ON THE INFLUENCE OF COROTATING INTERACTION REGIONS OF THE SOLAR WIND ON GALACTIC COSMIC RAY INTENSITY

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О ВЛИЯНИИ КОРОТИРУЮЩИХ ОБЛАСТЕЙ ВЗАИМОДЕЙСТВИЯ СОЛНЕЧНОГО ВЕТРА НА ИНТЕНСИВНОСТЬ ГКЛ

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https://doi.org/10.31725/0552-5829-2023-149-152

Кратко формулируются результаты моделирования, представления о коротирующих областях взаимодействия (КОВ) солнечного ветра и их возможном существенном влиянии на долговременные вариации интенсивности галактических космических лучей (ГКЛ). Выводы о сильном влиянии КОВ на важные для ГКЛ характеристики гелиосферы делаются по результатам МГД-моделирования, а на интенсивность ГКЛ – по результатам расчётов в простых 2D моделях. Обсуждаются также пути дальнейшего численного исследования эффектов.

Introduction

Corotating interaction regions (CIRs) are heliospheric regions resulting from the interaction between solar wind (SW) streams of different speed with significant changes in the longitudinal distribution of many characteristics including the heliospheric magnetic field (HMF) and galactic cosmic ray (GCR) intensity. For an observer at Earth these changes look like periodic time variations with a period near the synodic rotation period of the Sun ($T_☼ \approx 27$ days). As for GCR intensity these variations are rather weak (the relative amplitude $A_{27d} < 10\%$) so usually it is assumed that CIRs do not change the GCR intensity averaged over the solar rotation period (or longitude) which shows a long-term variation (a characteristic time of 11 and 22 years) with a much larger relative amplitude ($A_{11y} <100\%$). However, it may be so only if CIRs do not change the heliospheric characteristics averaged over longitude.

Recently, a complex analysis of these phenomena including a MHD-simulation of CIR formation and a Monte-Carlo simulation of the GCR intensity was accomplished (see references in [1, 2]). Consequently, we investigated large-scale changes CIRs made in the HMF structures important for GCR modulation according to [1] focusing on the situation for Carrington Rotation (CR) 2066 (January-February 2008). In short, our conclusion was that the large-scale changes the CIRs made to the HMF characteristics were significant so their influence on long-term GCR variations should be taken into account. The main results of our analysis are published in detail~~s~~ in [2, 3]. Here we discuss them, considering also some additional results and-ways to proceed with minimum of references (as in the extended abstract).

Large-scale heliospheric characteristics and CIRs

In [2, 3] some of the changes in the distributions of different HMF characteristics due to CIRs were calculated and illustrated with the help of a reference model in which the CIRs were not formed. Here we illustrate these changes without resorting to explicit reference to such model. In Fig. 1a the change of the form of the heliospheric current sheet (HCS) due to CIRs is shown as the change with distance of the quasi-tilt α_{qt} (equal to half of the range of latitudes the HCS occupies, the solid line) and the magnetic equator λ_{me} (the middle of this latitude range, the dashed line). The abrupt change of both characteristics is seen at $r \approx 10$ AU, while in case of the radial expansion without CIRs both α_{qt} and λ_{me} would be constant. In Fig. 1b the change with distance of the radial and latitudinal distribution of the absolute value of the HMF radial component, $|B_r|$, reduced to the inner sphere $r_{in} = 0.19$ AU of the MHD-simulation multiplying by $(r/r_{in})^2$ and averaged over longitude, is shown for $|B_r|$ averaged also over latitude (the solid line) and for the root-mean-square of the latitudinal distribution (the dashed line). In case of the radial expansion without CIRs both of these HMF characteristics would not change with distance. To illustrate how the rather homogeneous latitudinal distribution of $|B_r|$ near the Sun became quite inhomogeneous at larger distances the radial profiles of the reduced $|B_r|$ are shown for selected latitudes in Fig. 1c (labeled to the right of the panel).

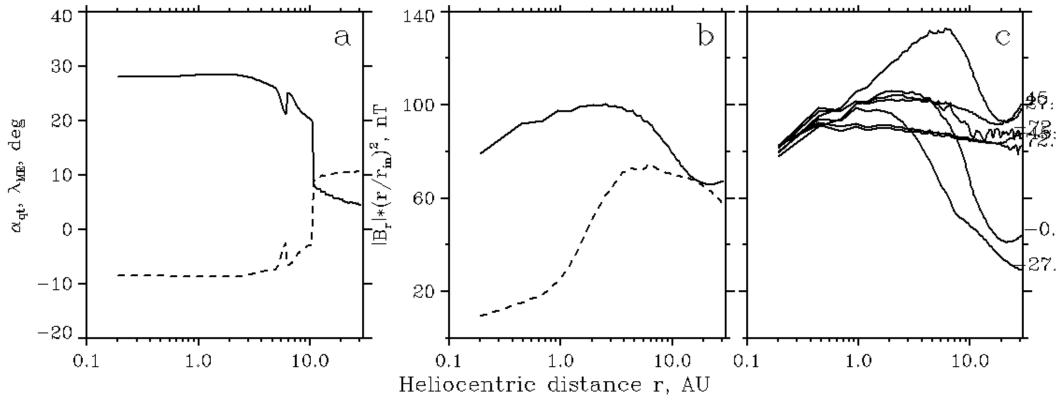

Fig. 1.

It follows that all three main assumptions usually made in models for the simulation long-term variations of GCR intensity – the constancy of the HCS form, the change of the HMF radial component as r^{-2} (Parker HMF model) and the constancy of the $|B_r|$ as function of latitude – are over-turned by CIRs for CR 2066 according to [1]. The additional effect on the HMF fluctuating component which we also consider as due to the CIRs, and important for the long-term GCR modulation, is the significant difference of both the spectrum power P_0 at a fixed frequency and the spectral index γ^{HMF} in the zone of the sector structure and outside it (see [2]).

Description of the effects due to CIRs in long-term GCR intensity

The GCR intensity $J(\mathbf{r},T)=p^2U(\mathbf{r},p)$, where $U(\mathbf{r},p)$ is the distribution function of particles with momentum *p* and kinetic energy *T* at the point (*r*, θ, φ) is described by Parker transport equation. In the steady-state case

$$\nabla\cdot(\mathbf{K}\cdot\nabla U)-(\mathbf{V}+\mathbf{V}_d)\cdot\nabla U+\frac{\nabla\cdot\mathbf{V}}{3}\frac{\partial U}{\partial \ln p}=0, \tag{1}$$

where the tensor $\mathbf{K}$ describes particle diffusion, $\mathbf{V}$ and $\mathbf{V}_d$ are SW and particle drift velocities in an inhomogeneous HMF and the last term describes the adiabatic energy change. With the usual boundary and "initial" conditions for *U* in a spherical heliocentric coordinate system one obtains a boundary-value problem to be solved for the GCR intensity description. This problem can have 3D and 2D forms and can be solved numerically by both Finite Differences and Monte-Carlo methods. In [2, 3] we concluded that for studying CIR's effects the most direct way is to use a Monte-Carlo method for the 3D problem and then average the intensity over the longitude.

However, our aspiration is that many aspects of CIR's effects on GCR intensity can be studied by solving much-simpler 2D and 3D problems. The specific of the 2D model used by the LPI group (which results are discussed here) is that for the regular and current sheet drift velocities it uses not those from the tilted HCS model but more general expressions

$$\mathbf{V}_d^{reg}=\frac{pv}{3q}\cdot F\cdot\left[\nabla\times\frac{\mathbf{B}_m}{B^2}\right],\quad \mathbf{V}_d^{cs}=\frac{pv}{3q}\cdot\left[\nabla F\times\frac{\mathbf{B}_m}{B^2}\right], \tag{2}$$

where *F* is the longitude-averaged HMF polarity and $\mathbf{B}_m$ is the "monopole," directed everywhere anti-sunward, axisymmetric HMF. The coefficients of (1) are determined by the longitude averaged radial components of the SW velocity and HMF in the base of the heliosphere. Parker's HMF model, the diffusion coefficients and the local interstellar proton spectrum are as described in [1] and the outer boundary sphere r_{out} = 122 AU of the GCR simulation.

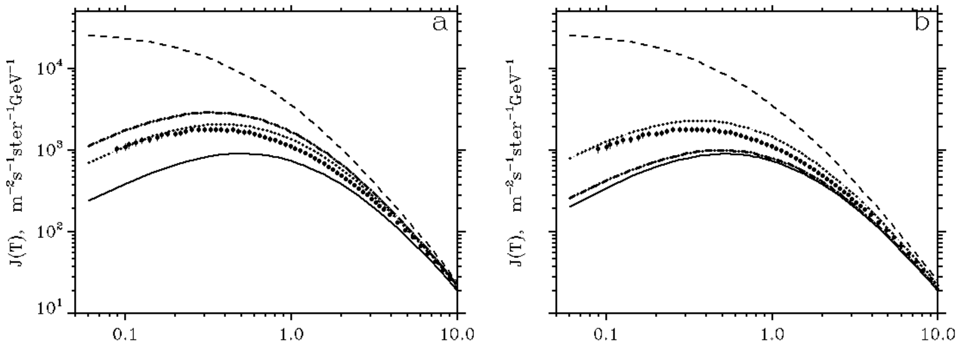

Fig. 2.

In both panels of Fig. 2 the dashed lines show the local interstellar proton spectrum, the vertical bars are for the proton spectrum near the Earth measured by PAMELA and the lower solid lines indicate the spectrum calculated for r = 1 AU, $\lambda = 0^o$ for the longitude averaged radial components of the SW velocity and HMF in the base of heliosphere taken from the MHD-simulation [1]. Two other lines in Fig. 2a show the range of the spectra accounting only for the change of the HMF polarity distribution in the base of the heliosphere due to CIRs, while the two nonsolid lines in Fig. 2b are for the range of the spectra accounting only for the change of the $|B_r|$ distribution there. As to the effects of a different spectral index γ^{HMF} in the zone of the HMF sector structure and outside it, this effect is too weak to be illustrated for such small diffusion coefficients as used in [1].

Solving a simple 2D problem may thus help in emulating some CIR effects on the GCR intensity averaged over longitude.

Conclusions

1. Both the indirect indications and the analysis of the results of a MHD simulation of heliospheric characteristics for one Carrington rotation (CR 2066, January–February 2008) shows significant changes in the averaged heliospheric characteristics over longitude important for GCR propagation in the heliosphere. These CIR effects should therefore be accounted for in the simulations of long-term variations in the GCR intensity.
2. A most direct way accounting for CIR-effects on the GCR intensity averaged over longitude is to use a MHD-simulation of heliospheric characteristics, then applying the Monte-Carlo method for a 3D GCR simulation and then averaging the calculated intensity over longitude. However, many aspects of CIR's effects on GCR intensity can be studied by solving simpler 2D and 3D GCR modulation problems using the results of MHD-simulations.
3. However, to be on the safe side, it is necessary to refine the methodology for both MHD simulation of heliospheric factors and Monte-Carlo calculations of the GCR intensity. The situation as in other CR periods also should be considered.

Xi Luo is grateful for the support of the Taishan Scholar Project of Shandong Province (202103143) and a grant from the National Science Foundation of China (NSFC, U2106201).

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