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Structure and Dynamics of the Solar Corona

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Abstract.
We briefly review several aspects of the quasi-stationary structure of the corona in relation with the helio-sheet and, also, of the more confined by the magnetic field structures, including streamers, loops, jets, plumes and narrow linear rays. Both the temperature and the density structures are tentatively considered. Flows deduced from proper motions analysis are discussed. We did not include CMEs and flares in this presentation but other more radial and possibly highly impulsive beams with flows are discussed. We stress the importance of the variations of the coronal magnetic field and inferred currents in explaining the observed structures.

1. Introduction

Coronal structure and dynamics are topics inevitably related to the problem of the dissipation of the magnetic fields generated by the Sun: active-regions fields; quiet-sun network fields; polar fields; etc. These questions are broadly discussed by the solar, the stellar and the space physics communities. Here, we will concentrate the presentation on a few highly selected subjects, trying to go from the most general and well established observations and interpretations to the more controversial and unknown, hopefully representative, details. However, because the topic is huge and our knowledge and capability is limited like the amount of pages and illustrations of this presentation, this attempt will remain just a rather superficial coverage of what was requested. In particular very important work will have to be "forgotten" and we are sorry for that and apologize for not citing those works. For the same reasons, we will not touch pure spectroscopic diagnostics, nor CMEs nor flares.
Multi-wavelength investigations include SXR, EUV, W-L and Radio imaging and measurements, complemented by numerical simulations and modelings which greatly help to evaluate observations and ultimately will give the comprehensive answers to the problems. It is difficult to evaluate this rich material. However, when interpreting the data, **interrelationships** between the apparently well confined in magnetic configurations coronal structures and the evolution of the induced magnetic field, including effects due to both slow and fast events with electric currents, is a central question which does not have a simple answer. Naively speaking, we should have in mind that "structures are not just field lines...". The effect of the magnetic field can indeed be a relative deficit of plasma pressure, including structures like cavities in the corona, near prominences and above sunspots for example. This deficit is possibly due to a deficit of heating, see the review of P. Démoulin in the present Proceedings. Here, we will better keep a rather conservative position, without discussing the heating problems.

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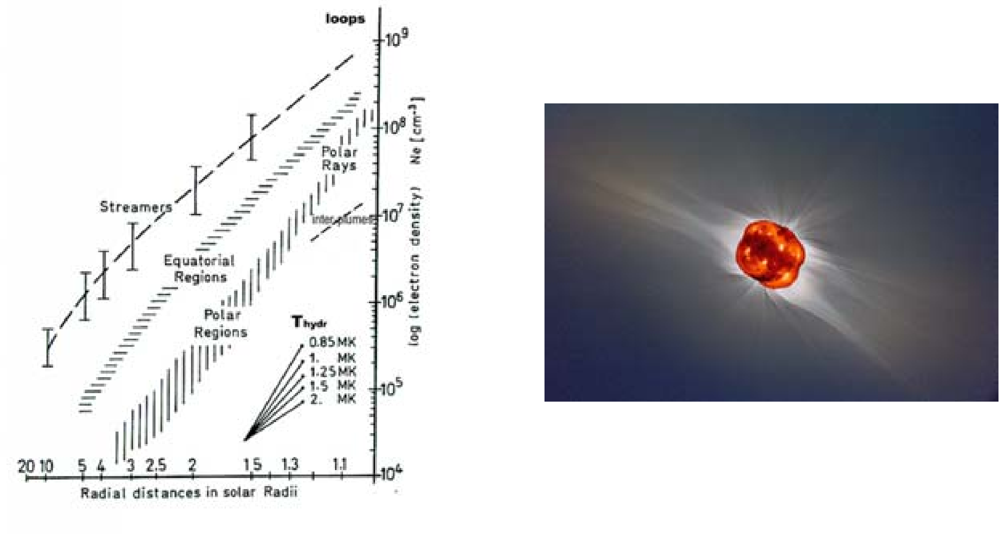

Figure 1.
(Left)Average electron densities Ne(r) measured inside the corona as a function of radial distances. Different typical parts of the corona are considered. Polar regions correspond to a minimum corona. Densities in polar rays (plumes), in coronal streamers and in threads (fine linear rays) are deduced using assumptions about their geometric parameters. The radial gradients directly correspond to hydrostatic temperatures shown at the bottom. From eclipse photometric works, see Koutchmy, 1994
(Right)Composite image of the typical extended W-L corona (eclipse observation by Ch. Viladrich- IAP on Feb. 26, 1998 in Guadeloupe) together with the X-Ray corona simultaneously observed from Yohkoh (ISAS). Equatorial streamers are apparently streched out by the wind and rays and plumes rise above both polar regions.

2. The quasi-stationary corona

To start the analysis of coronal structures and flows, taking into account the fundamental mass continuity equation, it is convenient to consider the approximation of a quasi-stationary corona, especially for large-scale structures like streamers. Additional assumptions used or at least suggested in the inner corona are: hydrostatic equilibrium; temperature variations; potential fields or force-free fields; heating functions; radiative losses, etc. Obviously, flare-induced processes, waves, CMEs, etc. are a priori excluded, although they cannot be completely ignored. A very important feature immediately appears when considering this approximation: the average radial variations of plasma pressure is well represented by the hydrostatic scale H, which means that the solar gravity g(r) is omnipresent everywhere in the corona (r is the radial distance measured in unit of solar radius). It is a fundamental "central" force which determines many phenomena in the corona, including the solar wind. Measuring the radial gradient of electron densities Ne(r), it has been possible to deduce the high temperature of the corona (Alfven, 1941) and, later, to understand the thermally driven wind (Parker, 1958-64). The typical radial scale height $H = \frac{kT}{<m>.g(r)}$ is of the order of 50 Mm in the inner corona (corresponding to a hydrostatic temperature of 1 MK) and goes to 100 Mm in the middle corona (corresponding to a 2 MK temperature), near 0.4 solar radius from the surface (r=1.4). Further out the speed of the flow may become non negligeable and the assumption of hydrostatic equilibrium is no more justified. We note that the average values of plasma densities and the corresponding radial gradients show large variations when considering

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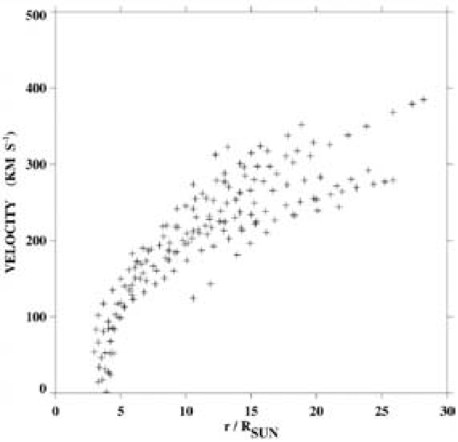

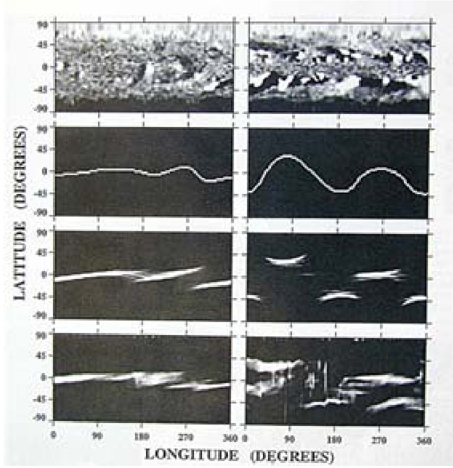

Figure 2.
(Left)Apparent proper motion velocities measured over outwardly flying "blobs" seen on movies taken in W-L using the SoHO/Lasco coronagraphs. From Sheeley et al. 1997.
(Right)Comparison of computed coronal brightnesses due to warped plasma sheets and the observed effects displayed on a synoptic map. At left, for February 1997; at right, for April 1998. Top row: synoptic maps of the surface magnetic fields; lower: lines of polarity reversal; computed and observed W-L intensities at r=3. From Wang et al. 2000.

different parts and different levels of solar activity, see figure 1 left. The temperature appears to systematically increase with radial distances in the inner "active" corona, see the behavior of densities of equatorial regions shown in figure 1. This has been well confirmed by the study of the X-ray corona as done during the Yohkoh mission.

Further, the popular approach to describe both the coronal structure and the dynamics of a not too active corona has been to consider first, the more equatorial corona which extends further out as a warped plasma sheet made of streamers, and second, to consider other parts of the corona being more or less homogeneous. Then, outside the "sheet" we have the quiet sun and polar regions. The picture is quite realistic to describe the corona near the Years of a solar minimum, see figure 1 right.

It is often conjonctured that the heliosheet is the source of a slow wind. Indeed, time sequences obtained from Lasco/SoHO observations (Sheeley at al. 1997) enable us to perform a proper motion analysis over small "blobs" or small plasma clouds) flying away along streamer stalks or edges. The results confirm that the wind there is slow, see figure 2 left. However, it is not clear what part of the wind is represented by those "blobs". In addition, there are parts of the corona which show a definite downward motion and observations of travelling cool plasmoids are also reported. A process of "detachment" of an elongated structure has been observed near r=3.5 in the eclipse corona by Koutchmy et al. 1973, as a result of an apparent instability of the stretched out magnetic field. The process of formation of "blobs" and "detachments" is not clear. To explain the more stable parts of the quasi-equatorial plasma sheet, the concept of current sheets is introduced, see e.g. Koutchmy and Livshits 1992. Then models are proposed, using extrapolations of the photospheric magnetic fields, see Wang et al. 2000, Mikic and Linker 1994, Wu et al. 2000 or from proxies of neutral sheets (polarity reversal lines), see Koutchmy, Merzlyakov and Molodensky, 2001. Figure 2 right is a composite display from Wang et al. 2000 which uses synoptic maps to illustrate how the extrapolated source surface model works. The neutral line is drawn for two different magnetic maps and different levels of activity. Computed W-L intensities of the corona at r= 3 are compared with the observed

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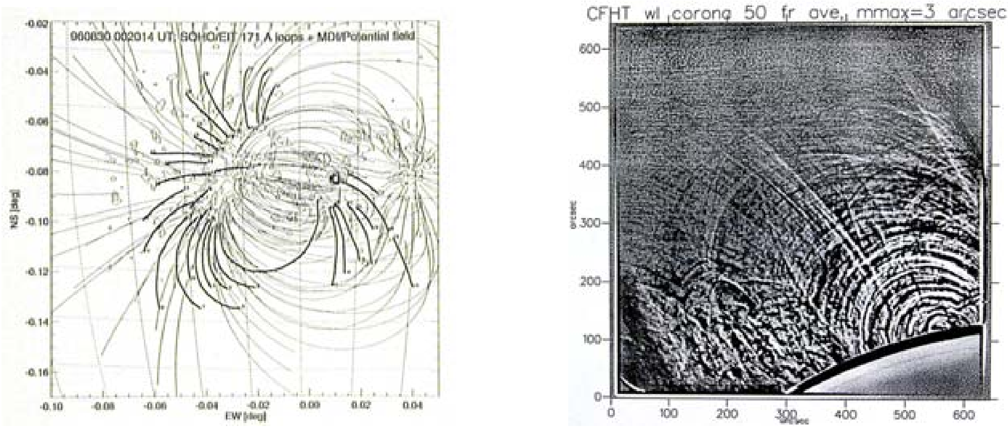

Figure 3.
(Left)EIT loop emissions seen in Fe IX/XI emission, in thick lines, and computed magnetic field lines, in thin lines, by Aschwenden et al. 1999. Note that calculated lines sometimes coincide with the observed one, and sometimes they are orthogonal.
(Right)Bright and dark loops seen in W-L after removing the large radial gradient and enhancing structures with small cross-sections. Intensity modulations correspond to plasma densities enhancements and emptinesses. The underlying region of the W-limb of the eclipse corona of July 11, 1991 is outside active regions and corresponds to different magnetic polarity patches with a line of polarity reversal. After November and Koutchmy, 1996 from the 70 mm camera CFHT observations.

from LascoC2/SoHO values, showing some rather good agreement. It confirms that large streamers are confined in sheets with folds giving enhanced W-L parts, sometimes at their edge. The thickness of the sheet is a matter of debate and is probably linked to the details of the flow along the sheet, including possible reconnections of field lines, which contradicts the assumption of quasi-stationarity. The approximation is still useful and an idealized axi-symetric model was proposed by Banaszkiewicz et al. to further take into account the existence of multiple equatorial sheets. This model seems to fit with the suggestion by Wang et al of the existence of three type of winds and, also, with the surprising observations of different equatorial structure in OVI and in Lyα by UVCS of SoHO, see Noci et al. 1997.

3. The fine-scale structures and confined flows.

3.1. *Inner corona structures*

Above active-region enhancements and condensations, fine loops and rays are observed. Tentative modelings were proposed for loops by many authors. For ex. Wang et al. 1997, proposed to use the potential field approximation of the photospheric magnetic field to compute the plasma density as observed above the limb in the green 530.3 nm Fe XIV line, with the approximation of a linear relationship between densities and the strength of the computed field (small variations of this law was also tried). This is justified by the relationship between heating and closed magnetic fields which dominate in these regions. A more realistic approximation would allow the field to be force-free to introduce more parameters in the modeling. Aschwenden et al. 1999, see figure 3 left, proposed models to match the EIT Fe IX/XI loops observed on the disk (near 1 MK temperatures). Later, even finer loops were observed with TRACE in the same spectral lines. It is not really clear what is observed (basically: some emission measure along a trajectory) and what

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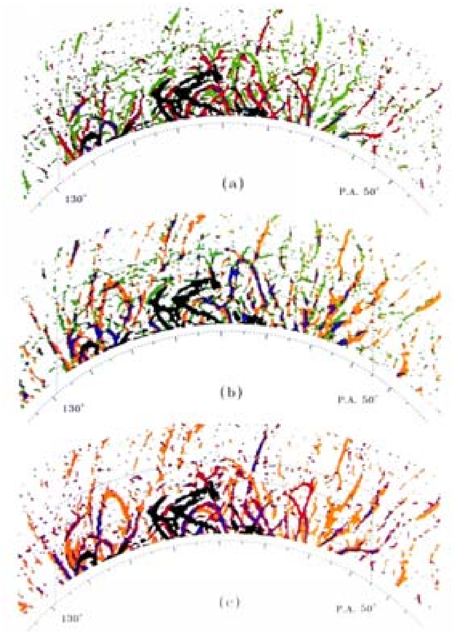

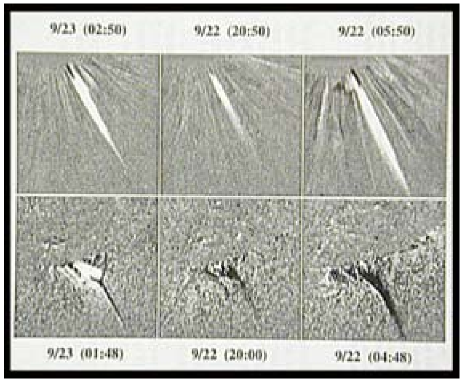

Figure 4.
(Left)The low corona simultaneously observed using different emission lines and enhanced contrasts above the E-limb of the eclipse corona of 1991. In black, are emissions recorded in the Hα line near 0.01 MK, in green emissions of the Fe XIV line near 2 MK, in red, emissions of the Fe X line near 1 MK and in orange, in W-L modulations. Note the lack of good correspondence. After Takeda et al. 2000.
(Right)Recurrent jet like phenomena reported by Wang et al. 1998. The upper row shows W-L rays appearing in the middle corona near r=3 to 4 one hour after the low corona explosive EIT 195 (Fe XII) events shown in the bottom row.

is modelised. Loops seen in EUV lines show an approximately constant "cross section" and their brightness is certainly variable, depending upon geometric parameters and effects of integration along the line of sight. Indeed, there is the suggestion that apparent loops reflect the distribution of separatrices in the magnetic field connectivity, see the review of L. Golub in the present Proceedings. November and Koutchmy 1996 suggested to represent their quasi-hydrostatic loop system observed in W-L, see figure 3 right, with quasi-emptinesses (cavities) due to flux tubes/ropes and density structures between them. This naive representation reflects the absence of a good diagnostic to deduce the magnetic field with many connectivities, without saying that currents exist higher up in the corona. It is however clear that structures with different dominant temperatures co-exist. This is well illustrated in the work of Takeda et al. 2000, see figure 4 left, which shows structures observed simultaneously (during the total eclipse of 1991) in different line emissions and in W-L, including the cool Hα emissions of large prominences. Density structures obviously also exist where some significant emission is recorded, but the overall picture does not permit a correct evaluation of what is the dominant physical process at work, leaving open the problem of the heating. Here a spectroscopic diagnostic would be useful but this is beyond this presentation. A last remark can be made: the higher is the resolution, the larger seems line emission variations. Outside active regions small scale features like rays, polar plumes and jets are recorded. Above polar regions and around, the W-L plumes are known for a long time from eclipses. EIT observations from SoHO show plumes quite well in all coronal emission lines. Wang et al. 1998 succeeded in

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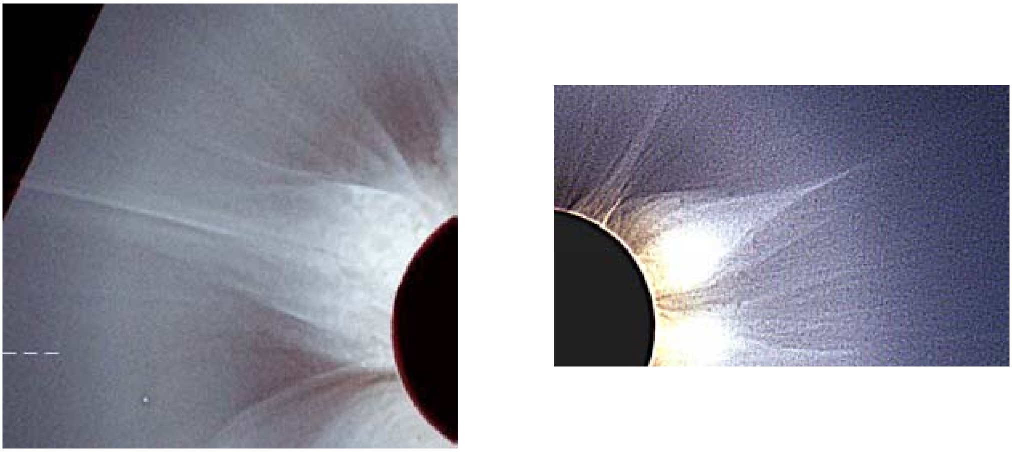

Figure 5.
(Left)W-L image of a part of the June 21, 2001 corona showing a linear ray rising above the E-limb active region enhancement.
(Right)W-L image of Streamers seen overlying the NW-limb of the June 30, 1973 eclipse corona. The radial gradient is removed using a radial neutral filter and the contrast is enhanced. From the author observations.

showing an excellent correspondence between well defined W-L transient rays recorded in the middle corona with Lasco/SoHO observations and “bursts” of EIT 195 (Fe XII) line emission in polar regions, right above the surface of the Sun. Typical proper motions of 600 km/s were reported in the middle corona. The phenomenon is also observed to be recurrent; a good example taken outside the polar region, is shown on figure 4 right. These bursts show a morphology strongly suggesting a phenomenon similar to the active region jets described by Shibata 1996 and Yokoyama and Shibata, 1996. Indeed, the scenario used by these authors could be suitable to describe at least the impulsive phase of polar rays. Plumes would be the more static counterpart left in the corona after a fast ejection of the collimated beam of the jet. The so-called anemone type configuration of the coronal magnetic field, recalling the former spheromacs configuration used to attempt to confine a laboratory plasma, could be used to propose a 3D numerical model and possibly bring some new light on the origin of the fast wind. An enigmatic curvature of polar plumes seems to be observed; overlapping effects could account for at least a part of this curvature. The subject is large and includes the relationship with spicules and macro-spicules, with explosive events and X-rays flashes and other brightenings in polar regions and around where the corona is open and mixed polarities are observed at the surface. It also puts into question the morphology of the network field emerging into the corona.

3.2. *Outer corona structures*

Among the most puzzling fine scale structures appearing in the outer corona are fine linear rays with sometimes unresolved cross-section (see Koutchmy and Nikoghossian, 2002). Eclipse images show the rays starting from a distance well above the surface, somewhere above the coronal enhancement of an active region. Their lifetime is at least one hour. Overlapping effects are often observed, so that the narrow ray is well identified during just a limited amount of time. Lasco C2 images show the corona above r=2.2 with linear rays above active regions but they are not at all prominent compared to CMEs and they are mostly not noticed. They are good candidates for being the W-L counterparts of type III radio bursts, see e.g. Aurass et al. 1994 and Kundu et al. 1995, which means beams of

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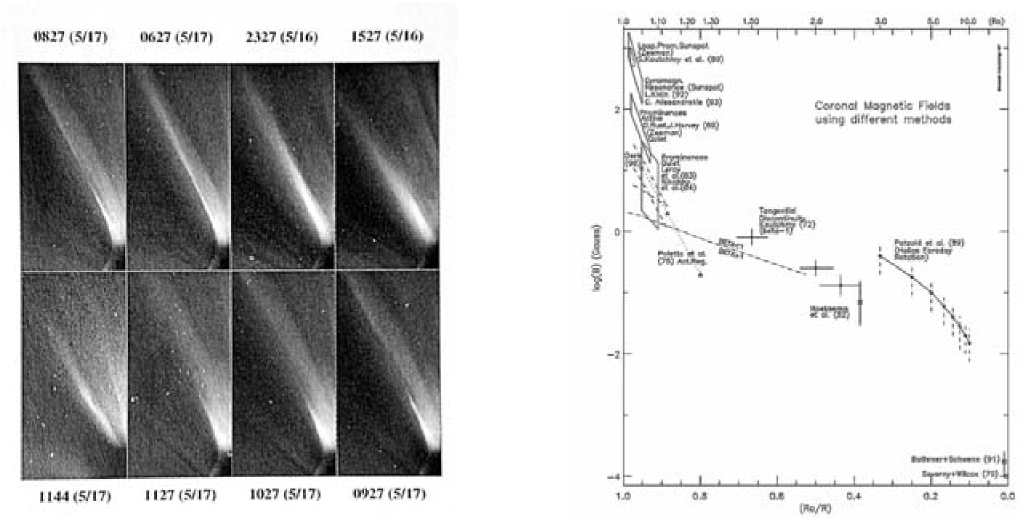

Figure 6.
(Left) W-L brightening of the edge of a streamer showing a detachment. From Wang et al. 1999. (Right)The strength of the coronal magnetic fields as appearing in selected works from the literature. The scale is chosen in order to try to capture all the studied space around the Sun and to show the importance of the middle corona

sub-relativistic electrons. In W-L they are seen to be perfectly linear but not radial; just outwardly extended. It tells us that the surrounding magnetic field is overcome by the beam of high velocity electrons. Color effects (both redshifts and blueshifts) produced by inverse Compton scattering are expected. Figure 5 left shows a part of the 2001 eclipse corona where a significant color effect was measured along a linear prominent ray which can be identified starting from a distance of 0.7 solar radius above the surface. The ray would have been confused with the stalk of a helmet streamer on a lower resolution image. We believe this is a new interesting class of fine scale feature of the middle corona which merits our attention due to consequences for the heating processes and for the origin of the fast wind outside coronal holes. Inside a streamer, some fine scale structures can be noticed. For a long time helmet streamers with a cusp above them were discussed. Cusps should be not confused with overlapping effects produced by the superposition of enhanced edges of the streamer sheet due to a fold. Sometimes, it is not obvious what is the 3D structure of a cusp, see figure 5 right. The cusp could just be an apparent effect due to superposition of fine streams or even the result of projection effects of a Witney cusp (see Vedenov et al. 2000). We have to wait for stereo observations to definitely resolve the question and should be cautious in inferring a definite magnetic structure of the upper parts of a streamer. Finally structure has been studied to understand the very sharp edges of streamers, when effects of integration along the line of sight give the impression of a magnetic tangential discontinuity appearing along the edge of the streamer, see Koutchmy, 1971. These discontinuities appear to be unstable, see Koutchmy et al. 1973 and the detachment of the elongated structure is observed. Recently, thanks to the C2 Lasco coronagraph observations, Wang et al. 1999 studied several cases of apparent discontinuities where the breaking of the flow along the discontinuity is observed near r=3.5, see figure 6 left. It is not clear if these detached parts of streamers correspond to the bulk motion of the slow wind. The interesting point is the type of magnetic structure which can be inferred from the photometric analysis of this typical structure.

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To maintain the large transverse gaz pressure gradient, a magnetic pressure is needed outside; the corresponding strength of the magnetic field can be deduced, see Koutchmy, 1971. A numerical model should be developed to analyse the dynamical behavior of the discontinuity and match observations shown on figure 6 left.

4. Conclusions

Both the most typical large scale and small scale structures of the corona were considered in order to infer some flow mechanisms. It is not possible to consider the problems arising without going further into discussing the coronal magnetic field. Up to now, the magnetic field has been directly measured only inside the very inner corona. Further out, some scarce and not direct measurements exist. We tried to put on a graph all inferred values, see figure 6 right. It is clear that the magnetic fields extrapolated from the surface are rapidly decreasing in strength and that coronal currents are responsible for the additional field in the mid corona, where the flow is not yet strong enough to smear and stretch out the field. In addition explosive and impulsive events are responsible for narrow linear rays. This is a whole field of research which should be done to understand the dynamics in the corona and probably all phenomena resulting from the unstabilities of the magnetic field, including the giant CMEs.

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