ABOUT SMALL PLASMOIDS PROPAGATING IN THE SOLAR CORONA

S. Koutchmy¹, O. Bouchard¹, S. Grib¹, L. November⁷, J-C. Vial³, P. Gouttebroze³, V. Koutvitsk⁴, M. Moloden⁴, L. Solov’ev⁴ and I. Veselovsky⁵

¹ Institut d’Astrophysique de Paris-CNRS, 98 bis Bd Arago, F-75014 (France) (associated with the Pierre et Marie Curie University of Paris VI, France)
² NSO/Sacramento Peak 89518, Sunspot (NM)
³ Institut d’Astrophysique Spatiale, Univ. Paris XI, 121, Orsay 91405 (France)
⁴ IZMIRAN, Troitisk-147092, Moscow Region (Russia)
⁵ Institute of Nuclear Physics, Lomonosov Univ. Moscow (Russia)

ABSTRACT

We investigate the sub-arcsec structure of plasmoids travelling outwardly through the inner corona. New observations were collected during the July 11, 1991 total eclipse at the prime focus of the 3.6 m aperture CFHT telescope.

The internal proper motion in and around the main plasmoid of 2 Mm size (average) is resolved using measurements done with the correlation tracking algorithm over the 210 sec long time-sequence. It is also demonstrated on the assembled movie showing the dynamical behaviour of the event.

A plausible model based on the known properties of a toroidal vortex structure is proposed. It puts constraints on the thermodynamical properties and/or confirms the inferred values of the temperature and densities. Finally, the magneto-structure of the plasmoid is theoretically investigated to establish the conditions of stability and existence.

1. INTRODUCTION

The SOHO community faces the challenge of addressing outstanding problems in coronal heating and mass loss of the corona. Classical, very large scale CME’s (Ref. 1) are considered at this conference, but these class of objects represent only ~10% or less of the mass loss of the Sun. Hence, studies of the morphology of these objects provide only a very limited view of the overall problem of mass loss.

The solar-corona plasma is fully magnetized, as evidenced by its structure over all spatial scale. Therefore it is important, in the context of all types of coronal transients, as well as CME’s, to consider small-scale phenomena.

a - Here we consider smaller-scale ejection phenomena or impulsive events (Ref. 2) which supply mass to the corona (see Figure 1). Impulsive events are ubiquitous around the entire Sun; the ejected plasma is highly inhomogeneous in both space and temperature, as evidenced by spectra of these events (Ref. 3). The best Hz filtergrams show multiple components in these events; acceleration processes, starting from the deepest levels of the chromosphere, are evident, as well the occurrence of spike-like or beam-like ejection phenomena (Ref. 4). The cool part of these events, by far the largest component, falls back to the photosphere after a quasi-ballistic flight over the chromosphere. This component is probably responsible for the systematic red-shift observed everywhere on the Sun, from TR lines, to chromospheric lines, to the highest photospheric lines. Cool ejecta are mainly responsible for mini-surges, or spicules. The explosive phase of impulsive events is also responsible for more illusive types of ejecta that reach TR temperatures in a few seconds (Refs 3, 4); such ejecta obviously travel through the corona but, unfortunately, up to now have not been detected by the best ground-based or space observations due to inadequate angular resolution.

b - The propagation of plasmoids through the corona were predicted with the earliest development of cosmical MHD theory, starting from Alfvén.

More recently, the physics of coronal plasmoids has been developed (Refs 5, 6, 7), but based only on general speculation and extrapolation, since no observations existed to substantiate these pioneering calculations. Plasmoids are indeed observed further out in the interplanetary medium (I.M.) and/or the heliosphere, as magnetic clouds, and full MHD models have been developed, e.g. by M. Dryer and co-workers (Ref. 8). However, these studies do not include questions such as the radiative output of coronal plasmoids and, conversely, their magnetic heatin g in the I.M., and the heliosphere, in fact, cooling apparently dominates.

c - The total solar eclipse of July 11, 1991 was observed at the prime-focus of the 3.6-m aperture Canada-France-Hawaii Telescope (CFHT), the largest optical telescope ever used to study the solar atmosphere. The main objective was to look at the smallest possible spatial scales where coronal heating and ejection phenomena are thought to take place. Thanks to the efforts of a rather large consortium of scientists and engineers, the dynamics of the corona, as recorded in the eclipse data, was analysed (Ref. 9). During the 4 minutes of totality, 3 movies were taken with both high speed photographic and video-CCD camera-array operated at a video rate (30 frames per sec). We consider here data obtained with a video-CCD imaging through an interference filter centered at 637 nm (FWHM 7 nm) that we call a “coronal camera”; any emission of low excitation lines was carefully avoided. The camera operated at the prime focus (Ref. 9); more than 6 x 10⁹ frames were taken over a f.o.v. of 135 x 105 arcsec⁻¹, with a spatial resolution near 400 km in the corona (0.06 and better).

2. OBSERVATIONS OF PLASMOIDS:
TEMPERATURE AND PROPER MOTION

The whole time sequence from the CFHT was digitized on the NSO/SPO’s video and computers facilities, and further processed using the software library of


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L. November (FITS-LIB). The first process applied permits an analysis of images of the plasmoid well above the noise background, by temporally-averaging over typically 1 bit, computed every 0.5 sec. From the raw data, the ratio between the maximum amplitude in a cut through the center of gravity of the plasmoid and the neighbouring coronal background at the beginning of the time sequence is of order of 3 %. The "Plasmoid" revealed during this eclipse is a high density bubble located at 1.15 Rʘ showing a large proper motion. It was mentioned that its size is typically 2 arcsec (approx. 1,400 km) but it is an averaged size, because along the sequence there are deep modifications of its shape and of its dimensions; from the beginning to approximately the middle of the sequence it has a compact structure of 2–3 arcsec. From the middle to the end of the sequence, we note the most important features: the breaking of the plasmoid in several parts with the apparition of links between them like "arms". Although they are not obvious on the mosaic, these separations appear when the main bubble is crossing the structures of the background corona; this becomes obvious when one watches the movie. This event brings two comments: first, it is impossible to determine if the plasmoid is really going through the structures (which are seen in the coronal background preferentially in a radial direction) or if they are just passing each other. The second comment concerns the reciprocity of the interactions: it is evident that a transfer of matter (increase of their intensity) is taking place between the plasmoid and the background structures.

The motion of the plasmoid is approximately monotenuous at the beginning, before the previously mentioned interactions. Its speed is constant at 100 km/s; the direction is not the radial one but it is the direction of the highest intensity gradient in the background corona. During the second part of the sequence, the direction of motion is almost the same for the main bubble (the central one) but has slowed down to 50 km/s. The motion of detached smaller plasmoids is quite the same (very low relative speed between them) except for the first one created at the very beginning of the sequence, whose motion has the same characteristics than those of the main bubble for the whole movie.

Regarding the lifetime of the plasmoid, it is significantly greater than 250 seconds (which corresponds to the period of the visibility of the plasmoid in our data) but it is clear that the lifetime of this event is not much longer, because the continuous interactions with the coronal background features imply a rather fast "dislocation". The origin of the plasmoid is unknown but if we follow back the direction given by the trajectory to the Sun, we find coronal interacting loops which could have ejected our bubble. With a velocity of 100 km/s it only needs a few hundred seconds to come in our field of view.

3. MEASURED "PHYSICAL" PARAMETERS

We now consider all physical parameters which can easily be deduced from these observations and also from general considerations of the static and from the dynamical equilibrium. To be shorter, only average values over the whole plasmoid are given in this rather preliminary report. From the absolute photometry of the eclipse images, we deduced the average electron density in the plasmoid: \( N_{\text{in}} = 3 \times 10^{6} \text{cm}^{-3} \) in excellent agreement with [4]; in the surrounding corona, at the same radial distance of \( r = 1.15 \text{ R}_ʘ \), we got \( N_{\text{ex}} = 3 \times 10^{5} \text{cm}^{-3} \), so \( N_{\text{in}} = 10 \times N_{\text{ex}} \). The electron temperature was evaluated at the very beginning of the time sequence, from the estimation of the ionization degree of H and the Ha-emission measure observed on our 3-m focus images taken with a radial filter: \( T_{\text{in}} = 2 \times 10^{5} \text{K} \); in the surrounding corona, we took \( T_{\text{ex}} = 2 \times 10^{6} \text{K} \), which means that kinetic pressures are such that: \( P_{\text{kin}}^{\text{in}} = 0.1 \times P_{\text{kin}}^{\text{ex}} \). It immediately follows that the plasmoid exists and is relatively stable thanks to its inner magnetic pressure which balances the external coronal pressure, due to a system of inner currents put on motion or generated before. The sonic velocity inside the plasmoid is of order of 20 km sec\(^{-1}\) which is the velocity we measure in Lagrangian coordinates in the external "shell" or the "skin" of the plasmoid observed to change in shape, from oblate to prolate form, in about 60 to 70 sec of time, over typically 1.5 Mm. These "oscillations" seem still close to acoustic global oscillations, although the overall behaviour of the plasmoid is rather alfvénic. Its average speed during its "trip" inside the corona, see [9], in Euler coordinates, is 60 to 70 km sec\(^{-1}\). Let us now estimate the magnetic field amplitude inside and outside, assuming Alfvén times are small, as usually the magnetic Reynolds number is large at these temperatures and scales. From the "static" equilibrium we should have:

\[
\frac{B_{\text{in}}^{2}}{8\pi} = \frac{B_{\text{ex}}^{2}}{8\pi} + N_{\text{ex}} \cdot k \cdot T_{\text{ex}} \tag{1}
\]

as we neglect \( P_{\text{kin}}^{\text{in}} \) in a first approximation; then \( B_{\text{in}} \approx B_{\text{ex}} + 1 \text{G} \). The corresponding electric currents inside the plasmoid are of order of \( 10^{4} \text{A} \) which is at least one order of magnitude smaller than inside a prominence. From the condition of dynamical equilibrium, neglecting \( P_{\text{in}} \), we get:

\[
\rho \nu_{\text{in}}^{2} \geq \frac{B_{\text{ex}}^{2}}{8\pi} \tag{2}
\]

We do not consider here the rather important details of the motion of the plasmoid in Euler Coordinates, so again to simplify we take \( \beta_{\text{ex}} = 1 \); than \( B_{\text{ex}} \approx 1 \text{G} \) and \( B_{\text{in}} = 2 \text{G} \); (2) is then satisfied. We then easily compute the Alfvén velocity:

\[
\nu_{\text{ex}}^{\text{2}} = 120 \text{kmsec}^{-1} \text{ and } \nu_{\text{in}}^{\text{2}} = \text{kmsec}^{-1}
\]

Note that these velocities are rather small: the observed velocities (in Euler coordinates) are largely comparable to these values which seems to confirm that the analysis of the plasmoid could also be made in the frame of the MHD-vortex theory [10].

4. EXISTENCE AND STABILITY OF A PLASMOID-LIKE MAGNETIC CLOUD

In this short paper there is no possibility to consider all aspects of this question; we refer the reader to the more extended paper in press [11]. In a first step, the magnetic structure of a toroidal vortex was instigated, based on a 2.5 d model (axi-symmetric torus) with a single current loop, see Figure 2; the Grad-Shafranov equation is considered in spherical coordinates. For this configuration, the plasmoid is found unstable when both the Spies and the Mercier criteria are applied in the frame of the ideal MHD. Going further, it was found that superior order solutions like the one shown on Figure 3 corresponds to indeed stable configurations in the external parts which are indeed surrounding the inner torus, like a shell (2nd radial mode). We then note that from the theoretical point of view, stable magnetic configurations with separatrices exist to explain the relative stability of the plasmoid and moreover, that both an external magnetic field and an external kinetic pressure are needed!
Figure 1. Field of velocities around the plasmoid as computed from the temporal intercorrelation analysis using several frames separated by 0.75 sec of time and a step of 0.6 Mm.
At this resolution the noise reaches a level of 6 km/sec\(^{-1}\); however, the signature of a hydrodynamical toroidal vortex is clearly apparent, justifying the characteristic velocity pattern schematically shown in Lagrangian coordinates at the top corner.

Figure 2. Possible axially-symmetric magnetic configuration of a plasmoid; at the bottom, a cut showing the behaviour of beta. The plasmoid is unstable everywhere.

Figure 3. As figure 2 but at higher order; the plasmoid is now stable in the external shell.

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5. CONCLUSIONS

A coronal plasmoid was described for the first time, thanks to observations performed with the most powerful "solar" telescope used during a total eclipse. The most important physical parameters of the plasmoid were extracted and a model of toroidal vortex is discussed. The magnetic field configuration has already been treated to propose a stable configuration. The interface with the surrounding corona should now be considered to understand both its origine and its evolution, see also [12]. Questions connected with the possible importance of the contact and/or tangential discontinuities between the shell of the plasmoid and the background corona with the role of "reflected" MHD-waves and the shock before could appear more fundamental.

6. REFERENCES

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