Introduction to special section on corotating solar wind streams and recurrent geomagnetic activity

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[1] This special section of the *Journal of Geophysical Research (Space Physics)* is devoted to research papers on corotating solar wind streams, corotating interaction regions (CIRs), and many facets of the associated recurrent geomagnetic storms and/or activity. The topics cover the physics related to these events at the Sun all the way to their effects in the Earth's ionosphere. This portion of space weather is complementary to the interplanetary and geomagnetic activity produced by solar flares and/or coronal mass ejections (CMEs), which occur most predominantly during the maximum sunspot phase of the solar cycle. Collisionless shocks ahead of fast interplanetary CMEs (ICMEs) accelerate energetic protons and higher Z ions to flux levels that can be hazardous to satellites and to humans in space. ICMEs and their upstream plasma sheaths cause intense and dramatic magnetic storms and auroras noted at Earth. On the other hand, high-speed streams associated with large coronal holes occur predominantly in the declining and minimum phases of the solar cycle. The interaction of the high-speed streams with upstream (further from the Sun) slow-speed streams leads to the formation of the magnetic compression regions called CIRs. Collisionless shocks typically form at CIR boundaries at distances greater than ~ 1.5 to 2.0 AU from the Sun, so energetic particle radiation formed at these (corotating) shocks is not a hazard at Earth. CIR interactions with the Earth's magnetosphere are gentler and produces only weak to moderate intensity magnetic storms.

[2] The history of recurrent magnetic storms and their solar origin is a long one and goes back for more than a century. *Maunder* [1904] noted a strong ~ 27 day recurrence in geomagnetic activity and speculated that this could be caused by particle streams emanating from the Sun. *Chree* [1912, 1913] was the first to quantitatively establish a

~ 27 day quasi-periodicity in geomagnetic activity using a superposed epoch method of analyses (this is the origin of what we now call "Chree analyses"). *Bartels* [1934], not being able to observe any obvious solar features that could be responsible for the recurrent storms, suggested that these "time patterns" were caused by unseen "M-regions" on the Sun (M stood for "magnetically active"). Later, beginning in the space age, knowledge of the cause of these storms and their effects accelerated rapidly. Direct, in situ, measurements of the time variability of the solar wind were first made by *Mariner 2*, which revealed a 27-day modulation of the solar wind speed [*Snyder et al.*, 1963; *Neugebauer and Snyder*, 1966]. *Krieger et al.* [1973] demonstrated that the source of these high-speed streams were "coronal holes" [*Altschuler and Perry*, 1972; *Munro and Withbroe*, 1972]. Coronal holes are detectable in soft X rays and not in visible light, thus solving what *Bartels'* mysterious M-regions were. These coronal hole streams, or some facet of them, were clearly the cause of the recurrent geomagnetic activity at Earth [*Sheeley et al.*, 1976]. For the reader interested in more details concerning the early history of this subject, we recommend the comprehensive *Chapman and Bartels* [1940] books and the references therein. An abridged and more recent historical account is given by *Crooker and Cliver* [1994].

[3] As previously mentioned, the high-speed solar wind streams do not simply propagate unimpeded to the Earth, but interact with upstream slower speed streams to form CIRs [*Smith and Wolfe*, 1976]. The antisunward portions of CIRs are compressed and accelerated slow stream plasma and the sunward portions are compressed and decelerated high-speed stream plasma [*Pizzo*, 1985]. It is the CIRs that cause recurrent magnetic storm main phases [*Tsurutani et al.*, 1995]. These recurrent magnetic storms are unique in that their "recovery" phases are exceptionally long, lasting from many days to weeks. These storm phases occur within the high speed streams characterized by large amplitude Alfvén waves. It has been shown that the southward component of the Alfvén waves leads to magnetic reconnection with magnetopause magnetic fields. The latter results in bursts of plasma injections into the magnetosphere sustaining the storm "recoveries" [*Soraas et al.*, 2004]. The resultant geomagnetic activity is called high-intensity, long-duration continuous AE activity or HILDCAAs [*Tsurutani and Gonzalez*, 1987, 1997]. It has been argued that at times, more solar wind energy is introduced into the magneto-

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Figure 1. The monthly average sunspot number and the time of the von Humboldt experiment.

sphere/ionosphere annually during this part of the solar cycle than during solar maximum [Tsurutani *et al.*, 1995; Turner *et al.*, 2006]. One manifestation of the energy injection is continuous high-latitude auroral displays. However, it is not certain what form these auroras take and what role the substorms play in the overall magnetospheric energy dissipation process [Tsurutani *et al.*, 2004]. An extremely important societal effect is the magnetospheric production of relativistic “killer” electrons during recurrent storm recovery phases [Paulikas and Blake, 1979]. The exact mechanisms of electron acceleration are currently being debated in a lively fashion [Horne *et al.*, 2006; Li, 2006]. A new mechanism for potential losses of these electrons is discussed in this issue [Borovsky and Steinberg, 2006].

[4] Almost 2 centuries ago, Baron Alexander von Humboldt reported results of a study that he made from his

home in Berlin between May 1806 and June 1807. On 21 December 1806 he observed a strong correlation between the occurrence of magnetic needle oscillations and overhead auroras. Figure 1 indicates the time during the solar cycle when von Humboldt made his observations. It was deep in the declining phase of the solar cycle, almost at solar minimum. Von Humboldt noted that the magnetic needle oscillations and overhead aurora lasted for ~ 6 hours, and when the auroras ceased so did the oscillations. He called this magnetic activity a “magnetisches ungewitter” or a magnetic storm. From the latitude of the location of the observations (Berlin), the length of time of the overhead auroras and the (implied) auroral electrojets (~ 6 hours), and the proximity of the year of the observation to solar minimum, all indicate that it is quite likely that von Humboldt made his observations in the “recovery” phase of a corotating solar wind stream-related magnetic storm

and not an ICME-related magnetic storm. Although the existence of subatomic particles such as electrons were unknown during von Humboldt's era, we think that he would be extremely surprised to know that million electron Volt particles are now associated with his magnetic needle oscillations and overhead auroras.

[5] In this special section we argue that space weather associated with CIRs and corotating solar wind streams occurring during the declining and minimum phases of the solar cycle are equally or even more important to mankind than the effects of CMEs occurring at and near solar maximum. However, the ways that they are important are substantially different from space weather effects during solar maximum. Most of the papers in this special section derive from contributed talks given at a Chapman Conference held in Manaus, Amazonas, Brazil, from 5 to 12 February 2005. Summaries of the review talks are being prepared for an AGU monograph and will give readers a broader perspective of this important facet of space weather.

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