Modulation of Cosmic Rays at and beyond the Heliospheric Termination Shock

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Abstract

The modulation of cosmic ray is studied with a numerical model including a solar wind termination shock, a heliosheath and drifts. Results show interesting features caused by the termination shock and the heliosheath which differ markedly for the two polarity cycles, with energy and with increasing solar activity. The heliosheath is found to be a distinguishable modulation 'barrier', especially during solar minimum activity.

1. Introduction

The possibility of significantly large modulation in the very distant heliosphere was first addressed by [5]. Recently, several observational publications addressed the issue of heliosheath ('barrier') modulation [3, 4, 6, 7]. These observations near the predicted location (85–90 AU) of the solar wind termination shock (TS) enabled us to study the modulation of galactic cosmic rays (GCRs) in the outer heliosphere in detail, especially how modulation may occur in the heliosheath, the region between the TS and the heliopause. The width of the heliosheath is not well known, it is estimated to be at least 30–50 AU. For this study a time-dependent, two-dimensional numerical model, including the solar wind TS, a heliosheath and drifts, is used to illustrate the effects of the TS and the heliosheath on proton modulation of different energies, for the two solar magnetic field polarity cycles, and as modulation changes from minimum to moderate maximum conditions. The model, the modulation parameters and the results are described in detail by [1, 2].

2. Results and discussion

Figure 1 depicts the modulation effects of the TS, of the heliosheath and the differences between the two magnetic field polarity cycles. These effects clearly diminish with increasing energy to the extent that 'barrier' effects remain effective only for $A > 0$ cycles. The model and observations are most reasonably compatible, illustrating that the TS model can represent the observed radial dependence

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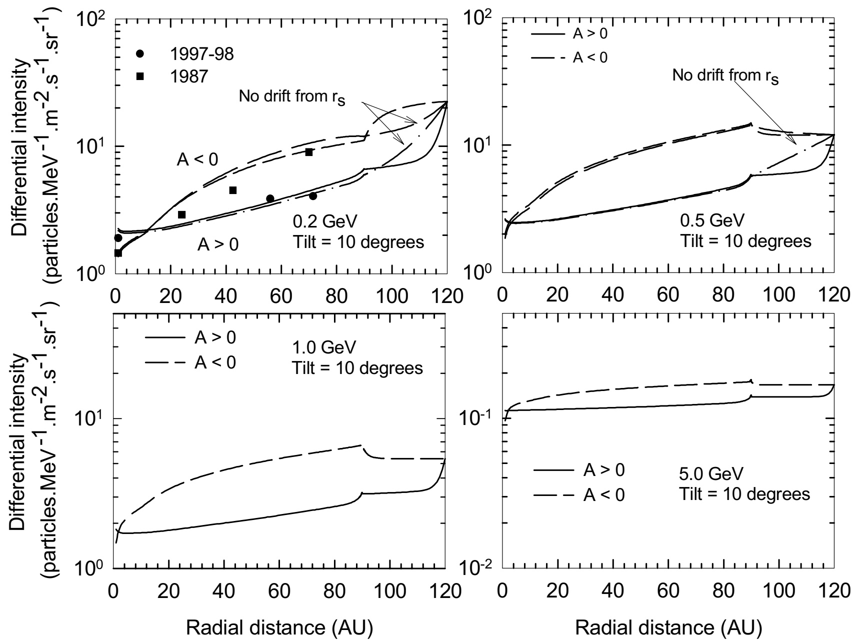

Fig. 1. Computed radial intensities for GCR protons for both polarity cycles in the equatorial plane at 0.2, 0.5, 1.0 and 5.0 GeV respectively, and for $\alpha = 10°$. LIS is at 120 AU. Filled circles represent $A > 0$ data, squares $A < 0$ data of IMP, Pioneer 10, Voyager 1 and 2 for solar minimum conditions [see 6]. For 0.2 and 0.5 GeV modelling was also done no drift in the heliosheath, instead of just a reduction of a factor s (compression ratio) in drifts.

for both polarity cycles, with the radial gradients for the $A > 0$ always less than for the $A < 0$ cycles for $r < 40$ AU at energies $> \sim 0.05$ GeV and similar between 40 and 90 AU at all energies. In the $A > 0$ cycles significant modulation happens beyond the TS, evidently decreasing with increasing energy, with the intensity at the TS always less than for the LIS at 120 AU. For the $A < 0$ polarity cycle, a more gradual increase in the radial intensities up to the TS occurs, with the intensity higher at the TS than at 120 AU, but this changes significantly at 0.2 GeV where the modulation is conspicuously different beyond the TS compared to the other energies. To establish to what extent drifts play a role in the heliosheath, solutions are repeated for 0.2 and 0.5 GeV with no drifts beyond the TS, instead of reducing drifts only by a factor of s as in the previous cases, where s is the TS compression ratio. The sudden changes at the TS then makes way for more gradual increases.

Figure 2 shows the modulation for increased solar activity and illustrates that as for solar minimum conditions, the modulation inside the TS is different for $A > 0$ and $A < 0$ cycles but these differences diminish with increasing energy. The reason is that the $A < 0$ intensities respond more significantly to changes in

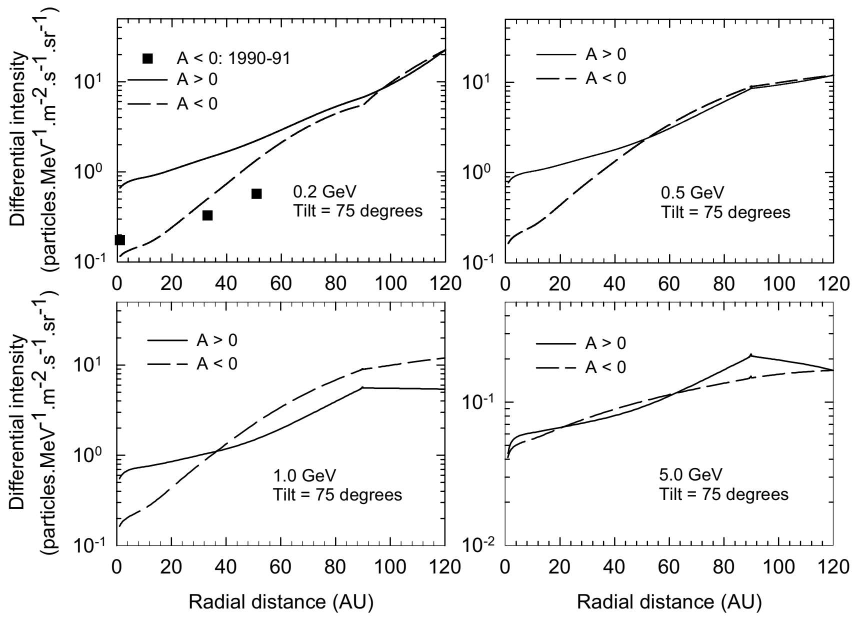

Fig. 2. Radial intensities for GCR protons for both polarity cycles in the equatorial plane at 0.2, 0.5, 1.0 and 5.0 GeV respectively, for $\alpha = 75°$ as function of radial distance. Squares represent $A < 0$ data for near solar maximum conditions [see 7], 1990–91.

the tilt angle. In contrast to solar minimum, the modulation difference beyond the TS between $A > 0$ and $A < 0$ is insignificant at lower energies but becomes more noticeable at higher energies. The 'barrier' effect has also changed significantly, in this case without the large increases for the $A < 0$ cycle. The modulation beyond the TS is still substantial for 0.2 GeV but becomes less significant with increasing energy compared to the amount of modulation inside the TS. For these conditions, the effect of the TS is the largest for the $A > 0$ cycle. The percentage of modulation in the equatorial plane beyond the TS w.r.t. the total modulation (between 1 and 120 AU) is summarized in Figure 3. Evidently, close to 100% modulation may occur in the heliosheath for both polarity cycles at energies $<\sim$0.02 GeV. For all four scenarios the modulation in the heliosheath eventually reaches 0%, but at different energies, e.g., with $\alpha = 10°$ for $A > 0$ at $\sim$ 10 GeV, but for $A < 0$ it happens between 0.3–0.4 GeV.

3. Conclusions

The heliosheath can be considered a distinguishable modulation 'barrier' but the impact on the total modulation depends on GCR energy and the magnetic field polarity. At solar minimum during $A > 0$ cycles the 'barrier' effect at lower energies is quite clear, e.g., it contributes 50% to the overall modulation

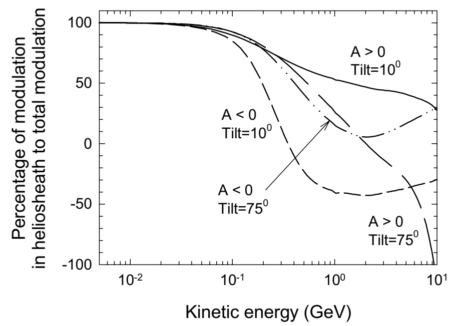

Fig. 3. Modulation (%) beyond the TS (inside the heliosheath) w.r.t. total modulation (between 120 AU and 1 AU) as function of kinetic energy for both polarity cycles ($A > 0$ and $A < 0$) and for solar minimum ($\alpha = 10°$) and maximum ($\alpha = 75°$) conditions in the equatorial plane. Negative percentages indicate that the intensity is actually increasing in the heliosheath as one moves from the outer boundary toward the shock.

at 0.5 GeV, but for $A < 0$ cycles it is almost negligible. At moderate maximum modulation the 'barrier' effect is also different and surprisingly less distinguishable below 1 GeV. Incorporating huge transient 'barriers' — global merged interaction regions — in the model may enhance the overall 'barrier' effect for maximum conditions.

4. References

1. Langner, U. W., Potgieter, M. S., and Webber, W. R., Adv. Space R., in press, 2003.
2. Langner, U. W., Potgieter, M. S., and Webber, W. R., J. Geophys. Res., in press, 2003.
3. McDonald, F. B., B. Heikkila, N. Lal, and E. C. Stone, JGR, 105, 1, 2000.
4. McDonald, F. B., et al., J. Geophys. Res., 107, SHH 2 1–9, 2002.
5. Webber, W. R., and J. A. Lockwood, ApJ, 317, 534, 1987.
6. Webber, W. R., and J. A. Lockwood, J. Geophys. Res., 106, 29323, 2001a.
7. Webber, W. R., and J. A. Lockwood, J. Geophys. Res., 106, 29333, 2001b.