Co-Rotating Cosmic-Ray Electron and Positron Variations

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Abstract

Because of the importance of drifts in the transport of cosmic rays in the heliosphere, we expect that co-rotating structures in the solar wind will affect cosmic-ray electrons and positrons differently. This will produce co-rotating variations in the relative amounts of electrons and positrons. The magnitude of these effects have been estimated using reasonable parameters in fully three-dimensional global model simulations of cosmic-ray transport in the heliosphere. It is demonstrated that the expected variations in the positron to electron ratio, over the 27-day corotation period, may well be of the order of 10-20%, a magnitude which should be readily observable by spacecraft. Observations of these corotating variations of electrons and positrons should provide a new and very useful diagnostic of the modes of cosmic-ray transport in the heliosphere. It is also pointed out that observations of the relative amounts of ions and electrons may also vary in a similar manner, because of their opposite charge.

1 Introduction:

It is now well-established that for a given overall sign of the interplanetery magnetic field, the modulation of galactic cosmic rays depends significantly on the sign of the charge of the particles. This was expected theoretically, since drift motions were shown to be important in cosmic-ray transport in the heliosphere, more than 20 years ago (e.g., Jokipii, et al 1976). A significant body of literature exists in which the basic picture involving drifts is shown to account well for observations of cosmic-ray ions and nuclei, for the different signs of the interplanetary magnetic field at successive solar sunspot minima. For a number of discussions of the current status of modulation observations and theory, see the book by Fisk, et al (1998). It is also possible that a net helicity of interplanetary turbulence (Bieber, Evenson, and Matthaeus 1987) could produce an additional charge dependence. Here we concentrate on the effects of drifts.

The cosmic-ray particle trajectories are a combination of the diffusive random walk and convection with the flow of the solar wind, which are both charge sign independent, and the causal drift motions caused by the large-scale variation of the interplanetary magnetic field. Since the drift trajectories reverse upon change in sign of either the magnetic field $\mathbf{B}$ or the particle charge q, two distinct kinds of physical effects are expected. First, since the magnetic field sign reverses and at each sunspot maximum and the other succeeding cosmic-ray maxima should differ to the extent that drift motions play a significant role in transport. Second, one would also expect that *simultaneous* observations of particles differing in the sign of their charge should differ in that positively – charged particles should behave similarly to negatively – charged particles in the previous cosmic-ray maximum, and vice versa. Changes in the ratio of particles of differing charge would occur as the modulation changes at any given time because of their differentially-varying drift motions.

Electrons and positrons are unique in that they are identical in every respect except their charge. Observations of electrons and positrons, therefore, would permit the precise analysis of the charge-sign dependent effects in modulation. In particular, co-rotating interaction regions (hereinafter called CIRs), a prominent feature of the quiet heliosphere, would expect to show co-rotating variations in the ratio of electrons to positrons. Hence, observations of electrons and positrons would provide a stringent further test of the physics involved in the modulation process. For a review of the current status of electron modulation, see the article by Evenson (1998). We find that the magnitude of the co-rotating variation in the relative intensity of electrons and positrons is such that it should be readily observable.

2 General Theoretical Considerations

The transport equation for the pitch-angle-averaged distribution function $f(\mathbf{r}, p, t)$ as a function of position $\mathbf{r}$, particle momentum p, and time t, may be written as (e.g., Parker, 1965)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)} \frac{\partial f}{\partial x_j}\right] - \mathbf{U} \cdot \nabla f - \mathbf{V_d} \cdot \nabla f + \frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ell n p}\right] + Q \tag{1}$$

where the successive terms on the right-hand side correspond to diffusion, convection, particle drift, adiabatic cooling or heating and any local source Q. Here, for particles of speed w, momentum p and charge q, the drift velocity is

$$\mathbf{V_d} = \frac{pcw}{3q}\,\nabla \times \left[\frac{\mathbf{B}}{B^2}\right] \tag{2}$$

where c is the speed of light and $\kappa_{ij}^{(S)}$ is the symmetric part of the diffusion tensor. In general, we may write $\kappa_{ij}^{(S)}$ in terms of the magnetic field components B_i and $\kappa_{||}$ and $\kappa_{\perp}$, the diffusion coefficients parallel and perpendicular to it as

$$\kappa_{ij}^{(S)} = \kappa_{\perp}\delta_{ij} - \left(\kappa_{\perp} - \kappa_{||}\right)\frac{B_i B_j}{B^2}. \tag{3}$$

The perpendicular and parallel diffusion coefficients are not well determined. In what follows, we will take them to be $\kappa_{||} = 1.5 \times 10^{22} P^{.5}\beta$, where P is the rigidity in GV, and the ratio $\kappa_{\perp}/\kappa_{||} = 0.02$.

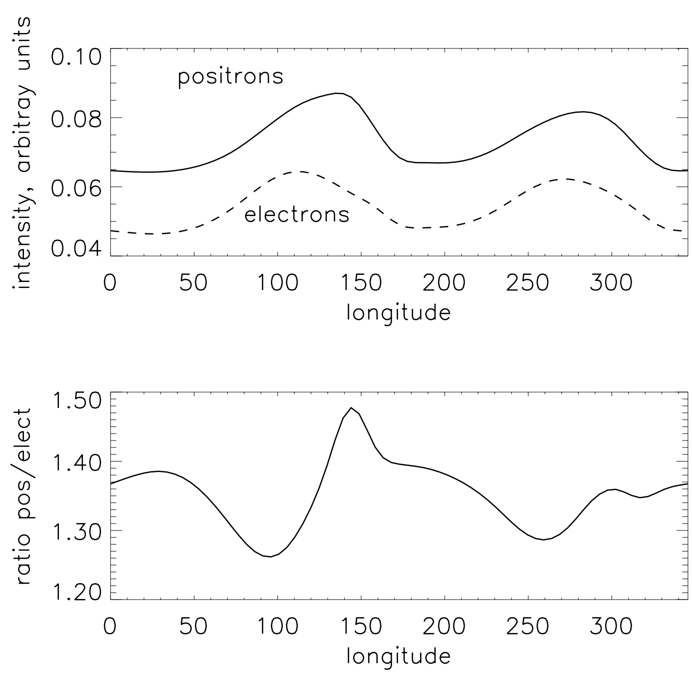

Figure 1. Computed variation of electrons and electrons, and their ratio with heliographic longitude. The plots are shown for points at a latitude of about 10°, at 1 AU, The diffusion coefficients are as defined in the text. and for electrons and postrons having energies of 1 GeV.

We solve the transport equation in a 3-dimensional model heliosphere which is close to that observed in the years around sunspot minimum, where the structure and dynamics is dominated by steady, high-speed solar wind at high latitudes and by the streamer belt and corotating interaction regions (herein CIRs). This heliosphere is steady in a coordinate system rotating with the sun. It is computed using the MHD equations and a boundary condition near the sun where there is a magnetic axis at an angle α relative to the rotation axis.

The wind at the inner boundary, near the sun, is taken to be slow (≈ 350 km/sec) at the magnetic equator, with a rather fast transition to a high-speed wind (≈ 750 km/sec) at high heliomagnetic latitudes. The transition latitude is taken to be 15^o heliomagnetic latitude for the simulations reported in this paper. The tilt of the heliospheric current sheet relative to the equator is 30^o. This boundary condition near the sun results in fast solar wind flowing behind slow wind, causing in the formation of CIRs, forward and reverse shocks, and a non-archimedean magnetic field at low heliographic latituds, throughout the heliosphere. All these effects are contained in our simulation. Once this model heliosphere is computed and steady in the co-rotating frame, it is used to determine the parameters for cosmic-ray transport, and equation (1) is solved for the distribution function f. Since we are considering galactic cosmic rays, the boundary condition on f is chosen to correspond to the expected galactic spectrum. This model has been shown to agree well with many features of observed cosmic-ray nuclei, ranging from ...

3 The Modulation of Galactic Electrons and Positrons.

In this paper we apply the above-described model to galactic electrons and positrons, in order to determine their different spatial variations. To illustrate the physics, we take the spectra at the modulation boundary to be the same for both positrons and electrons, and to be

$$\frac{\partial j}{\partial T} = p^2 f \propto p^{-1.5} \tag{4}$$

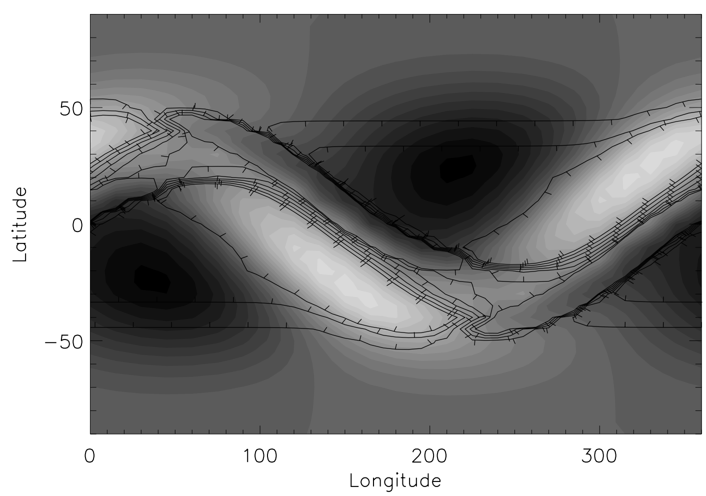

Figure 2. Computed greyscale contours of the deviation of the positron/electron ratio at 1 GeV, from its average, shown as a function of heliographic latitude and longitude at 1 AU. Light shading corresponds to a larger ratio than average and dark shading to lower values. The magnetic phase is $A > 0$ (northern magnetic field pointed outward from the Sun. Superimposed contour lines show the variation of the magnetic-field magnitude from its average. The ticks on the magnetic-field contours point toward lower values of the magnetic-field intensity.

Shown in Fig. 1 are typical results for the variation of electrons and positrons with heliographic longitude, at 1 AU. Clearly, the positrons and electrons have a significantly different variation with longitude, and the ratio of positrons to electrons varies by more than 10% over a solar rotation. The ratio oscillates around a value greater than unity because the of the assumption of equal spectra at the boundary, and the fact that for the $A > 0$ phase illustrated, positrons are less modulated. One may find the value for any prescribed ratio r at the shock by multiplying the values in the lower panel of figure 1 by r. Also, the precise values will change if the spectra at the boundary have different shapes (as they probably do). Nonetheless, it is likely that the general nature of the variations will be preserved. We conclude that observable variations in intensity of particles of opposite charge are produced in association with co-rotating interaction regions. In figure 2 are shown contour plots of the ratio of positrons to electrons as a function of heliographic longitude and latitude, for particles of energy 1 GeV. Superposed are contours of magnetic field magnitude. It is apparent that the co-rotating enhancements in the positron-electron ratio occur at the magnetic-field minima. The cause of this is not immediately apparent. It is possible that the large values of the magnitude of magnetic field shield the low values from the drift motions of the positively charged particles. We note that although the plot in figure 2 is for the $A > 0$ magnetic phase (the current sunspot minimum), the same plot would apply for $A < 0$, except that the plot would be for the ratio of electrons to positrons.

4 Summary and Conclusions

Full three-dimensional simulations of the transport of cosmic-ray electrons and positrons in the heliosphere demonstrate that CIR's cause significant ($O10\%$) deviations in the relative intensity of electrons and positrons in the heliosphere. The co-rotating variations should be observable over a wide range of energies, as the predicted effect is remarkably insensitive to the electron/positron energy. Observations of co-rotating variations in the electron/positron ratio should provide further valuable constraints on our understanding of cosmic-ray transport in the heliosphere. Observations carried out in the ascending or descending phase of the sunspot cycle, when CIR's are well-developed and persistent, would be most likely to reveal the expected effects. The co-rotating nature of the effect could make it easier to pick out the effect from noise and other extraneous effects. Unfortunately, adequate electron/positron observations may not be available, as we have been up to now limited to observations from sporadic balloon flights. It is possible that comparison of ions and electrons of similar rigidities might be useful in establishing the effects, but the differences in mass would make any definitive determination difficult.

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References

Bieber, J.W., Evenson, P., & Matthaeus, W.H., 1987, GRL, 14, 864

Evenson, Paul, 1998, in Cosmic Rays in the Heliosphere, pp 63-83, ed by Fisk, et al.

Fisk, L. A., Jokipii, J.R., Simnett, G.M., von Steiger, R., & Wentzel, K.-P., 1998, Cosmic Rays in the Heliosphere

Jokipii, J.R. , 1990, in Physics of the Outer Heliosphere, Cospar Colloquia Volume 1, p 169

Jokipii, J.R., Levy, E.H & Hubbard, W.B.,1976, ApJ, 180, 486.

Parker, E.N., 1965, Planetary & Sp. Sci., 13,9