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The Origin of Solar Diurnal Variation of Galactic Cosmic Rays above 100 GV

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Abstract: Recent observations of the Matsushiro deep underground muon telescope indicate that the solar diurnal variation (after correcting for the Compton-Getting anisotropy due to the Earth's orbital motion) has a significant solar cycle variation and a 0.04% daily wave extends to rigidities as high as several hundreds of GV during solar maximum. We construct a simple model to simulate the motion of high-rigidity particles in the heliosphere assuming different heliospheric current sheet (HCS) configurations. An ensemble of particle trajectories are traced back from Earth. The model includes regular motion as well as scattering due to magnetic field irregularities. We find that a highly tilted and warped sheet may result in an anisotropy, comparable to that observed at Matsushiro/Zohzan around 600GV. The variation of the predicted amplitude and phase is compared with the observed ones. The implications of the anisotropies will be discussed.

Introduction

The effects of the heliospheric magnetic field (HMF) on galactic cosmic rays (GCRs) decrease toward higher energies. GCRs of high rigidity become less sensitive to scattering on the irregular component of the HMF. At rigidities above tens of GV, the most visible heliospheric effects are the solar-induced anisotropies that appear as solar and sidereal diurnal variations in Earth-based observations. These anisotropies carry valuable information since high-rigidity GCR samples the large-scale of the HMF. Heliospheric effects should sooner or later cease. The transitions region, where this happens might abrupt or continuous [1], [2]. The nature of the upper limiting rigidity is not well understood.

Recently, a 20-year worth of the Zohzan observations revealed that heliospheric effects may extend to several hundreds of GV [3]. The Zohzan underground telescope (220m w.e.) has been operating at Matsushiro, Japan since 1984. Zohan monitors 17 directional channels, the median energy for the vertical channel is 659 GV. Figure 1 shows the summation dial of the year-by-year values of the mean harmonic diurnal vector. The Compton-Getting anisotropy resulting from the Earth's orbital motion was removed. Inspection of the amplitude and phase of the solar diurnal vector, shown in Figure 2, indicates that a small but significant genuine free-space anisotropy is present during the years of high solar activity, while no discernible anisotropy is present during solar minimum.

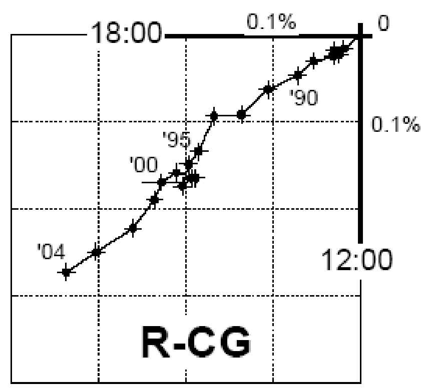

Figure 1: Summation dial of of the yearly harmonic vectors observed by Zohzan from 1985 to 2004, after removing the CG anisotropy.

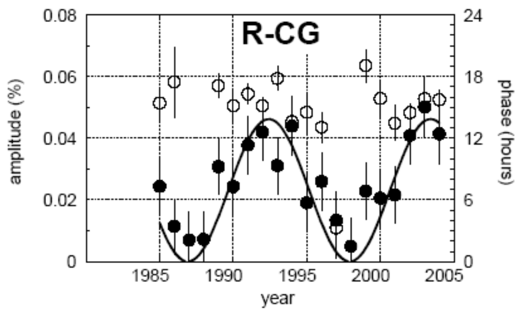

Figure 2: The amplitude and phase of the solar diurnal variation. The solid curve indicates a sinusoidal best fit.

In this work, we address the Zohzan observations and present numerical simulations conduced along the line of the work [4], assuming a corotating model HMF with a tilted and possibly warped heliospheric current sheet (HCS).

Numerical simulation and discussion

Particles of >100 GV rigidities are only weakly scattered in the heliosphere. Parker's [5] diffusive equation assumes frequent scattering, and becomes inaccurate at high rigidities. Instead, one may adopt alternative approaches [4], [6] that remain applicable for weak scattering. In this work, we follow the method of Erdős and Kóta [4], and trace back particle trajectories to compute the energy loss, ΔE, suffered along individual trajectories. Then, the relative change of flux, $\Delta J/J$, from a given direction is related to the relative energy change as

$$\Delta J/J = (\gamma + 2) * \Delta E/E \tag{1}$$

where J is the unmodulated flux at primary energy E, while γ stands for the exponent of the energy spectrum, $J \propto E^{-\gamma}$. The method outlined here emphasiyes the regular motion of GCR in the HMF. The typical pole-to-equator potential is a few hundred MV and this sets a natural scale for the expected anisotropies.

A steady potential field, in itself, or combined with isotropic scattering, would not cause anisotropy.

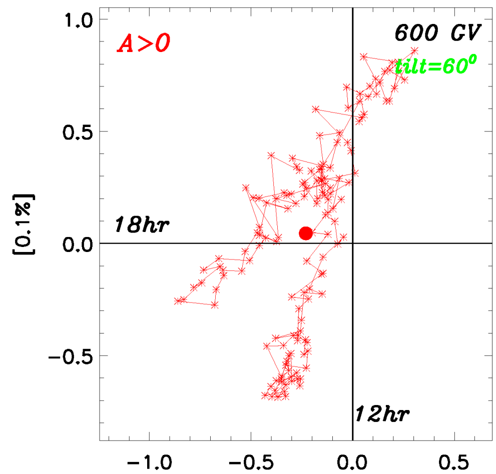

Figure 3: Simulation results for the $A > 0$ (positive) polarity prevailing during the 1990-es. Individual points represent different longitudinal locations relative to the HCS. The full circle indicates mean value.

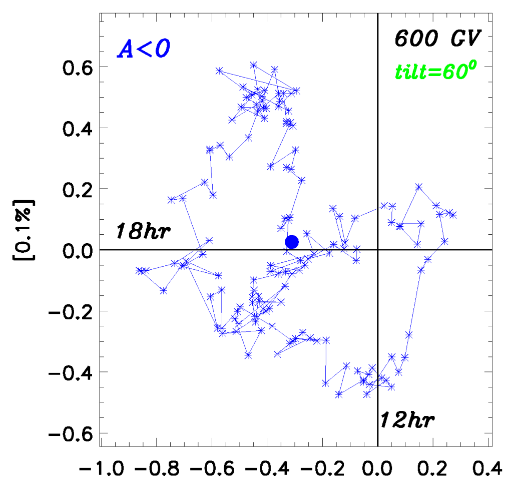

Figure 4: Same as Figure 3, for the negative polarity ($A < 0$).

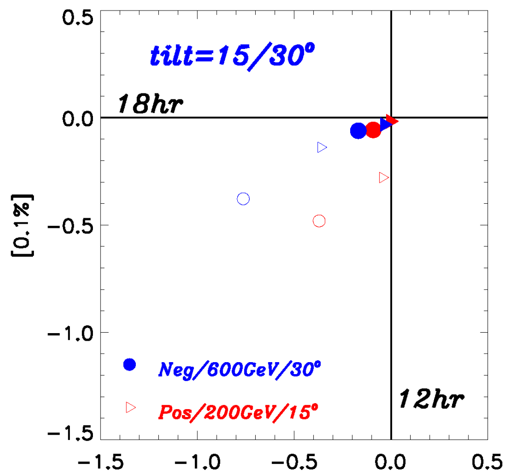

Figure 5: Longitinal averages of simulation results for low-medium solar activity, i.e. for tilt of 15^o (triangles) and 30^o (circles). Empty symbols refer to 200 GV, filled symbols refer to 600GV.

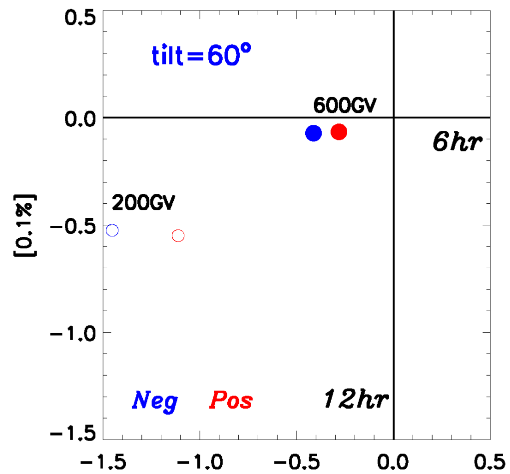

Figure 6: Same as Figure 5 for higher solar activity with 60^o tilted dipole HMF.

Arguably the largest and most dominant time-dependent structure of the inner heliosphere is the corotating wavy current sheet. Similarly as in [4] we considered a corotating HMF with a tilted and possibly warped heliospheric current sheet (HCS). Calculations were conducted for various tilt-angle/warp configurations for the two polarity states ($A < 0$ for 1980-1990, and $A > 0$ for 1990-2000), for rigidities 200GV and 600 GV.

By contrast with [4], which considered regular GCR trajectories, we also include weak scattering, by adding isotropic small-angle scattering.

Figures 3 and 4 show numerical results obtained for a highly tilted ($\alpha = 60^o$) and highly warped HCS. Individual data points represent averages over random trajectories reaching Earth in the helioequator at 1AU from the Sun, at different longitudinal positions relative to the corotating HCS. Full circles indicate averages over 27-days.

The tilt angle, α, is known to change from low value during solar minimum to high value during solar maximum. Shown in Figure 5 are the longitude-averaged simulation results obtained for low solar activity, assuming tilted dipole fields with small-to-moderate tilt angle ($\alpha = 15^o$ - triangles, and $\alpha = 30^o$ - circles). The results obtained for 200 GV are in general qualitative agreement with the characteristic 22-year cycle of the corotational anisotropy, i.e. that the anisotropy is smaller for small tilt angle, and its phase is close to 18hr local solar time (LST) for $A < 0$, while it shifts toward earlier hours during the $A > 0$ period (see [7] and references therein). For 600 GV, the simulation yields negligible harmonic vectors.

Figure 6 shows that the simulations obtained for a highly tilted dipole ($\alpha = 60^o$) do yield a ≈0.04% daily variation with a phase between 12 hr and 18 hr LST for 600GV, in qualitative agreement with the Zohzan observation (in Figure 2).

Finally, Figure 7 illustrates a simulation obtained for the same 60^o tilt-angle, but with a highly warped HCS (a considerable quadrupole moment). The predicted mean solar diurnal waves turn out to shift toward later hours for this warped HCS configuration. At this stage, we cannot tell whether this happens due to a random process or due to a systematic trend. Further, more extended and more quantitative, studies, are to be conducted in future.

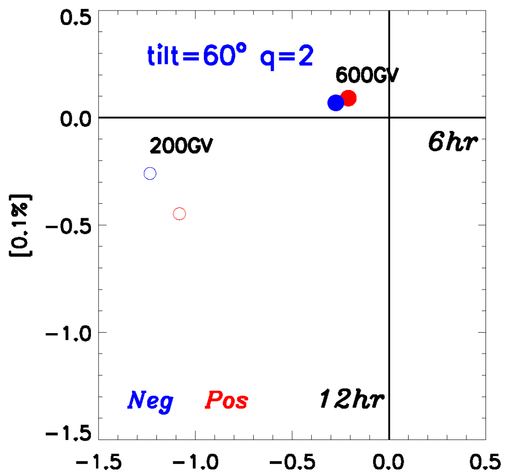

Figure 7: Same as Figure 6 for a 60^o tilted HMF, with a quadrupole component, resulting in highly warped HCS, added.

Conclusions

We conducted numerical simulations to explore if a highly tilted HCS prevailing during solar maximum can induce solar diurnal variation extending to GCR rigidities as high as 600GV. Our initial results indicate that this might occur, simulation results are in qualitative agreement with the Zohzan observations [3]. Our preliminary results give no discernible anisotropy for small tilt angles (i.e solar minimum) while a ≈0.04% diurnal vector, with phase between 12hr and 18hr LST, appears for the highly tilted HCS of solar maximum. More quantitative studies are planned in future.

Acknowledgments

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