Eclipse 99 – High Resolution Imaging:

Why and how ?

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Abstract. A very large white-light (W-L) coronal flux is made available during total eclipses. High speed analysis of very fine-scale structures of the magnetically dominated solar atmosphere is then possible, including the deeply seeded sources of the solar mass loss. Additional observations of both the disk and of the more outer corona should be simultaneously collected from space, using the SOHO and the Yohkoh missions to complement the data. The most optimum eclipse studies should concentrate on the intermediate corona where acceleration processes are taking place. MHD waves, including magneto-acoustic propagating waves and standing loop-resonance waves are everywhere present with rather short periods. W-L fine imaging at high-speed and high signal-noise ratio is needed to avoide the overlapping problem and measure their magnitude. Ubiquitous plasmoid-like objects are also produced in this region near the temperature maximum and they need a special attention. They are the rather privileged site where both the radiative cooling and the magnetic dissipation mechanisms are occuring. Eclipses are good opportunities to look at the dynamics of coronal ejecta. At larger scale, sharp edges of streamers and plumes can be used to deduce a 3-D view of the coronal neutral sheets, provided pictures taken at several hours interval are made available along the path of the totality. Both the quasi-rigid rotation and the more subtil outward motions of coronal material are then evidenced, giving a good tool to study the origine of the slow wind.

Key words: eclipse – corona – faint structure

1. Introduction

a/ The total solar eclipse of August 11, 1999 was already largely commented all around the world. In short, this eclipse will be observed from the Northern Europe, in particular France and Germany, to the Indian coasts of the Bay of Bengal. It is obviously a major event which will attentively be followed by all the medias. The eclipse of 1999 was called by certain 'eclipse of the millenium'. Nevertheless, on the strictly scientific level and according to the most thorough studies carried out by NASA, the probabilities of clear sky are about 50% on the best sites in Western Europe. The part located on the desert of high altitude in Iran, close to Esfahan, offers some probability of clear sky close to 100%. This observation has been the basis of our project of which we will say some words here.

b/ The traditional ground-based coronagraphy is today almost stopped because the main part of investment have been made in Europe on some operations in Canaries which carry on some other objective. No new optical coronagraph was built neither in France nor in Europe, since decades. Coronal physics however interests today a broader community. It is fortunately treated thanks to the radio waves and especially, in the fields of the EUV and X-ray, on space missions. Nevertheless the optical spectral region which provides the greatest density of coronal photons and thus the best signal/noise ratio, has a great interest. This is true with regard to the W-L corona, but also with regard to the emission lines what one always does not realize. The spectroscopic diagnostics are thus excellent there and one should not miss the occasion to implement them. However, we will speak about it little in this article which is devoted to the imaging alone.

c/ In this context, the total eclipse, with which one got the greatest discovery on the corona and the Sun (structuring of solar atmosphere and variations, prominences, forbidden emission lines and coronal temperature, new atomic element, chromosphere, ejection, solar corpuscular radiation and wind, current sheets and loops, etc.), is of large interest (for more details see Guillermier & Koutchmy, 1998).

d/ For the European teams implied on the ground in optical coronagraphic research, the total eclipses have been most significant and one wants for proof the many results exposed and/or published at the time of recent conferences or specialized workshops. Quote those of Tatranská Lomnica (Slovakia) in 1993, La Paz (Bolivia) in 1995, of Sinaia (Romania) in 1997, of Pointe á Pitre (Guadeloupe) in 1998, of Prague in connection with JENAM in 1998, also. In 1999, several conferences are already announced. In addition, the conferences of solar physics often comprise a session dedicated to works of eclipses.

e/ The team of IAP, for example, already proved the great interest of the coronal high resolution imaging at eclipses, as of testify the many reproduction of its images in the publications or in cover of textbooks, in posters, on Web sites and media like postcards, etc. Ph.D. Thesis and publications using the analysis of these observations are numerous. The large field image obtained in 1991 with a neutral radial filter at Mauna Kea although with non optimal atmospheric conditions, was printed over a double page of the most prestigious scientific magazine of the World, the *National Geographic Society Magazine.* This shows all the power of good images made at eclipses, even if it is just a snapshot or it is instantaneous with regard to the solar corona, with all the limitation that it is necessary to keep in mind when one considers a phenomenon which is essentially dynamical!

2. General scientific motivations

The motivation is essentially to seek in the context of recent works on

- the heating of the solar corona (wave heating and, ultimately, the dissipation of electrical currents at different scales) and

- the origin of the loss of mass, in particular in the 'slow wind', i.e. in structures like streamers and jets.

It means for the existence and propagation of waves and the formation of plasmoides as well as the physics of structure in sheets or blades (call usually streamers) which is still badly apprehended. The high resolution imaging alone is able for the moment to make progress on the subject, while waiting for that one day a solar probe will take some measurement in-situ after penetrating deeply into the corona. Being interested here with the plasma component of the corona alone which has an intensity strongly decreasing with the radial distance, we should first not confuse it with the almost W-L aureola of the F-corona (due to the scattering produced by the interplanetary dust), which dominates in the more external parts, see Figure 1, taken in part from the work of Koutchmy and Lamy (1985).

This component known as the F-corona is awkward and it is advisable to withdraw it thanks to a model well established today, see Figure 1. This is relatively easy because this component F is perfectly homogeneous and especially very constant in time. Figure 1 also presents the typical variations of intensities met in the corona. Once this component is subtracted, like that of the intensity of the sky which is rather constant over a field of several radii, the plasma corona appears much better with all its structure which suggest immediately the influence of forces of magnetic origin; these forces are in action for confining and maintaining the transverse gradients of the gaz pressure. It is of interest to notice that this procedure has also been adopted today to process images taken in space with W-L coronagraphs aboard the SOHO mission. In addition to the purely fundamental aspects of the physics of the solar corona, it is of importance to include the origin and the propagation of large dynamical phenomena which agitate enough often the corona, starting almost from the surface, and which arrive up to the border of the solar system. This forms a part of this new discipline called 'Space Weather' and the studies made with the solar eclipses enter naturally into this field of search.

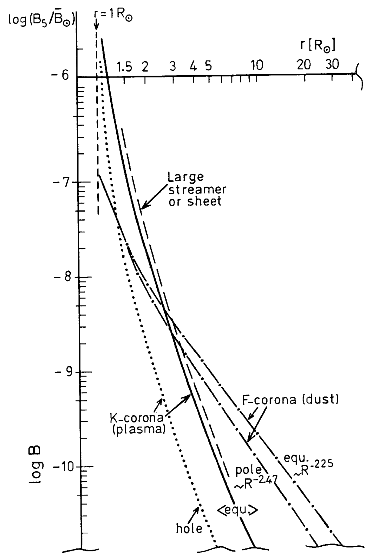

Figure 1. Radial variations of intensities for various components of the solar corona (Koutchmy & Lamy, 1985). Notice the logarithmic scales.

3. Study of the internal corona: Nonthermal speeds and proper motions

3.1. Coronal waves in magnetic structures

New recent observations on ground and in space have renewed the interest of the study of wave propagation in the internal corona, that which is located in the prolongation of chromospheric structures.

Without making a detailed review of it let us indicate that the magnetic field can play the role of guide or to be itself disturbed (coupling magneto acoustic and Alfvén waves) and that the periods which are concerned here locate around 3 to 5 min or more (low frequencies). Figure 2 is a schematized and somewhat confused representation of the base of this area, around an element of the chromospheric network which is at the origin of the magnetic structures of the quiet corona and where are observed dynamic phenomena, like spicules, and this permanently. The Figure 3, produced with computer with some simple and robust assumption, show in cut the structure of lines of magnetic field and in hue of gray, the value of magnetic pressures with the appearance of a singularity (zero of magnetic field magnitude) which can be the site of explosion and the origin of small ejection observed higher and which prolongs in a manner still badly known in the corona. It is not excluded the explosions and, especially, the sites of acceleration of the particles, are located in the 'deep' corona, in layers of currents being formed in a spontaneous way for ex.

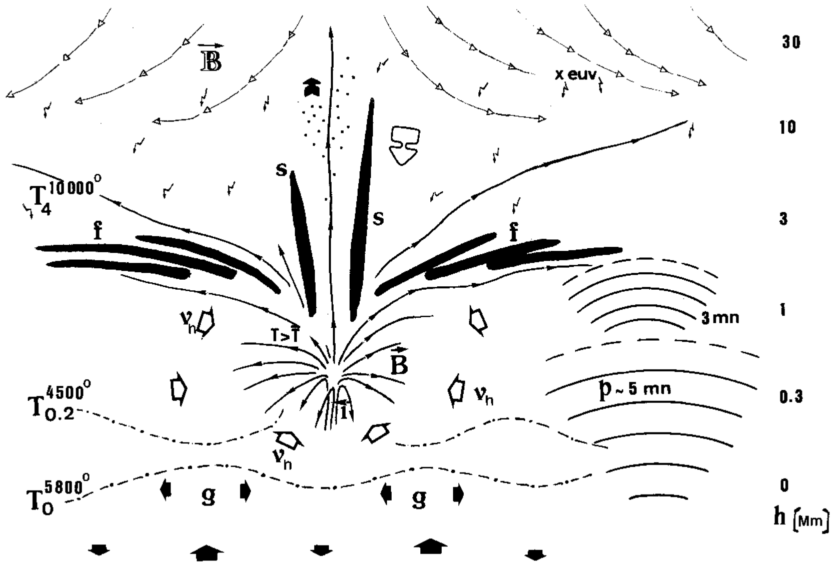

Figure 2. Very schematized representation of the solar surface in the vicinity of an element of the chromospheric network with concentration of magnetic field in the photosphere. The thick arrows indicate the field of velocities. Notice the logarithmic scale of heights H; B-magnetic field; T-temperatures; V_h-horizontal speeds; G-granulation; S-spicules; F- fibrils.

Nevertheless, it seems well that the gravity, which is in general ignored in simulations, does not have a completely negligible role in the assessment of the forces, and, moreover, that the losses by radiation are significant for the energy balance. Without speculating on the mechanism which is at the origin of these small explosions, note that some direct measurements of densities of plasma are possible, as well as some imperfect, because of brevity of totality, measurements of proper motions by following in time the small structures. Assuming, we can measure at the same time the index of color of the structure, it is even possible to roughly determine its temperature: a rather cold structure is increasingly redder than the ambient white-light corona because of the emission of the chromospheric lines H of hydrogen and D3 of helium, precisely located in the red-orange region of the spectrum. On coronal lines which are optically thin, and with low resolution, it seems difficult to identify above the solar limb the Doppler effects for each element, because of the effects of superposition of the contributions of several structures on the line of sight. For this reason to seek oscillations of short periods (some sec of time) during an eclipse is an extremely difficult job which presumably requires to resolve the structures on which one wants to make 'coherent' measurements! It is, on the other hand, possible to measure the 'integrated' effects over the width of the line. As the density in the

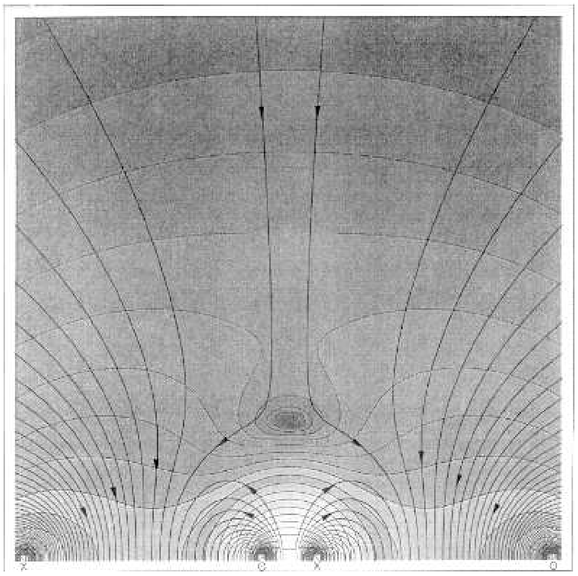

Figure 3. Axisymmetric numerical model of a simple structure of magnetic field induced by a horizontal loop of current located near the surface, and surrounded by another loop much wider and coaxial. Notice the null point or singularity of the field, into dark, at the top of the loops. The lines of field are drawn, some with arrows, indicating the direction, and the local value of the magnetic pressure is coded in hues of gray.

corona decreases very quickly with the height and that even if the temperature increases slightly in it with the height, the magnetic pressure decreases there less quickly than the gas pressure. One expects an increase in the amplitudes of these nonthermal speeds which will affect the widths of the lines seen above the solar limb. Finally, one is unaware of the critical regions where the propagation of waves already detected at the interface chromosphere-corona (CC) itself are carried out, nor where the waves itself transform in fast modes (i.e. become magnetic) and/or transverse (the purely acoustic waves propagate longitudinally) nor, finally, the behavior of turbulence which is omnipresent because of the viscosity of the magnetized plasma (the plasma is known as magnetized when the gyromagnetic radius of particles is small compared to the free mean path of particles like inside the internal corona which, however, is well collisional!)... No good Doppler measurements exist, although it can still be made on ground-based coronagraphs like the one at Sacramento Peak in New Mexico; those measurements brought some indications showing that it is necessary to look at larger radial distances, obviously accessible at eclipses. The SOHO/CDS data go exactly in the same direction. Note in addition that on the large structure and farther in the corona, it is also interesting to measure more directly the

Doppler shifts, in connection with the problem of loss of mass, because it seems then possible to resolve the large structures which are less 'turbulent' in a region where the plasma becomes no collisional but where it is strongly magnetized.

3.2. Ultra-fine Structures

With a rather simple experiment and operating quickly (video-CCD), it is interesting to reach the large spatial resolution provided by the mode of observation which consists in examining the perfectly regular 'scan' of the chromosphere by the edge of the Moon and to specify the height of formation in this region of transition of temperature. Good photographs with a resolution a little better than $2''$, were obtained in the past using a long focal length (10 m) and an objective of 10 cm in diameter only. It must be possible to make today much better?! One can think, for example, of a resolution comparable with that which is obtained by advanced amateurs on an object like the Moon, whose luminance is perfectly comparable with that of the internal corona. Thus, with a telescope of 20 to 30 cm of aperture equipped with a small CCD camera, it must be possible to make a kind of cut of the region CC; this is of large interest, including the selection of images as it is usual in solar observations; filtering somewhat the radiation, it is possible to avoid the influence of (relatively 'cold') chromospheric lines, in the red especially. Let us note that a high resolution imaging is really necessary to be freed from the risks due to the shredded profile of the Moon; this profile is nevertheless perfectly constant during the eclipse and it can thus be taken into account to deduce the true radial profiles in the corona.

It is finally possible to go beyond the purely static image and to approach the dynamics on the small-scales. That had also been tried at the focus of the telescope of 3.6 m aperture on the Mauna-Kea (the CFHT), at the eclipse of 1991. A synthetic drawing of the principal structures and the fields simultaneously studied with the various cameras was already published. It is made using the pictures obtained over a large field on an auxiliary experiment and with the radial neutral filter (see further). The Figure 4 shows the detail of one of fields studied using a spectral filter located in the red which includes the line H, combined with a film 6415 of 70 mm width used with an exposure time of 1/60 s and a cadence of 2 frames/s (November and Koutchmy, 1996). This image shows a small part of the quiet corona with undoubtedly the best resolution never reach and this thanks to the use of this great optical telescope (the largest never pointed to the Sun!). One discovers there a rather inextricable tangle of structures in loops that the algorithm used to process the images cannot completely resolve. However, let us note the predominance of structures in loops of rather constant 'sections'. The inclusion of the H line makes it possible to simultaneously visualize cold structures close to the surface. In 1991 we detected very small details and certain were showing a behavior and a nature completely new. Let us note while passing the diameter of the smallest structure: $0.4'' \pm 0.2''$; its lifetime in the small field analyzed using the video-CCD was about 40 s of time only (Koutchmy et al. 1993). It is probable that these scales are close to those where the ubiquitus turbulence dominates, but that would require to be looked at more closely.

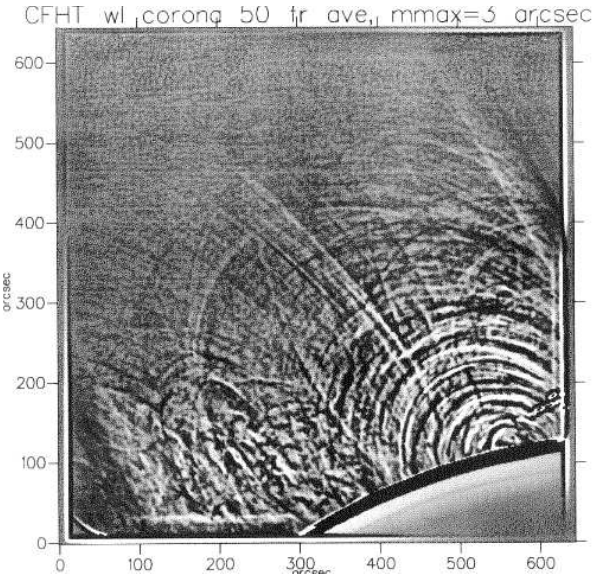

Figure 4. Undoubtedly the image of the corona obtained with the best resolution ever reached on such a field of view. Observation carried out with the CFHT at the eclipse of 1991, at the primary focus, with a camera of 70 mm format, on film 6415 exposed 1/60 s with a rate of 2 images/s. Digital processing using an algorithm intended to show the dominant gradients at 3″ scales.

3.3. Dynamic phenomena at very small-scale

It is indeed using a video-CCD, that we have obtained the best results in resolution, and this with a rather narrow interferential filter (7 nm of bandwidth) which allows to measure the coronal radiation not polluted by the ‘cold’ emissions, even from the faintest lines. Approximately 6000 elementary images were analyzed. The resolution which varies a little in time during this sequence of 210 s is on average of 0.7″ and sometimes, reaches the resolution theoretically given by the lens corrector of the telescope, near 0.4″. A small part of this sequence, around a very small area of 10″ x 10″, where a plasmoide have been followed by local intercorrelation to place it to some extent in Lagrangian co-ordinate, i.e., following the centre of gravity of the plasmoide was shown by Bouchard et al. (1994) It is clear that this small cloud of dimension not exceeding 3″, has a behavior extremely complex and in any case impossible to describe with a simple ballistic trajectory. Most astonishing on the purely theoretical level is the existence of this type of structure like a small cloud of coronal plasma immersed in the corona. Its proper motion was analyzed: its speed is typically about 100 km/s what is undoubtedly subsonic at coronal temperatures, but it is not at the temperature supposed for the small cloud. Bouchard et al. (1994) carried out a study of the phenomenon, without being able to still conclude on his nature: toroidal cold vortex; diamagnetic plasmoide; wave like propagating disturbance (this is not very probable but would rather satisfy the theoreticians who like to consider the problem within the framework of the MHD, where the pressure of the magnetic field is largely dominant...); elements of an 'invisible loop' which breaks by reconnexion (but no energy signature seems present!) or what still?

We are in the presence of the typical phenomenon which formerly could be identified with the turbulence. It is clear that other observations are necessary before one does progress in this field which seems rather fundamental in the context of the loss of mass of the Sun. Without a narrow filter, it is possible to reach these angular and temporal resolutions with a modest telescope if using a video-CCD or perhaps even a fast film, see Figure 5. With short exposure times, the image processing with suitable algorithms like the 'Maximum of Fourier magnitude' allows a significant improvement of the resolution given by the Earth's atmosphere during the totality which affects the images (image motion, aberrations). These experiments thus benefit from the most recent aspects of the technique of imagery.

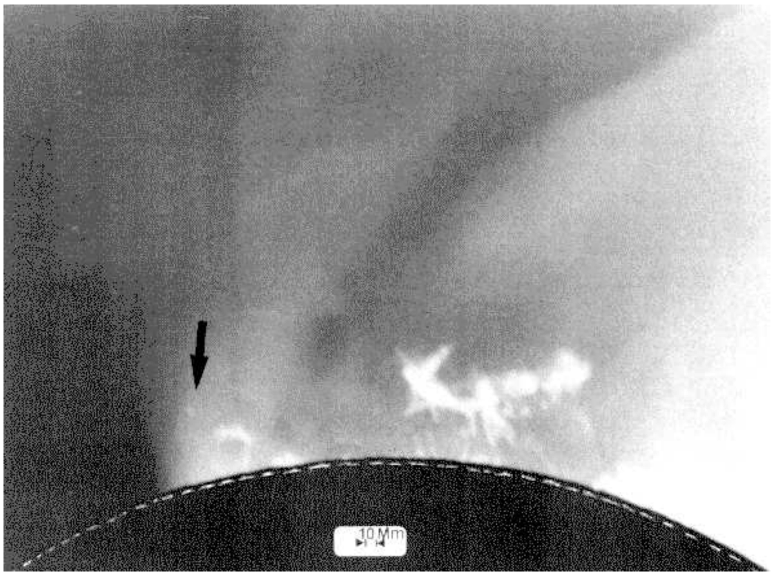

Figure 5. Portion of field in the vicinity of the E-limb of the 1991 corona, with the plasmoide (see the arrow) at the beginning of the sequence. Image taken with a red filter and a photographic film with a filter neutral radial and an exposure time of 20 s. The position of the limb of the Sun behind the Moon is indicated.

4. Study of the intermediate corona: currents sheets and fine structure of streamers

4.1. Structures in sheets and the ‘fibres coronales’

The internal corona is finely structured in loops (see Figure 4), but starting from a certain radial distance located around 0.3 to 0.5 $R_\odot$ of the limb, rather apart from the active areasand in a rather adjacent way to the chromospheric filaments, coronal blades or sheets somewhat inclined or curved, appear systematically on the instantaneous images, to see in Figure 6.

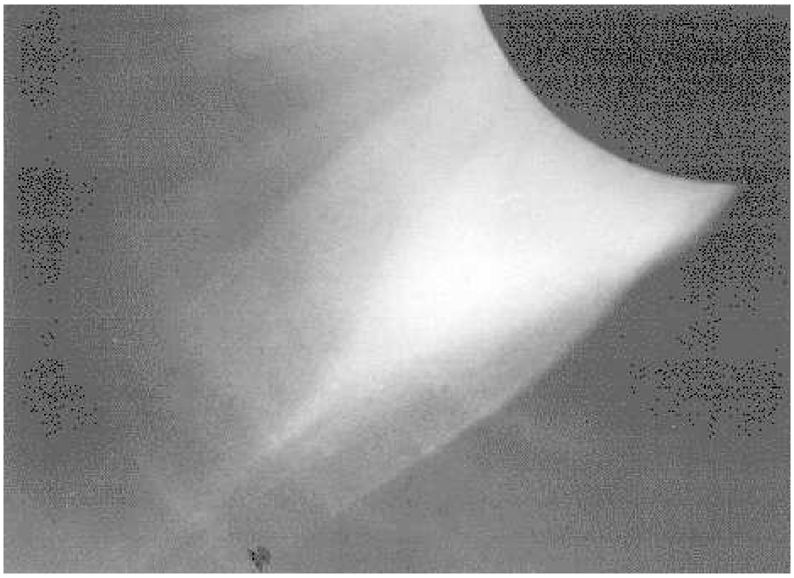

Figure 6. Portion of a picture of the 1961 corona (observation: M. Laffineur – IAP/CNRS) obtained on plate, with compensation of the radial gradient using a mechanical system. Around the streamer in bulb, a quasi-cylindrical sheet with tangential discontinuity is identifiable (see arrow). This historical picture was reproduced many times, e.g., Menzel (1961), Billings (1966).

In certain cases one can even speak about true tangential discontinuities such as it is predicted by the theory of plasmas. This theory resulting from work of laboratories, completely neglects the influence of gravity as well as the losses by radiation, which is less serious for a quasi-noncollisionnel plasma. It is then enough to satisfy an equilibrium equation of the pressures at each side of the discontinuity to have a balance, no flow taking place, by definition, through the discontinuity. Nevertheless, the stability of these structure which is never strictly radial, with respect to the gravity, and of the hydrodynamic flow along the discontinuity, is not obvious without counting that their origin is unknown.

Figure 7. Portion of the June 30, 1973 eclipse corona obtained on film-sheet using a radial neutral filter. On left, by a team of the Observatory of Kiev operating in Mauritania; on the right by the team of the IAP (CNRS) operating in Chad. On the edge of this large streamer which shows a discontinuity, a phenomenon of detachment (see the arrow) or disconnection have been observed for the first time, undoubtedly showing an instability of a new type, which itself propagates radially with a speed which have been measured using these observations and which have been found equal to 140 km/s.

The quasi-static equilibrium of the blade implies a layer of current which is well known in the case of the heliospheric sheet but which requests a more detailed analysis in the more internal corona where the medium is still collisional and the flow rather weak. One of most critical parameter to determine is the thickness of the layer and, for that, the measurement of the rate of polarization of the radiation scattered by the layer allows to reach the 3-D structure. Note that the knowledge of the 3-D topology of the sheet is necessary to compute the current and that, for the moment, it is difficult to apprehend it otherwise than using numerical simulation, see Figure 8. Stereoscopic visualization can help to raise certain indeterminations, but this will not be possible unless new space missions are flown around the Sun. For the moment it is nevertheless possible, with eclipses in particular, to take advantage of the quasi-rigid rotation of the coronal structure neglecting sudden variations, which is better satisfied in the intermediate corona, and visualize in space the structures using 2 moments separated in time by at least 1.5 hour. This was done once in 1991 by Molodensky with a surprising result: the layers appear in space very thin and sometimes, folds are present (Molodensky et al., 1996). Figure 8, calculated with a very simple model, illustrates the effects of projection.

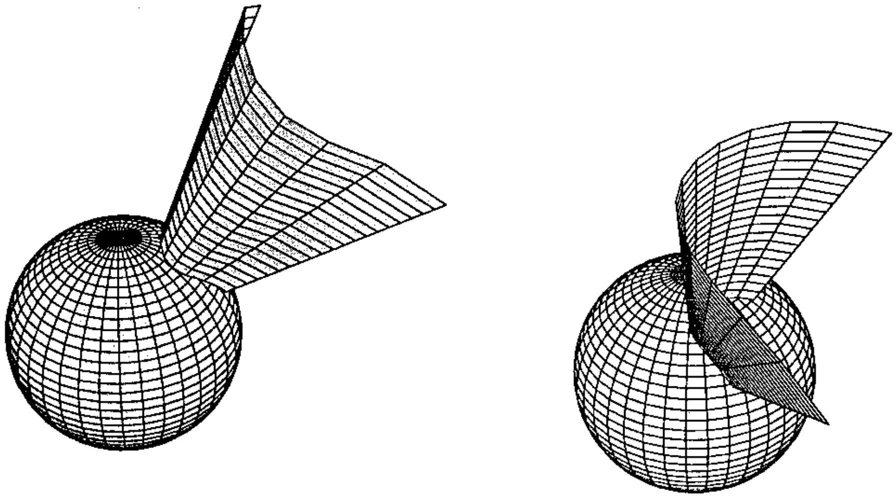

Figure 8. Simulation intended to illustrate the effects of projection met during the interpretation of the images of an eclipse corona. Notice that a curved layer can easily show a discontinuity.

It is easy to imagine that for certain angles of sight, a blade can appear very thin in projection. This would explain these very fine structures which are observed in the corona (threads). Sometimes those thread-like streams or jets extend rather radially over a large field and can be better followed using images obtained with a radial neutral filter. The fact that these threads or 'fibres coronales' appear more often in the corona of maximum of activity can suggest that these structure are the result of the passage or the 'run' of an energetic phenomenon which disturbed in-depth the medium and therefore the background magnetic field and that a phenomenon of 'focusing' of plasma is needed. This is still speculative and deserves to be examined in the future.

4.2. Example of experimental device

The W-L imaging can be carried out by the 'conventional' means of the color photographic photometry which already proved its reliability. A radial neutral filter perfectly known is laid out close to then focus to allow a precise photometry on all the extent of the corona. This filter is intended to compensate for the strong gradient of intensities of the internal and even the more external corona, (see Fig. 1). We use values of the radial attenuation coefficient of a filter which did not changed for 30 years. This filter is neutral or almost; it is obtained by vacuum deposition of a thin metallic (Al) layer on a corrected mineral glases plate. The size of the neutral filter must correspond to the scale of the photographic picture. Note finally that the exposure is selected so as to obtain optimal photographic densities for the resolution of the film. In general, it is necessary to work above the threshold of the curve of gradation of the film, but well below the saturation of the film, which would not be the case if a radial neutral filter was not used.

Progress of technology offers an alternative to this a little complicated device. Films of excellent resolution and sufficiently fast are produced today by different companies. The possibility far from expensive to digitize the pictures and the use of fast PC computers equipped with powerful software like 'Photoshop' makes it possible to carry out wonders. Figure 9 (see Plate I) shows a synthetic image of the 1995 clipse corona realized by a team of Japanese students and scientists (Hiei, 1998). The resolution is remarkable there on all the extent of the field. Progress will be still realized soon but it is necessary to retain the rather qualitative character of this work, unless a time sequence is considered. A good photometry and a polarimetry are necessary for the scientific analysis. This can be carried out rather easily thanks to the method of acquisition of well-known star images of the field simultaneously. On images of good quality it is indeed possible to reach the stellar magnitude 9 on a radial field of $6R_{\odot}$, for example. These star images are always sufficiently spread out to remain in the linear part of the curve of the film and the objects are very well-known; one could for example use the new and remarkable catalogue *Hipparcos* published by ESA. It is still necessary to mention the use of the CCD cameras with a great number of pixels (2000 x 2000) used for the first time at the eclipse of 1998 in the Caribbean. This camera is still expensive and its use seems to us more judicious to carry out measurements on coronal lines. It is nevertheless very probable that the race towards many megapixels will continue and one would have, as of the eclipse of 1999, a very interesting confrontation on the imagery, between supporters of films and those in favour of the CCDs.

The simultaneous images from space using the coronographs Lasco C2 and C3 of the SOHO mission should be compared with regard to the absolute calibrations of the external parts of the corona and to provide the 'dynamical' context for the analysis of the eclipse corona, although the inner corona cannot be seen with C2. EIT images from SOHO and SXT images from Yohkoh are also of great interest. While working in this manner the maximum of effectiveness will be reached.

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Discussion

Question (P. Cugnon): Which about spaceborne observations in the intermediate corona?)
Answer (S. Koutchmy): On SOHO several experiments are capable to observe the intermediate corona: 1) EIT observed the inner corona in lines of Fe IX-XI, XII and Fe XV

2) C1 coronograph of LASCO observed the corona in Fe XIV and Fe X lines. However, no W-L observations are provided in the intermediate corona. Densities are usually deduced by comparing different lines.
Question (P. Ambrož): Did you find on the super-high resolution pictures of solar corona some evidences of the presence of electric currents flowing along the treads (twisting, helical shape)? Do you find evidence of current flowing inside the finest coronal loops?)
Answer (S. Koutchmy): First the evidence is coming from the theoretical analysis of loops, providing you assume they are loops with circular cross-section and not sheets. To confine the plasma in loops you need currents and magnetic forces to balance the transverse plasma pressure. Regarding evidence from W-L observations, we rather see inhomogenities along loops which could be instabilities; however it is difficult to distinguish between apparent crossing of loops along the line of sight and true instabilities reminescent of current dissipation. In case of the thread-like streams (fan) there is some evidence of twisting which would be the result of a net current.