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CORONAL HOLES AND THE SOLAR WIND

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ABSTRACT

Coronal holes are the darkest regions of the ultraviolet and X-ray Sun, both on the disk and above the limb. Coronal holes are associated with rapidly expanding open magnetic fields and the acceleration of the high-speed solar wind. This paper reviews measurements of the plasma properties of coronal holes and how these measurements have been used to put constraints on theoretical models of coronal heating and solar wind acceleration. Heat deposition at the dense and collisional coronal base is of comparable importance (in determining, e.g., temperature gradients and asymptotic outflow speeds) as extended heating in the collisionless regions above 2 solar radii. Thus, a complete understanding of the physics requires both observations of the solar disk and inner corona (*Yohkoh*, EIT, CDS, SUMER) and coronagraphic observations of the wind's acceleration region (UVCS, LASCO). Although strong evidence has been found to suggest that the high-speed wind is driven mainly by proton pressure, the differences between proton, electron, and heavy ion velocity distributions are extremely valuable as probes of the dominant physical processes.

INTRODUCTION

The existence of coronal holes was first recognized by Waldmeier (1957, 1975), who noticed long-lived regions of negligible intensity in coronagraphic images of the 5303 Å green line. Waldmeier called the features that appeared more-or-less circular when projected onto the solar disk *Löcher* (holes), and the more elongated features were called *Rinne* (grooves) or *Kanal* (channels). The fact that coronal holes coincide with regions of open magnetic field that extend into interplanetary space was realized during the first decade of *in situ* solar wind observations (e.g., Wilcox, 1968). Coronal holes were effectively "re-discovered" in the early 1970s as discrete dark patches on the X-ray and ultraviolet solar disk, and their connection with the high-speed component of the solar wind soon became evident (Krieger *et al.*, 1973; Zirker, 1977). The term "coronal hole" thus has come to denote both the on-disk features and their open-field extensions off the solar limb. This paper provides a brief review of the physics of coronal holes and the acceleration of the high-speed solar wind.

Coronal holes become distinguishable from neighboring quiet and active regions several Mm above the photosphere, where the temperature exceeds $\sim 10^5$ K. At these low coronal heights, holes exhibit lower densities and temperatures than other regions (see, e.g., Esser & Habbal, 1997). At larger heights, as the plasma becomes less collision-dominated, coronal hole densities remain relatively low but the temperatures of different plasma components begin to depart strongly from thermal equilibrium, with $T_e < T_p < T_{ion}$. Despite the large-scale identification of coronal holes with open magnetic field lines, they contain a wide variety of magnetic structures, from X-ray bright points and spicules on the smallest scales to plumes and jets on larger scales (see Figure 1). At the minimum of the Sun's 11-year

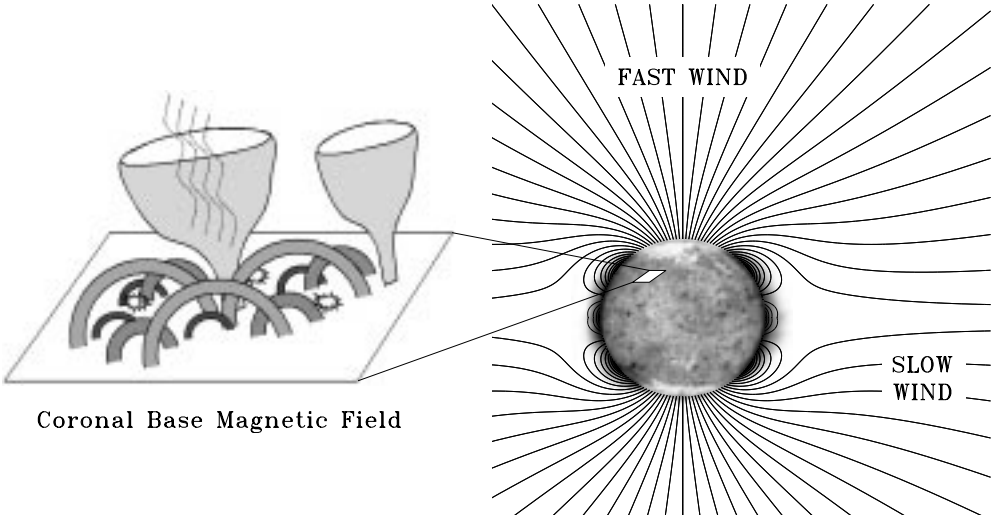

Fig. 1. Schematic view of the solar magnetic field at the minimum of the 11-year activity cycle. The stochastic distribution of small-scale loops and open flux tubes at the base (e.g., Dowdy *et al.*, 1986) gives way to a more ordered set of field lines in the extended corona (Banaszkiewicz *et al.*, 1998). The ultraviolet image of the solar disk (dark colors represent brighter regions) was taken by the EIT instrument on the *SOHO* spacecraft (Delaboudinière *et al.,* 1995).

activity cycle, large coronal holes exist at the north and south heliographic poles and extend into a large fraction of the volume of the heliosphere. At times other than solar minimum, smaller and more transient coronal holes appear at all latitudes, with plasma properties intermediate between those of polar coronal holes and the higher-density portions of the corona.

UNANSWERED QUESTIONS

The energy that heats the corona and accelerates the solar wind originates in subphotospheric convective motions. However, even after a half-century of investigation, the physical processes that transport this energy to the corona and convert it into thermal, magnetic, and kinetic energy are still not known (e.g., Parker, 1991; Marsch, 1999; Gómez *et al.,* 2000). Below are two lists of unanswered questions about the physics of coronal holes, separated by spatial scale into the coronal base and the extended corona.

The Coronal Base

1. *What physical processes are responsible for basal coronal heating?* To a certain extent, this major question cannot be answered until a more basic and phenomenological question is answered: "What is the time scale distribution of the mechanical energy pumped into coronal magnetic footpoints?" The traditional division into AC versus DC heating mechanisms (Ionson, 1985; Narain & Ulmschneider, 1990, 1996)—where AC [DC] denotes driving motions on time scales shorter [longer] than representative transit times—may give way to a more unified approach if the corona contains a continuous spectrum of time scales spanning both limits (e.g., Milano *et al.*, 1997). It is likely that the ultimate heating processes all involve the dissipation of fluctuations on kinetic "microscales," and thus requires physics beyond ideal magnetohydrodynamics (MHD); see, e.g., Viñas *et al.* (2000); Leamon *et al.* (2000).

2. *Are coronal holes distinguished by different heating rates than neighboring quiet regions, or do they appear different only because of different relative fractions of closed and open magnetic flux?* The answer to this question may be "the latter," but it depends on the elucidation of the nature of coronal heating on the smallest scales (see, e.g., Hearn, 1977; Axford *et al.,* 1999; Falconer *et al.,* 1999; Priest *et al.,* 2000).

3. *How is the mass flux of the high-speed wind determined and regulated?* Leer & Marsch (1999) contrasted two proposed scenarios: (1) that because the wind is driven by the energy deposition in the low corona, the mass flux should be proportional to this mechanical energy flux, and (2) that the supply of plasma into open "funnels" is constrained and determined by rapid ionization processes. These concepts may be related to one another and it is not yet apparent to what extent each process contributes (see also Sandbæk *et al.,* 1994; Peter & Marsch, 1997; Chashei, 1997).

The Extended Corona

1. *How much of the solar wind comes from coronal holes?* It is reasonably well established that the fast solar wind (i.e., with flow speed greater than $\sim$500 km s^{-1} at 1 AU) is accelerated in coronal holes, but it is unclear how much of the slow component of the solar wind comes from: (1) the edges of coronal holes (Wang & Sheeley, 1990), (2) transient reconnections in closed-field streamers (e.g., Wu *et al.,* 2000), or (3) active regions (Hick *et al.,* 1999). Conversely, there is also some controversy concerning how much of the fast wind may be associated with quiet regions on the solar disk (and thus *not* with the superradial expansion of coronal hole fields; see Habbal *et al.,* 2001).

2. *How and where are the plasma fluctuations (i.e., waves, turbulence, and shocks) that are believed to drive extended heating and acceleration produced and damped?* Propagating fluctuations are believed to dominate the energy and momentum deposition in the extended corona because the ultimate source is presumably from the solar surface, and thus *propagation* of some kind is required to reach large heliocentric distances. The self-consistent determination of the radial evolution of both: (1) the wavenumber spectrum of all relevant fluctuation modes, and (2) the velocity distributions of electrons, protons, and minor ions was called "the Holy Grail of this line of inquiry" by Hollweg (1999). The section below titled *Proposed Physical Processes* contains a summary of recent work toward this goal.

3. *Does the acceleration of the high-speed wind require independent momentum deposition, or are pressure gradient forces sufficient?* Recent UVCS observations of proton temperatures perpendicular to the magnetic field as large as 3–4 million K (see below) suggest that a significant fraction of the driving of the high-speed wind comes from the anisotropic pressure gradient force (e.g., magnetic mirror force) on protons. Traditionally, however, wind speeds at 1 AU in excess of 600 to 700 km s^{-1} have been explained only as a result of additional momentum deposition from wave pressure (Jacques, 1977), diamagnetic acceleration of plasmoids (Pneuman, 1986), or other processes (see also Tziotziou *et al.,* 1998). Cranmer (2002) produced a series of empirically based solar wind models which implied that a maximum $T_{\rm p\perp}$ of 6 million K was required—in a model *without* additional momentum deposition—to produce a realistic fast wind. It thus seems likely that momentum deposition is required, but the uncertainties in the determination of $T_{\rm p\perp}$ from H I Lyα line widths are still large enough so that it is not yet possible to answer this question definitively.

4. *To what degree do the observed filamentary inhomogeneities (e.g., polar plumes and jets) contribute to the mass, momentum, and energy budget of the fast wind?* Polar plumes contain denser (Ahmad & Withbroe, 1977), cooler (e.g., Kohl *et al.,* 1999), and slower (Giordano *et al.,* 2000; Wilhelm *et al.,* 2000) plasma than the "ambient" interplume corona. It is not known, though, whether the high-speed solar wind comes primarily from the interplume regions, or if it is a result of plume-interplume mixing somewhere between $\sim$20 and $\sim$60 $R_\odot$ (see also Reisenfeld *et al.,* 1999; Parhi & Suess, 2000; DeForest *et al.,* 2001).

SUMMARY OF OBSERVATIONS

In order to understand how coronal holes are produced and maintained, one must have detailed empirical knowledge about the properties of the plasma. The two most useful means of measuring these properties have been *in situ* spacecraft detection and the remote sensing of coronal photons. Some key results of such measurements are summarized below. Other diagnostic techniques that cannot be discussed in detail in this brief review are the scintillation of radio

waves passing through the corona (Bastian, 2001), the analysis of backscattered solar radiation by interstellar atoms (Bertaux *et al.,* 1996), and using comets as probes of the solar wind energy budget (Raymond *et al.,* 1998).

Spacecraft have measured particle velocity distribution functions and electromagnetic fields as close to the Sun as 60 $R_\odot$ (*Helios 1* and *2*), and as far as 12,000 $R_\odot$ (*Voyager 2*). Departures from Maxwellian velocity distributions have been used as sensitive constraints on the kinetic physics on microscopic scales (see, e.g., Feldman & Marsch, 1997). *In situ* instruments have also measured fluctuations in magnetic field strength, velocity, and density on time scales ranging from 0.1 second to months and years. Both propagating waves (mainly Alfvénic in nature) and non-propagating, pressure-balanced structures advecting with the wind are observed. Nonlinear interactions between different oscillation modes create strong turbulent mixing, and Fourier spectra of the fluctuations show clear power-law behavior—indicative of inertial and dissipation ranges—in agreement with many predictions for fully developed MHD turbulence (Goldstein *et al.,* 1995; Tu & Marsch 1995).

Because spacecraft measurements have not been able to probe the wind where its acceleration occurs (typically from the base of the corona to $\sim$10 $R_\odot$), we have relied on complementary observations of photons from the corona to study this key region. Instruments aboard the *Yohkoh*, *TRACE* (*Transition Region And Coronal Explorer*), and *SOHO* (*Solar and Heliospheric Observatory*) spacecraft—especially EIT, CDS, and MDI on the latter—have revealed strong variability and complexity at the coronal base on the smallest observable scales (100 to 1000 km; see, e.g., Watanabe *et al.,* 1998; Engvold & Harvey, 2000). The improved understanding of explosive, flarelike events from *Yohkoh* has led to many new ideas for the heating of the entire corona (e.g., Shimizu, 1996; Moore *et al.,* 1999; Priest *et al.,* 2000). The SUMER instrument on *SOHO* has investigated the origins of the high-speed solar wind in coronal holes by mapping out blueshifts in coronal emission lines (Hassler *et al.,* 1999). SUMER measurements have also shown that ion temperatures exceed electron temperatures at very low heights (Seely *et al.,* 1997; Tu *et al.,* 1998). Obtaining reliable electron temperatures above the limb ($\sim$1.1–1.4 $R_\odot$), though, has proved difficult. Relatively low values of $T_{\rm e}$ in the range 0.3–1.1 million K have been inferred by David *et al.* (1998) and Doschek *et al.* (2001) at these heights, which also agrees with the theoretical models of Hansteen *et al.* (1997). However, relatively high values of order 1.3–1.7 million K were inferred in coronal holes by Ko *et al.* (1997), Foley *et al.* (1997), and Aschwanden & Acton (2001). The reconciliation of this controversy may be the existence of non-Maxwellian electron distributions at low coronal heights (Esser & Edgar, 2000), but there also may be selection effects due to different instrumental sensitivities in an intrinsically multi-thermal distribution of temperatures.

In the acceleration region of the wind, the ultraviolet emission from coronal holes is at least 5 orders of magnitude dimmer than the solar disk. Thus, the technique of occulting the disk in *coronagraph* telescopes—often combined with spectroscopy to isolate individual ion properties—has led to a dramatic increase in our knowledge about how the high speed wind is driven. The UVCS instrument aboard *SOHO* provided the first measurements of ion temperature anisotropies and differential outflow speeds in the acceleration region of the wind (Kohl *et al.,* 1995, 1997, 1998). UVCS measured O^{5+} perpendicular temperatures exceeding 300 million K at a height of 2 $R_\odot$ (see Figure 2), with $T_\perp/T_\parallel$ of order 10–100. Temperatures for both O^{5+} and Mg^{9+} are significantly greater than mass-proportional when compared to hydrogen, and outflow speeds for O^{5+} may exceed those of hydrogen by as much as a factor of two (see also Cranmer *et al.,* 1999a). These results are similar in character to the *in situ* data, but they imply more extreme departures from thermodynamic equilibrium in the corona. Because of the perpendicular nature of the heating, and because of the ordering $T_{\rm ion} \gg T_{\rm p} > T_{\rm e}$, UVCS observations have led to a resurgence of interest in models of coronal ion cyclotron resonance (see below).

Note from Figure 2 that the protons (as measured by proxy via the H I Lyα emission line) are heated more strongly than electrons, and thus provide the bulk of the pressure gradient force in coronal holes. The observed proton temperature gradient allows us to estimate the heating rate *per proton* to be of order $\sim$0.05 to 0.1 eV s^{-1} at 2 $R_\odot$. Surprisingly, this is of the same order of magnitude as the heating rate per proton that is believed to exist at the coronal base, where an energy flux $F \approx 5 \times 10^5$ erg cm^{-2} s^{-1} (e.g., Parker, 1991) that is dissipated in a scale length ℓ of order 0.01 to 0.1 $R_\odot$, in a plasma with number density n of 10^8 to 10^{10} cm^{-3}, yields a heating rate per proton $F/(\ell n)$ in the range 0.01 to 1 eV s^{-1}. This result implies that both the base and the extended corona are of comparable importance in influencing particle velocity distributions in the high-speed wind.

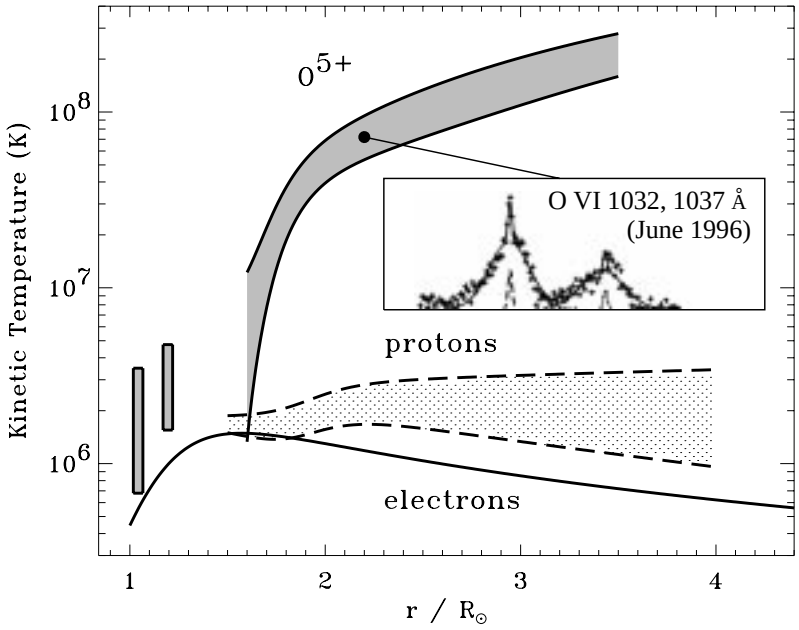

Fig. 2. Summary plot of coronal hole and high-speed wind temperature measurements. Perpendicular temperatures for protons and O^{5+} above 1.5 $R_\odot$ are from an empirical model that reproduced UVCS line widths (Kohl *et al.,* 1998; Cranmer *et al.,* 1999a). The two O^{5+} boxes at lower heights are representative of ion temperatures derived from SUMER line widths (e.g., Hassler *et al.,* 1997), and the electron temperature is from Ko *et al.* (1997). Additional uncertainties, mainly due to differences between plumes and interplume regions, and differences between coronal holes at various latitudes, are not shown here.

PROPOSED PHYSICAL PROCESSES

Different physical mechanisms for heating the corona probably govern closed magnetic loops, active regions, and the open field lines that dominate coronal holes (e.g., Priest *et al.,* 2000). There is also a growing realization that the coronal base ($r \lesssim 1.5\,R_\odot$) is probably heated by different processes than those that apply at larger heliocentric distances. This heuristic division into *creating* the lower corona versus *maintaining* and *evolving* the extended corona is supported by the drastic differences in Coulomb collision rates at the base (where all species seem to be collisionally coupled) and in the supersonic wind (which is nearly collisionless). The two regimes are also differentiated by the complexity and topology of the magnetic field (see Figure 1).

The remainder of this paper discusses the extended heating in the acceleration region of the high-speed wind, which as stated above is expected to be dominated by the dissipation of propagating fluctuations. It is not known, however, how or where the fluctuations responsible for extended heating are generated. Alfvén waves have received the most attention because they seem to be the least damped by collisional processes (i.e., viscosity, conductivity, resistivity) at the coronal base, but there have been recent observations that imply the presence of slow magnetosonic waves in various kinds of open flux tubes (Ofman *et al.,* 1999). At heights greater than 2–3 $R_\odot$, wave dissipation should be dominated by collisionless processes. The most likely dissipation mechanism seems to be ion cyclotron resonance, since Landau damping mainly tends to heat electrons in a low-β plasma (Habbal & Leer, 1982). Some have suggested that left-hand polarized ion cyclotron waves are generated impulsively at the base of the corona and propagate virtually unaltered to where they are damped (Axford *et al.,* 1999). A related idea is that the same basal impulsive events generate fast shocks that fill the extended corona and convert some of their energy into anisotropic heating and ion acceleration (Lee & Wu, 2000). Problems with these ideas include: (a) the neglect of minor ions that can easily absorb a basal fluctuation spectrum before any primary plasma constituents (protons or He^{2+}) can come into resonance (e.g., Cranmer, 2000, 2001), and (b) a significant shortfall in observed density fluctuations, compared to model predictions

consistent with basal wave generation models (Hollweg, 2000).

More numerous are proposed scenarios of local wave generation; i.e., where "secondary" fluctuations arise throughout the extended corona as the result of either turbulent cascade, plasma instability, or mode conversion (e.g., Hollweg, 1986; Matthaeus *et al.*, 1999; Markovskii, 2001). Ion cyclotron frequencies in the corona are typically 10 to 10,000 Hz, but the oscillation frequencies observed on the surface of the Sun (generated mainly by convection) are of order 0.01 Hz. Any wave generation mechanism must therefore bridge a gap of many orders of magnitude in frequency (or wavenumber). Most models of MHD turbulence favor the transfer of energy from small to large wavenumbers transverse to the background magnetic field ($\mathbf{k} \cdot \mathbf{B} \approx 0$); see, e.g., Shebalin *et al.* (1983); Goldreich & Sridhar (1997). However, ion cyclotron damping of Alfvénic fluctuations (believed to be the only mode that can survive into the solar wind) requires large *parallel* wavenumbers ($k_{\|} \approx \Omega_{\rm ion}/V_A$) that seemingly are not produced by MHD cascade. This inability to produce ion cyclotron waves locally in the corona is a major roadblock in our attempts to understand the origin of the observed anisotropic heating and preferential ion acceleration.

Despite our present lack of understanding about how ion cyclotron waves may be generated, there has been no shortage of attempts to "work backward" from the observational constraints to derive further details of the required wave properties and their kinetic effects. In addition to moment-based models assuming bi-Maxwellian distributions (e.g., Cranmer *et al.*, 1999b; Hu *et al.*, 1999; Tu & Marsch, 2001), there has been a recent flurry of activity to understand kinetic departures from simple parameterized velocity distributions (Galinsky & Shevchenko, 2000; Isenberg *et al.*, 2001; Vocks & Marsch, 2001; Cranmer, 2001). The results from these investigations are still being digested, and it is not yet clear which aspects of the physics can be neglected and which ones are required for a basic understanding.

CONCLUSIONS

Considerable progress has been made in the last decade in characterizing the plasma state of coronal holes and their associated high-speed solar wind streams. The observations have guided theorists to a certain extent, but *ab initio* kinetic models are still required before we can claim a full understanding of the physics. Future spectroscopic measurements of the corona are expected to provide constraints on specific departures from bi-Maxwellian velocity distributions (Cranmer, 2001), and NASA's *Solar Probe* (e.g., Möbius *et al.*, 2000) should make valuable *in situ* measurements as close to the Sun as 4 $R_{\odot}$. Observations of the coronal base from X-ray and ultraviolet space-based telescopes are a key ingredient in determining the source regions and lower boundary conditions of the wind. To make further progress, the lines of communication must be kept open between theorists and observers, and also between the two traditionally separated observational communities of "solar physics" (i.e., near-Sun astronomy) and "space physics" (i.e., interplanetary plasma physics).

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