CLOSED AND OPEN MAGNETIC FIELDS IN STELLAR ATMOSPHERES: EFFECTS ON MASS LOSS FROM COOL GIANT STARS

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ABSTRACT

We propose that the onset of rapid mass loss among cool giants, and the absence of hot coronal material from their atmospheres, is associated with a transition in the large-scale magnetic topology of the atmosphere from closed to open. According to this view, field loops in the atmospheres of giants of spectral class K and later cannot find equilibrium, but are in a state of dynamical evolution throughout their lifetime in the atmosphere.

INTRODUCTION

Mass loss from the highly ionized atmosphere of a star is permitted only in regions where the magnetic field is not rooted in the star in the form of a closed loop. Thus, the field can be either open to space (as in coronal holes on the sun), or bubbles of magnetic flux may become disconnected from the stellar surface and transport material away from the star in discrete events. In both cases, since magnetic fields are created in late-type stars by dynamo action in the form of bipolar pairs, the mass loss process requires that a mechanism must be at work in the stellar atmosphere to convert originally closed loops of flux into either open form or else disconnected bubbles.

In the solar corona, loops cannot always find a means of becoming open or disconnected. In such cases, the loops enter a stage of evolution which, although basically magnetohydrodynamic in character (due to the jostling of footpoints by convective flows), can nevertheless be described with fair accuracy as a sequence of quasi-steady equilibria. During this phase, the closed loop traps material, prevents mass loss, and the trapped material emits X-rays copiously.

Mass loss among cool giant stars sets in across a "velocity dividing line" in the HR diagram (Stencel and Mullan, 1980) which coincides rather well with a "temperature dividing line", along which hot coronal material disappears from the atmosphere (Linsky and Haisch, 1979). In the context

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of the above discussion, the coincidence of these two dividing lines in the HR diagram can be interpreted as follows: when a star evolves across either dividing line, closed loops can no longer exist in quasi-steady state, but must immediately enter a phase of dynamical evolution which ultimately leads to opening of the field lines, or disconnection from the star. In either case, enhanced mass loss is permitted, and the disappearance if closed loops removes the prime source of coronal X-rays from the atmosphere. Hence, the atmosphere no longer contains the hot material which is so characteristic of the closed loops in the solar corona.

The purpose of this paper is to report on a test of this hypothesis.

CLOSED MAGNETIC FIELDS IN STELLAR WIND

Pneuman (1968) has analyzed the case of an isothermal wind flowing around and above a region where the field is closed at low altitudes, but open higher up. This magnetic configuration gives rise to helmet streamers in the solar corona. Pneuman found that the outflow above the helmet passed through a sonic point at a radial distance r_s which was related to the radial distance of the last closed field line, r_c, by a simply relation: $r_s = 2\ r_c$.

Subsequently, Pneuman and Kopp (1971) considered the case of a steady solar wind flow imbedded in a global dipole magnetic field. They found that the field lines remained closed near the equatorial plane (at least with the initial conditions which they selected). And as before, the ratio of r_s to r_c which emerged from their calculations turned out to be close to the value of 2.

To make these estimates more precise, I have recently collaborated with R.S. Steinolfson in a time-dependent, two-dimensional MHD calculation of the interaction between the solar wind and a global dipole field. Rather than assuming isothermal flow, as was assumed in the previous studies, the flow was assumed to be polytropic, with index 1.05, for the initial, non-magnetic wind. A value was chosen for the coronal base temperature, T_b. At time t=0, the global dipole is superposed on the spherical wind solution, and the time-dependent evolution is followed until a steady state is reached. In the case of a solar model, some (1-2) thousand seconds of real time must elapse before steady state is reached. The dipole strength is parametrized by a beta value, which is the ratio of gas pressure to magnetic pressure at the base of the corona in the equatorial plane. The calculations showed that the steady state results were insensitive to β for all $\beta \lesssim 1$. In what follows we report on calculations which assumed β=0.5.

We found that as T_b increases, the size of the closed field region near the equator shrinks, until finally, for a critical value of T_b, no closed field lines exist in steady state. For T_b less than critical, we evaluated the ratio of r_s/r_c in the equatorial plane. In the case of the solar corona, the value turned out to be remarkably constant, varying by only ±6% around a mean value of 2.55 as T_b varied by 220%.

We calculated the flow for a giant star also, with solar mass, but with radius equal to 10 times solar. Here, the critical T_b value was found to be less than solar by a factor of 10 (i.e. 4×10^5K, rather than 4×10^6 K in the solar case). This is the scaling which would be expected if the corona were assumed to be strictly isothermal. And also in the case of the giant model, r_s/r_c turned out to be insensitive to T_b. The value remained constant (within ±16%) at 2.25, as T_b varied by 220%.

These calculations suggest that the radial distance of the last closed field line can be characterized rather well by a knowledge of the radial distance to the sonic point.

DISAPPEARANCE OF CLOSED FIELD LINES IN STELLAR CORONAE

This leads us to consider what happens in a star where the sonic point approaches closer than 2.2-2.6 stellar radii. In such a case, the last closed field line extends to a radial distance of less than one stellar radius, i.e. lies completely inside the star. Thus, in such a star, if a closed field line were to appear in the stellar atmosphere (by emerging from the photosphere due to buoyancy, for example), it could not find a steady state in the presence of the thermal wind from that star. In the absence of steady state, such a field line enters a phase of dynamical evolution. The final state of such a field lines is expected to be either open entirely, or else a state of disconnection from the stellar surface. In such a star, no long-lived steady closed loops persist. Thus, there are no analogs to the bright "building-blocks" which characterize the solar corona.

We now ask: where in the HR diagram does the sonic point radius approach closer to the star than 2.2-2.6 stellar radii? To answer this, we use the same technique which we used several years ago in estimating the "supersonic transition locus" (Mullan, 1978), i.e. a semi-empirical technique in which we combine the coronal base pressures derived by Kelch et al. (1978) from model chromospheric fits to spectral line data, with the minimum flux coronal concept. In the present case, however, we are not relying on the requirement that mass loss become rapid because the sonic point sinks into chromospheric material. Now, the sonic point remains well out in the corona. We have used evolutionary tracks for stars of 1.5, 3, and 5 solar masses to determine where the last closed field line disappears. The location of the relevant points in the HR diagram have already been published for the case $r_s/r_c = 2.0$ (Mullan, 1982). With the revised values of r_s/r_c reported here, the locations of the relevant points in the HR diagram shift slightly, but not by more than the size of the symbols which were used in Mullan (1982). Thus, the major point to emerge from that paper remains: the location of the transition from closed field lines to absence of closed field lines occurs in good coincidence with the empirical velocity dividing line.

We consider this support for our conjecture that the velocity and temperature dividing line(s) in the HR diagram are to be identified with a magnetic topology transition locus (MTTL).

ARGUMENT FROM MAGNETOSTATIC EQUILIBRIUM

Independent support for the MTTL concept is provided by Low's (1981) work on magnetic equilibrium in stratified atmospheres. Equilibrium requires that the parameter C $(=BL/4H(\Delta p)^{0.5})$ satisfy $C<1$. (Here, B is the field strength, H is the scale height, L is the separation between loop footpoints, and Δp is the pressure differential between magnetic and non-magnetic gas.) To optimize stability, we set $\Delta p=p_o$, the coronal base pressure, determined by Kelch et al. (1978). (In active chromosphere stars, where p_o may be larger, B is also probably larger in proportion to $p^{0.5}$ (cf. Mullan, 1975). Hence, C may be roughly equal in active and inactive stars.) Suppose $L \approx 0.1R$ (star). Then equilibrium requires that the atmospheric temperature T exceed $(2-4)\times 10^5$ B along the VDL. If solar coronal values of B are typical $(B \simeq 1G)$, then stars above the TDL (with $T<<10^5$) contain loops which are not in equilibrium, whereas stars below TDL (where $T>>10^5K$), can have closed loops in equilibrium.

CONCLUSION

Above MTTL, magnetic flux loops emerging into a stellar atmosphere are always unstable. Mass loss can be rapid, and X-rays will be weak because of the lack of closed field loops. Unstable loops can be used to interpret a wide variety of characteristics of late-type stellar chromospheres/coronae, including episodic mass loss, extended atmospheres, variability of emissions from chromosphere and coronae, hybrid atmospheres, enrichment of certain isotopes in the atmosphere, and supersonic macroturbulence (cf. Mullan and Cram, 1982; Mullan and Stencel, 1982).

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DISCUSSION

KUIN: What is the influence of the temperature distribution that you assume in the helmet streamer on the position of the sonic point? I am afraid that this would have a large influence on your results. In a different structure like a polar coronal hole one also observes that the sonic point lies much closer to the star than one would expect from the Parker solar wind.

MULLAN: I do not *assume* a temperature distribution. It is calculated at each point in the grid. The temperature is naturally found to be higher on closed field lines than in the open region. The calculation actually includes a coronal-type structure: around the poles, the field lines are open, and diverge faster than radial in steady state. Hence, the sonic point certainly lies closer to the surface in that part of our calculated flow. In fact, the polar sonic point approaches the surface (to $r \lesssim 1.2r_\odot$) at essentially the same value of T_b as the "last closed field line" disappears. Our steady state is definitely very different from a Parker solar wind.

GRAY: If one looks at those stars of luminosity class III showing hot temperatures vs. those showing cool temperatures in transition-region lines, you find that they fall on opposite sides of the rotational discontinuity. Would you comment on the possibility of rotation being the driving mechanism for the things you have discussed?

MULLAN: I have discussed magnetic effects without specifying where the fields originate. Presumably rotation contributes to field creation in some way. Until this contribution is better known, I cannot comment on how important the rotational discontinuity is. However, it is clear that onset of rapid mass loss across the velocity dividing line may be important in braking the G-K giants. Thus the connection between dividing lines in the H-R diagram is still obscure in the sense of isolating causes from effects.

ZWAAN: How do you explain that synchronized K-type binaries do show high-temperature lines, or, in other words, how does the atmosphere know that there is a companion?

WALTER: Let me comment on this question: I don't think that there is a problem with the RS CVn giants. As I recall, at K0 the various dividing lines are at about luminosity class II, and do not get to luminosity class III until about K5. Most, if not all the RS CVn giants lie below the lines and probably have closed fields.