Proceedings of ICRC 2001: 3577 © Copernicus Gesellschaft 2001

ICRC 2001

Recurrent depressions of galactic cosmic rays in CIRs: 22-year cycle

J. Kóta and J.R. Jokipii

University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ 85721-0092, U.S.A.

Abstract. Recurrent variations in the galactic cosmic-ray flux are produced by the interplay of diffusion and particle drifts. The enhanced scattering and consequent small diffusion in the compressed field of Corotating Interaction Regions (CIRs) causes recurrent cosmic-ray depressions at the passage of CIRs. Drift effects are primarily controlled by the structure of the heliospheric current sheet (HCS). Our earlier 3-D codes using a symmetric tilted dipole are extended to include more complex structures of the HCS. Simulation results are presented. We consider a southward displacement of the HCS during solar minimum. We also report on 3-D model simulations with a HCS resembling those observed at solar maximum (the latitudinal extension of the HCS increases and quadrupole components of the field become important as the Sun enters a more active phase). Recurrent longitudinal variations are discussed for the two polarity states of the 22-year cycle ($A < 0$ and $A > 0$). We find remarkable differences between the 26-day recurrent cosmic-ray variations predicted for $A > 0$ and $A < 0$. The magnitude of the 26-day wave may turn out larger for the $A > 0$, in qualitative agreement with the so far unexplained findings of Richardson et al. (1999), if the HCS happens to be placed asymmetrically.

1 Introduction

The transport of cosmic rays in the heliosphere is governed by particle diffusion, drifts, and adiabatic cooling or acceleration in the heliospheric magnetic field (HMF) carried by the solar wind (Parker, 1965). Corotating structures in the particle distribution appear as recurrent 26-day intensity variations both at the Earth's orbit (Richardson et al., 1999) and at high heliograpic latitudes (Simpson, 1998). Azimuthal variations in the flux of galactic cosmic rays (GCR) may arise due to (i) particle drifts (Kóta and Jokipii, 1982; 1983), (ii) variations in the solar wind speed (Newkirk and Fisk, 1985), and (iii) enhanced diffusion in CIRs (Burlaga et al. 1986; Kóta and Jokipii, 1991).

Corotating interaction regions (CIRs) are dominant features of the quiet heliosphere. The transition between the fast wind of large polar coronal holes and slow wind of the streamer belt around the heliospheric current sheet (HCS) leads to the formation of CIRs (Gosling and Pizzo, 1999). The passage of CIRs causes recurrent depressions in the flux of cosmic rays (Simpson, 1998; Richardson et al., 1999). This can be interpreted in terms of smaller diffusion coefficient in the stronger field of CIRs (Burlaga et al., 1985; Kóta and Jokipii, 1991). Large-scale drifts may modify the picure.

Recently Richardson et al. (1999) compared periods of consecutive solar minima and found that recurrent GCR variations at the orbit of Earth tend to be larger for the $A > 0$ cycle, when the HMF points outward on the northern hemisphere. This finding is contrary to what we might intuitively expect from drift models. Depressions caused by CIRs are expected to act similarly for both polarity states. Drifts, on the other hand, tend to produce significantly larger effects for the $A < 0$ cycle, when GCR ions drift inward along the HCS (Kóta and Jokipii, 1982). For $A > 0$, ions penetrate to the inner heliosphere through the polar regions thus they are insensitive to the structure of the current sheet. Numerical simulations including both drifts and CIRs (Kóta and Jokipii, 1991) have also predicted somewhat larger recurrent variations for $A < 0$.

One should bear in mind, however, that these expectations were based on tilted dipole models that assumed a basic north-south symmetry. For computational reasons, the HCS was placed symmetrically in our earlier 3-D models. It is the purpose of the present work to address deviations from this idealized symmetric case. We have extended our code to handle more complex HCS structures, including possible asymmetries. In the present work we address two types of asymmetries: a southward displacement of the HCS during solar minimum (Smith et al., 2000), and the inclusion of quadrupole components of the HMF in periods of higher solar activity.

Correspondence to: J. Kóta (kota@lpl.arizona.edu)

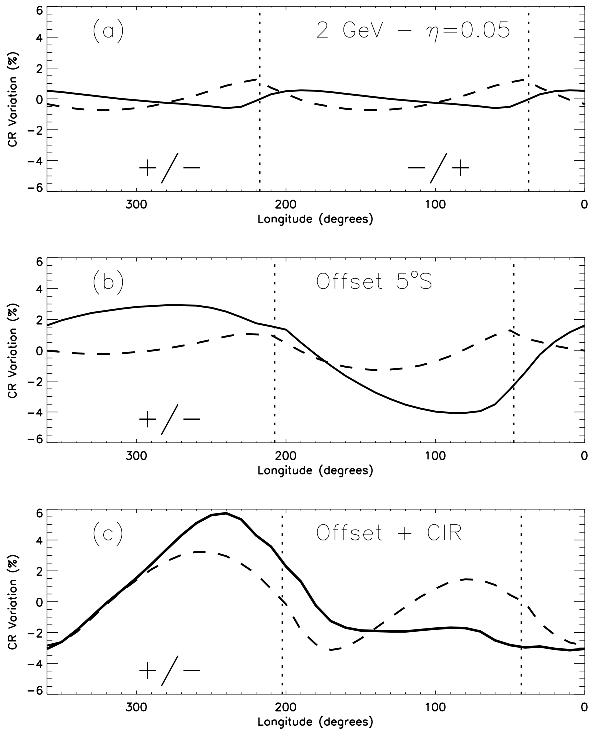

Fig. 1. Simulated azimuthal (27-day) variation of 2 GV cosmic-ray protons at the Earth's orbit for $A > 0$ (solid lines) and $A < 0$ (dashed lines). The tilt angle $\alpha = 30^o$. Dotted vertical lines indicate sector crossing. Panel (a) illustrates the effect of drifts for a symmetric HCS without CIRs. Panel (b) shows the result of a displacement of the HCS to the south. Panel (c) includes displacement plus CIRs (see text).

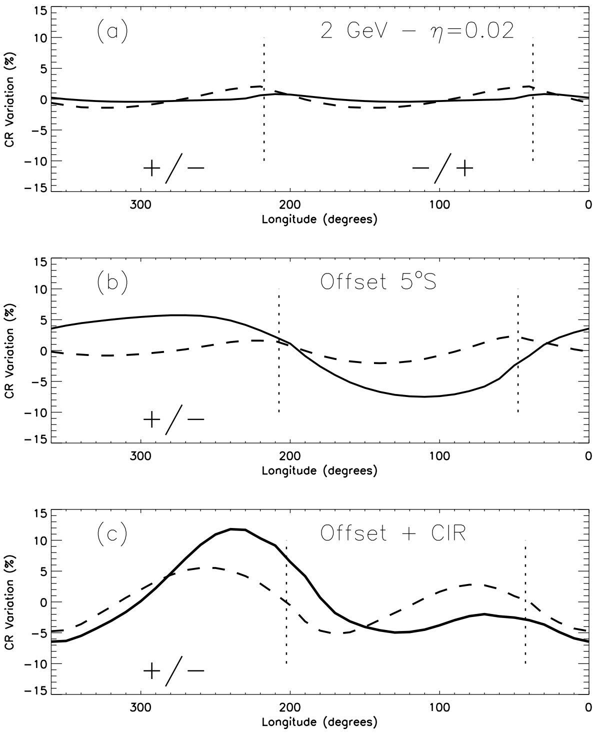

Fig. 2. Same as in Figure 1 but with a smaller perpendicular diffusion, $\kappa_\perp/\kappa_\parallel = 0.02$. Note that scales are changed in proportion of $1/\eta$.

2 North-South Asymmetry: Simulations with Displaced HCS

The tilted dipole model used in our earlier simulations (Kóta and Jokipii, 1991; 1998) assumed a basic north-south symmetry of the HMF. Recent observational evidences (Simpson et al., 1996; Smith et al., 2000) suggest a southward displacement of the HCS during the solar minimum around 1996. This offset of the HCS does also imply a stronger average field in the southern hemisphere.

Figure 1 shows how recurrent 27-day cosmic-ray variations change if the tilted HCS is displaced 5^o to the south. The upper panel (a) illustrates the effect of drifts in a symmetric model, without CIRs, assuming a tilt angle, $\alpha = 30^o$, and a uniform 400 km/s solar wind speed. The symmetric HCS results in 13.5-day waves: the intensity is highest at sector crossing for both polarities. The amplitude is significantly larger for $A < 0$, when particles drift inward along the current sheet. For $A > 0$, ions drift from the polar regions and are less sensitive to the waviness of the HCS.

Panel (b) shows a remarkable change in this picture when the HCS is offset by 5^o to the south. While the recurrent variation remains essentially unchanged for $A < 0$, a significant 27-day wave arises for $A > 0$. The underlying cause is that, for $A > 0$, in different sectors we sample different regions of the heliosphere. A large fraction of the particles observed in the outward sector (marked by $+/-$) come from the north while particles seen in inward sectors come primarily from the south. Hence, cosmic rays are quite sensitive to any north-south asymmetry in the $A > 0$ cycle. The weaker average field in the northern hemisphere causes an excess of cosmic rays in the outward sector (above the HCS).

Panel (c) shows simulation results with CIRs included. CIRs cause the recurrent variations to increase for both polarities. We find that, with the parameters used, the recurrent 27-day wave turns out larger for $A > 0$, while the 13.5-day wave is larger for $A < 0$. The displacement of the HCS, in this simplest form outlined above, would not account for the larger 13.5-day wave for $A > 0$ found by Richardson et al. (1999).

In the simulations presented here and later in this work we assume both diffusion coefficients, $\kappa_\parallel$ and $\kappa_\perp$, to scale inversely proportional to the magnetic field, B. We take $\kappa_\parallel = \beta\kappa_0(P/P_0)(B_0/B)$ with $\kappa_0 = 1.5\,10^{21}\mathrm{cm}^2/\mathrm{s}$, $P_0 = 1\,\mathrm{GV}$, and $B_0 = 5\,\mathrm{nT}$ (β is the particle speed per speed of light). The ratio of $\eta = \kappa_\perp/\kappa_\parallel$ is kept constant at $\eta = 0.05$.

We note that asymmetries between $A > 0$ and $A < 0$ become larger, while the general tendencies remain similar, if a smaller $\kappa_\perp$ is assumed. Figure 2 shows simulation results with $\kappa_\perp/\kappa_\parallel = 0.02$.

3 Simulations with HMF including Quadrupole Components

The simple tilted dipole model of the Sun (Gosling and Pizzo, 1999), which prevailed during quiet periods, no longer applies since the Sun entered a more active phase. Recent observations show that recurrent high speed streams still persist, though the large polar coronal holes of solar minimum shrink to smaller areas and move to lower latitudes (Smith et al., 2001). During solar maximum, the HCS extends to high latitudes. Tilted dipole model with high tilt angles has been studied by Burger and Potgieter (1999). In addition to the high latitudinal excursion, the HCS also takes a more complex structure. The dipole of the solar magnetic field decreases while quadrupole moments increase (Sanderson et al., 1999), resulting in a 4-sector configuration in most of the heliosphere. In the present work we extend our 3-D code, which we utilized in the past to model polar coronal holes and CIRs, to cover more complex structures of the HCS and CIRs.

Here we present a simulation where a significant quadrupole component is added to the dipole field. Figure 3 illustrates the simulated evolution of the HCS, solar wind density, speed, together with the resulting 2 GeV cosmic ray distribution at 1 AU heliocentric radius. The solid line indicating the HCS shows the resulting field is a 4-sector HMF. The regions of high-speed streams move naturally to lower latitudes, resembling to conditions in late 1999, discussed by Smith et al. (2001) and by McComas et al. (2001). We assume a speed of 550 km/s in the fast wind regions and slow 350 km/s wind elsewhere.

The right panels of Figure 3 show the resulting recurrent variations near the Earth in the plane of heliographic equator. Compression regions are formed, while variations in the speed of the processed solar wind decreases from its original values. Variations in the simulated cosmic-ray intensities are present, but they cannot be clearly associated with respective variations in the solar wind. The Earth would sample conditions along the dotted line, observing four sectors. We find that depressions in the compressed regions, the signatures of the passage of CIR, are present but not dominant.

The predicted 26-day variation of GCR flux (bottom right panel) is the combined result of CIRs and particle drifts. Also shown in the bottom right panel (dashed line) is the simulated cosmic ray variation that would result for the same configuration but with the opposite polarity ($A < 0$). The difference between the solid and dashed lines can be ascribed to drift effects.

We note that, in a symmetric dipole model, there are two sector crossings and these are essentially identical. In a more complex HMF this will no longer be true. Different sector crossings may yield quite different signatures in cosmic-ray variations. Intensity maximum can, in general, be expected near the crossing where particle drifts along the HCS ensures a preferential connection to the polar regions (Kóta and Jokipii, 2001).

4 Conclusions

We presented numerical simulations to extend our earlier 3-D modeling of cosmic-ray transport to include north-south asymmetries as well as quadrupole fields. North-south asymmetries may play a role during solar minimum (Simpson et al., 1996; Smith et al., 2000). We find that the recurrent variations may turn out larger for $A > 0$ in qualitative agreement with the findings of Richardson et al. (1999) if the HCS happens to be placed asymmetrically. We emphasize that, in general, cosmic-ray ions should be more sensitive to any north south asymmetry in the $A > 0$ cycle.

We have also addressed the possible role non-dipole fields, with more complex HCS may play. We considered a 4-sector field, with coronal holes moving to lower latitudes. We find that the high-speed streams assumed in our model produce depressions in the flux of GCR. These, however, remain less profound than those during solar minimum conditions. More detailed and more realistic future simulations are required for quantitative comparisons with observations.

Acknowledgements. This work has been supported by NASA under grants NAG5-6620, NAG5-4834, and NAG5-10884 and by NSF under grant ATM-9616547.

References

Burger, R. A. and Potgieter, M. S., *Proc. 26th Int. Cosmic Ray Conf., 7*, 13, 1999.

Burlaga, L. F., McDonald F. B., Goldstein M. L., and Lazarus A. J., *J. Geophys. Res., 90*, 12 127, 1985.

Gosling, J. T. and Pizzo, V. J., *Space Sci. Rev., 89*, 21, 1999.

Kóta, J. and Jokipii, J. R., *Geophys. Res. Lett., 9*, 656, 1982.

Kóta, J. and Jokipii, J. R., *Astrophys. J., 265*, 573, 1983.

Kóta, J. and Jokipii, J. R., *Geophys. Res. Lett., 18*, 1797, 1991.

Kóta, J. and Jokipii, J. R., *Space Sci. Rev., 83*, 137, 1998.

Kóta, J. and Jokipii, J. R., *Adv. Space Res.*, in press, 2001.

McComas D. J., Gosling, J. T., and Skoug, R. M., *Space Sci. Rev.*, in press, 2000.

Newkirk, G. Jr and Fisk, L. A., *J. Geophys. Res., 90*, 3391, 1985.

Parker, E. N., *Planet. Space Sci., 13*, 9, 1965.

Sanderson, T. R., Lario, D., Maksimovich, M., Marsden, R. G., Tranquille, C., Balogh, A., Forsyth, R. J., and Goldstein, B. E., *Geophys. Res. Lett., 26*, 1785, 1999.

Smith, E. J., Jokipii, J. R., Kóta, J., Lepping, R.P., and Szabo, A., *Astrophys. J., 533*, 1084, 2000.

Smith, E. J., Balogh, A., Forsyth, R. J., and McComas, D., *Space Sci. Rev.*, in press, 2001.

Richardson, I. G., Wibberenz, G., and Cane, H. V., *J. Geophys. Res., 104*, 12 549, 1999.

Simpson, J. A., *Space Sci. Rev., 83*, 7, 1998.

Simpson, J. A., Zhang, M., and Bame, S., *Astrophys. J. Lett., 465*, L69, 1996.

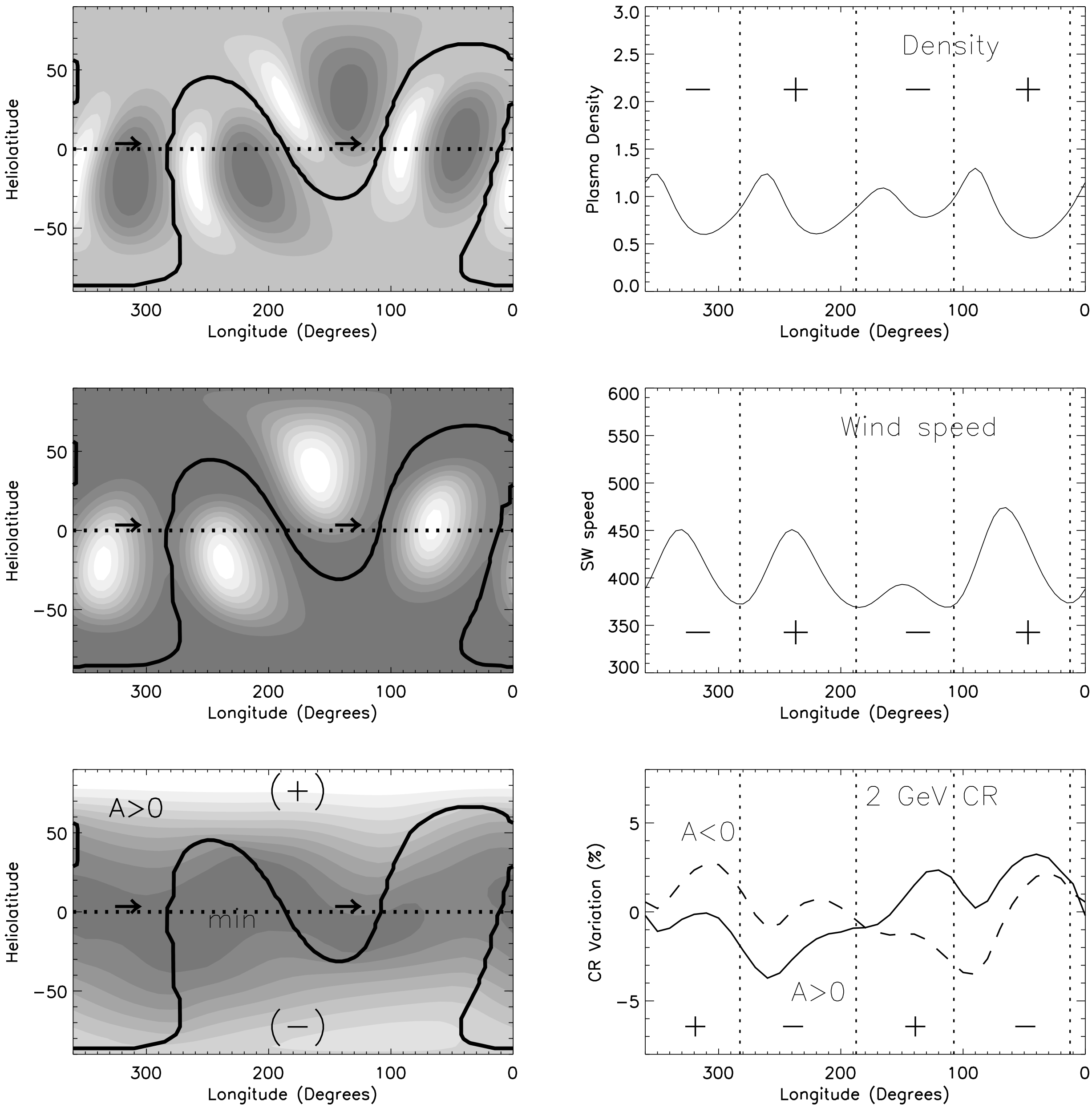

Fig. 3. Simulated variation of plasma density (top, compression regions are light areas), solar wind speed (middle, high speed regions are light) and 2 GeV cosmic-ray fluxes for $A > 0$ (bottom, higher intensities are light) at 1 AU. The thick line indicates the HCS. In one soler rotation the Earth samples conditions along the dotted line. The respective recurrent variations at Earth are illustrated in the right panels. Vertical dotted lines mark sector crossing. Also shown is the recurrent cosmic-ray variation that would be obtained for the same configuration, with opposite polarity (dashed line, in bottom right panel).