V. STELLAR WINDS AND SPINDOWN IN LATE – TYPE STARS

STELLAR WINDS AND SPINDOWN - OBSERVATIONS

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1. INTRODUCTION

Stars with masses $\lesssim$ 1 $M_\odot$ are observed to rotate more slowly as they age. The angular momentum loss is undoubtedly caused by the coupling of the stellar magnetic field to the escaping wind (Schatzman 1962). Chromospheric and coronal radiative losses depend upon rotation (Wilson 1966a,b; Kraft 1967; Skumanich 1972; Hall 1976; Bopp 1980; Walter and Bowyer 1981; Walter 1981; Vaiana et al. 1981). It is therefore likely that both magnetic fields (Skumanich 1972) and the mechanical energy fluxes required to drive mass loss also depend upon rotation as well. This complicated feedback between magnetic fields, winds, and rotation must control the variation of solar-type activity over much of the HR diagram, and may have very important effects on pre-main sequence evolution.

Unfortunately, we have almost no direct observations of magnetic fields in late-type stars. In addition, there are very few stars for which we can observe both winds and the effects of spindown. The only exceptions are the pre-main sequence T Tauri stars, whose positions in the HR diagram and interior structures are not well known. In general the observational situation is distressingly unconstrained, although there are several new clues which constrain spindown and the connection between magnetic fields and mass loss.

2. STELLAR WINDS

A. Evolved Stars

It is much easier to detect cool stellar winds than hot, solar-type flows. The reason is that in the absence of spatial resolution, mass loss must observed from doppler shifts in line profiles, and the spectral signatures of hot winds mostly occur at inaccessible wavelengths. So any discussion of stellar mass loss must begin with the study of cool winds and circumstellar shells.

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Mass loss is detected in the spectra of evolved, late-type giants in the form of circumstellar lines of low-excitation ions like Mg II, Ca II, Na I, and K I. As indicated in Figure 1, cool winds are observed only in the upper-right hand corner of the HR diagram. Circumstellar shell lines are generally not observed in stars with log g >1.5. Stars of higher surface gravity exhibit transition-region and coronal emission patterns similar to the Sun's (Linsky and Haisch 1979; Dupree and Hartmann 1980; Vaiana et al. 1981; Hartmann, Dupree, and Raymond 1982), and so presumably have solar-type winds.

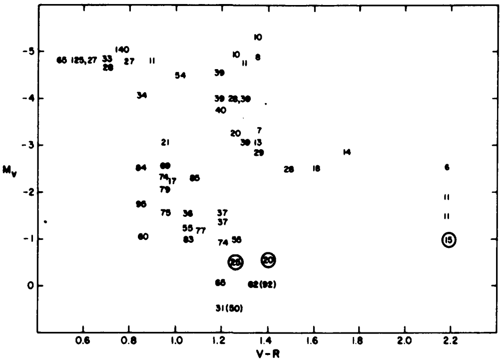

Figure 1. Domain of cool stellar winds in the HR diagram, with terminal velocities in km s^{-1}. Adapted from Reimers (1977).

Recent studies suggest that there may be a closer relation between cold flows and solar-type winds than previously thought. One line of evidence for such a connection comes from the observations of Ca II and Mg II line profiles by Stencel and Mullan (1980). They showed that red giant stars often exhibit an asymmetry in which the blue emission peaks of these chromospheric lines are weaker than the red peaks. This asymmetry is seen with increasing frequency in stars of lower gravity. Although the line profiles cannot be interpreted in a unique way, the sense of this asymmetry is consistent with what is expected from differential expansion due to mass loss.

Progressing towards the upper righthand corner of the HR diagram, the change in asymmetry is first seen in Mg II, then Ca II, followed by the appearance of true circumstellar shell lines (Figure 2). This behavior is exactly what one would expect if mass loss rates are smoothly increasing, rather than a discontinuous jump due to the turn-on of a new mass loss mechanism. Mass loss can be seen first in the Mg II resonance lines, since they have an order of magnitude more opacity per gram than the Ca II lines.

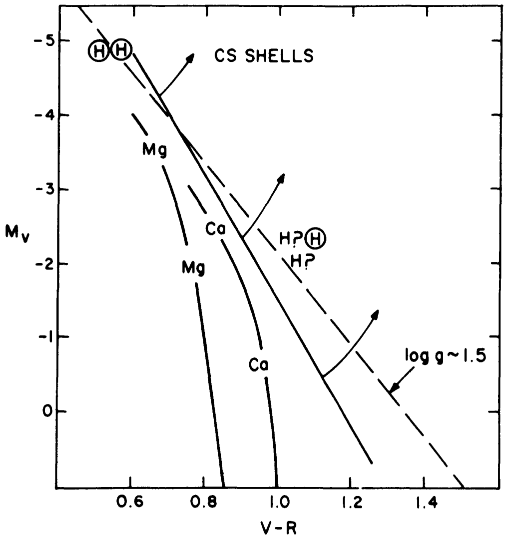

Figure 2. Hybrid stars (H symbols) are observed near the CS boundary in the HR diagram. Stars to the right of the Mg II and Ca boundaries tend to exhibit asymmetries indicative of mass loss in the respective resonance lines.

Another reason for suspecting a connection between hot and cool winds is the observation of stars with both hot outer atmospheres and cool winds (Hartmann, Dupree, and Raymond 1980,1981). These objects, called hybrid atmosphere stars, show C IV and N V emission and have UV line ratios very similar to the Sun's. They also exhibit circumstellar absorption features in Mg II and Ca II, demonstrating that solar-type activity is not incompatible with cool, low-velocity winds. The hybrid stars have positions in the HR diagram near the boundary of CS lines and the limit of transition-region emission (Figure 2). This property also seems to suggest a continuous progression in atmospheric properties, in agreement with the asymmetry data.

A more subtle reason for suspecting a connection between cool winds and solar- type flows concerns the energy balance of the extended atmospheres of red giants. Several investigations have led to the conclusion that "extended chromospheres" surround late-type stars in which transition-region and coronal emission is absent (cf. Goldberg 1979). The extended chromospheres are regions of temperatures ∿ 10^4K with scale heights far in excess of what would be expected from thermal pressure balance.

Stencel et al. (1981) used the IUE satellite to observe the density sensitive C II lines near 2325 A in a number of evolved stars. The line ratios indicate electron densities of order 10^8 cm^{-3} in the line-forming region for K giants like α Boo and α Tau. Combining the density with the observed flux, the emitting region is calculated to have a path length comparable to the stellar radius.

Examination of spectral features, such as the Hα and Ca II infrared triplet lines, also support the concept of extended chromospheres in low- temperature winds. For example, these lines exhibit blue-shifted cores in supergiant stars like α Ori (Figure 3), suggesting that at least part of the chromosphere is being formed in an expanding region. The photosphere of α Ori undergoes small, irregular pulsations, which the Hα core does not share (Goldberg 1979). This means that Hα is formed in a wind region physically distinct from the photosphere, probably extended over several stellar radii. Occultation techniques and speckle interferometry directly demonstrate the existence of the extended Hα zone (White, Kreidl, and Goldberg 1982; Goldberg et al. 1982).

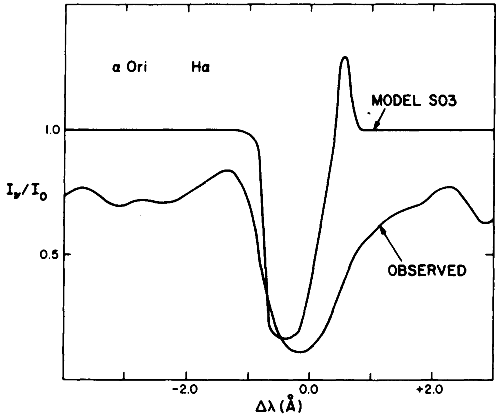

Figure 3. Observed Hα profile for α Ori (Goldberg, private communication). A wave-driven wind model has been calculated for comparison purposes (Hartmann, MacGregor, and Avrett 1982) (see section 2B).

The ionization of the extended chromosphere and the emission in excited- state lines such as Hα require some source of mechanical heating. It is difficult to make an accurate estimate of the required energy flux. The best present values are $\sim 10^4 - 10^5$ erg cm^{-2} s^{-1} emanating from the surface of the star (Hartmann and MacGregor 1980; Hartmann, MacGregor, and Avrett 1982). In my view this result may also indicate a connection between cool winds and solar activity, because the energy fluxes required by the solar wind are also of this order of magnitude (Withbroe and Noyes 1977). There is also evidence that energy and/or momentum is being deposited in the solar wind out to several $R_\odot$ (Munro and Jackson 1977).

If there are related mechanisms operating in both hot and cold stellar winds, why are the temperatures so different? Theoretical calculations show that the high densities and long flow times characteristic of the winds of low-gravity stars promote radiative cooling (Hartmann and MacGregor 1980; Hartmann, MacGregor, and Avrett 1982). In contrast, the solar wind does not radiate efficiently (Withbroe and Noyes 1977), so that heat energy being supplied to the gas goes into potential or kinetic energy.

It has been suggested that some features of the solar wind, particularly high-speed streams, cannot be explained by thermal acceleration alone, but require some direct deposition of momentum (Belcher 1971; Hollweg 1973; Jacques 1978). This suggestion leads to the idea of a natural sequence of winds which connects solar-type activity with circumstellar shells. In this view the winds of high-gravity stars are propelled by both momentum deposition and heating. In winds from low-gravity stars, the energy dissipated into heat is quickly radiated away before it can play a major role in wind acceleration. The mass loss observed is then driven primarily by the momentum deposition mechanism. This picture qualitatively accounts for the gradual increase in Ca II and Mg II asymmetries, the existence of hybrid stars, and the occurrence of extended chromospheres.

What is the momentum deposition mechanism? Alfven waves have been observed in the solar wind (Belcher and Davis 1971), and theoretical calculations show that wave fluxes $\sim 10^5$ erg cm^{-2} s^{-1} can account for high-speed streams (Hollweg 1973; Jacques 1978). Although magnetic fields or Alfvenic fluctuations on stars are not directly observable, it is possible that line broadening due to wave motions might be detected. There are indications of large "turbulent" motions in the envelopes of low-gravity stars. For instance, it is difficult to obtain the very large widths seen in the Hα profile of a star like α Ori (cf. Figure 3) without invoking some large (supersonic) turbulent velocity.

A remarkable and unexpected example of the large motions seen in low-gravity atmospheres is the discovery of broad transition-region lines in some stars. The optically-thin Si III 1892A and C III 1909A emission lines in the hybrid atmosphere star α TrA (K4II) exhibit velocity widths of 100 km s^{-1} (Hartmann, Dupree, and Raymond 1981). Such supersonic motions clearly indicate that hydrostatic equilibrium cannot be assumed. Somewhat smaller broadening velocities have been observed in the G2II star β Dra and in an active RS Cvn star (Ayres et al. 1982). These observational results make the idea that propagating waves are being excited more plausible.

B. Wave-driven Winds

In order to see what the physics of a wind driven by Alfven waves is like, consider the simplest possible situation, in which the flow is spherically symmetric and the magnetic field lines are all radial. With these assumptions, the introduction of pure Alfven modes results in an equation of motion of the form

$$v\frac{dv}{dr} + \frac{1}{\rho}\frac{d}{dr}\left(P + \frac{<\delta B^2>}{8\pi}\right) = - \frac{GM}{r^2} \tag{1}$$

(Hartmann and MacGregor 1980), where v, ρ , and P are the gas velocity, density, and pressure, respectively, and δ B is the magnetic field fluctuation. The structure of eq. (1) suggests that the effect of the turbulent magnetic pressure is analogous to the role played by the gas pressure in a thermally-driven wind.

The steady flow solution passes through a critical point, which determines the mass loss rate for given initial values of the magnetic field, wave flux, and gas density. The analogy with thermal-pressure driven winds makes the critical point conditions transparent. For example, the numerator = 0 condition at the critical point of a thermally driven (isothermal) wind is

$$\rho a^2 = \frac{GM\rho}{2r}$$

where a is the isothermal sound speed. The corresponding relation for a low-temperature wind driven by undamped Alfven waves is

$$\delta B^2/16\pi \sim GM\rho/2r \quad . \tag{2}$$

Similarly, the denominator = 0 equation for the thermally-driven wind, $\rho v^2 = \rho a^2$, becomes

$$\rho v^2 \sim \delta B^2/32\pi \tag{3}$$

for wave-driven winds.

Combining (2) and (3) with the energy flux dependence for undamped waves (which turns out to be $F_w \propto r^{-2}$ for low Alfvenic mach number), and assuming that the critical point distance scales with the stellar radius, one can explain the detailed wind calculations with the approximate scaling law

$$\dot{M} \sim 10^{-25} M^{-1.5} R^{3.5} (F_5/B_o)^2 M_\odot yr^{-1} \quad , \tag{4}$$

where M and R are the stellar mass and radius in solar units, F_5 is the initial wave flux measured in units of 10^5 erg cm $^{-2}$ s $^{-1}$, and B_o is the magnetic field strength in gauss. The difficulty in evaluating the applicability of eq. (4) is that mass loss rates are poorly known (Goldberg 1979) and magnetic field strengths are completely unknown. However, it is suggestive that the order of magnitude mass loss estimates (Bernat 1977; Reimers 1977; Hagen 1978) can be reproduced by solar-type surface conditions, with $F_5 \sim 1$ and $B_o \sim$ gauss.

The wave fluxes possible are obviously constrained by the magnetic field strengths. One can show that plausible limits on the initial density leads to the approximate scaling (Hartmann, MacGregor and Avrett 1982)

$$\dot{M} \sim 10^{-14} M^{-0.5} R^{2.5} B_o^{2} M_\odot \, yr^{-1} . \quad (5)$$

If Alfven waves propagate without dissipation, high wind velocities result (Hartmann and MacGregor 1980). This is fine for producing high-speed streams, but terrible for matching the low terminal velocities observed for cool winds (Figure 1). Hartmann and MacGregor (1980) showed that the Alfven waves must dissipate on length scales of a stellar radius in order to drive cool mass loss with acceptably small terminal velocities. Although there are several possible ways in which the waves can damp, there is no clear way at present to predict the detailed manner of dissipation. However, if one parameterizes the dissipation, it is clear that substantial gas heating must occur. If the radiative cooling rate is known, the balance of heating and cooling permit the calculation of the wind temperature structure, which can be compared with observation.

Radiative transfer calculations show that the wave heating predicted by this parameterized dissipation results in extended chromospheres which are in qualitative agreement with the previously mentioned empirical studies (Hartmann, MacGregor, and Avrett 1982). Specifically, the wave dissipation explains: (1) the C II density diagnostic line ratios observed in K giants; (2) free-free radio emission from α Ori (Altenhoff, Oster, and Wendker 1979; Bowers and Kundu 1979; Newell and Hjellming 1982); and (3) extended Hα emission surrounding α Ori (Figure 2). The quantitative agreement of theory with observation is reasonable, considering the simplifications introduced to make the calculations tractable.

Since most of the wave energy introduced into the cool wind is radiated away, the wave flux needed to produce a given mass loss rate can be empirically determined from an estimate of the radiative losses of the extended chromosphere. Present values for these losses are obviously consistent with the (poorly-determined) observed mass loss rates. In addition, Hartmann, MacGregor, and Avrett (1982) have shown that the limit of the cool wind region in the HR diagram can be explained by assuming $B_o \sim 3$ gauss and $F_5 \sim 3$.

These considerations show that there are many attractive features of wave- driven winds which suggest application to cool low-velocity flows. Although there are many observational uncertainties, and the simplifications of present theory may not be very realistic, the convergence of theory and observation to emphasize the importance of extended chromospheres is encouraging. We may learn a great deal about momentum deposition in the solar wind, which is difficult to distinguish from heating (cf. Munro and Jackson 1977), by studying the cool winds of late-type stars.

C. Pre-Main Sequence Stars

At first glance, the Hα profile of a T Tauri star displayed in Figure 4 has little in common with the Hα line of α Ori (Figure 3). Despite the obvious differences, there are two underlying aspects in common. The asymmetry of the Hα emission in DF Tau is one indication that mass loss is being driven off at temperatures which are too low for thermal acceleration to be important, as is the case for α Ori. A second point of contact is that there is evidence for large turbulent velocities in both T Tauri variables and evolved stars. P Cygni-type profiles in which the blue-shifted absorption reversal is at a smaller velocity than the emission component generally require some sources of line broadening larger than the local expansion velocities. Indeed, many of the T Tauri stars show much more symmetric line profiles, with hardly a hint of mass loss (De Campli 1981; Hartmann 1982).

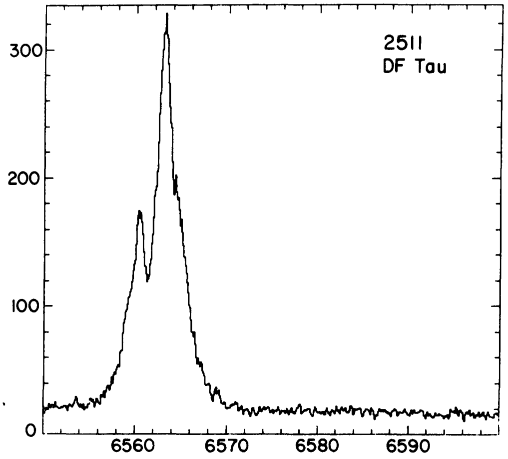

Figure 4. Hα line profile of the T Tauri star DF Tau (Hartmann 1982).

Recognition of the need for a momentum source which drives T Tauri winds led De Campli (1981) to investigate Alfven wave-driven wind models. He concluded that the mass loss rates must be $\lesssim 10^{-8}\ M_\odot\ yr^{-1}$ if one makes the plausible assumption that wave energy fluxes are less than the stellar luminosity. Although this mass loss limit was in conflict with previous estimates, De Campli showed that the introduction of large turbulent velocities could bring the observational mass loss estimates into better agreement with the theory.

Subsequently Hartmann, Edwards, and Avrett (1982) showed that the very existence of the waves driving the flow demanded large "turbulent" velocities. The critical point conditions include the intuitively reasonable constraint (cf. eq. (2)) that the wave force is comparable to gravity at this point. Since $\delta B/B = \delta v/A$ for an Alfven wave, where A is the Alfven speed, eq. (2) is equivalent to

$$\delta v_c^2 \sim GM/r_c \tag{6}$$

Flow speeds are typically less than the escape velocity within the critical point. Therfore wave motions generally dominate expansion in the dense regions of the wind, where most of the emission is expected to originate. The wave motions have the effect of producing much larger equivalent widths for the optically-thick Balmer lines at a given mass loss rate than would be calculated in the absence of wave broadening.

The terminal velocities of T Tauri stars are not well known, and so there is no requirement for wave damping as there is for giant and supergiant winds. However, there are very large emission-line fluxes for which some source of heating must be supplied. Adopting the same parameterization of wave dissipation for T Tauri stars as for evolved stars, Hartmann, Edwards, and Avrett (1982) showed that the strongest observed emission can be accounted for with mass loss rates $\sim 10^{-8}$ $M_\odot$ yr^{-1}, and wave fluxes $\sim 10^{-1}$ of the stellar luminosity, requiring $B_o \sim$ 200 gauss.

D. Main Sequence Stars

Unfortunately, we have really no observational information concerning the winds of late-type main-sequence stars. The only thing one can do at present is to make crude estimates based on comparison with the Sun.

Alternatively, one might consider the effects of momentum deposition by waves. It is interesting to note that eq. (7) reduces to the solar mass loss rate for field strengths $\sim$ gauss; this is consistent with suggestions that Alfven waves provide significant acceleration of the solar wind (cf. Hollweg 1973).

3. STELLAR SPINDOWN AND WINDS

A. Main Sequence

Little progress on determining stellar rotational velocities was made for many years after Kraft's (1967) work. Although improvements in spectroscopic observational techniques have led to more accurate measurements of low rotational velocities (Smith 1979; Soderblom 1980), a real breakthrough came from the realization that the rotational modulation of Ca II H and K emission can provide direct measurements of the rotational periods (Vaughan et al. 1981).

Although the objects observed in this survey are all field stars, I have attempted to place them in age groups according to their Ca II emission (S index). In particular, I have identified objects with emission levels that would place them within observed limits for the Hyades and for old field stars (cf. Wilson 1970; Vaughan and Preston 1980). One cannot be sure that objects with strong emission are all of Hyades age, but comparison with v sin i's measured for some Hyades members by Soderblom (1980) and Baliunas (1982) shows good agreement.

The combined data are shown in Figure 5, in which I have placed the new observations in the context of previous studies of earlier spectral types. The data give an impression of a slight decline in v_{rot} with decreasing effective temperature for stars of Hyades S index. Similarly, there is an indication of a modest decline in v_{rot} for G-K dwarfs of advanced age, although again it is difficult to be precise about this since the ages of the weak-emission field stars are not well known. In any event, the data suggest that rotational braking timescales are roughly similar in G-K dwarfs.

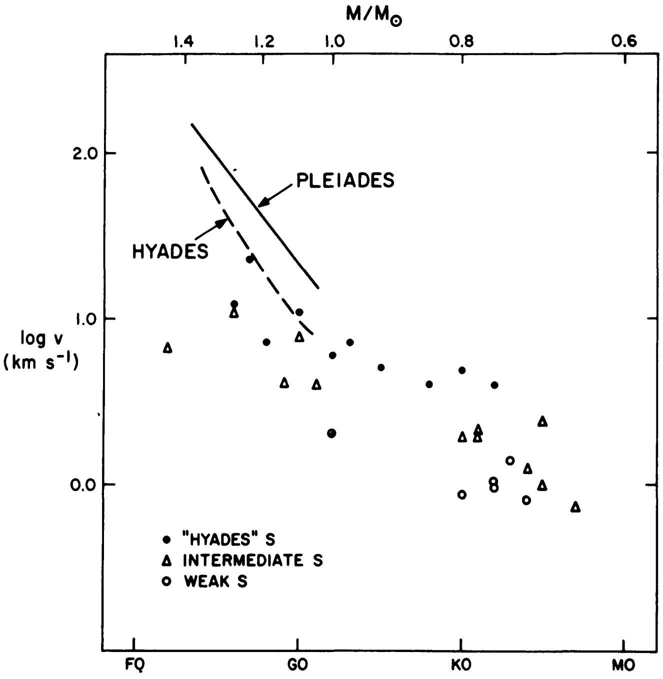

Figure 5. Main sequence rotational periods vs. spectral type.

The main sequence stars studied here clearly fall below the total angular momentum law $J \propto M^{0.57}$ suggested for earlier spectral types (Kraft 1970). For stars of Hyades emission, the data suggest $J \propto M^4$, although the exponent must be considered rather uncertain due to small number statistics and a small baseline in stellar mass M. This exponent is similar to the value derived by Kraft (1967) for the range $1.2 \lesssim M/M_\odot \sim 1.4$.

What can we infer about stellar winds and their braking effects from Figure 5? If the Skumanich law in the form $v_{rot} = v_o t^{-1/2}$ strictly held everywhere, the rotational velocities of all very old stars should approach the same value. The observational evidence seems to suggest that K dwarfs may have the same braking timescales as G dwarfs, but at lower equatorial velocities. If further studies bear out this result, the implication would be that angular momentum loss rates at a given equatorial velocity or rotational period remain relatively constant while the stellar moment of inertia decreases with decreasing mass ($\sim m^3$). What this means in terms of the dependence of $\dot{M}$ and B on rotation and spectral type is unclear, given the absence of any observational limits on mass loss rates.

Durney and Stenflo (1972) pointed out that the Skumanich law can be understood on the simple Weber-Davis model for stellar spindown if mass loss rates are constant, the mean magnetic field B_o scales as v_{rot}, and the Alfven radius r_A scales as B_o. It is amusing to point out that the Durney-Stenflo result also holds for the case in which the mass loss rate varies as B_o^2 (cf. eq. (7)). In this case the Alfven radius will remain relatively constant if wind velocity structure does not change dramatically; the stars would tend to remain more in the slow-rotator domain rather than becoming fast magnetic rotators (Belcher and MacGregor 1976).

There are other indirect means of studying main-sequence stellar spindown, involving close binaries. It has been suggested that angular momentum loss from a stellar wind can assist in forming contact binaries of the W UMa type by bringing the component stars together from an initially detached state (Huang, 1966; Okamoto and Sato 1970; Van't Veer 1979; Vilhu 1982). Similarly, it has been suggested that magnetic braking of the dwarf component of cataclysmic variables is important in driving mass transfer (Eggleton 1976; Verbunt and Zwaan 1981). The aforementioned authors have shown that a Skumanich-type braking law leads to the correct order-of-magnitude angular momentum loss required. In principle it might be possible to estimate spindown properties by these studies, but it seems more likely that observations of the braking of single stars will be more definitive, and more useful in analyses in the opposite direction, i.e. using observed angular momentum loss rates to predict cataclysmic variable accretion rates in more detail. Clearly it is of importance to extend our knowledge of stellar rotation to smaller masses (later spectral types) for this particular purpose.

B. Origin of the Sharp Break at F5

It has been clear for some time that the rapid break in main-sequence rotation near F5 is the result of a decrease in the efficiency of stellar wind braking in early spectral types. Since chromospheric emission disappears in this region, and convective envelopes shrink rapidly in proceeding to hotter stars, the natural conclusion is that dynamo-generated magnetic activity also disappears, and so no magnetic braking is expected (Schatzman 1962; Wilson 1966a,b; Kraft 1967). However, it is difficult to detect Ca II and Mg II emission at reasonable levels in early spectral types due to the increase in photospheric background. Therefore the disappearance of chromospheric emission cannot be regarded as a definitive measure of magnetic activity.

In this regard the observations of X-rays from A and F stars were somewhat of a surprise (Vaiana et al. 1981). Although it is possible that late-type companions account for some of the observed X-ray emission, high-resolution images of Sirius and Vega make it likely that these stars are actual (albeit weak) sources of X-ray emission. We have no direct evidence for magnetic fields in these stars, but is plausible to suppose that they may result from some analog of solar coronal emission.

Skumanich (1981) pointed out that the presence of X-ray emission might indicate significant magnetic fields, despite the observed lack of spindown. He suggested that one way out of this difficulty would be to assume a general change in magnetic topology, in which all the field lines close near the surface and therefore do not couple to the wind. However, such an extreme change in field structure may not be necessary. A and F stars appear to deviate from the general relationship between rotation and X-ray luminosity, in the sense that they have relatively weak emission for their rapid rates of spin (Pallavicini et al. 1981). Noyes (this volume) has discussed evidence from the Mt. Wilson survey that chromospheric emission in F stars is weaker than in later spectral types of comparable rotational periods. This suggests that the magnetic and mass loss activity of these stars may be more representative of more slowly rotating stars.

The median X-ray luminosity of the A-F stars is $\sim 10^{29}$ erg s^{-1}, comparable to the mean luminosity of G dwarfs in the Hyades (Stern et al. 1981). Suppose this means that the magnetic field strengths and mass loss rates, and therefore angular momentum loss rates, are the same for the A-F field stars and the Hyades G dwarfs. The latter have a braking time of order 10^9 years. From this it is clear that the rapidly rotating early F dwarfs would suffer very little spindown with the same angular momentum loss rate over their main-sequence lifetimes $\sim 10^9$ yrs. It appears that a change in the dependence of magnetic field and energy generation rates on rotation, rather than a complete cessation of mass loss and magnetic activity, can be compatible with the observations of both X-ray emission and rapid rotation in the A-F stars.

C. Rotation of Evolved Stars

In general there are fewer data concerning the rotation of red giants than dwarfs, because of (generally) smaller equatorial velocities. In addition, the internal structural changes involved in evolution off the main sequence make the connection between surface rotation and angular momentum loss more problematical.

Gray (1981,1982) has suggested that there is a sharp reduction in rotation near G5 III, and that these stars slow down from about 25 km s^{-1} to about 5 km s^{-1} in only a few spectral subclasses. Gray (1982; see also Gray and Endal 1982) find that redistribution of angular momentum within the envelope is insufficient to account for the reduction in equatorial velocity. Instead, Gray (1982) suggests that rapid braking occurs at this point, due to the increase of depth of the convective zone. This generates a very strong dynamo-generated magnetic field, which in turn couples to the stellar wind, and reduces the stellar rotation very rapidly.

There are problems with this scenario. Certainly stars from types F5 III to G5 III have chromospheric emission, which on the basis of solar studies suggests magnetic fields are already present. Thus, a subtle change in stellar structure must result in a large increase in the magnetic field. On the basis of the simple Weber-Davis (1967) formulation, one can show that the braking timescale τ is approximately given by

$$\tau \sim \frac{\alpha M v_A}{B_o^2 R^2} \tag{7}$$

where M and R are the stellar mass and radius, respectively, B_o is the surface magnetic field strength, and v_A is the wind velocity at the Alfven radius r_A. The factor α is the moment of inertia constant, $\sim 10^{-1}$.

Evolutionary calculations (cf. Iben 1965) suggest that the first crossing of the Hertzsprung gap is very rapid, and that the evolution of a giant through a few subclasses occurs in a few x 10^5 years or so. The rotational braking time must therefore be of this order. Substituting the values $M \sim 3\ M_\odot$, $R \sim 10\ R_\odot$, $v_A \sim 200$ km s^{-1}, and $\tau \sim 3 \times 10^5$ yr into Eq. (8), one finds $B_o \sim 50$G. Comparison with the Sun suggests that such surface averaged field strengths would result in (unobserved) strong chromospheric and coronal emission in G5 III stars.

The evolutionary calculations also show that stars with $M > 2.25\ M_\odot$ have blue loops in the HR diagram, and that they cross part of the Hertzsprung gap a second time after helium ignition (see also Gray and Endal 1982). This second crossing takes much longer than the first crossing, and so stars in this evolutionary state can be expected to dominate the distributions of giants in certain regions of the HR diagram. Alschuler (1975) suggested that G5 III and earlier stars are first-crossing stars of intermediate mass and age, while G8 III and later giants are mostly second-crossing stars, and backed up this contention with statistical analyses and improved evolutionary tracks. Gray and Endal (1982) suggest that the majority of G5 III stars must be second-crossing objects. If this picture is correct, then one should not be surprised to see a break in v sin i near G5 III, for this spectral type is near the division between objects of significantly different ages and internal structures.

If we do not need to invoke sharply peaked braking at G5 III, then we have little indicated need for wind-related spindown; Endal and Sofia (1979) have shown that the general decay of v sin i can be explained without mass loss, due to the effects of convection in transporting angular momentum and in changing the moment of inertia.

Chromospheric surface fluxes decline with decreasing effective temperature (Basri and Linsky 1979; Middelkoop 1982), which is likely to be correlated with spindown. If there is a sharp change in rotation at $\sim$ G5 III, irrespective of its explanation, one might expect this to be reflected in stellar activity. There is some evidence for this effect in Ca II emission (Middelkoop 1982), and transition-region fluxes generally become undetectable at K0 III (Linsky and Haisch 1979; Simon, Linsky, and Stencel 1982).

D. Spindown of Pre-Main Sequence Stars

Although we have more observational information about pre-main sequence winds than for solar-type stars, obtaining rotational velocities for these stars is very difficult. Not only are they relatively faint, but their chromospheric activity tends to wash out strong photospheric absorption lines or even turn them into emission lines. In addition, it is very difficult to place these stars on the HR diagram. Even with reasonable estimates of log g and T_{eff}, there are still substantial uncertainties in the internal structure of these stars, and so there is some question as to the accuracy of the evolutionary tracks to be used. The importance of this point can be appreciated from Figure 6. One can see that the assignment of the correct mass depends crucially on the adoption of the correct evolutionary tracks. This in turn is vital to understanding spindown, since the rotation of main sequence stars is a very sensitive function of mass in the 1-2 $M_\odot$ range.

Vogel and Kuhi (1981) have studied stars with ages $\sim 10^7$ years in several regions of the sky. It appears that the rotation of these pre-main sequence stars do not follow the Skumanich law for V_{rot} vs. age, in the sense that V_{rot} is smaller than the projection of V_{rot} backwards in time from the Hyades-Pleiades relation. To put it another way, the T Tauri stars seem to be slow rotators. However, if the change in the moment of inertia as a star evolves is taken into account, and the Skumanich law is changed to an angular momentum loss rate, then the agreement is improved (Vogel and Kuhi 1981). This result is not a very accurate test, given all of the uncertainties involved.

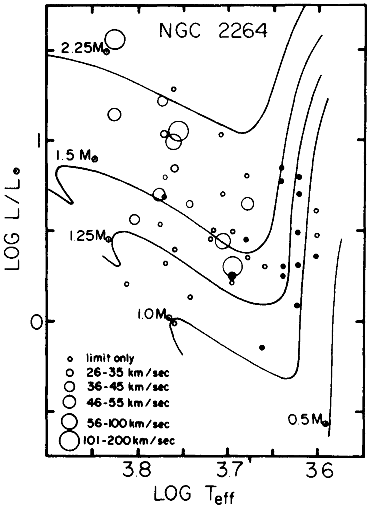

Figure 6. V sin i's of pre-main sequence stars in NGC 2264, with approximate evolutionary tracks indicated (Vogel and Kuhi 1981).

If T Tauri mass loss rates are less than 10^{-8} $M_\odot$ yr^{-1}, then clearly there must be a magnetic field to brake the stars as observed. Although the exact braking timescales are uncertain, they must be of order 10^6 yr. Then, if we use the simple Weber-Davis estimate (7), and assume $M \sim M_\odot$, $R \sim 3R_\odot$, $v_A \sim 200$ km s^{-1}, and $\tau = 10^6$ years, $B_0 \sim$ 170G. This field strength is of the order necessary to have the possibility of an Alfven-wave driven wind, and so suggests that we may be on the right track in interpreting T Tauri mass loss.

Another result of importance found by Vogel and Kuhi (1981) is that the fast rotators seem to generally occur among the high-mass pre-main sequence stars. In other words, there is some evidence that the break in rotation seen on the main sequence near F5 is already present in the T Tauri phase. This indication, if true, is extremely important, for it seems to suggest a qualitative difference between the formation processes of low and high mass stars.

One aspect of Figure 6 I find intriguing is the suggestion that there is a wide range of v sin i's present in the more massive stars. This seems qualitatively consistent with the results of Wolff, Edwards and Preston (1982), who found a similarly broad distribution of rotation in B-A stars and suggested that this distribution has a protostellar or pre-main sequence origin. These data indicate that protostars may form with widely varying angular momentum. The operation of wind braking with a Skumanich-type law, i.e. one in which the braking time decreases for increasing rotation, will tend to bring the older stars on the lower main sequence into a narrower angular momentum distribution than was initially present.

In recent years, observational studies have begun to address mass loss from protostars. Radio frequency observations of regions of star formation indicate that surprisingly large mass outflows are associated with very early stages of stellar evolution (Genzel et al. 1981; Bally and Lada 1982; see also Hartmann and MacGregor (1982) for further references). Space does not permit an adequate description of the problems associated with these outflows, and the field is evolving so rapidly that it is premature to attempt to review it. However, it seems quite possible that many of the concepts of magnetic wind braking developed to explain the angular momentum loss of main sequence stars may also be extended to describe protostellar spindown.

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DISCUSSION

NUSSBAUMER: I have a short comment on your mass loss formula. I have recently published (1982, *Astron. Astrophys.* **110**, p. L1) a short note on the possibility that *randomly emerging magnetic flux* may be at least partially responsible for stellar winds. I introduced factors into the formula to account for the fact that magnetic fields do not cover the total surface of the star, and that closed fields could rather inhibit than produce mass loss. The formula can explain the total solar mass loss with $B = 100$ G, and if it is assumed that 0.1% of the solar surface is covered by such fields, and that 0.1% of the emerging flux is efficient in producing mass loss. For the sun the area coverage factor can be determined observationally; to determine the second (efficiency) factor is a more difficult task. I think, however, that it is important not to neglect these efficiency factors.

HARTMANN: I agree that some area factors must be involved. However, nobody knows what they are for stars. Furthermore, the observed mass loss rates are uncertain by an order of magnitude or more. So for reasons of simplicity and ignorance I have left these factors out.

MULLAN: Mass loss in cool giants can be driven by unstable emerging fluxtubes. This appears to be as viable a mechanism as wave driving. In particular, emerging flux can account for macroturbulent broadening, episodic mass loss, highly variable chromospheric/coronal emission, etc. As regards the break in rotational velocity at ~F5, I have already suggested that the coincidence of main sequence lifetime with the age of the galaxy at ~F5 is important (cf. 1972, *Astrophys. Letters*). There need not be any break in convective efficiency at F5. It may occur much later (G-K). In the sun the major correlation between wind flux and surface features occurs when one considers X-ray bright points. These are known to be regions of emerging flux. This is a strong indication that emerging magnetic flux plays an important role in driving mass loss in the sun.

HARTMANN: The wind can open field lines up, so to some extent there is a question of which is the chicken or the egg, the open field lines or the mass loss. In addition, to the extent that emerging field lines exert an outward force on the gas, they might have properties in a time-averaged sense which look like some of the steady wave-driven wind properties.

GIAMPAPA: (1) Let me just comment that the X-ray emission observed in A stars is likely to be due to dMe stellar companions, although there is A star X-ray emission observed for some apparently single A stars. (2) Would you care to comment on Dr. R. Stencel's hypothesis that magnetic fields contribute significantly to the hydrostatic balance in the 10^4 K "extended chromosphere" of α.Ori?

HARTMANN: The out-flow of α Ori is fairly slow. So there is an extended region where the flow velocity is considerably less than the sound speed, and this region could be nearly in a hydrostatic equilibrium, with the gravitational acceleration being balanced by the turbulent magnetic pressure gradient.

UCHIDA: In talking about Alfvén waves I presume that you have in mind the stochastic generation of Alfvén waves in convective turbulence distributed all over the stellar surface. How then do you explain the time variations seen e.g. in T Tau stars? Such large time variations should be due to fluctuations coming from a smaller number of sources.

HARTMANN: The calculations are spherical and steady-state. These conditions have been assumed, not because we feel that they are correct, but because they simplify the problem. Undoubtedly magnetic fields are structured and variable if the sun is any guide, so we should expect wave-driven winds to be variable as well.

SHEELEY: You have used the term "extended chromospheres" several times. Have you tried to imagine what an extended chromosphere might look like if you took a spectroheliogram of it? Would it consist of a "hayfield" of very long spicules much like your lawn when you return from an extended vacation? Or would it consist of many large prominences? Or what?

HARTMANN: I have not thought much about it. There are speckle observations of α Ori by Goldberg and coworkers in Hα, which show irregular structure. In addition, α Ori exhibits irregular variations in polarization. These data indicate an irregularly moving surface, perhaps similar to solar spicules, but moving much further in a gravitational field $\sim 10^{-4}$ of the solar field.

CRAM: There is another class of giant stars whose "extended" chromospheres may be observed: eclipsing binaries like 31 Cyg and 32 Cyg. There is evidence for time-dependent structures of fairly large size in the chromospheres of these stars, and most observers of these objects have drawn an analogy to solar prominences, rather than spicules. The idea that these observed structures may be analogous to magnetically supported solar prominences is perhaps the only evidence we have for the existence of "important" magnetic fields in the atmospheres of giant stars.

GIAMPAPA: Just a comment on Lawrence Cram's remark: A radio flare has been observed by Boice et al. (1981, *Astrophys. J. Lett.* **245**, pp. L71-L74) on the M giant star α Ceti.

SHIELDS: The slightly blueshifted absorption line in the Hα emission profile of DF Tauri resembles some ultraviolet emission line profiles of quasars. How does one understand the existence of high velocity emitting gas when lower velocity absorbing gas is able to escape from the star's gravitational field?

HARTMANN: The blueshifted absorption occurs at a distance of a few stellar radii, where the escape velocity is lower than it is near the surface, while the broad emission originates near the surface, deeper in the gravitational potential well. In addition, the emission component is broadened further by optical depth effects.

ROSNER: Did I understand correctly that $v_{\parallel} \ll v_{\perp}$ at the base of the wind models? I am surprised by that because, in the presence of magnetic fields, I would have expected any anisotropy to obey just the opposite inequality, $v_{\perp} \lesssim v_{\parallel}$, because the base coincides with the region of wave generation, i.e. the region where $\beta \gtrsim 1$.

HARTMANN: We have not considered the wave generation zone, and have assumed that only transverse modes are propagating. This simplification is not correct. What is important is that δv can be much larger than the average or background net expansion of the wind. We assumed transverse modes, because it appears that compressive longitudinal modes dissipate fairly rapidly as they propagate outwards.

KOUTCHMY: Coming back to the comment by Dr. Mullan, I would like to say that we completely agree that large mass flows coming from coronal holes are produced by very small-scale events occuring in regions cospatial with X-ray bright points and elements of the chromospheric network. Dr. Brueckner's group at NRL and we in Paris have pointed out the importance of the so-called superenergetic events occuring very suddenly above enhanced network elements. They are named super-spicules, macro-spicules, or coronal spikes, and they are clearly the source of the filamentary structure of the wind flow.

MESTEL: This is by way of a philosophical comment. In magnetic braking one is trying to eat one's cake and have it. The angular momentum transport is equivalent to effective corotation being maintained out to the Alfvén surface. Within this surface, by definition the wind energy is below the magnetic energy, so that the magnetic stresses control the rotation of the outflowing gas; but equally the magnetic field will either inhibit or channel the wind. In particular, one expects that if the total magnetic flux emerging from the star is imagined being increased — e.g. due to a higher rotation yielding a more efficient dynamo — then there will be a correspondingly larger zone of closed field lines. In some computations done some sixteen years ago, I assumed the field structure to be dipolar and curl-free out to the Alfvénic surface, and radial beyond. Increasing the stellar magnetic flux did not then increase the angular momentum loss; the larger radius of the Alfvénic surface was compensated by the reduced area of the wind zone, so that we got the same rate of braking, but for a smaller mass loss. My model was certainly too conservative, but the results illustrate that it is dangerous to assume an enormous scaling-up of the braking rate with increase in stellar flux; the problem is a good deal more subtle.