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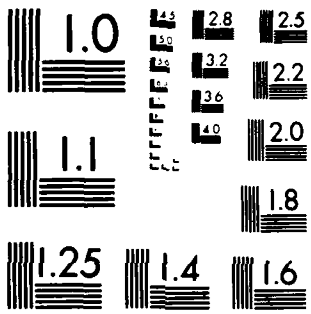

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PREDICTION OF SOLAR-TERRESTRIAL DISTURBANCES: DECAY PHASE OF ENERGETIC PROTON EVENTS

E. C. Roelof

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20707

Final Report
1 July 1979 - 30 September 1982

October 1982

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The decay phase of solar proton events, as observed at Earth, depends strongly on the proton injection history, the distribution of the proton population in solar longitude, and the state of the interplanetary medium. In an attempt to gain an additional diagnostic of these complex conditions, the evolution of the flux anisotropy is examined, both theoretically and observationally. In relatively simple events, the component of the flux anisotropy parallel to the interplanetary magnetic field proves to be a useful indicator. In more complicated events, additional information from solar wind, magnetic field, and lower energy

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(≤ 1 MeV) ions would appear to be necessary. Research papers on these related quantities are also cited.

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Introduction

We had anticipated that the 39 month period July 1979 - September 1982 would be primarily devoted to the analysis of the decay of energetic particle events, using first the JHU/APL IMP 7/8 CPME (Charged Particle Measurement Experiment) measurements, and then combining them with LECP (Low Energy Charged Particle) measurements on the VGR 1/2 spacecraft, launched in August 1977. However, continuing research by our own and other groups revealed new complexities in the behavior of low energy ($\lesssim$ 1 MeV) protons, the only protons for which we had anisotropy measurements from the CPME. Moreover, a full set of VGR particle, plasma and field data was not made available to us until last year.

Consequently, we modified our research program, concentrating during the early period on subjects relevant to the problem of decay phase prediction. This background proved beneficial when we were able to work on the main problem this past year. Some 15 papers were published, and 7 others are currently pending publication. They are listed (by number) in the following section.

Briefly, our publications fall into four general categories:

I. Interplanetary Particle Propagation: Papers 1, 2, 8, 12, 16 and 17.

II. Solar Wind and Geomagnetic Storms: Papers 3, 4, 6, 7, 9 and 13.

III. Solar Flares and Activity: Papers 5, 10, 14, 15 and 21.

IV. Diagnostics of Particle Propagation Using Energetic Ions Upstream of the Earth's Bow Shock: Papers 11, 18, 19, 20 and 22.

In the remainder of this Report, we summarize the research to date on the main problem, that of predicting the decay phase of solar proton events at energies $\gtrsim$ 1 MeV.

Theoretical Background

What information is contained in the particle flux anisotropy? Which component of the anisotropy gives the clearest indication of the evolution of the particle event? We turn to a global formulation of the propagation equations for the answers, because the evolution of an event is simply the competition among injection, escape, acceleration and deceleration. The equation which inter-relates all these processes is the equation of continuity (conservation of the particle density V at kinetic energy T in the presence of streaming $\underline{S}$). If we write this equation down in a local frame in which the electric field is zero, it takes the familiar form

$$\frac{\partial}{\partial t} V' + \nabla' \cdot \underline{S}' = 0 \qquad (1)$$

One such local frame is that moving with the electric field drift velocity $(c/B^2)\, \underline{E} \times \underline{B}$. Here $\underline{E}$ is in the rest (spacecraft) frame, so $\underline{E} = -(\underline{v} \times \underline{B})/c$ and consequently the drift velocity is $\underline{V}_{\perp}$, the component of the solar wind perpendicular to the interplanetary magnetic field. We have established, in Papers (2) and (8), that for protons with $T \lesssim 1$ MeV the streaming in the spacecraft frame is given very accurately by

$$\underline{S} = \underline{S}_{\parallel} + C\, \underline{V}_{\perp}\, U \qquad (2)$$

where C is the Compton-Getting factor for non-relativistic particles $2(\gamma + 1)/3$, $(-\gamma)$ being the slope of the spectrum differential in energy. Omitted from (2) is the gradient anisotropy term, proportional to $\underline{B} \times \nabla U$, since it scales as the gyroradius and hence it is usually unimportant at non-relativistic energies (as was borne out by our measurments). By the linearized transformation for weak anisotropies, the streaming $\underline{S}'$ which appears in (1) is related to $\underline{S}$ in (2) by

$$\underline{S}' = \underline{S} - C\,\underline{V}_{\perp}\,U \qquad (3)$$

which implies $\underline{S}'_{\parallel} = \underline{S}_{\parallel}$. We leave $\underline{S}_{\parallel}$ unspecified; it could be caused by diffusion, or it could be dominated by scatter-free propagation. Equation (1) is valid in either extreme.

One way to see the physical information contained in $\underline{S}_{\parallel}$ is to integrate (1) over the volume of a magnetic flux tube whose ends are formed by its intersections with the spherical surfaces $r = r_o$ (the upper corona, for example) and v (the spacecraft). Let these end areas of the tube be A_o and A, respectively. Then, applying the divergence theorem to $\nabla' \cdot \underline{S}'$ and recalling $\underline{S}'$ is parallel to the sides of the flux tube, we obtain

$$S_{\parallel r}\,A - S_o\,A_o + \int d^3x\,\frac{\partial}{\partial t}\,U' = 0 \qquad (4)$$

This says that he radial component of the parallel streaming $S_{\parallel r}$ (which is not the same as the parallel component of the radial streaming $S_{r\parallel}$), responds to the (radial) injection streaming S_o (which, being the net flow across the surface $r = r_o$, contains not only the source strength of new particles, but the flow of previously injected particles from interplanetary space back into the corona), and the co-moving time rate of change $\partial U'/\partial t$, integrated over the volume of the flux tube. This latter integral is not $\partial N/\partial t$, the time derivative of the total number of particles in the flux tube, because the derivative is taken in a different local frame at each point in space. The relationship between $\partial U'/\partial t$ and $\partial U/\partial t$, the time-rate-of-change of particle density observed at the spacecraft, can be derived from the equations Roelof published in the Proceedings of the 14th International Cosmic Ray Conference, (Munich, 5, 1716, 1975), under the assumption of negligible transverse diffusion, as validated in Paper (2):

$$\frac{\partial U'}{\partial t} = \frac{\partial U}{\partial t} + \underline{V}_{\perp} \cdot \nabla U + (\nabla \cdot \underline{V}_{\perp})\,CU \qquad (5)$$

The three terms should be familiar. The first, integrated over any volume, does give $\partial N/\partial t$ in the rest frame. The second is the apparent temporal change due to $\underline{E} \times \underline{B}$ convection of the particle population in the presence of a density gradient in radius, longitude, or even latitude, since $\underline{V}_\perp$ always has a latitudinal component whenever $\underline{B}$ does. For an ideal Archimedean spiral field, $V_\perp \propto r^2$ and is nearly azimuthal well inside 1 AU, while $V_\perp \approx V$ and is nearly radial well outside 1 AU. Likewise, $\nabla \cdot \underline{V}_\perp \approx 4\,\Omega^2 r/V$ in the inner heliosphere and $\nabla \cdot \underline{V}_\perp \approx 2\,V/r$ in the outer heliosphere, reaching a maximum value of about $3\,\Omega/2$ near 1 AU, where $\Omega r \approx V$; Ω is the sun's sidereal rotation rate. If there is interplanetary acceleration, for instance in the vicinity of the flare-associated shock wave, then a fourth (and positive) term should be added to (5).

We can now see what goes into the parallel velocity anisotropy $\xi_{\parallel r} = 3\,S_{\parallel r}/Uv$. Substituting (5) into (4), we find that

$$\xi_{\parallel r} = \xi_o \frac{U_o A_o}{UA} - \frac{3}{vUA} \int d^3x \; [\; \frac{\partial U}{\partial t} + \underline{V}_\perp \cdot \nabla U + \cdot \nabla \cdot \underline{V}_\perp) \; CU] \quad (6)$$

For a flux tube which is not too deformed from a spiral, $A_o/A \approx r_o^2/r^2$, so the source injection term is important at 1 AU only when there is an initial negative radial gradient, as strong as $U \propto r^{-2}$, for instance. Later on, as the gradients weaken, $\xi_{\parallel r}$ is determined by the volume integral, i.e., $(-\,\partial U'/\partial t)$ acts as an effective "source" for the parallel streaming $S_{\parallel r}$ at radius r. Conversely, if we took $r_o = 1$ AU and $r > 1$ AU, $\partial U'/\partial t$, if positive over the outer flux tube, would drive the streaming at 1 AU inward ($\xi_o < 0$), since the radial component of ξ becomes small at large r (because $B_r/B \ll 1$).

Use of Anisotropy Measurements in Predicting the Evolution of Solar Proton Events

The full complexity of Equation (6) does not always have to be considered in deciding the nature of a particle event. For instance, the rising phase of a new injection (even in the presence of a pre-existing population) is easily identifiable by the strong anisotropies which accompany the rise-to-maximum; no knowledge of global gradients is required for this signature. Anisotropy measurements can also be used by themselves to distinguish slowly rising solar events from "corotating" populations from a previous injection. For example, if the decaying population from an eastern flare (whose maximum spatial density was originally east of the Earth) were to "corotate" with the interplanetary field lines, the fluxes at Earth could increase ($\partial U/\partial t > 0$) even while $\partial U'/\partial t < 0$ in the corotating frame if $\Omega \partial U/\partial \phi < \partial U'/\partial t < 0$, since $\partial U/\partial t \approx \partial U'/\partial t - \Omega \partial U/\partial \phi$. We have neglected the adiabatic deceleration and radial gradient effects in (6) for the purpose of this example. We have documented many cases of this "coronal profile" effect (see Papers 1, 12, 16 and 17, for example), using the field-line mapping technique described in our previous Final Scientific Report (Gold and Roelof, AFGL-TR-80-100, March 1980). If we had anisotropy measurements, as well as intensities, the identification of a rise as a new injection is usually a straightforward matter of the presence of a non-equilibrium anisotropy.

For the decay phase, we cannot utilize the anisotropy measurements without making some assumptions concerning the spatial gradients of the intensity, either inside or outside of the radius of the spacecraft. The simplest assumption would be that the radial gradient is small in the decay phase. Krimigis and Roelof (Study of Traveling Interplanetary Phenomena/1977, Astrophysics and Space Library, 71, D. Reidel, 1977) showed from the University of Chicago simultaneous measurements of 11 - 20 MeV and 30 - 67 MeV protons on IMP-8 and Pioneers 10 and 11 that the radial gradients were small in the solar flare events of November 3, 1973 and November 5, 1974 between 1 and 5 AU when the spacecraft were in approximately the same flux tube. On the basis of conventional diffusion-convection theory, one expects a positive radial gradient very late in the event, but it should also be a small one, with a scale length > 1 AU at such energies.

If we assume that $|\partial(\ell n\ U)/\partial(\ell n\ r)| \ll 1$ and that the field is approximately spiral inside 1 AU, we obtain an approximate version of (6)

$$\xi_{\parallel r} \approx -\frac{r}{v}\left[\frac{\partial}{\partial t}\ell n\,U + \Omega_1\frac{\partial}{\partial\phi}\ell n\,U + \Omega_2\,C\,U\right] \qquad (7)$$

where Ω_1 and Ω_2 are angular velocities $\lesssim \Omega$, their values being the averages of $(V_{\perp\phi}/r)$ and $(V \cdot \underline{V}_{\perp})$ over the flux tube from r_o to 1 AU, respectively. The only quantity we can't measure directly with a single spacecraft is $\partial\ \ U/\partial\phi$. However, as we have demonstrated in our earlier work, if the solar wind velocity is varying sufficiently to make significant (~ 10°) changes in the connection longitude over a few hours, it may be possible to infer $\partial U/\partial\phi$ from the event time history. Note that $\partial\,\ell n\ U/\partial t < 0$ and $\Omega\ C\ U > 0$ tend to cancel in the decay phase. Thus, if all the terms on the RHS of (7) combine to give the observed anisotropy $\xi_{\parallel r}$, we can assume that the event is in its decay phase and that it will continue to decay according to the functional dependence already exhibited by U(t).

We have begun an examination of the simplifying assumptions necessary to be able to utilize the information contained in $\xi_{\parallel r}$. Multispacecraft observations are required, and this year we finally received the data which enabled us to begin comparisons of IMP 7/8 and VGR 1/2 particle measurements.

To illustrate our approach, we show in Figure 1 the intensity histories of two channels responding to 5 MeV protons, P5 on IMP-8 at 1 AU and CH10 on VGR1 at 1.5 AU, the event shown is the response to the Hα importance 2B solar flare of 0945 - 1108, 22 November 1977 (day 326). Flare coordinates were N24, W40 giving good connection to the flare site at 60° heliographic longitude. The flare was isolated, so the interplanetary medium was quiet, with $V \approx 300$ km s^{-1} so convection effects were small until the arrival of the flare shock. In Figure 1, the intensities (which agreed quite well shortly after launch of VGR1) are mapped back to their coronal connection longitudes, using hourly averaged solar wind speeds from each spacecraft. The large symbols are plotted at the beginning of each day, triangles for IMP-8 and pluses for VGR1.

Intensities are connected by straight lines at the beginning of each day. On days 327 and 328, IMP-8 is higher, probably because of the negative radial gradient expected near event maximum. However, by day 330, a rather steady azimuthal gradient has been established. There does not seem to be a measurable radial gradient after this time, because the azimuthal gradient is not much affected by significant changes in the differences between the convection longitudes. The azimuthal dependence can be estimated from the straight connecting lines as $\partial \ln U/\partial\phi \simeq + (35°)^{-1}$, while the residual temporal decay may be deduced from the slow lowering of the lines, yielding $\partial \ln U/\partial t \simeq -(3d)^{-1}$. If we substitute these values in (7) and use $V \simeq 400$ km s^{-1} for the post-shock velocity during this decay phase, we find

$$\xi_{\parallel r} \simeq - [(-0.020) + (0.008) + (0.005)] \simeq + 0.007 \qquad (8)$$

These numbers are only preliminary estimates, but they are sufficiently accurate to show some consistency with (7), if $\xi_{\parallel r} \simeq 0.7\%$.

We wanted to be able to examine the anisotropy in some detail, so we developed the graphical display shown in Figure 2. The eight gray-shaded columns represent the CH10 fluxes measured in the eight sectors scanned by the LECP telescope on VGR1. Large tic marks are at one-day intervals, and the small ones every 6 hours. The streaming directions run from approximately 0° on the left through 180° to 360° on the right. Protons flowing outward along the nominal spiral field would appear at ~ 135° on the plot (Sector 7). The arrow points to the direction for particles streaming away from the sun. The maximum and minimum fluxes are indicated to the right of the gray-shade, plotted as the logarithm in units of (cm^2 s sr MeV)$^{-1}$. The gray-shade assigns 16 shades linearly between the minimum and maximum flux in each sector for each hour. The small squares each hour give the direction of the interplanetary field from the MAG experiment, projected upon the LECP scan plane (which is tilted at this time about 10° from the ecliptic). The fluxes for each sector (and therefore the anisotropies) have been transformed into the local $\underline{E} \times \underline{B}$ frame for each hour.

The strong initial field-aligned anisotropy is evident during the rise to maximum on day 326, and decreases thereafter to a maximum ratio $\lesssim 1.1$, implying an anisotropy $\simeq 0.5\%$. Note how even the very weak anisotropies during the decay phase tend to follow the outward field direction, so that $\xi_{\parallel r} > 0$. Thus, to the accuracy of this preliminary analysis, our use of (7), with its attendant assumptions, appears to be valid for this event. Assuming we could obtain a reasonable estimate of $\partial \ell n\, U/\partial\phi$ from a single spacecraft, we therefore could have used our measurement of the parallel anisotropy (in the $\underline{E} \times \underline{B}$ frame) to conclude that the decay was primarily due to the temporal term $\partial \ell n\, U/\partial t$ (the other two being positive). Thus we would predict that the decay would proceed smoothly, until interrupted either by a change in interplanetary conditions, or by a fresh injection of new protons.

Conclusions and Recommendations

The example given above shows the conditions under which we can make a straightforward prediction for the decay phase of an event. The interplanetary medium is seldom in such a simple state. For example, the period one month earlier of September 1977 was strongly disturbed by a succession of flares from the transit of a major center of activity.

We obviously need further diagnostics of the interplanetary medium when its configuration is more complex. We have not yet analyzed the potential of relativistic electrons and lower energy ($T < 1$ MeV) ions in deducing such configurations, and their effect on $\gtrsim 1$ MeV proton fluxes at 1 AU. The fast electrons probe the outer heliosphere, while the slower < 1 MeV protons, with their stronger anisotropies, are sensitive indicators of the more immediate vicinity (within ~ 0.5 AU) of the spacecraft. We believe the IMP 7/8 and VGR 1/2 data sets are now ready for such an investigation, and that results to date would justify a further effort in this direction.

Personnel

In addition to persons supported directly by this contract (indicated by asterisks below), we also list the scientific collaborators who contributed to the published work under this contract. Professor Prince and Miss Hedeman were consultants to APL/JHU under this contract.

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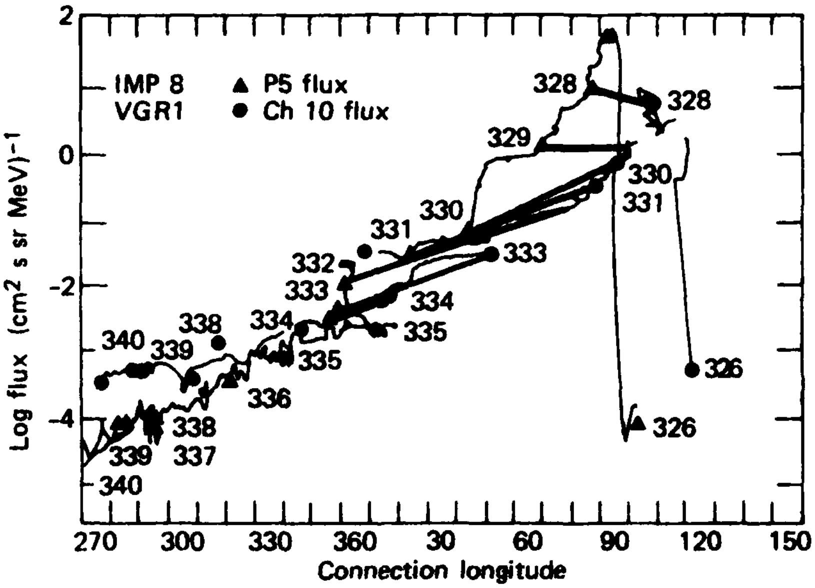
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Log flux (cm^2 s sr MeV)$^{-1}$
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Fig. 1

LECP experiment/Voyager 1
5 MeV protons

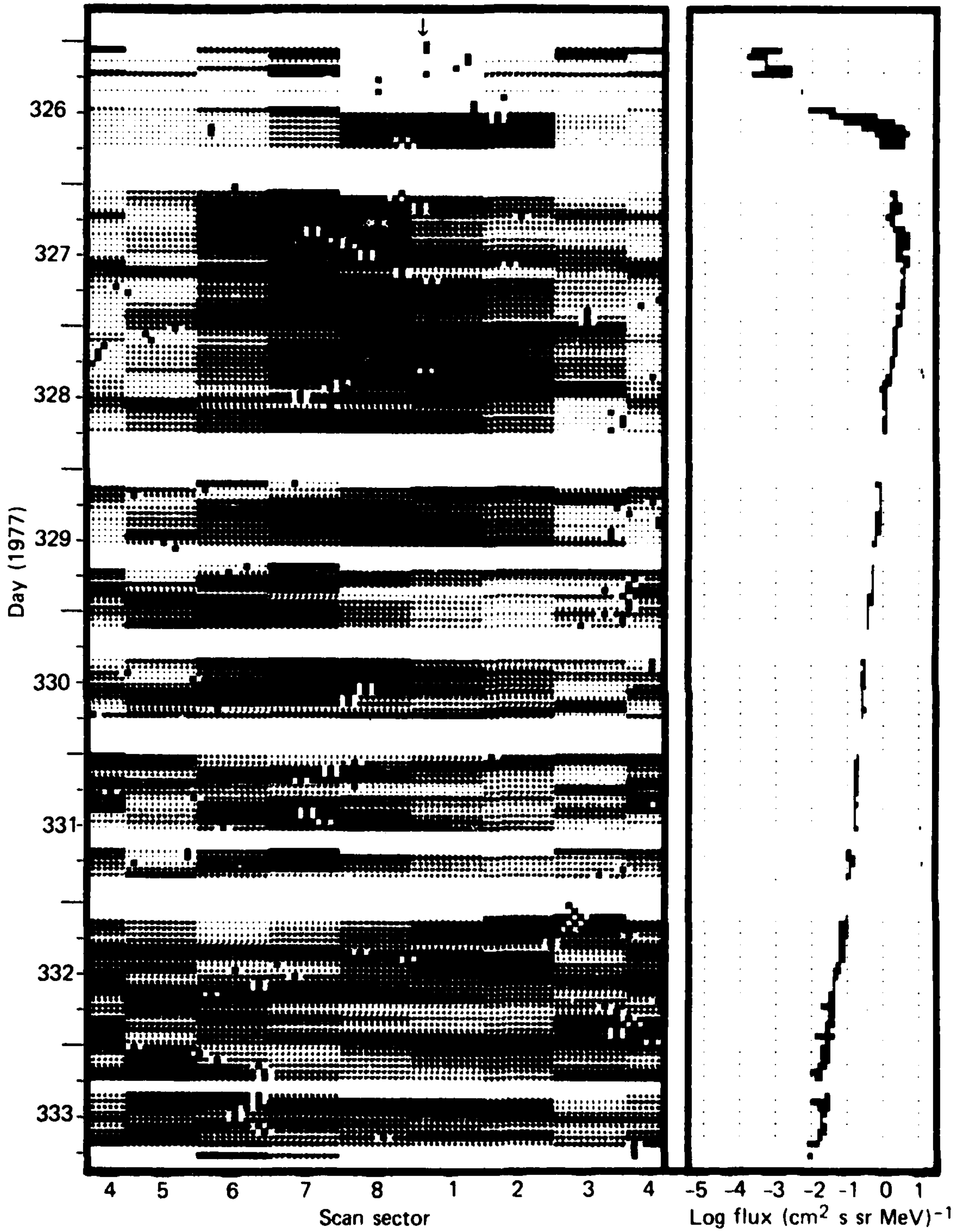

Fig. 2

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Sixteenth International Cosmic Ray Conference, (Kyoto, Japan. 6-18 August 1979)

R. E. Gold E. C. Roelof	Energetic particle recurrence and escape during solar cycle 20
R. D. Zwickl E. C. Roelof R. E. Gold	Cross-field transport of < 1 MeV protons in energetic particle events

1979 Fall AGU Meeting, San Francisco, December 3-7, 1979

D. G. Mitchell E. C. Roelof	> 50 keV ion events upstream of the Earth's bow shock 1. Dependence on shock parameters
E. C. Roelof D. G. Mitchell R. P. Lepping	> 50 keV ion events upstream of the Earth's bow shock 2. Association with IMF fluctuations

1980 Spring AGU Meeting, Toronto, Ontario, Canada, May 22-27, 1980

D. G. Mitchell E. C. Roelof	Heavy solar wind ions in high speed streams measured by IMP 7/8 EPE solid state detectors
R. E. Gold E. C. Roelof	Solar wind velocity histories at fixed longitudes
E. C. Roelof	A new theoretical approach to propagation of upstream energetic particles

1980 Fall AGU Meeting, San Francisco, California, December 8-12, 1980

D. G. Mitchell E. C. Roelof	Composition, temperature and velocity of iron ions in the peaks of high speed solar wind streams
H. W. Dodson-Prince E. R. Hedeman R. E. Gold E. C. Roelof	Co-evolution of solar wind streams and equatorial active regions at solar minimum (1975-77)
E. C. Roelof R. B. Decker D. L. Newman S. M. Krimigis D. Venkatesan A. J. Lazarus	Field-aligned gradients of galactic cosmic rays 1-5 AU between Voyager 1/2 and IMP 7/8

Seventeenth International Cosmic Ray Conference (Paris, France, 13-25 July 1981)

R. E. Gold H. W. Dodson-Prince E. R. Hedeman E. C. Roelof	The influence of solar active region evolution on solar wind streams, coronal hole boundaries and geomagnetic storms
E. C. Roelof R. B. Decker S. M. Krimigis D. Venkatesan A. J. Lazarus	Galactic cosmic-ray gradients, field-aligned and latitudinal, among Voyagers 1/2 and IMP 8
T. R. Sanderson R. Reinhard K.-P. Wenzel D. G. Mitchell E. C. Roelof	ISEE-3/IMP-8 observations of simultaneous upstream proton events

1981 Fall AGU Meeting, San Francisco, California, December 7-11, 1981

D. G. Mitchell E. C. Roelof	Local bow shock control over ~ 50 keV ion events in the Earth's foreshock
R. Reinhard T. R. Sanderson K.-P. Wenzel D. G. Mitchell E. C. Roelof	ISEE-3/IMP-8 observations of simultaneous upstream proton events
E. C. Roelof R. B. Decker S. M. Krimigis	Latitudinal and field-aligned cosmic ray gradients 2-5 AU: Voyagers 1 and 2 and IMP-8
H. W. Dodson E. R. Hedeman E. C. Roelof	Large-scale solar magnetic fields at the site of flares, the greatness of flares, and solar-terrestrial disturbances (late abstract)

COSPAR XXIV, (Ottawa, Canada, 16 May - 2 June 1982)

H. W. Dodson E. R. Hedeman E. C. Roelof	Large-scale solar magnetic fields at the site of flares, the greatness of flares, and solar-terrestrial disturbances
K.-P. Wenzel T. R. Sanderson R. Reinhard E. C. Roelof E. J. Smith	Simultaneous observations of upstream protons and low frequency waves on ISEE-3

1982 Spring AGU Meeting, Philadelphia, Pennsylvania, May 31-June 4, 1982

Helen W. Dodson E. Ruth Hedeman Edmond C. Roelof	Difference in electromagnetic spectra of large Hα flares in solar magnetic fields of different orientations
R. E. Gold E. C. Roelof	The evolution of solar wind velocity at fixed heliographic longitude
E. C. Roelof D. G. Mitchell	Detection at ~ 35 R_e of neutral atoms (E > 50 keV): Charge exchange of ring current ions?
T. R. Sanderson E. C. Roelof	Wave-particle interactions at ISEE-3: 32-62 keV upstream ions and 0.03 Hz waves

Informal Presentations

ISEE Workshops:

UCB, Berkeley, California, August 1979
JPL, Pasadena, California, April 1980
GSFC, Greenbelt, Maryland, February 1982

Gordon Research Conference on Space Plasma Physics, Wolfeboro, New Hampshire, June 1981

Chapman Conference on Origin of Plasmas and Electric Fields, Yosemite, California, January 1982

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