Galactic Cosmic-Ray Interactions With the Outer Heliosphere: a Self-Consistent Approach

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Abstract

Studies of self-consistent cosmic-ray interactions in the context of the global heliospheric model have been conducted previously in the hydrodynamic approximation only. A serious drawback of this approach is difficulty in treating the cosmic-ray diffusion process properly and the unavailability of particle spectra, making it difficult to make the results compatible with the galactic cosmic-ray (GCR) observations in the outer heliosphere. Moreover, previous studies have not focused sufficiently on calculating the correct magnetic field structure and MHD turbulence levels in the heliosheath and heliotail. Our recent work [3] has filled some of these voids by introducing a kinetic model of GCR propagation, using the accurately computed interstellar and interplanetary field geometries, in the axisymmetric case. This paper extends our earlier model by introducing GCR pressure gradient terms in the plasma MHD equations.

1. Introduction

At this time we are only beginning to understand to what extent cosmic rays affect the heliosphere. The degree of GCR dynamic influence on the plasma flow depends critically on the magnitude of the diffusion coefficient. In our preceding paper [3] we showed that the diffusion coefficient is generally too large to allow for a strong coupling between the low and the high energy particles. The only exception is the inner heliosheath, which contains the "modulation wall", a region with a strongly amplified magnetic field and a small diffusion coefficient. The wall blocks low-energy particles from accessing the inner heliosphere and has a large modulation effect on higher energy cosmic rays. Consequently, relatively large cosmic-ray pressure gradients exist in this region, offering a potential for plasma flow modification. The purpose of this paper is to evaluate the amount of flow mediation by GCR in the outer heliosphere.

GCR effects on the heliospheric interface were studied in [2,6] based on a hydrodynamic approximation for the cosmic rays. The current model improves on their work by including the interstellar magnetic field, using the kinetic GCR approach, and calculating diffusion coefficients using the plasma parameters, rather

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than relying on empirical assumptions. A similar kinetic approach was used in [5] in a 1D (spherically symmetric) model and in [2] in a 2D axisymmetric model, but the modulation wall was included only in a very limited way.

2. Global GCR Heliospheric Model

The global heliospheric model used in the simulation is described in detail in [3]. We briefly summarize its properties here. Solar wind and interstellar ions and the interstellar neutral atoms are described by a two-fluid set of equations and uses the charge exchange formalism developed in [7]. The energetic particles are described by their kinetic transport equation. GCR pressure (p_c) gradients calculated from the distribution function provide the energetic particle feedback on the plasma flow. We use theoretically derived diffusion coefficients based on the incompressible MHD turbulence formalism and quasi-linear like parallel diffusion assumption [8]. The diffusion coefficients are calculated as

$$\kappa_\parallel = \frac{27}{35}\frac{r_\mathrm{g}^{1/3} l_\mathrm{c}^{2/3} V}{A_\mathrm{sl}^2}\left[\frac{7}{27}\left(\frac{r_\mathrm{g}}{l_\mathrm{c}}\right)^{5/3} + 1\right], \quad \kappa_\perp = \alpha A_\mathrm{tot}^2 \kappa_\parallel, \tag{1}$$

where l_c is the correlation length, r_g is the cyclotron radius, $A_\mathrm{sl}^2 = \langle \delta B_\perp^2 \rangle / B^2$ is the amplitude of slab turbulence, A_tot is the total turbulence amplitude, and α is an empirical factor based on the hybrid simulation results for particle motion in a turbulent field [4]. The model is axisymmetric with respect to the interstellar wind direction, which is assumed to contain a flow-aligned magnetic field with a strength of $1.5\,\mu$G. The heliospheric magnetic field is included in a kinematic approximation as described in [3]. GCRs incident on the heliosphere are assumed to have a distribution produced by supernova shock acceleration and subjected to ionization losses.

3. GCR Pressure Gradient Effects

The difference between the positions of the termination shock (TS) and bow shock (BS) and the heliopause (HP) are shown in Figure 1. One can see that the heliosphere is slightly compressed as all three surfaces move to smaller heliocentric distances. However, the amount of change is quite small (see Table 1). Our result generally agree with those of [6] who found that the TS moves closer to the Sun by between 5 and 20 AU and becomes more spherical. The difference is smaller in our case because the TS itself is located at smaller heliocentric distance (100 AU vs. 150 AU in [6]). We note that the momentum-averaged radial diffusion coefficients calculated in our model [3] was generally between the high and the low limits used by [2] and [6]. In particular, it varied between $2 \times 10^{21}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ inside the modulation wall, $5 \times 10^{23}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ upstream of the TS and $10^{27}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ in the LISM.

Table 1. The location of the heliospheric surfaces.

	without GCR	with GCR
TS upstream	101 AU	98 AU
TS downstream	180 AU	166 AU
HP upstream	165 AU	162 AU
BS upstream	229 AU	225 AU

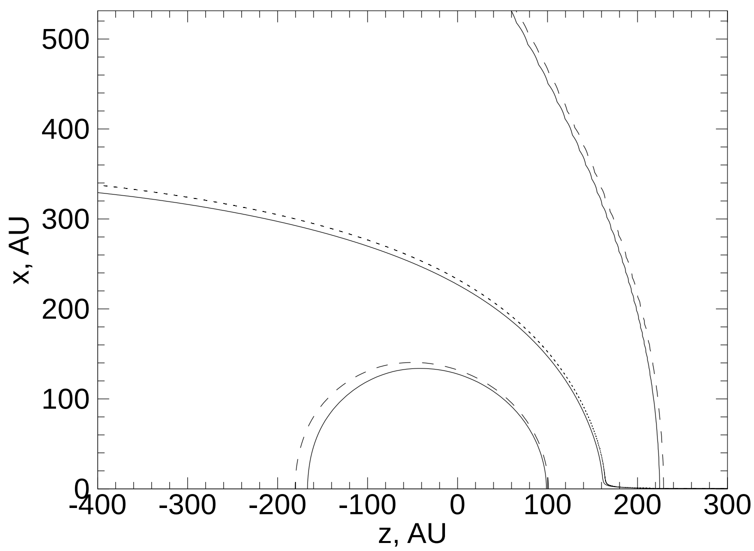

Fig. 1. Heliospheric structure with (solid) and without (dashed) the galactic cosmic rays.

1D cuts for the flow parameters along the symmetry axis are shown in Figures 2 and 3. We detect no measurable solar wind slowdown upstream of the TS. The heliosheath flow is modified to the extent that the plasma pressure is slightly higher compared to the case without the GCRs. The fact that GCRs, possessing the highest interstellar pressure out of the three principal interstellar particle species, have by far the smallest impact on the heliosphere is quite remarkable. To explain this result we note that less than 30% of the total interstellar GCR pressure of $0.23\,\mathrm{eV\,cm^{-3}}$ is available for the flow mediation inside the modulation wall, since the remaining pressure is contained in extremely energetic particles that do not experience any modulation. Conversely, plasma pressure increases dramatically toward the stagnation point on the heliopause and reaches a value of about $0.85\,\mathrm{eV\,cm^{-3}}$. Because the total pressure $(p_c + p_g)$ tends to be conserved in a subsonic flow [2], the plasma pressure is actually smaller near the HP and larger just downstream of the TS, opposite to the gradient in p_c. This results in

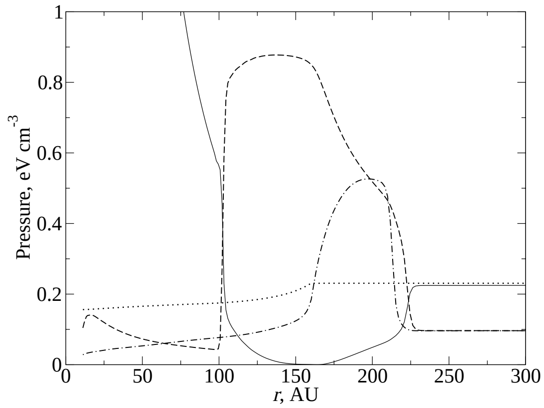

Fig. 2. Plasma dynamic (solid) and thermal (dashed) pressures, neutral hydrogen thermal pressure (dot-dashed) and GCR pressure (dotted) for the test-particle case.

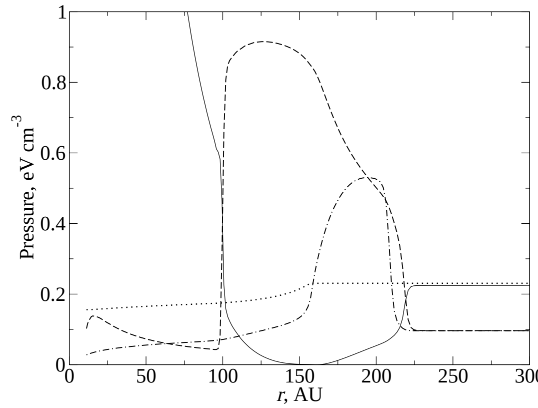

Fig. 3. Plasma dynamic (solid) and thermal (dashed) pressures, neutral hydrogen thermal pressure (dot-dashed) and GCR pressure (dotted) for the self-consistent case.

the motion of the discontinuities toward the Sun that we observe.

4. Conclusion

Using the new self-consistent global heliospheric model for the interaction of the plasma, neutral atoms and galactic cosmic rays, we found that GCRs have a relatively small effect on the location of the heliospheric boundaries. The three principal discontinuities move to smaller heliocentric distances by several AU. The amount of GCR modification of the plasma flow in the outer heliosphere calculated in our kinetic-GCR model is comparable to the effect previously published using a simpler hydrodynamic approximation [2,6].

5. References

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