Magnetic Fields across the Hertzsprung-Russell Diagram
ASP Conference Series, Vol. 248, 2001
eds. G. Mathys, S.K. Solanki, and D.T. Wickramasinghe

A Model for the Decline of Coronal X-ray Emission of Cool Giant Stars

V. Holzwarth, M. Schüssler, S.K. Solanki

Max-Planck-Institut für Aeronomie, Max-Planck-Str. 2, D-37191 Katlenburg-Lindau, Germany

Abstract. The coronal activity of giant stars as detected in soft X-rays and the strength of 'hot' UV emission lines declines strongly for luminosity class III stars cooler than K1...K3. We show that this transition coincides with the onset of the trapping of magnetic flux tubes in the stellar interior due to the increasing magnetic curvature force.

1. Introduction

Observations indicate a significant drop of EUV and coronal X-ray emission for stars around the 'coronal dividing line' (CDL) near spectral type K1..K3 III (Ayres et al. 1981, Haisch et al. 1992). Rosner et al. (1995) suggest that this decline can be explained by the change of magnetic field topology in the atmosphere of the star from large, closed magnetic loops, confining hot coronal plasma, to open magnetic field lines, along which a cool stellar wind can escape from the star. Considering the dynamics of magnetic flux tubes, we show that this transition can be understood in terms of the 'trapping' of flux tubes in the stellar interior as the star evolves toward the giant branch.

2. Numerical investigations of rising magnetic flux tubes

We assume a strong azimuthal magnetic field, which is generated in a rotational shear layer at the interface between the convection zone and the radiative core. The magnetic field is stored in the form of toroidal flux tubes in mechanical equilibrium in the stably stratified overshoot layer until the (undulatory) Parker instability leads to the formation of loops rising through the convection zone. After the emergence at the stellar surface, the loops form bipolar active regions and large coronal loops (Schüssler et al. 1994). We use post-main-sequence models from calculated evolutionary sequences for 1, 1.5, 2, 2.5 and 3 $M_\odot$ stars (cf. Figure 1). The critical field strength for loop formation is determined by a linear analysis (Ferriz-Mas & Schüssler 1995). We then follow the non-linear evolution of the instability by numerical simulation on the basis of the thin-flux-tube approximation (cf. Caligari et al. 1995).

We find two different characteristic behaviours of rising magnetic flux tubes in evolved stars. *Erupting flux tubes:* When the evolving stars leave the main sequence (and develop a significant outer convection zone), flux eruption proceeds in a similar manner as in non-evolved stars (Figure 2). *Trapped flux tubes:*

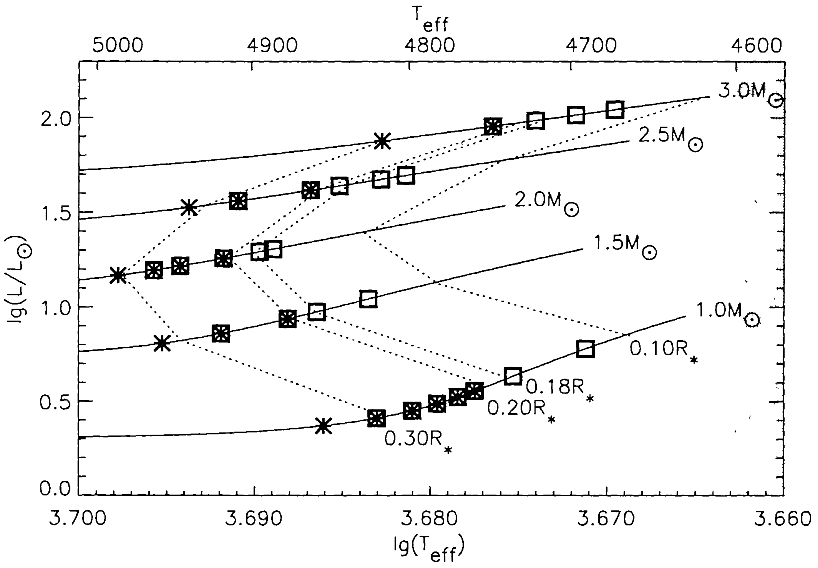

Figure 1. The HR region left of the 'coronal dividing line' (in grey). Solid lines indicate evolutionary sequences, dashed isolines the corresponding fractional depth of the radiative core. Asterisks denote stars with loops erupting at the surface, squares signify stars with non-erupting flux tubes; both symbols are overplotted when some tubes are trapped while others emerge.

Once the radius of the radiative stellar core becomes smaller than about 20% of the stellar radius, loop emergence is inhibited; initially unstable flux tubes find a new equilibrium and become trapped deep within the stellar interior (Figure 3). In our set of stellar models, this evolutionary stage is reached in the temperature range $T_{\rm eff} \approx 4700 \ldots 4900\,{\rm K}$, which is close to the region where observations indicate the CDL (Figure 1). We find no significant dependence of the transition location in the HR diagram on rotation rate $(0.1\,\Omega_\odot < \Omega < 10\,\Omega_\odot)$, initial magnetic field strength, and on the details of the internal stratification of the stellar model.

3. Why do flux tubes become trapped?

We suggest that two effects lead to the trapping of magnetic flux tubes in giant stars (cf. Figure 4). Firstly, the *shrinking core* results in a decrease of the radius of curvature of the equilibrium flux tube. This increases the initial magnetic tension force which opposes the buoyancy force and tends to retard the rise of an unstable flux loop. Secondly, the *expanding envelope* requires more stretching of the rising loop, which also increases the tension force. At a certain point of the evolution toward the giant branch, the tension force gets the upper hand and the rise of a loop is stopped before it reachs the surface: the flux tube becomes trapped. At the beginning of the evolution the tension force leads to a slip of the bottom part of the flux tube towards the pole since the component tangential to the surface of the core is no longer compensated by the buoyancy

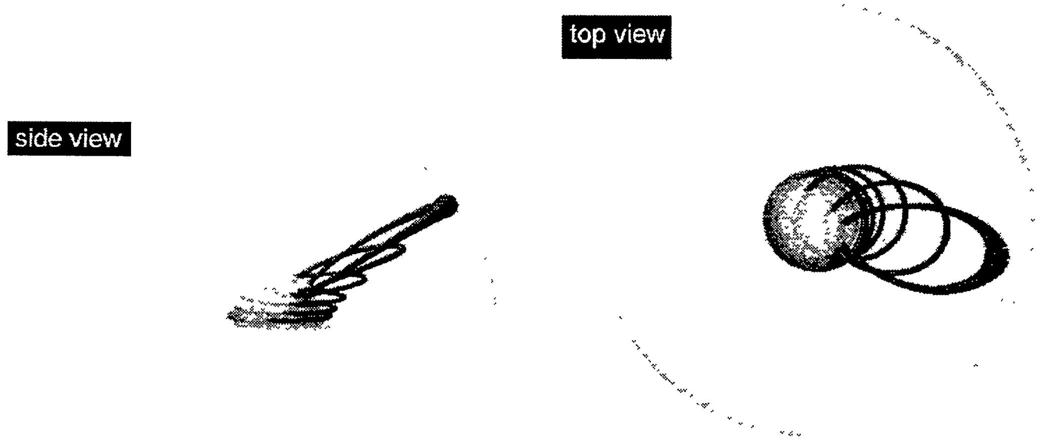

Figure 2. An erupting flux tube in the $1\,M_\odot$ model at an age of 12.14 Gyr ($T_{\rm eff} \simeq 4760\,$K). The inner (darker) hemisphere represents the radiative core of the star ($r_c/R_\star \simeq 0.21$). The flux tube is initially at 10° latitude. Subsequent configurations are shown until the rising loop has nearly reached the stellar surface (after about 1300 days). To improve its visibility, the diameter of the tube was magnified by a factor of 10.

Figure 3. A trapped flux tube. The star model is only 70 Myr older than in the previous figure ($T_{\rm eff} \simeq 4735\,K, r_c/R_\star \simeq 0.18$). In this case the rise of the loop is stopped by magnetic tension. The bottom part crosses over the pole and the tube slips equatorward until it reaches a new stable equilibrium in the equatorial plane. The whole development takes about 2600 days.

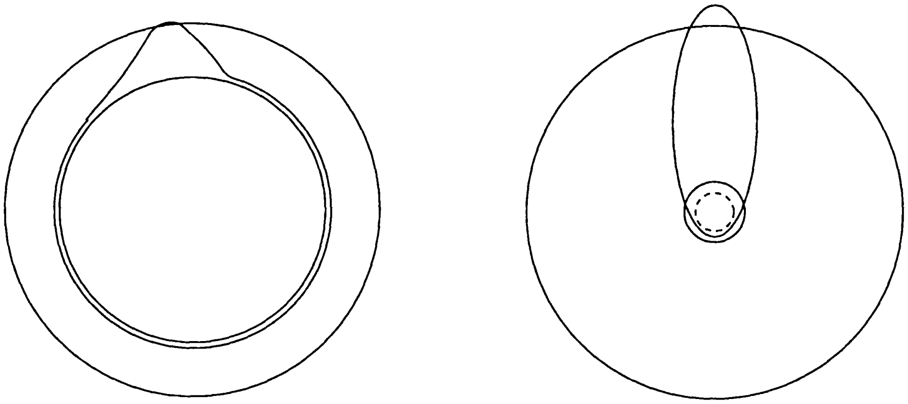

Figure 4. Schematic sketch illustrating the different amount of stretching required for an erupting flux loop in a star with a large radiative core (left) and a giant with a small core (right). Both stars are drawn normalized to the respective stellar radius.

and Coriolis forces. After crossing the pole an equatorward slip sets in due to the same reason. The flux tube slowly drifts to the equatorial plane where it finally finds a new stable equilibrium.

4. Summary

We suggest that the decline in X-ray emission of cool giant stars across the 'coronal dividing line' is related to the *trapping* of magnetic flux tubes inside the star. This mechanism can cause a significant reduction and even the termination of solar-like activity with large bipolar magnetic regions and extended coronal loops (cf. Rosner et al. 1995). Small-scale fields generated by a turbulent dynamo in the convection zone or 'shredded' flux from trapped flux tubes could produce small loops and intermittent emission by reconnection, maintaining the lower level of X-ray and UV emission that is observed for some stars to the right of the CDL. At the same time, such small-scale fields would not interfere with a substantial stellar wind.

References

Ayres, T.R., Linsky, J.L., Vaiana, G.S., Golub, L., & Rosner, R. 1981, ApJ, 250, 293

Caligari, P., Moreno-Insertis, F., & Schüssler, M. 1995, ApJ, 441, 886

Ferriz-Mas, A., & Schüssler, M. 1995, Geophys. Astrophys. Fluid Dynam., 81, 233

Haisch, B., Schmitt, J.H.M.M., & Fabian, A.C. 1992, Nature, 360, 239

Rosner, R., Musielak, Z.E., Cattaneo, F., Moore, R.L., & Suess, S.T. 1995, ApJ, 442, L25

Schüssler, M., Caligari, P., Ferriz-Mas, A., & Moreno-Insertis, F. 1994, A&A, 281, L69