MASS BALANCE AND MAGNETIC STRUCTURE IN QUIESCENT PROMINENCES.

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Abstract

We discuss implications for prominence models of the apparent downward motions which are frequently observed at the limb. Both the reality of these motions and the value of the material density in prominences are presently subject to a great uncertainty so that firm conclusions about the mass balance of prominences can hardly be reached.

As a consequence it is not still clear whether quiescent prominences need a more or less permanent mass supply like that which is assumed in siphon-type models or if quasi-static models of the Kippenhahn and Schluter family are sufficient to explain the overall stability of the prominence phenomenon. It is concluded that coordinated determinations of several physical parameters (magnetic and velocity fields; electron density) in the same prominences are wanted to allow a progress on this critical problem.

1 - Introduction

Two years ago was held at Oslo a Colloquium devoted to solar prominences : as progress of our knowledge has not been specially fast since the meeting it is clearly useless to repeat here all the conclusions which were reached at this occasion. Rather I want to discuss a more limited question, although it has implications in many parts of the physics of prominences, which is the problem of mass balance in quiescent prominences. One cannot claim that this is now the only important unknown question on the topics but, as we shall see, a better understanding of the mass balance would immediately help to choose between the various prominence models which are presently under discussion.

2 - Static and dynamical mass balance in prominences

Everybody has in mind beautiful Hα pictures of quiescent prominences where the general blade shape as well as the filamentary structure are well visible.

An important point we shall have to discuss is that quiescent prominence movies display an apparent slow downflow of material visible in Hα. One must stress that this is an apparent motion as seen on the plane of the sky, not a motion derived from a Doppler analysis.

Another fundamental point which is well known (Koutchmy, 1977) is the peculiar location of quiescent prominences in the corona where they are very frequently seen at the bottom of streamers. Most striking is the fact that they are often surrounded by a dark cavity and by arches which have been known for many years (Kawaguchi, 1967; Saîto and Tandberg-Hanssen, 1973). The dark cavity has been generally interpreted as a proof of the "condensation" of coronal matter into a prominence and we meet there what can be called the "static mass balance problem" when we try to compare the mass available from a cavity and the mass necessary to build up a prominence.

One starts with the results of spectroscopic diagnostic. As which concerns the density, in which we have presently most interest, the possible range is still spread over nearly two orders of magnitude (Hirayama, 1979; see table 3) this scatter being due either to inaccurate determinations or to real variations among different prominences. Useless to say this uncertainty on the actual value of the density will hamper all the following analysis on mass balance.

Once one has derived the electron density, the ionization of hydrogen and the filling ratio,it is possible to derive an average mass Mp for a quiescent prominence which is found to be of the order of 10^{16} g. Note that this is not a negligible part of the total coronal mass (3×10^{17} g) so that the mass balance in prominences may be a point of interest for the more general problem of the coronal mass balance.

It is also possible to estimate the mass Mc which has become available after the depletion of a coronal cavity (Saîto and Tandberg-Hanssen, 1973) and it turns out that Mp >> Mc which raises two questions : whence comes prominence material ? What is the nature of the cavity-prominence association, if any ?

The situation remains confuse if we switch to what can be called the "dynamical mass balance problem" which is related to the apparent downflow of prominence material as seen on Hα movies. That this effect is conspicuous is proved by the fact that this apparent motion was taken many years ago as a criterium for prominence classification by Menzel and Evans (1953). Recent careful studies by Engvold (1976) show that one can adopt a figure around 1 - 10 Km/s for the apparent downward velocity and eventually one is left with the following dilemma : either it is considered that these are real material motions, because it is not so easy to explain the observations by variations of excitation or ionization of prominence matter. Therefore one finds that the whole prominence will be emptied in some hours. As a matter of fact the figure of 5 hours was quoted by Anzer (1979) at one of the Oslo concluding workshops. Or one considers that the real material motions are not systematically downwards, and this point of view is supported by Doppler studies of filaments on the disc, specially by the recent observations of Martres et al (1980) who find no systematic downward velocities. In that case the material loss by a prominence is very slow and could be counterbalanced by the matter injected into the corona at the time of Disparitions Brusques (Engvold, 1980). But more Doppler studies of filaments on the disc are necessary before any conclusion (Kubota, 1980).

Both wide range of derived prominence density and uncertain signification of apparent downward motions make possible very different conclusions about the time lapse sufficient to empty a prominence : by contrast with the figure of 5 hours mentioned previously you can read that, at another workshop of the Oslo Colloquium Maltby (1979) suggested a time lapse of the order of 10 days... Such an uncertainty obviously has important consequences on prominence models !

3 - The mass-balance in some prominence models

Having in mind the idea that prominence material must be renewed within some hours some authors have felt it impossible to find enough available matter in the neighbouring corona and have been led to siphon-type models whose the first famous example was given by Pikelner (1971).

Recently there has been a lot of investigations concerning the magnetic stability and the thermal equilibrium in coronal arch structures with specific models of quiescent prominence by Ribes and Unno (1980) and by Uchida (1980). Concerning this family of models one can make three remarks : it is the only type of prominence model in which one can see clearly the origin of prominence material; but it postulates a magnetic configuration with a central dip which has not been observed clearly in the corona (Serio et al., 1979); and, finally, when the prominence is formed the type of support which is invoked is of the type of the classical Kippenhahn and Schluter model which will be considered later.

Although the model put forward by Pneuman (1972) does not invoke siphon mechanism its analysis could probably be extended to the case where material is supplied from below. The interest of Pneuman's work is to show that the existence of prominences at the bottom of streamers and the occurence of coronal cavities could be a natural consequence of density and temperature adjustments to satisfy energy and mass balance conditions at the bottom of a streamer. In such a view a quiescent prominence is usually formed in a generally bipolar magnetic configuration (see figure 2 and 6 in Pneuman's paper).

In the case where we need alittle material to make up a prominence, because it is emptied very slowly, different authors have studied the possible occurence of thermal instabilities in specific regions of the corona where prominences would "condense". By contrast with the bipolar magnetic geometry assumed by Pneuman, Kuperus and Tandberg-Hanssen (1967) consider the neutral sheets which might appear over neutral lines of the photospheric field and show that they cannot remain in thermal equilibrium so that matter starts cooling which could ultimately result into the formation of a prominence (figure 4 in Kuperus and Tandberg-Hanssen paper).

4 - The prominence-corona association

Before any comparison between measured magnetic field and the configurations forecasted by Pikelner, Pneuman and Kuperus (to quote only these three main families of models) one can notice that the corona-prominence association should be different in these three cases so that there could be already observational tests based upon morphological properties which could help to choose the most likely model (but differentmechanism giving cool prominences in the hot corona can simultaneously be at work in the solar atmosphere !). Unfortunately observational data do not seem to give, up to now, a consistent idea of the prominence-corona association : for instance Fort and Martres (1974) have shown that coronal arches surrounding a prominence are more nearly parallel than perpendicular to the long axis of the prominence and that the classical view of a coronal cavity thought as a tunnel observed edge-on is not often consistent with the real geometry of the filament; thus even a model like Pneuman's which, at first glance, seems to be able to explain the observed corona-prominence association, would probably require deep geometrical modifications.

On the other hand, the observation of X-ray arches over neutral lines has been taken as an argument against the magnetic configuration assumed in the Kuperus-Tandberg-Hanssen model (Mc Intosh et al., 1976, Sheeley, 1979) but one must admit that X-ray arches are not very conspicuous in the vicinity of quiescent prominences and that they are generally observed much higher. We have already mentioned that no central bending of coronal arches has been observed on X-ray pictures (Serio et al., 1979) which does not support a geometry of the type chosen by Pikelner.

A fundamental test which bears directly on the mass balance problem would be to try to observe ascending motions in the vicinity of filaments (on the disc) for radiations corresponding to intermediate stages of ionization. Although some indications of this type have been provided by OSO 8 (Lites et al., 1976) this question certainly deserves much more attention. Ground-based observations at the limb can also bring useful information about the "prominence tails" which may be the most important part of the corona-prominence interface as which concerns the mass balance problem (Kawaguchi and Oda, 1972). One remembers, for instance, the evidence for occasional large horizontal velocities found by Engvold et al. (1978) at the edge of some prominences.

5 - The magnetic support

Another way to attack the mass balance problem in quiescent prominences is to make it clear whether the prominence material can be kept in mechanical and thermal equilibrium in the lower corona, which would correspond to static models, or if we are observinga more or less continuous dynamical process. The physical parameter which has a critical role at this step is magnetic field in which prominence material is embedded. Therefore prominence models had to consider the support of cool matter which can be explained in several ways. It has already been mentioned that in the Pikelner model the material support is of the type early proposed by Kippenhahn and Schluter (1957). As a matter of fact more or less similar models have also been put forward (Tandberg-Hanssen, 1974) but the Kippenhahn and Schluter model still remains after 25 years one of the most successful and it has been the subject of detailed investigations including stability analysis (Anzer, 1969).

An interesting question, in view of the apparent downward motion in prominences, was to know whether the horizontal magnetic configuration which is foreseen in the Kippenhahn and Schluter model can keep material in strict static equilibrium or if slow vertical motions are allowed. Mercier and Heyvaerts (1977) have shown that the relative downward diffusion of neutral atoms is negligible but that, taking into account the Joule dissipation in subphotospheric regions of the currents which are pervading the prominence, one can explain downward velocities of some hundreds of meters per second.

The Kippenhahn and Schluter type of support is likely to be efficient also in the magnetic configuration considered previously in the case of the Pneuman model. On the opposite in the case of the Kuperus and Tandberg-Hanssen model the description of the prominence support takes into account the boundary condition set by the photosphere. Van Tend and Kuperus (1978) argue that the direction of the current in the Kippenhahn and Schluter model leads to unstable filament currents and they postulate a current in the opposite direction. But therefore the Lorentz force due to the ambiant magnetic field would be downwards and the support of cool material must be due to another mechanism. According to Kuperus and Raadu (1974) the global effect of the photosphere can be represented by a photospheric current flowing antiparallel to the prominence filament current which gives a force upward with the right order of magnitude (cf. figure 2 in their paper). Further investigations on this topics have been made recently by Lerche and Low (1980 a and b.).

Obviously, the axial current along prominence long axis modifies the initial ambiant coronal field. Anzer and Tandberg-Hanssen (1970) have computed the resulting lines of force for increasing values of the current in a Kippenhahn and Schluter configuration. As it is probable that there is a component of the background field along the prominence long axis, lines of force are actually helices. Therefore we get a field configuration which would explain the often mentioned spiral-like structures in prominences (Rompolt, 1975); such a situation certainly exists in erupting prominences but it can also been argued (Malville, 1976; Stenflo, 1979) that in quiescent prominences at rest spiral lines of force with subtelescopic structure are also existing.

Another point which has become clear in the recent year is that the magnetic vector makes a small angle with the prominence long axis instead of being directly across the filament like in the original Kippenhahn and Schluter work. This shear appears to be intimately linked to the thermal equilibrium of the prominence as it has been clearly shown in a recent investigation by Milne et al. (1979). These authors have shown that in a generally horizontal magnetic configuration cool material can exist only for a narrow range of values of β (the ratio of kinetic to magnetic pressure) and α (the angle between the field vector and the prominence long axis); see figure 9 in the paper of Milne et al. Modifying the heating function it is possible to produce solutions for less stringent values of α and β but there is always a limit $\beta < 0.8$ and $\alpha > 7^\circ$ for the existence of prominences.

6 - Observed versus forecasted magnetic structures

This problem has been discussed (Anzer, 1979) during one of the concluding workshops of the Oslo Colloquium. Although the result is slightly disappointing, because observations do not seem to be sufficient to retain already a single model, it is interesting to follow the résumé written by Anzer (see figure 1 in his paper).

Models of the Malville's type with large helical structures do not fit observations except in destabilized erupting prominences (see Tandberg-Hanssen, 1979, figure 4). Butpresent magnetic field measurements cannot discard the possibility of helical structures along the horizontal long axis prominences if the diameter of helices is below the resolving power of instruments ($\simeq$ 2000 Km). On the other hand observations seem to exclude structures like vertical helices which would have been more intuitive in view of the limb appearance of prominence ...

The Kuperus and Tandberg-Hanssen model has some features which do not fit observations : 1) the field is far from being horizontal 2) the transverse field strength is probably smaller than observed (Raadu, 1979) 3) the shear of lines of force does not seem to be easy to understand 4) the field polarity in prominence material should be opposite to the field polarity in the neighbouring photosphere.

Rust (1979) has emphasized that such was not the case and that he had always observed field polarities identical in the photosphere and in the prominence. My own feeling was the same at the beginning of investigations on the Hanle effect but I believe now that there are at least some cases where the field in prominences has a polarity oppositeto the photosphere : actually as the field vector is nearly along the prominence long axis it is rather difficult to ascertain experimentally what is the polarity of the field in prominences. This point which seems critical for the choice of the most probable prominence model certainly deserves further observational work.

Eventually, and even with some confusion about the question of the field polarity, it seems to me that present magnetic field measurements are more often consistent with the Kippenhahn and Schluter model than with the other one, but this opinion must not be taken as a definitive conclusion. In this connexion I have tried to compare some of the results of Milne et al(1979) with my recent measurements : first one can notice that the strength of the prominence field is now well known (Leroy, 1979, see figure 9) and that the agreement between Zeeman and Hanle method (Sahal-Bréchot et al., 1977) is excellent. As for the angle α between the magnetic vector and the prominence long axis I have obtained recently good data concerning prominences of the polar crowns which confirm that α is around 25° for these objects while it is somewhat smaller for prominences inside active regions. This is well consistent with the requirement that $\alpha > 7°$ (Milne et al. 1979), but one must remember that the observations would be identical for an unresolved horizontal helical field of subtelescopic scale with a pitch angle of about 35°. At last I have given on figure 1 the repartition of B_T which is the supporting component of the field, perpendicular to the prominence axis (figure 1 refers again to prominences of the polar crowns). Following Milne et al. there must be the condition

$$\beta < 0.8 \text{ i.e. } kNT < 0.8\, B_T^2 / 8\pi$$

or

$$Ne < 1.1 \times 10^{10}\, B_T = Ne \max \quad (\text{for } N \simeq 2.5 \times Ne)$$

Thus the upper scale of figure 1 shows the maximum value Ne max which can be supported by the field B_T.

If one retains low values of Ne like those which have been computed recently

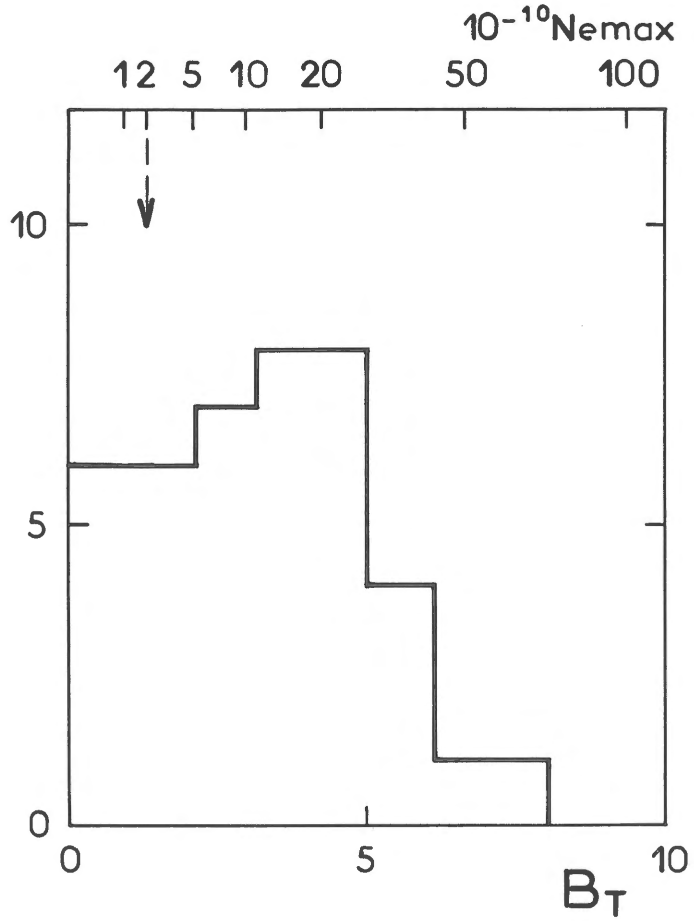

Figure 1.

Repartition, for a sample of 41 prominences of the polar crowns, of measured values of B_T (lower scale) : B_T is the component of the magnetic vector across prominence long axis, expressed in Gauss. The upper scale gives the corresponding values of Ne max defined following the equality :

$$kNmaxT = 0.8 \times B_T^2 / 8\pi \quad \text{with } Nmax = 2.5 \times Ne\ max.$$

by Heasley and Milkey (1976; see model c 1) and seem to fit quite well spectroscopic data, it is seen that the magnetic support is generally much larger than necessary according to figure 1; therefore the prominence magnetic field is probably not far from a force-free configuration.

7 - Conclusion

If we cannot find presently a model which fits completely magnetic observations it may be that models have not included something essential and the fine structure of prominences has often been mentioned at this stage. Together with the problem of geometrical fine structure one has to deal with a question of life time of prominence material : it is true that a given neutral line can remain the seat of prominence appearance during several months and it is true that a given prominence can last several weeks. But when one is observing with better resolving power it becomes clear that the lifetime of individual knots or threads is much smaller, of the order of 10 minutes only (Engvold, 1976). Therefore it may be erroneous to search prominence models in which cool material can reach mechanical as well as thermal equilibrium and one can be tempted to think towards dynamical models as Priest and Smith (1979) have recently proposed it (see figure 8 in their paper). I don't know whether one can explain theoretically heating or cooling times of only several minutes but, from the experimental point of view the idea of a quiescent prominence as a medium in always evolving thermal state, within a generally favorable magnetic configuration, would nicely fit many observations. Such a point of view would also modify drastically some topics linked to the mass balance problem that we have discussed previously.

From the observers side much remains to be done and it seems to me that the most essential requirement would be now to recover, for a given prominence, a complete set of data concerning the electron density, the velocity field and the magnetic configuration. This aim is not impossible to reach if several observatories are involved in such an endeavour. On the other hand, further researches on the shape of coronal structures in the vicinity of prominences are much wanted : they should be undertaken in future space experiments with help of EUV images corresponding to various excitation stages and having as good as possible spatial resolution.

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