The Solar-Stellar Connection

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Abstract

Solar observations offer the *luxury* of high spatial resolution and signal-to-noise ratios. It is essential that we are aware of the physical processes that take place on the Sun when we try to understand other cool stars. However, cool stars can help us to understand our Sun as they take these processes to extremes and extend enormously our parameter space. The study of cool stars of different mass, activity levels, rotation rates and surface abundances, allows us to trace the history of the early Sun and predict its levels of activity in the years to come. In the present paper we review recent work in the cool star area and give emphasis on some of the solar techniques applied to stellar studies. We discuss the rotation activity connection, outline current observational approaches to the problem of chromospheric and coronal heating and derive conclusions on the structure and dimensions of stellar coronae.

The Rotation-Activity Connection

Solar and stellar magnetic activity is associated with a wide range of phenomena such as flares, spots and plages, rotational modulation or simply the appearance of chromospheric and coronal emission. Intense chromospheric and coronal emission has been found to occur in spectral types F2 and later, a spectral type where convection starts to have a significant contribution to the energy transport. One of the most significant finding in this field is the Dividing Line (DL) in the H-R diagram (Linsky & Haisch 1979). The DL divides late-type giants into two groups; those with X-ray emission (G and earlier) and those without any X-ray emission (K and later). The disappearance of X-ray emission in cool giants is strongly linked with the onset of very strong winds in these stars (Haisch & Schmitt 1996).

The inverse square law of Skumanich (1972) ($F_{CaII} \propto t^{-0.5}$), provided the first strong evidence that activity rotation and age are related in the sense that the younger a star, the faster it rotates and the more active it is. This relation holds for stellar clusters of various ages as well solar neighborhood stars including the Sun. The same conclusion is also valid for the coronal emission which decreases faster as a function of age ($F_X \propto t^{-1.3}$, Stern et al. 1981). The chromospheric and coronal emission of active fast rotating stars, *saturates*. Saturation can be understood in terms of the limited area of the stellar surface. As more magnetic field is generated by increased rotation and deeper convection, a point is reached where the stellar surface is totally covered with active regions. The heating reaches a maximum and so does the radiative emission. An alternative interpretation is that the dynamo itself saturates. As the increased angular velocity generates stronger fields, the ratio of total magnetic and kinetic energy approaches unity. The equipartition achieved can provide an upper boundary to the total magnetic energy as the $J \times B$ forces suppress convection (Glatzmaier 1985).

The level of coronal saturation seems to decline in very fast rotating stars ($v \sin i > 50$ km s^{-1}). This effect is termed *super-saturation*. The ratio of X-ray luminosity to the bolometric luminosity (R_X) is a measure of the coronal heating efficiency. In Fig 1 we show R_X as a function of the line of sight rotational velocity for two open clusters (data from Stauffer et al. 1997). The decline of X-ray emission in ultra-fast rotators, is evident. With increasing rotational velocity the

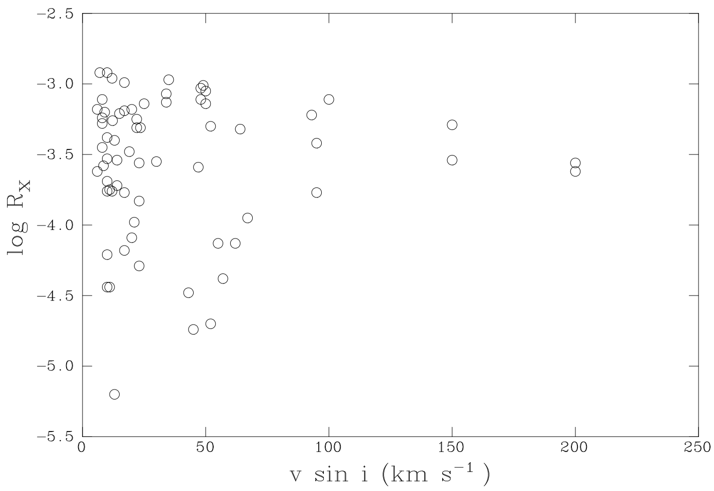

Figure 1: X-ray luminosity normalized to the bolometric luminosity (R_X) as a function of the rotational velocity for members of the open clusters IC 2391 and IC 2602. The drop of R_X at high rotational velocities, (i.e super-saturation), is apparent (data from Stauffer et al. 1997).

surface gravity decreases, and the hot coronal plasma becomes unstable and cools to chromospheric temperatures. More cool loops, emitting in chromospheric lines, can exist but not in X-rays. If the dynamo itself saturates, the X-ray emission would decrease even more with increasing rotation (Antiochos et al. 1986, Stern 1999).

Two Component Heating in Stellar Chromospheres

Convection has a two fold influence on atmospheric heating. Firstly, through its interaction with rotation giving rise to the magnetic dynamo and secondly with the generation of acoustic waves from the turbulent motions. An examination of the Mg II h&k emission as a function of spectral type, shows a large spread in the levels of activity at any given spectral type (Fig 2). Magnetic processes dominate the heating of the atmosphere for the vast majority of the sources. However, there is a well defined lower limit or minimum flux which is a strong function of spectral type. This basal flux indicates that all late-type stars have chromospheres. There is sufficient energy dissipated in their atmosphere to produce a temperature rise. It was suggested that the minimum flux is a measure of acoustic heating in the atmosphere (Schrijver 1987, Rutten et al. 1991, Mathioudakis & Doyle 1992).

A detailed comparison between the observed basal flux and time-dependent models of acoustically heated chromospheres was carried out by Buchholz et al. (1998). They investigate the heating of the chromosphere with acoustic waves by solving the hydrodynamic equations together with the radiative transfer and statistical equilibrium equations. The Mg II h&k radiation emerging from the atmosphere was then compared with the observations (Fig 2). The good agreement indicates that acoustic heating could provide sufficient energy to balance the radiative losses in the chromosphere of low activity dwarfs. Even if acoustic heating has some significance in atmospheric heating it co-exist with a magnetically heated component.

Acoustic heating can not explain the large spread in the Mg II fluxes at a given spectral type. One of the most promising approaches to this problem is the work of Cuntz et al. (1999) who model the nonmagnetic (acoustic) and magnetic components (longitudinal tube waves) simultaneously. The magnetic component comprises of flux tubes which are distributed either uniformly or in a distribution

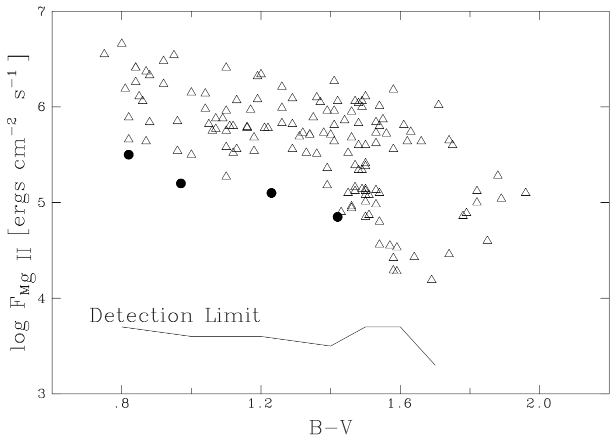

Figure 2: The Mg II h&k surface flux for K and M dwarf stars (△, from Mathioudakis & Doyle 1992). The model calculations of Buchholz et al. (1998) (•) are in good agreement with the minimum flux.

similar to the solar chromospheric network. The number of flux tubes is constrained by the magnetic filling factor which is in turn determined from magnetic field measurements based on Zeeman splitting. Their work has shown that acoustic heating is insignificant in fast rotating dwarfs (e.g. $P_{rot} < 30$ days) but becomes important in the slowest rotators (e.g. $P_{rot} > 40$ days) where the dynamo generated wave heating diminishes. However, there are some low activity dwarfs that have well defined solar-like activity cycles (e.g. HD 4628, Baliunas et al. 1995). We can not exclude the possibility that the basal chromospheric emission from these objects is due to a basal magnetic rather than acoustic heating process. Such a process could be provided by the turbulent magnetic field which is known to have a weak dependence on rotation and it exists even in the absence of rotation (Durney et al. 1993). Quantitative predictions of the energy generated by the turbulent magnetic field will allow us to distinguish between these possibilities.

Coronal Heating - Microflares & High Frequency Waves

The efforts associated with the heating of the solar corona can be grouped into two main categories. The first has to do with current dissipation following the millions of small scale reconnections throughout the corona (Parker 1988), while the second deals with the generation and dissipation of magneto-hydrodynamic waves (MHD) which propagate from the lower atmosphere and dissipate through ion viscosity and electrical resistivity (Hollweg 1981).

Microflares are short and impulsive energy releases and were first reported in hard X-ray observations of the Sun (20 keV) (Lin et al. 1984). In the stellar case Robinson et al. (1995) observed UV microflares on the M dwarf CN Leo using the High Speed Photometer on HST. They last typically for less than 30 seconds and occur with a frequency of $\approx$ 10-20 microflares per hour. They release 10^{26} - 10^{29} ergs with an average deposition rate of 10^{24} - 10^{28} ergs s^{-1} (the high values in this range refer to stellar microflares). For comparison we note that large M dwarf flares occur at less than 0.2 flares per hour with energy releases of up to 10^{35} ergs. The number of microflares increases with decreasing energy. This led Lin et al. (1984) to suggest that micro-nanoflares could provide enough energy to heat the quiescent solar corona. However, the test of this hypothesis is beyond the capabilities of current instruments.

MHD waves may be divided into Alfven waves and magneto-acoustic waves.

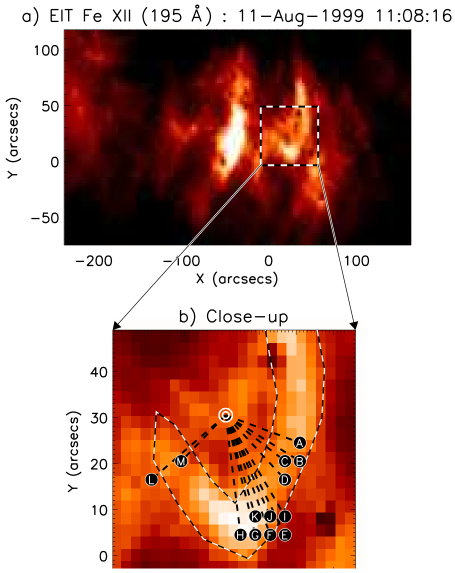

Figure 3: (a) Prominent coronal loops in active region NOAA AR 8651 observed with the SOHO EIT. (b) Close up of the loop showing the indexed points where the 0.16 Hz oscillation was detected (from Williams et al. 2001b).

Alfven waves may either be transverse and incompressible, propagating along the field, or compressional. Magneto-acoustic waves cause compression and rarefaction of the plasma as they propagate. Observationally one may expect Alfven waves to cause Doppler shifts while magneto-acoustic waves, (slow mode or fast mode), will cause intensity variations since the emission measure varies as N_e^2. Koutchmy et al. (1983) gave the first report of Doppler velocity oscillations in the range of 0.003 - 0.02 Hz. The Doppler shifts, seen in the Fe XIV green line, were interpreted as resonant Alfven oscillations. De Moortel et al. (2000) detected propagating intensity oscillations in Fe IX (10^6 K) in a solar active region. The frequency resemblance between these oscillations (0.002 - 0.006 Hz) and the photospheric 0.003 Hz oscillations, suggests that photospheric motions could be driving the coronal loop. However, these slow mode oscillations, (70 - 165 km s^{-1}), do not have sufficient energy for heating the corona. The feasibility of coronal heating by high frequency MHD waves has been investigated by Porter et al. (1994a,b). The main finding of their work is that wave heating of the corona is viable for high frequencies $\nu > 0.01$ Hz. These frequencies could be impulsively generated, possibly associated with reconnection events.

Williams et al. (2001a,b) recently reported the detection of a 0.16 Hz intensity oscillation in an active region coronal loop (Figs 3,4) using the Solar Eclipse Coronal Imaging System (SECIS). This oscillation is associated with a fast mode wave which travels through the loop apex with a velocity of $\sim$ 2000 km s^{-1}. A number of criteria need to be examined in order to assess if this wave can heat the loop. The first criterion is energy related. This wave could provide sufficient energy for heating the loop as its energy, $E_{wave} \propto \rho v_{rms}^2 v_g \approx 5 \times 10^6 erg\, cm^{-2} s^{-1}$, is one order of magnitude in excess of the radiative losses ($E_{losses}^{rad} \propto n_e^2 P_{rad} \approx 10^5 erg\, cm^{-2} s^{-1}$). The second requirement is that the wave travels sufficiently far (distance $> \lambda/4\pi$), a criterion that is again met. However, the dissipation length ($l_{diss} \approx 5 \times 10^{11}$ cm) is well in excess of the active region loop length ($l_{loop} \approx 10^{10}$ cm) and therefore it crosses the loop without damping its energy. Effective damping requires dissipation lengths of $\sim 10^9$ cm (Laing & Edwin 1995). Although this high frequency wave was not caught in the act, the relatively unexplored high frequency domain may provide some answers to the long standing problem of solar coronal heating.

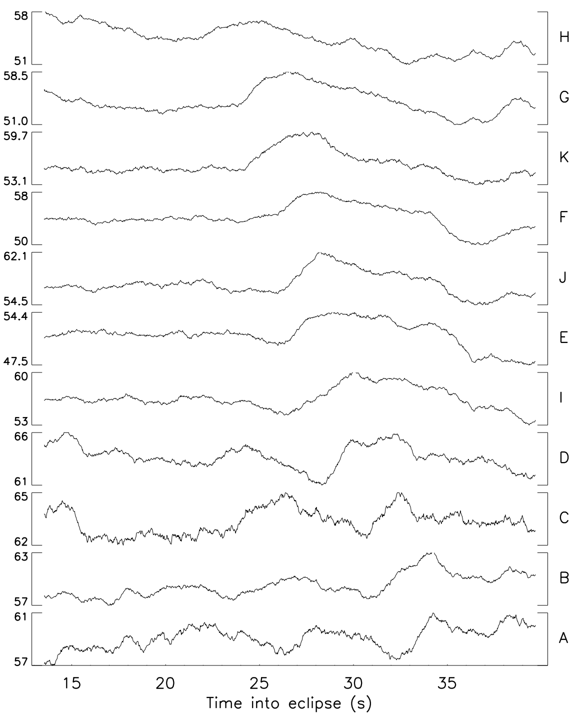

Figure 4: Plot of the intensity in the SECIS Fe XIV channel as a function of time at each point of the loop of Fig. 3 showing the motion of the peak intensity. The lightcurves are plotted sequentially according to increasing distance from point L along the loop apex (from Williams et al. 2001b).

New Insights In Stellar Coronae

The high time and spectral resolution observations from space missions such as Chandra and XMM-Newton, have brought stellar observations to solar standards. In Fig 5 we show a Chandra spectrum of the RS CVn binary Capella and a solar flare spectrum obtained with the Solar Maximum Mission (SMM). One of the parameters that needs to be determined in stellar coronae, is the electron density. A method extensively used in the solar case involves the use of line ratios from He-like ions. Lines of He-like O (O VII) near 22Å are well resolved in the spectrum of Capella. The derived electron density is $N_e = 2 \times 10^{10}$ cm^{-3}. Another important question has to do with opacity. Opacity effects in the solar corona have been known for several years. Acton & Catura (1976) provided the first convincing evidence that radiative transfer effects can be seen in X-rays. In this process, a photon from a resonance line is absorbed by an ion in the ground state. The excited ion then emits a photon at the same wavelength but propagating in a new direction. The process of absorption and re-emission can not be distinguished from scattering (resonant scattering).

One of the fundamental assumptions in the study of stellar transition region and coronae, is that the emission is optically thin. Although this may be a good approximation for the vast majority of coronal lines, a number of lines exist that can have significant optical depth. The optical depth at line center is given by (Jordan 1977)

$$\tau_0 = 1.2 \times 10^{-14} \lambda f \sqrt{\frac{M}{T_e}} \frac{N_{ion}}{N_{el}} \frac{N_{el}}{N_H} \frac{N_H}{N_e} N_e L \qquad (1)$$

where, λ is the wavelength in Å, f the transition oscillator strength, M the mass of the absorbing atom (a.m.u.), L the path length in cm, and N_{ion}, N_{el} and N_H are the number density (cm^{-3}) of the ion, element, and hydrogen respectively. Hence strong lines (i.e. those with high f values) can have high optical depths. In that

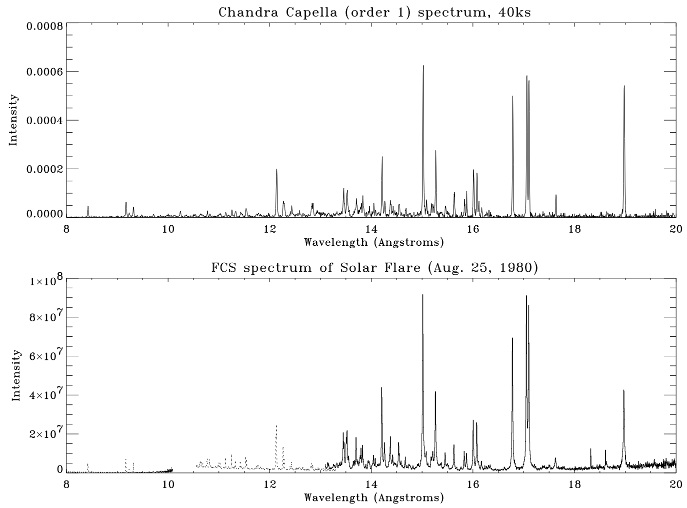

Figure 5: The Chandra spectrum of Capella is very similar with the decay phase of a solar flare observed by SMM (from Phillips et al. 2001).

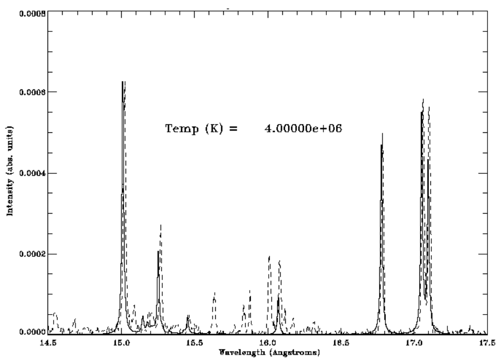

Figure 6: The Capella spectrum in the Fe XVII region (15 - 17Å) (dashed line), compared with a theoretical spectrum (solid line) computed under optically thin conditions. Fe XVII & Fe XVIII are the only lines included in the theoretical spectrum (from Phillips et al. 2001).

case the line flux equals the optically thin line flux multiplied by the photon escape probability ($P_e = \frac{1}{\tau_0\sqrt{\pi ln \tau_0}}$). We emphasize that high optical depths do not mean that the photons will be trapped; this will only occur for values of τ greater than about 10^3, and hence the transition region and corona remain effectively optically thin. Although the photons will escape, the presence of dense structures along the line of sight means that some will be scattered away and therefore will not be detected.

When the line intensity ratio is used to study opacity, the lines considered generally fall into two groups: (i) pairs of lines from a common upper level and (ii) pairs of lines from a common lower level. In optically thin conditions, the flux ratio of lines belonging to the first category will be equal to the ratio of the radiative transition probabilities, while the flux ratio of lines in the second category will be equal to the ratio of their collision strengths.

Opacity can be used as a diagnostic tool. The optical depth is proportional to the electron density and the line of sight path length. Optical depth estimates combined with measurements of the electron density, will allow direct estimates of loop lengths and scale heights in the corona. Given the emission measure, (EM $= N_e^2 V$), the volume of the emitting plasma can be determined. This volume can provide the filling factors of the emission. We have found significant deviations from the optically thin approximation in the transition region (10^5 K) of active stars. These deviations become more pronounced during flares where the Si IV line ratio becomes 1.2, compared to 2 in optically thin conditions. Combined with the electron density, we have derived line of sight path lengths of ≈ 10 km (Mathioudakis et al. 1999). These path lengths may seem quite short but they are consistent with the semi-empirical modeling of Houdebine & Doyle (1994).

The Fe XVII lines between 15 - 17Å are very intense in the X-ray spectrum of Capella. These lines have been used extensively in solar spectra as an opacity diagnostic. The strong Fe XVII line at 15.012Å has a high oscillator strength ($f = 2.66$). The flux of this line is significantly reduced in solar active regions and flares (in some cases as much as a factor of 5) when compared with Fe XVII 16.776Å ($f = 0.1$) (Phillips et al. 1996). In Fig 6 we present the Chandra spectrum of the RS CVn binary Capella in the Fe XVII wavelength region. The observed spectrum compares very well with the theoretical spectrum which was derived in optically thin conditions. There is no evidence for opacity in the corona of Capella. The fact that the Fe XVII 15.012Å is not appreciably reduced, compared with the other Fe XVII lines, gives a limit to the optical depth in the atmosphere ($\tau_0 < 0.3$). Combining this with the density determined from O VII, we conclude that the path lengths in the corona must be $L < 3000$ km while those derived for the transition region, (using O IV), are ≈ 75 km (Phillips et al. 2001). Both the Capella and YZ CMi estimates neglect the possibility that the plasma distribution may be highly inhomogeneous but offer a good indication of surprisingly small path lengths.

The emitting volume of the corona is $\mathrm{V}_{Capella}^{corona} \approx 10^{31}$ cm^3, five order of magnitude smaller than the stellar volume ($\mathrm{V}_{Capella} \approx 10^{36}$ cm^3). The above parameters would imply that the X-ray emission originates in very small/compact emitting regions. We remind that in the solar case the two volumes are almost equal ($\mathrm{V}_{\odot}^{corona} \approx V_{\odot} = 10^{33}$ cm^3).

Concluding Remarks

- The coronal (10^6 K) and transition region (10^5 K) observations of Capella and other active cool stars, reveal similar electron densities (10^{10} cm^{-3}) in these two regions of the atmosphere. The apparent pressure imbalance suggests that the coronal material could be organized in different loops that are isolated from the transition region. The relatively high electron density implies tiny coronal emitting volumes.
- The Fe XVII lines near 15.00Å are widely used as an opacity diagnostic in the solar corona. Early studies of stellar coronae show no evidence for opacity. This suggests that the emission originates from a homogeneous distribution of loops/active regions where opacity effects average out. However, significant opacity has been detected in the transition region of several late-type stars. These results suggest that the transition region is extremely thin (a few tens of km) and at a very high column mass.
- There are a range of processes that can contribute to the heating of stellar and solar coronae. These processes are divided into two classes, namely magnetic reconnection events and waves. Most of the studies so far have focused on low frequency magneto-acoustic waves. There are strong theoretical arguments in favor of high frequency waves as a source of coronal heating. The recent detection of high frequency intensity oscillations in a solar active region coronal loop, has produced some very encouraging results. The wave parameters such as group velocity, energy density and dissipation lengths, need to be combined with simultaneous estimates of the local plasma conditions, (i.e. T_e, N_e and $\mathrm{E}_{losses}^{rad}$), in order to assess if the heating criteria can be met.
- The reduction in the coronal emission of ultra-fast rotating stars, (i.e. supersaturation), is quite puzzling. Current theories predict that this is due to the

hot coronal plasma becoming unstable and cooling down to chromospheric temperatures. This would predict that super-saturation will not be detected in the chromosphere, a prediction that needs to be tested.

- The two component approach of Cuntz et al. (1999) is an excellent piece of work that combines both acoustic and magnetic heating. Their quantitative results show that acoustic waves can dissipate sufficient energy in the chromospheres of low activity stars, while in active stars magnetic heating dominates. However, some form of magnetic heating is required to explain the activity cycles of some basal stars. Quantitative calculations of the energy generated by the turbulent velocity field may provide an answer.

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