WIND, HOLES AND BRIGHT POINTS

J. B. Zirker
National Solar Observatory
National Optical Astronomy Observatories**
Sunspot, New Mexico 88349

ABSTRACT

In this review, I will summarize recent attempts to explain the heating of the corona and the acceleration of the solar wind, particularly in high speed streams that originate in coronal holes. As we shall see, acceleration by Alfvén wave pressure remains a possibility, but has not yet been confirmed observationally. Meanwhile, coronal heating by transient events has emerged as an interesting alternative to magnetic reconnection.

Several excellent reviews of this subject have appeared recently (Axford, 1985; Parker, 1986, 1987; Pneuman, 1986); the reader is encouraged to consult them.

Solar Wind

Let us recall a few basic properties of the solar wind that any acceptable model must reproduce:

1. Most of the fast wind (say, v > 500 km/s) originates in coronal holes.

2. Near the Earth, i.e., in the ecliptic, the wind speed (v) ranges from about 300 to 800 km/s, the proton density (n) from 5 to 10 cm$^{-3}$, and the product (nv) is nearly constant at about 3 x 10$^8$ cm$^{-2}$ s$^{-1}$.

3. A fast wind stream originating in a diverging coronal hole requires an energy flux input of at least 2-3 x 10$^3$ erg cm$^{-2}$ s$^{-1}$.

4. Interplanetary scintillation observations (Coles et al, 1980) indicate polar wind speeds as high as 600 to 750 km/s. The mass flux in such polar streams is uncertain, however.

5. A classical analysis of the density profile in a polar wind stream (R. Munro, B. Jackson, 1977) suggests that the acceleration region lies within a few (2-5) solar radii of the sun (See Fig 1).

6. The profile of resonantly-scattered Lyman alpha radiation implies a hydrogen kinetic temperature no greater than about 1.2 million Kelvin (Withbroe, et al., 1985), and decreasing with radius beyond 1.5 radii (see Figure 2). Ionization temperatures, inferred from the charge state of light ions, are consistently below 1.5 million degrees (Galvin et al., 1984).

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

© AURA • Provided by the NASA Astrophysics Data System
Figure 1. Electron density and inferred velocity (for $nv = 3 \times 10^8$ cm$^{-2}$ s$^{-1}$) in a polar hole. R. Munro and B. Jackson, 1977.

The basic problem in explaining the wind acceleration is that a Parker-type, thermally-driven wind model would require coronal temperatures in excess of 2.5 million degrees to account for the observed wind speeds, while the empirical coronal temperatures lie well below this. Leer, et al. (1982) carried out an exhaustive parametric study of wind acceleration, under the basic assumption of a conductive, thermally-driven wind. Figure 3 shows the effect of varying the coronal base density and the base temperature on the particle flux density and flow speed at one AU. Three different laws of heat conduction were incorporated in their work: classical, collision-dominated; magnetically-inhibited; and collisionless inhibited. Any model that predicts a speed of 500 km/s or more requires a base temperature greater than about 2.5 million Kelvin and a base density less than 1x10$^7$ cm$^{-3}$, in conflict with the observations. A diverging geometry, such as seen in coronal holes, makes little difference to these conclusions.

Extended heating over several radii has been tested as a possible way to accelerate the solar wind. Such models show that if the heating occurs below the critical point, the mass flux increases in proportion to the base density, but the terminal wind speed does not increase. Heating above the critical point can produce the desired high speeds, but generally too far out into the wind to match the Munro-Jackson acceleration zone. Moreover, the wind temperature at 1 AU turns out to be too high. Extended heating has consequently fallen out of favor as a possible mechanism.

Alfven waves that arise in the chromosphere can, in principle, accelerate the wind by exerting wave pressure on the plasma. An extensive literature has grown up concerning the generation and propagation of Alfven waves along open magnetic
Hollweg et al. (1982) have also offered evidence for coronal waves. They analyzed the fluctuations in the carrier signals from two Helios spacecraft, which were occulted by the solar corona. The minimum heliocentric distance of the ray path from Helios 2 was only 8 solar radii, so that these fluctuations can be used to probe a region close to the Munro-Jackson acceleration zone. The measurements yield two interesting quantities: the integrated electron content and the integrated Faraday rotation along the ray path. Both fluctuations have typical periods of about an hour.

The authors rule out coronal electron density fluctuations as the prime cause of the Faraday rotation, and show that the rotation fluctuations are consistent with a

*Figure 2. Kinetic temperature derived from hydrogen Lyman alpha profiles (points), calculated photon temperature (light solid line) and proton temperature corrected for Alfvén wave motions (short dashes). G. Withbroe et al., 1985.*
Figure 3. Predicted proton flux density and wind speed at 1 AU, in a thermally-driven wind: (a) classical conduction law, (b) magnetically inhibited conduction, (c) collisionless inhibited conduction. E. Leer et al., 1982.
Figure 4. Predicted proton flux density and wind speed at 1 AU, in a wave-driven wind: (a) coronal base temperature $1.1 \times 10^6 \text{K}$; (b) $1.3 \times 10^6 \text{K}$. $n_e T_e = 2 \times 10^{14} \text{ cm}^{-3}\text{K}$. Solid line: spherical symmetry; dashed line: rapidly expanding wind. E. Leer et al., 1982.
flux of Alfvén waves sufficient to heat and accelerate high speed solar wind streams. However, pure Alfvén waves are non-compressive, so that the observed density fluctuations must arise from some other (unspecified) cause.

Finally, Withbroe et al. (1985) compared the hydrogen kinetic temperature they determined from Lyman alpha line widths to the predictions of the Sturrock-Hartle, two-fluid model for the wind, as shown in Figure 2. They interpret the difference between predicted proton temperature and measured hydrogen temperature as evidence for non-thermal heating or motions between 1.4 and 4 solar radii. If the excess line broadening of hydrogen is attributed to Alfvén waves, the required rms amplitude is less than 70 km/s, below 4 solar radii.

Several authors have explored the range of coronal parameters required to produce fast wind in a wave-driven model. As one example, we refer to Leer et al. (1982), who showed that wind speeds as high as 700 km/s, with a proton flux near $3 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ can be produced with Alfvén wave amplitudes of 25 to 30 km/s, with low coronal base temperatures (1.1 to $1.3 \times 10^6 \text{ K}$), and reasonable base density ($10^8 \text{ cm}^{-3}$) (See Figure 4).

Thus, although the observational evidence for coronal Alfvén waves is still weak, the theory of wave-driven winds suggests that the observed range in wind properties can be predicted with plausible wave amplitudes. Further observations are urgently needed to test the hypothesis of wind acceleration of wave pressure.

We note, in passing, a curious paper by Lallement et al. (1986), who re-examined the Munro-Jackson analysis that has influenced the subject so strongly. They point out that observations of hydrogen Lyman alpha, scattered from interstellar hydrogen near the Sun (Lallement et al., 1985) imply that the proton flux in a polar hole may be a factor of 3 smaller than assumed by Munro and Jackson. As a consequence, the inferred flow speed in the hole need not exceed 200 km/s below 5 solar radii. The authors suggest that the coronal density observations used by Munro-Jackson are consistent with a pure thermally-driven wind, with no additional energy added in the 2-5 solar radii region. Since, however, the interplanetary scintillation measurements imply polar wind speeds greater than 500 km/s, energy must be added somewhere in the polar wind: if not below 5 solar radii, then above it.

**Coronal Heating by Transient Events**

Most of the magnetic field in the quiet and active sun consists of closed loops. Parker (1987) has pointed out the difficulty of dissipating Alfvén waves in coronal loops whose length is comparable with the wavelength. Following suggestions by Gold (1984), Rosner et al. (1978), and Sturrock and Uchida (1981), he has proposed (1981, 1986) that the shuffling of magnetic footpoints in the photosphere by convective motions produces twisting, braiding and ultimately reconnection of the field in the corona, with a consequent release of energy. In this picture, the heating of the corona may result from many discrete sporadic events, rather than a continuous inflow of energy. Recent observations of the chromosphere and transition zone have revealed transient events that may be related to such a reconnection process, or that may arise from a different cause, but nevertheless produce coronal heating. Among such events are coronal bright points, "jets" and transition zone "microflares." Spicules have also been mentioned as possible sources of energy for heating the corona.
Coronal bright points were discovered during the Skylab mission as small regions bright in X-rays (Golub et al., 1974). Subsequent studies have shown:

1. They are magnetic loops with footpoints in magnetic dipoles. Typical dimensions are 3000 x 12000 km (Harvey and Martin, 1973; Sheeley and Golub, 1979).

2. A maximum of perhaps 1500 of them appear over the Sun, with a distribution in latitude broader than spots, (Golub, et al., 1974).

3. Their number varies by a factor of three, 180 degrees out of phase with the 11-year sunspot cycle (Golub, et al., 1979; Davis, 1983).

4. Within a coronal hole their surface density appears to increase with the age of the hole (Davis, 1985).

5. They may fluctuate in X-ray brightness by a factor of two within a few minutes (Nolte, et al., 1979).

Coronal bright points are also visible at radio wavelengths (Kundu, et al. 1987) and in the EUV. Habbal and Withbroe (1981) studied nine bright points using EUV spectroheliograms from the HCO experiment on Skylab. They found occasional brightening of the points in the MgX 625A line, which forms at a temperature of 1.2 x 10^6K. A typical event consists of an intensity pulse of a factor of two within 5 minutes. The data suggest that bright "points" consist of small internal structures of varying brightness. Calculations of cooling rates indicated that coronal heating in bright points is intermittent, and the authors suggest that the heating is due to twisting of the magnetic loop by granular motions. In larger coronal bright points (and perhaps in the large-scale quiet corona) the frequency of brightenings is so high as to appear continuous.

Thus the bright points, because of their small size, may reveal a type of intermittent heating that is prevalent, but more difficult to detect in larger coronal structures.

Similar results have been obtained by Kundu and Schmahl (1987). They observed coronal bright points at 6 cm and 20 cm with the VLA, for a period of 10 hours. The spatial resolution attained was 3.9" at 6 cm and 12.5" at 20 cm, with a time resolution of 10 minutes. They confirm that the bright points overlie magnetic dipoles and fluctuate in brightness within minutes.

Another type of transient (the "jet") was discovered by Brueckner and Bartoe (1983) in Carbon IV spectra obtained by HRTS I, II and III. A jet is perhaps 5 arc-seconds wide, accelerates upward to speeds as high as 400 km/s, and has a lifetime of about a minute. A large jet is estimated to carry a kinetic energy of 3x10^{26} ergs. The spatial density and birthrate of jets is highly uncertain, but if we adopt the observed geometric mean birthrate of 25 \text{ s}^{-1} over the whole solar surface, the energy flux to the corona is 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}, comparable to the required amount.

However, the most recent statistics on the spatial density of jets (from Spacelab II) imply a much smaller energy flux. Porter et al. (1987) have reported "microflares" in the quiet Sun's magnetic network that may correspond to the jets recorded in the HRTS spectra. The microflares were observed in Carbon IV spectroheliograms (1548A) with the UVSP on the Solar Maximum Mission Satellite.
Some microflares are short-lived (< 2 minutes), while others last as long as an hour. Sizes range from less than 6 arcseconds to as much as 30 arcseconds. Intensity fluctuations by factors of 2 to 7 have been observed, within a few minutes. The sites of the microflares coincide with the neutral lines of magnetic dipoles, raising the possibility that they are smaller versions of coronal X-ray bright points.

The existing data on microflares and on jets are too sparse to allow a positive identification of one with the other. However, the authors suggest that their lifetimes and spatial scales are similar, and that the higher sensitivity of the HRTS experiment accounts satisfactorily for the difference in areal density observed by the two experiments. No estimates have been reported yet of the energy flux such microflares might inject into the upper atmosphere.

These recent observations suggest that small-scale, explosive events occur, over a wide range of spatial scales, within magnetic dipoles that are distributed broadly over the solar surface, but are possibly concentrated in the photospheric magnetic network. The relevance of such events to global chromospheric and coronal heating remains to be established. The observed events may be by-products of a heating process that occurs in the corona, i.e., they may be an effect rather than a cause of heating.

However, the possibility that the entire corona is heated by a multitude of many small sporadic events is attractive and deserves much further study.

REFERENCES

Parker, E. N. 1987, these Proceedings.