JOINT DISCUSSION NO. 5

VERY HOT PLASMAS IN CIRCUMSTELLAR, INTERSTELLAR, AND INTERGALACTIC SPACE

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THE SOLAR CORONA

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Abstract. Recent observations from space have shown that the solar corona is spatially a very structured medium and temporally a very dynamic one. The consequent changes in the current theoretical ideas about coronal physics are reviewed. The role of the magnetic fields in shaping and heating the coronal structures is especially underlined.

This Joint Discussion on Very Hot Plasmas in Space starts quite appropriately with an exposition of our present understanding of the physics of the solar corona. The importance of coronal studies for the whole subject stems from many different and complementary considerations. There is an historical reason: the solar corona has been known to exist for many decades and several diagnostic techniques have been devised to obtain information on its physical state. The same techniques are becoming available for the study of other objects and systems. There is a practical reason: the Sun's proximity allows us to perform better and more detailed observations, that hopefully will make it possible to distinguish between the important features and the marginal ones. This improved insight will help us in understanding the behavior of other cosmic plasmas. There is a conceptual reason: although very hot plasmas are generated in terrestrial laboratories, their spatial and temporal scales are so vastly different from those encountered in space as to make extrapolations unsafe. The Sun represents, therefore, an astrophysical laboratory, where relevant plasma experiments are continuously performed and whose results can be scaled to more extended systems with some degree of confidence.

In this review I shall consider as a definition of the solar corona that part of the solar atmosphere whose temperature ranges from 10^6 K up. To fix the physical range of the various parameters, temperatures of 10^6 K to more than 10^7 K can be considered as typical, along with densities from $\sim 10^8$ cm^{-3} to more than 10^{10} cm^{-3}, the lower and upper limits referring to very quiet regions (coronal holes) and to the core of flaring regions, respectively. Since the corona overlies much cooler regions, it is clear that it cannot be radiatively heated. Other mechanisms must be operating to form and to maintain this hot and dilute

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plasma at the top of the solar atmosphere. Let's for the time being consider a spherically symmetric, homogeneous model of the solar corona. The validity of such a model is at best very questionable and we shall come back to this point later, but it serves here for the purpose of illustration. At the lower boundary, the corona terminates abruptly, the temperature falls precipitously to chromospheric values ($\sim 10^4$ K) over a very short distance, of the order of 10^2 km, that must be compared with typical scale lengths of 10^4 km or more in the corona. This thin transition region is of vital importance because it represents the link between the corona and the more standard underlying layers and we believe that what happens in the corona has its ultimate origin far below. Luckily enough, we are now in the position of having a very detailed knowledge of this region, since many EUV lines are formed there. I would like to stress the fact that the transition region is indeed very thin as compared to the rest of the atmosphere and occupies a minute fraction of the total volume. Yet, its importance in determining the physics of the solar corona can hardly be overestimated. It represents the first of many examples in coronal physics, as will be seen in this and in the following presentations, of thin structures whose importance for the understanding of what is going on exceeds by far their volumetric importance. There are now reasons to believe that the key to the interpretation of many relevant solar phenomena will come from a proper understanding of the physics of these thin regions. This should come as no surprise, since the importance of "boundary layers" in fluid dynamics and MHD is well known.

Before discussing this, however, let me give a quick look at the relevant energy sources and sinks for the solar corona, again considering a spherically symmetric model for the quiet Sun. If we assume a net balance between the various inputs and losses of energy, the energy equation is written as

$$\nabla\cdot(\vec{F}_r+\vec{F}_c+\vec{F}_m+\vec{F}_g+\vec{F}_k+\vec{F}_e) = 0$$

where F_r is the radiation flux, F_c the thermal conductive flux, F_m represents the mechanical flux due to some unknown heating mechanism, and the last three terms are convective terms associated with the solar wind and refer to the gravitational energy, the kinetic energy and the enthalpy fluxes, respectively. These three terms can be grouped together and their sum will be indicated by F_w. The order of magnitude of the various fluxes (in the quiet corona) are

$$F_r \simeq 2\text{x}10^5 \text{ erg cm}^{-3}\text{ s}^{-1}$$
$$F_c \simeq 1\text{x}10^5 \text{ erg cm}^{-3}\text{ s}^{-1}$$
$$F_w < 5\text{x}10^4 \text{ erg cm}^{-3}\text{ s}^{-1}$$

which gives $F_{total} \simeq 3.5\text{x}10^5$ erg cm^{-3} s^{-1}, that must be compared with an estimated chromospheric loss of $4\text{x}10^6$ erg cm^{-3} s^{-1}. The ratio F_{chr}/F_{cor} is therefore of the order 10 and if we consider the divergence of the

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fluxes, to get the energy loss per unit volume, the ratio becomes larger since the coronal scale height is much larger than the chromospheric one. From the above it is clear that energy-wise the problem of coronal heating is marginal with respect to that of chromospheric heating and indeed it is not a problem at all, since many different mechanisms are conceivable that have enough energy to heat the corona, and no discrimination between them can be found on purely energetic grounds. The problem of coronal heating is therefore a question of detail: if a convincing solution of this problem has to be found, the approximations introduced in the basic assumptions should not be larger than the effects we want to explain. This brings us to the question of the homogeneous models.

It has been known for a long time that inhomogeneities were present in the corona, for instance from high-resolution radio observations, but this structuring was considered to be of minor importance, at least for the understanding of the physical processes taking place in the solar atmosphere. The assumption of homogeneity allowed the construction of analytic or semi-analytic models, capable of explaining the average properties of the solar plasma. It is sometimes felt that the smoothing implied in homogeneous modeling must somewhat correspond to the observational averaging, due to finite resolution effects. This, however, is not generally true, as can be easily seen by considering any phenomenon presenting a threshold. The commonly accepted wisdom before the availability of the present-day, high-resolution observations was that the average, background properties had to be studied first and that the investigation of the structures could be performed independently afterwards. Today, observations are possible to a few arcseconds resolution from radio to X-ray wavelengths. They clearly indicate that the structuring of the solar corona is so extreme as to devoid of significance the homogeneous models. The solar corona appears to be rather a collection of widely different individual regions, than a uniform medium on which small perturbations are superimposed. A more sensible approach seems therefore that of studying first the physics of the individual building blocks and take averages only afterwards, if necessary. The essential nature of inhomogeneities in the corona has been especially stressed by Vaiana and Rosner (1978) and their view is now shared by many solar physicists.

Structure means geometry. The full three-dimensional shape of the various elements that constitute the solar corona must be taken into account and the question of what shapes those elements naturally arises. The answer comes straight from observations that show beyond doubt that the magnetic field is the direct responsibility of the coronal structuring. The magnetic field not only defines and separates the different regions, but it is also most likely a determinant of the local physical state of the coronal plasma. A direct measurement of coronal magnetic fields has proven so far impossible. But the observation of coronal structures, such as the coronal holes or the active-region loops, and the extrapolation, under given assumptions, of the measured photospheric line-of-sight fields, clearly point toward the importance of the topology of the magnetic fields for the determination of the physical state of the plasma. Thus, active regions are generally associated with "closed" magnetic field topologies and coronal holes with "open" topologies. The global, large-scale geometry of the magnetic field is that of a potential (current-free) field, as shown by the generally good agreement between the observed structures and the potential field lines computed starting from magnetospheric magnetograms. However, on the scale of the single structures, deviations from the potential field are apparent, which is interpreted as evidence for the presence of currents in the coronal plasma.

The existence of currents is also predictable on theoretical grounds. In fact, if we consider the high electrical conductivity of the solar plasma, which implies the freezing of the field lines in the plasma, and the high inertia of the photospheric material as compared to the coronal one, we easily realize that every motion at the photospheric level induces stresses in the field at the coronal level, which imply the flowing of currents. In the plasma physics language we may say that those currents are related to the fact that in the photosphere $\beta = 8\pi p/B^2$ is larger than unity, whereas in the corona $\beta < 1$.

The physical structure of loops is somewhat controversial: observations at different wavelengths, that is at different temperatures, of the same active region, clearly show the presence of loops. It is not clear if they are co-spatial, in which case we would have a radial temperature distribution with the axis cooler than the edge, or if they are different loops closely packed together. It seems that the first possibility applies to cool ($T \lesssim 10^6$ K) loops, the second to the hotter X-ray loops. Coronal flares appear almost invariably to take place in loop structures and this, together with the relative stability of the loop prior to flaring, poses one of the more exciting problems in solar plasma physics (Van Hoven et al. 1977). The modeling of coronal loop structure is still in a preliminary stage. Simple scaling laws have been proposed, connecting the loop's length, L, with its pressure, p, assumed to be constant, and the maximum temperature attained in the loop, T_m. Rosner et al. (1978a) find $(pL) \sim T_m^3$, in reasonably good agreement with the observations.

Let us turn now to the all-important problem of coronal heating, or, maybe better, heatings, since there are many different types of structures that must be heated and it is not obvious that a unique mechanism heats them all. If different emissivity is associated with different heating rate, it is clear that the corona is heated in a very inhomogeneous way, and that the active region-loops are heated more efficiently. However, the heating of loops is only a part of the story, since the long-lived structures known as coronal holes have temperatures only a factor of two lower than those of active regions. If a unifying factor has to be found, again it can only be the magnetic field. The magnetic field, in fact, besides being intimately connected with the physical structure of the corona, appears to be the only quantity whose spatial and temporal variation can match the observed scales of solar activity. It is likely, therefore, that the magnetic field has not only the passive role of defining and shaping the different regions of the solar corona, but also the active role of controlling the energy deposition rate in those regions. Most of the recent work on coronal heating concentrated, therefore, in the study of mechanisms related to the magnetic field. The proposed models can be roughly classified in two broad categories: wave heating and current heating. We shall briefly summarize the positive and negative aspects of both. An extensive discussion on heating mechanisms can be found in Hollweg (1979a).

Wave heating. This class of models postulates that the heating is due to the dissipation of waves that generate in the photospheric or sub-photospheric layers and propagate upwards, possibly being refracted or reflected by the inhomogeneities encountered on their way. The various models differ by the choice of the type of wave and of the damping mechanism. Acoustic (or internal gravity) waves have been for a long time considered strong candidates within the framework of homogeneous models and have often been used to make predictions on coronae of other stars. Although probably important for chromospheric heating, these models seem incapable of transporting enough energy at coronal levels. In addition, these waves are not connected with the magnetic field structure, which makes them unattractive. The attention has therefore turned to wave modes directly tied with the magnetic field, such as the Alfven and fast MHD modes and the alfvenic surface waves.

Alfven waves can be easily generated by twisting the foot-points of magnetic flux tubes. Due to the effective anchoring of the field lines in the photospheric plasma, any movement at this level can be the source of such twisting motions. Purely torsional Alfven waves have been studied in detail by Hollweg (1979b), both in open and closed field geometries. They easily reach coronal heights and the Poynting fluxes associated with them seem to be sufficient to heat the chromosphere and corona, if this energy can be efficiently damped. This is actually a weak point of the model since the damping mechanism is poorly understood. There are various possibilities, ranging from joule, viscous and frictional damping, to nonlinear damping by coupling into compressional modes or into MHD fast waves. Each of these mechanisms presents, however, its own problems and more detailed studies are required.

Fast MHD waves are refracted by the coronal structures and this can lead to selective dissipation of energy (Habbal et al. 1979). From this point of view the coronal active region loops delineate the region of preferred fast wave energy deposition and therefore their shape is only indirectly associated with the underlying magnetic structure. It must be kept in mind, however, that thermal conduction, that acts practically only along field lines, will tend to make the hot structures aligned with the magnetic field. The advantage of the fast waves is their ability to carry energy across the field lines and this results in a lower requirement for the energy density that has to be concentrated in these waves. This model also presents problems with the damping mechanism. If the fast waves come from below the transition region, they can be totally reflected and never reach the corona. The energy deposition is assumed to proceed through collisionless Landau damping and this may not work in the denser regions. Finally, if long wavelengths are involved, the use of geometrical optics may not be justified.

The existence of structure implies the presence of gradients of various quantities. For instance the Alfven velocity is bound to change rapidly near the edges of the loops. In this situation, alfvenic surface waves can be generated in response to the shaking of magnetic flux tubes (Ionson 1978). In spite of their name, these waves do effectively occupy most of the tube cross-section in a number of cases (Wentzel 1979), so that the energy flux density requirements are easily fulfilled. The distinctive feature of the heating mechanism based on surface waves is the predicted existence of a very thin, high-temperature sheath. The conversion of the surface wave energy into heat takes place via a resonant interaction with a (kinetic) body wave, which can dissipate. The model thus predicts quite naturally the occurrence of radial temperatures profiles with the edges hotter than the axis. The thickness of the hot sheath, for reasonable values of the physical parameters, turns out to be 1 km or less. There are a few interesting dynamical consequences of this model. The high-temperature sheath drives upward convection in a layer next to the sheath. The up-convected plasma then crosses the field lines due to a Rayleigh-Taylor instability at the top of the loop, undergoes radiative cooling and finally falls down in the cool core. The downflows could be identified with the observed "coronal rain." The thickness of the convective layer is estimated a few tens of km, below the present-day resolution limits. Again we are faced with a situation where the postulated relevant physical processes take place in a very small region. One problem with this model comes from its incapability of explaining heating over extended regions. In fact, all the attempts to find a mechanism able to spread the heat outside of the dissipative sheath have so far failed.

Current heating. We have already seen that one can expect currents to be present in the solar corona and ohmic dissipation of currents could heat the coronal structures. The models of this class are obviously very attractive because of their intrinsic relationship with the field structure and evolution. There are a number of questions, however, that must be properly answered before accepting them. In the basic model of Rosner et al. (1978b) currents are supposed to flow in a thin (again!) sheath on the outside of the loop. Although suggested by the studies of Parker (1974) on magnetic flux ropes, this does not seem to be the only possible structure. If currents are so confined, it is possible to show that classical resistivity (i.e., that due to coulomb collisions between electrons and ions) is insufficient to heat the loops. In essence, the argument runs as follows: to heat the loop strong currents are required, but when these currents exceed some critical threshold the plasma becomes turbulent and anomalous resistivity should be considered instead of classical. At this point there are various possibilities, depending on the characteristics of the turbulence that develops. Ion-acoustic turbulence has been shown by Rosner et al. to have many of the properties required to construct a viable model. However, in order to maintain a steady-state ion-acoustic turbulence the electrons must be much hotter than the ions. This condition greatly reduces the allowed thickness, ΔR, of the current sheath: for $T_e/T_p = 10$, $\Delta R < 6$ cm! The problem appears even more difficult, if the effect of the turbulent diffusion is taken into account, that tends to increase the sheath thickness, thus quenching anomalous resistivity. Alternatively, electrostatic ion-cyclotron turbulence has been considered by Vlahos et al. (1979). In this case we can have $T_e = T_p$ and the computed thickness appears to have reasonable values. To make this model work, however, many conditions have to be satisfied, which makes it less attractive. In addition, troubles may arise when this mechanism is applied to long loops.

To summarize, we can say that anomalous resistivity seems to be required in this class of models, but it is difficult to create, to maintain and to spread it over large volumes. More generally, the observed structures seem to suggest very strongly the existence of thin sheaths, but the thickness of the theoretical sheaths is well below the instrumental resolution, which makes very difficult the discrimination among the various models by means of the observations. The long-standing problem of coronal heating is still there, as challenging as ever.

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