SH 2.2.12

Corotating Interaction Regions in the Heliosphere: Workshop Report

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Abstract

In June 1998 a workshop was held at the International Space Science Institute ISSI, Bern, Switzerland, on "Development and effects of Corotating Interaction Regions in the Heliosphere". The workshop was the last of a series of three and the results will be published shortly in Space Science Rewiews and in the Space Science Series of ISSI. The development of CIRs throughout the Heliosphere as observed in plasma and field parameters will be discussed. Effects of CIRs include the acceleration of low energy charged particles and the partial rejection of galactic particles from the inner Heliosphere. Results from ULYSSES at high latitudes and from the outer Heliosphere show that the effects can be observed far beyond the actual extent of the CIR in the Heliosphere. The major results of the workshop will be presented in this paper.

1 Introduction:

Reasons for revisiting and reviewing Corotating Interaction Regions in a series of three workshops were:

1. CIR's can only be studied extensively during times of decreasing and minimum solar activity.
2. Until the last solar minimum CIR's could only be observed close to the ecliptic plane or in the outer heliosphere at latitudes up to 35 degrees. Since 1992, however, Ulysses is exploring the higher heliospheric latitudes and therefor exploring the 3rd dimension of CIR's as well.
3. Ulysses encountered a very long lasting stream of CIR's and was able to observe effects of the CIR's even at ist highest heliolatitude, far beyond the expectation.
4. A new picture of the CIR affects on particles developed from the ULYSSES observations.
5. With the appearnce of the first major solar particle events and of the onset of the new solar activity chances of observing CIR's have decreased considerably and will stay that way for about the next 5 years.
6. Observations at high latitudes demanded new models and test methods.

Two 4-day workshops were held in March 1996 and April/May 1997 at Elmau Castle/Germany with ~35 scientists contributing observations in the area of plasma, magnetic field and particle measurements from the inner, outer, and high latitude heliosphere as well as models and theoretical calculations. Besides short sessions with review/introductory and contributed talks working groups with 8-15 participants lead by two co-chairs performed the most important tasks by investigating aspects of plasma and fields, energetic particles (CIR acceleration and modulation), and models/theory. Splinter groups discussed within or between working groups more specific topics (e. g. spectra, composition, modulation) or detailed correlations.

The third workshop, held at the International Space Science Institute at Bern, Switzerland, in June 1998 prepared for publishing the workshop results as a special issue of Space Science Reviews and a book of the ISSI Space Science series containing introductory and working group papers (Kunow et al, 1999).

2 Solar Origin and Formation in the Inner Heliosphere of CIRs:

Significant progress in understanding the coronal origin of CIRs was made by achieving a characterisation of the fast solar wind and by recognizing the slow solar wind as a complex mix of material emerging at the boundaries of coronal holes and from closed magnetic structures, in the form of transient ``blobs'' and CMEs.

- **Coronal origin of CIRs:** CIRs are a consequence of (a) solar wind streams of significantly different velocities emitted at the same solar latitude at adjacent longitudes, and (b) the relative stability, over several solar rotations, of the coronal source regions. The characteristics of the fast solar wind streams associated with large coronal holes are well understood from observations in the inner heliosphere and in three dimensions by Ulysses. The slow solar wind emerging from the streamer belt is much less understood. The transition between the two kinds of solar wind leads to the variability in interplanetary space resulting from coronal magnetic structure details.

- **Modelling coronal magnetic and plasma structures:**. Several complementary techniques predict quite successfully open field regions in the upper corona from photospheric magnetic fields, and to match these to coronal hole observations. Increasing sophistication of coronal models can lead to a better understanding of source regions, in particular of boundary regions between open and closed magnetic fields. Modeling of the temporal dependences in sufficient detail, however, is still a problem.
- **Interplanetary dynamics in the inner heliosphere:** A good match exists of stream structure and coronal sources. The transitions between slow and high velocities are, on average, steeper at 0.3 AU than at 0.5 AU and beyond. Compressive effects cause renewed steepening at greater distances. Stream interfaces are difficult to identify both close to the sun and at 1 AU with the critical question being the complexity (temporal, spatial variability) of the boundary between the coronal sources of high and low speed solar wind streams. Despite occasional Helios observations inside 1 AU, corotating shock formation as a result of stream-stream interactions is generally observed at distances greater than 1 AU.
- **Compositional signatures at stream interfaces:** Measurements of the elemental and charge state composition of the solar wind have contributed significantly to the distinction between fast and slow solar wind streams. Compositional signatures are the best indicators of coronal origin and can be used to define the complex interfaces between different solar wind types. The complexity of interfaces arises not only from the coronal structures but also as a result of their temporal evolution and dynamics. Slow solar wind coronal plasma emerges from flux tubes of different composition and temperature. Compositional signatures are better able to identify streams from coronal holes (and by implication, ‘‘slow" streams), than kinematic variables such as velocity and temperature.

The formation and evolution of CIRs is a strong function of coronal morphology and temporal characteristics of the source regions and the transition region between closed and open magnetic field lines. The most important questions are related to the origin(s) of slow solar wind streams and to the details of coronal dynamics at the boundaries of coronal holes. Only a better understanding of the slow speed solar wind phenomenon can lead to newer insights into the formation and initial dynamic development of CIRs.

3 CIRs at High Heliographic Latitudes:

The huge three-dimensional extent of corotating interaction regions (CIRs) and its importance in structuring the quiet heliosphere became obvious only with ULYSSES observations at higher latitudes. Surprising is the observation of CIR related accelerated particles as well as of modulation effects on galactic and ACR particles up to the highest latitudes even in the absence of local shocks. Observed effect can best be ordered by remote fieldline connection to shocked plasma regions originating from coronal hole regions and particle transport along the fieldlines with transit time dependant loss rates.

4 CIRs in the Outer Heliosphere:

CIRs and their successors evolve while convected to greater heliocentric distances. Most structures observed below 15-20 AU are co-rotating. CIRs are dominant at 2-8 AU and are replaced by MIRs at 8-12 AU. Beyond ~12 AU shocks decline in frequency and strength and MIRs are replaced by corotating pressure enhancements. Beyond ~15-20 AU, two different structures are observed: Near the solar equator, Pioneer 10 and Voyager 2 observed broad non-periodic enhancements in solar wind density and temperature with constant speed. Lack of periodicity suggests a relation to temporal variations at the source region. At higher latitude Voyager 2 observed periodic enhancements in solar wind temperature and speed with constant density. The cause is unsolved but may be related to latitude gradients, cycle variations, or pickup ion effects.

Energetic particle enhancements similar to shock events are observed out to 45 AU during declines of cycles 21 and 22 associated with enhanced H/He ratio of 15-30, similar to ratios at reverse shocks at smaller distances. The origin of these particle enhancements without shock evidence remains to be determined.

Near the 1986 and 1997 solar minima, particle enhancements disappear, but periodic modulations were observed with ~26 days periods. These events were often anti-correlated with B

5 Modulation of Cosmic Rays and ACRs by CIRs:

Despite large progress in modelling the effects of CIRs on energetic particles, much remains open to fully understand the observations. Global models of the heliosphere exist, including self consistent solar wind flows and incorporating solar wind velocity variation with latitude producing co-rotating interaction regions in a self consistent manner. However, full time-dependence is not yet included. Instead, the flow and the cosmic-ray configuration are assumed time independent in the rotating coordinate system.

Detailed models exist of particle acceleration and transport at planar collisionless shocks, but not yet of fully consistent three-dimensional hybrid simulation of a collisionless shock leaving conclusions tentative.

For transport of energetic charged particles normal to the average magnetic field, in particular in latitude direction there are currently two distinct molds. The first is random walk or braiding of magnetic field lines, so that particle motion normal to the average magnetic field can occur, even though the particles travel mainly along fields line. The field lines themselves are meandering randomly. This leads to a significant perpendicular diffusion coefficient. Another approach to latitudinal transport is to have a θ component of the magnetic field generated by general plasma motions near the sun. The magnetic field configuration discussed by Fisk is one possibility. No global transport code is presently available to incorporate a large-scale, causal, latitudinal magnetic field component.

It should be possible in the not too distant future to incorporate full time dependence into the global transport codes, as opposed to the simpler co-rotating systems so far available. Only than it would be possible to determine the degree of impact of CIRs on the global modulation.

6 Origin, Injection and Acceleration of CIR Particles:

6.1 Observations:

The observational features are reported in table 1 and must be fitted by any theory of CIR energetic particle acceleration and transport.

6.2. Theory:

It is generally agreed that diffusive or 1. order Fermi acceleration at the corotating shocks is responsible for corotating energetic particle events. Acceleration is most efficient in the region of well developed shocks at about 3-5 AU. Energetic ion increases have also been observed at trailing edges of compression regions even when no reverse shock was detected. Currently, it can not be decided whether acceleration in these cases occurs at the trailing boundaries of these compression regions in a similar fashion as at shocks, or whether acceleration occurs at localized shocks and the particles then undergo cross-field diffusion onto field lines not connected with the shock. The theory of shock acceleration is rather well developed, the missing ingredients regarding CIR shock acceleration are radial, energy, and mass/charge of the spatial diffusion tensor. Another open question is the importance of the large-scale structure and spatial extent of the CIR shocks on the acceleration. Pickup ions are accelerated within the corotating interaction regions by stochastic acceleration in the magnetosonic turbulence. The so-called seed particle or injection problem of solar wind particles is outstanding. There is no problem to inject pickup ions at shocks: 1.) An important injection/acceleration mechanism for pickup ions at (quasi-)perpendicular shocks is shock surfing. 2.) Part of the pickup already constitute a suprathermal particle population. These ions get further accelerated by shock drift acceleration or in a Fermi type shock acceleration process if they are able to diffuse across field lines. One of the most important outstanding questions is a self-consistent determination of the cross-field diffusion coefficient down to thermal energies. Electron acceleration at CIR shocks has not received much theoretical attention. The question is whether electrons can get accelerated out of the solar wind, or whether an energetic background population is further accelerated by, e.g., shock drift acceleration. Since electrons can more easily probe large distances along the magnetic field, the large-scale IMF structure is important for an understanding of the electron time-intensity profiles.

Table I: Key Observational features of CIR energetic particles

Source location	• peak intensity at 4 AU with $1/r^2$ fall off at large distances • peak intensity at ~20° latitude with e-folding distance 6-8°
Transport	• at 1 AU observe generally sunward flow • puzzling non field aligned flow at peak intensities at 1 AU • transport of CIR ions to latitudes well above shock locations • varying ratio of He^+ to He^{++} from 1 to ~5 AU implies poor inward transport of low energy He^+ at 10s of keV/nucleon • strong inhibition of particle transport across stream interface
Spectral forms	• power law from 10s of keV/nucleon to ~1 MeV/nucleon • steepening above ~1 MeV/nucleon • spectral forms do not change out to large (10s of AU) distances
Acceleration mechanism	• ion intensity peaks coincide with forward and reverse shocks • low energy (10s of keV) ions at 1 AU observed even absence of shocks • same time profiles from He through Fe Q/M independence of acceleration mechanism • mechanism to produce electrons 50- hundreds keV several AU; small intensities at 1 AU
Composition & seed population	• similar to solar system except for factor 2-3 enhancement of He and C relative to O • increase of He/O and Ne/O ratios with solar wind speed • He abundance increases from 1 to 5 AU • Mg/O ratio same in both forward and reverse shock periods, and close to average of solar wind slow- and fast- solar stream values • relation of composition to pick up ion sources in heliosphere: local interstellar neutrals, dust, and others?

7 CIRs Morphology, Turbulence, Discontinuities, and Energetic Particles:

The basic morphology of CIR plasma and field features is well understood, but complexities regarding the relative positions of features, variability of feature signatures, multiples of features, and transient features are topics of current studies. Rather than simply resolving details, these studies may yield refreshing new views of global heliospheric structure and dynamics. Patterns of magnetic fluctuations and energetic particles relative to the basic plasma and field features are reasonably well understood in a statistical sense, but they raise a number of questions currently under investigation regarding particle transport, particle acceleration, and the interaction of fluctuations with shocks and structures. These studies are expected to yield a greater understanding of the dependence of energetic particle propagation on magnetic field fluctuations and structures within and around CIRs, and hence the energetic particle population throughout the heliosphere.

Acknowledgements

I am grateful to all participants of the workshop for their important contributions especially to all authors and to the International Space Science Institute, Bern, for sponsoring the final workshop and book publication.

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