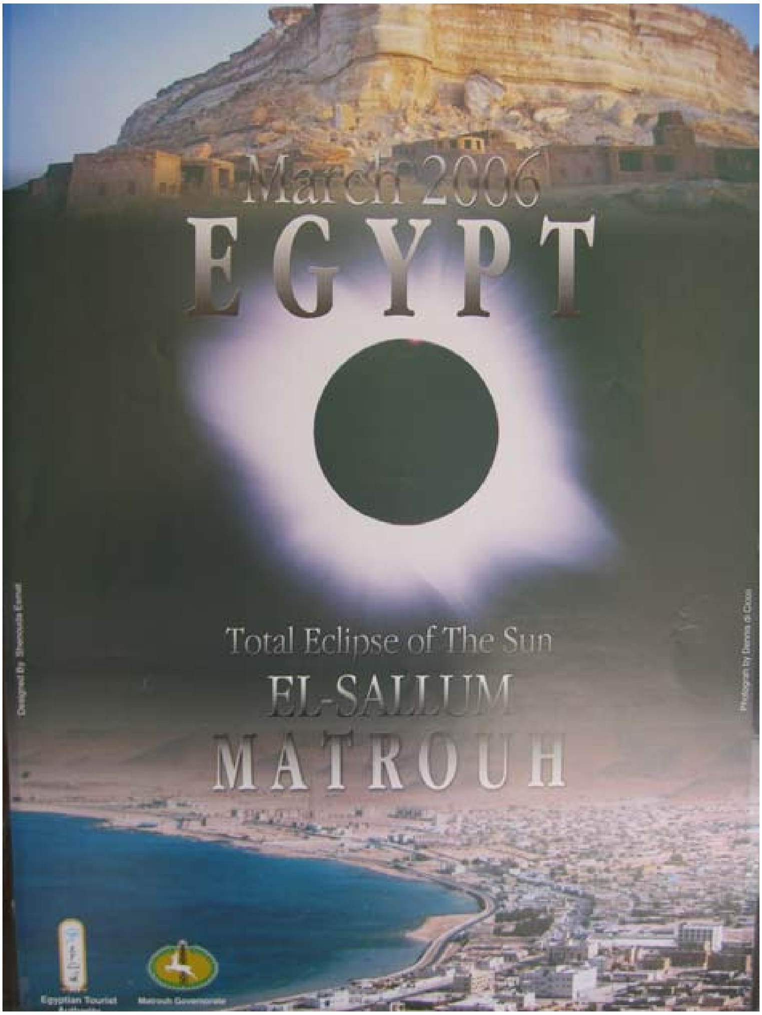
Session 4

Large-scale Coronal Structure – space and ground-based Observations



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https://doi.org/10.1017/S1743921306001876 Published online by Cambridge University Press

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https://doi.org/10.1017/S1743921306001876 Published online by Cambridge University Press

Solar Activity and its Magnetic Origin
Proceedings IAU Symposium No. 233, 2006
V. Bothmer & A. A. Hady, eds.

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doi:10.1017/S1743921306001876

A Review of White Light Streamers at the End of Cycle 23

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Abstract. This is a brief review of the quiescent large scale visible corona with an emphasis on the origin, structure and role of streamers in the solar wind. The review is mostly based on results from the last 10 years of the SOHO mission and the goal is to provide a coherent picture of what is known about streamers at the end of the current cycle.

Keywords. Sun: activity, Sun: corona, Sun: magnetic fields, solar wind

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This presentation is given on the occasion of a solar eclipse, one of the most spectacular natural phenomena on Earth. For ages, natural eclpses were the only way to observe with our own eyes the corona, the faint outer atmosphere of the sun. The aesthetic pleasure of the phenomenon aside, visible observations of the extended corona carry significant scientific value. In the last 200 years, numerous expeditions have trekked into remote locations, fought against limited resourses, unpredictable weather and capricious instrumentation to obtain a limited set of images over the few minutes that a total eclipse may last (Zirker 1995).

But advances in coronal physics require long-term observations of the corona. Such observations have been made possible by specialized telescopes, called coronagraphs, which block the light from the solar disk to create an artificial eclipse. Space-based coronagraphs in particular allow continuous observations of the corona for years. The most recent example of space-based instruments are the LASCO coronagraphs (Brueckner *et al.* 1995) aboard the SOHO mission. LASCO observations have contributed significantly in our understanding of the corona over the last 10 years. We now know a great deal about the physics, morphology and evolution of the corona which is impractical to summarize in such a short reviewh. Interested readers can find more information in dedicated textbooks (Golub & Pasachoff 1997; Aschwanden 2004). Here I give only a brief overview of some key concepts of the large scale corona and describe what is known about the origins and structure of the building blocks of the corona, the white light streamers, and their role in the solar wind.

1. General Properties of the Large Scale Corona

Although the term "large scale corona" usually implies the visible corona, there exist several other "coronae" depending upon the mechanism responsible for their emission. The visible corona or *K-corona* is created by the reflection of the photospheric light by the coronal electrons through the Thomson scattering process. The same photospheric light is reflected by larger, dust particles to create the *F-corona*. But the F-corona is actually a nuiscance for coronal studies because it obscures the visible corona above a few solar radii and its removal becomes an integral part of coronal data analysis. The same dust particles also radiate themselves in the infrared to form the *T-corona*. Finally, the coronal electrons can emit radiation at several spectral lines, from X-rays to the infrared. This

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so-called *E-corona* can be recorded over the whole solar disk and provides some of the most spectacular images of the sun. It is described in more detail in van Driel-Gesztelyi (2006). However, E-corona becomes extremely weak within a couple of radii above the surface. Here I focus only on visible light (K-corona) observations (Figure 1).

One of the fascinating aspects of coronal observations is its changing morphology with time. It varies from a relatively simple disk seen edge-on during solar minimum to a bewildering collection of ray structures all around the disk during solar maximum (Figure 1a). The dependence of the coronal morphology on the solar cycle reveals its magnetic origin as we will see in more detail later.

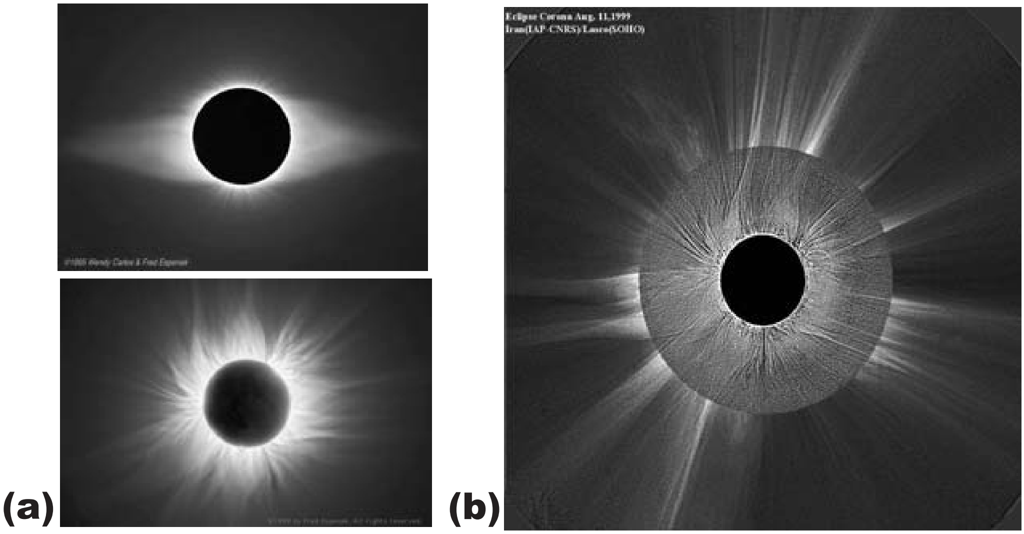

Figure 1. (a) Views of the large scale corona during solar minimum (top) and maximum (bottom) obtained during natural eclipses (courtesy of F. Espeniak). (b) Composite of images taken during the Aug, 11, 1999 eclipse. The inner image has been edge enhanced to reveal the fine structures. The outer image is taken by LASCO/C2 (courtesy of S. Koutchmy)

Because the coronal signal is just a reflection of the bright photospheric light, it is several orders of magnitude weaker than the solar disk. For this reason it is visible only when the sun is eclipsed. Atmospheric scattering limits the maximum height at which the corona is detected from the ground to about 3 R_{sun}. The best observations are obtained from space where the coronal signal is detectable out to 30 R_{sun} or more. Coronagraphs have been flown in sounding rockets since the 60s and on satellites since the 70s. The latest such instruments are the LASCO coronagraphs which observe the corona from 1 to 32 R_{sun} continuously since early 1996. A new set of coronagraphs and heliospheric imagers, called SECCHI (Howard *et al.* 2002), will soon be launched aboard the STEREO mission.

There are two methods of coronal observations. The first records the polarized brightness (pB) of the corona by obtaining observations through a set of polarizers in 3 or 4 different angles and then summing the resulting images appropriately (Billings 1966). This is the traditional technique for ground-based instruments because it removes the contributions of the F-corona and the sky background which are both unpolarized at heights below a few R_{sun}. However, the pB technique also removes the unpolarized part of the K-corona and is insensitive to coronal structures at large angles from the limb due to the angular dependence of the pB intensity (Vourlidas *et al.* 2000). For space-based

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observations, there is no need to resort to pB observations; there is no sky background signal to remove and the F-corona is polarized anyway above about 5 R_{sun}. The majority of the LASCO observations are total brightness observations which record a larger portion of the coronal brightness and are much more sensitive than pB observations to structures away from the solar limb. For this reason, total brightness observations can detect the faint coronal mass ejections along the Sun-Earth line.

Electron densities can be directly extracted from coronagraph observations of the quiet corona. Historically, they are estimated from the inversion of the equations that relate the electron density to the polarized brightness (van der Hulst 1950) for the simple reason that the pB equations are easier to invert. But pB observations from space are costly (in terms of on-board resources) to obtain and provide less information compared to total brightness observations as we have discussed already. On the other hand. there has been no way to access the density information in the large number of available total brightness observations from LASCO. The situation has changed recently. Hayes, Vourlidas & Howard (2001) demonstrated a technique for the inversion of total brightness observations with very good results. However, both inversion techniques rely on the assumptions of axisymmetric coronal density. This is a rather simplistic assumption about the true 3D structure of the corona, especially during solar maximum. More sophisticated approaches to derive the density of coronal structures have appeared over the last few years. Frazin (2000) and Frazin & Kamalabadi (2005) have demonstrated a tomographic tecnhique for reconstructing the density from a time series of coronal observations and Thernisien & Howard (2006) have developed a forward modeling technique that fits various structures (e.g., a streamer, a flux-rope) to observations and estimates the electron density based on a minimization scheme.

Besides the electron density, coronal physics are also controlled by the magnetic field. Both density and magnetic field vary during the course of the solar cycle and from active regions to quiet sun areas. The typical variation and magnitude of these quantities, is shown in figure 2. A more interesting quantity is the ratio, β, of the plasma pressure to the magnetic pressure, which reveals the relative importance of magnetic to plasma processes. This ratio is also shown in figure 2. The interplay between magnetic field and coronal plasma can be seen in the changing morphology of the corona with increasing

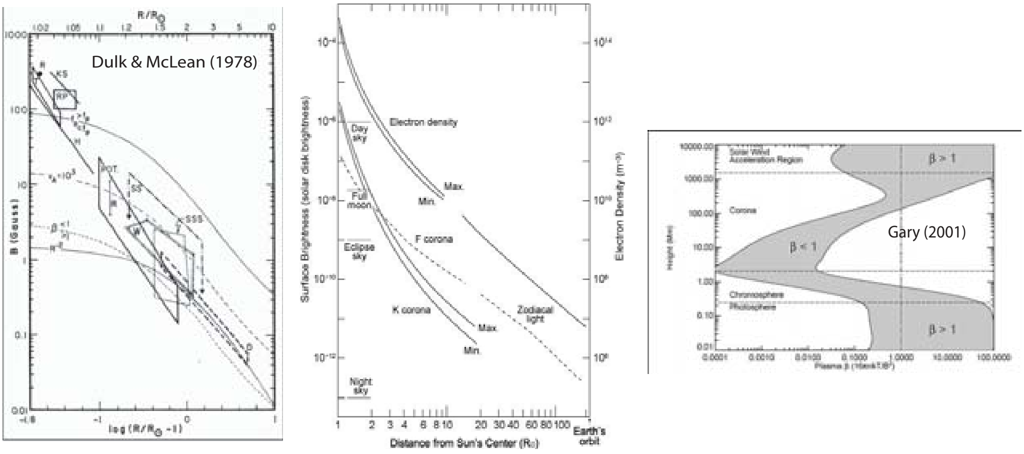

Figure 2. Plots of the magnetic field (left), electron density (right), and plasma β (bottom) as a function of height for typical coronal conditions.

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distance from the surface. Figure 1b is a composite of an inner corona image taken during the eclipse of August 11, 1999 and of the outer corona image taken with the LASCO/C2 coronagraph. The inner coronal image has been edge-enhanced to reveal fine features and shows that closed structures dominate whereas the outer corona consists of only filamentary or ray-like structures. As we will see later, this morphology reflects the transition from closed to open field regions.

2. Streamers: What are they?

Here we address the question of where does the structure of the corona come from. But first we need to introduce some terminology. The corona consists of helmet-like structures, the *streamers*, that progressively thin out to a single ray, or *stalk* (Figure 3). The location where the streamer transitions from a bulge to the stalk is called the *streamer cusp*. The *core* of the streamer is the inner part of the streamer under the cusp. Since the coronal appearance depends on the magnetic solar cycle, it is natural to assume that the streamer morphology is also influenced by the large scale magnetic field of the sun. Early on, Howard & Koomen (1974) proposed that the heliospheric current sheet could be an extension of the low corona streamer structure. Subsequent work has verified the connection between streamers and the neutral surfaces of the large scale solar magnetic field.

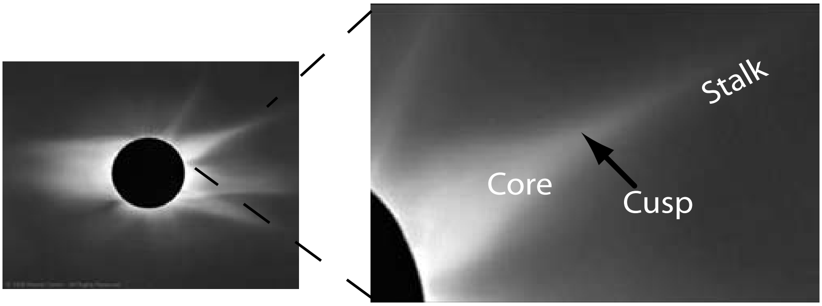

Figure 3. Definition of a streamer and other commonly used terms.

For example, Wang *et al.* (1997) and Wang, Sheeley & Rich (2000) have modeled the streamers as locations of bends of the magnetic current sheet. The magnetic field was extrapolated using the source surface model under the assumption that the source surface was located at a height of $\sim 2.5\ R_{sun}$ (Wang & Sheeley 1992). They assumed a plasma sheet of thickness of $3^\circ - 5^\circ$ around the magnetic current sheet. The brightness of these structures was then calculated via the standard Thomson scattering equations. As can be seen in figure 4, the simulation reproduces very well the appearance of the corona in the LASCO images.

An easy way to visualize the coronal evolution at different heights is provided by synoptic or Carrington maps (see $http : //lasco - www.nrl.navy.mil/carr\_map/agu2000.htm$ for details and examples). These maps are essentially 360° slices of the corona at a given height, put together in reverse time sequence. When we compare synoptic maps of the current sheet and the visible corona, the relation between the two becomes obvious (Figure 5). As the solar cycle progresses, the shape of the current sheet becomes twisted and the number of streamers increases but some of the observed complexity is missing from the simulated results (Fig. 5). The global photospheric magnetic field is the lower boundary for the coronal magnetic field extrapolations that determine the shape of the current

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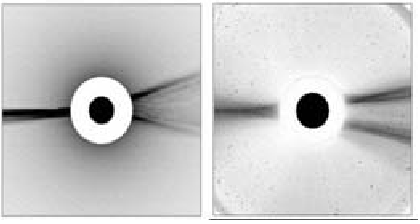

Figure 4. Comparison of streamer simulation (left) to LASCO observation (left) (Wang *et al.* 1997).

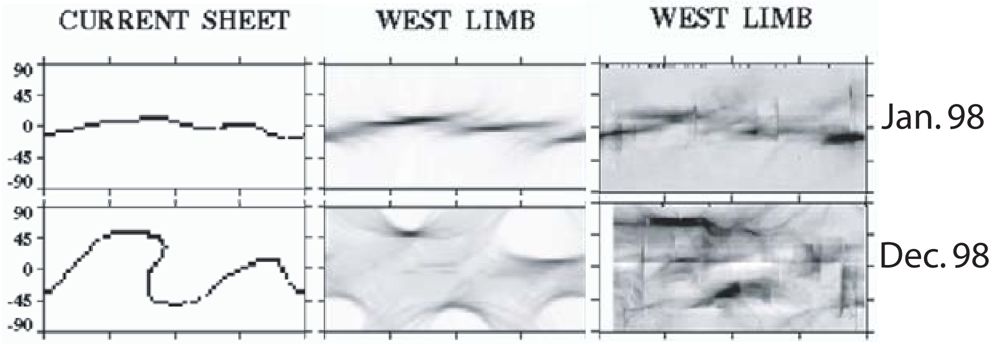

Figure 5. Evolution of the current sheet (left) and streamer structure (right) during the ascenting phase of cycle 23. The middle panel shows the simulated corona. The difference between the simulations and the observations can be attributed to the rapid photospheric changes that are not captured by synoptic magnetic field obsrvations (from Wang *et al.* 2000).

sheet. Since, magnetograph observations are only possible on the visible part of the disk, the backside magnetic field must be extrapolated from synoptic observations over a whole rotation ($\sim$ 27 days) assuming that the photosphere remains unchanged during that time. While this might be a good assumption during solar minimum, it is increasingly wrong as the cycle ascents. Then the global magnetic field extrapolations cannot capture magnetic changes that occur over the course of a few hours of even days and the resulting streamer predictions start to deviate from the observations in detail. However, one can use the white light observations to correct the magnetic field extrapolations. Saez *et al.* (2005) have followed this approach by introducing additional features on the predicted current sheet to match the LASCO synoptic maps. They showed that these photospheric field corrections were not arbitrary but corresponded to coronal features seen in EUV maps.

3. Small Scale Streamer Structure

An inspection of Figure 4 shows significant small scale structure within the streamers when they are seen face-on. A new forward-modeling technique developed recently at NRL was used to model this fine scale structure successfully (Thernisien & Howard 2006). The derived electron density profiles suggest that density within the streamer can vary by as much as a factor of 10. No satisfactory explanation for this effect has been proposed so far.

Filamentary structures low in the corona (below 2-3 R_{sun}) are nothing new. Careful analysis of eclipse observations by Koutchmy *et al.* (1994) has revealed threads with subarcsecond widths (i.e., a few hundred kms). These threads seem to be short-lived (lifetimes of 100s - 1hr) and some correlate well with rays seen in LASCO-C2 (Figure 1b). It

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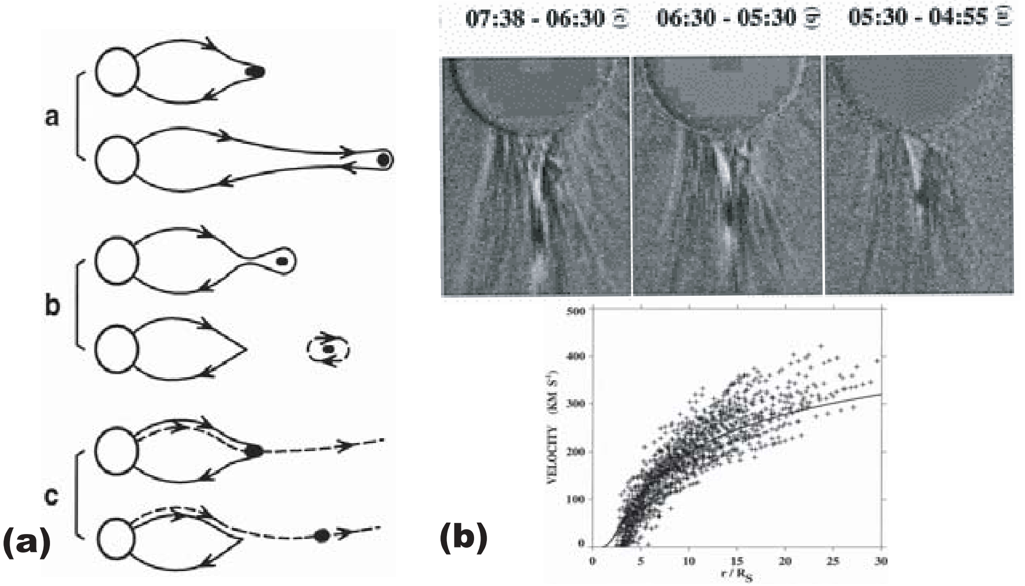

Figure 6. (a) Mechanisms for ejecting plasma from closed loops to the plasma sheet. (a) the plasma pressure overtakes the magnetic pressure and stretches the loop to infinity creating new open flux. (b) Reconnection at the loop top creates a new plasmoid. In a 3D configuration, this process creates a fluxrope with its ends attached to the sun. (c) Reconnection between a neighboring open field line and a closed loop ejects plasma along the open field line. In a 3D configuration, this process corresponds to footpoint exchange and no new open flux is created. (b) A typical white light blob observed in LASCO running difference images. Measurements of a large number of them agree with slow solar wind velocity profiles (from Wang *et al.* 2000).

is not yet clear what determines the small scales of these threads. It is plausible that some of the threads could be the white light counterparts of type-III radio bursts (Koutchmy 2004). To solve this mystery, long-term, extremely high-resolution observations of the inner corona are needed but no such mission is being implemented or planned for the near future.

Another population of extremely fine-scale coronal threads has been observed but this time at large distances from the sun. Woo & Habbal (1999) using radio scintillation experiments detected small scale density variations of the order of 20 km at 20-30 R_{sun}, which they attributed to coronal thread-like structures. These threads are assumed to be long-lived, ubiquitous and to trace open field lines from the quiet sun (Woo 2005; 2006). However, none of these structures has ever been traced down to the surface while it is difficult to explain how long-lived open field lines could extend radially from the surface to 30 R_{sun}. Also, the plasma β is becoming significant at such large distances from the surface and the electrons do not necessarily follow field lines. The existence of such fine structures in the solar wind and their relation to the inner corona threads and ultimately to the solar magnetic field remains an intriguing mystery.

4. Streamers and the Solar Wind

We know that the loops under the streamer cusp are closed confining the coronal plasma. At the same time the streamer stalks extend to large distances into the heliosphere. Where does their plasma come from? Figure 6 shows three possible ways that plasma from a closed loop can be ejected into the plasma sheet (Wang *et al.* 2000).

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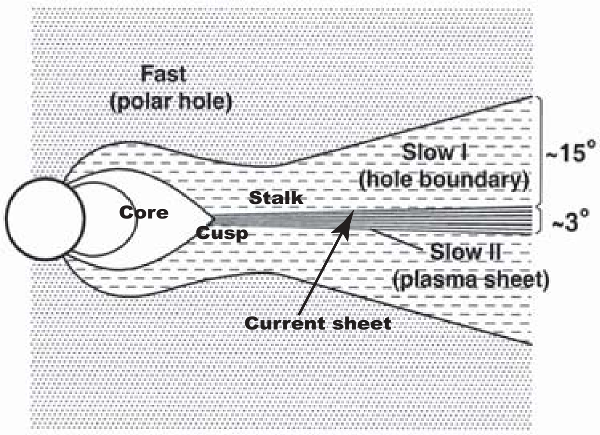

Figure 7. A graphical summary of our current understanding of the morphology of streamers and their role in the generation of solar wind (Adapted from Wang *et al.* (2000)).

Although all three processes are likely in the corona, the most common must be the last one (reconnection with open field lines at the streamer boundary) which does not destroy the streamer. If that is true, we should expect to see flows at the streamer boundaries. Indeed, one of the first UVCS observations revealed a depletion of OVI at the streamer core relative to the its boundaries (Kohl *et al.* 1997). The effect can be explained by gravitational settling of O VI in the core (Noci *et al.* 1997; Raymond *et al.* 1997), which implies that the plasma at the boundaries is streaming out.

Reconnection and flows at streamer boundaries are also invoked by MHD models of the slow solar wind (Einaudi *et al.* 1999; Karpen & Dahlburg 1997). The models predict that the velocity shear between the plasma near the current sheet relative to the plasma at the boundary will lead to MHD instabilities which in turn will give rise to turbulent eddies and plasmoids. Such structures have been observed with LASCO (Sheeley *et al.* 1997; Wang *et al.* 1997) as moving blobs along streamer stalks. Figure 6b shows an example of a typical LASCO blob and velocity measurements of a large number of them from Wang *et al.* (2000).

5. Conclusions

As the current cycle draws to an end and the next one begins with the availability of a new set of instruments (STEREO, SDO), it is useful to reflect on what we know about the visible corona and what questions we might be able to answer in the future. Our discussion can be summarized as follows:

- Streamers are Thomson scattered photospheric light by electrons located on folds of the large scale current sheet. The plasma sheet thickness is only $3° - 5°$ wide.
- The streamers have fine structure and observations both in the inner and outer corona reveal the existence of scales smaller that a couple 100 Kms.
- The plasma sheet is created by continous ejection of plasma via reconnection at the boundaries of the streamer.
- The slow solar wind seems to be generated by these plasma flows.

But several questions remain unanswered that could be addressed by the upcoming missions. For example,

- Where does the small scale streamer structure come from?
- What is the latitudinal extent of streamers?

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- What is the density structure within the streamers?
- How far in the heliosphere do streamers extend? Can we see their imprints at 1 AU?

Finally, figure 7 summarizes, in a graphical form, our discussion on the relation of white light streamers to the large scale magnetic field and the origin of the solar wind.

Acknowledgements

I want to thank the meeting organizers for their kind invitation to present this review. LASCO data analysis at NRL is supported by NASA grants.

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