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Niagara Falls Cascade Model for Interstellar Energetic Ions in the Heliosheath

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Abstract: The Niagara Falls cascade model is proposed that the heliopause is a permeable boundary for direct entry of suprathermal and more energetic ions from the upstream LISM plasma 'river' through the turbulent heliosheath boundary region into the supersonic outer heliosphere.

Introduction

The Sun and surrounding heliosphere are moving upstream in the local interstellar medium (LISM) through a "river" of hot plasma and higher energy cosmic ray ions originating from some unknown combination of local and more distant galactic sources. The higher energy (> 70 MeV/n) fluxes of protons and alphas in Figure 1 mainly originate from these galactic sources and undergo energy losses [1] on entry into the heliosheath boundary region and thereafter into the supersonic heliosphere bounded by the solar wind termination shock (TS). Even in the outer heliosphere, upstream of the TS, the lower energy particles were heavily modulated in 2000 – 2003 during peak activity of Solar Cycle 23, while the higher energy galactic cosmic ray (GCR) fluxes were only slightly affected during this epoch.

Neutral interstellar atoms have unrestricted entry into the heliosphere as measured by Ulysses [2,3], but plasma and energetic charged particles are assumed to be diverted around the flanks of the heliosphere beyond the yet-unexplored heliopause boundary. The so-called anomalous cosmic ray (ACR) component of helium flux below 30 MeV/n in Figure 1, and the relatively higher flux of this component as compared to 30-69 MeV/n helium during 1997 – 2000, arise in this view from heliospheric solar wind pickup of photo-ionized interstellar neutrals, convective transport to the TS, whereupon acceleration to produce ACR ions presumably occurs [4]. Gradient-curvature drift [5,6] brings enhanced fluxes of positively-charged ACR ions down from the polar to the equatorial heliosphere during A > 0 (northward solar dipole) solar minimum periods as during 1997 – 1999. Even 10^2-MeV protons at

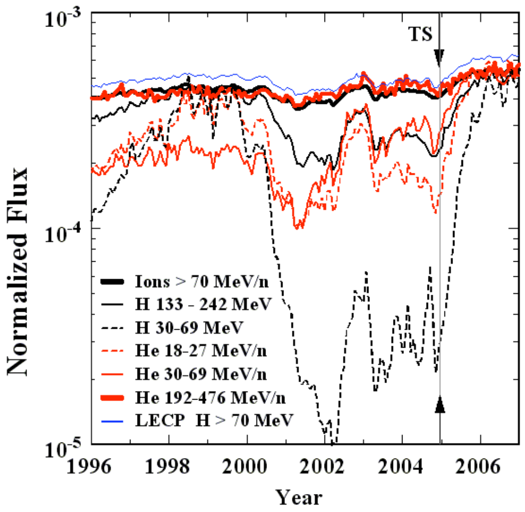

Figure 1: Fluxes and count rates for cosmic ray protons and helium over the past decade as measured by the Cosmic Ray (CRS) and Low Energy Charged Particle (LECP) experiments on Voyager 1. Each time profile (black and red respectively for CRS proton and alpha fluxes as 26-day averages, blue for LECP proton fluxes as daily averages) is roughly normalized to the peak intensities in the rise to solar minimum during 2006. "TS" and the vertical line denote the date of the termination shock crossing, Dec. 16, 2004.

solar minimum appear to have an ACR component attributable to TS acceleration [7,8]. Most modeling efforts for ACR transport and modulation in the heliosphere have assumed that TS acceleration provides the principle source.

Confirmation of the neutral LISM source for ACR ions comes from charge state and compositional abundance measurements, e.g. from measurement of singly charged ions, relatively high abundances for species with high first ionization potential, and lower abundances for carbon and other more easily ionized species. However, ACR charge states are directly measured only near Earth at highly modulated intensities by using the geomagnetic field and Størmer cutoff theory, and knowledge of actual LISM ion and associated neutral composition is very limited in the absence of in-situ LISM measurements.

Voyager 1 Data for the Heliosheath

The Voyager 1 crossing of the TS, as detected by magnetic field [9] and energetic particle [10,11] measurements, provided a unique opportunity to test the ACR source model with direct in-situ measurements. Interpretation of TS-crossing profiles in Figure 1 is complicated by the general rise in GCR and ACR fluxes to solar minimum levels during this epoch, and fluxes continue to rise beyond the TS into the heliosheath, but there is absolutely no indication of a local source of ACR protons or helium at the shock. The time profiles of these fluxes are apparently dominated by global heliospheric transport processes and not by local acceleration at the TS.

A further test of TS acceleration comes from the suprathermal ions measured by the Voyager 1 LECP experiment as shown in Figure 2. For ions at energies below 1 MeV, there is an increase in flux at the TS. But this higher flux level continues with variations into the heliosheath and is likely related to higher energy density in the more compressed magnetic field [9] of the heliosheath. The LECP data therefore show enhanced fluxes bounded by the TS, and extending throughout the heliosheath, but offer no compelling evidence for a local source at the TS. Absence of higher energy ACR flux enhancements at the TS have been attributed [12] to blunt geometry of the upwind TS and more favorable acceleration conditions along the flanks of the heliosphere with respect to the upwind direction of LISM neutral gas flow. This model is testable with measurements of energetic neutral atom emissions from the heliospheric boundary regions by the Interstellar Boundary Explorer (IBEX) due to launch in 2008 [13]. ACR and suprathermal ion sources may also originate beyond the TS, e.g. from distributed regions in the heliosheath, or else from outside the heliosphere as suggested earlier [14].

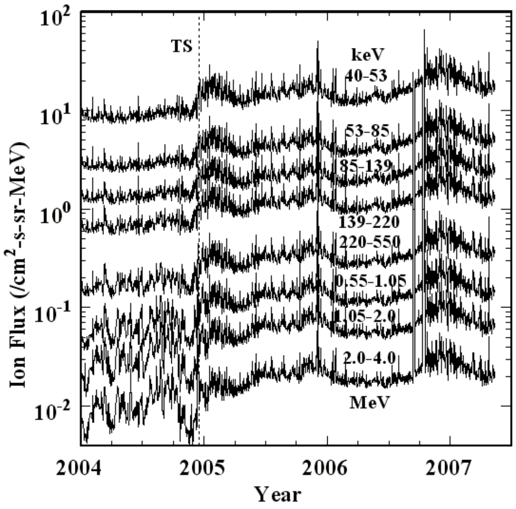

Figure 2: Time profiles of absolute sector-averaged fluxes for energetic ions measured by Voyager 1 LECP upstream and within the heliosheath. The TS crossing date, and LECP ion channel energy band (keV for 40-550, MeV for 0.55-4.0) for each profile, are shown.

The relatively constant ratios of the suprathermal flux channels in Figure 2, despite the absolute variations in flux, suggest convergence to a common spectral form throughout the heliosheath from some combination of distributed and external sources. An earlier compilation [14] of full-range proton spectra near, within, and as modeled beyond, the heliosheath is shown again in Figure 3. The constant flux channel ratios in Figure 2 correspond closely to the overall $E^{-1.5}$ power-law form of the near and in-situ suprathermal (0.001 – 1 MeV) spectra in Figure 3. This is the expected "universal" power-law form [15,16] for cascading particle acceleration in compressional magnetic turbulence characteristic of the heliosheath region. This process, involving bidirectional exchange of energy with the magnetic field turbulence, also accounts for quiet-time suprathermal ion spectra in the inner heliosphere [17,18].

The excellent extrapolation [14] for the LISM model spectrum in Figure 3 over eight decades of energy from observationally-constrained plasma to high energy cosmic ray fluxes for protons suggests that this process may also be active in the LISM. Continuing LECP measurements [19] indicate that the suprathermal ion spectra are unfolding to the cascade form with increasing Voyager 1 distance beyond the TS, albeit with some spectral variances potentially attributable to some combination of local heliosheath source or transport effects.

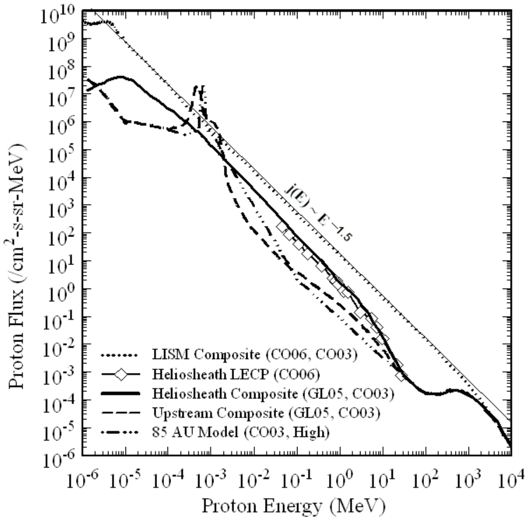

Figure 3. Composite proton flux spectra at plasma to cosmic ray energies upstream of the solar wind termination shock (GL05 [15], CO03 [20]), in the inner heliosheath (GL05 [15], CO06 [14]) and as projected with the $E^{-1.5}$ spectrum (CO06 [14]) for the local interstellar medium (LISM).

Conclusions

The alternative suggestion is offered here that *all* variances from the LISM model spectrum, as measured upstream of and within the heliosheath, are due to different transport effects for ion gyroradii less than, comparable to, and greater than the coherence scale of magnetic turbulence in regions within and beyond the heliosphere. The "third source" [19] for ions in the transitional energy region from below 1 MeV, where cascade processes are dominant, to the ACR and higher total energies above 100 MeV, where cross-field diffusion and gradient-curvature become dominant, might arise from anomalous transport along heliosheath field lines from distant source or boundary regions. The actual source of suprathermal and more energetic ACR ions is suggested to be in the LISM charged particle environment outside the heliosphere. There would still be a source of low energy pickup ions from interstellar atom photo-ionization within the heliosphere, but acceleration to ACR energies would not be limited to, or significantly occur at, the TS.

This alternative requires a relatively permeable heliopause for penetration of interstellar energetic particles (ISP) into the heliosheath and beyond into the supersonic heliosphere. The heliopause is idealized in MHD models of LISM-heliosphere interactions as the smooth and impermeable boundary separating outflowing solar wind plasma from inflowing interstellar plasma. However, this assumption may be substantially violated by the boundary layer turbulence expected to arise from Raleigh-Taylor and Kelvin-Helmholtz instabilities [21] at in the presence of flow density and velocity gradients. Other relevant processes include ion-neutral coupling between hot ions and the cold interstellar neutral gas, magnetic connection between turbulent inner and outer heliosheath fields across the heliopause, and the non-MHD dynamics of hot pickup ions with large magnetic gyroradii that require hybrid modeling approaches for accurate simulation of boundary layer effects.

The traditional mode of TS acceleration as the main source of accelerated pickup ions in the outer heliosphere is arguably not supported by the Voyager 1 heliosheath data. Here the suggestion with regard to TS acceleration is that the emperor has no clothes. Measurements from the expected Voyager 2 TS crossing in the next few years will be critical to further confirmation or refutation of the LISM source alternative. Although Voyager 1, potentially expected to reach the heliopause in the remaining operation lifetime, does not have a working plasma instrument to measure direct plasma flows across this boundary, the radial gradients of energetic particles measured by LECP and CRS should be informative. If the Niagara Falls cascade model is correct, there should be little change in suprathermal and ACR-energy ion fluxes across the boundary into the upstream outer heliosheath region of the LISM. The LISM-heliosphere interface is then suggested here as potentially analogous to Niagara Falls with largely unimpeded flow from a great river of local interstellar plasma into the heliosheath cascade regions of enhanced compressional magnetic turbulence and then onward into the supersonic heliosphere. Soon we may finally sense the true source of the upstream flow beyond the cascading flows and energetic ion mists of the heliosheath.

Acknowledgements

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