CORONAL HOLES AND SOLAR MASS LOSS

Jack B. Zirker
Sacramento Peak Observatory*

During the declining phase of solar activity, and possibly at other phases, solar mass loss occurs in the form of high speed streams in the solar wind. These streams originate in low density, low temperature coronal regions, called "holes." The physical properties of the wind streams and the holes will be discussed. Preliminary models for the three-dimensional structure of the wind, at different phases of the solar activity cycle, will be sketched. Remaining problems in developing a self-consistent theory of solar wind acceleration will be reviewed.


During past years we have learned a great deal about the origins of the solar wind. In particular, there has been an explosion of knowledge about the influence of the structure of the solar corona and its large-scale magnetic field on the spatial and time variations of the wind. At the present time we are looking forward to the flight of the International Solar

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Polar Mission, sometime in the early 1990s, to refine and extend the knowledge that we’ve gained in the past decade. It is an appropriate time in which to review what we know and where we are headed. The understanding that we gain from the Sun will hopefully serve as a guide toward understanding solar mass loss in other stars.

This lecture has three parts. In Part I, I will summarize some of the salient features of the solar wind, particularly, properties of the high speed wind streams that seem to be among the most important and most easily understood aspects of the wind. In Part II, I will review the properties of the coronal holes, where all the high speed wind and perhaps all the wind, originates. In Part III, I will try to sketch some of the most important questions that remain to be answered and indulge in a little speculation. The reader who is interested in more details on this whole subject should look into the references listed at the end of this chapter (1).

I. THE SOLAR WIND
A. The Average Wind

We must always keep in mind that nearly all the in situ measurements we have of the solar wind were taken in or near the ecliptic. Some interplanetary probes, such as the Helios experiment, and the Mars and the Jupiter probes, have sampled the wind at large distances from the earth but still within the ecliptic plane. Most of the heliosphere remains as unknown territory.

The solar wind group at the Los Alamos Scientific Laboratory has collected one of the longest and most homogeneous sets of direct measurements of the wind presently available. They find that the speed of the solar wind near the earth fluctuates with timescales of minutes to days. Figure 1, drawn from their data (2), shows a histogram for the wind speed for each year between 1962 and 1974. The wind speed ranges between 250 and 800 km/s. In years of declining and near minimum solar activity, such as 1962, 1964, 1973 and 1974, very high wind speed (above 650 km/s), is observed more frequently. As we shall see a little later on, these high speeds occur in discrete streams in the solar wind. Except for the appearance of this high speed tail, there doesn’t seem to be a very systematic variation of the average wind speed throughout the solar cycle. The Los Alamos group has examined the properties of wind with high, average and low mean speeds. "Low" is defined as anything below 350 km/s and "high" is anything above 650 km/s. Table 1 summarizes their results (3). The first point to notice is that the average proton flux
Figure 1. Distribution of wind speed over a solar cycle. The arrows indicate annual means. Reprinted courtesy J. Gosling et al. and Journal of Geophys. Res., © 1977 The American Geophysical Union.
### TABLE 1*

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>AVERAGE</th>
<th>LOW SPEED</th>
<th>HIGH SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>σ</td>
<td>% VAR</td>
</tr>
<tr>
<td>N (cm⁻³)</td>
<td>8.7</td>
<td>6.6</td>
<td>76</td>
</tr>
<tr>
<td>V (km s⁻¹)</td>
<td>468</td>
<td>116</td>
<td>25*</td>
</tr>
<tr>
<td>NV (cm⁻²s⁻¹)</td>
<td>3.8x10⁸</td>
<td>2.4x10⁸</td>
<td>63</td>
</tr>
<tr>
<td>Φᵥ (degrees)**</td>
<td>-0.6</td>
<td>2.6</td>
<td>430</td>
</tr>
<tr>
<td>Tᵥ (⁰K)</td>
<td>1.2x10⁵</td>
<td>0.9x10⁵</td>
<td>75</td>
</tr>
<tr>
<td>Tᵥ (⁰K)</td>
<td>1.4x10⁵</td>
<td>0.4x10⁵</td>
<td>29</td>
</tr>
</tbody>
</table>

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**Angle between wind vector and earth-sun line. Φ > 0 means corotation with sun.
near the earth is about the same within a factor of two for all conditions of wind speed. Secondly, the percentage variation about the mean for all quantities, with the possible exception of wind speed, is the lowest for high speed wind. In other words, the high speed wind represents the most stable, uniform and structureless type of wind known and in this sense, is easiest to interpret. Near the Earth, and indeed at distances greater than some tens of solar radii from the Sun, the wind is a collisionless plasma so that the electron and proton temperatures are not equal. The number density of helium ions (alpha particles) represents 4 to 5% of the total, independent of the value of the maxium speed. This table doesn't show a rather curious property at low wind speed, however: namely, that the helium abundance can very radically from one low speed interval to another and even during a particular interval. The full range covers two orders of magnitude.

We can now estimate the average mass loss from the Sun, assuming isotropic flow. Using the product of \( n \sigma \) from Table 1, we find a value of \( 2 \times 10^{-14} \) solar masses per year, an amount which is utterly trivial for the evolution of the Sun. A more interesting quantity is the angular momentum loss of the Sun due to the wind. The wind flow is not quite radial from the Sun but appears to flow from a direction making an angle between 1 and 2 degrees either east or west of the Sun. Feldman et al. (3) caution us about relying too much on their measurements because they contain systematic uncertainties greater than the measured deviation from zero and because all the measurements relate to the ecliptic and there may be significant variations in wind direction with solar latitude. Nevertheless, even a rough estimate suffices to illustrate the possible importance of this effect. The rate of angular momentum loss is \( n \Sigma \mu r \), where \( \mu \) is the proton mass and \( r \) is the astronomical unit. If we select values from Table 1 corresponding to the average wind, assume that the flow direction is one degree east of the radial direction and integrate over a 60° belt of latitude centered on the solar equator, we find that the wind exerts a braking torque on the Sun of \( 3 \times 10^{38} \) dyne cm. Since the angular momentum of the Sun is of the order of \( 2 \times 10^{48} \) dyne cm sec, the wind torque is sufficient to brake the solar rotation in about \( 7 \times 10^{17} \) s or \( 2 \times 10^{10} \) years. This is only a few times longer than the age of the Sun.

As we said before, this calculation is subject to many uncertainties, but it does suggest that the wind could have been a significant factor in spinning down the Sun.
B. High Speed Wind Streams

As we have seen above, the solar wind in the ecliptic reaches speeds of 800 km/s a small fraction of the time. The flight of Mariner 2 to Venus in 1962 provided data that showed that these high speed events are organized in streams flowing nearly radially from the Sun and rotating with the Sun with the equatorial rotation period of 27.1 days. Moreover, the rotation of these streams past the Earth was highly correlated with the recurrence of geomagnetic storms. Feldman et al. (4) have summarized the physical properties of 19 high speed streams observed between 1971 and 1974 by plasma analyzers aboard IMP 6, 7 and 8. They defined high speed as anything above 650 km/s and found the following properties.

First, the streams have an average full width at half maximum of 90° in solar longitude. In other words, the most common pattern they saw was a system of four quadrants with alternating high and low speed wind. Within a stream, the interplanetary magnetic field is unipolar, directed either predominantly inward or outward from the Sun. These two results remind one strongly of the sector structure of interplanetary magnetic fields, first described by Wilcox and Ness (5). The high speed streams overlap but do exactly coincide with the magnetic sectors. Streams last anywhere from one to 18 rotations and are most stable and persistent during the declining phase of the solar cycle, namely 1973 to 1974.

Geophysicists have been aware since 1934 that geomagnetic storms occur with a period of 27 days, which implies a solar influence. Bartels (6) gave the name "M-region" to the source on the Sun of this influence. The Mariner 2 results showed that high speed streams are the connecting link between the Sun and the Earth. But the question remained open during the early 1970s as to the source of the streams. Statistical studies pointed to areas between active regions on the Sun. A final convincing identification was made by Krieger, Timothy and Roelof in 1973 (7). They identified a coronal hole as the source of a high speed wind stream.

Thus, coronal holes would be interesting for no other reason than that they are the source of high speed wind. But in addition, they display a number of other intrinsic properties which are interesting and challenging in the context of stellar physics. We turn now to a discussion of the holes themselves.

II. CORONAL HOLES

Figure 2 shows a large coronal hole observed from Skylab

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Figure 2. The corona photographed in X-rays from Skylab. Coronal hole No. 1 is the black north-south lane. Reprinted courtesy A. Krieger of American Science and Engineering.

with an X-ray camera built by the American Science and Engineering, Inc. The camera records X-rays in wavelength bands 44 to 60 Å, which are produced by thermal bremsstrah-

lung at temperatures between 1 and 3 million degrees. Although Skylab produced perhaps the best observations ever made of coronal holes, their existence was first recognized by Waldmeier (8) around 1957, who noticed persistent and recurring gaps in the monochromatic emission line corona recorded with his coronagraph. Around 1968, the Harvard experiment on OSO-4 recorded large dim areas in the corona as observed in the Mg X line at 625 Å (9), and later in OSO-7 the same regions appeared on the disk in the Fe XV line 284 Å (10). Synoptic observations of the white light corona made by the High Altitude Observatory with a K-coronometer over a decade, clearly show the evolution and birth of coronal holes (11). Thus a long history of observations that hinted at the existence of large dim regions in the corona preceded Skylab but the opportunity to observe these regions continuously on the disk for nine months from Skylab made all the difference in understanding their properties.

A. Empirical Properties

The Skylab data confirmed the assertion of Krieger, Timothy and Roelof (7) that solar streams originate in coronal holes. Of 69 central meridian passages of coronal holes between solar latitudes of ± 30°, 75% were found to be associated with streams near Earth, 9% possibly associated and 16% not associated. The lifetime of coronal holes is also consistent with the hypothesis that they are the coronal roots of high speed wind streams. Of the nine coronal holes present during Skylab, two had lifetimes shorter than three rotations, four lasted more than five rotations and three had lifetimes of ten rotations or more. The solar poles were covered by coronal holes throughout Skylab. The area of these polar holes shrank and nearly disappeared with the rise of solar activity toward the maximum in 1980. Coronal holes that extend in a north-south direction, such as the one shown in Figure 2, seem to be
fairly uncommon. With the rise of solar activity since 1974, new coronal holes have appeared at mid-latitudes, are small and last at most a few rotations.

Coronal holes contain a unipolar magnetic field which diverges rapidly with increasing height. This conclusion is based upon calculations rather than measurements of the coronal magnetic field. Coronal magnetic field measurements are still in their infancy, although a group from the High Altitude Observatory, resident at the Sacramento Peak Observatory, is attempting to measure them throughout the flight of the Solar Max Mission. In order to calculate magnetic field lines in the corona, one begins with global measurements of the line-of-sight component of the magnetic field over the photosphere and assumes that no electrical currents flow in the corona. It is then possible to solve Laplace’s equation for a potential field between the photosphere and an imaginary spherical potential surface commonly placed at about 2 solar radii from the Sun’s center. The tangential component of the magnetic field is assumed to vanish on this outer boundary; the measured field is taken as a condition on the inner boundary. Figure 3 illustrates some typical results of this technique. Only field lines that cross the outer spherical surface have been drawn in this figure, i.e., all field lines that loop back to the photosphere inside the spherical surface have been suppressed. This figure suggests that all field lines that extend far out into interplanetary space across the outer spherical boundary, are rooted in coronal holes. (This may be an artifact of the calculation, however.) The corona can thus be divided into closed magnetic field regions from which no wind escapes and open magnetic field regions rooted in coronal holes from which all the wind escapes. The accuracy and validity of these potential magnetic fields is open to question, but they do seem to outline at least the large-scale coronal structures that can
Figure 4. Rotation periods of photosphere, sunspots, emission line corona and coronal holes. Reprinted courtesy A. Krieger and the Colorado Associated University Press.

be seen in white light during eclipses, for example.

Note the rapid divergence of the field lines. Within the inner corona, the magnetic energy density is larger than the gas energy density so that the magnetic field strength is sufficient to confine and channel the gas flow. The diverging geometry provides a kind of Laval nozzle whose shape, in combination with the radial variation of energy and momentum deposition, controls the acceleration of the wind. Such diverging geometries tend to decrease the height of the critical point in solar wind solutions, as Parker pointed out in the early 1960s, and as Kopp and Holzer have confirmed more recently (12). Finally, coronal holes do not seem to partake of the differential rotation of the photosphere. They rotate instead nearly as rigid bodies as Figure 4 illustrates. This property has raised all sorts of questions regarding the existence of a deep-seated rigidly rotating source of magnetic flux (13).

The solar chromosphere underlying coronal holes differs

very little from that under normal quiet coronal regions. The only perceptible difference is a slight reduction in contrast of the chromospheric network as seen in the He I line at 10830 Å.

B. Derived Properties

The High Altitude Observatory operated an externally occulted coronagraph aboard Skylab that recorded pictures of the white light corona continuously. Since the white light originates from photospheric light scattered by free coronal electrons, the distribution of electrons can be determined from an analysis of the intensity and polarization of the white light corona. Munro and Jackson (14) carried out such an analysis for the hole at the north pole of the Sun. By comparing a series of photographs taken during several rotations, they were able to determine the geometry of the boundaries of the hole. The hole has the shape of an expanding funnel centered over the polar axis. Assuming cylindrical symmetry, they were then able to derive a three-dimensional model for the electron density distribution within the hole. Their results for the axes of the hole are shown in Figure 5. Next, assuming that the solar wind stream with a typical proton flux of $3 \times 10^8$ cm$^{-2}$ s$^{-1}$ escapes from the hole, and using the equation of continuity, they determined the velocity profile along the hole’s axis, also shown in Figure 5. The velocity increases from about 80 to 450 km/s between 2 and 5 radii. Since the velocity of sound is only about 150 km s$^{-1}$, the critical point of this flow lies within this distance range, i.e. the principle acceleration of the solar wind in the hole occurs close to the solar surface. Without further assumptions, they could not determine the temperature profile in the hole, but the fact that the maximum acceleration of the wind occurs below 2.5 solar radii suggests that energy and/or momentum is being deposited to at least this height.

The spectroscopic data derived during Skylab have been thoroughly analyzed in an attempt to determine the run of
temperature and pressure and the energy balance throughout a hole. These attempts have been partially successful in understanding some of the major attributes of the hole. For example, the hole is dim at all wavelengths, primarily because the electron density is less by a factor of three than in a normal region at the same height. The spectra also imply a much lower temperature at a given height in a hole than in its neighborhood. At a height of .1 R⊙ for example, Mariska finds a temperature of 1 to 1.1 million degrees, lower by as much as 600,000 degrees than the neighborhood.

The low temperature at a given height implies a smaller temperature gradient in the hole and as a result the heat conducted downward through the transition zone is lower by a factor of four than in the neighboring quiet regions. Table 2 shows this result as well as other terms involved in the energy budget of a hole and a normal closed field, coronal region. Notice that the solar wind loss (extrapolated to the Sun from measurements near Earth) greatly exceeds downward heat conduction in the hole. Notice also that the energy loss associated with downward enthalpy flux may be the principle loss in both kinds of regions (15). At this time we have no reason to believe that the total energy supply to a coronal hole is any different than that to its neighborhood but the distribution of losses among the different mechanisms may differ in the hole and in its neighborhood.

The spectroscopic data from Skylab were insufficient to establish the maximum temperature in a hole. This quantity is very important if we are to understand the mechanisms that accelerate the solar wind. In the classical Parker theory, it is the gradient of the gas pressure that accelerates the wind. The wind speed near Earth rises monotonically with the maximum coronal temperature and with the distance over which maximum temperature prevails. In the most favorable case, an isothermal wind, a temperature of about 2.5 million degrees would be needed to produce a speed as high as 800 km/sec. While we are not sure of the maximum temperature in a coronal hole, we can be sure that the stream is not isothermal, so that a temperature in excess of 2.5 million would be needed.

Recently, the High Altitude Observatory and Center for Astrophysics collaborated in an experiment to measure the proton temperature in a coronal hole from 1.5 to 3 solar radii (16). The proton temperature was derived from the profile of the Lyman alpha radiation that originates in the chromosphere and is scattered from neutral hydrogen atoms in the corona. Despite uncertainties due to the presence of turbulent motions and systematic outflow, the most probable proton temperature lies between 1.4 and 1.8 million degrees at a distance of 2
TABLE 2

Coronal Energy Losses (erg cm^{-2} s^{-1})

<table>
<thead>
<tr>
<th>Loss</th>
<th>Coronal Holes (Open B)</th>
<th>Quiet Corona (Closed B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Conduction</td>
<td>(6 \times 10^4)</td>
<td>(2 \times 10^5)</td>
</tr>
<tr>
<td>Radiation</td>
<td>(10^4)</td>
<td>(10^5)</td>
</tr>
<tr>
<td>Wind*</td>
<td>(7 \times 10^5)</td>
<td>(&lt; 10^5)</td>
</tr>
<tr>
<td>Subtotal</td>
<td>(8 \times 10^5)</td>
<td>(3 \times 10^5)</td>
</tr>
<tr>
<td>Enthalpy (Transition Zone)</td>
<td>(2.5 \times 10^5 - 2.5 \times 10^6)</td>
<td>(2.5 \times 10^5 - 2.5 \times 10^6)</td>
</tr>
<tr>
<td>Total</td>
<td>(10^6.0 - 10^6.5)</td>
<td>(10^5.7 - 10^6.4)</td>
</tr>
</tbody>
</table>

*Gravitational, kinetic and enthalpy energy losses.
radii from the Sun’s center. This recent result reinforces a
suspicion that arose during analysis of the Skylab data, namely
that the temperature in a coronal hole is too low to produce
the observed acceleration at low heights and the final wind
speed near Earth. There is now reason to think that momentum,
in addition to energy, is being deposited throughout a coronal
hole and helps to accelerate the wind stream. This momentum
deposition might occur, for example, by a gradient in wave
pressure due to acoustic or MHD waves that also deposit energy
at these heights. These ideas have been explored theoretically
by a number of theorists but a consistent model of wind stream
heating and acceleration by waves has not yet appeared.

One of the complications in building such a model is that
the classical theory of heat conduction does not apply to a low
density plasma like the wind. A diffusive conduction theory is
valid where the mean free path of electrons is small compared
to the distance over which the temperature changes
appreciably. This condition breaks down within 2 or 3 solar
radii of the Sun’s center in a wind stream. There is no
generally accepted theory of heat transport to replace the
classical theory, however.

C. A Model for the Heliosphere Near the Minimum of Solar
Activity

As we have seen, the solar wind is dominated by long-
lived, stable wind streams from a relatively small number of
holes during the declining phases of solar activity. During
this time, the polar holes have reached their maximum areal
extent and some of the largest holes seen at mid-latitudes, are
simply equatorial extensions of these polar holes. These
simplifying conditions have led to the construction of the
schematic model to describe the three-dimensional wind just
before solar minimum.

The basic insight derives from an investigation by Wagner
(17). He correlated the sign of the interplanetary magnetic
field with the appearance of recurrent coronal holes at
different latitudes, as observed in the Fe XV line from OSO-
7. Wagner found that the best correlation existed between the
interplanetary magnetic field in the ecliptic and coronal holes
at solar latitudes between 40 and 80°. In short, the magnetic
field observed near the Earth seemed to be rooted near the
polar regions of the Sun. Since the wind streams follow the
diverging field lines near the Sun, Wagner’s result implies
that the wind near the Earth is dominated by polar flows from
the Sun.

This result was extended by Hundhausen, who examined the
correlation between wind speeds near the Earth and the recurrence of high latitude polar holes that are extensions of the polar holes. Once again, a high correlation was found. Hundhausen was led to the highly simplified model of the heliosphere shown in Figure 6. Just before solar minimum, the large-scale magnetic field of the Sun can be represented as a modified dipole whose axis is tipped with respect to the solar rotation axis. Large coronal holes cover both of the solar poles. Magnetic field lines do not loop directly from one solar hemisphere to the other but approach each other asymptotically along a neutral current sheet that lies along the equator of the magnetic dipole. Near the solar surface
Figure 7. A comparison of coronal brightness (proportional to $N_\alpha$), coronal magnetic polarity and the properties of wind streams near Earth. Polar holes influence wind flow in the ecliptic. Reprinted courtesy of A. Hundhausen and the Colorado Associated University Press.

This current sheet extends from a belt of closed magnetic field that runs around the Sun near the solar equator. Because the field lines are closed, the electron density in the belt is high and it appears bright in white light. Figure 7 is a map of the coronal white light brightness for a full rotation toward the end of the Skylab mission. It shows this closed belt very well. Because the belt and its extension, the magnetic neutral sheet, are tipped with respect to the ecliptic, solar rotation sweeps alternately portions of the northern and southern polar coronal holes into the line of sight from the Earth. As a result, we detect at Earth, first a high-speed stream with a magnetic polarity characteristic of the northern hemisphere, then slow wind as the closed magnetic belt comes into the line of sight, and then a high speed wind stream, with a characteristic southern hemisphere magnetic polarity. These relations are shown in Figure 7, and are compared there with the actual wind streams and magnetic polarity observed at Earth during this rotation. The model seems to characterize the heliosphere fairly well under these extremely simplified circumstances prevalent around solar minimum. Naturally, the situation gets much more complicated as solar activity builds up and large areas of the Sun are covered with active regions at mid-latitudes. We hope that the international Solar-Polar Mission will be able to test this simplified model and that it will fly near solar minimum when interpretation is easiest.

III. SOME QUESTIONS FOR THE FUTURE

At this stage, we are left with a long list of questions regarding the origin of the solar wind and the structure and evolution of coronal holes. In this last section I’ll discuss a few of these.
Much of the discussion above has concerned the high speed wind, partly because it is steadier and more uniform in its properties and partly because it is more challenging to the theorist. To make further progress in modeling the high speed streams, we obviously need more observations to guide the theory. We would like to know the profiles of temperature and velocity near the critical point between 2 and 10 radii. As we have seen, a start has been made to get this information, using the scattered resonance line of hydrogen. Mechanical waves are probably important in accelerating the wind. We need to get an observational handle on them. What is the wave flux as a function of height? What are the characteristic wave modes? What is the height dependence of the deposition of energy in momentum? To get better stream models, we need to incorporate some new physics, such as a refined theory of electron heat transport in diffuse gases.

With all this emphasis on the high speed wind, we must not forget the slow wind. At this point I think it's fair to say that we don't have a clear idea where on the Sun the slow wind originates. One possibility is near the edges of the high speed streams. Note and his colleagues (18) have shown that the peak speed within a wind stream increases with the area of a coronal hole associated with it. This finding is consistent with MHD calculations that show that the field lines are more closely parallel in the middle of a hole, and diverge rapidly toward the edges (19). The large increase of cross-sectional area with height that such field line divergence implies, would tend to slow down the wind near the edge of a hole. But this is probably not the whole story. There are unquestionably other places on the Sun than coronal holes where open field lines appear and there are opportunities for the flow to be modified with increasing distance from the Sun. We don't really understand how this occurs and how it may bear on the origin of the slow wind.

We are just beginning to piece together information on the evolution of coronal holes throughout the solar cycle. Broussard and his colleagues collected all the X-ray and XUV solar images that they could find throughout the period 1963 to 1974 (20). They found that during solar minimum, polar coronal holes are prominent and decrease as activity increases. At solar maximum, coronal holes occurred poleward of the sunspot belts and in the equatorial region between them. The holes were small and lasted only a few rotations. Information on the development in coronal holes during the present solar cycle, Cycle 21, is building up (21).

We obviously need more information about the morphology of coronal hole development before we can tackle the larger
question of the origin and the pattern of development of holes. To quote Harvey and Sheeley (22), "Non-polar holes form whenever the magnetic flux from bipolar magnetic regions interacts to produce a large region of locally unbalanced flux. The term 'locally balanced' is not precisely defined and the burden to explain the origin of holes is shifted to explaining why magnetic fields erupt, interact and dissipate in the way that they do." This statement accurately represents our state of ignorance at the present time. We have only phenomenological models to explain both the pattern of development in latitude and the possible organization in longitude that coronal holes seem to display throughout the solar cycle. For example, Svalgaard and Wilcox (13) have observed magnetic patterns that last for more than one sunspot cycle and suggest that they arise from a long-lived subsurface structure, possibly certain modes of the solar dynamo.

What we have learned so far about the structure of the heliosphere and its evolution throughout the activity cycle emphasizes the essential role of the large-scale magnetic field in channeling the gas flow and the energy fluxes. Is it possible that all the complications I've described in this chapter, would disappear in an early type star, where magnetic fields are presumably absent or weak? I doubt it. Even such stars show rapid fluctuations in chromospheric lines like H\textalpha{} (23) and possibly also in X-rays. I'd be surprised if their winds did not fluctuate in space and time. Possibly some analog of a coronal hole (i.e. large-scale inhomogeneities in the lower atmosphere) exists.

References

(1) General references:


