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The role of drifts in the galactic cosmic ray transport

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We have earlier presented a 2D-axisymmetric model of the transport of galactic cosmic rays in the heliosphere which is based on the stochastic simulation technique and allows us to study different aspects of cosmic ray modulation process separately. In addition to the basic modulation effects (convection, adiabatic cooling by the solar wind, scattering on magnetic inhomogenities), our model also includes particle drift along the wavy heliospheric current sheet whose tilt angle can be varied.

Here we present our first results from a refined modelling of the current sheet drift. The drift effect is shown to play an important role in the modulation process and should be included in any detailed calculations of cosmic ray transport. We visualize the drift effect by presenting the particles' streaming in the heliosphere for both positive and negative polarity periods.

1. Introduction

When galactic cosmic rays enter the heliosphere, both their flux and energy are modulated due to their interaction with the heliospheric magnetic field and solar wind. Modulation is effective for particles with < 100 GeV energy, for higher energies the heliosphere is almost transparent. We have earlier presented a 2D-axisymmetric model of the heliospheric transport of cosmic rays, which included the basic modulation processes: convection by the solar wind, adiabatic cooling by the expansion of the heliospheric magnetic field and scattering on the inhomogenities of the heliospheric magnetic field [1]. Drifts were not included in that study.

The solar magnetic field points outward in one hemisphere and inward in the other. The magnetic field has a spiral structure due to solar rotation. The heliospheric current sheet (HCS) is created in the interface of the oppositely oriented magnetic field sectors. Due to the gradients of the magnetic field around the sheet and the reversal of the direction of the magnetic field from one side of the sheet to the other the particles experience an effective drift along the sheet. The direction of the particle drift depends on the polarity of the solar magnetic field which changes every 11 years. During positive/negative polarity periods, positively charged particles drift outward/inward, respectively.

The HCS drift effect has been proposed long time ago [2]. Here we perform a detailed study of particle streaming due to this drift. We study the transport of cosmic rays through the heliosphere by stochastic simulation, i.e., we send test particles from the heliospheric boundary and follow their path in the heliosphere step by step. With simulations of millions of particles we are able to model the drift pattern of particle velocities in the heliosphere.

First we consider the flat HCS. The equation of averaged drift velocity is then as follows:

$$\frac{\langle v_D \rangle}{v} = \frac{1}{\pi} \int_0^1 \left(\int_{-\pi/2}^{\pi/2} \frac{v_D}{v} d\psi \right) d\mu \qquad (1)$$

where

$$\frac{v_D}{v} = \frac{sin\beta}{\beta}\sqrt{1-\mu^2},\ \beta = acos\left[sin\psi - \left(\frac{y_0}{R_L}\right) \frac{1}{\sqrt{1-\mu^2}} \right],$$

μ is the cosine of the particle's pitch angle, ψ is the phase of the particle's Larmor rotation, y_0 is particle's distance from the current sheet and R_L is particle's Larmor radius and v is particle's velocity. Here we assume the form of the Parker spiral for the heliospheric magnetic field and an infinitely thin current sheet.

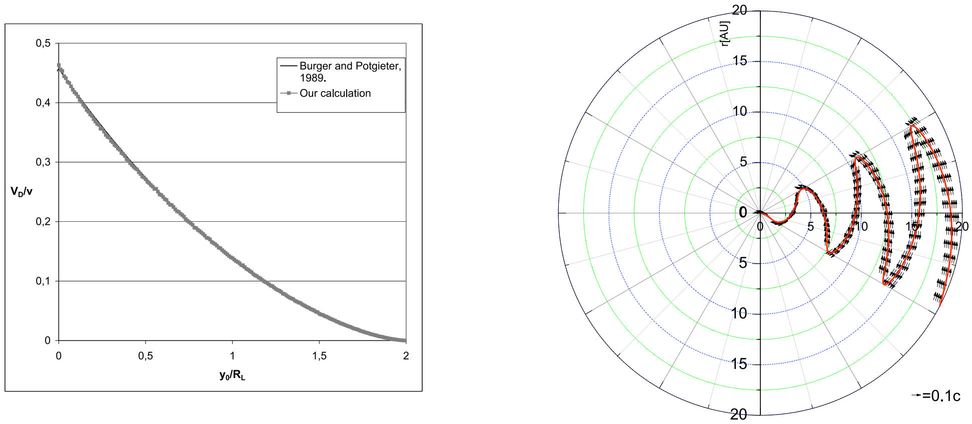

Figure 1. a) Average current sheet drift velocity relative to particle's velocity. Our calculation (grey line) and calculation by [3] (black line). b) Drift vectors for a 2 GeV particle at $30°$ tilt angle current sheet and $0°$ azimuth angle.

From Eq. 1 we get the relation between drift velocity and particle's velocity as a function of y_0/R_L. Figure 1a shows that our calculation for the flat current sheet drift agrees well with earlier calculations [3]. Note that drift velocity goes to zero if particle's distance from the sheet is more than two Larmor radii.

We can approximate the result for the flat sheet in Figure 1a as follows:

$$\frac{\langle v_D \rangle}{v} = -0.0062\left(\frac{y_0}{R_L}\right)^3 + 0.1066\left(\frac{y_0}{R_L}\right)^2 - 0.4181\left(\frac{y_0}{R_L}\right) + 0.4550 \tag{2}$$

We can use Eq. 2 in the case of a wavy sheet. Although a wavy sheet is a 3D-problem we will study it in a 2D-model with heliospheric distance r and polar angle θ as coordinates. First we calculate the drift velocity for all azimuth angles separately and then average the result. For a given position and energy of the particle, we find its Larmor radius and distance to the sheet. We assume the sheet to be locally flat and apply Eq. 2 to calculate particle's relative drift velocity at position (r, θ) near the sheet whose tilt angle is α and azimuth angle ϕ. Figure 1b shows the drift velocity vectors for the case $\alpha = 30°$ and fixed azimuth $\phi = 0°$. The figure shows how the drift area around the sheet is thinner in inner heliosphere, where the magnetic field strength is higher and particle's Larmor radius smaller. After averaging the result over ϕ we find that the latitudinal component of the total current sheet drift is negligibly small so the drift can be approximated to be radial.

Adding this effect to the basic 2D model [1], we combine all the modulation processes. We trace a large set of test particles from the heliospheric boundary to the Earth's orbit. As a result we get the streaming patterns of cosmic ray particles in the heliosphere.

2. Discussion

Figure 2 shows the streaming patterns for 2 GeV protons during positive and negative polarity periods with tilt angle of the sheet $\alpha = 15°$. Here we show streaming of only those particles which finally reach the Earth's orbit.

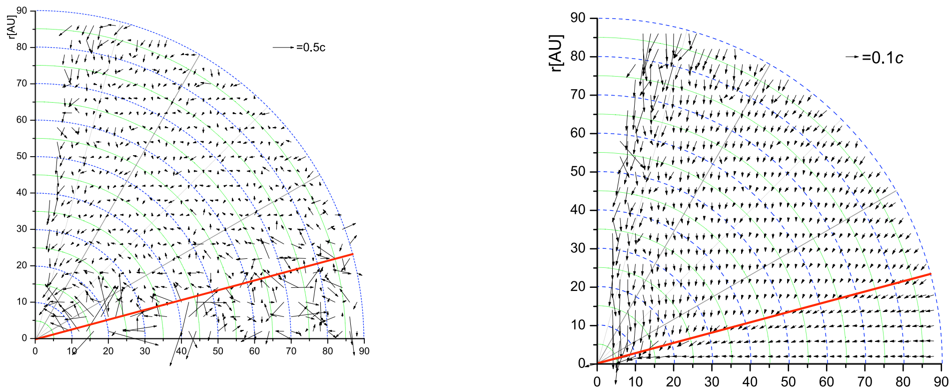

Figure 2. Streaming pattern for 2 GeV particles during a) positive polarity, b) negative polarity period inside 90 AU. The thick line denotes the tilt angle of the sheet.

Figure 2 depicts a clear difference in particle behavior during the two polarity periods. During the positive polarity period particles tend to avoid the tilt cone. Particles make large latitudinal excursions and reach the Earth's orbit at 1AU mainly from the polar regions. The particle motion is mainly diffusive. During negative polarity period streaming from polar regions is again clearly shown, but there's also another streaming pattern: particles at lower latitudes tend to move first towards the tilt cone and then drift nearly radially along the sheet towards the Sun. The drift effect clearly dominates and we see a very organized streaming pattern.

The magnitudes of the average drift velocities for a 2 GeV particle are of the order of $0.01 - 0.05c$, so they are relatively small compared to particle velocity $\sim 0.96c$ and to the drift velocities in a flat sheet shown in Figure 1a. For a wavy sheet there are many particles inside the tilt cone that are far away from the sheet itself and do not feel the drift effect. This makes the average drift velocity lower. Figure 3 shows two examples of how the HCS drift velocity relative to particle's velocity changes over polar angle and radial distance from the Sun. It is seen that the relative drift velocity is larger for lower tilt angles. The drift velocities are lowest in the equatorial plane and tend to increase towards the edges of the tilt cone.

3. Conclusions

The result of Figures 2a and 2b show that the current sheet drift clearly has an important role on the solar modulation of galactic cosmic rays. Particle behavior is very different in different polarity periods. During positive polarity period particles make large latitudinal excursions and reach the Earth's orbit from the polar regions. During negative polarity particles reach the Earth also from equatorial plane drifting along the HCS. Further studies should be done to estimate the HCS drift effect in different modulation conditions.

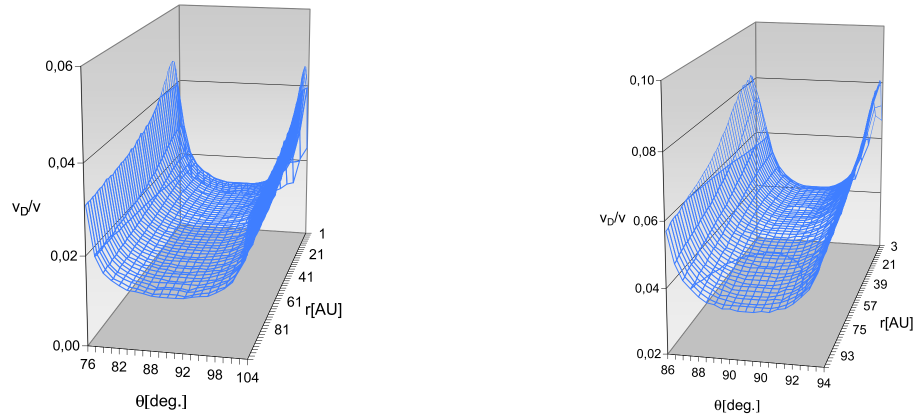

Figure 3. Average current sheet drift velocity for 2 GeV particles for a) 15° tilt angle of the sheet b) 5° tilt angle of the sheet

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