SH 2.2.01

Estimating the Fluxes of Energetic Neutral Atoms Produced from Ions Accelerated in Co-rotating Interaction Regions

K. C. Hsieh[1], A. Czechowski[2], J. Kota[3], J. R. Jokipii[3] and M. Hilchenbach[4]
[1]*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[2]*Space Research Centre, Polish Academy of Sciences, Bartycka 18A, 00-719 Warsaw, Poland*
[3]*Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721, USA*
[4]*Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, D-37191, Germany*

Abstract

The use of energetic neutral atoms (ENAs) as a means to image energetic ions in space plasmas has come of age. The modeling of ENA production in different populations of space plasmas in planetary magnetospheres, interplanetary space and outer heliosphere can now be compared directly with actual measurements of ENA fluxes coming from the respective regions. In interplanetary space, away from the influence of any planetary magnetospheres, the ENA flux has two major persistent origins - anomalous cosmic rays (ACR) within and beyond the solar-wind termination shock and ions accelerated in the co-rotating interaction regions (CIR). Here we examine the ENA flux of the latter origin, in anticipation of their potential detection by the HSTOF of CELIAS on SOHO. Since the ENAs are produced by the charge exchange between the energetic ions accelerated in CIR and the penetrating neutral atoms of the local interstellar medium (LISM), the spatial distributions of both ingredients determine the anisotropy of the ENA flux. This study will help in the interpretation of the anticipated observation and lead to a better understanding of the spatial distribution of a CIR. Present results of this study also lend support to the interpretation of the recently reported detection of ENAs by SOHO as of ACR origin.

1 Introduction:

The presence of magnetic fields and the Lorentz force have confined the study of charged particles of non-relativistic energies in space to *in situ* observations. Intrinsic to *in situ* observations is the difficulty of distinguishing between temporal changes and spatial variations in the distribution of the ion population. The ability to detect energetic neutral atoms (ENAs) in space removes this difficulty and allows one to study the spatial distribution of ion populations at a distance. This is because the ENAs in space were originally energetic ions (mostly +1) that became neutral by transcharging with atoms in the ambient neutral gas, a process that preserves the momenta of the ions at the instant of their respective neutralizations. The energy dependence of the ENA spectrum, therefore, is that of the original ions modified only by the charge-exchange cross sections (Shih, 1993). Generally, both the intensity of the ion fluxes and the charge-exchange cross sections decrease with increasing ion energy; therefore, the ENAs of interest are well below 1 MeV. The direction of flight of each ENA is essentially that of the momentum of the original ion at the instant of neutralization. These features make ENAs the unique means for direct sampling the non-radiating energetic-ion populations in regions of space that are not easily accessible to *in situ* observations. (See reviews by Gruntman (1997), Hsieh and Curtis (1998), and references therein.)

In interplanetary space, away from the influence of any planetary magnetospheres, the ENA flux has two major persistent origins - the anomalous cosmic rays (ACR) beyond the solar-wind termination shock and the ions accelerated in the co-rotating interaction regions (CIR). Estimates of these ENA fluxes - based on the theoretically calculated ACR spectrum at the solar-wind termination shock, measured proton fluxes associated with CIRs, and the observed distribution of penetrating neutral H and He from the local interstellar medium (LISM) - were performed in anticipation of opportunities to observe (Hsieh *et al*., 1992; Roelof, 1992). These opportunities have arrived with the launch of SOHO in December 1995 and that of Cassini in October 1998. The flux of energetic H atoms first observed in interplanetary space during quiet times in 1996 and 1997 was identified as of ACR origin (Hilchenbach *et al*., 1998). Implications of this observation are discussed in SH 4.4.02 of this conference.

In both cases, the ambient neutral gas is that of the local interstellar medium (LSM). While the energetic ions of the ACR reside in the outer heliosphere, those of the CIR are confined to a narrow range of heliocentric radii between 2 and 20 AU. The spatial distributions of the LISM gas in these two regions of the heliosphere are significantly different. As we shall show, such differences make it possible to separate the ENAs from the two distinct populations.

As the Sun begins its new activity cycle, we expect the ENA flux of CIR origin to rise. Since the detection of these ENAs would provide the unique means to observe the extended spatial structure of the CIR, we estimate here, in anticipation, the spatial features of the CIR generated energetic H and He as would be detected by the same instrument used by Hilchenbach *et al.* (1998), *i.e.* CELIAS/HSTOF on SOHO. A description of the particle model of CIR, the propagation of ions in the interplanetary space, and the production of ENAs in CIR will be followed by a discussion of the resulting ENA flux of CIR origin in contrast to that of ACR origin.

2 Modeling of ENA production in CIR:

Our model of CIRs is based on the tilted dipole model of the sun (Kóta and Jokipii, 1995; 1998). The solar-wind speed changes from the low value of 350 km/s in the streamer belt to a high value of 750 km/s in the polar region. The transition occurs fairly sharply about 15° from the heliomagnetic equator (*i.e.* current sheet). Typically we use a tilt angle in the 10° - 40° range. In the runs we used here the tilt was 20°.

The time (radial) evolution of the solar-wind plasma is calculated from a MHD simulation (Jokipii and Kóta, 1995), which is simplified but contains the most essential physics. The major simplification is that the solar-wind velocity is kept strictly radial, latitudinal and longitudinal deflections due to transverse forces (pressure gradients or magnetic tension) are not included. It is assumed that the structure of the current sheet remains stable for several solar rotations, thus steady state is assumed for the solar-wind plasma and magnetic fields in the frame co-rotating with the Sun (at the equatorial rate of rotation). Forward and reverse shocks form typically 2-3 AU from the sun, and they merge around 15-20 AU.

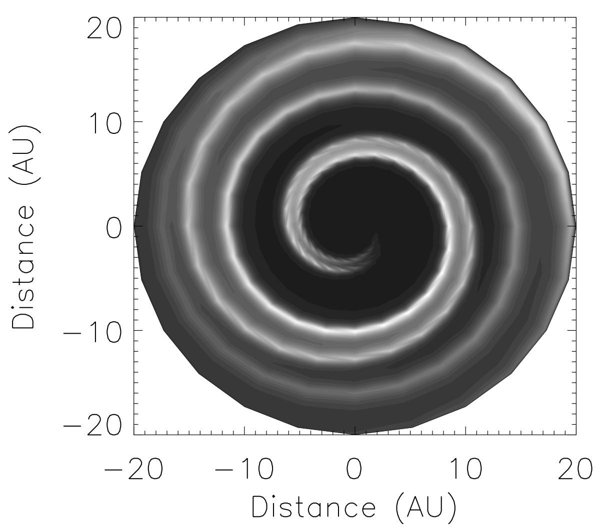

Figure 1: Contour plot of ~100 keV in a model CIR near the ecliptic. The model is confined to heliocentric radius of 20 AU. Within 20 AU, the bright areas contain the shock pair. The brighter shade represents the higher ion flux.

In the calculations we consider a sphere of 20 AU radius. We assume that this region (as for the CIRs and energetic ions) rigidly co-rotates with the sun. Asymmetries in the heliopause (and possibly in the outer heliosphere) are not expected to affect the inner regions significantly. The distribution of the interstellar neutral hydrogen is fixed in the fixed frame. It is a symmetric distribution around the direction of the interstellar wind, but largely asymmetric in the apex and anti-apex or upwind/downwind directions. The distribution of neutral hydrogen is described by the model of “hot” interstellar gas (Thomas, 1978). For comparison, the analytic solution of (Holzer, 1977) corresponding to the "cold" approximation was also considered. The spatial distribution of the hydrogen gas, with large (~5 AU) asymmetric cavity around the Sun extending farther in the LISM anti-apex direction is reflected in the directional dependence of the production of ENA. To an observer orbiting the Sun, as SOHO does, the distribution of neutral hydrogen has a annual variation due to the orbiting motion of the observer while the distribution of energetic ions has a 26-day variation due to the rotation of the Sun. The flux of energetic neutral atoms, thus, will be determined by the combination of these two variations.

The numerical code includes convection, diffusion, drifts and adiabatic cooling and acceleration of the CIR-accelerated ions. At the energies of interest, <150 keV, the code does not have sufficient resolution to model the acceleration at the shock from the injection energies, which takes place on a short scale length. We impose instead a power law spectrum at the shocks and compression regions as a source of accelerated population wherever the divergence of the solar wind velocity is negative (implying compression). The source strength is assumed to be proportional to V_{sw}/r^2. A spectrum of $J \sim E^{-2}$ is taken but the results are not sensitive to the precise value of the spectral exponent.

The transport and cooling or possible further acceleration of this charged particle population is modeled by our 3-D numerical code (Kóta and Jokipii, 1995; 1998). We find that, at low and medium latitudes, energetic ions are enhanced at the CIRs, thus the results are fairly insensitive to the precise values of the parallel and perpendicular diffusion coefficients. The results to be presented here were obtained with $\lambda_{//}$ = 0.1 AU, and $\kappa_{\perp} = 0.02\ \kappa_{//}$.

The resulting calculated ENA flux corresponds to the field-of-view of the CELIAS/HSTOF instrument on SOHO in the ecliptic, which has a line of sight directed at 37° west of the Sun (Hilchenbach *et al.*, 1997). The time variation of the flux reflects both the propagation of the CIR and the orbital motion of the spacecraft. The variation of the order of 20% in the ENA intensity on the scale of one solar rotation, is mostly caused by the most intense part of the CIR structure sweeping across the field-of-view and is specific to the CIR-generated ENA. The yearly variation reflects the density distribution of the background hydrogen, with the lowest flux of ENA arriving from the anti-apex of the heliosphere.

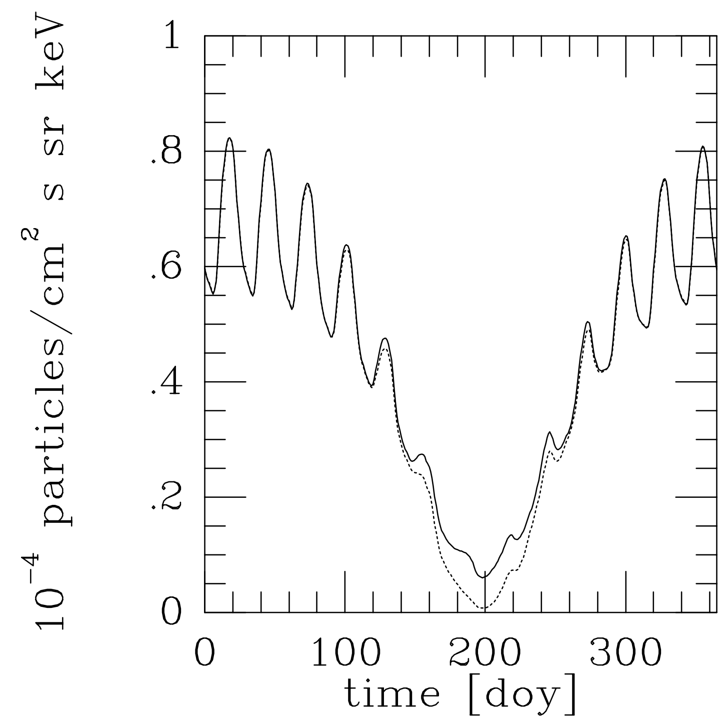

Figure 2: Flux of 100 keV H atoms coming form the protons accelerated in the CIR as would be seen by the instrument CELIAS/HSTOF on SOHO during a typical year. On DOY 194, the instrument looks into the heliotail. The depletion of LISM gas in the wake of the Sun reduces the production of ENA from the CIR. The dotted line is for a cold LISM gas, and the solid line for one with a temperature of 10^4 K. The 26-day periodic structure is due to the relative motion of the CIR and SOHO, and its phase is arbitrary.

The magnitude of the expected ENA flux depends on the source strength, *i. e.* the magnitude of the power law imposed. Our simulation gives CIR-accelerated proton fluxes comparable to those observed at Ulysses (Desai et al, 1999); *e. g.*, the CIR-proton flux at 100 keV peaks at ~1×10^{1} protons (cm^2 sr s $keV)^{-1}$. The resulting H flux (Figure 2) is consistent with that of Hsieh et. al. (1992). The H flux shown in Figure 2 is also comparable to that of ACR origin as observed by Hilchenbach et al. (1997) and the simulated in SH 4.4.02 of this conference. This fact suggests that the ENAs from ACR and that from CIR can best be distinguished by their anisotropy and the observation time relative to the solar cycle.

3 Opportunities of observation:

The opportunities of observing CIRs in ENAs are now existent. The instrument CELIAS/HSTOF on SOHO at L1 point, has already yielded the first detection of energetic hydrogen atoms of ACR origin (Hilchenbach *et al*., 1997). It will continue to collect data, which should contain ENAs from CIRs as the Sun continues to move towards the next solar maximum. Simultaneously, the dedicated ENA imager, MIMI/INCA, on Cassini is now cruising towards Saturn (Krimigis *et al*., 1999). With its larger geometrical factor, ~2.5 cm^2 sr, and lower energy threshold, ~30 keV, we should expect to see for the first time the latitudinal extends of the CIRs from different heliocentric distances. We note that the CIRs are prominent only during the rising and falling phases of the sunspot cycle.

4 Conclusion:

The use of a realistic 3-D CIR model for the production of ENA flux has demonstrated the general longitudinal feature of a CIR that can be observed by an instrument capable of detecting ENAs, such as CELIAS/HSTOF on SOHO. Because of the limited spatial extent of CIR and the distribution of the LISM gas in the inner heliosphere, the CIR-generated ENA flux has an anisotropy that is exactly out of phase with that of ENA flux of ACR origin, *i. e.* while the former peaks in the apex or upwind direction of the interstellar wind, the latter peaks in the anti-apex or downwind direction of the interstellar wind. This conclusion supports the report of Hilchenbach et al., (1997). The difference in anisotropy and the observation time relative to the solar cycle, together, give the best means to distinguish the two distinct populations, especially their flux levels are comparable. As the demand for using ENA as a means to image space plasmas increases, we expect the interaction between observation and modeling to bring us more realistic understanding of space-plasma populations, such as CIR and ACR.

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