Solar stormwatch: tracking solar eruptions

Article

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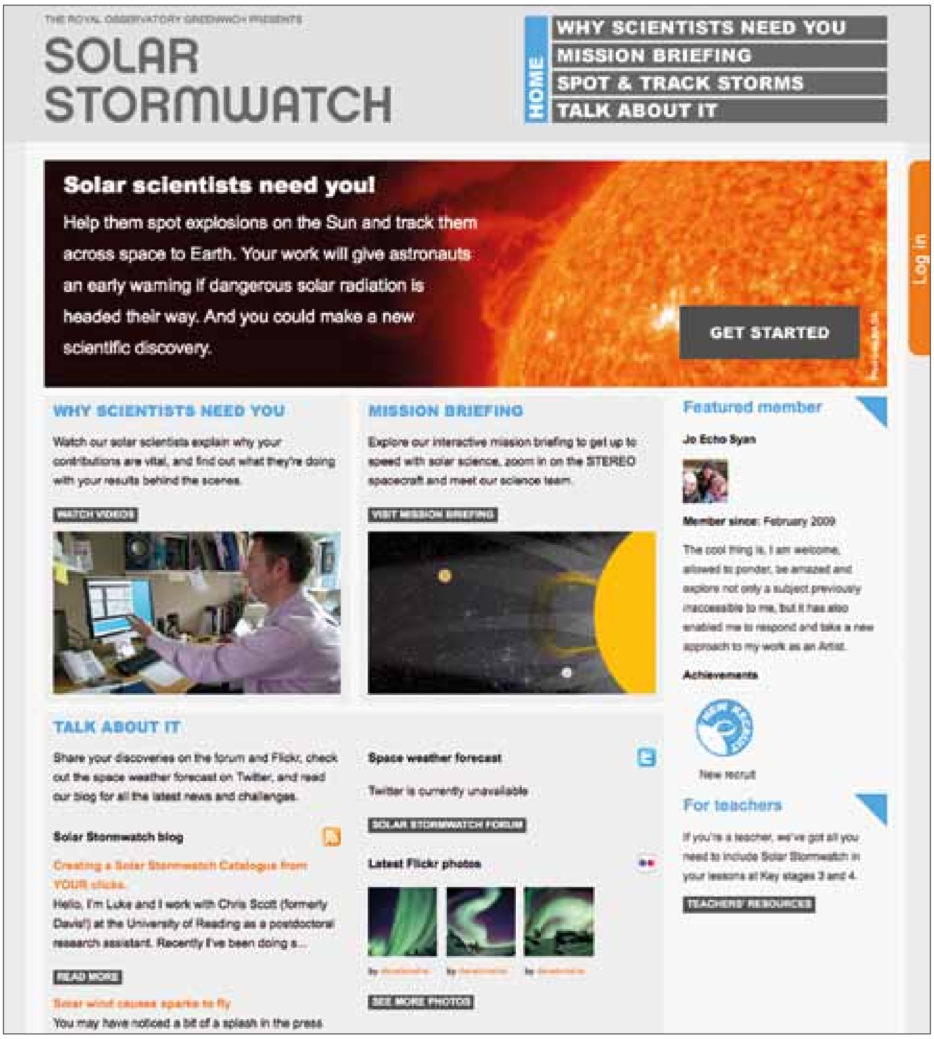
Solar Stormwatch: tracking solar eruptions

The **Solar Stormwatch team** reviews progress and prospects for this highly effective citizen-science project focused on the Sun.

Solar Stormwatch (http://www.solarstormwatch.com) is a citizen-science project in which participants identify and characterize coronal mass ejections (CMEs) observed by the Heliospheric Imager (HI) instruments aboard the twin STEREO spacecraft. The tasks carried out by citizen scientists are time-consuming but require a degree of expertise, skill and judgement which has so far frustrated attempts to automate them. Anybody is welcome to participate in Solar Stormwatch and the project has now been running for approximately five years, with input from more than 16000 citizen scientists resulting in a dataset of more than 38000 profiles of CME trajectories. With these data, Solar Stormwatch is producing novel science, but it has also proved to be an exceptionally effective form of outreach, fostering a relationship with a community of people interested and motivated to learn more about space weather and the science of our Sun.

Launched in late 2006, the STEREO spacecraft are STEREO-Ahead (STA) and STEREO-Behind (STB). Both are in Earth-like heliocentric orbits, but STA (STB) drifts ahead of (behind) Earth, by approximately 22° per year. Both STA and STB carry the SECCHI instrument package, which includes two HI white-light cameras, HI1 and HI2. Together, the cameras can image density structures in the solar wind over an elongation range from 4° to more than 70° in the ecliptic plane. Therefore, with HI it is possible to follow CMEs from the outer limits of the solar corona all the way to Earth's orbit.

In this article we will review the main science results achieved by Solar Stormwatch and discuss what the future may hold for the project. This is timely as the recent change to solar conjunction mode operations of the STEREO spacecraft, and the associated loss of STB, have affected several of the Solar Stormwatch activities. We also provide an insight into the community aspects of citizen-science projects.



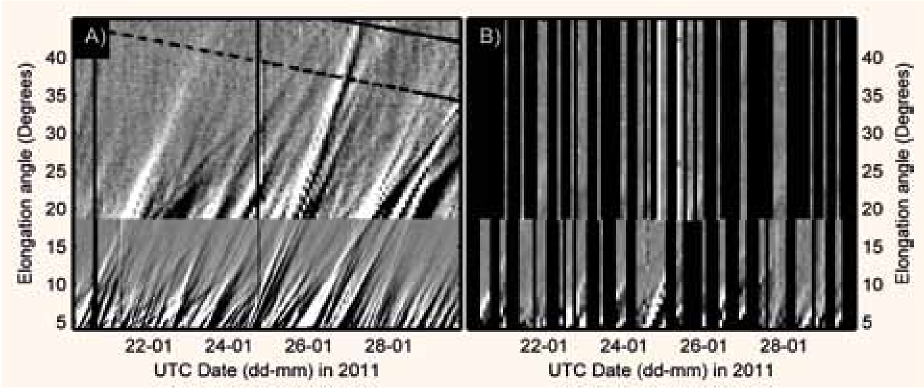
1 There's plenty to engage with on the Solar Stormwatch website.

Activities

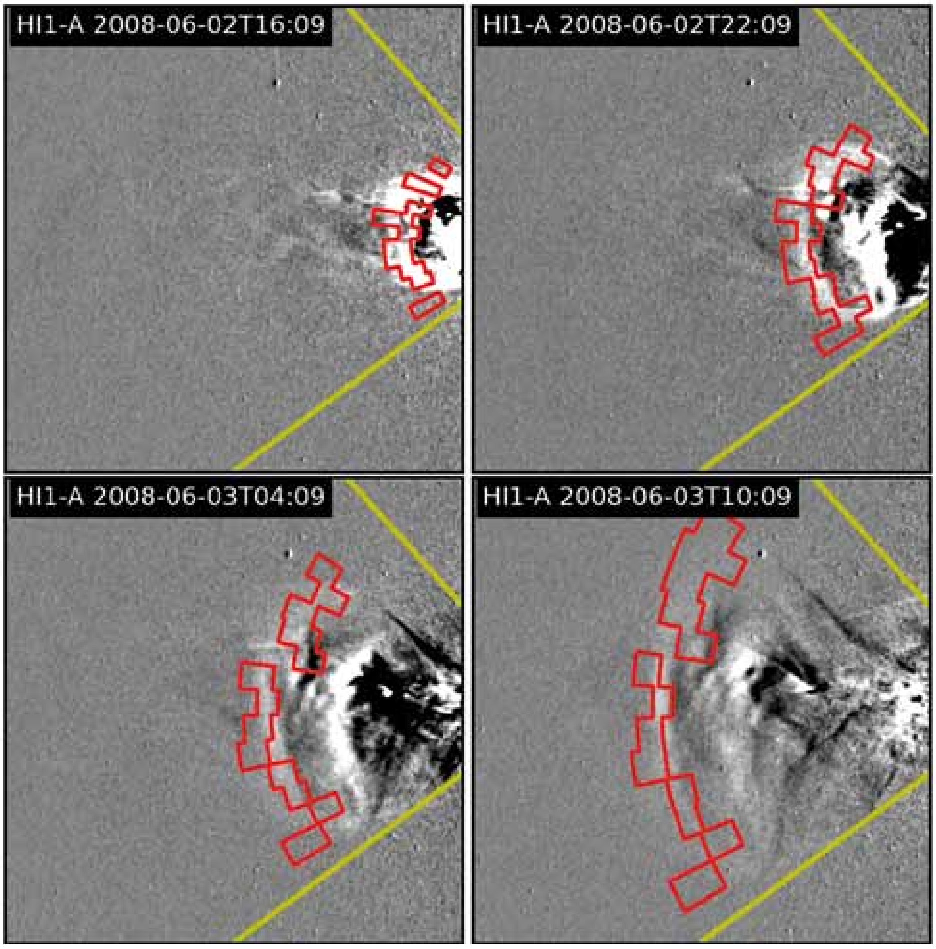
There are six Solar Stormwatch activities, each of which is completed via an online tool. We describe them briefly here; for a more complete description see Barnard *et al.* (2014).

Spot is the fundamental activity. Participants visually identify CMEs in 14-day movies of HI1-A and HI1-B science images, noting the times when a CME first enters the field of view and when the CME is half-way across it, along the position angle corresponding with the ecliptic plane.

The activity *Trace-it* characterizes the trajectory of CMEs in J-maps, which are time–elongation maps at a fixed position angle (PA) (Davies *et al.* 2009, Sheeley *et al.* 1999). An example J-map, constructed



2 (a) A J-map constructed with HI1-A and HI2-A science-quality data. (b) A J-map constructed from the real-time RTB data spanning the same period as the science data in panel (a). In each plot, vertical black bars mark regions of missing data.



3 This image sequence shows the evolution of a CME through HI1-A differenced images, over a period of 16 hours. The ecliptic plane lies horizontally in the middle of each panel. The CME front, identified by averaging the time-elongation profiles produced by the *Trace-it* activity, is marked by the red contours. The yellow lines mark the limits of the PA range considered in the *Trace-it* activity.

from HI science images, is shown in figure 2a. To create these J-maps, the HI field of view is split into 18 distinct PA bands, each band spanning 5° such that 85° of PA in the HI field of view is analysed; this is the region between the yellow lines in figure 3. Participants are shown J-maps and are directed to times at which the brightness profile corresponding to a CME identified in the *Spot* activity may be visible. They are then required to place up to 20 markers characterizing the time–elongation profile of the CME front in this J-map.

Incoming Spot is similar to *Spot* except that, instead of analysing movies made from HI1-A and HI1-B science-quality data, participants are shown the most recently available real-time beacon (RTB) mode data. The RTB data mode is lower resolution than the science data, in both cadence and spatial resolution (see figure 2b). This activity updates as more RTB data become available. Also, the RTB data are downlinked from the spacecraft on a "best-efforts" basis and consequently this data stream has significant gaps in coverage. This activity is used in determining the requirements for real-time warning of Earth-directed CMEs.

The task *Incoming Trace-it* is similar to *Trace-it*, except that the J-map that is analysed is built from the most recent RTB data. Furthermore, CMEs are only tracked along a 5° PA band centred on the ecliptic plane. As this J-map is built from the RTB data, it is also of lower resolution and has frequent data gaps. This activity also updates as more RTB data become available.

In the activity *What's that?*, participants are asked to identify the frames of any movie in which they think there is something unusual. Four predetermined categories are presented: "comet", "dust impact", "optical effect" and "something else". Building a catalogue of these events is useful in providing context to the quality of the CME observations and in achieving some secondary scientific goals such as estimating the distribution of dust around Earth's orbit.

And for *Track it back*, participants are invited to follow and characterize CMEs previously identified in the HI data back through the COR2 and COR1 coronagraphs and finally back to EUV images of the solar disc. The participant is shown images of the solar disc in four extreme ultraviolet wavelengths observed by the EUVI instrument and asked to choose the wavelength that reveals the erupting material most clearly. This gives an indication of the temperature of the erupting material. The participant is asked to mark the location of the source of the eruption on the solar disc.

CME catalogue

The project has resulted in a new catalogue of CMEs. When characterizing CMEs in HI data, the analysis is usually performed manually. This often involves a researcher identifying the time–elongation profile corresponding to the CME front in J-maps formed from the HI data. This process is time-consuming and laborious and the results are subjective, depending on the skill and expertise of the investigator. The CMEs identified in the Solar Stormwatch CME catalogue are profiled many times by multiple participants and this allows the calculation of consensus profiles for each event. Tests show the consensus profile is usually very close indeed to that generated by an expert, yet it does not suffer from the subjectivity of individual researchers identifying and tracking CMEs.

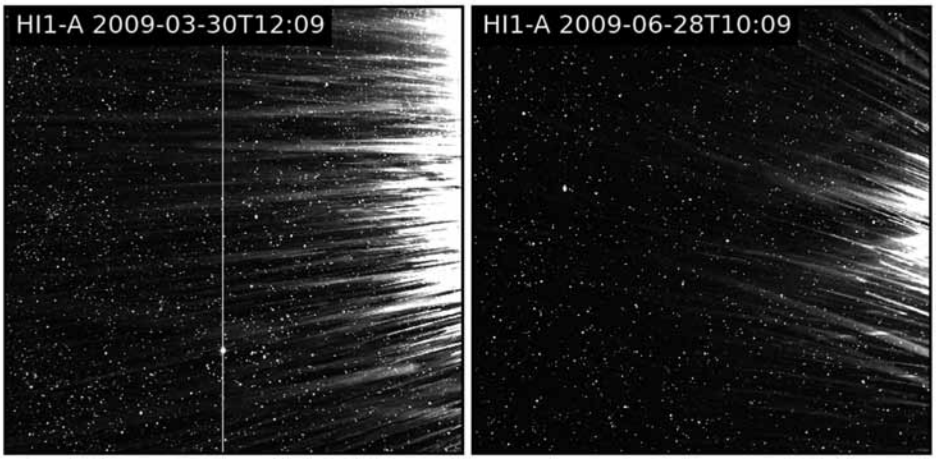
To build the Solar Stormwatch CME catalogue, the results of the *Trace-it* activity are used, in which the time–elongation profiles of CME fronts are identified in J-maps made from differenced HI images, including more than 38 000 profiles. Barnard *et al.* (2014) used these data to produce a catalogue of CMEs observed by STA and STB between January 2007 and February 2010.

The first stage was quality control; several criteria are applied to these time–elongation profiles to remove erroneous traces; for example, some profiles mistakenly track the orbit of planets in the HI field of view. When many participants identify the same feature in the *Trace-it* J-maps, the result is a clustering of the number of profiles as a function of time in the J-map coordinates. In the Solar Stormwatch CME catalogue, CMEs are defined by identifying these clusters of time–elongation profiles. A constant threshold is used to identify the largest, most well defined clusters. Each cluster is then automatically checked to test whether the profiles it contains are consistent with each other. For example, some clusters can contain the profiles corresponding to two almost simultaneous events, which must be identified and separated.

Once clusters of profiles representing single events have been identified, the individual time–elongation profiles generated by the participants can be averaged together, yielding a consensus profile of the CME front and an uncertainty in the consensus profile. This is demonstrated in figure 3, which shows the propagation of a CME through a sequence of HI1-A differenced images. The CME front identified in the Solar Stormwatch CME catalogue is shown by the red contours; the width of the bounded region reflects the uncertainty in the consensus profile along a given PA. The yellow lines mark the limits of the PA range analysed in *Trace-it*. This process defined 144 CMEs, 110 in the STA-HI observations and 77 in the STB-HI observations, with some CMEs seen by both craft.

With the CME fronts identified, established methods were then used to estimate the CME speed, direction and latitudinal extent (Rouillard *et al.* 2008, Sheeley *et al.* 2008, Davies *et al.* 2012). This demonstrated that over the observation period of January 2007 to February 2010, Solar Stormwatch has almost exclusively identified slow CMEs, with a mean estimated speed of 353 ± 8 km s^{-1}. This is consistent with these CMEs originating during the deep minimum in solar activity between solar cycles 23 and 24 (Lockwood *et al.* 2012).

All of the data used to create the Solar Stormwatch CME catalogue are publically accessible online at http://www.met.reading.ac.uk/~spate/solarstormwatch. The data are available at each stage of processing, from the raw *Trace-it* data, to the consensus time–elongation profiles of the CME fronts at each available PA.



4 These two background-subtracted HI1-A images are examples of how the secondary particle trails appear as they propagate across the HI field of view.

Real-time predictions

CME speeds and arrival times at 1 au can be predicted by applying the fixed-phi fitting (FPF; Sheeley *et al.* 2008, Rouillard *et al.* 2008) and harmonic-mean fitting (HMF; Lugaz 2010) methods to the time–elongation profiles of the CME fronts in the HI field of view. The FPF and HMF methods assume different geometries of the CME structure and that the CME front propagates with a constant speed and direction. Using results from the *Incoming Trace-it* activity with the FPF and HMF methods, 60 real-time predictions of Earth-directed CME speeds and arrival times were generated between December 2010 and May 2013.

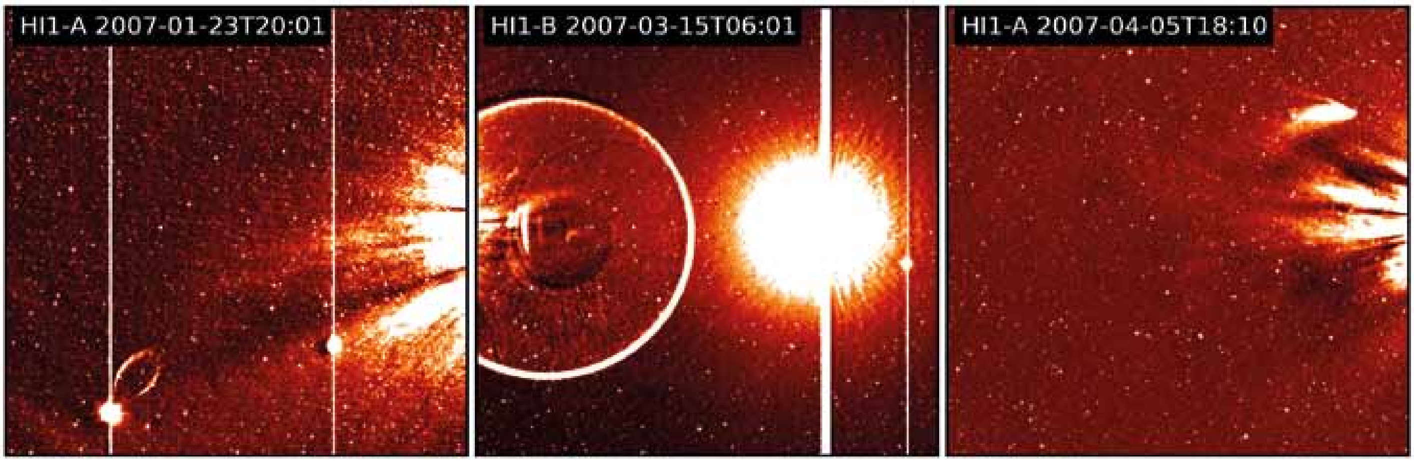
Comparing these to an online catalogue of CME arrivals at Earth (Richardson & Cane 2010, http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.html) resulted in 20 hits of an identifiable ICME at Earth within 1.5–6 days, with an average error in predicted transit time of 22 h, and average transit time of 82.3 h. The average error in the predicted arrival speed is 151 km s^{-1}, with an average arrival speed of 425 km s^{-1}.

In the same period, there were 44 CMEs for which there are no corresponding Solar Stormwatch predictions, and there were 600 days on which a CME was neither predicted nor observed. Thus, these real-time predictions have a hit rate of 31% and a false-alarm rate of 64%. In comparison with some other real-time CME arrival time predictions discussed by Zhao & Dryer (2014), the Solar Stormwatch predictions have a somewhat lower hit rate and higher false-alarm rate. However, considering the severe telemetry limitations of the RTB HI data, this is reasonable performance. Figure 2 highlights this point, by comparing two J-maps constructed from HI1+2 science data (panel A) and HI1+2 RTB data; it is clear that the RTB data can have very poor data coverage, which strongly limits our ability to generate reliable real-time predictions.

"Pointing direction errors occur when a dust particle strikes the HI instruments"

Further investigations probed whether the accuracy of the Solar Stormwatch predictions could be improved by not assuming that the CMEs propagate with a constant speed, as do the FPF and HMF methods. Three models of ICME propagation were applied to the same RTB data: two of constant acceleration and one of aerodynamic drag. This revealed that taking account of interplanetary acceleration can improve the average errors of transit time to 19 h and arrival speed to 77 km s^{-1}.

In addition to the science and RTB data, STEREO also returns end-of-day data which have better coverage than the RTB data, but at lower resolution than the science data. The end-of-day and science data are downlinked once per day via a dedicated schedule using the Deep Space Network, so are of limited use for real-time forecasting purposes. However, in future work we will use these data to replicate the Solar Stormwatch predictions and examine how the CME hit rate and false alarm rate varies with the coverage and resolution of the HI observations. Our aim is to find the best balance between the increased telemetry costs of higher resolution data with good coverage and the hit rate and false-alarm rate of these predictions. For further details see Tucker-Hood *et al.* (2015).



5 Examples of HI images that provoked forum discussions on the website.

Interplanetary dust distributions

Davis *et al.* (2012) investigated the orbital distribution of dust impacting upon STA and STB through observation of both "secondary particle debris trails" and unexpected pointing direction errors in the HI cameras. Pointing direction errors occur when a dust particle directly strikes the HI instruments, temporarily nudging the instrument off its nominal pointing direction, manifest in the HI images as discontinuous jumps in the location of the background star field. Secondary particle debris trails occur when debris from the impact of a primary dust particle striking the STEREO satellites propagates through the HI field of view. Figure 4 shows an example of how these trails appear in the background-subtracted HI1 images. HI-A observes more secondary debris trails but suffers fewer pointing direction errors than HI-B. This arises from the different locations of the HI instruments on the STA and STB spacecraft: STA-HI is located on the lee of the spacecraft, while STB-HI faces the direction of motion. The asymmetry in the number of trails seen by each spacecraft and the fact that there are many more pointing direction errors in the HI-B data than that from HI-A indicates that, as might be expected, the majority of impacts are coming from the apex direction.

Solar Stormwatch participants produced a catalogue of HI1-A and HI1-B images in which the secondary particle trails were visible, like those in figure 4. Another survey of particle strikes was compiled by a single expert observer analysing differenced HI1 images, rather than the background subtracted images analysed by the Solar Stormwatchers; this expert survey revealed some additional fainter tracks, but was not as robustly defined as the Solar Stormwatch catalogue. Comparing the Solar Stormwatch and expert surveys reveals consistent distributions of dust as a function of solar longitude. There is no clear correlation between the dust distributions and the corresponding distribution of meteor streams. However, there are some broad features consistent with the helion, toroidal and apex sources of the sporadic meteor population. From the frequency with which the dust strikes occurred, it was also possible to estimate that the dust particle masses were greater than 10^{-17} kg.

Evolving CME structure

Savani *et al.* (2012) used the HI instruments and Solar Stormwatch to investigate the radial expansion and 2D aspect ratio of four CMEs as they propagated from 0.1 au to approximately 0.7 au. These CMEs were observed by either HI-A or HI-B and were identified by Solar Stormwatch participants. Each CME was observed to propagate at low speed (i.e. less than 300 km s^{-1}), each being effectively embedded in the slow solar wind. The time–elongation profiles of both the frontal and rearward density enhancements associated with each CME were identified from J-maps constructed along the PA corresponding to each CME's central axis. Using these time–elongation profiles and the FPF and HMF techniques, the radial speed and direction of each CME was estimated. The PA width of each CME was calculated too. These estimates were subsequently used to convert the time–elongation profiles to time–distance profiles, from which it was then possible to compute the radial width of the CME and the 2D aspect ratio, as a function of heliocentric distance. It was demonstrated that, within the HI field of view, the radial width and aspect ratio of each CME increased linearly as a function of heliocentric distance. This result was in contrast to previous studies of *in situ* measurements of CMEs, which concluded that the radial width of a CME as a function of heliocentric distance could be modelled as a power-law (Bothmer & Schwenn 1994, 1998; Wang *et al.* 2005). The mean expansion rate of the four CMEs was calculated to be 7.1% of the bulk flow. An earlier independent case study of a single CME observed in HI data (Lynch *et al.* 2010) estimated the CME expansion rate to be 6.3% of the bulk flow, which is consistent with the estimates generated by Savani *et al.* (2012).

It was noted by Savani *et al.* (2012) that these results were generated by considering only slow CMEs embedded in slow solar wind and that a different relationship may exist for faster CMEs and CMEs interacting with fast solar wind. They argued that, as these results are based on a small sample of slow CMEs, future work should re-examine this topic with a larger set of events that also considers faster CMEs and *in situ* measurements too. It is hoped that the recent publication of the Solar Stormwatch CME catalogue makes such research targets more easily attainable.

> **"Typical questions concerned optical effects and artefacts in the Spot videos"**

Solar Stormwatch forum

More than 16 000 people participate in Solar Stormwatch; 250 of them have contributed to the forum (http://forum.solarstormwatch.com) and many more have browsed as "guests" without contributing. Volunteers come from 94 countries and those from the USA and UK combined make up 65% of the volunteers. Four experienced volunteers from different countries (Canada, Belgium, Germany and UK) moderate the forum, which is conducted in English.

The main function of the forum is to answer questions from volunteers. At the start of the project people were still trying to make sense of what they were looking at and asked questions about some of the objects appearing in the HI1 videos. For example, typical questions concerned optical effects and artefacts in the *Spot* activity videos and the identification of comets and planets appearing in "What's that?" (see below), some examples of which are shown in figure 5.

Forum members also asked questions about the STEREO mission itself, particularly the evolving field of view of the HI cameras as the spacecraft travelled away from Earth. As the project matured the topics broadened to include general solar physics (sunspots and flares, rotation dynamics, the effects caused by impacting sun-grazing comets and methods of estimating CME kinematics, for example). Science team members regularly contribute to forum discussions, providing science input when needed. In response to the most commonly asked questions, the moderators created several information threads which together provide a Solar Stormwatch resource for new and experienced volunteers. Examples include: "Planet hunting" (http://tinyurl.com/o7tm7tw) – how to identify planets using the SECCHI orbital simulator; "What's that?" (http://tinyurl.com/lczetf9) – a collection of optical effects and how to classify them; and "SSW video index" (http://tinyurl.com/lxr5s5x) – a comprehensive ordered collection of Solar Stormwatch videos.

All questions, including those less mainstream, are responded to and always in a constructive way. Discussion based on information rather than speculation is encouraged. For example, a forum member's statement that there existed a causal relationship between CMEs and seismic activity on Earth was countered with a polite reminder that there is no evidence for this relationship. When the subject was raised again, the posters were invited to compare a list of earthquakes and a list of CMEs to find there was no observable correlation between the two.

"Recent data cover the rise into the solar maximum, with a rise in solar activity"

The moderators have used and promoted several publicly available online resources when answering questions, notably the SECCHI viewer to identify planets (http://secchi.nrl.navy.mil/STEREOorbit), the von Rainer Kracht comet list to identify comets (http://www.rkracht.de/secchi/comets.htm) and the STEREO Science Center for information about the mission (http://stereo-ssc.nascom.nasa.gov).

Another benefit of having an open forum for communication between the citizen scientists and the science team is that it allows collaborative research to take place. Volunteers can bring unusual findings to the attention of the science team, prompting further investigation, and the science team can request that the volunteers keep an eye out for events that are not picked out by the classification interface. Interactions such as these have resulted in two out of the four Solar Stormwatch publications.

Shortly after the project launched, citizen scientist Elisabeth Baeten posted a question about a frame that contained a single faint streak, not related to the solar wind outflow, asking if it was a particle strike. Science-team member Chris Scott immediately confirmed it was a type of particle strike, and noted that it was "Not very spectacular on this occasion but if anything, that makes it even more interesting". This prompted a lively discussion, with more examples posted by multiple volunteers, with rough estimates given as to how often they were seeing these faint particle strikes. This unexpected find led to the more detailed analysis of the dust around the STEREO spacecraft than was previously thought possible, by Davis *et al.* (2012).

Another means of communication used in the project is a blog (http://blog.solarstormwatch.com), where science team members share updates on the project and work being done. For example, Neel Savani described some of his PhD research on CME case studies, analysing the shape of the CME as it progresses through the HI field of view. He explained that "circular storms" were the best types for him to study, and asked the volunteers to keep an eye out for them. Over the next few months, numerous examples were found and shared on the forum. Neel provided feedback on the examples, helping the volunteers identify the best candidates. The following year, he again asked for help, this time with finding storms with clearly defined storm fronts, identifying their starting times and the last time that all four edges of the front are visible, the results of which were used in the Savani *et al.* (2012) study.

Both the forum and the blog, therefore, play a vital role in informing members of the Solar Stormwatch community of the value and outcome of their participation. The forum, in particular, is a place where participants can discuss the project, the science and topics that go beyond the information presented in the tutorials and on the website. It allows participants to highlight serendipitous discoveries and allows for the development of additional short projects as well as providing a ready source of beta-testers for new Solar Stormwatch tasks.

As well as the educational and science aspects, the forum also has a social side which promotes a sense of community through chat and shared interests. In summary, the forum is a place where everyone can "meet", an important consideration when a community is spread around the globe. Those Solar Stormwatch volunteers who choose to visit the forum benefit from the added value that it represents as a place to ask questions, to learn from peers and science team members, to have the opportunity to become more involved and to showcase and discuss the interesting and the unusual.

The future of Solar Stormwatch

From the outset, Solar Stormwatch was an ambitious project, asking volunteers not only to watch fascinating movies of the solar wind, but also to analyse secondary data products such as J-maps which, while scientifically useful, are less engaging to the casual observer. The fact that volunteers have spent so many combined hours in analysing these data is a testament to their enthusiasm for the underlying science. Indeed, the ability to track CMEs in real time has produced a valuable insight into the challenges of operational space-weather forecasting. While the position of the spacecraft has subsequently evolved beyond that which is useful for real-time forecasting, there is still merit in continuing to analyse the more recent HI data through the Solar Stormwatch web interface because these cover the rise into the most recent solar maximum, with an associated rise in solar activity.

Recently, communications with the STB spacecraft have been lost. Attempts to recover communications are ongoing but, even if these are unsuccessful, the scientific legacy of the mission remains in the remarkable dataset collected by both spacecraft and the data that continues to be collected by STA. The comprehensive analysis of the HI data undertaken by the Solar Stormwatch project demonstrates the enthusiasm the public have for this remarkable mission. We look forward to the future scientific advances provided by their continued support. ●

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MORE INFORMATION
Solar Stormwatch http://www.solarstormwatch.com

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