Coronal Holes

Coronal holes are regions of low-density plasma on the Sun that have magnetic fields that open freely into interplanetary space. During times of low solar activity, coronal holes cover the north and south polar caps of the Sun. During more active periods, coronal holes can exist at all solar latitudes, but they may only persist for several solar rotations before evolving into a different magnetic configuration. Ionized atoms and electrons flow along the open magnetic fields in coronal holes to form the high-speed component of the SOLAR WIND.

When observing the solar disk in visible light, coronal holes cannot be distinguished from surrounding regions, and it is primarily in ultraviolet and x-ray wavelengths that they appear as distinct structures. This is because the outermost layer of the solar atmosphere (the CORONA) has a temperature of about a million K. Plasma at this temperature naturally emits most of its radiation in the ultraviolet and x-ray bands. The underlying static surface of the Sun (the SOLAR PHOTOSPHERE) has a much lower temperature of 5800 K, and it emits radiation in visible (primarily yellow) wavelengths. The reason for the steep rise in temperature as one moves outward from the photosphere to the corona is not yet understood completely, and the ongoing search for CORONAL HEATING MECHANISMS is one of the most active fields of solar physics.

Much can be learned about coronal holes by obscuring the light from the bright solar disk to resolve how the corona extends into interplanetary space. This happens naturally during solar ECLIPSES, but, with the invention of the coronagraph (a telescope designed to simulate an eclipse by blocking out direct solar rays) in the 1930s, the extended corona is viewable at any time. In eclipse and coronagraph images, coronal holes can be observed in visible light—as well as ultraviolet and x-rays—as dim regions surrounded by brighter and more complex CORONAL STREAMERS. Spaceborne coronagraphs have observed the light emitted by coronal holes in discrete spectral lines formed by specific atoms and ions (see ATOMS AND SPECTRA and SOLAR SPECTROSCOPY). Because the density in the extended corona is so low, many different species of atoms and ions do not interact with one another, and thus they can exhibit different plasma properties (temperatures and flow speeds, for example). By probing these particles with spectroscopy, solar physicists are learning about the physical processes that produce the coronal holes and the high-speed solar wind.

Observational properties

The existence of coronal holes was first recognized in the late 1950s, when M Waldmeier noticed long-lived regions of negligible intensity in images made with a visible light coronagraph (see CORONAGRAPHS). In the 1960s and 1970s, ultraviolet and x-ray images of the Sun taken with rocket-borne and orbiting telescopes confirmed that coronal holes exist as discrete patches of lower brightness on the solar disk. The highest-intensity x-ray features, known as CORONAL LOOPS and SOLAR ACTIVE REGIONS, were observed to pepper the remaining 'quiet Sun', which is a generic term for regions too bright to be coronal holes, but too dim to be considered magnetically 'active'. In coronagraph images, between 1 and 30 solar radii from the Sun's center, the coronal holes extend into regions of extremely low brightness and the quiet and active Sun expands to form bright and wispy coronal streamers.

Instruments aboard the *Skylab* space station were used for the first continuous monitoring campaign of coronal holes in the early 1970s. Subsequent spaceborne observations have tracked coronal holes for several 11 yr SOLAR CYCLES. For approximately 7 yr around the minimum of every solar cycle, coronal holes persist as large northern and southern polar caps, as illustrated in figure 1(*a*), an image from the EIT instrument aboard the *Solar and Heliospheric Observatory* (*SOHO*). As solar activity increases, and the magnetic fields on the Sun become more complex, coronal holes can emerge anywhere on the solar disk and persist for, on average, three to five solar rotations (see figure 1(*b*)). Although the solar photosphere is observed to rotate faster at the equator than at the poles (see SOLAR INTERIOR: ROTATION), coronal holes seem to rotate rigidly with a period of about 27.5 days, independent of their latitude. This characteristic of the corona has raised many questions regarding the origin and evolution of the solar magnetic field.

The observability of coronal holes on the solar disk depends on the temperature of the plasma being sampled. Spectral lines are formed by a single type of atom or ion that only exists in a finite range of temperatures, so the observation of many different lines allows the temperature stratification in the corona to be probed. Typically, lines from ions formed around 10 000 K sample the CHROMOSPHERE, which is characterized by a cell-like pattern of 'supergranular' convective motions. The supergranular network is the same in coronal holes and quiet Sun areas. As the temperature increases past 100 000 K in the thin and chaotic TRANSITION REGION, coronal holes become distinguishable as areas of lower density and temperature. In this region, coronal holes are also revealed to contain stronger plasma fluctuations (waves or turbulent eddies) than the quiet Sun, and this may be important in accelerating the solar wind that emerges from holes.

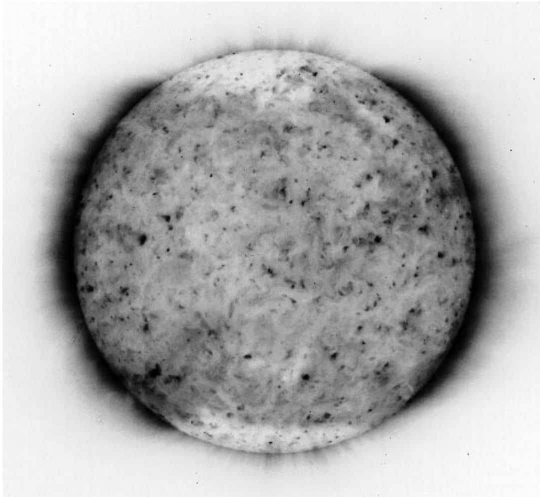
As seen in figure 1, the corona is highly structured on small scales (100–10 000 km). Coronal holes contain large numbers of rapidly varying bright points that often coincide with the boundaries of supergranular cells (see SOLAR CORONA: X-RAY BRIGHT POINTS). The SUMER instrument aboard SOHO has revealed these network-edge regions in coronal holes as possible 'launching' sites for the high-speed solar wind; strong Doppler shifts of coronal emission lines indicate outflow velocities of approximately 10 km s^{-1} on the solar disk. Also, the chromospheric plasma underlying coronal holes occasionally bursts upward to form discrete jets known as macrospicules (see CHROMOSPHERE: SPICULES). While probably not a significant component of the accelerating wind, macrospicules may be detailed probes of the complex dynamics of magnetic reconnection in the corona; for example, some macrospicules have been recently observed to have rotational, 'tornado-like' motions of up to 50 km s^{-1} in amplitude. A final example of small-scale structure in coronal holes is POLAR PLUMES, which appear to be open magnetic flux tubes with a slightly higher density than the ambient, interplume corona. Many plumes seem to be rooted in x-ray bright points, and they can be traced out to at least 10 solar radii ($R_\odot$) with coronagraphs to follow the large-scale expansion of the coronal hole magnetic field.

The high-speed solar wind

One of the reasons that coronal holes are important to study is that they are thought to be the primary sites of acceleration for the high-speed solar wind. Since the supersonic solar wind was first detected by spacecraft plasma instruments in the early 1960s, it has been found to be composed of both high-density, low-speed (300–400 km s^{-1}) streams and low-density, high-speed (500–800 km s^{-1}) streams. The comprehensive *Skylab* observations in the early 1970s allowed Krieger, Timothy and Roelof to make the connection between rotating coronal holes and transient high-speed streams at the Earth's orbit. The *Ulysses* spacecraft, which passed over the north and south poles of the Sun in the early 1990s, found that, outside a $\pm 20^\circ$ range around the ecliptic plane, the solar wind is exclusively high speed. Because *Ulysses* observed the heliosphere during the declining phase of the solar cycle, this large volume of high-speed wind can be correlated with the long-lasting northern and southern polar coronal holes that are observed on the disk near solar minimum.

The open magnetic field lines rooted in coronal holes are expected to expand *superradially,* i.e. into a larger volume than would be expected if the field pointed radially away from the center of the Sun. This arises because the SOLAR MAGNETIC FIELD near solar minimum has a strong dipolar component, with closed loops at the bases of the equatorial coronal streamer belt. At large distances from the Sun, the energy in the outflowing plasma begins to exceed the magnetic energy, and the solar wind is thus able to 'stretch' the magnetic field lines nearly radially. The resulting equilibrium structure can be modeled by several empirical and theoretical approaches. Figure 2 shows an example of an axially symmetric field configuration at solar minimum. The boundaries of the coronal hole are at approximately 60° north and south latitude, but the open field lines from the holes expand into the majority of the extended corona.

The atoms, ions and electrons in the high-speed solar wind accelerate to terminal coasting speeds of about 700–800 km s^{-1} over several solar radii above the poles. In the late 1950s, E Parker showed that a hot (million K) corona will naturally 'evaporate' and form a steady-state, accelerating flow; it is the total gas pressure of the dominant protons and electrons that counteracts the inward pull of gravity to form the wind (see SOLAR WIND: CORONAL ORIGINS and SOLAR WIND: THEORY). However, in the 1960s and 1970s it was realized that to maintain the observed plasma conditions in the high-speed wind, one requires an *extended* source of either energy or momentum in addition to the basal heating that produces the hot corona. It is this twin problem of understanding the extended energy deposition and the high-speed wind acceleration that propels recent investigations of coronal holes. Measurements of the detailed thermodynamics and kinetic properties of the wind particles are required to constrain theoretical models.



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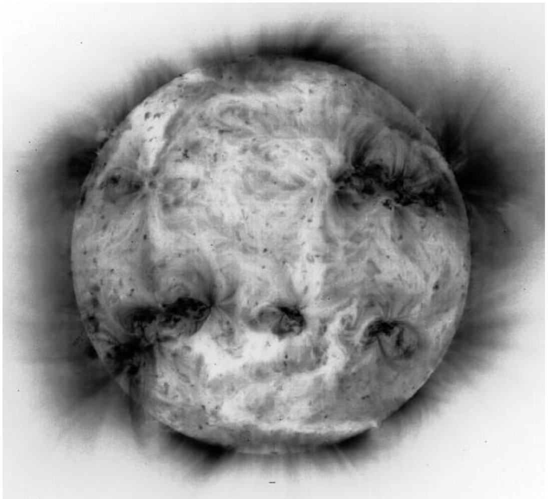

(*b*)

Figure 1. Images of the Sun taken with the Extreme Ultraviolet Imaging Telescope (EIT) aboard *SOHO* on (*a*) 23 May 1996 and (*b*) 9 December 1998. Darker shading represents higher intensity in the 195 Å emission line of highly ionized iron. Images courtesy of the *SOHO*–EIT consortium. *SOHO* is a project of international cooperation between ESA and NASA.

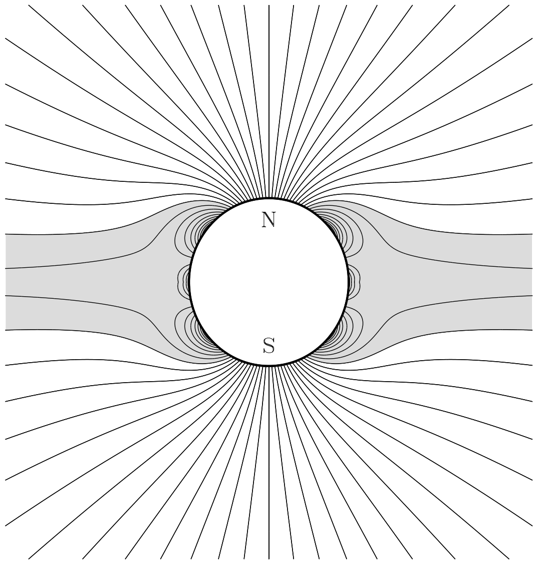

Figure 2. Depiction of lines of magnetic force in the semi-empirical multipole–current-sheet coronal model of Banaszkiewicz, Axford and McKenzie. The high-speed solar wind fills the unshaded volume above the solar surface.

Plasma characteristics

Any hypothesis concerning the origin of the hot corona and the high-speed solar wind must be tested by comparing the predicted properties of the plasma with observations. Quantities such as density, flow velocity, temperature and elemental abundance can be measured either by directly sampling solar wind particles (so-called *in situ* detection by interplanetary spacecraft) or by the analysis of photons generated or scattered by these ions and electrons near the Sun. The *in situ* data are described in more detail elsewhere (see, for example, SOLAR WIND: GLOBAL PROPERTIES and SOLAR WIND: KINETIC PROPERTIES), but the following characteristics for the high-speed wind should be noted.

1 The dominant proton–electron plasma flows outward more slowly than other, less numerous, positive ions such as He^{2+}. The difference between these velocities is approximately equal to the propagation speed V_A of *Alfvén waves* in the wind (see below), where

$$V_A = B_r \left(4\pi \sum_{\text{ions}} m_{\text{ion}} n_{\text{ion}} \right)^{-1/2}$$

B_r is the magnetic field strength in gauss and m_{ion} and n_{ion} are the masses and number densities of the positive ions, summed above to form a total plasma mass density. The Alfvén speed V_A is of order 30–100 km s^{-1} in the *in situ* solar wind, but may be as large as several thousand km s^{-1} in the inner corona.

2 The proton temperature exceeds the electron temperature by about a factor of 2, and the temperatures of other positive ions are greater than the proton temperature by at least their ratio of masses:

$$\frac{T_{\text{ion}}}{T_p} \gtrsim \frac{m_{\text{ion}}}{m_p}.$$

3 The microscopic velocity distribution functions of most particle species depart from equilibrium Maxwell–Boltzmann distributions. Protons and other ions have higher temperatures in directions perpendicular to the magnetic field than in directions parallel to the field (i.e. $T_\perp > T_\parallel$). Electrons exhibit a broad non-Maxwellian 'tail' in their distributions characteristic of a temperature 5–10 times their primary 'core' temperature.

At present, information about the plasma in the acceleration region of the solar wind (1–10$R_\odot$) can only be gathered remotely, for example by observing the solar disk (see SOLAR SPECTROSCOPY AND DIAGNOSTICS) or by using eclipses and coronagraphs to see the faint extended corona. The radial dependence of density above polar coronal holes has been well constrained by measuring linearly polarized visible light in the corona. This 'polarized brightness' is dominated by the Thomson scattering of visible light photons by free electrons, and thus the brightness is proportional to the total number density of electrons along the line of sight. The electron density in coronal holes is anywhere from 3 to 10 times smaller than the electron density (at corresponding heliocentric distances) in coronal streamers. Because the coronal plasma originates in the electrically neutral gas of the photosphere, the numbers of positive and negative charges must remain equal even when the gas becomes ionized. Thus, the electron density can be combined with this constraint and information about the abundances of different chemical elements in the corona to derive the densities of protons and other ions.

The outflow velocities of solar wind particles can be measured in several ways. If both the density n and the cross-sectional area A of magnetic flux tubes (formed by neighboring lines of magnetic force that channel the plasma) are known, and the flow is assumed to be steady in time, one can use the FLUID DYNAMICS constraint of mass flux conservation to solve for the outflow velocity v:

$$nvA = \text{constant along a flux tube.}$$

Also, as mentioned above, near the base of the corona Doppler shifts of spectral lines can be used to put limits on the flow speeds in coronal holes. The propagation speeds of fluctuations in the solar wind can be probed by both radio scintillation methods and the direct kinematic tracking of density modulations in coronagraph images. Finally, measurements of ultraviolet spectral lines formed in the corona by the scattering of solar-disk photons can be analyzed to deduce flow velocities by the phenomenon of *Doppler dimming.* This effect is a decrease in the line intensity I that depends on the flow speed and parallel ion temperature, with

$$I \approx I_0 \exp(-m_{\text{ion}} v^2 / 2kT_{\parallel})$$

where I_0 is the intensity that would have been scattered if $v = 0$ and k is Boltzmann's constant. When the flow speed v of the ions increases, their motions become Doppler shifted away from the source of photons on the solar disk (which is not shifted because there is nearly zero velocity on the disk), and fewer photons are available to be scattered, leading to an overall dimming of the line intensity.

The various methods outlined above have been used over the last few decades to measure the wind velocity above coronal holes. Most measurements agree that the high-speed wind accelerates rapidly to about 100–200 km s^{-1} in the first solar radius above the photosphere, and to nearly its ~700 km s^{-1} terminal speed by 5–10$R_\odot$. The Ultraviolet Coronagraph Spectrometer (UVCS) aboard *SOHO* used the Doppler dimming technique to also probe the acceleration of highly ionized oxygen (O^{5+}) above polar coronal holes, and between $2R_\odot$ and $3R_\odot$ the oxygen outflow velocity may be as much as twice the bulk hydrogen velocity; this seems to be related to the faster outflow for minor ions seen much further out in the *in situ* measurements.

The temperatures of electrons, protons, and other ions are crucial to measure in coronal holes to be able to constrain coronal heating mechanisms. As with the outflow velocity, there are numerous methods of measuring the temperatures of different coronal particles, which will be described in more detail below. Figure 3 shows a summary of electron, hydrogen and oxygen temperature data gathered remotely (between $1R_\odot$ and 5 $R_\odot$) and *in situ* (greater than $60R_\odot$, or 0.3 AU) in the high-speed wind. The latter values were measured by the *Helios 1* and *2* spacecraft (between 0.3 and 1 AU), the *IMP* series spacecraft, *Ulysses*, *Pioneer 10* and *11*, and *Voyager 1* and *2* (at and beyond 1 AU), and many others. The radial dependence of the proton and electron temperatures provides evidence for extended heating of the plasma beyond 0.3 AU, because a purely adiabatic medium (i.e. without extra heat addition) would have a temperature that drops off more steeply with radius ($T \propto r^{-4/3}$) than is observed.

The electron temperature T_e above coronal holes is known to rise to about 800 000 K by $1.1R_\odot$, but above that height there is some controversy. Some observations suggest T_e rapidly decreases to about 300 000 K by 1.3–1.4$R_\odot$, while others indicate that T_e continues to increase to 1.5 million K by $1.5R_\odot$ before beginning to decrease (see figure 3). The low T_e values come from measurements of temperature-sensitive intensity ratios of pairs of spectral lines of the same ion. The different lines arise from different atomic energy levels, which are excited by collisions with free electrons with different energies (or temperatures). The high T_e values come primarily from detecting the observed *in situ* ionization stages of many ions and mapping them back into the corona, where the ionization state is thought to be determined (see EXCITATION AND IONIZATION and SOLAR WIND COMPOSITION). The high inferred T_e values are also consistent with x-ray measurements with the Soft X-Ray Telescope aboard the *Yohkoh* satellite. The discrepancy between high and low values may arise because different diagnostics emphasize different regions of plasma along the line of sight (plumes and interplume regions, perhaps), or there may be hidden assumptions and uncertainties that have not yet been taken into consideration.

Temperatures for hydrogen atoms and minor ions can be somewhat more solidly constrained by measuring the *line widths* of coronal emission lines. The existence of random thermal motions of particles along the observational line of sight leads to random Doppler shifts of the scattered photons. Larger ranges of microscopic velocities (and thus larger atom or ion temperatures) lead to broader spectral line profiles. This diagnostic only strictly samples the line-of-sight component of the temperature—which is nearly equal to the component $T_\perp$ perpendicular to the open magnetic field lines—but Doppler dimming (see above) can be used to constrain $T_\parallel$ and thus place limits on departures from Maxwellian distributions in the corona. Note also that the random motions sampled in the line widths may also contain macroscopic motions that are *unresolved* over the observed volume of plasma. The line width $\Delta\lambda$ can thus be related to a most-probable speed Δv that is decomposed into two components:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\Delta v}{c} = \frac{1}{c}\left(\frac{2kT_\perp}{m_{\text{ion}}} + \xi^2\right)^{1/2}$$

where λ_0 is the rest wavelength of the center of the line, c is the speed of light and ξ is an unresolved 'non-thermal' component of the velocity that is often attributed to motions induced by MAGNETOHYDRODYNAMIC WAVES or SOLAR WIND TURBULENCE.

In figure 3 there are representative line-width temperatures for neutral hydrogen (H^0) and ionized oxygen (O^{5+}) measured by the SUMER (1–1.2$R_\odot$) and UVCS (1.5–4$R_\odot$) instruments aboard *SOHO*. The UVCS values for $T_\perp$ are results from a self-consistent 'empirical model' that takes line-of-sight and other RADIATIVE TRANSFER effects into account. The upper and lower limits for the derived temperatures represent both experimental uncertainties and reasonable lower and upper limits on the unresolved wave–turbulence speed ξ. Note that $T_\perp$ for O^{5+} exceeds 100 million K, which is a temperature even greater than in the deepest SOLAR INTERIOR. The UVCS empirical models also constrain the ratio $T_\perp/T_\parallel$ for O^{5+} to exceed values of 10–100 by a height of $3R_\odot$. Clearly the heating mechanism that produces hot and non-Maxwellian ions in the *in situ* high-speed wind begins to take effect in coronal holes, only a few solar radii from the photosphere.

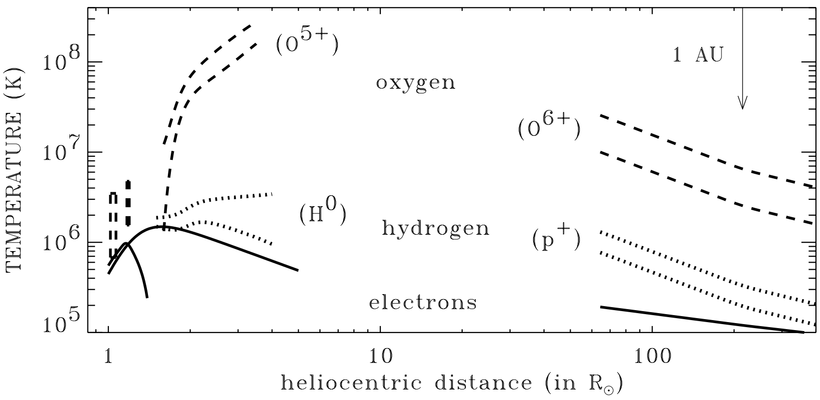

Figure 3. Summary plot of coronal hole and high-speed wind temperature measurements. Solid lines denote electron temperatures, dotted lines denote hydrogen temperatures (neutral hydrogen in the corona; protons in the *in situ* wind) and dashed lines denote oxygen temperatures (O^{5+} in the corona; O^{6+} in the *in situ* wind). The radius of the Earth's orbit at 1 AU is shown by an arrow.

Wave-particle interactions

Many CORONAL HEATING MECHANISMS have been suggested to produce the sharp TRANSITION REGION between the 10 000 K chromosphere and the million K corona. However, the extended heating that produces stunning departures from a single-temperature equilibrium in coronal holes (see figure 3) seems possible only via processes able to transport energy at least 0.01–0.1$R_\odot$ above the photosphere before depositing it as heat. Traveling magnetohydrodynamic waves have been proposed as a natural possibility, although the way the waves *dissipate* and heat up the plasma is not understood completely. Acoustic and magnetoacoustic waves, which are characterized primarily by density and pressure fluctuations, damp too easily to survive out into the corona. Conversely, most types of Alfvén waves, which can be thought of as tensile vibrations of magnetic field lines, do not damp easily enough and propagate past 10–20$R_\odot$ without losing significant energy to the plasma.

The *in situ* high-speed solar wind is observed to contain Alfvén-like fluctuations with periods ranging from seconds to days (see SOLAR WIND PLASMA WAVES). In the *Helios* measurements at 0.3 AU the fluctuations are primarily outward propagating, but at larger distances both outward and inward modes coexist. The complex spectrum of wave-like oscillations in velocity, density and magnetic field strength can be best interpreted as a form of *turbulence,* where large-scale, slow motions drive a cascade toward smaller-scale and more rapid motions. Although much is known about the evolution of solar wind turbulence in the heliosphere, its ultimate generation (probably as Alfvén waves) in the corona is not nearly as well understood.

One promising idea that may explain some of the observed plasma properties in coronal holes and the high-speed wind is the dissipation of extremely high-frequency Alfvén waves, with periods of order 0.001–0.1 s. These waves have not yet been detected directly, but there are several probable theoretical mechanisms that can generate them in the corona. Millisecond period waves may be produced by small (1–10 km sized) magnetic reconnection events in the low corona, by a turbulent cascade from lower-frequency modes or by plasma instabilities induced by particles in non-Maxwellian distributions. The latter two mechanisms can occur anywhere in the corona and solar wind, not just at the base. These high-frequency waves oscillate with the same periods as the helical gyrating motions that positive ions exhibit in the presence of a magnetic field. Ions experiencing such a *cyclotron resonance* are able to efficiently sap the waves' energy, and they can be rapidly accelerated with respect to the bulk proton–electron plasma. In addition, they are driven into non-Maxwellian velocity distributions with $T_\perp > T_\parallel$ and temperatures greater than proportional to their masses. This process thus may be able to explain many of the observed ion characteristics, but it also gives rise to many new questions concerning the kinetic physics of the plasma and the origin of its fluctuations (see also COLLISIONLESS PROCESSES IN ASTROPHYSICAL PLASMAS).

Future prospects

Much has been learned over the last half century about coronal holes and their effects on the solar wind. However, solar physicists are still far from a comprehensive theoretical understanding of how the corona is heated and how the solar wind is accelerated. It is clear that the mean state of the coronal and heliospheric plasma is intimately coupled with fluctuations about that mean, and theories of turbulence, wave dissipation and instabilities must be developed along with broad-brush solar wind models. More precise theories should be constrained by better measurements, and one important upcoming mission will be the *Solar Probe* that will pass through the corona, sampling the plasma down to about 4$R_\odot$. Remote sensing measurements, however, still have incredible potential for learning about the Sun. Proposed next-generation spaceborne telescopes will measure velocity distributions of dozens more ion species (and electrons) above coronal holes, constrain the magnetic field strength and geometry and resolve millisecond period oscillations in the lower corona.

Bibliography

Fleck B and Svestka Z (eds) 1997 *The First Results from SOHO* (Dordrecht: Kluwer)

Jokipii J R, Sonett C P and Giampapa M S (eds) 1997 *Cosmic Winds and the Heliosphere* (Tucson, AZ: University of Arizona Press)

Parker E N 1991 Heating solar coronal holes *Astrophys. J.* **372** 719–27

Pneuman G W 1986 Driving mechanisms for the solar wind *Space Sci. Rev.* **43** 105–38

Suess S T 1979 Models of coronal hole flows *Space Sci. Rev.* **23** 159–200

Zirker J B (ed) 1977 *Coronal Holes and High Speed Wind Streams* (Boulder, CO: Colorado Associated University Press)

Steven R Cranmer