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3D simulations of heliospheric propagation of heavy-ion solar energetic particles

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In recent years, a wealth of spacecraft measurements of heavy ion solar energetic particles have become available, thanks to data from the ACE and STEREO spacecraft. Interesting features in heavy ion time intensity profiles, such as the decay of the Fe/O ratio over time in some events, have been observed. Heliospheric propagation effects have been invoked in the literature as a possible cause of Fe/O decays. Recent modelling work has shown that drifts due to the gradient and curvature of the large scale Parker spiral magnetic field, are a significant source of perpendicular transport for partially ionised heavy ions. Modelling these effects requires a fully 3D description. Here we present results of 3D test particle simulations of heavy ion SEP propagation in the heliosphere, for a Parker spiral magnetic field, in the presence of scattering. We simulate intensity profiles of heavy ions as would be observed at 1 AU and derive the time dependence of the Fe/O ratio.

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1. Introduction

Measurements of Solar Energetic Particles (SEPs) taken by spacecraft in the interplanetary medium can be used to infer properties of the acceleration phenomena and of the propagation of the particles through space. Heavy ion SEP data are particularly useful in this respect and a variety of measurements, including those of abundances and charge states, have been used to attempt to characterise whether the particles were accelerated in a flare or at a Coronal Mass Ejection (CME) driven shock. In particular the Fe/O ratio averaged over an SEP event (mean Fe/O ratio) has been used frequently as diagnostic of the particles' flare or shock origin [1].

The Fe/O ratio has been shown to decrease over time in a number of SEP events [2, 3, 4]. Scholer et al. ascribed this behaviour to the rigidity dependence of the scattering mean free path [2]. In this interpretation, as Fe has a larger m/q than O, it experiences less scattering and is able to reach a detecting spacecraft earlier than O, resulting in a large Fe/O ratio at the beginning of an event. Modelling of heavy ion transport including this effect was able to reproduce the data for several ionic ratios in 17 SEP events [3]. Other researchers have ascribed the observed temporal behaviour of Fe/O to acceleration and escape of SEPs at CME-driven shocks [5, 6] or to the presence of a flare component early in an event [7]. A study analysing multi-spacecraft data at Ulysses and Wind concluded that the likely cause of the temporal profiles of Fe/O is interplanetary transport [8].

In recent work, we carried out 3D full orbit test particle simulations of SEPs in a Parker spiral interplanetary magnetic field (IMF), in the presence of scattering, and found that drifts due to the gradient and curvature of the Parker IMF produce significant transport of SEPs across the field [9, 10]. They are also responsible for deceleration additional to the standard adiabatic deceleration [11]. The importance of drifts in the propagation of Galactic Cosmic Rays (GCRs) is well established but they had previously been neglected for SEPs. Recently, drift effects have been incorporated in a first version of an SEP forecasting model [12].

Drifts are especially strong for partially ionised heavy ions, due to their large m/q [9, 10]. In this paper, we carry out simulations of heavy ions in a Parker spiral IMF and investigate the influence of drifts on the intensity profiles measured at 1 AU from the Sun, and the Fe/O ratio.

In Section 2 we describe the simulations, in Section 3 we present the results and Section 4 presents a discussion and conclusions.

2. Model and simulations

The model used for the simulations is a full-orbit test particle code which derives the trajectories of a population of SEPs injected near the Sun [10]. A unipolar Parker spiral configuration, with magnetic field pointing outwards from the Sun at all latitudes, is used, and particles experience scattering events with a frequency consistent with a specified value of the mean free path λ.

In the simulations described below, particles are injected from a $6^\circ\times6^\circ$ region at the Sun, centered at longitude 0° and latitude 20°. Therefore the source of the particles is a small localised region which may be taken to represent a flare region, as opposed to an extended source as a CME-driven shock would be.

We inject a population of oxygen ions with atomic number A=16 and charge number Q=7, giving a mass to charge ratio A/Q=2.3, and a population of iron ions with atomic number A=56

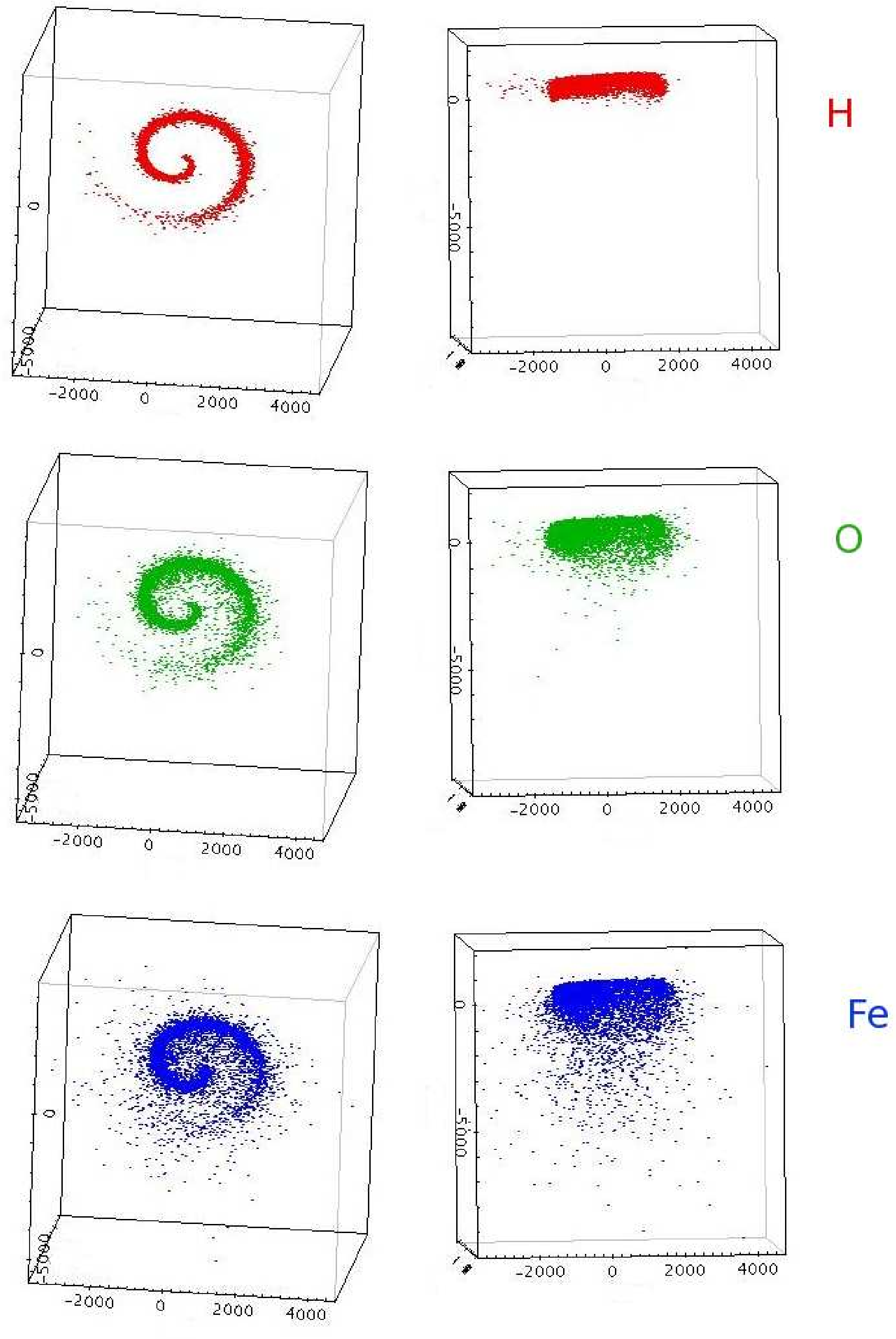

Figure 1: Spatial distributions of protons, oxygen ions and iron ions at t_f=4 days.

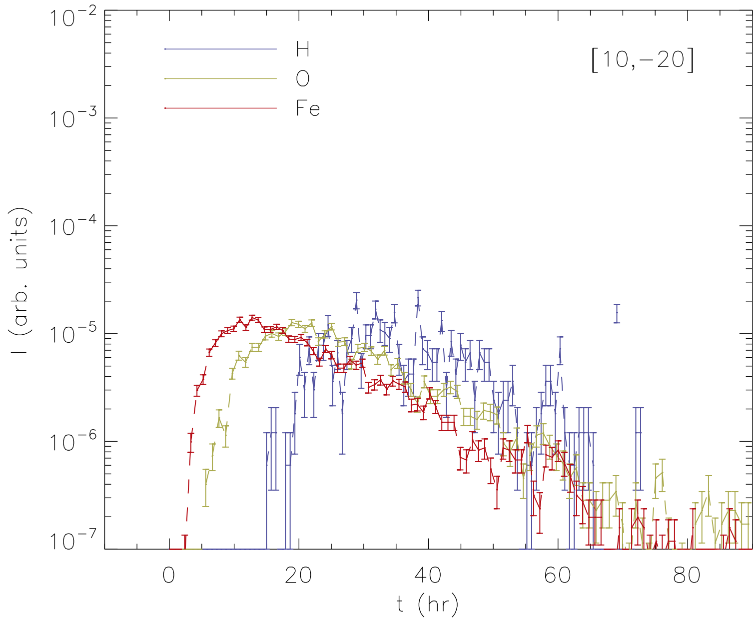

Figure 2: Time-intensity profiles of H (*blue*), O (*green*) and Fe (*red*) at 1 AU from the Sun, at longitude ϕ=10° and latitude δ=−20°, relative to the magnetic field line connected to the centre of the injection region.

and charge number Q=15, giving a mass to charge ratio A/Q=3.7. For comparison we also consider a population of protons, for which A/Q=1. The heavy ion charge states used are consistent with SEP measurements in gradual SEP events [13].

For all species, the initial energy distribution follows a power law with spectral index γ=1.1 in the energy range between 10 and 400 MeV/nuc. As far as directions of initial velocities are concerned, these are uniformly distributed in the semihemisphere in velocity space pointing away from the Sun. The number of simulated particles in each species is N=100,000.

In the first instance, we neglect any dependence of the scattering mean free path on m/q and assume λ = 1 AU for protons, oxygen and iron ions. Particles are followed until a final time t_f=4 days.

3. Results

Figure 1 shows the spatial distribution of protons, oxygen and iron ions at the final time t_f=4 days. Here one can see that the Fe ions (largest A/Q) experience the strongest drift and therefore spread in both the latitudinal and longitudinal direction more than O and H ions. The latter display the smallest drift.

Figure 2 shows time intensity profiles of H, O and Fe at 1 AU, integrated over all energies, from our test particle simulations, for a 10°×10° collecting area on the 1 AU sphere. The area is centered at $[\phi,\delta]$=[10°,−20°], with ϕ the heliographic longitude and δ the heliographic latitude, relative to the location with best connection to the injection region at the Sun. Therefore the coordinates [0,0] indicate the location at 1 AU directly connected to the source region. Positive values of ϕ indicate locations to the West of the directly connected field line and positive values of δ locations to the

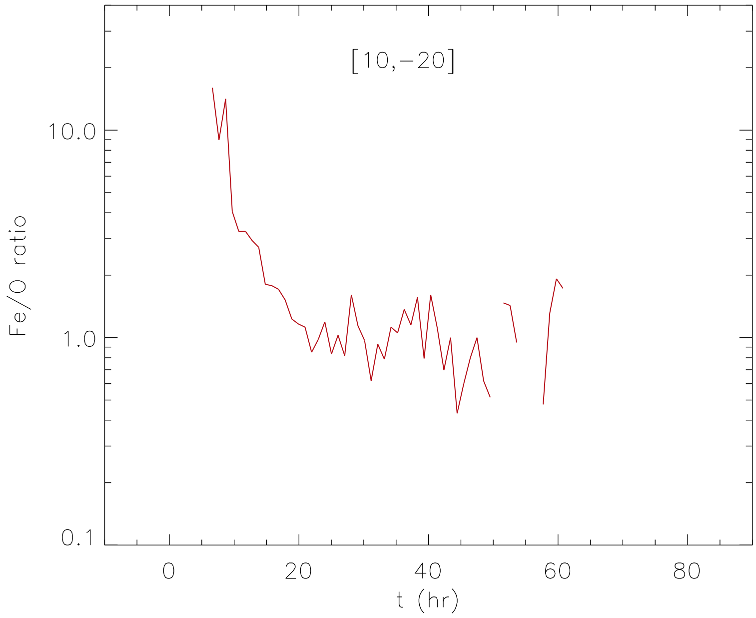

Figure 3: Fe/O ratio versus time at 1 AU, at longitude ϕ=10° and latitude δ=−20°, relative to the magnetic field line connected to the centre of the injection region. The same number of Fe and O ions were injected at the Sun.

North of it. Figure 2 displays intensity integrated over all energies to obtain sufficient statistics in each collecting area at 1 AU.

Figure 3 shows the Fe/O ratio versus time, for the same observer location as shown in Figure 2. It should be noted that the same number of Fe and O ions are modelled, therefore the injection Fe/O ratio is 1.

4. Discussion

Figure 1 shows that Fe drifts more than O (and H), due to its higher m/q ratio, and therefore experiences much more perpendicular transport in both longitude and latitude.

This has an influence on profiles measured at 1 AU: Fe is found to reach many locations away from the best connected location at 1 AU earlier than O (and H), because it drifts more. This is the qualitative behaviour seen in Figure 2.

H is found to arrive last at several not well connected locations. This is not observed in SEP events, however it should be noted that in our simulations we injected equal number of H and e.g. Fe ions, while in reality H ions are much more abundant than Fe ones. This increases the likelihood of H being detected a given location at approximately the same time as heavier ions, through a combination of scattering events and drift.

The time behaviour of the Fe/O ratio depends on the observer's location. For a number of locations, including that shown in Figure 3, the Fe/O ratio from the simulations displays a decrease over time, similar to that observed in SEP data (see e.g. [4]). This feature appears naturally within our simplified model, which only includes a localised injection region and does not consider other important effects like field line random walk [14].

In conclusion, 3D test particle simulations show that Fe ions reach some locations that are not well connected to the injection region earlier than O, resulting in profiles of Fe/O ratio decreasing over time. The cause of this behaviour is the larger A/Q ratio of Fe compared to O, causing Fe to experience stronger drifts, associated with the gradient and curvature of the Parker spiral magnetic field. Therefore drifts are a transport effect that may explain the time decrease of Fe/O ratio observed in several SEP events.

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References

[1] D. V. Reames, *Particle acceleration at the Sun and in the heliosphere*, *Space Sci. Revs.* **90** (1999) 413–491.

[2] M. Scholer, D. Hovestadt, B. Klecker, G. Gloeckler, and C. Y. Fan, *Temporal development of the energetic particle composition during solar flares*, *J. Geophys. Res.* **83** (1978) 3349–3354.

[3] G. M. Mason, G. Li, C. M. S. Cohen, M. I. Desai, D. K. Haggerty, R. A. Leske, R. A. Mewaldt, and G. P. Zank, *Interplanetary Propagation of Solar Energetic Particle Heavy Ions Observed at 1 AU and the Role of Energy Scaling*, *ApJ* **761** (2012) 104.

[4] P. Zelina, S. Dalla, and T. Laitinen, *Multi-spacecraft observations of heavy ion solar energetic particles*, in *International Cosmic Ray Conference* (A. van den Berg, ed.), Proceedings of Science, 2015.

[5] A. J. Tylka, D. V. Reames, and C. K. Ng, *Observations of systematic temporal evolution in elemental composition during gradual solar energetic particle events*, *Geophysical Research Letters* **26** (1999) 2141–2144.

[6] C. K. Ng, D. V. Reames, and A. J. Tylka, *Effect of proton-amplified waves on the evolution of solar energetic particle composition in gradual events*, *Geophysical Research Letters* **26** (1999) 2145–2148.

[7] H. V. Cane, T. T. von Rosenvinge, C. M. S. Cohen, and R. A. Mewaldt, *Two components in major solar particle events*, *GRL* **30** (2003) 8017.

[8] A. J. Tylka, O. E. Malandraki, G. Dorrian, Y.-K. Ko, R. G. Marsden, C. K. Ng, and C. Tranquille, *Initial Fe/O Enhancements in Large, Gradual, Solar Energetic Particle Events: Observations from Wind and Ulysses*, *Solar Phys.* **285** (2013) 251–267.

[9] S. Dalla, M. S. Marsh, J. Kelly, and T. Laitinen, *Solar energetic particle drifts in the Parker spiral*, *Journal of Geophysical Research (Space Physics)* **118** (2013) 5979–5985, [arXiv:1307.2165].

[10] M. S. Marsh, S. Dalla, J. Kelly, and T. Laitinen, *Drift-induced Perpendicular Transport of Solar Energetic Particles*, *ApJ* **774** (2013) 4, [arXiv:1307.1585].

[11] S. Dalla, M. S. Marsh, and T. Laitinen, *Drift-induced Deceleration of Solar Energetic Particles*, *Astrophys. J.* **808** (2015) 62, [arXiv:1506.04015].

[12] M. S. Marsh, S. Dalla, M. Dierckxsens, T. Laitinen, and N. B. Crosby, *SPARX: A modeling system for Solar Energetic Particle Radiation Space Weather forecasting*, *Space Weather* **13** (2015) 386–394, [arXiv:1409.6368].

[13] A. Luhn, D. Hovestadt, B. Klecker, M. Scholer, G. Gloeckler, F. M. Ipavich, A. B. Galvin, C. Y. Fan, and L. A. Fisk, *The mean ionic charges of N, Ne, MG, SI and S in solar energetic particle events*, *International Cosmic Ray Conference* **4** (Aug., 1985) 241–244.

[14] T. Laitinen, A. Kopp, F. Effenberger, S. Dalla, and M. S. Marsh, *Solar Energetic Particle Access to Distant Longitudes via Turbulent Field-Line Meandering*, *ArXiv e-prints* (Aug., 2015) [`arXiv:1508.03164`].