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Cosmic ray anisotropies near the heliopause

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When the Voyager 1 (V1) spacecraft crossed the heliopause (HP), energetic particle observations showed unexpectedly large anisotropies in the local interstellar medium (LISM). For high energy galactic cosmic rays (GCRs), the anisotropy is such that a deficiency of particles near pitch-angles of 90 degrees was recorded. For low energy anomalous cosmic rays (ACRs), the anisotropy is completely different; an enhancement near 90 degrees was observed. We put forward a simple explanation for these seemingly incongruous anisotropies based on (perpendicular) diffusion across the HP that is more efficient at certain pitch-angles. We motivate our choice of transport parameters and present results that are in qualitative agreement with Voyager measurements, vindicating to a certain extent our modelling efforts.

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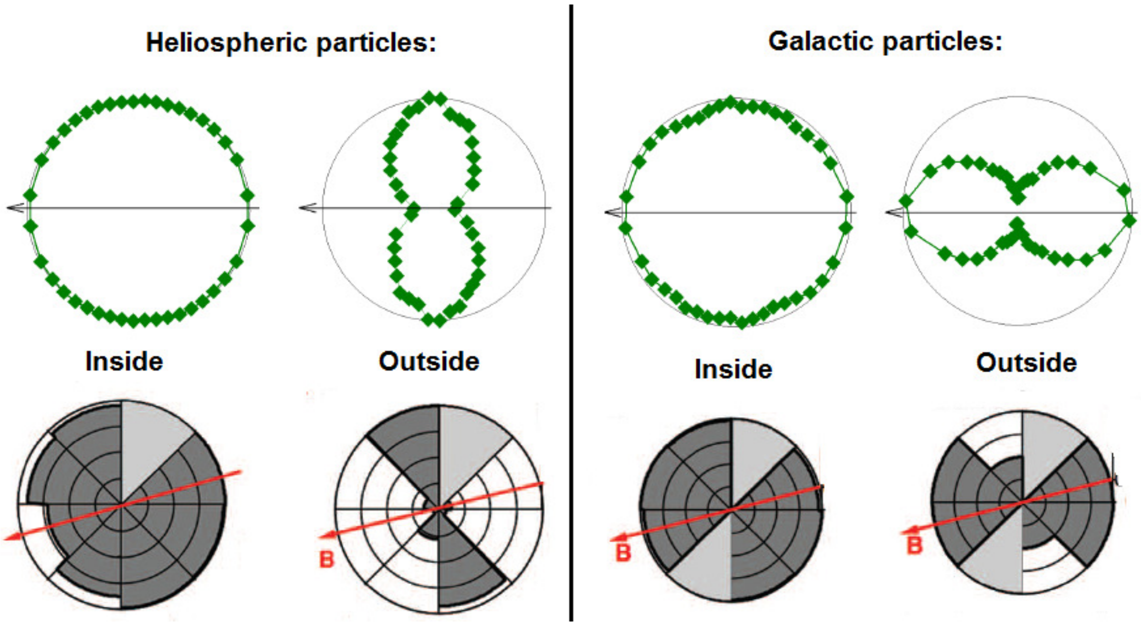

Figure 1: The top panel shows modelled sector diagrams, from [6], for ACRs and GCRs, inside and outside of the heliosphere. The bottom panels are the corresponding observations from [3].

1. Introduction

In August 2012, V1 crossed the HP [1, 2] and has, since then, been sampling the very LISM *in-situ*. In the LISM, the observed ACR and GCR intensities show significant anisotropies [3]. The observed sector diagrams of these anisotropic distributions are shown in the bottom panel of Fig. 1 for ACRs (referred to as heliospheric particles) and GCRs (referred to as galactic particles), with the red arrow indicating the magnetic field direction. Note that both distributions are still isotropic inside the heliosphere. It is interesting that the anisotropies are in the opposite sense for both distributions: ACRs show an enhancement at pitch-angles of 90° (or, in terms of the pitch-angle cosine, $\mu = 0$), while GCRs show a depletion near $\mu = 0$. [4] and [5] investigated the cause of the ACR anisotropies and could reproduce the observed features, but only for ACRs. We however believe that a common process should be responsible for both the ACR and GCR anisotropies and such a process, as discussed by [6], is put forward in this proceeding.

2. Modelling results

In [6] we proposed that these anisotropies are simply due to more effective perpendicular diffusion across the HP at certain pitch-angles. By assuming that the perpendicular diffusion coefficient, on the pitch-angle level, has the functional form $D_{\perp} \sim v_{\perp} \sim \sqrt{1-\mu^2}$ (this dependence is motivated in the next section), we showed that, at least qualitatively, the anisotropic behaviour of both cosmic ray species could be explained. Results form this model are shown in the top panel of Fig. 1, in the form of modelled sector diagrams. The modelled behaviour is in agreement with the observations: The ACR distribution, in the LISM, peaks at $\mu = 0$, while the GCR distribution reaches a minimum there. The reasoning is that $\mu = 0$ particles have the highest mobility across the HP: The $\mu = 0$

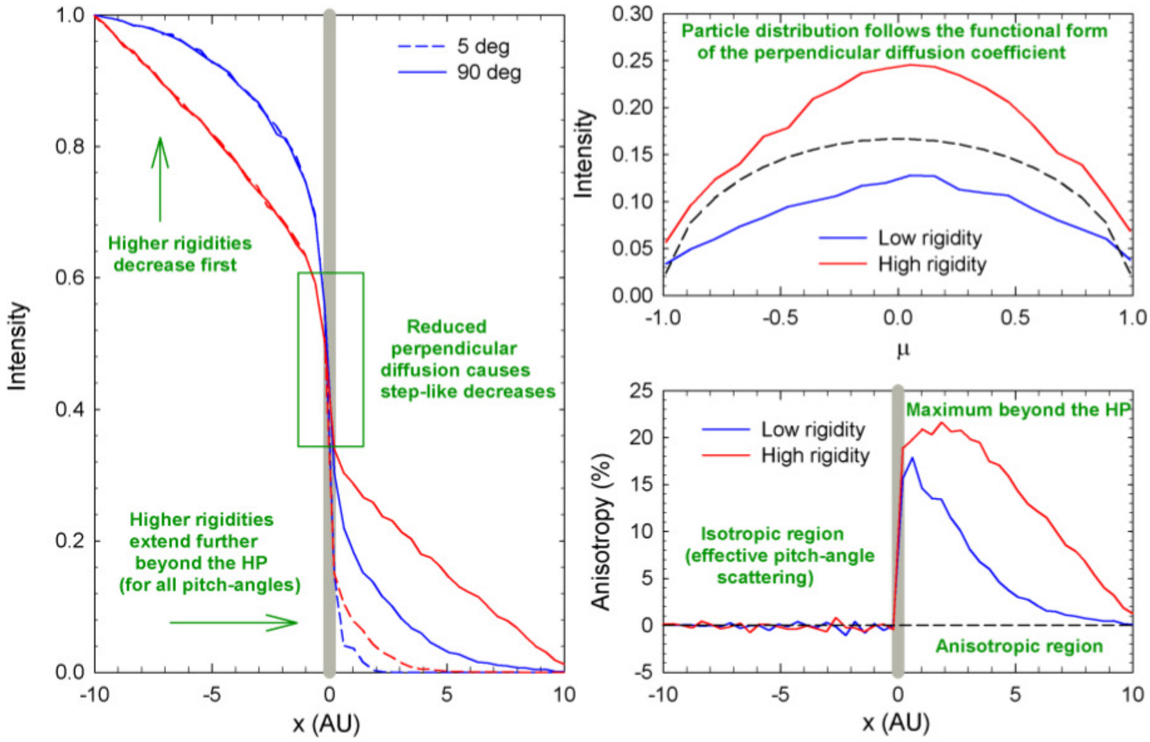

Figure 2: Applying the model of [6] to ACR transport across the HP for two different rigidities: Red curves correspond to the higher rigidity ACRs.

ACRs can thus readily *escape* across the HP, and hence, there should be an enhancement of these particles in the LISM. Similarly for GCRs, the $\mu = 0$ particles enter the heliosphere more readily and a deficiency of these particles should be observed in the LISM. The assumed form of $D_\perp$ results from drift effects, and as such, generally increases linearly with rigidity, $D_\perp \sim P$. The model of [6] was again used to model the transport of ACRs across the HP, but now for two different rigidities, and the results summarized in Fig. 2. The left panel shows the intensity for ACRs, of two different rigidities, across the HP, with the higher rigidity particles' intensity decreasing first in front of the HP, and remaining higher in the LISM, in accordance with the V1 observations of [5].

3. Parameter motivation

The fluctuating 2D component, believed to be primarily responsible for perpendicular diffusion, is generalized to include a component along the mean field $\delta\vec{B} = \delta B_x\hat{x} + \delta B_y\hat{y} + \delta B_z\hat{z}$. In the supersonic solar wind, the fluctuations are usually observed to be transversal in nature, i.e. $\delta B_z \approx 0$ [7]. However, observations near the HP indicate that the fluctuations are mostly longitudinal (compressional) in nature [8], so that we assume $\delta B_x, \delta B_y \ll \delta B_z$, and proceed to calculate $D_\perp$ due to non-resonant interactions. Assuming magnetostatic fluctuations, where the correlation function decays exponentially, we get $D_\perp(\mu) = \left\langle v_\perp^2 \right\rangle \tau_{\mathrm{dec}}$. Perpendicular motion is assumed to be due to random drift motion of the guiding center across the mean field. For purely longitudinal fluctuations, the guiding center drift velocity perpendicular to the mean field is

$$^{g}V_{\perp} = \frac{vr_L}{2l_{\perp}} \left(1-\mu^2\right) \frac{\delta B_z^2}{B_0^2}. \tag{3.1}$$

Furthermore, the decorrelation time is taken to be the time it takes a guiding center to drift across a perpendicular correlation length, $l_{\perp}$, so that $D_{\perp}$ becomes

$$D_{\perp}(\mu) = \frac{vr_L}{2} \left(1-\mu^2\right) \left\langle \frac{\delta B_z^2}{B_0^2} \right\rangle, \tag{3.2}$$

which follows, in principle, the assumed dependence assumed *ad hoc* in the previous section. Also note the linear dependence on momentum (rigidity) contained in r_L.

4. Conclusions

By choosing the appropriate functional form for the pitch-angle dependent perpendicular diffusion coefficient, we are able to reproduce a number of observed features in the LISM related to the anisotropy of both ACR and GCR species. We believe that these results show additional, qualitative, observational support for our explanation of the observed anisotropies.

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References

[1] E.C. Stone at al., *Voyager 1 Observes Low-Energy Galactic Cosmic Rays in a Region Depleted of Heliospheric Ions*, *Sci* **341** 150 2013.

[2] D.A. Gurnett et al., *In Situ Observations of Interstellar Plasma with Voyager 1*, *Sci* **341** 1489 2013.

[3] S.M. Krimigis et al., *Search for the Exit: Voyager 1 at Heliosphere's Border with the Galaxy*, *Sci* **341** 144 2013.

[4] V. Florinski et al., *Energetic Particle Anisotropies at the Heliospheric Boundary*, *ApJL*, **776** L37 2013.

[5] V. Florinski at al., *Energetic Particle Anisotropies at the Heliospheric Boundary. II. Transient Features and Rigidity Dependence*, *ApJ* **803** 47 2015.

[6] R.D. Strauss & H. Fichtner, *Cosmic ray anisotropies near the heliopause*, *A&A Lett.* **572** L3 2014.

[7] A. Shalchi *Nonlinear Cosmic Ray Diffusion Theories*, Springer-Verlag, Germany 2009.

[8] L.F. Burlaga at al., *Magnetic Field Fluctuations Observed in the Heliosheath and Interstellar Magnetic Field by Voyager 1 at 115.7–124.9 AU during 2011–2013*, *ApJ* **792** 134 2014.