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IMPACT: Science goals and firsts with STEREO

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Abstract

The in situ measurements of particles and CME transients (IMPACT) investigation on the twin STEREO spacecraft focuses on the solar energetic particle, solar wind and suprathermal electron, and magnetic field measurements needed to address STEREO's goals. IMPACT will provide regular, identical, in situ multipoint measurements bracketing Earth as each spacecraft separates from it at a rate of ~22°/yr along Earth's orbit. Combined with the PLASTIC and SWAVES investigations, IMPACT fills a critical role in the STEREO quest to connect SECCHI's 3D coronal images to their interplanetary consequences.

Keywords: STEREO; Coronal mass ejections; Space weather; Solar activity; Space missions

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1. Introduction

The in situ measurements of particles and CME transients (IMPACT) investigation is a multiinstitutional and multinational effort to provide the solar energetic particle (SEP), solar wind and suprathermal electron, and magnetic field measurements for the STEREO mission (see Kaiser et al., this volume). IMPACT consists of seven different sensors, an instrument data processing unit (IDPU), and a six-meter boom that separates three of the instruments from the spacecraft. These are identical for each of the two heliocentric orbiting observatories, with the exception of minor mechanical and mounting characteristics needed to obtain the desired fields of view. The institutions contributing to the instrumentation are listed in Table 1. The IMPACT IDPU provides a single interface to the spacecraft for all of the IMPACT instruments as well as for the PLASTIC investigation, which completes STEREO's in situ plasma coverage by detecting and identifying the ions (see Galvin et al., this volume). An arrangement with the SWAVES radio and plasma wave investigation (see Bougeret et al., this volume) enables sharing of event triggering and clock information in burst mode operations to obtain occasional high time resolution observations. IMPACT is managed by the University of California at Berkeley Space Sciences Laboratory.

The IMPACT instruments, indicated on a picture of the leading or Ahead STEREO spacecraft in Fig. 1, are based on a long heritage of space hardware development at the providing institutions. SWEA is the solar wind electron analyzer; STE, the suprathermal electron telescope; MAG, the magnetometer; SIT, the suprathermal ion telescope; SEPT, the solar electron and proton telescope; LET, the low energy telescope; and HET, the high energy telescope. Each (see Table 1) makes a well-defined and unique contribution toward the STEREO goals of: understanding the causes and mechanisms of CME initiation; characterizing the propagation of CMEs through the heliosphere, discovering the mechanisms and sites of energetic particle acceleration; and developing a 3D time-dependent model of the solar wind. Together, they make as complete a set of in situ measurements of SEPs, electrons and magnetic fields as possible within the mission and resource constraints.

IMPACT's basic measurements are also summarized in Table 1. The SEP Suite of instruments including SIT, SEPT, LET and HET cover energetic ion composition over a nearly continuous energy range from ~100 keV/nucleon to ~30 MeV/nucleon from He through Fe, and energetic electron and proton fluxes from 10 keV to ~10 and ~100 MeV, respectively, as shown in Fig. 3. The extent of the various SEP instruments' composition

Table 1
Basic IMPACT measurements

Experiment	Instrument	Measurement	Energy or mag. field range	Time res.	Beacon time res. (*)	Instrument provider
SW	STE	Electron flux and anisotropy	2–100 keV	16 s	2D × 3E, 1 min	UCB
	SWEA	3D electron distrib., core and halo density, temp. and anisotropy	~0–3 keV	3D = 1min 2D = 8s Mom = 2s	Moments, 1 min	CESR, UCB
MAG	MAG	Vector field	±500 nT, ±65536 nT	1/4 s	1 min	GSFC
SEP	SIT	He to Fe ions	0.03–2 MeV/nuc	1 min	3Species × 4E, 1 min	U. of Md., MPAE, GSFC
		^{3}He	0.15–0.25 MeV/nuc	1 min	–	
	SEPT	Diff. electron flux	20–400 keV	1 min	4E, 1 min	U. of Kiel, ESTEC
		Diff. proton flux	60–7000 keV	1 min	4E, 1 min	
		Anisotropies of e,p	As above	1 min	–	
	LET	Ion atomic numbers 2–28 flux and anisotropy	~3–30 MeV/nuc	1 min	(He, CNO) × 3E; (Fe) × 4E, 1 min	Caltech, GSFC, JPL
		^{3}He ions flux and anisotropy	2–15 MeV/nuc	1 min	2E, 1 min	
		H ions flux and anisotropy	1.7–12 MeV	1 min	3E, 1 min	
	HET	Electrons flux	1–6 MeV	1 min	3E, 1 min	GSFC, Caltech, JPL
		H	13–100 MeV	1 min	3E, 1 min	
		He	13–100 MeV	1 min	3E, 1 min	
		^{3}He, CNO, Fe	15–60 MeV/nuc	1 min	He × 3E, CNO × 2E, Fe × 1E	
	SEP Common	–	–	–	–	Caltech, GSFC
IMPACT Common	IDPU (+Mag analog)	–	–	–	–	UCB

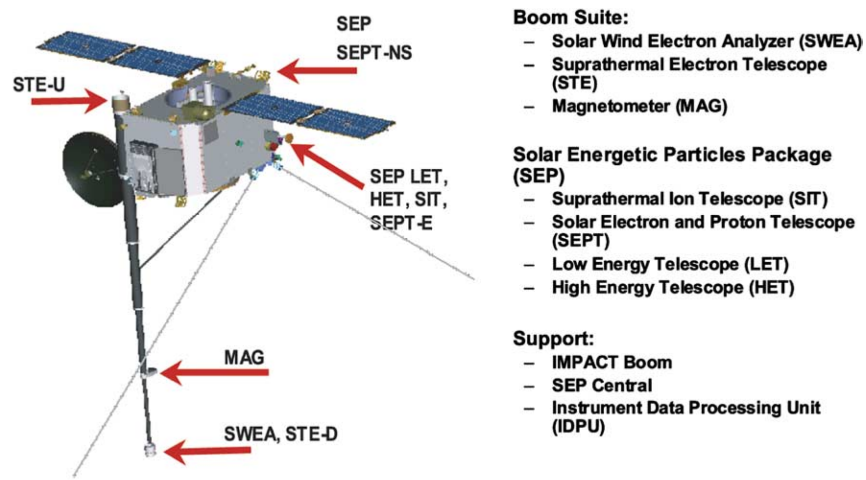

Fig. 1. Illustration of the STEREO-A (Ahead or leading) spacecraft, showing the locations of the IMPACT instruments and Boom.

measurements is illustrated in Fig. 4. The Boom Suite includes the plasma and suprathermal electron detectors, SWEA and STE-U,D (U and D for upstream and downstream sensor heads), whose energy ranges are also shown in Fig. 3. The magnetometer (MAG) provides critical information about the local interplanetary vector magnetic field for both magnetic topology extrapolations, and organization and analysis of the measured particles.

As illustrated by Fig. 5, most of the particle IMPACT instruments have focused fields of view along the nominal Parker Spiral field direction. SEPT and LET look both up and down the field to obtain anisotropy information. The SEPT instrument adds the perspective from a duplicate particle telescope (SEPT-NS) whose field of view is orthogonal to the ecliptic plane (e.g., pointing North and South). SWEA has nearly 4π coverage to capture the details of the often narrow field-aligned heat flux electron distributions both in the solar wind and throughout interplanetary CME (ICME) disturbances. A subset of the IMPACT data will be transmitted in real time as part of the STEREO Beacon mode of operation (see Thompson et al., this volume). Detailed descriptions of the IMPACT and other STEREO instruments are forthcoming in a future issue of Space Science Reviews.

2. Science with IMPACT

The scientific questions that are the target of IMPACT and STEREO are based on decades of solar and heliospheric research with both single and serendipitous multispacecraft in situ measurements, as well as solar imaging and radio remote sensing. However, one other mission that exploited a multispacecraft approach to regular in situ measurements was the Helios twin spacecraft mission launched by ESA in the mid-seventies (see Mariani et al., 1978; Rosenbauer et al., 1977; Kunow et al., 1977). The Helios observations were made along highly elliptical heliocentric orbits traveling between 0.3 AU perihelia and a ~1.0 AU aphelia. These were used together with near-Earth observations on IMP8 and ISEE-3 spacecraft to sort out the now widely accepted spatio-temporal scenario of ICMEs and their associated SEPs in Fig. 2 (Cane et al., 1988; Reames et al., 1996). In addition, some of these analyses took advantage of the overlapping SolWIND and SMM (Solar Maximum Mission) coronagraph observations of coronal mass ejections. Such efforts to connect solar activity to in situ observations of both shocks and ICME ejecta at several heliospheric locations (Sheeley et al., 1985; Bothmer and Schwenn, 1994) provide the jumping-off point for IMPACT science.

Findings from the earlier multipoint studies that included solar imaging gave substance to the inferred relationships between interplanetary shocks and CME ejecta "drivers," and SEPs and interplanetary shocks. In particular, the now familiar paradigm emerged of the corona ejecting a plasma and magnetic field structure with the general topological properties of a flux rope (see Fig. 2), at the time of a CME. The ejecta travels outward at speeds sometimes higher than the ambient solar wind speeds, and/or undergoes expansion as it travels, resulting in a preceding shock. In observations, the shock is followed by the compressed solar wind sheath created by the ejecta driver, though the ejecta may not always be detected because the shock has wider longitudinal extent. When detected, the ejecta magnetic field can sometimes be fit with a flux-rope model (Burlaga, 1991) for comparison with the solar magnetic fields at the inferred site of the CME eruption. Comparisons carried out by Bothmer and Schwenn (1994) suggested a relationship between the coronal fields inferred from erupting filaments in the polar crown, and the polarity and handedness of the rotating

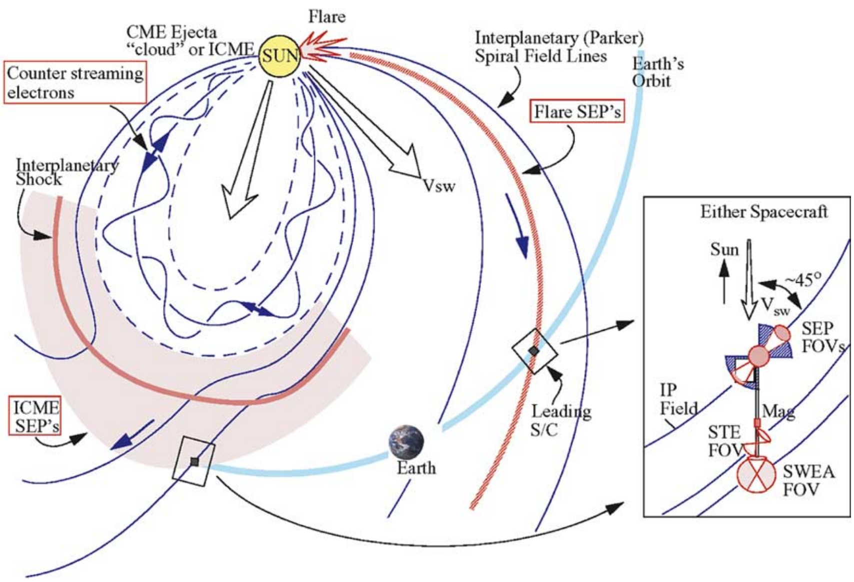

Fig. 2. Illustration of the pre-STEREO concept of the effects of a Coronal Mass Ejection (CME) on the inner heliosphere. The main features are the disturbance, the ICME, including an interplanetary shock created by the ejecta "driver," the sheath region of deflected compressed solar wind and piled up ambient interplanetary field between the shock and ejecta, and the solar energetic particles or SEPs generated at the moving shock and/or in flaring regions on the Sun in the vicinity of the CME eruption. The inset illustrates the IMPACT instrument locations on the spacecraft, their orientations, and their approximate fields of view.

fields of at least some ICME ejecta. The variety of observed SEP time profiles can be organized by the picture in Fig. 6 (adapted from Reames, 1999). Note that Helios tested this picture on numerous occasions with snapshots rather than statistical studies from single point observations. SEPs appear to be continuously produced, albeit with spatially varying strength, at the location of the shock as it travels (e.g., Kallenrode, 1993, 1995). The role of flares in producing SEPs in these CME related events, and of ion composition measurements in sorting out the source location(s) and acceleration mechanism(s), could not be addressed in detail until the more advanced instrumentation on WIND and ACE became available.

As of this pre-STEREO year, the magnetic structures of ICME ejecta continue to be analyzed in terms of various local flux-rope models fitted to magnetic field measurements (e.g., Lepping et al., 1990; Mulligan and Russell, 2001). Additional validation of the topology has been attempted using highly field-aligned suprathermal (100 s of eV to few keV) electrons measured on ISEE-3, WIND and ACE spacecraft (e.g., Gosling et al., 1995; Larson et al., 1997; Kahler et al., 1999), and energetic ions (e.g., Kahler, 1994; Richardson and Cane, 1996). However, modern numerical simulations of CMEs indicate that the assumed flux rope topologies can often be misleading (e.g., Riley et al., 2003). The images from SOHO have been especially valuable in revealing their solar origins and morphologies (Howard et al., this volume). Real CME ejecta generally have more complicated initial topologies than that shown in Fig. 2, with additional distortions developing as they travel through the structured ambient corona and solar wind to 1 AU (e.g., Gosling et al., 1987; Riley et al., 2003). Hence, one of the overarching emphases of IMPACT data analyses will be the determination of more realistic pictures of ICMEs as a whole, consistent with

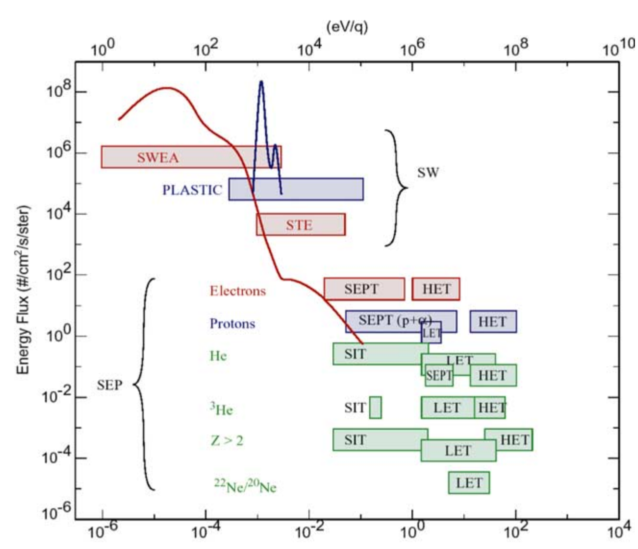

Fig. 3. Summary of the spectral coverage of the IMPACT plasma electron (SWEA), suprathermal electron (STE) and SEP ion and electron (SIT, SEPT, LET and HET) instruments. The coverage of the solar wind plasma ions by the PLASTIC investigation is also indicated. The solid lines indicate the shapes of typical plasma electron and ion energy spectra.

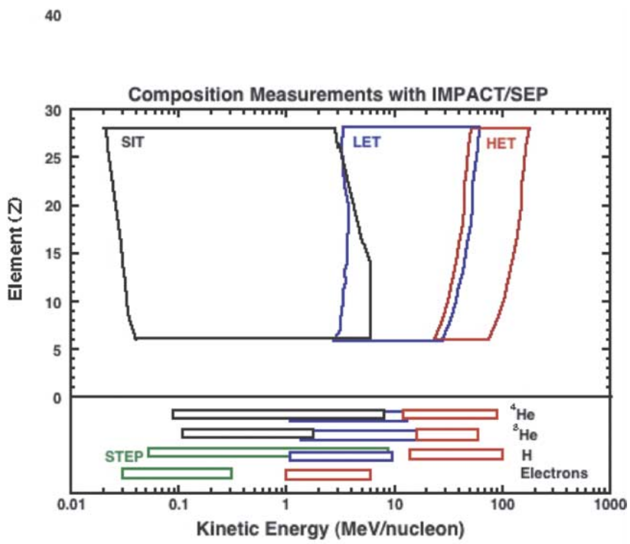

Fig. 4. Summary of the SEP composition coverage of the IMPACT SEP suite of instruments: SIT, SEPT, LET and HET.

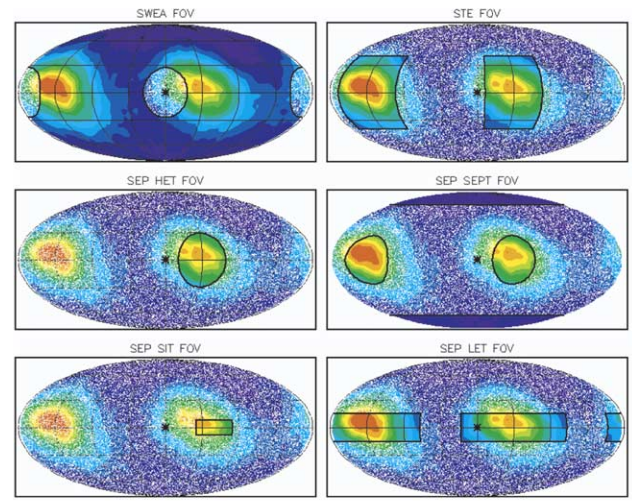

Fig. 5. Illustration of the IMPACT particle instrument fields-of-view. The contours show the distribution of the interplanetary magnetic field directions on a projection representing a flattened sphere. The solar direction is at the center of each plot. The unhatched areas surrounded by black lines are the fields-of-view. SWEA, in the upper left panel, has nearly 4π coverage in order to capture details of the heat flux electron directional distribution. STE, upper right panel, SEPT, below it, and LET, lower right panel, look up and down the average Parker spiral field direction. In addition, SEPT has a second telescope pair that looks orthogonal to the ecliptic plane. SIT and HET, left center and lower panels, look up the Parker Spiral field toward the Sun.

coronal and heliospheric CME images from SECCHI (Howard et al., this volume) and the shocks remotely sensed by SWAVES (Bougeret et al., this volume).

SEP ion composition and anisotropy information obtained from the WIND and ACE spacecraft show fea-

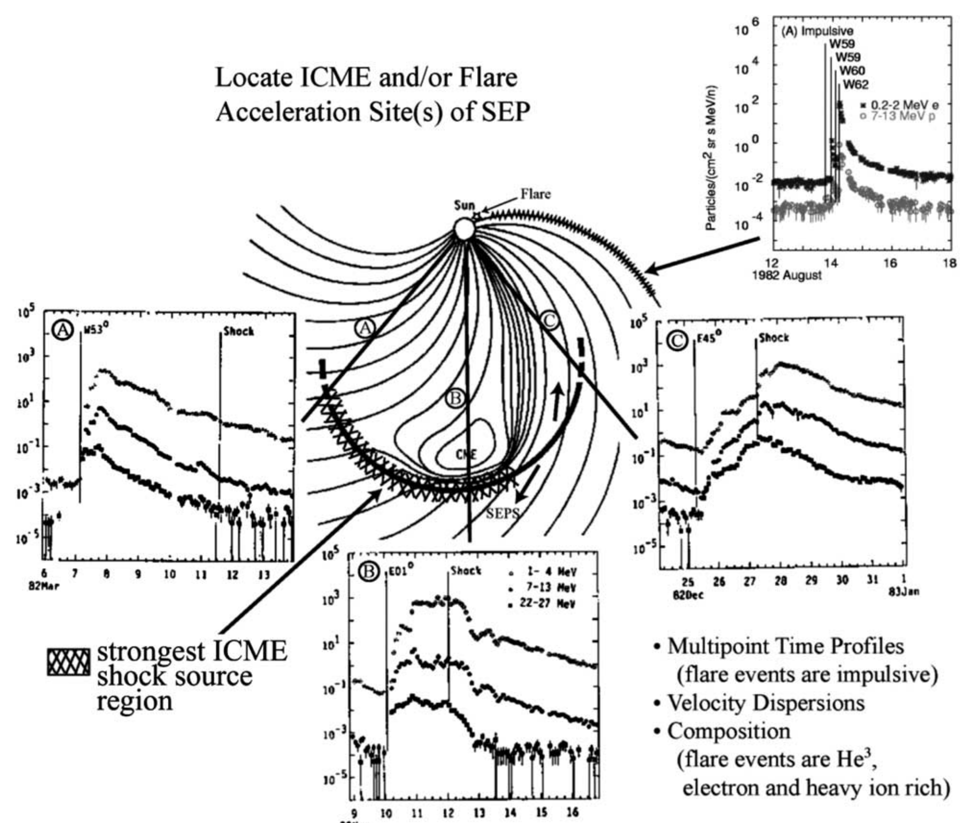

Fig. 6. Illustration of the currently held explanation for the different time profiles of SEP events. This view (adapted from Reames, 1999) was constructed from the statistics of single spacecraft measurements, but appears consistent with the available multipoint analyses. IMPACT on STEREO will provide regular, variably spaced, multipoint observations, including important ion composition diagnostics.

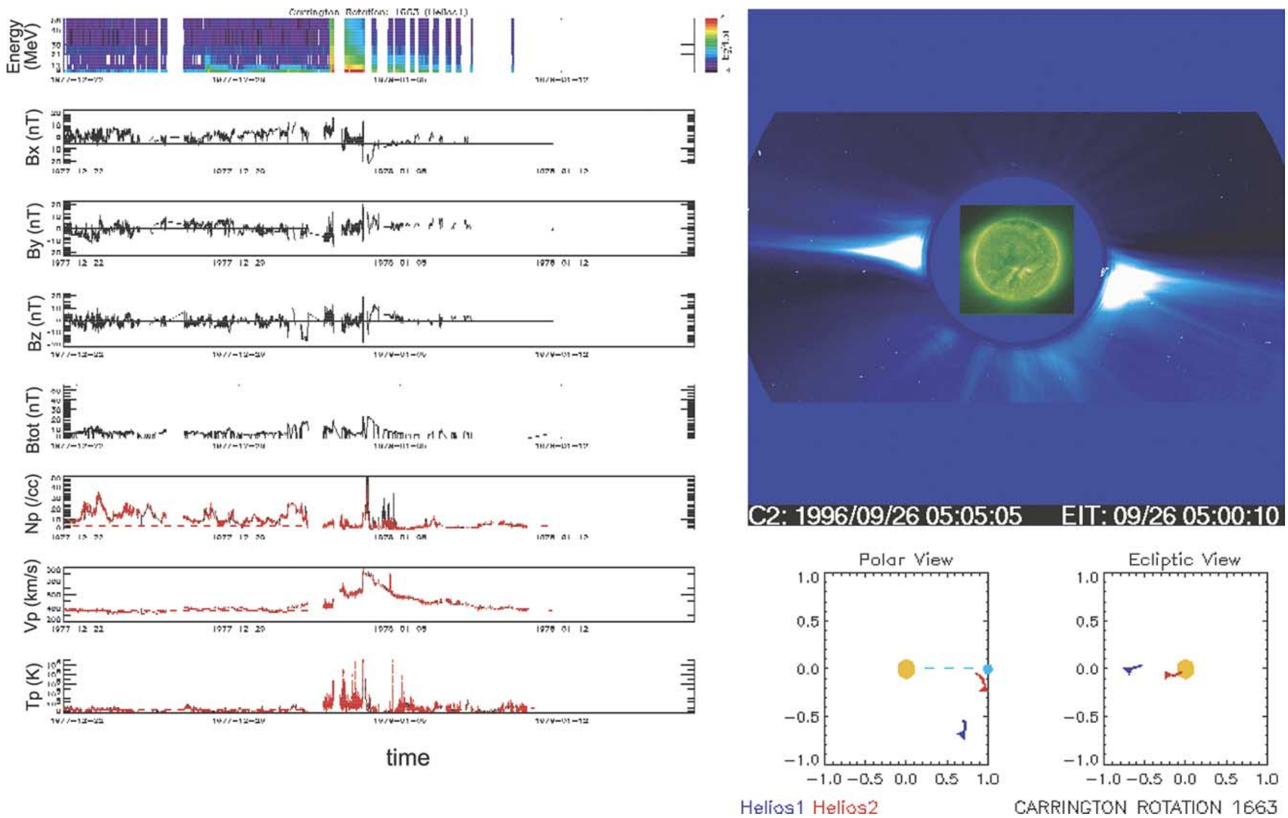

Fig. 7. Preliminary design of an IMPACT data browser webpage, showing a representative Carrington Rotation summary plot from Helios including plasma (bottom 3 panels), magnetic field (time series in center 4 panels) and SEP spectrogram data. The Helios spacecraft locations relative to Earth are shown in two projections at lower right. The SOHO place-holder image will be replaced by a movie of the solar events occurring during this period by SECCHI observations. The user will be able to toggle between STEREO spacecraft and also a complementary ACE spacecraft page with SOHO images.

tures that suggest a combination of source populations, including flare-generated particles, are present in major SEP events at 1 AU (e.g., Cane et al., 2003). Flares may produce a modestly energetic, comparatively iron-rich seed population in the corona that is then accelerated to energies >10 MeV/nucleon in the associated CME ejecta-driven shock. The SEP time profiles in Fig. 6 can be interpreted as arising from (left to right): prompt particles from the coronal phase of the shock at altitudes below ~20 R_{sun} (e.g., Kahler, 2001), where larger abundances of heavy ions such as iron from a flare-seeded ambient medium may be present; a somewhat weaker prompt phase followed by a spectrally softer flux enhancement at the time of arrival of the interplanetary shock, the latter with a more solar-wind-like ion composition; connection to the strongest part of the shock source at the nose from behind, leading to a delayed peak flux and long rise time; and the generally weaker impulsive flare bursts whose He3 and Fe-rich narrow time profiles can sometimes be detected in the ~day-long intervals of the ICME ejecta (Mazur et al., 1998). Such impulsive flare events, observable in both suprathermal ions and electrons, are valuable tracers of the local magnetic field connections to fixed sources in flaring regions on the Sun (e.g., Larson et al., 1997). Delay times to maximum in the prompt and impulsive events at different energies can constrain the solar event association and altitude of injection (e.g., Kahler, 2001; Larson et al., 1997), as can the timing and location relative to coronal radio bursts (Larson et al., 1997).

Thus the new science of IMPACT: the fleshing out of a realistic picture of the 3D interplanetary medium, the CMEs that disturb it, and the SEPs that result, demands that we regularly use the IMPACT data in an uprecendentedly collective way, in the context of the whole of STEREO observations. IMPACT plasma electron, magnetic fields, and energetic particles analyzed independently cannot fulfill our scientific goals. Advances in data access, manipulation, and visualization, as well as numerical modeling of the time-dependent 3D corona and heliosphere will be brought to bear on IMPACT and STEREO data analysis and interpretation. Toward this end we are developing a preliminary data browse capability specifically designed to bring out the comparative aspects of the in situ multipoint measurements and the ultimate integration with remote sensing information. Several such browsing capablilities are anticipated.

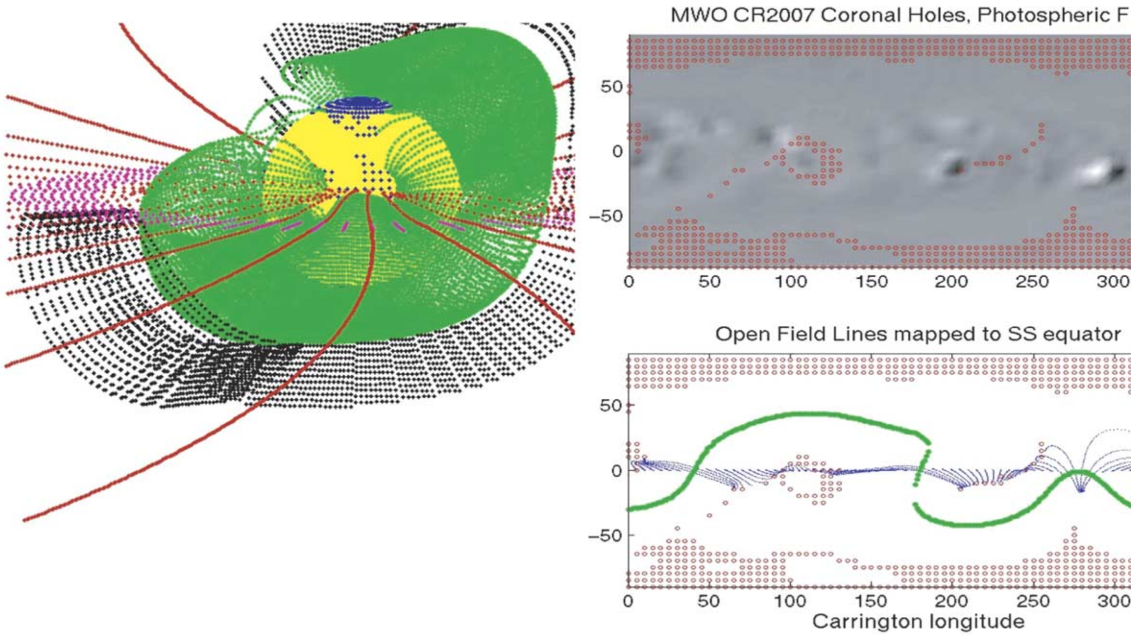

Fig. 8. Illustration of the use of solar magnetogram-based photospheric field maps to construct a model of the expected ecliptic plane solar wind sources (long field lines on the left, and near-equatorial field lines on the lower right represent the prevailing open field line flow channels for this Carrington Rotation). Such models will help to connect observed solar wind plasma and interplanetary stream structure to solar features such as coronal holes (in the model, dotted areas on the left and right) in EUV images. The closed field lines on the left represent the helmet streamer belt that organizes the low speed solar wind. The black dotted, warped surface represents the base of the heliospheric current sheet- rooted at the neutral line shown in the lower right panel.

Those at the STEREO Science Center (Thompson et al., this volume) will emphasize the Beacon mode observations. For retrospective evaluation of periods of interest, IMPACT will provide key-parameter type information including ∼1 min cadence magnetic fields, plasma electron moments and angular distributions, and SEP fluxes

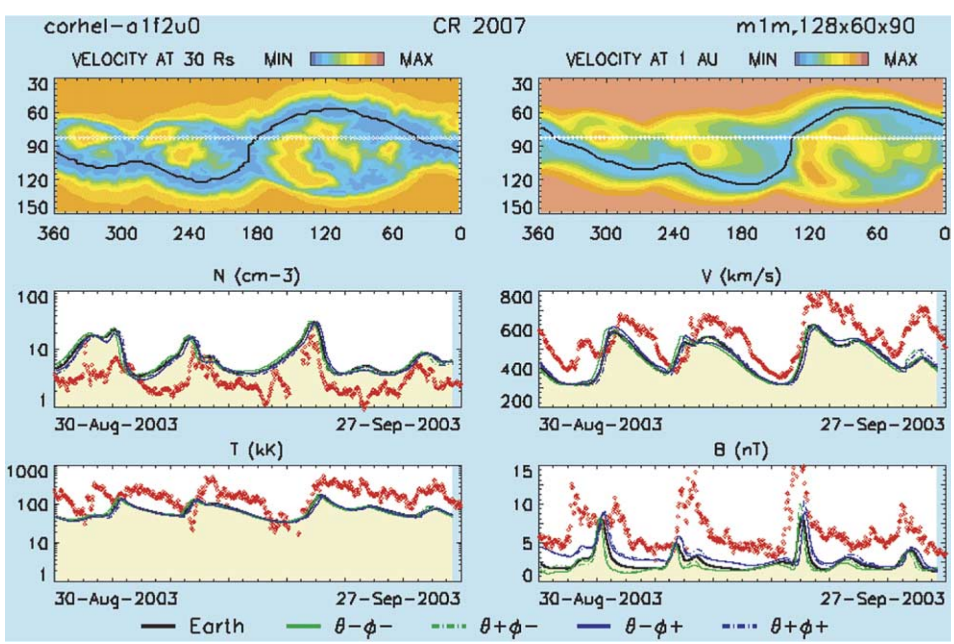

Fig. 9. Magnetogram-based solar wind model results for the same Carrington Rotation as shown in Fig. 8. The model used is that described by Odstrcil et al. (2004). The top color panels show the velocities at the inner boundary of the model at 30 solar radii (left), and the velocities at 1 AU (right). The comparison of simulated 1 AU time series of density, velocity, temperature and magnetic field magnitude with ACE observations (dots) are shown in the lower four panels.

and anisotropies through browsers designed specifically for multipoint in situ data and initial comparisons to solar images.

An illustration from a preliminary IMPACT data browse website, developed using Helios and SOHO data as placeholders, is shown in Fig. 7. In this example, the in situ data plot contains summary data from the Helios SEP telescope, together with solar wind plasma and field information (Kunow et al., 1977; Rosenbauer et al., 1977; Mariani et al., 1978). To make the solar connections clearer, and enable comparisons with models, the in situ data are organized by Carrington Rotation. The STEREO counterparts of the SOHO images are expected to be movies from SECCHI summarizing the CME(s) during the Carrington rotation. It is planned that each in situ data plot and movie can be toggled between spacecraft sources. A complementary ACE plot and SOHO movie is also planned as part of this browse tool in order to provide the central, Earth viewpoint. The IMPACT browse data will be downloadable as ascii for further analyses. It complements the planned open-access, CDF format, Level 1 data set and a more complete in situ and radio Key Parameter (Level 2) and Event (Level 3) data set to be distributed through the UCLA data center at http://www-ssc.igpp.ucla.edu.

Lastly, the role that models will play in IMPACT and STEREO science analyses and interpretation should not be underestimated. A number of modeling approaches, especially 3D MHD simulation, have made it possible to use photospheric magnetograms to approximate the invisible 3D coronal magnetic field (e.g., Fig. 8), the associated solar wind parameters (Fig. 9), and the dynamic coronal mass ejection effects from the corona to 1 AU (Fig. 10). With numerical experimentation still ongoing, especially in the areas of realistic CME initiation (e.g., see Antiochos et al., 1999; Linker et al., 2003; Manchester et al., 2004) and propagation (Riley et al., 2003; Odstrcil et al., 2004), the possibilities for mutual enlightenment between modelers and STEREO data analysts are highly anticipated. SEP modeling is also becoming a more integrated endeavor as models of SEP fluxes and time profiles based on the properties of the shocks in the 3D MHD CME simulations are developed (e.g., Roussev et al., 2004). These traditionally separate observational and modeling efforts will come together in several STEREO teams, including IMPACT's, to allow detailed comparisons of the measured plasma and magnetic field parameters and SEPs, with the results from fully coupled 3D corona and heliospheric system simulations. In many ways the models will provide the "glue" that integrates all of the different

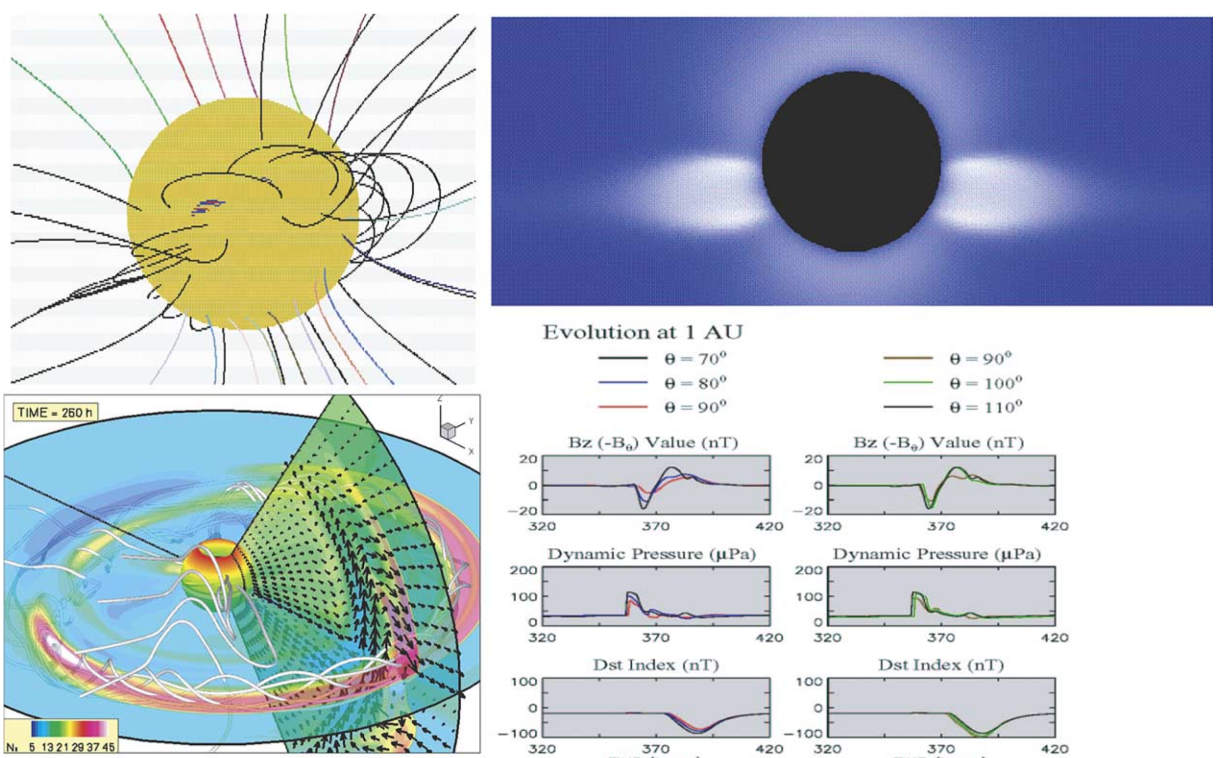

Fig. 10. Example of a CME event simulation showing initiation at the Sun, in this case by flux cancellation in the photosphere (upper left), coronagraph image-like visualization of the event as polarization brightness (upper right), transport of the ejecta through the solar wind to 1 AU (lower left), and the resulting time series of in situ plasma and magnetic field parameters at a provisional Earth or spacecraft location. The global nature of such simulations will help us to collectively interpret the measurements from the two STEREO spacecraft as well as ACE and SOHO.

coupled physical domains and aspects observed by STEREO.

3. Concluding remarks

With the launch of the STEREO mission in early 2006, little more than a year away, it is important to prepare to take full advantage of its new views of the Sun. At first the two STEREO spacecraft will be closely spaced (see Kaiser et al., this volume), providing mostly modest contrasts between the multipoint measurements of the large (fractions of an AU) ICME structures and SEP spatial distributions. We will be able to watch how the increasing spacecraft separation, at ~22°/yr with respect to the Earth–Sun line, reveals larger and larger differences in the detected plasmas, fields and particles. We will have opportunities for observing the edges of Earth-directed CMEs, and eventually for comparing CMEs seen as limb events on one STEREO spacecraft with the in situ data on the ICME obtained on the other – in what are often called quadrature observations (e.g., Sheeley et al., 1985). Comparisons with ACE in situ measurements (see Cohen et al., this volume) and SOHO images will add further dimensions and constraints to the data analyses and interpretations. In addition, the launch of Solar B in 2006 will allow detailed observations of the active regions involved in STEREO events. Notably, we could not perform a number of our IMPACT data interpretations or any of the model comparisons without access to both SOHO MDI and ground-based observatory magnetograms. Synoptic maps from SOHO MDI, as well as the GONG Network of ground-based magnetographs (Harvey et al., 1996), are essential to maintaining the continuity of photospheric field observations demanded by the many sophisticated IMPACT and STEREO data interpretations. As the mission progresses, the Sun will become increasingly active compared to its near-minimum activity at the time of launch. We thus have the opportunity to catch the solar wind and ICMEs in both their simplest and most complex realizations.

In summary, the IMPACT investigation is poised to participate in integrating solar and in situ measurements and models toward understanding the corona, solar wind, CMEs and SEPs as never before. We look forward to the scientific fruits of the investments in IMPACT's technical design and fabrication by our team members and project supporters, and to the collaborative scientific efforts STEREO will inspire.

Acknowledgements

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