Local Reacceleration of Galactic Cosmic Rays at the Heliosphere's Termination Shock

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Abstract

The measured intensities in the ecliptic plane of the GCR He (265 MeV/n) and ACR Oxygen (7 - 17 MeV/n) at 70 AU over the solar minimum (1996-1998) of cycle 22 are significantly less than that observed over the 1987 solar minimum of cycle 21 at 42 AU. The GCR He at 42 AU is 36% greater than that at 70 AU while ACR O is 5x greater. The different intensity levels and their very different time histories in the opposite phases of the heliomagnetic cycle represent a challenge to modulation theory and must in part be a drift related effect.

Kóta and Jokipii [1] have modelled the transport of GCRs and ACRs in a 1D model that includes a termination shock and a heliosheath region and in a 2D heliosphere that includes not only drifts but also the effects of an extended heliosheath region. They find that near the plane of the ecliptic in qA<0 cycles there is a significant enhancement of GCRs produced by local reacceleration in the heliosheath. This is accompanied by a much larger increase in the ACR O intensity, consistent with the Pioneer/Voyager observations.

1. Introduction

Galactic cosmic rays traversing the heliosphere must first cross the region of the heliosheath and the termination shock before encountering the outward flowing, turbulent supersonic solar wind. It was expected that the intensity of these cosmic rays would be systematically reduced with decreasing heliocentric distance by the processes of convection, diffusion and adiabatic energy loss and that gradient and curvative drifts in the interplanetary magnetic field would play a major role in their transport inside the termination shock.

The detailed observations of the temporal and spatial variations of galactic and anomalous cosmic rays by the Voyager and Pioneer spacecraft are steadily revealing the complexity of this modulation process as they extend to ever increasing heliocentric distances and over multiple phases of the 22-year heliomagnetic cycle.

In this note we re-examine previously reported observations of the intensity

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and time history of galactic cosmic ray He and anomalous cosmic ray O over the solar minimum period of cycle 21 and 22 [2,3,4] in the context of recent theoretical studies and simulations [1,5,6] which indicate that the local re-acceleration of galactic cosmic rays at the termination shock can play a role in the modulation process at solar minimum.

2. Observations

The time history of 7 - 17 MeV ACR O and 265 MeV/n GCR He is shown (Fig. 1) for 1972 - 1999.0 using data from IMP, Wind and Sampex at 1 AU and a combination of Pioneer 10 and Voyager 1 in the outer heliosphere. As Cummings and Stone [2] and McDonald *et.al.* [3,4] have found previously, the intensity of 7 - 17 MeV ACR O in the solar minimum of cycle 21 is ∼5x larger than that at the solar minimum of cycle 22 at 70 AU. For 265 MeV/n GCR He the cycle 21 intensity is 36% greater.

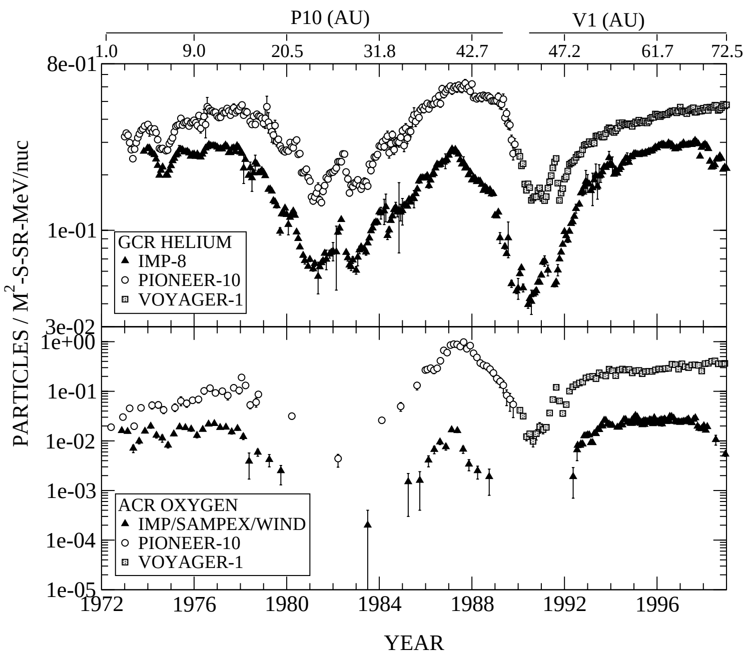

Fig. 1. Time History of 265 MeV/n GCR He and 12.5 MeV ACR O (26 day AVG) for 1972-1999.0 at 1 AU and from P-10 and V-1.

An examination of the energy spectra over these two periods (Fig. 2) shows no significant energy dependence for this qA<0 enhancement for 100 - 400 MeV/n GCR He and the ACR O. For ACR He the relative enhancement is approximately the same as that of GCR He down to an energy of ∼27 MeV/n. However there is a large increase in lower energy ACR He in cycle 22 that peaks at 6.5 MeV/n compared to 21.5 MeV/n in 1987.

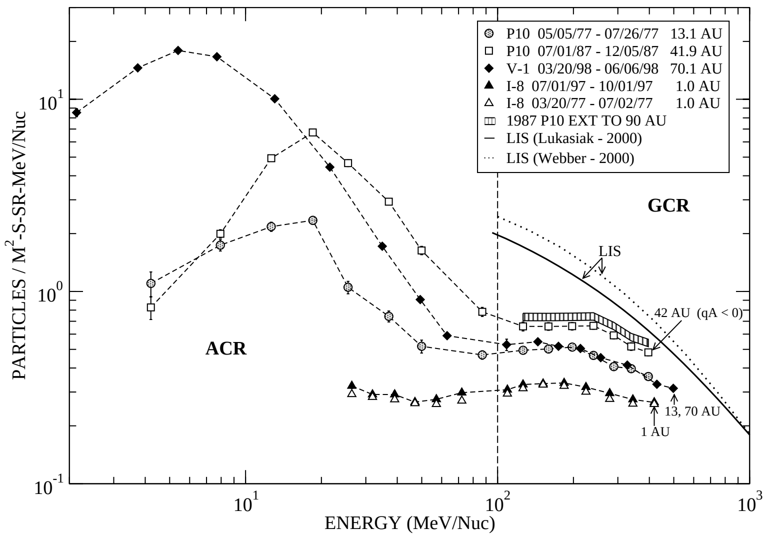

Fig. 2. Cosmic ray energy spectra over the solar minimum periods of cycle 21, 22 and 23.

3. Discussion

Previous studies have shown that both the recovery and the peaked intensity over solar minimum for cycle 21 are controlled by the inclination of heliospheric current sheet as would be expected for a qA<0 epoch when particles drift in along the current sheet and out through the polar regions of the heliosphere. For the cycle 22 solar minimum this flow pattern is reversed, the response to the current sheet inclination is greatly reduced and the observed time history shows a much flatter inclination.

In an early study Jokipii [7] showed that particles could be accelerated at the solar wind boundary by outward-moving magnetic irregularities. Webb, Forman and Axford [8] examined cosmic ray acceleration at stellar wind terminal shocks and concluded that with this process early-type stars could supply a significant fraction of the energy required by galactic cosmic rays. Kóta and Jokipii [1] studied the spatial variation of the galactic cosmic ray intensity at the solar wind termination shock and found that at higher energies diffusive shock reacceleration of galactic cosmic rays did occur. They noted that this effect was qualitatively the same for both polarity states but that drift effects inside the termination shock would produce observable differences. Similar conclusions were reached by Steenberg [5] and by Potgieter and Ferreira [6] for galactic cosmic ray electrons.

A sample simulation using the Kóta-Jokipii approach is shown in Fig. 3. At 42 AU the enhancement in the ecliptic plane of GCR He for qA<0 relative to qA>0 is on the order of 45% and is a factor of 9 for ACR O. While the gradients inside the termination shock are larger than the measured values, the predicted enhancements are in reasonable agreement with the observations in the outer heliosphere. Since reacceleration at the termination shock is not strongly drift dependent [1], the difference in the outer heliosphere intensities over successive solar minima mainly reflects the effects of drifts on particle transport inside the termination shock. GCR reacceleration is clearly a process that must be included in models of cosmic ray modulation.

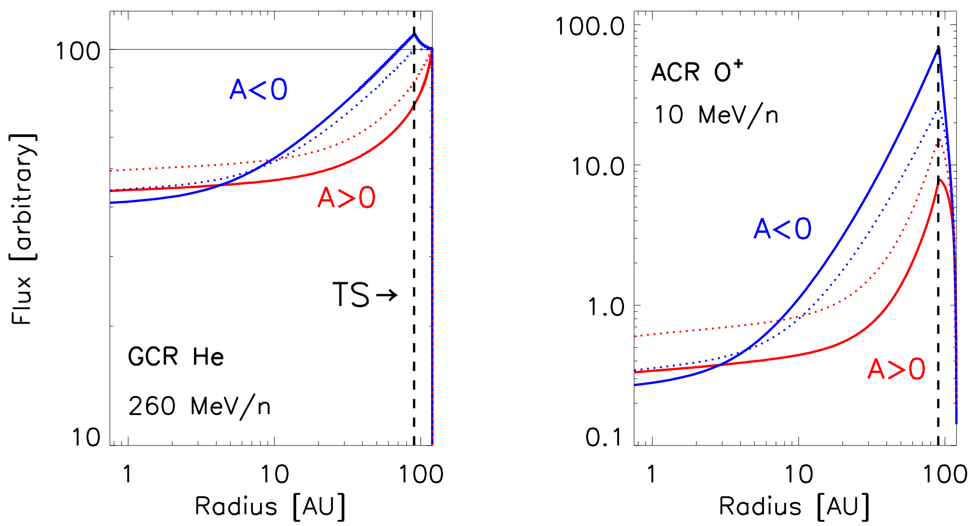

Fig. 3. 2D simulation of GCR He transport from the heliopause to 1 AU and ACR oxygen from the termination shock to 1 AU for qA>0 and qA<0 solar minimum periods with $K_{\|} = 5 \times 10^{22}$ cm^2/s and $K_{\perp} / K_{\|} = .02$. The solid lines are for $\lambda =$ 0 and the dashed lines immediately adjacent to these curves are for a heliolatitude of 30°.

4. References

1. Kóta, J. and Jokipii, J.R., Adv. Space Res. 13 (No. 6) 257, 1993 *and* Jokipii, J.R., Kóta, J. and Merényi, E., Astrophys. J. 405, 782, 1993.
2. Cummings, A.C. and Stone, E.C., Adv. In Space Research 23, 509, 1999.
3. McDonald, F.B., Lal, N., & McGuire, R.E., J. Geophys. Res. 103, 373, 1998.
4. McDonald, F.B., Cummings, A.C., Lal, N., McGuire, R.E., and Stone, E.C., Proc. 27th ICRC (Hamburg) 9, 3830, 2001.
5. Steenberg, C.D., Ph.D. Thesis, Potchefstroom University CHE, 1998.
6. Potgieter, M.S., and Ferreira, S.E.S., J. Geophys. Res. 10.1029/2001, JA 009040, 2002.
7. Jokipii, J.R., The Astrophys. J. 152, 799, 1968.
8. Webb, G.M., Forman, M.A., and Axford, W.I., Astrophys. J. 298, 684, 1985.