How Do Coronal Hole Storms Affect the Upper Atmosphere?

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The solar cycle, often described as an increase and decrease of solar activity with a period of about 11 years, can strongly affect Earth's thermosphere and ionosphere. Although the longest direct record of solar activity is based on sunspot number, a more quantifiable parameter is solar irradiance at extreme ultraviolet (EUV) wavelengths, which varies by more than a factor of 3 over the sunspot cycle. To first order, upper atmospheric variation is a result of changes in ionizing fluxes at EUV wavelengths.

As the solar cycle passes its EUV peak and approaches minimum, the number of solar active regions declines, leading to a reduction and then a near absence of coronal mass ejections (CMEs)—episodic events of high-energy bursts of solar plasma that cause geomagnetic storms at Earth. During the solar cycle's declining phase, coronal holes begin to occupy lower latitudes on the solar surface and fall in line with the ecliptic plane.

Coronal holes are solar regions of open magnetic field lines and lower temperature from which solar wind plasma continuously emanates at high speeds, peaking between 750 and 800 kilometers per second. As the cycle declines toward a minimum, low-latitude coronal holes become the dominant cause of geomagnetic activity at Earth, potentially causing satellite disruptions due to increases in relativistic electrons, disturbances in radio wave transmission due to increased structure in ionospheric electron density, and increased satellite drag due to increased atmospheric density. These disruptions can affect the Earth's geospace environment for days to weeks at a time.

The scientific community is only now, through global-scale observations, new models, and new analysis methods, able to investigate how the upper atmosphere is affected by solar coronal holes. This, when combined with studies on the CMEs that dominate solar maximum, will allow researchers to create a fuller picture of how the solar wind influences Earth's upper atmosphere throughout the cycle.

Thermospheric and Ionospheric Response to Coronal Holes

Signatures of coronal holes have been observed by scientists since the field of space weather was in its infancy. For example, *Maunder* [1904] first reported recurring geomagnetic activity at the solar rotation period of 27 days. *Bartels* [1934] was the first to suggest invisible "magnetically active regions" on the Sun as the source of this recurring activity, in the absence of visible sunspots (solar minimum). Much later, *Krieger et al.* [1973], using satellite-borne soft X-ray detectors, were able to identify these magnetically active regions as coronal holes and the solar source of recurrent high-speed solar wind streams.

These streams create relatively mild geomagnetic disturbances compared to intense CME-driven storms. However, storms induced by coronal holes linger much longer, as long as the hole is facing Earth, and recur over multiple solar rotations. Toward solar minimum, storm conditions resulting from coronal holes commonly persist for a few days to weeks, whereas CME storms typically last 1–2 days. Storms born of coronal holes often repeat every 27 days (one solar rotation period) because the features rotate with the Sun.

A recent discovery in the thermosphere-ionosphere system is the remarkable cycles of about 7, 9, and 13.5 days found in globally averaged thermospheric density variations at around 400 kilometers in altitude [*Lei et al.*, 2008; *Thayer et al.*, 2008]. Ionospheric total electron content (TEC), and other thermospheric-ionospheric properties, shows similar periodicities but with complex distributions over the globe. The periodicities arise due to subharmonics of the 27-day solar rotation period. This is likely because coronal holes do not appear in isolation but in groups of two to three, spaced in longitude at nearly regular intervals. Solar rotation leads to periodic forcing of the thermosphere-ionosphere system by these multiple hole structures distributed in longitude about the solar surface. The density fluctuations that manifest on these short periods can cause enhanced satellite drag that leads to poor satellite tracking and shortening of satellite lifetime, both of which modify the orbital debris environment.

Studies of geomagnetic storms have established that geomagnetic activity increases high-latitude thermospheric winds due to three main factors: the transfer of momentum from collisions within an accelerated ionosphere, heating caused by surges in ionospheric currents, and the precipitation of energetic electrons of magnetospheric origin. Concentrations of atomic and molecular constituents in the thermosphere are affected by heating and winds, as high-latitude heating causes upwelling of heavier molecular constituents, which are then redistributed globally by the disturbed wind pattern. Thus, storms induced by coronal holes can generate large-scale changes in the upper atmosphere of a magnitude similar to storms caused by CMEs because their effects are enhanced by the relatively long duration of the events. A recent solar minimum study using satellite measurements of airglow data from NASA's Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission shows significant periodicities of roughly 9 days in the ratio of oxygen to nitrogen (O/N_2) in the thermosphere at a range of latitudes. These periodicities correlate with known occurrences in coronal hole behavior. The upwelling of nitrogen into the thermosphere and

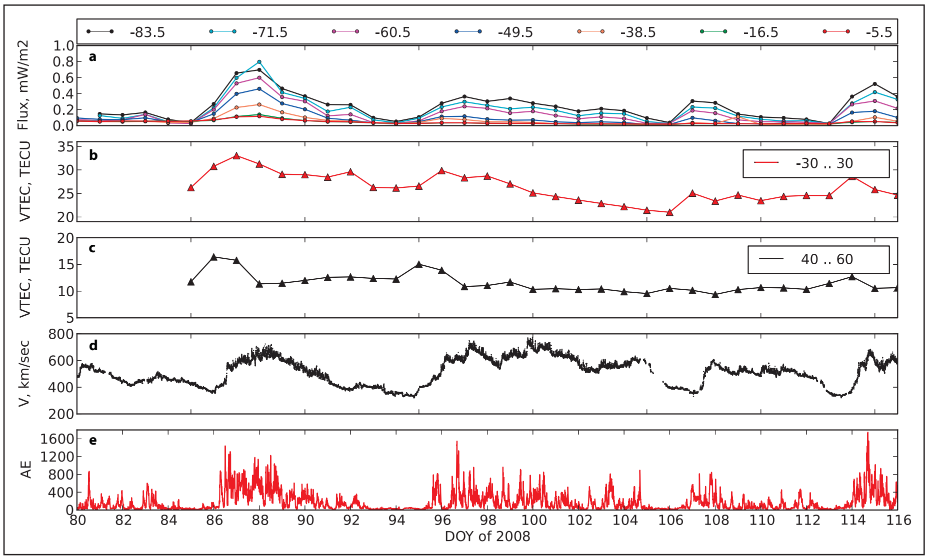

Fig. 1. Thermospheric and ionospheric conditions from 25 March to 25 April 2008, a period of recurring geomagnetic activity due to high-speed streams from coronal holes. (a) Daily thermospheric cooling rate averaged in seven latitude bins corresponding to the central geographic latitudes on Earth of -83.5°, -71.5°, -60.5°, -49.5°, -38.5°, -16.5°, and -5.5°. (b and c) Daily averaged daytime (from 1200 to 1400 solar local time) vertical ionospheric total electron content (TEC) in the solar geomagnetic latitude ranges from -30° to +30° and from 40° to 60°. (d) Solar wind speed and (e) geomagnetic index (AE) of auroral activity. Slightly modified from Verkhoglyadova et al. *[2011]. Note how the high-speed solar wind (Figure 1d) creates changes in the thermosphere and ionosphere and in the AE (Figure 1e).*

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