STELLAR WINDS AND SPINDOWN IN RED GIANTS

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ABSTRACT

Recent observations of rotation rates in G and K giants show a sudden drop in the rotation rate at spectral type G5. The observed behavior requires a strong external brake, such as applied by a magnetized stellar wind. Since spectral type G5 coincides with the onset of deep envelope convection in giants, a dynamo mechanism is suggested as the controlling factor. Stellar evolution models have been used to estimate the time scale for the rotational braking, the angular momentum loss rate, and the required magnetic field strengths.

1. INTRODUCTION

In an earlier paper in this session, D.F. Gray described some very interesting observational results on the rotation of G and K giants. I will present an interpretation of these results, based on first-crossing (FC) models of intermediate mass ($3M_\odot$) stars. The mass was chosen on the basis of the estimated luminosities of these stars; the results are not very sensitive to this parameter. The question of whether FC models are appropriate will be deferred to a later section.

2. PREDICTIONS FOR STARS WITH CONSTANT ANGULAR MOMENTUM

Figure 1 shows the observed rotational velocities (v sin i) for giants of spectral types F8-K2. The lines indicate predicted velocities for a $3M_\odot$ star evolving from the ZAMS with an initial velocity of 180 km/s This initial value corresponds to the observed $\langle v \rangle = (4/\pi) \langle v \sin i \rangle$ for late-B main sequence stars. The solid line shows the predictions for convective envelopes in rigid-body rotation (Case 2 of Gray and Endal, 1982) and the dashed line shows predictions for uniform specific angular momentum in convective regions (Case 3). The models were computed by the techniques described by Endal and Sofia (1976, 1978).

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 493–498.

For spectral types F8-G2 (and for earlier spectral types - see Endal and Sofia, 1979) the observed <v> agrees with the predictions. At G5, there appears to be two groups of stars. One group is consistent with the predicted velocities of 20-30 km/s, while the second group shows values of 5 km/s or less. Gray (1982) interprets this as evidence for a strong rotational brake setting in near G5. This is consistent with the uniformly slow rotation of the giants of later spectral types.

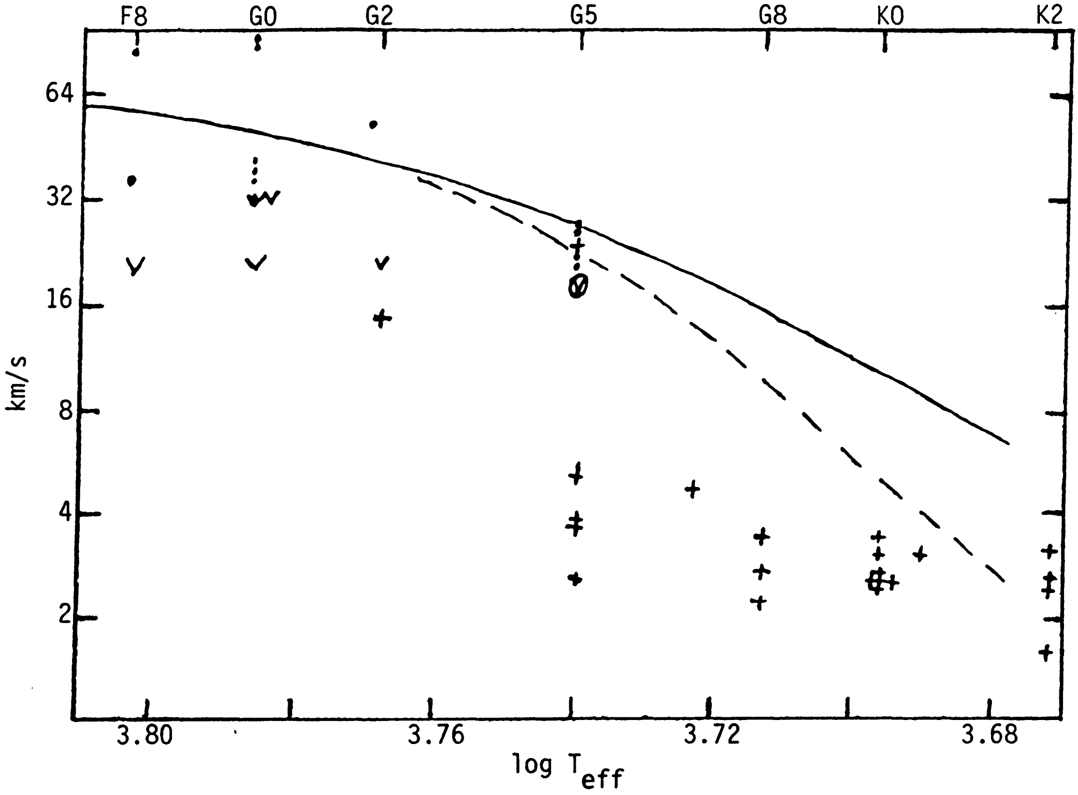

Fig. 1 - Observed and predicted velocities for F8-K2 giants. Heavy dots and carets (upper limits) show observations by Alschuler (1975). The circled caret at G5 represents 12 stars. Crosses show measurements listed by Gray (1982).

3. ANGULAR MOMENTUM LOSSES

Using the information from the stellar evolution models, we can calculate the rates of angular momentum removal required to bring the predictions into agreement with the observations. The results of such a calculation are given in Table 1. I have assumed, in these calculations, that the braking affects only the convective envelope. This is a reasonable (though not entirely safe) assumption. The last two lines will be explained in Section 4.

Table 1. Spindown of $3M_\odot$ Giants*

Sp. Type:	G5	G8	K0	K2
Observed <v>	4.8	4.1	3.5	2.5
Predicted <v>	27.4 (23.1)	15.3 (9.6)	10.9 (5.3)	5.6 (2.3)
$\dot{J}$ (dyn-cm)	$>4.5\times10^{36}$ $(>4.3\times10^{36})$	1.6×10^{37} (1.2×10^{37})	6.5×10^{36} (2.4×10^{35})	none (none)
$f^{-1/2}B_s$ (gauss)	>16.7 (>16.4)	67.2 (57.8)	34.9 (6.7)	-- --

*Values in parentheses refer to Case 3 rotation.

Several points should be made with regard to the values given in Table 1. First, the growth of the convective envelope during the evolution from G5 to K2 plays a very important role in the calculations. The deepening of the envelope is illustrated in Figure 2. This brings up additional angular momentum from the unbraked core and requires that the braking continue throughout the later spectral types. This could be avoided by assuming that the initial braking affects almost all of the star but this seems unlikely since the convective envelope at G5 contains only ∿1% of the total mass. Second, the time scale for the braking at G5 is not known. I have used the time required to evolve from G2 to G5 as an upper limit. Considering the sharp distinction between rapid and slow rotators at G5, the real time scale is probably much shorter. Third, the values at K2 should not be taken seriously. This group of stars is very close to the red giant branch and, therefore, contaminated by low-mass stars with very different histories.

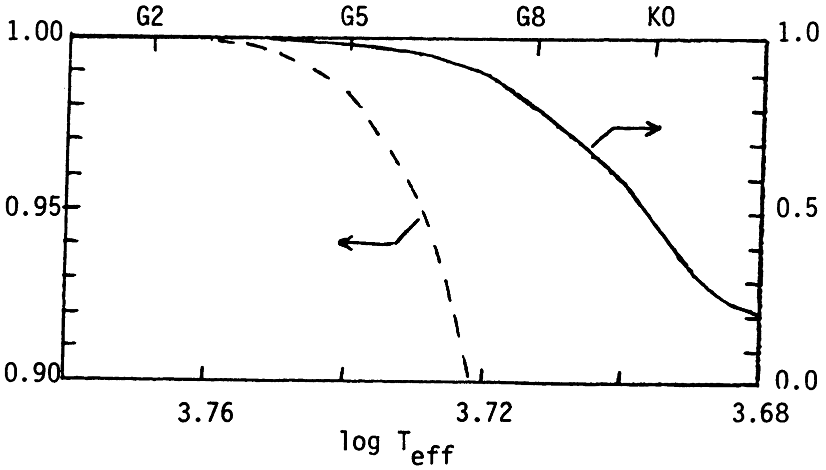

Fig. 2 - The depth of the convective envelope (M_r/M at the bottom of the envelope) for a $3M_\odot$ star. Arrows indicate whether values should be read from the left or right axis.

The rate at which the solar wind carries away angular momentum is $\sim 7\times10^{30}$ dyn-cm (Brandt and Heise, 1970). The $\dot{J}$ values in Table 1 are roughly a million times larger. The total loss during the evolution from G5 to KO is 65% (Case 2) or 35% (Case 3) of the initial angular momentum.

4. MAGNETIC FIELDS

The large $\dot{J}$ values in Table 1 require a very efficient braking mechanism, such as provided by a large-scale magnetic field embedded in a stellar wind. This hypothesis is supported by the correspondence between the start of the observed braking and the onset of deep convection (see Figure 2). Via a dynamo, this provides a means for generating the required magnetic field. In order to estimate the magnitude of this field, I have used a simple model of a magnetized stellar wind. The derivation given here will necessarily be sketchy; a more detailed derivation and justifications for the assumptions will be published elsewhere.

Following Weber and Davis (1967), the rate at which a magnetized wind carries away stellar angular momentum may be written as

$$\dot{J} = (2/3)\ \dot{M}\ (\Omega_s r_A{}^2) = (2/3)(4\pi r_A{}^2 \rho_A w_A)(\Omega_s r_A{}^2), \qquad (1)$$

where $\dot{M}$ is the mass-loss rate, Ω_s is the angular velocity of the stellar surface, r is radius, ρ is density, and w is the radial wind speed. A subscript A means the quantity is to be evaluated at the Alfvén point, though $\dot{M}$ could be evaluated at any distance. At the Alfvén point, the kinetic energy density of the wind equals the energy density of the radial magnetic field:

$$\text{kinetic energy} = (1/2)\rho_A w_A{}^2 = (1/2)\rho_A w_A f(GM/R)^{1/2}, \qquad (2)$$

$$\text{magnetic energy} = (1/8\pi)B_A{}^2 = (1/8\pi)B_s{}^2(R/r_A)^4. \qquad (3)$$

In equation (2), I have assumed that w_A is some fraction f of the plasma escape velocity and equation (3) assumes that the radial field scales back to the stellar surface (r=R) as $1/r^2$. Equating the energies at the Alfvén point, solving for $\rho_A w_A$, and substituting into equation (1), the result can be written as

$$f^{-1}B_s{}^2 = (3/2)(GM/R)^{1/2}R^{-4}(\dot{J}/\Omega_s). \qquad (4)$$

Note that all of the quantities on the right side of equation (4) can be determined from either the stellar models or the observations. The results are given in the last two lines of Table 1. Since $f^{-1/2}\sim 1$, this gives an estimate of the required magnetic field which couples the wind to the stellar surface. Note that this estimate refers only to that component of the field which extends to the Alfvén point. Localized surface fields may be much larger.

5. WARNINGS AND CONCLUSIONS

The interpretation presented above is based solely on FC models. An alternate interpretation would identify the rapid rotators of spectral types G5 and earlier as FC stars, while the slow rotators from G5 to K2 would be considered second-crossing (SC) stars. This would still require rotational braking, but the time scales would be much longer and $\dot{J}$ would be correspondingly smaller. I estimate that this would reduce the required magnetic fields by a factor of 5 (Case 2) or 10 (Case 3).

Theoretical models (Iben, 1965) suggest that the SC loop does not extend as early as G5 in intermediate mass stars. This conclusion is supported by the "clump giants" commonly observed at spectral types G8 and later in intermediate-age clusters (Cannon, 1970). Giants of spectral type G5 are relatively rare, in agreement with the short time scale of the FC evolution. Thus, the available information favors the FC interpretation for the G5 giants but may require SC models to interpret the G8 and later giants.

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REFERENCES

Alschuler, W.M.: 1975, *Astrophys. J.*, 195, pp. 649-660.
Brandt, J.C., and Heise, J.: 1970, *Astrophys. J.*, 159, pp.1057-1066.
Cannon, R.D.: 1970, *Mon. Not. Roy. Astron. Soc.*, 150, pp.111-135.
Endal, A.S., and Sofia, S.: 1976, *Astrophys. J.*, 210, pp.184-198.
Endal, A.S., and Sofia, S.: 1978, *Astrophys. J.*, 220, pp.279-290.
Endal, A.S., and Sofia, S.: 1979, *Astrophys. J.*, 232, pp.531-540.
Gray, D.F.: 1982, preprint.
Gray, D.F., and Endal, A.S.: 1982, *Astrophys. J.*, 254, pp.162-167.
Iben, I., Jr.: 1965, *Astrophys. J.*, 142, pp. 1447-1467.
Weber, E.J., and Davis, L., Jr.: 1967, *Astrophys. J.*, 148, pp.217-227.

DISCUSSION

ROXBURGH: It is dangerous to use a radial field — radial fields do not exist — only drawn out non-radial fields (e.g. dipole - multipole). In this case the angular momentum loss does not vary as B_0^2. Indeed for a dipole field the variation is like $B_0^{2/3}$, for a quadrupole field it is independent of B_0.

ENDAL: I agree that the radial-field assumption is an oversimplification. However, I do not think that we know enough about the multipole structure of non-solar fields to justify a more complex treatment.

WALTER: If you look at the figure showing the data, and scale the curve down to fit the G stars (to account for $\sin i$), the fit looks reasonable. In the K stars, the *average* $v \sin i$ may not be physically meaningful, because you are likely to be mixing evolving A stars with evolving (non-rotating) stars of approximately solar mass plus (non-rotating) second-crossing stars, which will decrease the average. The curve is not clearly discrepant — does the break really exist?

ENDAL: More data are certainly needed to be absolutely sure about the break in the rotation rate. I have interpreted the available data as they exist. On the other hand, the Hyades giants (at K0) certainly came from A stars. Their rotational velocities are consistent with those of the other stars in the sample.