CONVECTION AS A REGULATOR OF DYNAMOS

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ABSTRACT: Evidence is given for convection controlling dynamo activity and the rotation of some stars.

1. INTRODUCTION

Rotation, being the ultimate source of magnetic energy in stars, can be referred to as a "driver" of dynamos without further explanation. But a somewhat more subtle process, involving convection and dynamos, may be at work in stars, a process whereby the physical properties of the convection control the generation of magnetic field and through it the rotation of the star. I refer to this convective control of rotation as the "Rotostat Hypothesis", for reasons that will become clear presently.

2. REVIEW OF PAST MATERIAL

The rotation velocity of class III giants and of subgiants show abrupt drop-offs at G5 III and G0 IV, respectively, as shown in Figs. 1 and 2. An explanation of the drop in rotation as the result of the sudden start up of a strong magnetic brake, as these stars evolve from left to right in the HR diagram, has been presented (Gray 1981, 1982a, 1982b, Gray and Nagar 1985). The essential thread of the argument (for giants) says that rapidly rotating main sequence

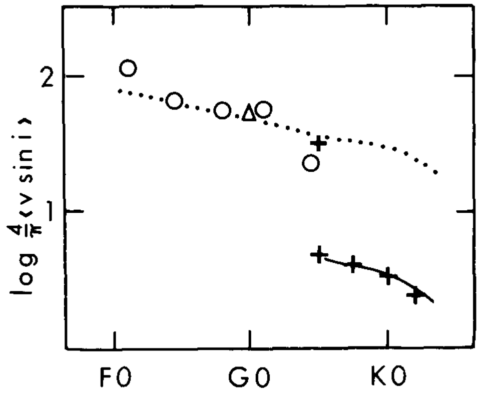

Fig. 1. Mean rotation velocities of class III giants are shown as a function of spectral type. A sharp drop from ~ 30 to ~ 5 km/s at G5 III is indicated by this data (from Gray 1982b).

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stars are still rotating ~ 30 km/s by the time they evolve to G5 III, and they still have a Maxwell-Boltzmann distibution of rotation velocities as they approach this stage. Envelope convection has begun to develope, however, and it is sufficiently deep and strong at G5 III to interact with the rotation to produce a dynamo and with it a magnetic brake. Rotation of the convective envelope is reduced rapidly, that is, within the time required to evolve a fraction of a spectral class.

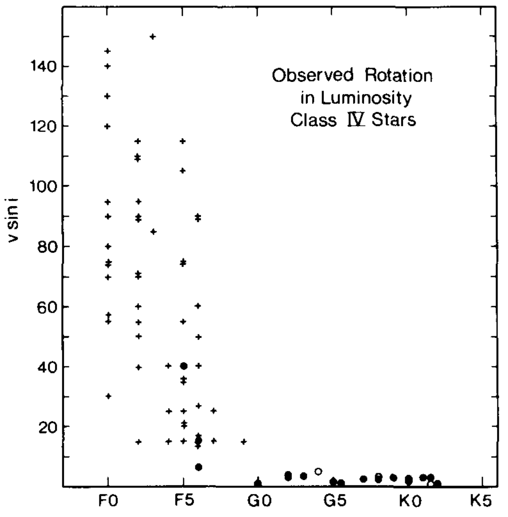

Fig 2. The individual rotation velocities for subgiants are plotted here. A sharp drop occurs near G0 IV (from Gray and Nagar 1985).

Now we arrive at an important point for the Rotostat Hypothesis: the rotation is not driven to zero by the braking process, but is observed to be ~ 5 km/s at the bottom of the rotational discontinuity. The suggested explanation here is that rotation < 5 km/s is too low to be a driver for the type of strong dynamo that produced the rapid braking. If true, we then expect the original Maxwell-Boltzmann distribution of rotation velocities to be destroyed because, while essentially all of these stars have sufficient rotation to turn on the brake, the turn-off is controlled by the internal structure of the star (which is approximately the same for all G5 III stars). Other material relevant to this point can be found in Gray (1982a), Duncan et al. (1984), Rengarajan (1984), and Noyes et al. (1984).

3. THE EVIDENCE UNDER CONSIDERATION HERE

The observed rotation decreases from ~ 5 km/s at G5 III to ~ 2.5 km/s at K2 III, as shown in Fig. 1. Probably the cores of these stars continue to rotate rapidly, and we certainly expect the convection zone to deepen over this spectral interval. As it does so, high angular momentum material from the core becomes part of the convective envelope. The surface rotation should increase again with time if, indeed, the brake were truly off. Since it does not, we naturally suspect additional braking takes place. Perhaps the dynamo flickers on and off; on whenever the rotation builds up sufficiently, off when rotation drops below some critical value. The slow decrease in rotation from G5 III to K2 III, according to this line of thought, then represents a boundary line along which the physical conditions for dynamo activity are at their limiting values.

Dimensional arguements by Durney and Latour (1978), Mangeney and Praderie (1984), and Durney and Robinson (1982) indicate that certain general relations are needed for dynamo activity. Since the results are all rather similar, I choose the simplest one given by Durney and Latour, that in order for a dynamo to run, rotation must exceed

$$v_r = v_c/(\ell/R), \quad (1)$$

where ℓ/R is the convection zone depth expressed as a fraction of the stellar radius, and v_r and v_c are the rotation and convective velocities. Logically, we ask about the size of ℓ and v for stars in the G5 III-K2 III interval. Models of giant-star convective envelopes were computed by A.S. Endal while visiting the University of Western Ontario in May 1984. Specifically we wanted some quantitative measure of the growth of the convection zone and the velocties involved as a function of spectral type. Fig. 3 summarizes the first quantity. This essentially confirms earlier expectations of the smooth continuous growth of ℓ.

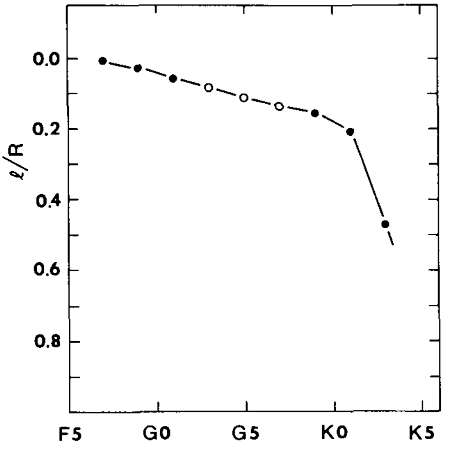

Fig. 3. The convection zone grows smoothly and monotonically in 2.25 $M_\odot$ models with the mixing length parameter $\alpha = 1.0$. Open circles indicate interpolated values.

The convective velocities for these same models (mixing length formulations are used here) show a rather steep, but smooth, decline with increasing depth. I have extended the dimensional arguement leading to eq. (1) by taking $\langle v \rangle = v_c$, here $\langle v \rangle$ is the convective velocity 2/3 of the way into the convection zone from the surface. Since these velocity functions are all smooth curves, it matters little which characteristic velocity is actually chosen. The interesting result is shown in Fig. 4. Here, across the G5 III-K2 III region, $\langle v \rangle$ is seen to show a plateau. If we now employ the limiting condition $v_r = v_c/(\ell/R)$, or $\langle v \rangle/(\ell/R)$ in this case, we obtain the comparison with real stars shown in Fig. 5. Since this is a dimensional argument, only the shape of the curve has significance, not its absolute vertical position. Agreement is reasonable across the plateau.

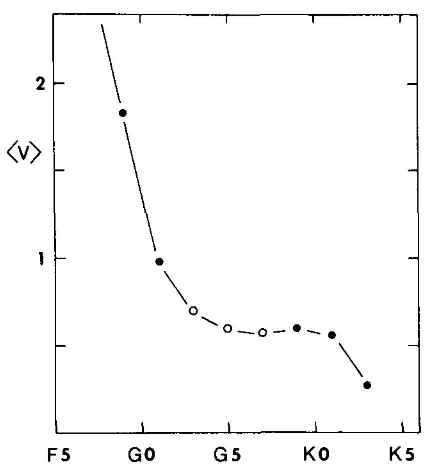

Fig. 4. The characteristic convective velocity, $\langle v \rangle$, is plotted vs. spectral type.

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Prior to G5 III the v_r boundary condition shows a more gradual decline than my data. I see two alternatives here, 1) the data may be too few; perhaps the real decline is less steep than

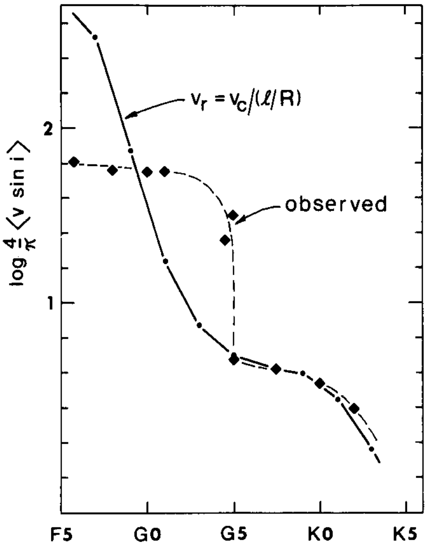

Fig. 5. The dynamo criterion for the giant star models, $v_r = v_c/(\ell/R)$, is shown as the solid line. The rotation data from Fig. 1 is shown in the individual symbols connected by the dashed line.

indicated by the available data. Some evidence for this might be seen in the outer atmospheric emission measurements studied by T. Simon (1985), or 2) a second criterion may have to be satisfied before a dynamo will run, for example, the convection zone depth may have to exceed a certain minimum value before the helicity can build up sufficiently, or before the bouyancy-rise time is sufficiently long.

3. CONCLUSION

The evidence in Fig. 5 implies to me a magnetic brake that is easily capable, when it is on, of dissipating the entrained angular momentum, and as the star evolves, the dynamo rides along at its turn-on configuration, flickering on and off to maintain the star's rotation at $v_r = v_c/(\ell/R)$. The result: the actual rotation of the star is precisely controlled by the convection zone.

The convection is thus a controller of the dynamo. It is a rotostat that meters out the angular momentum dissipation.

4. SPECULATION FOR DWARF STARS

Is it conceivable that this process also functions in main sequence stars? Is it possible that the very slow decrease in rotation we see for dwarfs is under the firm control of the slow evolutionary changes of convection zones in the dwarfs and not just a coasting phenomenon with a weak brake applied, as we have thought? Perhaps the large secular changes in solar magnetic activity is the flickering of the dynamo as rotation is forced to the v_r condition.

As I was preparing this material, an interesting study by D. Soderblom (1985) was published giving angular velocities for late F to early K dwarfs. He shows how the upper bound I had found earlier (Gray 1982a) is a constant-Rossby-number line, i.e., the $v_r = v_c/(\ell/R)$ criterion holds along this upper bound. This detail strengthens the idea expressed in this earlier work that the observed upper bound corresponds to the turn-off of a strong braking phase. The dwarfs give a whole mass sequence that corresponds to the one point of the giants' where rotation declines to ~ 5 km/s at G5 III.

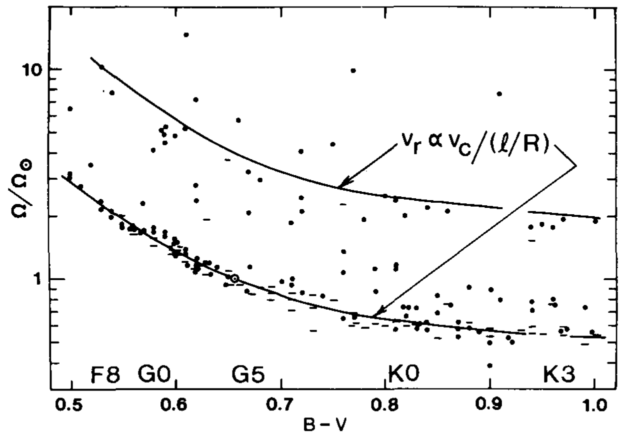

Fig. 6. Angular rotation velocities for dwarfs deduced by Soderblom (1985) are shown vs. B-V color index. High velocity stars are shown by dashes. The smooth curve is the dynamo criterion of eq. (1).

Might we conclude the following? A rapid angular momentum dissipation phase ends at the upper v_r curve. The rotostat functions between the two v_r curves producing the slow decay phase. And finally, after a sufficient time, which depends on mass, the lower v_r curve is reached and the dynamo braking is effectively turned off completely and permanently. This causes dwarfs beyond a certain age to pile up on the lower bound. If these ideas are near the truth, the Sun is close to the end of its rotational braking, and possibly its magnetic activity.

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