., 74, 4973, 1969.

Hurford, G.J., R.A. Mewaldt, E.C. Stone, and R.E. Vogt, The Energy Spectrum of 0.16 to 2 MeV Electrons During Solar Quiet Times, Astrophys. J., 192, 541, 1974.

Jokipii, J.R. and E.N. Parker, On the Convection, Diffusion, and Adiabatic Deceleration of Cosmic Rays in the Solar Wind, Astrophys. J., 160, 735, 1970.

Kinsey, J.H., Identification of a Highly Variable Component in Low-Energy Cosmic Rays at 1 AU, Phys. Rev. Lett., 24, 246, 1970.

Krimigis, S.M., E.C. Roelof, T.P. Armstrong, and J.A. Van Allen, Low-Energy (> 0.3 MeV) Solar Particle Observations at Widely Separated Points (> 0.1 AU) during 1967, J. Geophys. Res., 76, 5921, 1971.

Krimigis, S.M., J.W. Kohl, and T.P. Armstrong, The Magnetospheric Contribution to the Quiet-Time Low Energy Nucleon Spectrum in the Vicinity of Earth, Geophys. Res. Lett., 2, 457,1975.

Lupton, J.E. and E.C. Stone, Solar Flare Particle Propagation -- Comparison of a New Analytic Solution with Spacecraft Measurements, J. Geophys. Res., 78, 1007, 1973.

McDonald, F.B. and U.D. Desai, Recurrent Solar Cosmic Ray Events and Solar M Regions, J. Geophys. Res., 76, 808, 1971.

McDonald, F.B., B.J. Teegarden, J.H. Trainor, and T.T. von Rosenvinge, The Interplanetary Acceleration of Energetic Nucleons, Astrophys. J., 203, L149, 1975.

Roelof, E.C., On the Measurement of Energetic Particle Flux Anisotropies with a Class of Spinning Detectors, J. Geophys. Res., 79, 1535, 1974.

Roelof, E.C. and S.M. Krimigis, Analysis and Synthesis of Coronal and Interplanetary Energetic Particle, Plasma, and Magnetic Field Observations over Three Solar Rotations, J. Geophys. Res., 78, 5375, 1973.

(Received October 18, 1976;
accepted November 11, 1976.)