ON THE ORIGIN OF "DIVIDING LINES" FOR LATE-TYPE GIANTS AND SUPERGIANTS


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ABSTRACT

We show how a change in the nature of the stellar dynamo can lead to a transition in the topological character of stellar magnetic fields of evolved stars, from being mainly closed on the blueward side of the giant tracks in the H-R diagram to being mainly open on their redward side. If such a topological transition occurs, then these stars naturally segregate into two classes: those having hot coronae on the blueward side, and those having massive cool winds on the redward side, thus leading naturally to the so-called dividing lines.

Subject headings: stars: coronae — stars: mass loss — stars: magnetic fields — supergiants

1. INTRODUCTION

The region of the H-R diagram containing late-type giant and supergiant stars has been well explored by UV and X-ray observations from the IUE, HEAO 1, Einstein, and EXOSAT observatories, and—most recently—from the ROSAT and ASCA observatories. Taken as a whole, the UV and X-ray data clearly indicate the existence of several roughly coincident "boundary lines" in the H-R diagram: An X-ray dividing line, separating yellow giant and supergiants into those with (blueward) and without (redward) prominent X-ray emission (Ayres et al. 1981; Haisch & Simon 1982; Maggio et al. 1990; Haisch et al. 1990; Haisch, Schmitt, & Rosso 1991; Reimers & Schmitt 1992; Haisch, Schmitt, & Fabian 1992); a transition region dividing line, separating stars showing evidence for (blueward), or no evidence for (redward), transition region plasma emission (Linsky & Haisch 1979); and a wind dividing line, separating stars showing evidence for (redward), from those showing no evidence for (blueward), a massive cool wind (cf. Dupree 1986).

The possible origins of these "dividing lines" have been much discussed (cf. Linsky & Haisch 1979; Simon, Linsky, & Stencel 1982; Dupree 1986; Mullan & Steinolfson 1983; Böhm-Vitense 1986; Antiouchos, Haisch, & Stern 1986; Antiouchos 1987; An et al. 1990a). Rosner et al. (1991) suggested a solution to two related questions: Why do these dividing lines exist, and why are they coincident? They proposed that an evolved star's surface magnetic field topology determines the nature of its surface activity: A "closed" topology leads to plasma confinement; and an "open" topology allows for, but does not require, wind outflow. If Alfvén waves dominate the mechanical energetics of the outer atmospheres of these stars, with the Alfvén wave flux independent of the star's magnetic field topology, then this change in topology will necessarily lead to the observed bifurcation in atmospheric properties: Massive cool ($10^4 < T < 10^5$ K) winds are driven by Alfvén waves in open magnetic field configurations, while these waves lead to plasma heating, but little outflow, for closed configurations. The mechanism leading to the change in field topology was not identified. This Letter's aim is to resolve this remaining puzzle and thus to provide a completely consistent physical picture of the formation of the "dividing lines."

Any model for the "dividing lines" must contend with several basic physical constraints (cf. Rosner et al. 1991): First, emission from hot ($> 10^6$ K) gas in the outer atmospheres of late-type giants can take place only if these gases are magnetically confined—in the absence of magnetic confinement, confinement by gravity alone of significant amounts of coronal matter near their surface at these temperatures is not possible. Thus, a key difference between stars on either side of the X-ray emission "dividing line" must be the existence of confining surface magnetic fields. It does not follow that there must be large outflows whenever confinement is absent—it is physically perfectly possible that stars without confining magnetic fields simply do not have magnetic fields of any sort, nor any other mechanism for imparting energy and momentum to an outflow, and hence have a simple, essentially static and cold, outer atmosphere. However, observations show that essentially all late-type giants have either mass outflows, or emission from hot coronal gases, or both (e.g., Haisch et al. 1990). Is there a simple explanation for this behavior?

One such explanation (Rosner et al. 1991) assumes that heating of the hot gas in the magnetically confined case occurs via some type of Alfvén wave damping and shows that in the absence of confinement (e.g., in the presence of largely open magnetic fields), the very same Alfvén waves may then accelerate the (cool) unconfined atmosphere. Detailed calculations (cf. Hartmann & MacGregor 1980; An et al. 1990b; Velli 1993; Lou & Rosner 1994; Krogulec et al. 1994) indeed show substantial momentum transfer to the gas in "open" regions, and thence an outflow of gas. This flow has several of the desired properties of observed winds: It is (i) cool, and (ii) has relatively low terminal speed. This model has a crucial defect: It leaves the physical reason for the change in magnetic field geometry across the dividing lines entirely unexplained. We proceed to remedy this defect in the next section.

2. STELLAR DYNAMOS AND THE GEOMETRY OF STELLAR MAGNETIC FIELDS

The question of whether the magnetic field of a star is confining or not largely reduces to the question of what the mean

4 Thus, there must be similar outflows along "open" field lines in the atmospheres of late-type evolved stars with otherwise confining magnetic geometries, e.g., stars to the blueward side of the "dividing lines." Hence, slow winds will emanate from such stars as well, but with the total mass-loss rate reduced by the fraction of the surface magnetic flux which is topologically closed. Observations need to test this prediction.
ratio of the gas pressure to the magnetic pressure, $\beta \equiv P_{\text{gas}}/P_{\text{magnetic}}$, in the atmosphere is: A confined atmosphere ought to have its mean $\beta$ well below unity. Furthermore, since the Alfvén wave flux in the confined and unconfined cases seems to be essentially identical (i.e., the wind luminosity of stars to the low effective temperature side of the dividing lines is of order the X-ray/transition region luminosity of the stars on the high effective temperature side of this locus; Reimers 1989), it is highly suggestive that the total unsigned surface magnetic flux of these stars does not differ significantly when transversing the dividing lines. Recall that the observed total energy fluxes from the (confined) “quiet Sun” and (open) solar coronal holes are of the same order (to within factors of 2; cf. Withbroe & Noyes 1977), and that from the point of view of simple surface magnetic field observations, it is very difficult to distinguish (closed) quiet Sun and (open) coronal hole regions on the solar surface (e.g., Zwaan 1987). Thus, we shall assume that the total surface magnetic flux does not change significantly as one traverses the dividing lines, not on the basis of theory, but rather simply as an empirical constraint. In that case, magnetic fields in the overlying atmosphere can differ on either side of the dividing lines only if the spatial distribution of this flux differs in some systematic way.

Differences in surface magnetic field morphology can readily lead to the desired result. Consider the following explicit example: Assume that the surface fields can in all cases be regarded as a random (and sparse) spatial superposition of surface bipoles of fixed flux, with the separation between the bipoles, $d$, the only (control) parameter characterizing the surface field spatial distributions. (This sort of picture can be readily generalized in a formal sense to truly random surface field distributions for a solenoidal field.) The magnetic field strength for a single bipole varies with height $z$ above the solar surface as $B(z) \propto (z^2 + d^2/4)^{-3/2}$, hence, for a fixed bipole strength, the far ($z/d \gg 1$) field of such bipoles is, to leading order, a function of the ratio of the bipole separation to the distance from the bipole, $B_{\text{far}}(z) \propto (d/z)^2 [1 - (3/8)(d/z)^2 + \cdots]$, while in contrast the near ($z/d \ll 1$) field is instead only a weak function of this ratio, $B_{\text{near}}(z) \propto 1 - 6(z/d)^2 + \cdots$. Thus, for fixed height $z$, one is in the far field of bipoles with $d < z$, and in the near field of bipoles with $d > z$. Furthermore, the magnetic field in a stellar atmosphere will rapidly vary with height (e.g., $\propto z^{-3}$) as soon as one reaches heights comparable to the typical correlation length of magnetic flux bundles at the stellar surface; at such heights, it becomes possible for the gas pressure to overwhelm the magnetic pressure, i.e., for the field lines to “open.” That is, consider the radial gas pressure variation in an isothermal static atmosphere, $p(r) \sim \exp [R_\odot (R_\odot - r)/H]$, where $H \equiv 2kT/m_H g_\star$ is the gravitational scale height at the stellar surface, $r$ is the radial distance from the stellar interior, $T$ is the (isothermal) temperature, and $g_\star$ is the stellar gravitational acceleration at the surface $r = R_\star$. The height above the solar surface, $z = r - R_\star$, at which the gas pressure begins to dominate over the magnetic pressure is determined by setting $p(z) \sim B^2(z)/8\pi$ (cf. Fig. 1). In our simple static illustrative case, the gas pressure inevitably dominates the magnetic pressure at sufficiently large heights above the stellar surface because at large $r$, the magnetic pressure falls off as $r^{-6}$, while the gas pressure goes asymptotically to a constant. Hence, the “closed” structures will tend to have length scales comparable to, or smaller than, the typical bipole separation scales. Furthermore, as the typical bipole scale decreases, the scale of the “closed” structures can become substantially smaller than the atmosphere’s pressure scale height; the “closed” atmosphere can then make a transition from the “hot” state characteristic of solar-like coronal structures to a “cool” state (Antiochos et al. 1986). In this manner, the transition from an atmosphere which is “open” on large scales can be accompanied by a second transition in which the confined gas also changes its preferred state, from hot (coronal) to cool (chromospheric).

This line of reasoning suggests that changes in stellar magnetic field topology may be simply related to a systematic change in the spatial size distribution of stellar surface magnetic fields; that is, we obtain the desired result if stars blueward of the dividing lines are characterized by magnetic flux distributions with large characteristic scales, while stars redward of the dividing line locus are characterized by small-scale surface flux distributions. Are such effects known in the one case in which we can examine surface fields in great detail, i.e., the Sun? The answer is yes—at times of maximum activity, solar surface magnetic fields are dominated by large active region complexes, whose dimensions are of order the convection zone depth; in contrast, during times of activity minimum, the surface magnetic fields are dominated by the classic “salt-and-pepper” small-scale fields. Furthermore, several authors have argued that the total unsigned flux contained in these two distinct solar magnetic flux distributions are comparable in magnitude (cf. Zwaan 1987). Not only does the Sun show evidence for both types of magnetic flux distributions, with one dominating the other at different times, but it also shows a definite spatial separation of these two types of flux systems. In particular, large-scale bipolar regions never arise near the poles, whereas the poles definitely show evidence for the “salt-and-pepper” types of flux elements. Interestingly enough, the Sun’s poles are the location of essentially ever-present “coronal holes,” regions where the Sun’s magnetic field is open in the present sense, and where it is believed substantial mass loss from the solar corona occurs. Thus, our naive abstraction finds support in the Sun’s case.

Now, here we need to provide a physical reason that stars bluer than the dividing line locus are always (or, in some loose
Theoretical work on magnetic field evolution in turbulent fluids (Meneguzzi, Frisch, & Pouquet 1981; Vainshtein & Kichatinov 1986) suggests one possible answer to this puzzle, based on the existence of two general classes of dynamos in natural systems. The first class is usually held responsible for the generation of magnetic fields over a wide range of scales, from large scales (e.g., comparable to the system—the star—under study) to small scales (e.g., scales lying within the fluid turbulence inertial range) and depends for its existence on the nonvanishing of the mean fluid (kinetic) helicity $\langle \mathbf{u} \cdot \nabla \times \mathbf{u} \rangle$. This class contains within it the classical $\alpha-\Omega$ dynamos first pioneered by Parker (cf. Parker 1979). The second class of dynamos leads to the generation of magnetic fields on the spatial scales of the turbulent flow field, i.e., small spatial scales; and while requiring fluid turbulence for its existence, does not require a nonvanishing mean kinetic helicity. Thus, while mean helicity-related dynamo action is a requirement for a convective star to show large-scale organized surface magnetic field structures, the absence of such a dynamo in systems in which even extremely weak seed fields are present nevertheless can lead to the generation of locally strong magnetic fields, for timescales comparable to or longer than typical evolution timescales on the giant branch. Thus, the implication is that stars redward of the dividing lines have mean helicity-related dynamo action suppressed, and that stars blueward of the dividing lines are mean helicity dynamo-active (leading to large-scale, organized, magnetic fields). (Durney, De Young, & Roxburgh 1993 have discussed a related problem in the rather different context of the evolution of young, low-mass, main-sequence stars.)

Why this change in the dynamo? Observational work on stellar rotation (Gray 1989; Herbig & Spalding 1955; De Medeiros & Mayor 1990; Schrijver & Pols 1993) provides abundant evidence for a sharp drop in angular velocity of evolved stars later than $\approx 0.6$ (the precise spectral type depending somewhat on luminosity class). Because the spectral sequence of evolved stars blueward of $\approx 0.6$ essentially reflects temporal evolution (since the stellar mass in this range for stars with initial masses $\approx 0.6$ or slightly larger, is approximately constant; Sargent & Gross 1978; Mengel et al. 1979), Gray (1989) argues that as these stars evolve redward, the steep decline in rotation rate must result from a turn-on of large angular momentum loss (via a magnetized wind); in particular, this turn-on of rapid spindown arises because there is a turn-on of magnetic activity as stars evolve redward. But such an explanation is no plausible because it leaves unexplained the clearly magnetically related X-ray activity shown by stars blueward of these transition lines (magnetically related because of the necessity for confinement of the observed hot plasma).

The coronal transition line may be instead a magnetic boundary (with magnetic field production shut off as stars evolve redward; Maggio et al. 1990; Gray 1990). The underlying idea is that—in the context of a mean field dynamo theory—if the dynamo number falls below the critical value for marginal stability as stars evolve redward, the linear dynamo instability can shut off. This suggestion is actually too simple because if magnetic field production is suppressed entirely, then we would be left with no way of driving the observed winds in this region of the H-R diagram. Furthermore, simple calculations of the critical dynamo number $N_d$ (or of the Rossby number $R = \rho / \tau_s \approx N_d^{1/2}$) on the giant branch (Gilliland 1985) suggest—to the contrary—a strong increase in activity level (because as such a star evolves redward, its convective zone becomes deeper and its characteristic convective turnover time $\tau_s$ increases, while its period $P$ changes relatively little).

Instead, we suggest that as stars age on the giant branch, their increased magnetic activity levels initially lead to both increased levels of coronal emissions and enhanced mass loss via a magnetized wind. This wind can then very effectively despin the star even for relatively modest mass-loss rates because of the large effective lever arm afforded by the highly active stellar magnetosphere: The spin-down efficiency is a strong function of the strength of the low-order multipole (e.g., dipole and quadrupole) components of the star's magnetosphere (Roxburgh 1983; Meisel & Spruit 1987). Indeed, similar effects on stellar spin-down resulting from the absence of large-scale surface magnetic fields have already been suggested for the rapidly rotating dM stars in the Hyades (Durney et al. 1993).

However, this process contains the seeds of its own destruction: The spin-down process has the effect of increasing the Rossby number, and hence leads to a decrease in classical, helicity-related, dynamo-driven activity. The key point is that this suppression of a large-scale dynamo (leading to the disappearance of large-scale organized stellar magnetic fields) need not imply the suppression of magnetic field production at small scales, driven by the turbulent motions in the surface convection zones of these stars. Thus, as the dynamo number for an evolving star falls below the critical value for classical dynamo activity, there is a consequent transition in the spatial character of the surface magnetic activity, e.g., a change from a large-scale structured and closed stellar magnetosphere to a highly disordered stellar magnetosphere which is open on large scales (cf. Fig. 2). This transition is clearly not well understood and remains to be studied in detail; the so-called hybrid stars may represent this transition stage, as they show evidence for both X-ray emission and copious mass loss (cf. Dupree 1986). Kashyap et al. (1994) have recently shown on the basis of ROSAT X-ray observations of the hybrid star $\alpha$ TrA that compact hot X-ray-emitting structures on this star cannot be in steady thermodynamic equilibrium (following Antiochos et al. 1986); and that there is considerable evidence for highly intermittent emission even during periods of apparent "quiet" behavior. Thus, these observations are consistent with the picture that $\alpha$ TrA's X-ray corona does not have a quiescent component reminiscent of the Sun's quiet Sun, but rather that its magnetosphere is dominated by small-scale magnetic structures.

One consequence of our model is that the transition from a closed, very active X-ray-emitting outer atmosphere to an open, wind-dominated atmosphere should be rapid because of a powerful feedback effect: Once the star begins to lose angular momentum at a high rate, the decrease in stellar angular velocity depresses the dynamo number yet further. This transition is identified in our model with "hybrid" stars such as $\alpha$ TrA.
3. SUMMARY AND DISCUSSION

We have constructed a consistent model for the transition from solar activity–like behavior to strong, cool mass outflows as evolved stars cross the locus of "dividing lines" in the H–R diagram: We relate changes in surface activity to changes in surface magnetic field geometry and, ultimately, to changes in the nature of stellar magnetic dynamos. As stars cross the dividing lines, classical dynamo activity may cease as they despise. Hence, large-scale organized surface magnetic flux emergence normally associated with stellar activity disappears, and is replaced by small-scale magnetic flux emergence arising from weak seed fields placed in the turbulent convection zones of these stars. Thus, the character of stellar activity changes, but its essentially magnetic nature remains intact.

This reduction in dominant spatial scale of the emerging magnetic flux has two consequences: First, the atmosphere on large spatial scales becomes largely "open" because of a strong increase in the mean plasma β on large scales; as a result, Alfvén waves outward propagating within the previously confined atmosphere (where they heated, and whence led to transition region and coronal emissions) now can accelerate the now unconfining plasma (Rosner et al. 1991; Velli 1993; Lou & Rosner 1994). Second, the remaining "closed" structures can no longer remain in the hot corona; what if the spatial scale of these structures falls below the atmosphere's pressure scale height (Antiochos et al. 1986). The result: a cool wind, with relatively low terminal speed, and a complete absence of X-ray emission.

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