Multi-Point Observations of Corotating Interaction Regions from STEREO and ACE

R. A. Leske*, G. M. Mason†, R. A. Mewaldt*, C. M. S. Cohen*, A. C. Cummings*, A. W. Labrador*, E. C. Stone*, M. E. Wiedenbeck‡, and T. T. von Rosenvinge§

**California Institute of Technology, Pasadena, CA USA*
†Johns Hopkins University/Applied Physics Laboratory, Laurel, MD USA
‡Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA USA
§NASA/Goddard Space Flight Center, Greenbelt, MD USA

***Abstract*. Although solar energetic particle (SEP) activity has been at a minimum for the last few years, significant particle enhancements due to corotating interaction regions (CIRs) have regularly appeared at 1 AU, providing an ideal opportunity to study CIR particles without SEP contamination. Observations of CIR time profiles from the two STEREO spacecraft commonly show delays that are often roughly as expected from the corotation time lag between the two spacecraft. However, in many cases different features seen at Ahead and Behind may suggest that transient disturbances in the solar wind alter connection to or transport from the shock, or that temporal changes occur in the CIR shock itself. We present CIR observations from STEREO and ACE at energies from ∼2-10 MeV/nucleon and examine the evolution of CIR time profiles as a function of spacecraft separation in longitude, radius, and heliographic latitude.**

***Keywords*: Corotating Interaction Regions, STEREO, ACE**

I. Introduction

Corotating interaction regions (CIRs) develop when high-speed solar wind overtakes and interacts with the preceding slow solar wind. Forward and reverse shocks often form at CIR boundaries, usually beyond 1 AU, where they may accelerate particles to ∼20 MeV/nucleon that diffuse inward along the magnetic field to 1 AU [1]. CIRs are especially prominent during the declining phase of the solar cycle, when the heliospheric magnetic field has a well-developed sector structure and coronal holes may extend to low latitudes. Additional CIR properties and their effects on energetic particles are discussed in various reviews (e.g., [2]).

Since early 2007 solar energetic particle (SEP) activity has been practically non-existent, yet significant CIR particle enhancements have regularly been observed at 1 AU, allowing the study of CIRs free of SEP contamination. During this period, the twin STEREO spacecraft have been making in-situ observations from locations up to ∼90° apart in longitude and up to ∼10° apart in heliographic latitude near 1 AU (Fig. 1). Among the instruments making up the IMPACT suite on STEREO is the Low Energy Telescope (LET) [3] which measures elemental composition from H to beyond Ni at ∼2 to ∼50 MeV/nucleon. We report CIR observations from this instrument during the present solar minimum; earlier results from this study may be found in [4].

II. Single-Point Observations

An overview of the recent CIR energetic particle activity is shown in Fig. 2. Except for several small SEP events, nearly all the low energy proton increases detected by STEREO/LET since the start of 2007 have been due to CIRs. Although all these CIR particle increases are associated with high-speed solar wind streams [4], as expected, the converse is not true; many high-speed streams have no associated particle increases at 1 AU at MeV energies. Differences in whether the streams create a shock, and the characteristics of any such shocks (location, size, strength, obliquity, etc.) presumably account for the differences in the particle activity; detailed modeling may be required to further address this issue. Since the beginning of 2009 the prevalence of the high-speed streams (and their maximum speed) has decreased, and along with it the occurrence rate of CIRs, as is typical of CIR behavior at true solar minimum. This appears to correspond to a decrease in the tilt of the heliospheric current sheet (HCS) below ∼30° [5] making it less likely for high-speed wind from high-latitude coronal holes to reach the ecliptic.

The CIR proton spectral indices (Fig. 2) tend to be quite soft at energies of several MeV, ranging from ~ -3 down to -6, similar to indices reported in other studies at these energies ([1], [6]). The small SEP events in Fig. 2 typically had considerably harder spectra, while the days with the hardest spectra have the lowest proton intensities and correspond to galactic cosmic ray (GCR) and anomalous cosmic ray (ACR) quiet-time levels.

The He/H ratio at 1.8-3.6 MeV/nucleon in these events is seen to vary by a factor of ∼2 on either side of ∼0.03 (Fig. 2), with the small SEP events typically having lower He/H ratios. The highest He/H ratios, appearing during the quietest days, are due to the presence of ACR He at these energies. Our CIR He/H ratio agrees with that reported in earlier studies at comparable energies

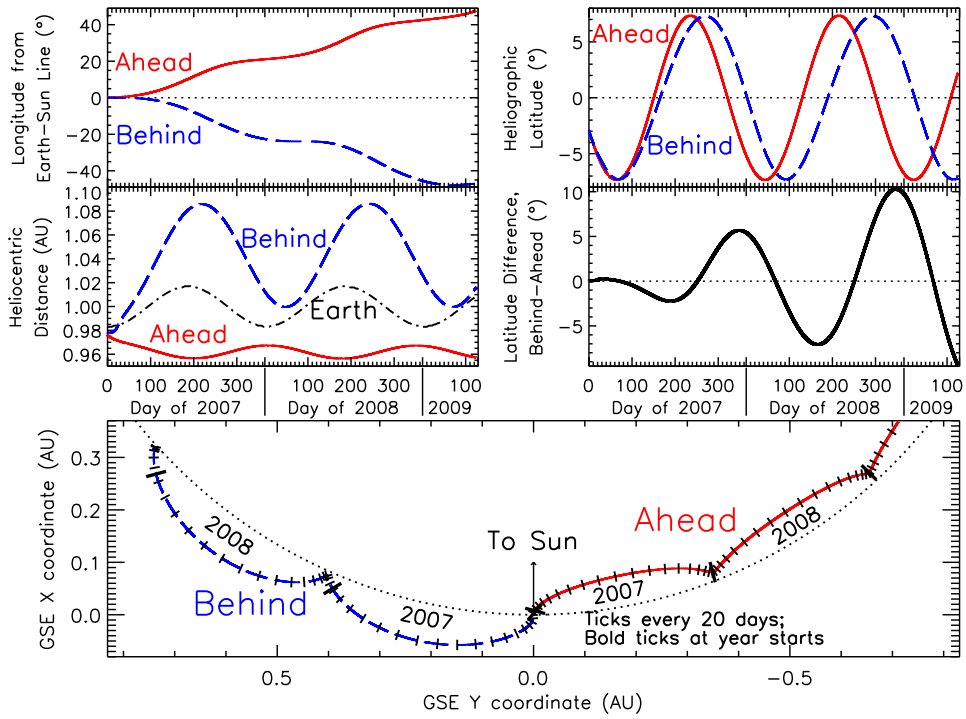

Fig. 1. STEREO position data for Ahead (*solid red curves*) and Behind (*dashed blue curves*) with quantities as indicated. The *dotted arc* in the *bottom panel* indicates a Sun-centered circle of 1 AU radius.

[1], [7]. Although the He/H ratio in these events often appears to have a significant energy dependence [4] when including data at 0.2–1 MeV/nucleon from the Suprathermal Ion Telescope (SIT) on STEREO [8], heavier ion abundance ratios have been found to be nearly independent of energy over this same energy range [6].

Examining selected CIR periods in more detail with higher time resolution (Fig. 3) reveals some of the diversity of time-dependent behavior observed during the course of an event, as the point of magnetic connection moves along the CIR shock. Sometimes a second, smaller particle increase is seen when the solar wind velocity is declining; these generally have a harder spectrum than the initial event. Based on double-peaked proton time profiles observed beyond 1 AU [9], these secondary increases may be due to connection to the reverse shock. Rather than causing a particle increase, sometimes a high-speed stream is associated with an abrupt end to the particle event (as in the 5th column of Fig. 3) presumably because the connection to the CIR shock is broken. At times, the spectral index and He/H ratio are nearly constant throughout an event (e.g., 5th column of Fig. 3), while in cases such as that shown in the 4th column of Fig. 3 both values vary widely and abruptly. We discuss other unusual features of the latter period in the next section.

III. Multi-Point Observations

Timing differences in the CIR profiles observed at the two STEREO spacecraft, Ahead and Behind, are discussed in some detail in [4] and are summarized here in Fig. 4. Corotation time differences were calculated for a range of solar wind speeds, accounting for the radial and longitudinal separation of the spacecraft (Fig. 1). After being slightly negative in early 2007 when the spacecraft were nearly radially-aligned, these calculated differences grow almost linearly with time, plateauing when the longitudinal separation rate of the spacecraft slows. The expected differences vary less with solar wind speed (the curves are more closely spaced) when the radial separation of the spacecraft is smaller. The observed timing differences roughly follow the expected corotation trend, but the expected spread in the timing differences is always less than ∼0.5 days whereas the scatter in the observed CIR timing differences is often several days. As was pointed out in [4], one should not neglect the fact that the heliographic *latitude* of the two spacecraft can differ by several degrees (Fig. 1), even though both orbit in the ecliptic. If the CIR boundaries have a low inclination to the heliographic equator, a small difference in spacecraft latitudes can easily introduce a timing spread of the observed magnitude. To illustrate this in Fig. 4, we have taken the location of the coronal magnetic neutral line from the Wilcox Solar Observatory's "classic" (2.5 R_s source surface) model, convected it out to each STEREO orbit, and calculated the expected time differences between the spacecraft for crossing the HCS, which often bounds the CIR particle increases [4].

The expected corotation time differences between Ahead and Behind were nearly constant in early 2008

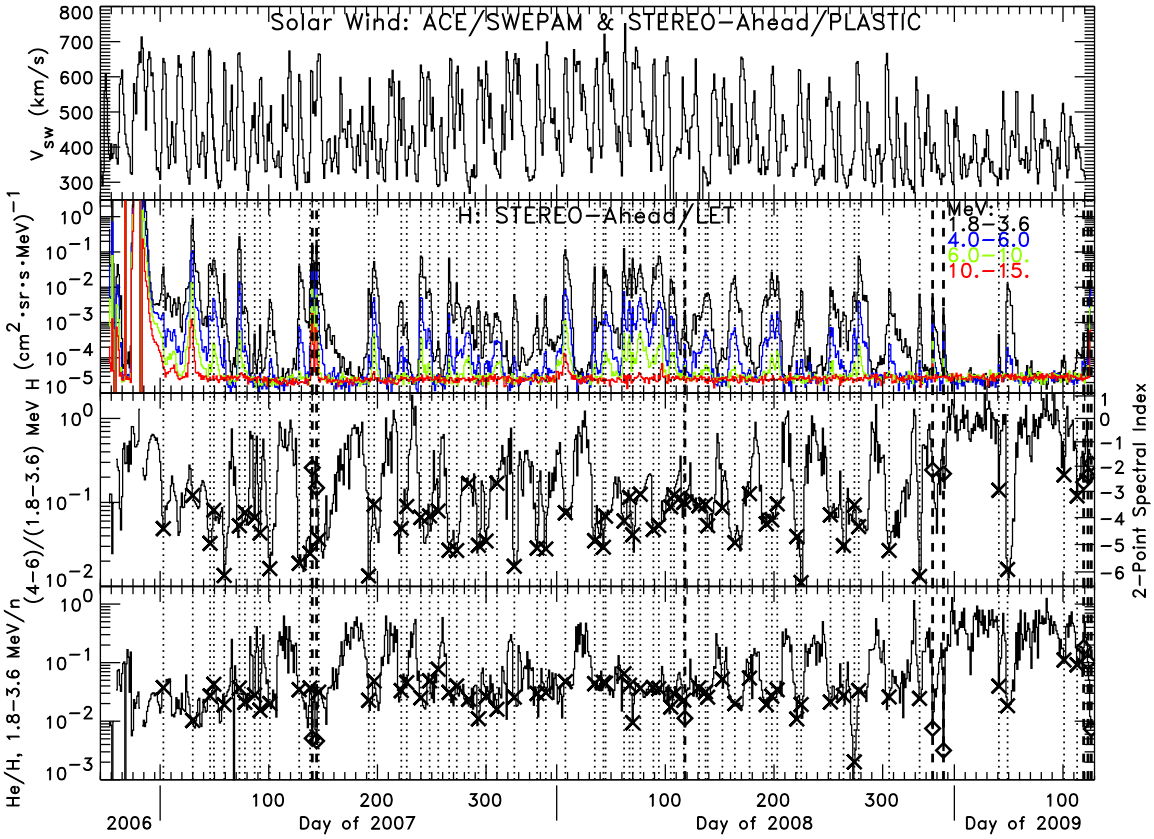

Fig. 2. Daily-averaged solar wind speeds from STEREO/PLASTIC on the Ahead spacecraft or ACE/SWEPAM (*top panel*), compared with daily-averaged proton intensities from STEREO/LET at the energies indicated (*second panel*). *Dotted lines* mark the local maxima of the CIR events; *dashed lines* indicate likely small SEP events. The *third panel* shows the ratio of the (4-6)/(1.8-3.6) MeV proton intensities, with the corresponding power-law spectral index shown on the *right axis*. Values at the CIR peaks are indicated by *crosses* and at the SEP peaks by *diamonds*. The *bottom panel* shows the He/H ratio at 1.8-3.6 MeV/nucleon, with the CIR and SEP peaks indicated as before.

(Fig. 4). A plot of Ahead, Behind, and ACE proton time profiles with the appropriate time offsets (Fig. 5) confirms this expectation, showing generally excellent agreement in the CIR boundaries observed by the 3 spacecraft during the first 100 days of 2008. The peak intensities, however, vary significantly and systematically among the spacecraft, either due to temporal changes in the intensities over the 3.3 day interval between observations or spatial (radial or latitudinal) intensity differences between the observers. If these changes are temporal, they do not continue at the same rate during the ∼27 days between observations, as the peak intensities are essentially back where they started by the next rotation and repeat the same pattern (Behind>ACE>Ahead). If these changes are due to a purely radial gradient, the small radial separation between the spacecraft at this time (∼0.04 AU; Fig. 1) makes this gradient ∼3000%/AU, nearly an order of magnitude larger than the ∼400%/AU or so more commonly reported for CIRs [7] (although local radial gradients at 1 AU as high as ∼700%/AU have been reported [10]).

It seems likely that a major contributor to the intensity differences is a latitudinal gradient; a similar conclusion was independently reached in [11] for other STEREO events at lower energies. If we estimate a *longitudinal* gradient from the CIR time profiles by equating a change in time with a change in longitude at the rate of 13.33°/day, we find an average intensity change of ∼35%/° during the rises and ∼10%/° during the decays during this period. Using the heliographic latitudes of the spacecraft (Fig. 1) and the peak intensities measured at each, we calculate an average latitudinal gradient during this time of ∼40%/°, comparable to that deduced for the longitudinal gradient. Note also that the peak intensities are most similar for the event near day 60, when the spacecraft are at the same latitude.

Abrupt changes in spectral hardness and the He/H ratio seen in the 4th column of Fig. 3 around days 68-73 and a rotation later at day ∼95 correspond to peaks in Fig. 5 that appear only at Ahead. Some transient event apparently affected the particle environment only at this one observer. Although this might be expected once from a small solar particle event, a recurrence one rotation later seems unlikely, and there is no obvious evidence of any associated activity on the Sun at these times. Additional study of CIRs from multiple vantage points, together with detailed modeling, may help to better explain such observations and further elucidate the physics of particle acceleration and transport in the heliosphere.

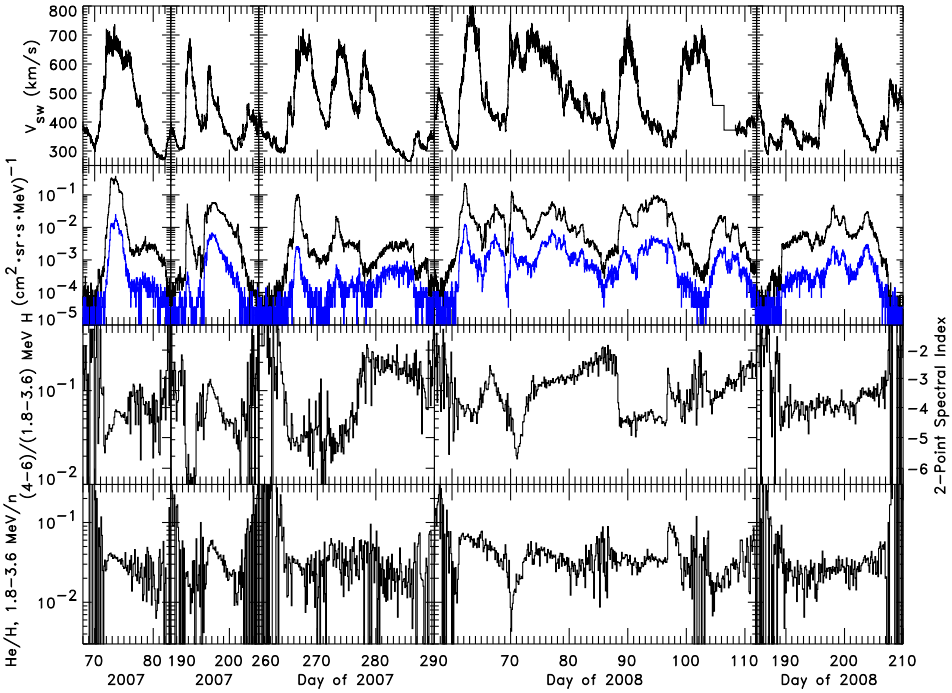

Fig. 3. Hourly-averaged solar wind speeds from STEREO/PLASTIC on the Ahead spacecraft (*top panel*), compared with hourly-averaged proton intensities from STEREO/LET at 1.8–3.6 and 4–6 MeV (*second panel*) for selected time periods. The *third panel* shows 3-hour averages of the ratio of the (4-6)/(1.8-3.6) MeV proton intensities, with the corresponding power-law spectral index shown on the *right axis*. The *bottom panel* shows 3-hour averages of the He/H ratio at 1.8-3.6 MeV/nucleon.

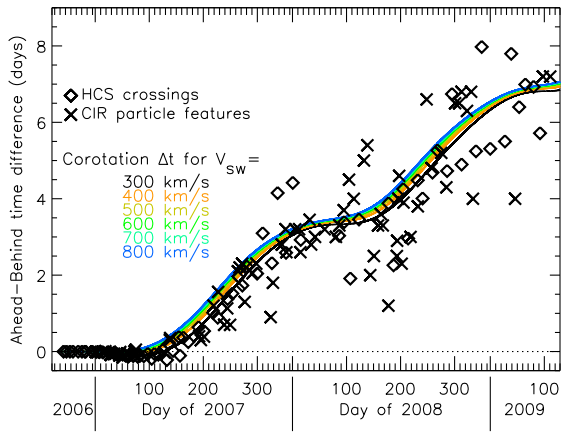

Fig. 4. Calculated corotation times between the STEREO spacecraft (based on their heliographic radii and longitudinal separation) for a variety of solar wind speeds (*colored curves*) compared with crossing time differences of the HCS (*diamonds*), which depend on the HCS tilt at the spacecraft latitude, and time differences in observed features in CIR time profiles (*crosses*).

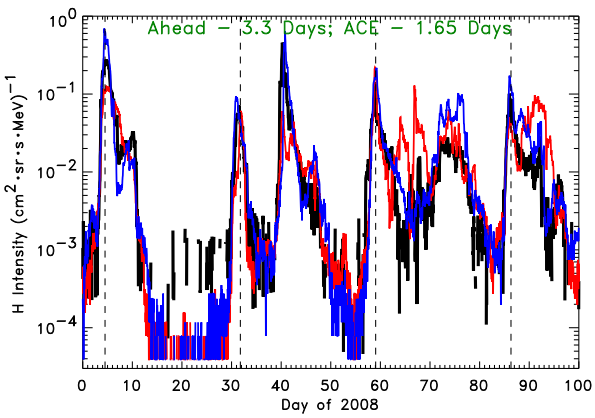

Fig. 5. Hourly-averaged 1.8-3.6 MeV proton intensities from STEREO/Ahead (*red*) and Behind (*blue*), compared with scaled values interpolated to the same energy from ACE/EPAM (*black*). Ahead and ACE data have been shifted throughout by 3.3 and 1.65 days, respectively. *Dashed lines* are spaced by a Carrington rotation.

ACKNOWLEDGMENTS

NASA grants NAS5-03131 and NNX08AI11G supported this work. We thank STEREO/PLASTIC (NASA contract NAS5-00132) investigators for making their data publicly available, the Wilcox Solar Observatory for the HCS data, and the ACE/EPAM team and ACE Science Center for the EPAM data.

REFERENCES

[1] F. E. Marshall and E. C. Stone, *JGR* **83**, 3289, 1978.
[2] I. G. Richardson, *Space Sci. Rev.* **111**, 267, 2004.
[3] R. A. Mewaldt, et al., *Space Sci. Rev.* **136**, 285, 2007.
[4] R. A. Leske, et al., in *Particle Acceleration and Transport in the Heliosphere and Beyond*, AIP Conf. Proc. **1039**, 131, 2008.
[5] R. A. Leske, et al., *Proc. 31st ICRC (Łódź)*, SH 3.4, paper 0536, 2009.
[6] G. M. Mason, et al., *ApJ* **678**, 1458, 2008.
[7] I. G. Richardson, et al., *JGR* **98**, 13, 1993.
[8] G. M. Mason, et al., *Space Sci. Rev.* **136**, 257, 2007.
[9] C. W. Barnes and J. A. Simpson, *ApJL* **210**, L91, 1976.
[10] R. A. Mewaldt, E. C. Stone, and R. E. Vogt, *GRL* **5**, 965, 1978.
[11] G. M. Mason, et al., *Solar Phys.* **256**, 393, 2009.