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.

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 streams 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 comparison is 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).

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 polar coronal holes (“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 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,
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 quasilogarithmic 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. Guarneri 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
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 ($B_{sw}$)?
- 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 $D_s$? Why is the $D_s$ signature low for HSS?
- What is the role of ring-current injection mechanism?

During HSS events, the energy injection into the radiation belts 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).

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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References