CHROMOSPHERIC INHOMOGENEITIES: ORIGINS AND DYNAMICS

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ABSTRACT

Observations of the solar chromosphere in selected spectral lines reveal a large number of inhomogeneities These inhomogeneities owe their origin to local enhancements of the photospheric magnetic fields. The detection of chromospheric inhomogeneities in other sun-like stars can be considered as the evidence for magnetic structures in such stars. This article gives a brief description of solar chromospheric structures as well as the evidence for similar inhomogeneities in stellar chromospheres.

INTRODUCTION

It is well known that thermonuclear reactions generate energy in the core of the sun. This energy diffuses out towards the surface and escapes as sunlight. The layer of gas at which this leak of photons begins is known as the photosphere Since there is less interaction of radiation with the more tenuous gas above the photosphere, one would expect the temperature to decrease outwards. However, eclipse observations have revealed the existence of hotter layers above the photosphere[1] which led to the concept of mechanical heating of the solar atmosphere. The chromosphere is one such region which begins at a temperature of 4000 K and rises to some 10^5K within a height of 2000 km above the photosphere. Since the chromosphere emits copiously in the red hydrogen line (6563 Å), it appears as a pink flash at second contact during a total solar eclipse and owes its name to that colour It was soon recognized that the emission component of the strong Ca^+ doublet at 3933 Å and 3968 Å originated mainly in the chromosphere. For cool stars at least, the appearance of these emission components, was a definite indication of chromospheres. The study of chromospheres has since then progressed along two parallel tracks. One track concentrated on the morphology and dynamics of the various chromospheric inhomogeneities visible on sun. The other addressed itself mainly to the influence of various stellar parameters like age, surface temperature, surface gravity and rotation on the strength of the chromospheric emission. However stellar chromospheres were also known to be inhomogeneous from their variable emission. Recent efforts have been mainly devoted to constructing a consistent picture of chromospheric dynamics by combining the knowledge derived from both the sun and the stars. This article will first discuss the solar chromospheric inhomogeneities and then use this knowledge as a basis for describing stellar chromospheric inhomogeneities.

SOLAR CHROMOSPHERIC INHOMOGENEITIES

The close proximity of the sun enables us to resolve many of its chromospheric inhomogeneities. The two spectral lines used for these observations are the H_α 6563 Å line and the Ca^+ 3933 Å line. Of these, the atoms absorbing H_α are present both in the photosphere and the chromosphere Thus the chromospheric information obtained by this line is contaminated by photospheric effects. However the larger abundance of H atoms and the strength of the H_α line both make this line very popular for chromospheric observations. It is only recently that the capabilities of the HeI 10830 Å line is being realised and one hopes to obtain quite new and exciting information about chromospheric dynamics by a fuller exploitation of the potential of this line[1,2] The other popular line *viz* the 3933 Å Ca^+ line (called the K line by Fraunhofer), has emission components which can be considered to be formed in the lower chromosphere. With the advent of observations from outer space, the Mg^+ lines 2802 Å and 2795 Å could also be measured and they provide excellent diagnostics for the upper chromosphere

The nomenclature of various chromospheric structures has unfortunately not been systematised, and we now have different names for the same entities depending on the spectral line in which they are observed. In this article, some of the confusion will be hopefully resolved. For a majority of cases, the origin of the inhomogeneity can be traced to local enhancements of the underlying photospheric magnetic field, although the precise role played by this field is not yet fully understood.

A conspicuous chromospheric feature is the plage or flocculus seen near sunspots and above fields of moderate strength. The plage is a manifestation of the active chromosphere. Its frequency of occurrence and the intensity of emission are maximum at sunspot maximum and vary with the well-known 11-year cycle seen in the sunspots. Each individual plage is a short-lived feature lasting for approximately three weeks. The plages themselves are made up of smaller elements called coarse mottles seen in Ca^+ light and rosettes in H_α light. This rosette or coarse mottle is actually an active region in microcosm[3] and certainly deserves further study. It is known to exist for 4 hr, after which it breaks up into still smaller elements called fine mottles or bright points in Ca light The same are seen as both dark and bright features in H_α and are called the dark and bright H_α mottles. The Ca^+ fine mottles are known to brighten up and decay with a time-scale of 200s[4]; dark H_α mottles live slightly longer whereas the bright H_α mottles live for roughly 500s[5]. Commonsense makes us believe that each structure is not an entirely different entity but different manifestations of the same entity viewed at different heights, temperatures and in varying degree of agglomeration. The fine mottles are also seen outside of plages in the so-called "quiet" chromosphere. In the quiet condition, they are arranged on the boundaries of hexagonal cells which are known to possess steady circulation patterns lasting for a day or so These cells, known as sugergranules, show an upward moving flow at their centre and downflow at the boundaries It is now known that this circulation can enhance the magnetic field at the boundary of the cells[6] Even in the network (as this pattern is called) the fine mottles are arranged into coarse mottles or rosettes and these larger bunches are found all along the boundary[3]

All this morphology is evident when we view the sun face on. When viewed in a tangential direction, on the limb, we see thin jets of cool dense gas shooting out at supersonic velocities. These jets, called spicules, are shortlived and it is only recently that their transient nature was exploited in modelling the flow within spicules[7] The bulk of the matter thrown up by spicules returns back in yet obscure forms, although the downward flow seen in lines of high excitation, as also the downflows inferred in "dark condensations"[4] could be an evidence of this return flow[8].

THEORETICAL CONSIDERATIONS OF SOLAR CHROMOSPHERIC STRUCTURE

Magnetic fields seem to dictate the morphology of the chromospheric structures, although precise magnetohydrodynamics modelling is not yet available. Emperical models based on spectroscopic data are available for a few individual cases and it appears that plages are generally denser and hotter than their surroundings A remarkable feature of the chromospheric plasma is that the ratio of average gas pressure to average magnetic pressure is much smaller than unity. Such a situation arises because gas pressure decreases almost exponentially with height, whereas magnetic pressure decreases less rapidly as some polynomial function of the height As a result, the magnetic field configuration must necessarily assume a force-free configuration, wherein it exerts no dynamical pressure on the gas Though this has to be the general structure, it will not hold at each and every point in the plage. This is more so because the photospheric magnetic fields continuously change their con figurations on various time scales. Small departures from force-free configurations will then lead to large fluctuations in the gas pressure. Furthermore the chromospheric gas is prone to a thermal instability at temperature $T \gtrsim 20{,}000$ K[9]. This instability arises because the heating and cooling processes are different functions of density and temperature An increase in the density will lead to an increase in the radiative losses If this cannot be compensated by a corresponding increase in the heating process, the gas will cool further becoming denser all the time A combination of pressure fluctuations caused by magnetic forces and the thermal instability could well lead to a variety of structures, but no serious thought seems to have been given so far, to this process.

Outside of plages, the network is now generally understood as being caused by the interaction of supergranulation with magnetic fields. The fine structure within the network (the fine mottles) is perhaps the chromospheric extension of photospheric magnetic elements[10] The formation of the photospheric magnetic elements is now supposed to result from a convective instability of weaker fields[11-13] although a recent study including radiative heat transport[14] puts a lower limit on the sizes of these elements. Solar physicists have not paid serious attention to the problem of the clustering of these elements into rosettes or coarse mottles, or for the different lifetimes of each chromospheric entity

The reason for this apparent lack of interest in questions of dynamics perhaps lies in the preoccupation of solar physicists with the more fundamental problem of chromospheric heating. Many energy budgets have been presented[15] and many processes have been considered but the arduous task of explaining the detailed morphology of inhomogeneous heat deposition is still left unexplored. It is known that the generation of dipole and monopole magnetoacoustic waves in magnetic regions far surpasses the generation of acoustic wave energy in non-magnetic regions[16]. There have been theories of magnetosonic shock wave energy dissipation in the solar atmosphere[17] Moreover some detailed calculations have been made for modelling non magnetic chromospheres in terms of radiation hydrodynamics[18]. The next task is to put theoretical ideas regarding generation, propagation and dissipation of waves together, and see whether they do reproduce the observations.

LESSONS FOR STELLAR CHROMOSPHERES

One can obtain several clues from solar studies which can be applied in the context of stellar chromospheres. One such clue concerns the width of the emission feature in the CaK line. It is well known that this width is directly related to the luminosity of a star for a wide range of spectral types and luminosity classes (the Wilson-Bappu effect)[19]. On the sun, it is the fine mottle that fits in this general relation and not the plage[4]. The fine mottle moreover shows only marginal changes in its Ca profile parameters from solar maximum to solar minimum, whereas the plage shows conspicuous variation with the solar cycle. Thus it has been suggested that stars deviating largely from the Wilson-Bappu relation are better candidates for showing stellar activity cycles[20]. There is another clue which shows that the ratio of residual intensities in the cores of H and K lines are different in plages and in fine mottles[21]. A final clue is the correlation between intense chromospheric emission and enhanced magnetic fields[10]. All these clues require very high dispersion for detection and hence can only be exploited using sophisticated equipment. A lot of knowledge has been accumulated meanwhile, using less demanding observations which we shall examine next.

STELLAR CHROMOSPHERIC INHOMOGENEITIES

The most popular index of chromospheric activity in cool main sequence stars, like the sun, is the Ca^+ H and K line core index defined as a ratio between the sum of the line fluxes over a bandwidth of 1 Å to continuum fluxes over 20 Å windows in neighbouring spectral regions free of lines. This index was used to monitor several stars showing chromospheric activity and was seen to vary with a period compatible with the rotational period of the star[22]. A wealth of other information lies untapped in the data as, for example, the sizes and lifetimes of the large complexes of activity analogous to those seen on the sun.

The optical observations have been complemented by ultraviolet and x-ray observations. X-ray observations are more indicative of coronal structure. The analogy from solar x-ray emission makes us believe that coronal loops are the most dominant sources of x-rays. This has even tempted some workers to model stellar x-ray loops and to predict their sizes, using scaling laws[23]. More conservative approaches also require two temperature-coronal models to fit the spectral data[24], thus hinting at 'open' and 'closed' magnetic topologies in these coronae. A recent study shows that the spectral lines emitted from hotter plasma show better rotational modulation than those emanating from cooler plasma[25]. This can be understood only if the hotter plasma is more unevenly distributed than the cooler chromospheric structures.

Chromospheric indices also show a correlation with age and rotation[26]. Thus it is seen that slower rotation is correlated with lower chromospheric activity. This is quite compatible with a dynamo origin for the magnetic fields. On the other hand, the stellar rotation is observed to slow down with age, which could probably explain the rotation-age-activity correlation. There is a small complication here though. Magnetic braking of rotation can take place both by coupling of the non-rotating stellar environment with the stellar atmosphere as well as by loss of angular momentum via stellar winds. It is also known from solar studies that the wind is topologically connected to the photosphere only in localised regions with open field lines. Thus magnetic braking by mass loss would be more important when 'open' regions are more prevalent. On the other hand, intense chromospheric emission is mostly indicative of 'closed' regions. As the magnetic fields produced by the dynamo decrease in intensity, the general braking produced by the first mechanism would reduce. However, the increase in 'open' type inhomogeneities would lead to increase in magnetic braking by the second mechanism. It would be interesting to examine the interplay of these two effects in a more quantitative manner.

Although one would expect the chromospheric activity to die down at the end of a star's main sequence life, a recent study has shown tha this may not be so[20]. Stars in the giant phase ar seen to exhibit a rejuvenated chromosphere. Thi has been explained in terms of an increase dynamo action produced in the star's interio when the core spins up during its pos mainsequence contraction[27] The emergence these newly created fields to the surface occu when the convection zone extends in dept during the post main sequence dynamical ev lution and finally touches the dynamo zone magnetic field production. By virtue of t turbulence of the convection zone, these new emerged fields must be 'patchy' or inhom geneous in nature. Perhaps, this 'patchine could be tested, although the outer envelopes these giants normally rotate too slowly for easy detection of chromospheric modulation.

CONCLUSIONS

The lessons that we learn from a study of solar chromosphere could be used for und standing stellar chromospheric variabili However, the range of parameters like rotati age and chemical composition is so varied stars that care must be taken while applying so concepts to these cases. On the other hand, same wide range in the parameters could be u to understand the phenomenon of chron spheric activity in more diverse ways than possible for the case of the sun. The solar-ste connection is thus a two-way connection w has been finally recognized in current trend chromospheric research.

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