Abstract

High-speed solar-wind streams emanate from solar coronal holes; the fast wind interacts with upstream slow streams producing regions of enhanced magnetic field strength and particle density that are known as co-rotating interaction regions. Due to the recurring nature of coronal holes near solar minimum, this results in periodic driving of the magnetosphere that can last for several days and input as much energy as a storm driven by a coronal mass ejection.

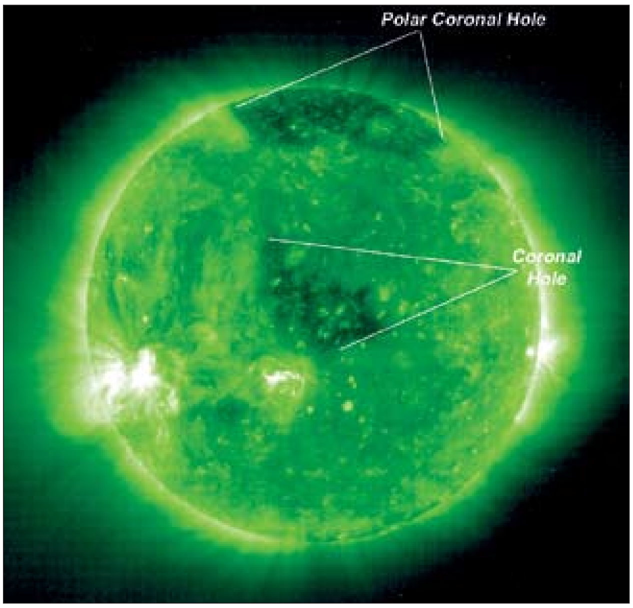
High-speed solar-wind streams and geospace interactions

Andrew Kavanagh and Michael Denton summarize the topics discussed at the Lancaster University Workshop on High Speed Streams and Geospace Interactions, held in September 2007.

When we talk about space weather we can often conjure images of large coronal mass ejections (CMEs) or dramatic solar flares that drive spectacular effects in the Earth's near-space environment, such as the northern and southern lights. Recent coverage of the exciting images provided by the STEREO spacecraft (Davis and Bewsher 2007) only highlights the importance of understanding these dramatic events that can generate massive geomagnetic storms. However, despite the importance of these transient features it has become increasingly apparent that recurrent high-speed solar wind streams (HSS) are also very important for driving activity in the Earth's magnetosphere. These events dominate near the minimum of the 11-year solar activity cycle and can drive important physical processes over longer periods than the more transient, CME-driven geomagnetic storms can (for a comparison of co-rotating interaction region- vs CME-driven storms see Borovsky and Denton 2006).

Coronal holes and high-speed streams

The flow of charged particles from the solar corona is non-uniform in both time and space. Observations from the solar orbiting Ulysses spacecraft (Phillips *et al.* 1995) have shown a latitudinal dependence of the solar-wind speed; over the poles the wind is fast (~500–800 km s^{-1}), while at lower latitudes the velocities tend towards ~300–400 km s^{-1}. The fast wind emanates from coronal holes, dark regions in the corona where the magnetic field is "open", streaming into interplanetary space (e.g. figure 1). Coronal holes can also appear at mid-to-low solar latitudes, either as discrete openings or as a narrow, finger-like extension from a polar coronal hole. These near-equatorial holes can form at any time during the 11-year solar cycle, but are more noticeable in the declining phase and close to solar minimum when the comparatively more stable Sun means that a coronal hole can last for several months and so reappear with the 27-day rotation period of the Sun (e.g. Tsurutani *et al.* 2006).



1: SOHO observation of the Sun at 195Å on 6 October 2005. Note the dark regions that indicate the presence of coronal holes at both polar and low latitudes. The latter was responsible for a HSS that struck the magnetosphere on 8 October 2005. (SOHO/EIC consortium)

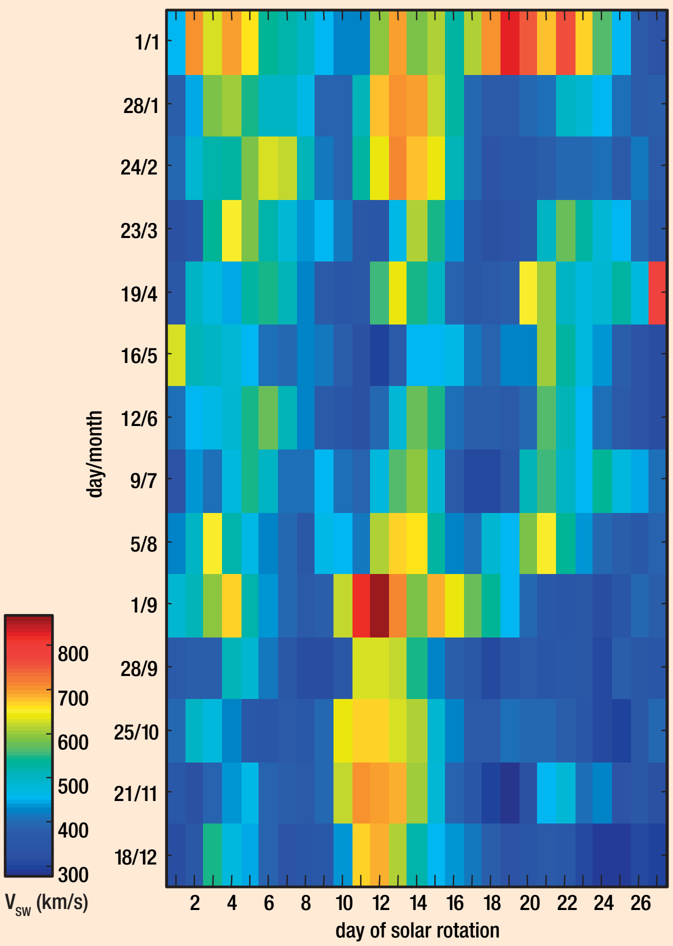
Just as with the polar holes, low-latitude coronal holes are source regions for HSSs. Fast wind from such holes catches up with downstream slow solar wind, forming a co-rotating interaction region (CIR) followed by a HSS. With stable coronal holes the HSS can reappear with a ~27-day period and an example is provided in figure 2, which shows the solar-wind velocity as a function of solar rotation during 2005. A particularly persistent stream appeared in the latter half of the year, appearing on or around day 10 of each solar rotation

CIRs and HSSs have typical features at 1 AU that can be detected by upstream solar-wind monitors such as the WIND satellite: the solar-wind speed increases from "slow" to "fast" and remains elevated for several days; the direction of the solar wind changes from east to west indicating the interaction region; the plasma density increases and then drops to a minimum; the interplanetary magnetic field (IMF) has a local maxima. The last two signatures are caused by the pile up of plasma in the interaction region at the edge of the fast wind. Since the IMF is anchored in the solar-wind plasma ("frozen-in flux"), it reaches its maximum at the same time as the plasma density. Figure 3a provides an example of a HSS with preceding CIR in October 2007. The solar-wind speed increases early on 8 October and remains elevated for several days. Both the magnetic field strength (|**B**|) and the ion density (*N*) maximize before the increase in speed, with the latter subsequently dropping to lower than pre-CIR levels because the fast flow is rarefied. Both the velocity and the IMF $\mathbf{B}_Z$ show large fluctuations that indicate large-amplitude, nonlinear Alfvénic structures that persist for several days. Such structures have important implications for coupling to the magnetosphere (e.g. Tsurutani *et al.* 2006).

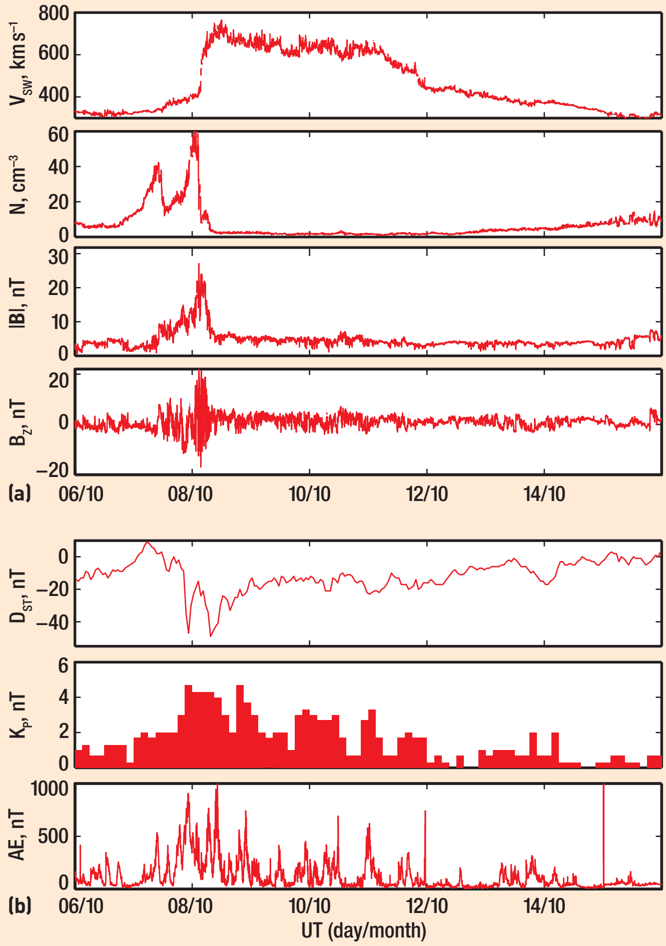
Geomagnetic activity

CIRs and HSSs are important drivers of geomagnetic activity, though they are not usually associated with large geomagnetic storms which are usually CME-driven. Storm strength is traditionally judged from the D_{ST} index, which is a measure of the magnetospheric ring current derived from near-equatorial ground magnetometer measurements. During large geomagnetic storms the D_{ST} has a minimum of less than –100 nT; such storms also have a strong solar-cycle dependence, peaking at solar maximum because they are driven by CMEs, which occur more often on an active Sun. Weak storms ($-75 < D_{ST} < -35$ nT) have a much smaller solar cycle dependence, being more common in the declining phase of the solar cycle (e.g. Gonzalez *et al.* 1990)

Although CIRs do not produce strong ring currents, they do drive storm-levels of other phenomena such as enhanced convection,



2: Solar-wind velocity as a function of solar rotation during 2005 (and early 2006). This was in the declining phase of solar cycle 23. Red indicates high solar-wind speed while blue is slow. A recurrent high-speed stream (HSS) is clearly visible on or around day 10 of each rotation from August onwards, indicating the approximate 27-day rotation period of the coronal hole source region. This stream may have appeared as early as June and had progressively shorter recurrence times. Note the stream that begins on day 20 – it forms in March before disappearing after August.



3 (a): Solar-wind data in October 2005 exhibiting typical signatures of a co-rotating interaction region (CIR) and subsequent high-speed solar-wind stream (HSS). Plasma density and IMF field strength increase after 18:00 UT on 6 October 2005. A large step in velocity occurs at ~3:30 UT on 8 October 2005 and high speeds persist for more than 4 days, accompanied by rapid Alfvénic fluctuations in the interplanetary magnetic field (IMF). (b) Geomagnetic indices during October 2005. The D_{ST} (a proxy for ring current strength) remains relatively low though a minimum is clear at ~8:00 UT on 8 October. The K_P index (a proxy for magnetospheric convection strength) rises from low levels (<2) to moderate (~4) during the CIR before decaying back over ~4 days during the HSS. The auroral electroject index (AE) shows large and persistent variations during the CIR and HSS. Some of this activity corresponds to substorm onsets during the weak storm.

precipitation and relativistic electron energization. The reason for the difference during CIR and CME storms is likely to arise from the nature of the IMF; during CMEs there is usually a large, persistent southward turning of the IMF (negative B_Z) accompanied by high solar-wind speed. This enhances magnetic reconnection on the dayside, which adds open magnetic flux into the Earth's magnetotail and transfers energy into the system. This energy is released via explosive reconnection events in the tail known as substorms (e.g. Akasofu 1964), which inject energetic particles into the inner magnetosphere and cause the precipitation that produces dynamic auroral displays. With sufficient dayside driving, the polar cap (the region of open magnetic flux) can be so enlarged that the aurora appears over mid-latitudes (e.g. Wild 2006). In comparison CIR do not have extended periods of southward IMF and so the rate of dayside reconnection is much smaller. However, the Alfvénic structures in the solar wind/IMF persist for several days, which suggests that intermittent reconnection occurs over a longer period than during CME storms and hence leads to more continuous driving of the system (e.g. figure 3a). This means that energy input to the magnetosphere during a HSS event is comparable to or even greater than the input during a CME event.

Geomagnetic indices

Figure 3b shows some of the geomagnetic indices associated with the HSS in October 2005. During this event the D_{ST} reached a minimum of only −44 nT and the K_P index (a proxy for convection strength) was moderate (on a quasi-logarithmic scale from 0 to 9). The AE index, which is a measure of the strength of the auroral electrojet and as such a proxy for the level of auroral activity, was highly variable for several days. Observations of auroral emissions during such periods have found that there is low-intensity aurora from dayside to night side (e.g. Guarnieri 2005), indicating a complex interaction between solar wind and magnetosphere. At the same time there are weak injections of particles from the tail, which is consistent with a moderate ring current (e.g. Søraas *et al.* 2004). This does not preclude substorm activity and electron injections and subsequent precipitation suggest increased substorm activity (e.g. Tsurutani *et al.* 2006).

The prolonged, energetic precipitation driven by HSS (e.g. Longden and Denton 2007) has consequences for mesospheric chemistry. In particular the creation of NO_x species may be

The workshop

In September 2007 Lancaster University hosted an international workshop at Ambleside, Cumbria, entitled "High Speed Streams and Geospace Interaction" (HSS-GI). This brought together 40 scientists from across the world to discuss the physical processes that occur during HSS and their influence on the terrestrial system in comparison with other transient phenomena such as CME. The workshop considered coupling and consequences throughout the Sun–Earth system, with topics that included the source and structure of CIRs and HSSs, coupling with the magnetosphere, energization of the radiation belts and the atmospheric response to HSS-driven activity.

Not only did the workshop present an opportunity to share scientific results related to HSSs and CIRs, but it also acted as a means to co-ordinate future studies. During the meeting several important outstanding questions were identified in order to help direct research efforts:

- What determines coupling efficiency between solar wind and magnetosphere during HSS? How important are fluctuations in solar wind velocity (V_{sw}) and magnetic field ($\mathbf{B}_s$)?
- Which waves are the most dominant for heating of radiation belt particles? What drives such waves?
- What causes relativistic electron dropouts? How can we quantify the relative wave–particle loss rates?
- How are Pc5 waves made? Which process dominates? Why are Pc5 waves so dominant in HSS events?
- What in the solar wind drives high D_{ST}? Why is the D_{ST} signature low for HSS?
- What is the role of ring-current composition during HSS? What is the main ring-current injection mechanism?
- How do rapid EUV changes affect the ionosphere/plasmasphere during HSS?
- How important is particle energy deposition compared to EUV energy input during HSS?

Two events have been selected for further co-ordinated study by workshop participants and others (10–22 October 2003 and 10–16 November 2003). A second workshop in two years (autumn 2009) is planned so that progress on these science issues can be discussed.

4: Some of the workshop participants in Ambleside.

enhanced and suitable transport via the polar vortex could lead to increased ozone depletion (Seppälä *et al.* 2007). This is a topic in great need of further study.

As well as driving more obvious geomagnetic activity such as aurora, fast solar-wind streams also drive ultra-low-frequency (ULF) waves in the magnetosphere. These can transfer energy directly from the solar wind through the system to the ionosphere. These magnetic oscillations have periods ranging from 10s to 100s of seconds (known as Pc5 waves) and have been shown to depend strongly on solar-wind speed (e.g. Mathie and Mann 2000). The production mechanism for these waves is not completely understood, but a leading candidate is the Kelvin–Helmholtz instability at the magnetopause, which can energize waveguide modes that carry pulsation power into the inner magnetosphere and ionosphere. Recent estimates based on observations suggest that the energy can be significant in comparison with substorms (e.g. Rae *et al.* 2007). One important aspect of the Pc5 waves is their potential ability to accelerate electrons to relativistic energy within the outer radiation belts (e.g. Elkington *et al.* 1999).

Relativistic electrons

One area that is the subject of a concentrated research effort is the mechanism for generation and loss of relativistic electrons in the radiation belts. Large geomagnetic storms can have drastic effects on the population of relativistic electrons in the inner magnetosphere; this can include the creation of new radiation belts at low latitudes (e.g. Baker *et al.* 2004). The effect of CIRs and HSSs on the relativistic electron flux is almost as dramatic. During CIRs dramatic drop-outs occur in the electron fluxes in the outer radiation belt; this is followed by a gradual increase to above pre-CIR levels during the HSS and subsequent decay. The cause of the initial drop-out is unknown, though there is evidence to suggest enhanced precipitation (e.g. Green *et al.* 2004) through possible interaction with a number of different magnetospheric waves. The mechanisms for accelerating electrons to MeV energies are clearly efficient. Radial diffusion though interaction with Pc5 waves is one possible mechanism and energy diffusion by cyclotron resonance with electromagnetic whistler mode waves is another. The relative strengths of these mechanisms are currently unknown but it is clear that acceleration is enhanced during HSSs (e.g. Mathie and Mann 2000). ●

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