Proceedings of ICRC 2001: 3581 © Copernicus Gesellschaft 2001

ICRC 2001

Compressive-diffusive acceleration of energetic charged particles

J. R. Jokipii

Abstract. We discuss the phenomenon of the acceleration of charged particles in a compressing diffusive medium and apply it to recent ACE observations in the interplanetary medium. It has been recognized that the phenomenon of diffusive shock acceleration can readily be generalized to the case where the the shock is replaced by a gradual change in the velocity of the flow over a length scale L. Let U be the flow speed and κ the energetic particle diffusion coefficient normal to the plane of the compression. Then, if the dimensionless parameter $\kappa/(UL)$ is large compared with unity, the energetic particles are accelerated much as in diffusive shock acceleration. We have applied this to the case of a co-rotating interaction region near the Sun, where it has not yet developed into a shock. We find significant acceleration of charged particles. Our results are compared with recent observations carried out on the ACE spacecraft.

1 Introduction

Energetic charged particles, observed by Earth-orbiting spacecraft which corotate with the Sun, have previously been explained in terms of particle acceleration at the forward and reverse shocks bounding a corotating interaction region (CIR) at distances > 2 AU (Barnes and Simpson ,1976 and McDonald, et al, 1975). The shock-accelerated particles must then propagate back to the observer at 1 AU (Fisk and Lee, 1980). Recent observations by ACE do not seem to fit this picture (Mason, 2000). Instead, we suggest here that energetic particles are accelerated within the transition region from slow to fast solar wind, which is a more gradual change than the near instantaneous jump across a shock. Other work has suggested wave-particle interactions as an acceleration mechanism (Schwadron, et al, 1996).

We investigate the acceleration of charged particles in compressing diffusive medium, where the particle mean-free path, $\lambda_{||}$, is large compared to the width of the compression, Δ_c. This may be the case for energetic particles encountering a CIR near 1 AU where the forward and reverse shocks have not yet formed. If particles diffuse through the velocity gradient associated with the CIR formation, they will be efficiently accelerated due to the fact that this gradient is very large. Consequently, considerable acceleration can occur before the shocks form (< 2 AU) and this can lead to a peak in the intensity within the CIR. This might explain recent observations by Mason (2000).

Correspondence to: jokipii@lpl.arizona.edu (Email)

2 Analytical Background

The general transport equation for fast charged particles in an irregular magnetic field was first written down by Parker (1965) and may be written for the particle distribution function f as a function of momentum p, position $x_i$and time t, and in terms of the diffusion tensor κ_{if}, flow speed **U**, and any local source Q as.

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial \ell n(p)} + Q. \quad (1)$$

Here the drift velocities, if important, are contained in the diffusion tensor.

In order for acceleration to occur at a compression region, we require that the diffusive length scale Δ_d be larger than the compression region width Δ_c. This gives,

$$\Delta_c < \Delta_d = \kappa_{rr}/w \quad (2)$$

where κ_{rr} is the diffusion coefficient along the propagation direction of the compression region (assumed to be radial) and w is the particle speed. It is readily demonstrated that in the limit $\Delta_c \ll \Delta_d$ all of the results of diffusive shock acceleration are recovered (Drury, 1983).

We consider the acceleration of interstellar pickup ions by a solar wind compression region which corotates with the Sun. It is known that there will be a forward and reverse shock at distances beyond $\sim$ 2 AU. Near 1 AU, however, there is a smooth transition from the fast to slow solar wind which occurs over a scale which is much larger than the gyroradius of the pickup ions. We further assume that the gradient associated with the plasma compression is aligned with the radial direction. Using these considerations, it is straightforward to show that Eq. (1) leads to $\Delta_c < \lambda_{||}$. If, however, $\lambda_{||}$ is too large, the particles will not scatter downstream (the same side as the Sun) of the compression region and will instead be mirrored in the strong magnetic field near the Sun. This will not lead to any significant acceleration. Consequently, we require both that the mean-free path is larger than the width of the compression, but smaller than about 1 AU. Pickup ions probably satisfy these criteria and, therefore, we expect them to be efficiently accelerated at solar wind compression regions. The mechanism is similar to diffusive shock acceleration in that the particles are accelerated as they scatter off of converging scattering centers.

The acceleration can occur for any particles, provided that their mean-free path is large enough to sample the velocity gradient and small enough to be scattered downstream of the compression region. The highest energy attainable, therefore, can be estimated by setting the mean-free path to the heliocentric distance of the compression region. A compilation of observations of particle mean-free paths by Palmer (1982) has shown that even 1-10 MeV particles can have mean-free paths which are smaller than, or are comparable to 1 AU. Consequently, we conclude that pickup ions can be accelerated by corotating compression regions (at distances smaller than where the forward and reverse shocks form) up to energies of about 1-10 MeV.

It is important to realize that, for the case of particle acceleration in the inner heliosphere where the particle mean-free paths may be comparable to the size of the system (~ AU), significant anisotropies are expected and we cannot use the diffusive approximation. Hence we will use a full test-particle simulation and trace actual particle trajectories. Our results turn out to be similar to those expected for diffusive acceleration, but we are not subject to the limitations of the diffusion approximation.

3 The Numerical Approach

We apply the ideas discussed above to acceleration of charged particles at a CIR at radii small enough that it has not yet formed the associated shocks. We construct a simple model of the flow speed and density associated with the CIR and, from this, we determine the electromagnetic fields using magnetohydrodynamics. We then integrate the trajectories of an ensemble of test particles in the model fields to obtain the distribution function.

First, consider a steady, radial solar-wind in the frame which corotates with the Sun. The continuity equation for the plasma in this frame is given by

$$-\Omega_\odot \frac{\partial}{\partial \phi}(r^2 \rho) + \frac{\partial}{\partial r}(r^2 \rho U) = 0 \quad (3)$$

We next determine the density, ρ, for a given functional form of the flow speed U. We do this by solving Eq. (2). We assume the following form for the flow speed:

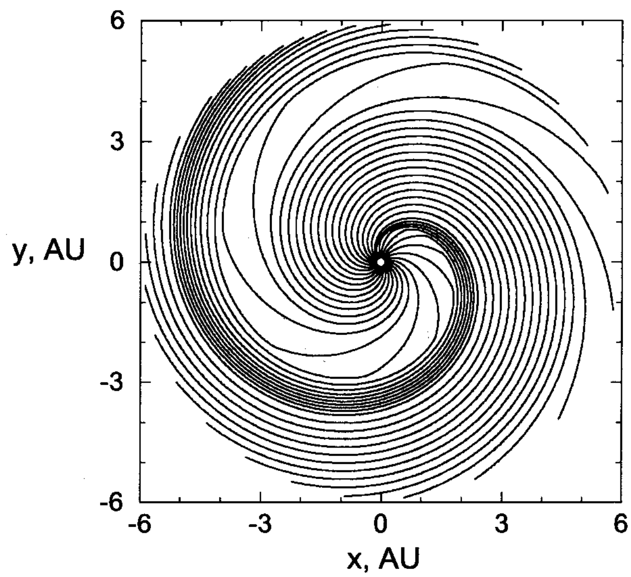

Fig. 1. Magnetic field lines projected onto the solar equatorial plane for $\theta = 80°$. The parameters are: W=300 km/s, $\Delta\phi_c = 1°$ (Δ_c = 0.012 AU), $\Delta\phi_{rf} = 25°$, U_f=800 km/s, U_s=400 km/s, $\phi_c = 90°$, and $\phi_{rf} = 20°$

$$U(r,\phi) = U_s + \frac{1}{2}(U_f + U_s)\tanh\left(\frac{\phi_c - \phi - r\Omega_\odot/W}{\Delta\phi_c}\right)$$
$$-\frac{1}{2}(U_f - U_s)\tanh\left(\frac{\phi_{rf} - \phi - r\Omega_\odot/W}{\Delta\phi_{rf}}\right) \quad (4)$$

where W is a constant speed and $\Omega_\odot$ is the solar rotation frequency. U_s and U_f are the slow and fast solar-wind speeds, respectively.

This form for U contains both a compression region, with a azimuthal width $\Delta\phi_c$, and a rarefaction region with an azimuthal width $\Delta\phi_{rf}$. The constants ϕ_c and ϕ_{rf} specify the location the compression and rarefaction regions. It is readily shown that the thickness of the compression region along a given radius vector is given by $\Delta_c = W\Delta\phi_c/\Omega_\odot$. The speed W can be thought of as the speed at which these disturbances move radially outward in the inertial (not rotating) frame of reference. If W is slower than the slow solar-wind speed, then the disturbance will be a "reverse" compression (similar to a reverse shock); whereas for W faster than the fast solar-wind speed, the disturbance will be a "forward" compression.

A solution of Eq. (2) using Eq. (3) is given by

$$\rho(r,\phi) = \rho_s \frac{U_s - W}{U(r,\phi) - W}\left(\frac{r_\odot}{r}\right)^2 \quad (5)$$

where $r_\odot$ is the solar radius and ρ_s is the density in the slow solar wind at $r = r_\odot$. To avoid the singularity in Eq. (4), we consider cases where W is everywhere smaller, or larger, than U.

We next specify a divergence-free magnetic field for the above fluid flow pattern as

$$\mathbf{B}(r,\theta,\phi) = B_r\hat{e}_r + B_\phi\hat{e}_\phi \quad (6)$$

where

$$B_r(r,\theta,\phi) \propto B_r(r_\odot,\theta)\rho(r,\phi)U(r,\phi)$$

$$B_\phi(r,\theta,\phi) \propto r\rho(r,\phi)\Omega_\odot \sin\theta \quad (7)$$

In Figure 1 are shown magnetic field lines for the magnetic field given by Eqs. (5) and (6). The parameters are shown in the caption. The compression region is evident. Note that because we have chosen W to be slower than the slow solar-wind speed, there are no magnetic field lines originating in the slow wind which intersect the compression region. Hence, this is a reverse compression region.

Test particles (helium ions) are followed numerically in the magnetic field given by Eq. (5). The orbits are integrated by solving the Lorentz force acting on each particle. The particle orbits are computed in the corotating frame of reference. Each particle is followed until it crosses an outer boundary which is placed at 3 AU. Particle distributions are computed by binning along the trajectory at a constant time interval. This method gives the steady-state distribution as a function of r, ϕ, and momentum $\mathbf{p}$.

Scattering is introduced in a phenomenological manner. A scattering time is chosen from an exponential distribution with a given mean. The mean scattering time is related to the parallel mean-free path, $\lambda_{\|}$. We use two forms for $\lambda_{\|}$: $\lambda_{\|} \propto w^{2/3}$ (quasi-linear theory), and $\lambda_{\|}$=constant.

We consider two type of sources in this study. The first are ionized interstellar neutrals, or pickup ions. These are singly-ionized particles which we release from rest in the inertial frame of reference (the non rotating frame in which the solar wind flows radially outward). The spatial distribution is determined from the analytic model of Vasyliunas and Siscoe (1976), using a characteristic ionization distance of 0.7 AU and an interstellar density of 0.01cm^{-3} which are representative of interstellar helium. For simplicity, we assume that the interstellar flow speed and temperature are both zero. The second type of source that we consider is solar-wind alpha particles. These particles are doubly ionized. A kappa distribution is assumed to determine their initial speed ($\kappa = 3$). Their density at 1 AU is assumed to be 0.5cm^{-3} and falls off as r^{-2}. Their temperature is determined from the adiabatic law (at 1 AU it is $2\text{x}10^5$K).

4 Model Results and Interpretation

Shown in Figure 2 are particle fluxes (lower frame) and plasma flow speed (top frame) as a function of the variable $\phi/\Omega_\odot$, which has units of time. The results shown are for the case of an interstellar pickup-ion source. An observer at rest with respect to the rotating Sun would see this structure every solar rotation period. The energies for each of the curves shown are in the caption. The simulation parameters are the same as that shown in Figure 1 except that here we used $\Delta\phi_c = 2°$ which gives $\Delta_c = 0.025$ AU. Also for this case we used $\lambda_{\|} = 0.056(w/U_s)^{2/3}$ AU. Note that at all energies the particles have a mean-free path which is larger than the compression width.

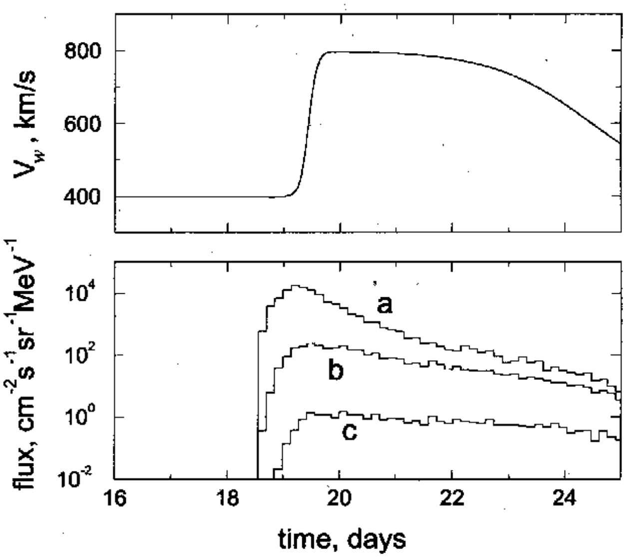

Fig. 2. (top frame) flow speed as a function of time ($\phi/\Omega_\odot$. (bottom frame) energetic particle fluxes as a function of time for the case of a interstellar pickup-ion source. The energies are: (a) 50-250 keV (b) 250-500 keV and (c) 0.5-5 MeV.

Figure 2 shows that the particle fluxes rise with the passage of the compression region and that the fluxes drop off at different rates depending on their energy. These are both consistent with the observations described by Mason (2000). Shown in Figure 3 is the energy spectrum at 1 AU integrated over all ϕ for the case of an interstellar pickup-ion source. The turnover at high energies is due to the fact that those particles have mean-free paths which are comparable to the distance from the Earth to the Sun. For this case, particles with a speed $75U_s$ (an energy of $\sim$ 5 MeV) have a mean-free path of 1 AU. This is somewhat higher than where the turnover in energy occurs. The discrepancy is due to the fact the inside 1 AU the mean-free path is significantly reduced by the stronger magnetic field near the Sun.

Shown in Figure 4 are the energy spectrum observed at 1 AU for the case of a constant mean-free path for two input source distributions: a solar-wind source which has a high-energy tail (kappa distribution), and a pickup-ion source. Note that the abundance of solar-wind He^{++} and interstellar He^{+} are about equal at high energies. At larger heliocentric distances the pickup ions will dominate since their density falls off less rapidly than the solar wind density.

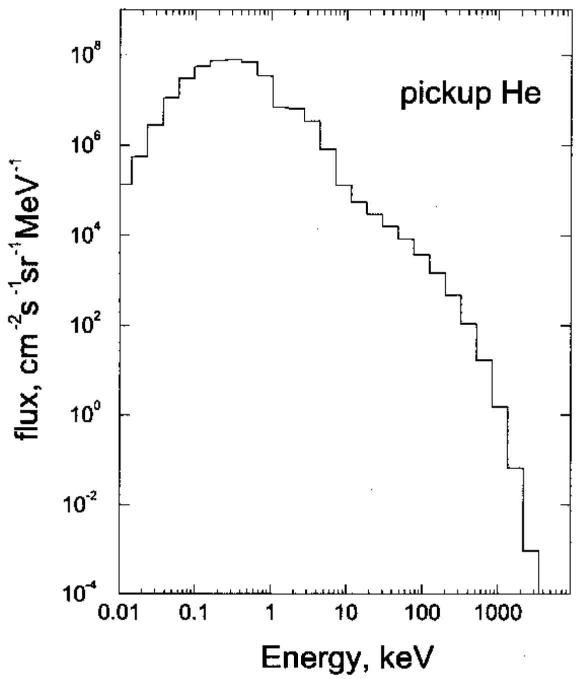

Fig. 3. Energy spectrum of accelerated interstellar pickup helium at 1 AU.

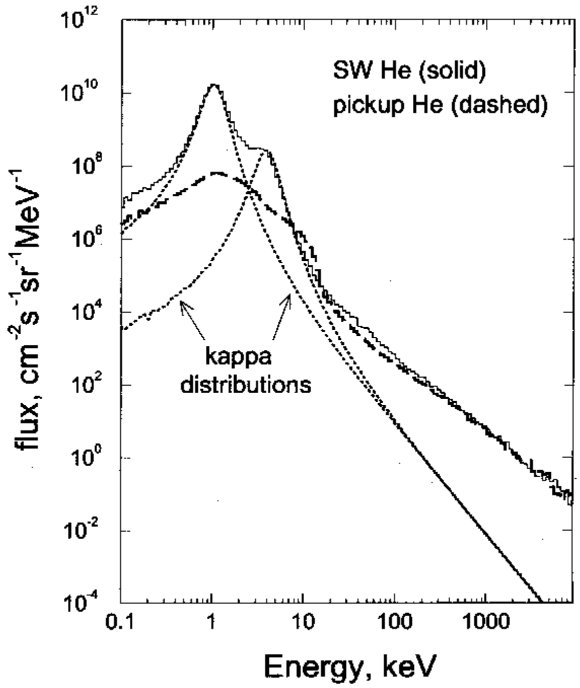

Fig. 4. Energy spectra for solar-wind alpha particles (solid line) and interstellar pickup helium (dashed line) at 1 AU. The dotted curves shown are κ-distributions for the fast and slow winds which were used as the source for the solar-wind alpha particles. A constant mean-free path (0.056 AU) was considered for both species.

5 Summary and Conclusions

We have presented a new view of particle acceleration at co-rotating interaction regions. Instead of wavy-particle or shock acceleration, we suggest that acceleration at compression regions, rather than shocks may play a significant role. This process is very much like diffusive shock acceleration in that the energy gain arises from the compression between converging scattering centers. In this situation, in order for low-energy particles to be accelerated, they must have a long enough mean-free path to sample the gradual velocity gradient associated with the compression, but short enough for acceleration to occur in the available time. Spacecraft observations indicate that pickup ions, and other low-energy particles, have long mean-free paths (of the order of an AU). Thus, compression regions in the inner heliosphere may accelerate pickup ions to high energies (1-10 MeV) in the absence of shock or wave-particle acceleration. Our model calculations suggest that this may be a viable explanation of the spacecraft observations..

Acknowledgements. This work has been supported by NASA under grants NAG5-2251, NAG5-662, and NAG5-10884 and by NSF under grant ATM-9616547.

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