The Tale of Two Minima and a Solar Cycle in Between: An Ongoing Fast Solar Wind Investigation

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Abstract. We have measured the physical properties of polar coronal holes from the minimum activity phase of solar cycle 23 (1996–1997) to the present minimum of solar cycle 24 (2007–2009) using the UVCS instrument on SOHO. Observations in H I Lyman alpha (121.6 nm) and O VI (103.2, 103.7 nm) provide spectroscopic diagnostics of proton and O5+ bulk outflow velocities and velocity distributions as a function of heliocentric distance above the poles of the Sun. These observations have allowed us to follow the changes in the physical properties of the polar coronal holes during solar cycle 23 and its approach to the current minimum. Recent ground- and space-based observations have reported a variety of phenomena associated with the current minimum. We present the comparison of observed oxygen line intensities, line ratios, and profiles for polar coronal holes at both minima and during solar cycle 23 and show how this new minimum manifests itself in the ultraviolet corona. The comparison of the physical properties of these two minima as seen by UVCS in the extended corona, now possible for the first time, may provide crucial empirical constraints on models of extended coronal heating and acceleration for the fast solar wind.

1 Introduction

Polar coronal holes are magnetically open large-scale spatial structures that are present for most of the solar cycle, and their role is far from being well understood. It is clear that strong connections exist between large coronal holes and the highest-speed wind streams (Krieger et al. 1973; Zirker 1977).

Recent ground- and space-based observations have reported a variety of phenomena associated with the current solar minimum. Solar cycle 23 was a longer than expected activity cycle, and the current solar cycle 24 minimum did not produce a quiescent equatorial streamer belt. The solar wind during the previous sunspot minimum presented a stable bimodal structure, composed of low-speed streams around the equator and high-speed streams over the poles. However, the solar wind from the current minimum period differs from this typical configuration. During this minimum, large low-latitude coronal holes, which are also sources of fast solar wind, were located at the equator for an extended period of time, unlike in the previous minimum (see, e.g., Galvin et al. 2008; Miralles 2008; Tokumaru et al. 2009).

The current polar coronal holes and the fast solar wind have significantly different properties than at the 1996–1997 minimum. In situ observations of the solar wind from both polar coronal holes show that the fast solar wind is slightly slower, less dense, cooler, and has a lower momentum flux than during the 1996–
1997 solar minimum (McComas et al. 2008; Issautier et al. 2008). Magnetic field measurements from the Wilcox Solar Observatory and the Michelson Doppler Imager (MDI) (Scherrer et al. 1995) on the Solar and Heliospheric Observatory (SOHO) show that the polar fields are weaker than in the preceding minimum (Sun et al. 2008). In addition, polar hole perimeter measurements using images from the Extreme ultraviolet Imaging Telescope (EIT) (Delaboudinière et al. 1995) on SOHO indicate a reduction of the coronal hole area in both poles of about 15% between 1996 and 2007 (Kirk et al. 2009).

The exact manner in which the plasma in coronal holes is heated and accelerated is still unresolved. An improvement in our understanding of the physical processes responsible for the solar wind have come from the past decade of observations, analysis, and theoretical work associated with the SOHO mission. For example, the importance of magnetohydrodynamic (MHD) waves has been emphasized by the observations of the Ultraviolet Coronagraph Spectrometer (UVCS) (Kohl et al. 1995, 2006) on SOHO that heavy ions are heated to hundreds of times the temperatures of protons and electrons, and that the velocity distributions are anisotropic, indicating Alfvén wave dissipation via ion cyclotron resonance (Kohl et al. 1997, 1998, 2006; Cranmer et al. 1999, 2008). These advances were based on observations of polar coronal holes at the last solar minimum (1996–1997). Coronal holes observed since that time have higher electron densities, lower kinetic temperatures, slower outflow velocities, and less divergent magnetic field geometries (Miralles et al. 2001a, b, 2002, 2004; Miralles 2006). It appears that the physical processes controlling the extended heating and acceleration may depend on the density and on the magnetic field geometry.

This paper provides an overview of the physical properties of the polar coronal holes during solar cycle 23 and the current cycle 23/24 minimum derived from observations by UVCS. In particular, spectroscopic diagnostics in polar coronal holes are discussed. The resulting plasma properties of these coronal holes are compared. For a review of the physics of coronal heating and solar wind acceleration of the associated high-speed solar wind, see Cranmer et al. (2010, these proceedings).

2 North and South Polar Coronal Holes in Cycle 23

Figure 1 illustrates the evolution of polar coronal holes from 1996 to 2002 with solar cycle sunspot activity. During the first half of solar cycle 23, the Sun’s activity increased from its lowest level in 1996 to its maximum in 2000, then decreased again only to rebound in 2001. This second increase in the Sun’s activity level created a double-peaked activity maximum (Figure 1, bottom-right). During the solar minimum phase (1996–1997), the Sun displayed a coronal hole at each of its poles. These polar coronal holes were relatively stable structures that existed for several years (see Figure 1). As the solar activity increased, the large polar coronal holes shrank and disappeared near solar maximum 2000, and other smaller coronal holes emerged at other latitudes (Miralles et al. 2002, 2004). These coronal holes of varying size, shape, and polarity lasted for several solar rotations. As the solar cycle continued, the coronal holes completed their apparent migration to the opposite pole and the Sun’s magnetic polarity reversed. The times of reappearance of the northern and southern polar coronal
holes differed by over one year in solar cycle 23. The north polar coronal hole reappeared in February 2001 (Miralles et al. 2001b, 2002) nearly simultaneously with the large-scale magnetic polarity reversal of solar cycle 23 (Wang et al. 2002). The reformation of the north polar coronal hole with the new magnetic polarity began with the development of a high-latitude coronal hole. It was an
3 Polar Coronal Hole Properties versus Solar Cycle

Figure 2 shows the variation of O VI line widths (top) and the O VI line ratio (bottom) with time during solar cycle 23 at a height of 2.4 $R_\odot$. If we look at the O VI line width data for the polar coronal holes, we can see that at solar minimum, the line widths were broad and the temperature of the plasma was the highest. When the north and south polar coronal holes reformed in early 2001 and mid-2002, respectively, the O VI line widths were narrower. After 2002, the line widths became progressively broader. After 2006, the north and south polar coronal holes started the approach to the extreme plasma temperatures measured with UVCS at the last solar minimum (1996–1997).

If we look at the O VI line ratio for the polar holes at a height of 2.4 $R_\odot$, we can see that the lowest O VI line ratios (i.e., the highest outflow speeds) were measured at solar minimum. When the north and south polar holes reformed in 2001 and 2002, respectively, the ratios were at the highest values measured for polar holes in this cycle implying that the outflow speeds for those new-polarity polar holes were the lowest. After 2002, the O VI line ratios decreased with time and the outflow speed of the polar holes became larger along the cycle. In early 2007, the north and south polar coronal holes reached the values of the fast outflow speeds measured by UVCS at solar minimum in 1996–1997.

Figure 3 (top) shows the variation in integrated line intensities for O VI 1032 Å in both north and south polar coronal holes at a height of 2.4 $R_\odot$. After solar maximum, when the north and south polar coronal holes reappeared, the intensities were higher than at the 1996–1997 solar minimum. After that, the intensities show a downward trend and reached solar-minimum values by 2007. In July 2008, there seems to be a decrease in the O VI 1032 Å intensities. This seems to be co-temporal with lower EUV irradiance values observed toward the end of 2008 (Woods 2010, Didkovsky et al. 2010, these proceedings). This may be the result of a higher electron temperature or a lower electron density. This
change in coronal intensities may be consistent with lower electron temperatures and densities measured in the heliosphere (e.g., McComas et al. 2008).

Figure 3 (bottom) shows the O VI line widths versus the O VI line ratio at a height of 2.4 \( R_\odot \) for large coronal holes observed at different phases of the solar cycle. There seems to be a trend in the physical properties of these coronal holes. For large coronal holes, the heavy ions show a strong correlation between their perpendicular heating and their wind speed (Miralles et al. 2002, 2004). There are clearly “zones of avoidance”: low line intensity ratios do not occur with the narrowest profiles, and large line ratios do not occur with the broadest profiles. In addition, polar coronal holes seem to occupy a different range in parameter space than low-latitude (equatorial and mid-latitude) coronal holes.
Figure 3. O VI 1032 Å integrated line intensities versus time (top) and O VI 1032 Å line widths versus the O VI line ratio (bottom) at a height of 2.4 $R_\odot$ for polar coronal holes observed at different phases of solar cycle 23 and the cycle 23/24 minimum: 1996–1997 solar minimum (blue circles), north (red circles), south (green circles) polar coronal holes, and low-latitude, mid-latitude, and equatorial (squares) coronal holes are shown.

at a height of 2.4 $R_\odot$. Polar coronal holes have O VI line ratios between 0.8 and 1.9, and line widths between 300 and 410 km s$^{-1}$. Low-latitude holes have O VI ratios between 1.8 and 3.3, and line widths between 200 and 360 km s$^{-1}$. Polar coronal holes show the most extreme plasma parameters, even at reformation after solar maximum, in comparison to other coronal holes at lower latitudes.

4 Summary

UVCS/SOHO spectroscopic observations of polar coronal holes during solar cycle 23 have shown marked variations of ion properties in the solar wind acceler-
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Polar coronal holes seem to exhibit different kinetic temperatures and acceleration rates. These observations show that the north and south polar coronal holes in 2007–2009 exhibited similar extreme properties (intensities and line widths) as those measured by UVCS in the 1996–1997 previous minimum. From the analysis of the line widths, we can infer that the O VI heating seems as strong as in the previous solar minimum. A slight decrease in the polar coronal O VI intensities is seen that may be consistent with in situ measurements of lower electron temperatures and densities in the fast solar wind. The coronal magnetic field is \( \sim 40\% \) lower (Sheeley 2010, these proceedings), but this magnitude of decrease in the ion heating may not be present in the corona.

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