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Anomalous oxygen acceleration and modulation in the heliosphere

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Abstract.

Measurements of the singly charges oxygen component of the heliospheric cosmic ray flux taken at quiet times of minimum modulation out to 69 AU are compared with a combined terminal shock and modulation model which seemed to explain anomalous He^+ fluxes. In particular, we use a radial diffusion coefficient given by $k = 3 \times 10^{22} v^{1.4} r^{0.6} cm^{-2} s^{-1}$ where v is particle velocity and r is solar radial distance. Although this spherically symmetric acceleration plus modulation model fits 0^+ data in the inner solar system above 10 MeV/nucl., it fails to explain data below 3 MeV/nucl. which exhibit an up-turn at low energies far out. However, the radial gradient, which is observed to be small, is reproduced in our model. We suggest that interplanetary acceleration following injection at low energy could be adding to the component most probably originating at the terminal shock. Alternatively, misidentification of the contribution of the anomalous component to the total oxygen spectrum may have occurred.

1 Introduction

We consider a recent compilation of singly charged, anomalous oxygen data, (Christian et al., 1999), together with previous data collected by Steenkamp and Moraal, (1993) taken between 1 AU and 69 AU in the energy range 1-50 MeV/n. in relation to predictions of the favoured acceleration model operating at the heliospheric termination shock. Recent papers call into question the single origin theory, involving ionisation of interstellar neutrals, solar wind transport to the termination shock followed by diffusive shock acceleration. Blake et al. (1995) find that although at quietest solar times, ACRs dominate the 0.5-7 MeV/n. O^+ flux, an apparent CIR component is noticable in this energy range. Mewaldt (1999) finds that the Mg, Si and S fluxes at 1AU, 8 MeV/n. are a factor 10-100 too large to be explained in terms of the interstellar neutrals abundances, suggesting an additional seed population. Hamilton et al. (1999) suggest interplanetary acceleration below the low energy upturn of the He and O spectra. Schwadron et al. (2000) discuss an inner source involving absorption and reemission by dust grains for O^+ and C^+. Reinecke et al. (1999a) cannot find a consistent, single diffusion coefficient to explain ACR He^+ within the heliosphere at two successive solar minima, unlike simple fitting of galactic H modulation data.

2 Shock And Modulation Model

We consider diffusive shock acceleration at the heliospheric termination shock, distance 120 AU, maintained by a 450km/s flow, with singly charged O^+ injection at 10 keV/n. A spherically symmetric heliosphere model is assumed when integrating the combined shock injection and modulation equations because of the well-known need to reduce the drift in latitude in a full 3-D modulation model and the work of Reinecke et al. (1999b). These last authors fitted galactic hydrogen data to 1, 2 and 3D models and found the no-drift 2D model showed the greatest sensitivity in chosing the diffusion coefficient but that there was little difference to the 1D model except within 15 AU and even here, intensity predictions were within 40%. Beyond 42 AU, all models failed to reproduce spectral shape, suggesting extra time variation or acceleration effects. The pole-equator ACR O^+ intensity difference is in any case only a factor 2 (Heber et al, 1999). We solve the steady state transport equation in distribution function, f, at radial distance, r, in the shock/heliospheric rest frame;

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 k \frac{\partial f}{\partial r}) - V\frac{\partial f}{\partial r} + \frac{2}{3}\frac{V}{r} v \frac{\partial f}{\partial v} = 0 \quad (1)$$

In this non-relativistic equation, v and V are respectively particle and wind speeds and k the radial diffusion coefficient. The shock boundary condition assuming only convective flow in the high turbulence downstream is

$$k(\frac{\partial f}{\partial r})_1 + \frac{v}{3}(\frac{\partial f}{\partial v})_1 V_1 = \frac{v}{3}(\frac{\partial f}{\partial v})_2 \beta V_1 \quad (2)$$

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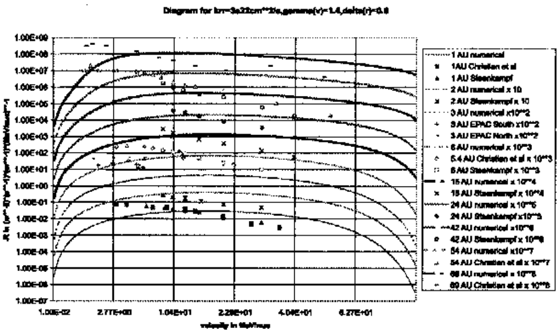

Fig. 1. Intensity versus Velocity in MeV/nuc

where 1 and 2 refer to upstream and downstream conditions and β is the inverse compression ratio. Although the compression may be 4 for a strong unmodified shock, 6 for a cosmic ray pressure modified shock or as low as 2 for a weak shock, the results are insensitive to the exact value and we take 4. The above equations are solved by combining them into a single finite difference equation and inversion of the resulting quindiagonal matrix, subject to the assumption $k = k_o v^\gamma r^\delta$ according to the method detailed by Savopulos, Quenby and Bell (1995). As discussed by Savopulos and Quenby (1997), realistic numerical computations of the radial diffusion coefficient suggest $k \sim 3 \times 10^{22} cm^2 s^{-1}$ at 20 AU, 100 MeV/n while observation of the wave power r dependence and quasi-linear theory suggest $\gamma = 1.0 \rightarrow 1.5$ and $\delta \sim 0$.

3 Data And Theoretical Fits

Figure 1 shows the ACR O^+ data at the 1977-78 and 1987 solar minima compiled by Steenkamp and Moraal (1993) and the 1997-1998 minimum compiled by Christian et al. (1999). We show intensity in $m^2 s^{-1} sr^{-1} (MeV/n)^{-1}$ versus energy in MeV/n., representing velocity. Intensities beyond 1AU are scaled as indicated. Theoretical fits generated according to the solution of the previous section were obtained with $k = 3 \times 10^{22} v^{1.4} r^{0.6} cm^2 s^{-1}$. It has been possible to generate the small radial gradient, 1-2 %/AU noted by Christian et al. (1999), but there is a significant upturn in the data at lower velocities which the model does not reproduce. In contrast, ACR He^+ data in 1977-78 and 1987 were well fitted over the complete spectral range by Savopulos and Quenby (1997) by a simlar model with $k = 2.5 \times 10^{22} v^{1.3} r^{0.5} cm^2 s^{-1}$. It is unlikely that the mismatch at the lowest O^+ energies are due to an increase in mean free path with energy decrease since we are effectively in the 100-1000MV rigidity range where no such behaviour has been expected. Moreover, use of a 1D model is unlikely to be the basic problem since a rather more limited approach by Steenberg, Cummings and Stone (1999) fitting H, He and O data at 55 AU and 70 AU but with a full drift 2D +neutral sheet model have rather similar problems with oxygen.

4 Discussion

While it is tempting to think that the figure 1 discrapancy between model and data is due to misidentification of the ACR contribution at the lower energies, the positive radial gradient down to 1 MeV/n. of Christian et al. (1999) argues against a solar particle origin, at least without additional acceleration. Instead, it is more likely that the extra acceleration suggested in the Introduction is important, especially coupled with the inner source origin postulated by Schwadron et al. (2000). These authors note the similarity of the C^+ and O^+ composition to that of the solar wind and also the inability of interstellar neutral O to penetrate close to the Sun. Hence they provide a model whereby solar wind ions are absorbed by heliospheric dust grains and are then re-emitted by outgassing. Dissociation and subsequent ionisation of the neutrals provides the solar wind-like composition of C^+ and O^+ but H^+ experimentally is very depleted and He^+ not easily detected in the Ulysses experiment employed. Transport involves long, > 2AU mean free paths and is accompanied by adiabatic cooling. If the mean free path significantly decreased with increased rigidity in this 'pick-up' range, subsequent acceleration could favour higher atomic numbers. This subsequent acceleration needs to take place in the extra turbulence in CIR's via transit time damping, since Schwadron et al. (1996) show that pick-up ion flux is correlated with $|\boldsymbol{B}|$ variability and these authors model a possible process. The observed average inner solar system O^+ pick-up distribution function is $0.1 km^{-6} s^3$ at 780 km/s while the ACR O^+ distribution function is $1.2 \times 10^{-11} km^{-6} s^3$ at 3.1×10^4 km/s. Joining these fluxes represents a v^{-6} power law for f, steeper than observed for H at the injection velocity and hence there seems to be an adequate supply from the inner source to contribute significantly to the ACR O^+ flux.

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