Solar Phys (2009) 256: 475–488
DOI 10.1007/s11207-009-9362-5

STEREO SCIENCE RESULTS AT SOLAR MINIMUM

STEREO SECCHI and S/WAVES Observations of Spacecraft Debris Caused by Micron-Size Interplanetary Dust Impacts

O.C. St. Cyr · M.L. Kaiser · N. Meyer-Vernet · R.A. Howard · R.A. Harrison · S.D. Bale · W.T. Thompson · K. Goetz · M. Maksimovic · J.-L. Bougeret · D. Wang · S. Crothers

Received: 25 January 2009 / Accepted: 1 April 2009 / Published online: 21 April 2009

Abstract Early in the STEREO mission observers noted that the white-light instruments of the SECCHI suite were detecting significantly more spacecraft-related "debris" than any previously flown coronagraphic instruments. Comparison of SECCHI "debris storms" with S/WAVES indicates that almost all are coincident with the most intense transient emissions observed by the radio and plasma waves instrument. We believe the debris is endogenous (*i.e.*, from the spacecraft thermal blanketing), and the storms appear to be caused by impacts of large interplanetary dust grains that are detected by S/WAVES. Here we report the ob-

STEREO Science Results at Solar Minimum
Guest Editors: Eric R. Christian, Michael L. Kaiser, Therese A. Kucera, O.C. St. Cyr.

O.C. St. Cyr (✉) · M.L. Kaiser · W.T. Thompson
NASA-Goddard Space Flight Center, Greenbelt, MD, USA
e-mail: chris.stcyr@nasa.gov

N. Meyer-Vernet · M. Maksimovic · J.-L. Bougeret
LESIA, CNRS, UPMC, Université Paris Diderot, Observatoire de Paris, 5 Place Jules Janssen, 92190 Meudon, France

R.A. Howard · D. Wang
Naval Research Laboratory, Washington, DC, USA

R.A. Harrison · S. Crothers
Rutherford-Appleton Laboratory, Chilton, Didcot, Oxfordshire, UK

S.D. Bale
Physics Department and Space Sciences Laboratory, University of California, Berkeley, CA, USA

W.T. Thompson
Adnet Systems, Inc., Rockville, MD, USA

K. Goetz
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA

D. Wang
Interferometrics, Herndon, VA, USA

servations, compare them to interplanetary dust distributions, and document a reminder for future spacebased coronagraphic instrument builders.

1. Background

Coronagraphs are instruments specifically designed to detect a very faint signal that is spatially adjacent to a much more intense source (Lyot, 1933). Numerous spacebased coronagraphs have provided measurements that have revolutionized heliophysics, the science of Sun – Earth connections. In accomplishing this, lessons concerning spacecraft contamination of remote sensing instruments have been learned and, apparently, relearned.

A significant fraction (10%) of the images acquired by the Skylab Apollo-Telescope Mount S-052 coronagraph (MacQueen, 1974) were contaminated by bright streaks. Examples can be seen in Eddy and Ise (1979, several figures on page 119), and analysis by McGuire (1976) indicated that the particulates were likely expendables associated with astronaut activity and "water dumps". They concluded that direct (forward) scattering of sunlight by ice particles within 200 m of the spacecraft could account for the contamination of the coronagraphic images.

St. Cyr and Warner (1991) reported several hundred sightings in the *Solar Maximum Mission* (SMM) coronagraph (MacQueen *et al.*, 1980) of particulate contamination. Although a few of these may have been sightings of other spacecraft in Earth-orbit, they concluded that the majority of events appeared at orbital sunrise and were associated with paint flaking off the SMM spacecraft.

Although unpublished, we are aware that the SOHO LASCO coronagraphs (Brueckner *et al.*, 1995) have also detected transient bright objects in the fields of view of the two white-light instruments C2 and C3. Early in that mission these were identified as debris from the spacecraft, and detections were particularly evident when other instruments opened aperture doors, indicative of thermal blanket material being knocked loose and floating away from the spacecraft, into the fields of the coronagraphs. One of us (OCS) catalogued these sightings as part of a CME report (St. Cyr *et al.*, 2000). A preliminary comparison of the STEREO-Ahead SECCHI COR2 debris sightings to those of LASCO C2/C3 over an 18 month period following launch (similar to the time frame reported in this manuscript) indicates a factor of $\sim 20\times$ more debris seen in STEREO-Ahead COR2 compared to SOHO LASCO. A partial listing of the LASCO debris sightings appears at http://lasco-www.nrl.navy.mil/index.php?p=content/debris.

NASA's twin STEREO spacecraft were launched on 26 October 2006, with the primary scientific goal of understanding the initiation and propagation of solar coronal mass ejections (CMEs). To image CMEs near the Sun and during their interplanetary transit to Earth, multiple coronagraphs with nested fields-of-view were selected as part of the payload (the SECCHI instrument suite, Howard *et al.*, 2008). Further details of the mission and the remainder of the payload can be found in Kaiser *et al.* (2008).

Here we report optical tracks detected by the white-light instruments comprising the STEREO SECCHI suite. Some of these tracks appear to be associated with detections of micron-size interplanetary dust measured by the low-frequency radio and plasma waves instrument onboard STEREO (S/WAVES, Bougeret *et al.*, 2008). There are at least three different types of STEREO observations associated with this population of dust particles near 1 AU: (1) millisecond transients in the antenna-spacecraft voltage measured by the S/WAVES instrument; (2) optical tracks in the SECCHI images; and (3) reports from the SECCHI on-board cosmic ray scrubbing algorithm.

In this manuscript we provide details on these three observations, and we discuss the engineering implications for consideration by future spacecraft designers. We also compare a subset of the SECCHI debris sightings with S/WAVES transients and find $> 90\%$ correlation. Finally we compare the deduced impact rates with the interplanetary dust measurements and estimate the size of the impacting grains producing the debris.

2. Optical Tracks in SECCHI

Spurious optical streaks (hereafter referred to as "debris") were seen in the white-light instruments of the SECCHI suite almost immediately upon the initiation of commissioning activities (STEREO-Ahead 03 January 2007; STEREO-Behind 06 March 2007). Hereafter, we will identify the spacecraft and instruments as either "-A" or "-B". Figure 1 shows examples of nominal images (top row) from STEREO-A immediately preceding (in time) debris-contaminated images (bottom row). Note that in these contaminated images the scientific quality of the Heliospheric Imager (HI) data has been rendered useless. Although this is not the usual case, it has occurred numerous times during the period studied here. The period of the study reported here is slightly less than 18 months (01 January 2007 through 15 June 2008) and, with only a few exceptions, represents nominal operations of the spacecraft and instruments.

Table 1 shows the characteristics for each of the SECCHI white-light telescopes that are relevant to this report. The COR telescopes are Sun-pointed, have a limited field-of-view, and operate regularly with short exposures and hence a limited duty cycle; the HI1 and HI2

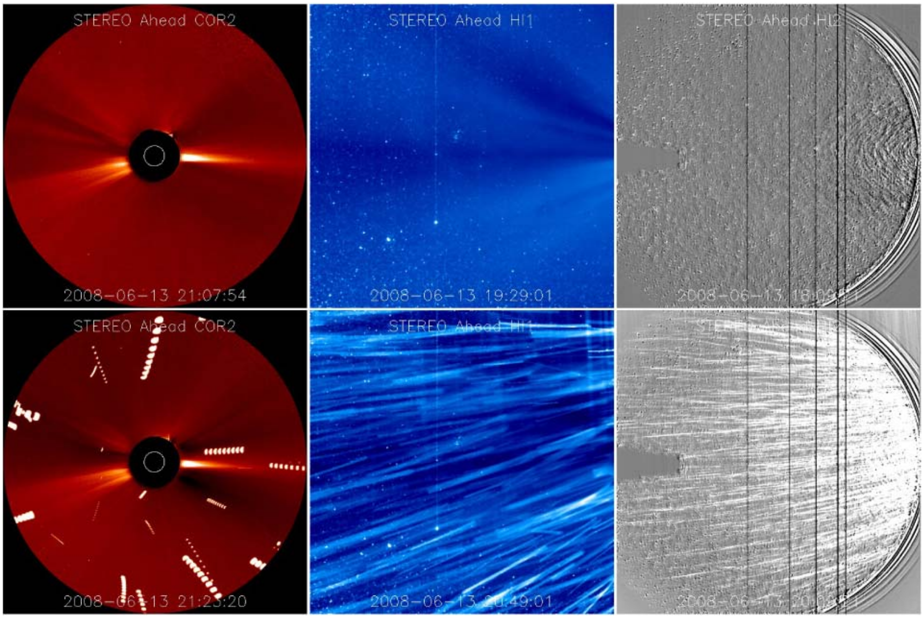

Figure 1 STEREO-A images from COR2, HI1, and HI2 immediately before (top panel) and during (bottom panel) the debris storm on 13 June 2008. Times of each image are shown, and the degradation to the scientific quality is evident. The COR1 images were not affected during this storm. The size and location of the Sun are shown as a white circle in the COR2 image; the Sun is to the right of the HI1 and HI2 images.

Table 1 Relevant telescope characteristics for SECCHI white-light telescopes. Note that COR1 and COR2 are Sun-pointed, whereas HI1 and HI2 view the ecliptic along the Sun – Earth line. Half of the COR2 images are double exposures at 0° and 90°, and only one composite image is downlinked. HI1 acquires 30 images of 40 second exposures that are summed (total exposure time 1200 s) to give images at a cadence of 40 minutes; for HI2, 99 images with a 50 second exposure time are summed (total exposure time 4950 s) leading to an image cadence of 120 minutes

	Inner FoV [° w/r Sun]	Outer FoV [° w/r Sun]	Solid Angle Viewed [sq °]	Fraction of Sky Observed	Exposure Time [s]	Polarization Components Downlinked	Summed Images	Nominal Exposure Cadence [s]	Nominal Number of Images per day	Fraction of Day Shutter is Open
COR1	0.43	1.1	3.51	0.0085%	1	3	N/A	300	288	0.042%
COR2	0.67	4.0	63.0	0.15%	1	3	N/A	1800	48	0.007%
HI1	6.02	26.02	400.0	0.97%	60	N/A	30	2400	36	50.0%
HI2	16.32	86.32	4900.0	11.88%	60	N/A	99	7200	12	68.8%

telescopes view the ecliptic along the Sun-Earth line, have relatively large fields-of-view that look progressively further from the Sun, and operate quasi-continuously. A few debris detections have been made in HI2 images, but these are much less frequent than HI1 and will be addressed in a later section. This manuscript will focus on debris detections in HI1.

Figure 2 shows the debris detections and the duty cycles for HI1-A and HI1-B. Time is shown horizontally, and the number of images per day containing debris streaks is shown in the histograms. The asterisks at the top of the graph represent the times of "debris storms" – HI1 images with 10 or more streaks. HI1 typically returns 36 images per day from each spacecraft. The HI1 telescopes obtain exposures for 30 out of every 40 minutes (summing 30 images of 40 second exposure for a total exposure time of 1200 s) to give images at a cadence of 40 minutes. One can see from the histograms in the lower panels that the number of images collected by both instruments is high for this period with totals of 16 732 images [15 465 images] obtained by HI1-A [HI1-B]. The vertical scales are the same, and one can readily see from the top panels that debris appears much more frequently in HI1-A.

We have measured locations, lengths, and directions of the streaks in HI1-A and HI1-B. For HI1-A [HI1-B] there were 1038 [256] images containing 2221 [609] streaks. The distribution of the lengths of streaks is broad, ranging from a few 10's of pixels to the full diagonal across the image. If we assume that each streak represents the motion of a particle relative to the HI1 field during a single 40 second exposure, then the average angular motion is $14.1^\circ\,\mathrm{min}^{-1}$ [$16.1^\circ\,\mathrm{min}^{-1}$].

The HI instruments are mounted on the side of each STEREO spacecraft. For both spacecraft, over 75% of the streaks appear preferentially with one endpoint near the sunward-side of the image frame, indicating that their origin is the body of the spacecraft. The streaks also extend preferentially parallel to the ecliptic plane, with 83% lying within $\pm 20^\circ$ of horizontal in the frame. We will discuss these points later in the manuscript.

Although the spacecraft attitude remains fixed with respect to the Sun, the onboard schedules follow an Earth-based 24-hour clock. However, we did not detect any preference for time-of-day in the appearance of the individual streaks or the storms.

The numbers presented here certainly represent an "under-count" of visual detections of debris in HI1 images because we have excluded several classes of questionable features: (1) linear streaks near the sub-solar point could be mistaken for deflections of existing coronal features; and (2) linear streaks sometimes appear at the sides of CMEs/structures as they move radially away from the Sun. Also, bright CMEs and planets can spread throughout an image, masking streaks. HI1-B has an additional peculiarity whereby a fraction of the images each day appear to have unstable pointing. The cause is unknown, but that leads to difficulty in examining running difference images to search for debris streaks.

3. Debris Storms Detected in the HI Cosmic Ray Removal Counters

In order to achieve the desired signal-to-noise ratio in the HI images, long exposures are necessary (typically 1200 seconds during 30 minutes for HI1, and 4950 seconds during 120 minutes for HI2). These are done incrementally onboard the spacecraft using exposures that are first "scrubbed" of cosmic rays before they are summed and put into telemetry (*e.g.*, Howard *et al.*, 2008; Harrison, Davis, and Eyles, 2005). The cosmic ray scrubbing algorithm works on pairs of images, replacing bright pixels with dim ones when the intensity in the current image pixel exceeds five times the expected photon noise in the same pixel in the previous image. The information about the number of pixels replaced in each incremental image is preserved in the header of the single downlinked sum.

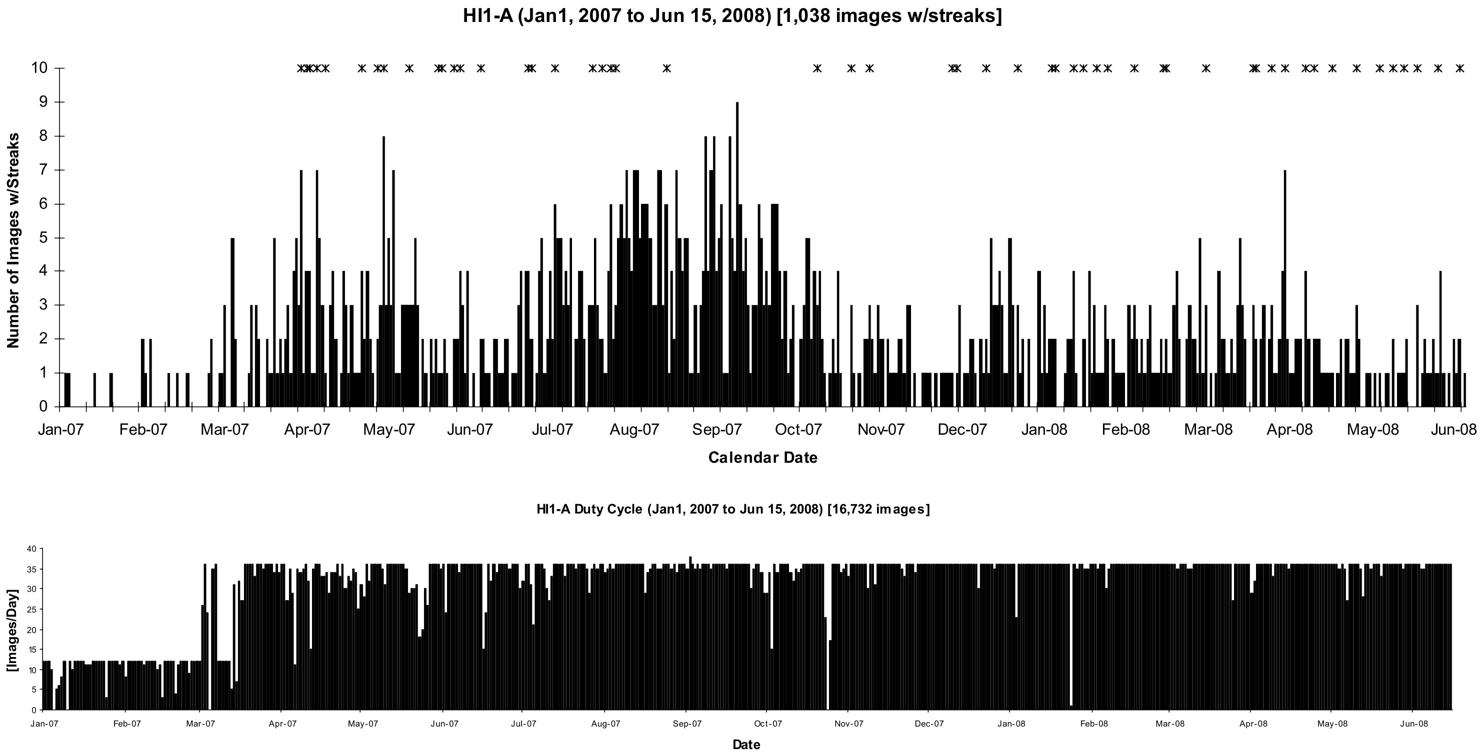

Figure 2 (a) Histograms of HI1-A duty cycle and debris detection from 01 January 2007 through 15 June 2008. A nominal duty cycle for this instrument is to return 36 images per day, which it has through most of this period. The asterisks denote days when "debris storms" have been detected (see Figure 1).

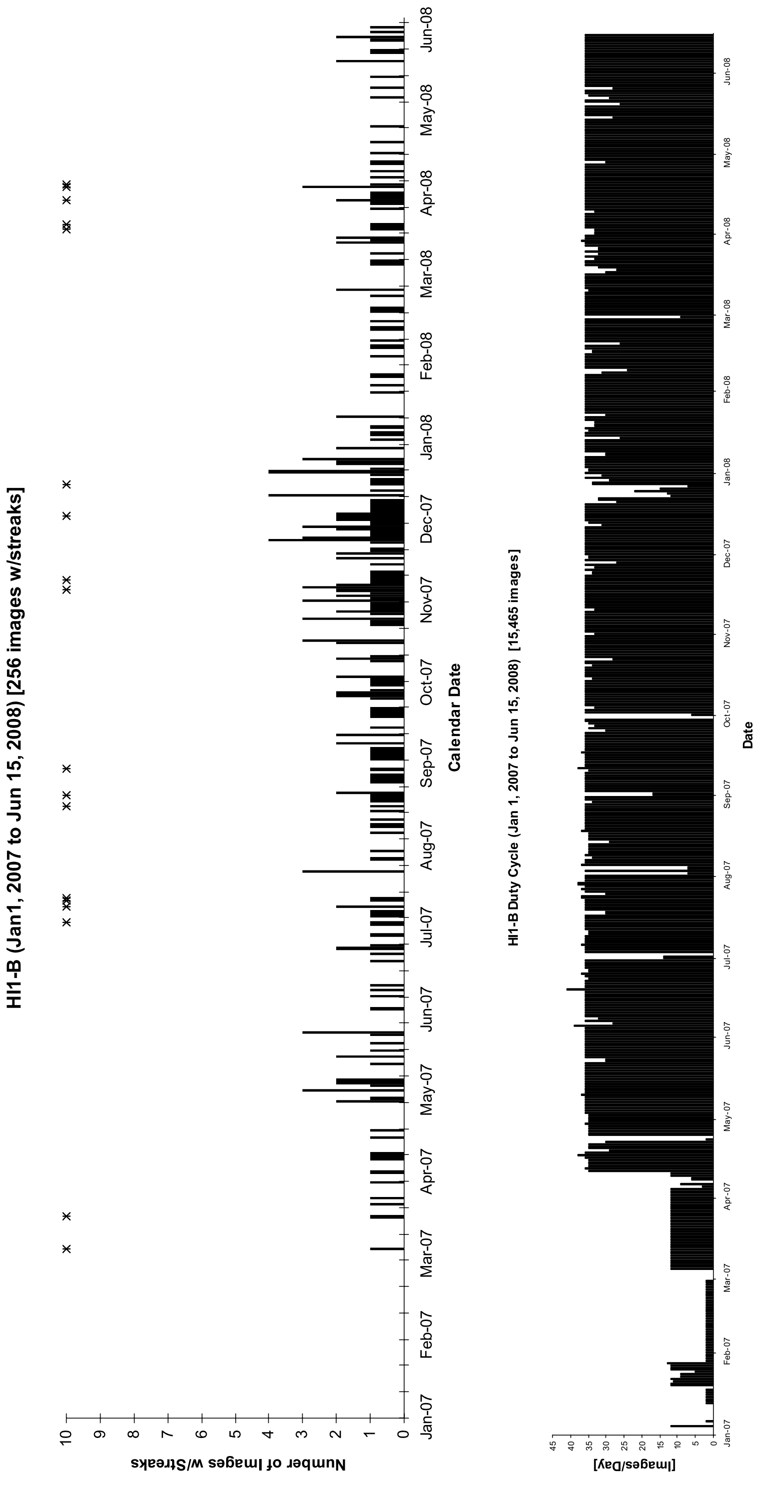

Figure 2 (*Continued.*) (b) Same histograms for HI1-B.

Table 2 Cross-instrument statistics for the HI1 debris storms (defined as a single image containing 10 or more streaks) for the period 01 January 2007 through 15 June 2008. Statistics for and the length of time the debris was seen in the HI1 and HI2 cosmic ray removal counter (CR counter) are also shown.

	HI1 Storms	HI1 CR Counter Average Duration [min]	In COR1 Images	In COR2 Images	In HI2 Image	HI2 CR counter	HI2 CR Counter Average Duration [min]	HI1 Events During S/WAVES Quiet Times	S/WAVES Event
HI1-A	68	7.8	24 (35%)	47 (69%)	6 (9%)	50 (74%)	9.9	34	32 (94%)
HI1-B	17	7.6	2 (12%)	4 (24%)	2 (12%)	13 (76%)	7.3	17	16 (94%)

A typical cosmic ray removal count for a 30-sum HI1 is $\sim$5000 pixels per incremental exposure, and there is always a larger value in the first incremental exposure because the 10 minute gap between downlinked images results in a larger accumulation of cosmic rays and a larger motion of the stellar background.

For HI1 images showing debris storms, we were able to determine the minute (within the 30 minute accumulation period) that the storm began by examining the cosmic ray counter. There were 68 [17] debris storms whose average pre-event cosmic ray scrub was 5326 pixels [7998 pixels] removed in the minute before the storm appeared. On average, over 837 000 pixels [391 000 pixels] were removed by the cosmic ray scrubbing in the following minute; and the cosmic ray count required an average of 7.8 minutes [7.3 minutes] to return to a pre-event background level. The longest storm duration as measured by the cosmic ray counter returning to background was 18 [18] minutes. The maximum number of pixels removed in a single sequential image was 4.19×10^6 [2.2×10^6]. That value for HI1-A implies that nearly all of the pixels in the 2k $\times$ 2k image were replaced.

Table 2 indicates that the HI1 debris storms seldom appeared visually in HI2 images – a point that will be addressed in the discussion section. However, it is also evident that the storms were detected in the HI2 cosmic ray removal counter with average durations comparable to those of HI1.

4. HI1 Debris Storms Comparison to S/WAVES

There is a long history of detection by onboard radio and plasma wave instruments of small particles impacting spacecraft bodies. Of particular note are the many *Voyager and Cassini* passages through the outer portions of Saturn's ring plane (*e.g.*, Kurth *et al.*, 2006 and references therein). The specific signature detected by wave instruments is a very rapid rise (or fall) in detected voltage on the antennas followed by a rapid recovery, all taking place within a few milliseconds. These signals are due to micron-sized (ice, in the case of Saturn) particles impacting at high velocity against the spacecraft body where the kinetic energy of the particle is converted to heat which vaporizes the particle and part of the spacecraft material thereby producing a small partially ionized cloud of gas. The ionized cloud expands and the residual charge produces an electric pulse which is detected by the antenna – receiver system. These detections at the outer planets have been extended to the nanometer size, with a simultaneous detection of nanoparticles by the wave instrument and by the on-board dust detector on *Cassini* (Meyer-Vernet *et al.*, 2009a).

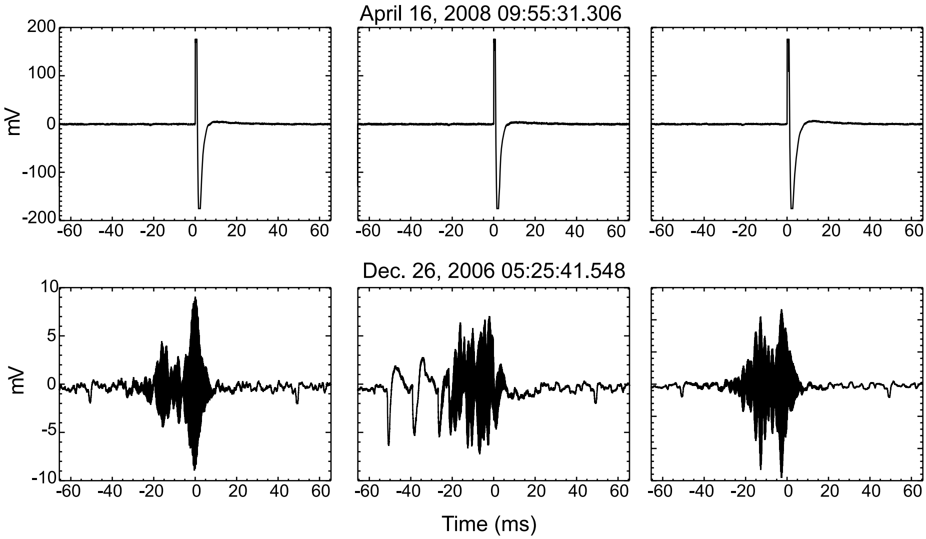

Figure 3 Top panels show an example of an impulse-like event recorded by all three electric antennas connected to the S/WAVES TDS instrument on the Ahead spacecraft. TDS samples the voltages on all three antennas 125 000 times per second. This particular event occurs during the same one minute interval as one of the HI1 debris storms. The TDS event is characterized by a brief rise to maximum intensity (saturation) followed by a large excursion in the opposite direction. The total duration of the event and others like it is typically 5 – 10 milliseconds. The bottom panels show a typical *in situ* Langmuir wave event recorded by the TDS. Langmuir wave and other *in situ* solar wind events rarely, if ever, saturate the TDS and are always much longer in duration than the impulse-like events. Note the different scale for the vertical axes between top and bottom panels.

Recently, Meyer-Vernet *et al.* (2009b) have reported similar dust impact signatures (extending down to nanometer size) recorded by the S/WAVES instruments in interplanetary space. The events were detected in both the frequency-domain receiver (LFR) and the time-domain receiver (TDS), and their very large impact rate corresponds to interplanetary nanoparticles. The signatures of the events are broadly similar to those detected by the wave instruments at Saturn, since interplanetary nanoparticles are moving so fast that they produce a signal similar to that of the much larger grains (*e.g.*, micron size) of moderate speed. However, nanoparticle events generally do not produce a voltage pulse on all three S/WAVES electric antennas simultaneously because they are due primarily to charging of the individual antenna elements. Larger micron-sized particles, in contrast, affect the overall spacecraft charging, so they usually produce simultaneous pulses on all S/WAVES antennas.

Figure 3 (top panels) shows the S/WAVES TDS signals from all three antennas corresponding to a SECCHI debris event of 16 April 2008. The event lasts for only a few milliseconds and briefly saturates the instrument (about ± 175 mV). This event and the corresponding SECCHI HI1 debris storm were simultaneous to within one minute. The bottom panels of Figure 3 show a typical *in situ* Langmuir wave detected by the TDS instrument to illustrate the dramatic contrast with the impact signature. Langmuir events and other *in situ* solar wind events rarely, if ever, saturate the TDS receiver (note the change in vertical scale between the top and bottom panels). The impact signatures like those shown in the top panel, on the other hand, are nearly always saturated.

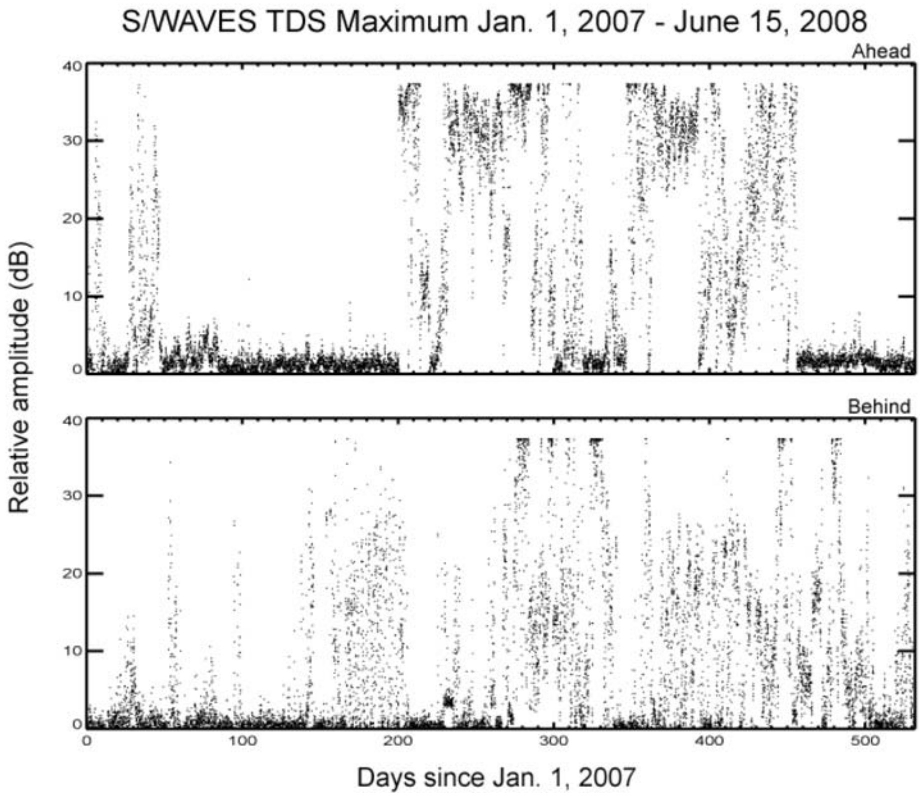

Figure 4 The average hourly maximum excursion (absolute value) of S/WAVES TDS events like those shown in Figure 3 for the Ahead (top panel) and Behind (bottom panel) spacecraft for the interval of study, 01 January 2007 to 15 June 2008.

Over the nearly 18 months studied here, the S/WAVES nanoparticle events have been sporadic, appearing almost continuously for days-to-months. Figure 4 shows the overall level of activity (relative hourly maximum signal) in the TDS receivers for both STEREO-A and -B for the same period of study reported here for SECCHI HI1. Most of the spikes evident in Figure 4 are due to nanoparticle events, with S/WAVES on Ahead [Behind] recording 81 851 [34 733] such events on at least one antenna. In contrast, during the 18-month interval S/WAVES on Ahead [Behind] detected 4186 [3229] saturated impact events like the top panels of Figure 3 (*i.e.*, involving all three antennas).

Since the debris are expected to be produced by large grains whose impact rate is much lower than that of nanoparticles, we have selected "quiet" periods in S/WAVES, where the sporadic dust signals due to nanoparticles largely disappear. We have examined the coincidence of SECCHI HI1 debris with SWAVES during several of those "nanoparticle-quiet" periods. The time of the HI1 debris events can be specified to within one minute from the cosmic ray counter, and we have examined the S/WAVES data for TDS events at those times. The rather impressive results of the comparison appear in Table 2 where 94% [94%] of the events are simultaneous.

5. Discussion

Because of the extremely high coincidence between these three methods of detection (S/WAVES TDS, HI1 images, and HI1/HI2 cosmic ray counters), we conclude that these detections have a common origin. The most likely origin is that interplanetary dust strikes the fragile indium-tin-oxide (ITO) coated thermal blanketing on the Sun-facing side of the spacecraft; the short-lived plasma cloud is detected as an event by S/WAVES TDS; pieces of the ITO or the blanketing are ejected from the spacecraft and detected by SECCHI as in Figure 1; and as they move past the HI fields-of-view (and as the spacecraft move out from under this debris cloud) they are considered "transients" to the cosmic ray counter. We now dissect that hypothesis to see if it holds together.

The first assumption is that the ITO-coated thermal blanketing on STEREO is a ready source of particles that depart the spacecraft. Driesman, Hynes, and Cancro (2008) describe the design and fabrication of the twin STEREO observatories. They note that one of the instruments in the IMPACT suite (Luhmann *et al.*, 2008) "... necessitated a requirement to have spacecraft body at a uniform and low electrical potential with respect to the (ambient) plasma... (so) the Sun-facing surfaces of the spacecraft were covered with indium-tin-oxide (ITO)-coated silver Teflon thermal blankets." Personnel who worked with the spacecraft noted that this material was very reflective but difficult to handle and easy to "flake". This anecdotal evidence is in agreement with Gilmore (2002) who notes that ITO is fragile and may be degraded with even minimal handling. He states further that "wiping for cleaning purposes can ruin the surface, as can bending during manufacture or storage." A manufacturer of ITO notes that "connecting ground leads to ITO coated surfaces is difficult. The coating is fragile... " (www.sheldahl.com).

Earlier we noted that a significantly larger amount of debris is seen with STEREO COR2-A as compared with SOHO LASCO C2/C3. These instruments have comparable fields-of-view and duty cycles, but the treatment of the sunward faces between the spacecraft was significantly different. Instead of ITO-coated silver teflon thermal blanketing (STEREO), SOHO had highly-reflective ITO-coated glass tiles on the sunward face that the instrument apertures penetrated. Thermal blanketing was used around the bodies of the instruments on SOHO, commensurate with the idea that debris sightings were predictably seen when another instrument opened it's aperture door. Our expectation is that the ITO on tiles would be more stable than ITO on blankets because the thermal expansion difference is smaller between ITO (glass) and the glass tiles as compared to ITO and silver teflon. Also no matter how gently one handles a thermal blanket, the ITO-coated silver teflon becomes cracked.

What about the disparity in debris sightings between HI-A versus HI-B? A measure of this distinction is evident in that the ratio of A/B debris images is fairly constant at $\sim 4\times$, no matter which parameter is selected. If we assume that the ITO thermal blanketing is the source of the particles, then it is important to recall that only the sunward surface of the spacecraft is wrapped in ITO thermal blankets. This means on A, the HI instrument package is "sheltered" by the body of the spacecraft from the ram direction, but when particles come off the sunward face, the orbital motion of the spacecraft means they will eventually appear in the HI-A field-of-view. It is the opposite case for B, where HI is viewing the sky in the same direction as the spacecraft velocity vector, so only particles coming off the sunward face near the HI instrument aperture become visible. The spacecraft and instrument geometry is depicted in Figure 5.

Note that the ratio of S/WAVES saturation events between Ahead and Behind is only 1.3. We would not expect S/WAVES to be strongly affected by the spacecraft orientation relative

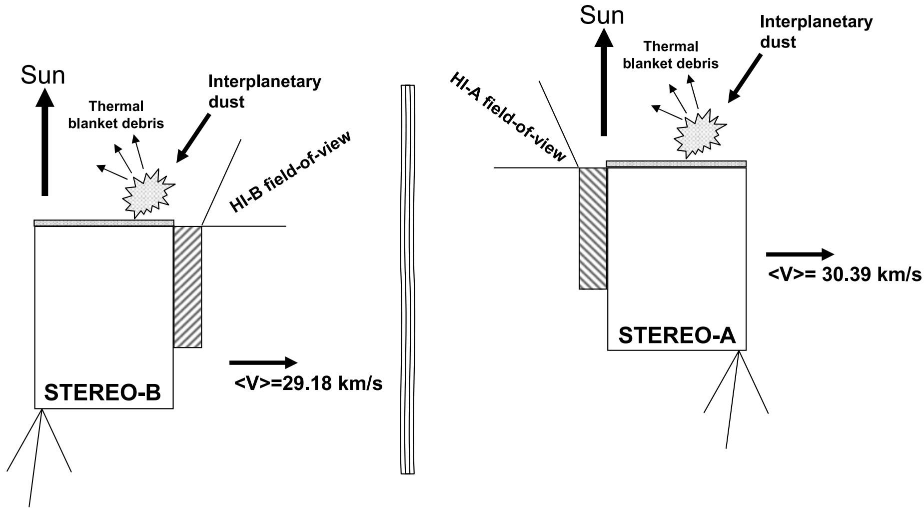

Figure 5 The orientation of STEREO-A and -B, showing the relative location of the SECCHI HI imagers (cross-hatched rectangle) with respect to the spacecraft motion (*i.e.*, ram direction). The HI fields-of-view and the location of the three S/WAVES antennae on each spacecraft are depicted schematically. A stylized "explosion"of particles from an interplanetary dust impact is shown coming off the sunward face of each spacecraft, which is covered with an ITO-coated silver Teflon thermal blanket. The debris particles movement opposite the orbital motion of the spacecraft puts the debris cloud into [away from] the HI1-A [-B] field of view.

to the velocity vector – the argument given above to explain the difference between HI-A versus HI-B with a ratio of four. However, it is conceivable that there is a small disparity between the amount of interplanetary micron-sized dust in the vicinity of the two spacecraft, which are only 0.1 AU apart in radial distance from the Sun, but with one leading Earth (Ahead) and the other trailing (Behind).

What about the relative appearances of debris in the different SECCHI white-light instruments? With the much smaller fields-of-view and lower duty cycles of COR1 and COR2 compared to HI1, it may be surprising that they see any debris. However, note that the COR apertures are on the sunward face of the spacecraft, actually piercing the ITO blanketing. The fact that they see some of the debris storms strengthens the assumption that the ITO blanketing is the source.

There are three other remote sensing devices that could conceivably detect debris: two other telescopes in the SECCHI suite (EUVI and the guide telescope), and the spacecraft star tracker. For EUVI, the $>10^{13}$ rejection of visible (as well as ultraviolet and infrared) light is accomplished using thin metal filters. The guide telescope (GT) has a 50 nm passband centered at 570 nm. Both of these telescopes are sensitive to solar intensities, while the debris particles are $\sim 10^7$ fainter (*i.e.*, coronal intensities). No sign of debris has been detected in either of these instruments. Also note that the GT has only four pixels, each about 6×6 arc minutes in size, with roughly half of each looking straight at the photosphere. The star tracker is mounted on the aft end of the spacecraft, angled so that it points almost anti-sunward. Since we believe the particles come off the sunward face of the spacecraft, it is difficult to visualize how they could ever get into the field-of-view of the star tracker. In addition, the appearance of debris in the star tracker field of view would not persist long enough to cause any action by the spacecraft guidance and control system.

From Table 1 we saw that the HI2 field-of-view is significantly larger than HI1, and the HI2 duty cycle is also superior – why does it see only some of the storms? There are several possibilities: particles in the HI2 field will be further from the spacecraft, so the scattered light from both the Sun (and from the bright face of the spacecraft) will be fainter compared to a particle near the spacecraft. Also, if the bulk of the light arises from forward scattering of sunlight, then the HI1 field will be better placed to detect the debris. Finally, the relative contribution of a debris particle will be "averaged" in the accumulation of 99 HI2 images compared to 30 for HI1.

If the debris sightings are the result of "secondaries" from dust striking the ITO-coated blanketing, then how do the SECCHI data compare to a standart interplanetary dust model? Using the HI1-A statistics, there were 16 732 images, each representing 1200 second accumulations – thus 2.008×10^7 seconds of observation (out of the nearly 18 months, yields a 42% duty cycle). If we assume that the sunward face of STEREO is $\sim 1\ m^2$ and the 68 debris storms represent interplanetary dust strikes on that face, then from the graph of dust at 1 AU in Grun *et al.* (2004) we conclude that these are grains of $\sim 10^{-8}$ grams (or radius ~ 10 microns).

Finally, we are particularly impressed by the 94% correlation between the SECCHI events and the S/WAVES events during the S/WAVES quiet intervals. For the Ahead spacecraft, we have looked at the two relatively long nanoparticle-quiet intervals 01 March through 20 July 2007 and 01 April through 15 June 2008 (269 280 minutes total). During those two intervals, S/WAVES detected 1671 saturated events like the top panels of Figure 3 (or 0.0062 per minute) while SECCHI detected 34 debris storms (0.000126 per minute). The probability that 32 of the SECCHI events were coincident by chance with S/WAVES events within the one minute time resolution is vanishingly small. Given the percentage of sky coverage of HI1 and the duty cycle from Table 1, we would have predicted SECCHI would detect 22 or 23 events during this interval if they were all in the sunward hemisphere (as is our premise), remarkably close to the actual number detected.

6. Conclusions

We report that STEREO SECCHI sees significant amounts of debris in the white-light instruments, apparently associated with micron size interplanetary dust impacting the spacecraft. The debris is detected on both spacecraft visually in all four instruments and in the cosmic ray counters for the HI's. Major debris sightings (storms) are detected in numerous ways, including visually, cosmic ray counters, and the S/WAVES instrument. Similar to S/WAVES detections of nanometer-sized dust impacts, the amount of debris seen on STEREO-A is significantly higher than on STEREO-B, in spite of the spacecraft being separated radially by only 0.1 AU. The asymmetry in debris sightings as a function of both heliographic longitude and distance from Earth remains a topic of study. For the S/WAVES detections, this might be due to differences in the spacecraft location with respect to Earth; whereas for the SECCHI HI detections of micron-size dust impacts reported here, it may be due to the orientation of the spacecraft with respect to the ram direction.

The STEREO debris storms affect a relatively small number of individual images and have not affected completion of the mission's scientific goals. Coronagraph instrument providers had ample evidence from previous space missions to be concerned about particulate contamination; however, it seems that builders of spacebased sensitive remote sensing instruments have again learned a lesson concerning materials near their apertures. Two future missions in the planning stages have wide-field white-light imagers in their straw payloads. Project managers for ESA's Solar Orbiter and for NASA Solar Probe+ would be wise to consider the recent STEREO experience reported here.

Acknowledgements The SECCHI data used here are produced by an international consortium of the Naval Research Laboratory, Lockheed Martin Solar and Astrophysics Laboratory, and NASA Goddard Space Flight Center (USA), Rutherford Appleton Laboratory and University of Birmingham (UK), Max-Planck-Institut für Sonnensystemforschung (Germany), Centre Spatiale de Liège (Belgium), Institut d'Optique Théorique et Appliqueé, and Institut d'Astrophysique Spatiale (France). The USA institutions were funded by NASA; the UK institutions by Particle Physics and Astronomy Research Council; the German institutions by Deutsches Zentrum für Luft- und Raumfahrt e.V.; the Belgian institutions by Belgian Science Policy Office; the French institutions by Centre National d'Etudes Spatiales and the Centre National de la Recherche Scientifique. The NRL effort was also supported by the USAF Space Test Program and the Office of Naval Research. The S/WAVES data used here are produced by an international consortium of the Observatoire de Paris (France), the University of Minnesota (USA), the University of California Berkeley (USA), and NASA Goddard Space Flight Center (USA). The French contribution was funded by CNRS, and the USA institutions were funded by NASA. We also gratefully acknowledge contributions from K. Baldwin (NRL), J.-P. Olive (ESA), A. Dreisman (JHU/APL), and C. Edgerton (Edge Space Systems).

References

Bougeret, J.-L., Goetz, K., Kaiser, M.L., Bale, S.D., Kellogg, P.J., Maksimovic, *et al.*: 2008, S/WAVES: The radio and plasma wave investigation on the STEREO mission. *Space Sci. Rev.* **136**, 487.

Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Michels, D.J., Moses, J.D., Socker, D.G., Dere, K.P., Lamy, P.L., Llebaria, A., Bout, M.V., Schwenn, R., Simnett, G.M., Bedford, D.K., Eyles, C.J.: 1995, The Large Angle Spectroscopic Coronagraph (LASCO). *Solar Phys.* **162**, 357.

Driesman, A., Hynes, S., Cancro, G.: 2008, The STEREO observatory. *Space Sci. Rev.* **136**, 17.

Eddy, J.A., Ise, R.: 1979, *New Sun: The Solar Results from Skylab* **SP-402**, NASA, Washington.

Gilmore, D.G.: 2002, *Spacecraft Thermal Control Handbook*, AIAA, Washington. ISBN 188498911X, 9781884989117.

Grun, E., Dikarev, V., Frisch, P.C., Graps, A., Kempf, S., Kruger, H., Landgraf, M., et al.: 2004, Dust in interplanetary space and in the local galactic environment. In: Witt, A.N., Clayton, G.C., Draine, B.T. (eds.) *Astrophysics of Dust, ASP Conference Series* **309**, 245.

Harrison, R.A., Davis, C.J., Eyles, C.J.: 2005, The STEREO heliospheric imager: how to detect CMEs in the heliosphere. *Adv. Space Res.* **36**(8), 1512.

Howard, R.A., Moses, J.D., Vourlidas, A., Newmark, J.S., Socker, D.C., Plunkett, S.P., Korendyke, C.M., *et al.*: 2008, Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI). *Space Sci. Rev.* **136**, 67.

Kaiser, M.L., Kucera, T.A., Davila, J.M., St. Cyr, O.C., Guhathakurta, M., Christian, E.: 2008, The STEREO mission: An introduction. *Space Sci. Rev.* **136**, 5.

Kurth, W.S., Averkamp, T.F., Gurnett, D.A., Wang, Z.: 2006, Cassini RPWS observations of dust in Saturn's E ring. *Planet Space Sci.* **54**, 988.

Luhmann, J.G., Curtis, D.W., Schroeder, P., McCauley, J., Lin, R.P., Larson, D.E., Bale, S.D., *et al.*: 2008, STEREO IMPACT investigation goals, measurements, and data products overview. *Space Sci. Rev.* **136**, 117.

Lyot, B.: 1933, The study of the solar corona without an eclipse. *J. Roy. Astron. Soc. Can.* **27**, 265.

MacQueen, R.M.: 1974, The High Altitude Observatory white-light coronagraph experiment of Skylab. *J. Opt. Soc. Am.* **64**, 523.

MacQueen, R.M., Csoeke-Poeckh, A., Hildner, E., House, L., Reynolds, R., Stanger, A., Tepoel, H., Wagner, W.: 1980, The High Altitude Observatory Coronagraph/Polarimeter on the solar maximum mission. *Solar Phys.* **65**, 91.

McGuire, J.P.: 1976, Contamination from Skylab as determined from the solar coronagraph data. NASA TM X-73353, Washington, DC.

Meyer-Vernet, N., Lecacheux, A., Kaiser, M.L., Gurnett, D.A.: 2009a, Detecting nanoparticles at radio frequencies: Jovian dust stream impacts on Cassini/RPWS. *Geophys. Res. Lett.* **36**(3), L03103.

Meyer-Vernet, N., Maksimovic, M., Czechowski, A., Mann, I., Zouganelis, I., Goetz, K., Kaiser, M.L., *et al.*: 2009b, Dust detection by the wave instrument on STEREO: nanoparticles picked-up by the solar wind? *Solar Phys.* this issue.

St. Cyr, O.C., Warner, T.: 1991, SMM coronagraph observations of particulate contamination. *Publ. Astron. Soc. Pac.* **17**, 126.

St. Cyr, O.C., Plunkett, S.P., Michels, D.J., Paswaters, S.E., Koomen, M.J., Simnett, G.M., Thompson, B.J., Gurman, J.B., Schwenn, R., Webb, D.F., Hildner, E., Lamy, P.L.: 2000, Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998. *J. Geophys. Res.* **105**(A8), 18169.