The Production of Anomalous Cosmic Rays by the Solar Wind Termination Shock

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Abstract

We have modeled the injection and acceleration of pickup ions at the solar wind termination shock and investigated the parameters needed to produce the observed Anomalous Cosmic Ray (ACR) fluxes. A non-linear Monte Carlo technique was employed which in effect solves the Boltzmann equation and is not restricted to near isotropic particle distribution functions. This technique models the injection of thermal and pickup ions, the acceleration of these ions, and the determination of the shock structure under the influence of the accelerated ions. The essential effects of injection are treated in a mostly self-consistent manner, including effects from shock obliquity, cross-field diffusion, and pitch-angle scattering. Using recent determinations of pickup ion densities, we are able to match the absolute flux of hydrogen in the ACRs by assuming that pickup ion scattering mean free paths, at the termination shock, are much less than an AU and that moderately strong cross-field diffusion occurs. Simultaneously, we match the flux *ratios* He^+/H^+ or O^+/H^+ to within a factor ~ 3. If the conditions of strong scattering apply, *no pre-termination-shock injection phase is required* and the injection and acceleration of pickup ions at the termination shock is totally analogous to the injection and acceleration of ions at highly oblique interplanetary shocks recently observed by the Ulysses spacecraft.

1 Introduction

It is believed that Anomalous Cosmic Rays (ACRs) originate as interstellar pickup ions (Fisk, Kozlovsky, & Ramaty 1974) which are accelerated at the solar wind termination shock (Pesses, Jokipii, & Eichler 1981). Such ions originate as neutrals that are swept into the solar system from the external interstellar medium, and subsequently ionized by the solar UV flux or by charge exchange with solar wind ions. Recent observations of pickup ions by the Ulysses spacecraft (e.g. Gloeckler et al. 1993) adds to the indirect evidence for this scenario, which by now has become quite compelling. However, one essential element of the process, namely how pickup ions are first injected into the acceleration mechanism, has engendered controversy. We show here that standard and well-tested assumptions of diffusive shock acceleration allow the direct injection and acceleration of pickup ions without a pre-injection stage.

We have employed our Monte Carlo simulation code (e.g. Ellison, Baring, & Jones 1996) to study the physical parameters that the solar wind termination shock must have in order to produce the observed ACR fluxes. For input at the termination shock, we use a standard expression for the shape of the isotropic pickup ion phase-space distribution based on the derivation of Vasyliunas & Siscoe (1976) (e.g. Gloeckler et al. 1993, 1994; le Roux, Potgieter, & Ptuskin 1996), and normalize this to the values reported by Cummings & Stone (1996) for the interstellar ion flux in the heliosphere. For typical cases, we require that $\lambda_{\parallel} \sim$ 5-10 r_g, where $\lambda_{\parallel}$ is the ratio of the scattering mean free path parallel to the mean magnetic field and r_g is the ion gyroradius. This length scale of diffusion parallel to the field seems fairly typical of that inferred in the vicinity of planetary bow shocks (Ellison, Möbius, & Paschmann 1990), interplanetary shocks (Baring et al. 1997), supernova shocks (Achterberg, Blandford, & Reynolds 1994), and that found in hybrid simulations of quasi-parallel shocks (e.g. Giacalone, et al. 1993).

Our principal result is that we can model the *absolute* hydrogen flux with no pre-acceleration. This is in clear contradiction with the conclusions of most previous work (discussed in Ellison, Jones and Baring 1999) addressing pickup ion injection at the termination shock. We are somewhat less successful in matching the ACR flux *ratios*, He^+/H^+ and O^+/H^+, seeing less enhancement based on mass/charge than reported by Cummings & Stone (1996). We do, however, match the ratios to within a factor of ~ 5, a relatively small difference given the uncertainties of extrapolating flux densities to the termination shock and the possibility that species-dependent heating or pre-acceleration could occur in the solar wind before pickup ions reach the termination shock. Details of the results presented here can be found in Ellison, Jones and Baring (1999, hereafter EBJ99).

2   Results

The Monte Carlo technique we use here has been described in detail in Ellison, Baring, & Jones (1996). Briefly, we have developed a technique for calculating the structure of a plane, steady-state, collisionless shock of arbitrary obliquity and arbitrary sonic and Alfvén Mach numbers greater than one. We include the injection and acceleration of ions directly from the background plasma and assume that, with the exception of pickup ions, no *ad hoc* population of superthermal seed particles is present. The model assumes that the background plasma, including accelerated particles, and magnetic fields are dynamically important and their effects are included in determining the shock structure, i.e. shock-smoothing interior to the termination shock. The three most abundant ACR species, H^+, He^+, and O^+, are included self-consistently in the determination of the shock structure. Since our Monte Carlo technique has not yet been generalized to spherical geometry, we are forced to assume that the termination shock is plane. However, the most important process we investigate, the injection of pickup ions, occurs locally and will not be seriously affected by this approximation.

Details of the solar wind and pick-up ion distributions and parameters at the termination shock used in our model are presented in Ellison, Jones and Baring (1999), as are parameters for three models used to explore a variety of possible situations. An example of our results is depicted in Figure 1. In the left panel, we depict spectra resulting from a low Mach number (i.e. weak) shock of obliquity $\Theta_{Bn1} = 87°$ with compression ratio $r \simeq 2.8$, produced using a slow solar wind speed of 360 km/sec at the termination shock. Due to the intrinsically steep spectra produced, we require a moderately low value of the ratio $\eta = \lambda_{\parallel}/r_g$ of the ion mean free path to its gyroradius to approximately match the observed ACR data from the Voyager 1 spacecraft (Cummings & Stone 1996). This value is quite possible given the low η inferred from spectral data at nearby interplanetary shocks (Baring et al. 1997). Models with stronger shocks can achieve similar injection efficiencies with considerably higher η. Furthermore, since the flux of model-generated ACRs is strongly anti-correlated with the shock obliquity, we find that (EBJ99) a shock of obliquity $\Theta_{Bn1} = 80°$ can roughly replicate the observed flux levels in the limit of Bohm diffusion ($\eta = 1$), using injection in the absence of pick-up ions, by directly accelerating the solar wind population.

The spectra exhibited in the left panel of Figure 1 possess the so-called mass (Am_p) to charge (Qe) enhancement. This effect, namely that the acceleration efficiency of shocks that are smoothed by the pressure of accelerated particles is an increasing function of A/Q, has been known for some time (e.g. Eichler 1979; Ellison, Jones, & Eichler 1981) in quasi-parallel scenarios. It depends only on the conservation of momentum and a spatial diffusion coefficient which is an increasing function of energy, and occurs because non-relativistic ions with larger A/Q (i.e. larger rigidities) have longer upstream diffusion lengths, at a given energy per nucleon. The fact that the shock is smoothed means that the high A/Q particles 'feel' a larger effective compression ratio and are accelerated more efficiently and, the greater the smoothing, the greater the enhancement. Enhancements have been confirmed at the quasi-parallel Earth bow shock (i.e. Ellison, Möbius, & Paschmann 1990) and should occur regardless of the shock obliquity *as long as the shock is smoothed.* To demonstrate its
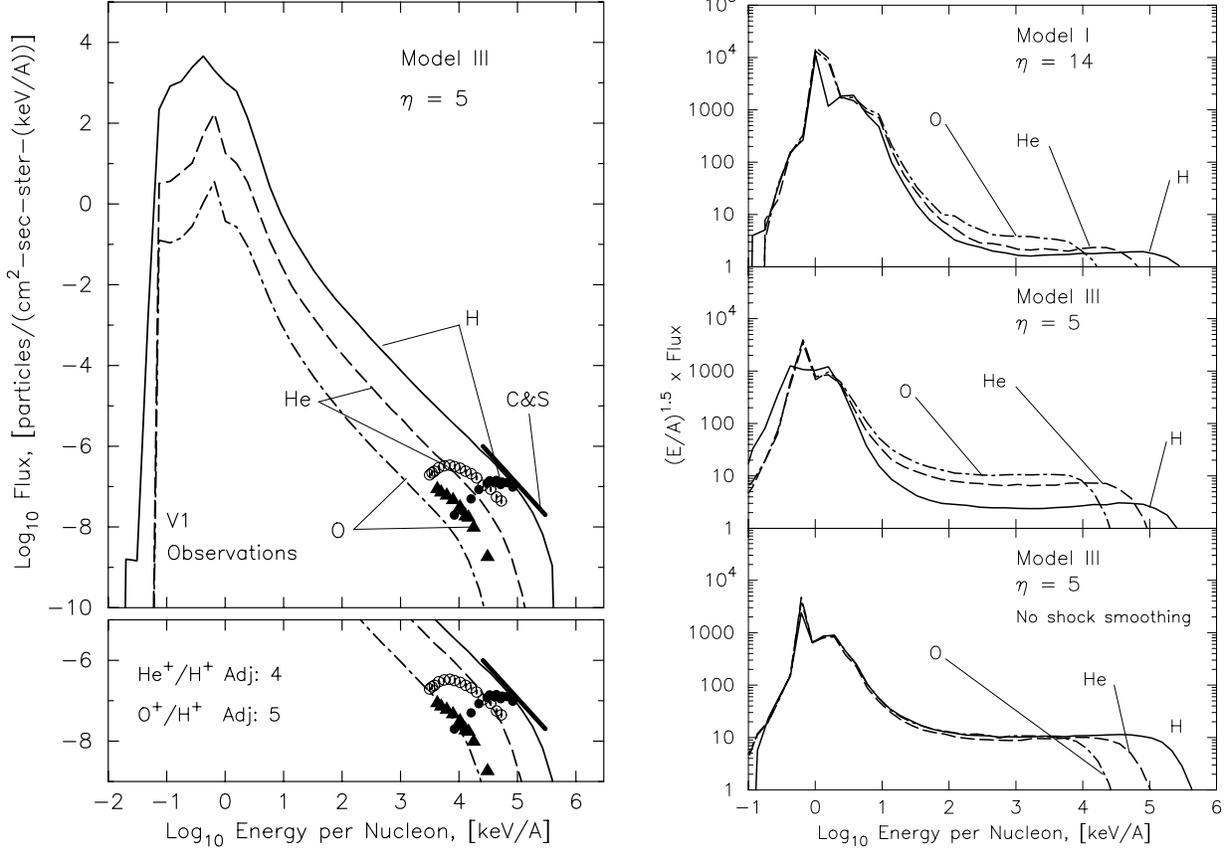
Figure 1: *(Left Panel)* Comparison of Voyager 1 observations of ACR H, He, and O (made during 1994/157-313 when V1 was at an average radial location of ~ 57 AU) to Model III spectra (see Ellison, Jones & Baring 1999 for a discussion of models) calculated *at the termination shock*. The model spectra have an absolute normalization determined by the injection parameters, i.e. $n_{\mathrm{p,TS}} V_{\mathrm{sw}} = 5.5 \times 10^4$ cm^{-2} s^{-1} for the protons and corresponding values for the He and O. The value of $\eta = \lambda/r_g$ has been chosen to give a general fit to the intensities of the observed ACR's. The sharp thermal peaks show the relatively cold solar wind ions that have not yet thermalized. As the observation position is moved downstream, these peaks broaden. Note that the H thermal peak intensity is ~ 11 orders of magnitude above the observed ACR intensity. The heavy solid line is the Cummings & Stone (1996) estimate for the ACR proton intensity at the termination shock. In the bottom left panel, we have individually adjusted the normalizations to match the ACR observations. The relative adjustments for He$^+$ and O$^+$ are labeled. *(Right Panel)* Spectra from Models I and III renormalized and multiplied by $(E/A)^{1.5}$. In each case, we have normalized all spectra to the same pickup ion density, i.e. for Model I we have multiplied the He spectrum by $n_{\mathrm{p}}^{\mathrm{pu}}/n_{\mathrm{He}}^{\mathrm{pu}} \simeq 43$ and the oxygen by $n_{\mathrm{p}}^{\mathrm{pu}}/n_{\mathrm{O}}^{\mathrm{pu}} \simeq 1800$, and for Model III, we have multiplied the He spectrum by $n_{\mathrm{p}}^{\mathrm{pu}}/n_{\mathrm{He}}^{\mathrm{pu}} \simeq 170$ and the oxygen by $n_{\mathrm{p}}^{\mathrm{pu}}/n_{\mathrm{O}}^{\mathrm{pu}} \simeq 7000$. In the top two panels, the self-consistent smooth shock is used to produce the spectra and a clear A/Q enhancement of He$^+$ or O$^+$ to H$^+$ is seen. In the bottom panel, we determined the spectra using the test-particle, discontinuous shock and essentially no enhancement (other than statistical variations) is present.

appearance in the simulation results here, we provide a "normalized" representation of spectra from two of our models in the right panel of Figure 1, together with a simulational example where shock smoothing has been artificially suppressed and a sharp discontinuity retained. While there is a clear A/Q enhancement, it is insufficient to explain the observed abundances in the Voyager 1 data of Cummings and Stone (1996).

One consistency check with our modeling is to verify that the time we compute for acceleration is consistent with experimental limits obtained from charge-stripping rates. Such ionization is relevant to species heavier than He (whose stripping timescales are long), in this case oxygen. Adams & Leising (1991) showed that 10 MeV/A singly charged oxygen ions will be further stripped, in conflict with observations, if they propagate more than $\sim$ 0.2 pc in the local interstellar medium. This corresponds to a stripping timescale of around 3–5 years at 10 MeV/A. BJE99 demonstrates that the acceleration timescales for shock obliquities exceeding around 70° fall short of this observational constraint, thereby validating our assumption that oxygen is singly-ionized at all (but perhaps the highest; see Mewaldt et al. 1996) energies.

In conclusion, using standard solar wind quantities and basic microphysical parameters, we have shown that diffusive shock acceleration operating at the termination shock can account for observed ACR proton fluxes by directly accelerating pickup ions from solar wind speeds to $\sim$ 150 MeV, without any imposition of a pre-injection phase. The only requirements for direct injection is that local magnetic turbulence exists (presumably self-generated) such that $\kappa_\perp/\kappa_\parallel \gg 10^{-3}$ and that $\lambda_\parallel$, for pickup ions injected at the shock, is a small fraction of an AU. These criteria are not difficult to satisfy in heliospheric environments. From our results, we conclude that the acceleration process at the termination shock is, as far as limited observations allow us to determine, identical in all important respects to diffusive particle acceleration observed at inner heliospheric systems such as the Earth bow shock and travelling interplanetary shocks.

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