THE REMARKABLE ROTATIONAL BRAKING OF G5 GIANTS

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ABSTRACT
The strong rotational braking seen in the G5 III stage of evolution may be the key to understanding how stellar dynamos work.

We are all familiar with the leisurely spin-down seen in cool main-sequence stars like our Sun. The time scales here are ~ 10^9 years and the accepted cause is the loss of high angular momentum mass in the form of stellar winds interacting with the stellar magnetic field. The magnetic field is believed to result from the interaction of envelope convection with the rotation of the star through a dynamo mechanism. Our understanding of how a dynamo actually operates, how that operation depends on the driving forces of rotation and convection, what kind of stochastic and secular time variations are to be expected, remains fragmentary even though many inventive minds have contributed. One reason for slow progress is simply that the Sun is almost the only example of a stellar dynamo we have had. But nature has given us another, much more powerful dynamo in the G5 giants, it just took us a little longer to discover it.

Figure 1 shows the observational results: v sin i vs. spectral type for luminosity class III stars. Most of these v sin i values were obtained by Fourier analysis of the line broadening (details can be read in Gray 1981, 1982b). The crosses in Fig. 1 represent means for groups by spectral type but increased by the statistical projection factor of $4/\pi$. The inset graph shows these same means along with means for earlier spectral types according to Fukuda (1981). The observed fact, then, is that the rotation drops abruptly at G5 III from ~ 25 km s^{-1} to ~ 5 km s^{-1}.

Note here how the giant spectral sequence tells us the time order of events in contrast to the main-sequence where we get an ordering by mass. Several people have used evolutionary models to study the expected changes in rotation as a star moves off the main-sequence. I have chosen to use the comprehensive and up-to-date calculations of

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 461–466.

Endal and Sofia (1979). Starting with a main-sequence rotation of ~ 150 km s^{-1}, simple evolutionary expansion results in a sixfold increase in the moment of inertia and satisfactorily reproduces the observed 25 km s^{-1} rotation as a star enters G5 III. This is shown by the dashed lines in Fig. 1. The theoretical calculations did not anticipate the remarkable brake that occurs at this point. However, if I scale the dashed line down arbitrarily by 5.7 times, it agrees very well with the observations (crosses in Fig. 1). In other words, from G5 III, after the braking, to K2 III, the internal moment of inertia once again controls the rotational decline. The braking not only started abruptly at G5 III, it also ends abruptly at G5 III.

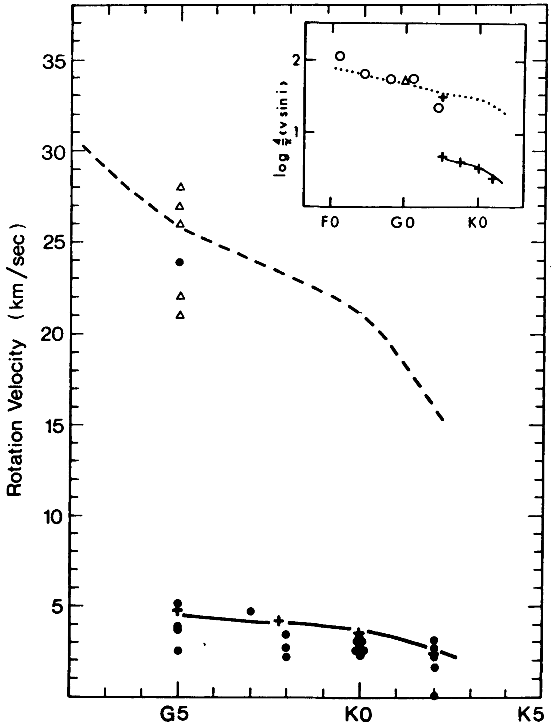

Fig. 1. Observed rotation velocities, v sin i, are shown by the dots and triangles. Means for spectral type groups which have been increased by 4/π are shown by crosses. Model calculations are shown by the dashed and solid lines. The inset graph shows 4/π times the mean v sin i's (on a log scale) over a wider spectral interval (from Gray 1982b).

Considering that the moment of inertia for a G5 giant is an order of magnitude larger than for a solar-type star, and the braking time scale ratio is $\sim 10^4$ yrs/10^9 yrs, the brake at G5 III is $\sim 10^6$ times stronger than the solar variety. Admittedly this is a rough estimate, but it brings home the point that this dynamo brake is unequivocally vigorous compared to what we are accustomed to considering for the Sun.

Let me jump now directly to the dynamo explanation and refer you to the cited references for some considerations of alternative hypotheses. First, we are led to a dynamo explanation because it is at G5 III where significant envelope convection is added to the rotating star, giving the star the driving forces it needs to generate a dynamo field and the resulting magnetic brake. Second, as angular momentum is removed from

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the star, the rotation eventually becomes too small to drive the dynamo. This happens at a surface rotation rate of ~5 km s^{-1} for G5 III stars, but we would guess it might be a function of mass.

We are now in a position to estimate the rate of dissipation of angular momentum and the size of the dynamo magnetic field. Further, we can ask about what actually happened when the dynamo stopped and what the envelope parameters (thickness, run of velocities, densities, etc. with depth) were at the time of cessation. These data will help us understand how a dynamo works.

Now let us turn back to main-sequence stars. When stars destined to be on the cool half of the main-sequence are in their adolescent stages, they have those two special ingredients of rotation and convection. We saw the remarkable reaction in G5 giants when these were brought together. Who then could deny the possibility of a similar magnetic brake functioning in young stars and/or pre-main-sequence stars? The important feature I wish to consider here is the abrupt turn-off of the brake. Adolescent stars would be spun down until the rotation was insufficient for dynamo action---at least the virile type of dynamo responsible for the brake we are considering. Therefore, we would expect young stars to appear on the main-sequence with a rotation rate reflecting the dynamo turn-off characteristics appropriate to their mass. That in turn implies an upper bound to the rotation rate along the main-sequence. Figure 2 shows that the observed main-sequence rates do indeed have an upper bound, although this observed one corresponds to a somewhat later time ~ $10^{8.5}$ yrs. Under the dynamo-magnetic-brake hypothesis, the upper bound becomes a map proportional to the dynamo turn-off

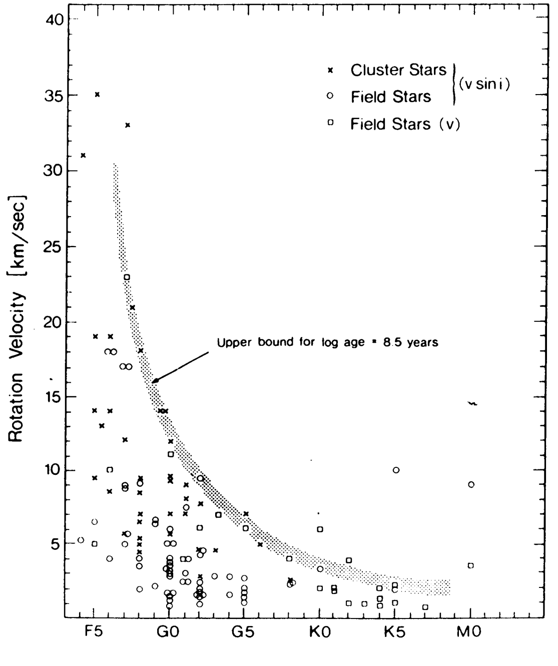

Fig. 2. Rotation rates for main-sequence stars are shown as a function of spectral type. The subjectively drawn upper bound is indicated (from Gray 1982a).

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rotation rates. We are faced with the delightful prospect of being able to identify the internal structure, as a function of mass, when the strong dynamo mechanism ceases operating.

Certainly there is more to the rotational history of a main-sequence star, and much of it has been known for a decade or longer. Specifically, points in Fig. 2 will lie below the upper bound because of (1) the sin i projection factor and (2) the slow spin-down going ~ age$^{-\frac{1}{2}}$, resulting from the puny solar-type dynamo brake.

It is also of interest to notice that the quantity L = MRv, a psuedo-angular momentum, (M=mass, R-radius, v=surface rotational velocity) varies as M^7 for points along the upper bound of Fig. 2. The relation

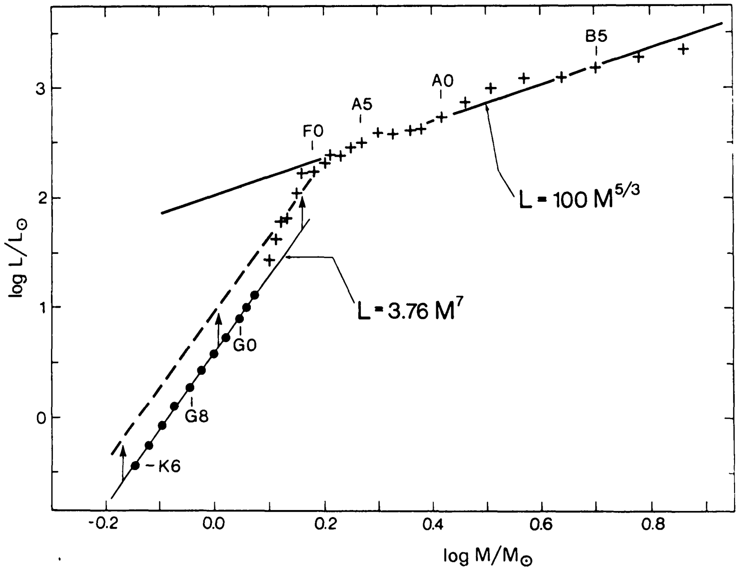

Fig. 3. The psuedo-angular momentum, L = MRv, is shown as a function of mass. The points defining the M^7 relation correspond to the uppper bound shown in Fig. 2. The dashed line corresponds to the upper bound at a younger age ~ 10^8 yrs.

to the upper main-sequence is shown in Fig. 3. A "de-aging" of the M^7 portion by 0.3-0.4 dex leads to one smooth break in slope near F0 or a mass of ~ $1.5M_\odot$. This may imply that the actual brake-turn-off velocities are 2 to 2.5 times larger than those shown in the observed upper bound of Fig. 2.

Studies of stellar braking may give us the observational guidance we need to firm up our understanding of dynamos.

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DISCUSSION

SCHÜSSLER: Have these stars also been observed at X-ray and Ca II wavelengths and—if yes — do these observations show the same sort of behaviour?

GRAY: The X-ray data for class III giants show the same discontinuity at G5 III. But the X-ray flux scale has to be compressed by a factor of two relative to the rotational velocity scale, implying that X-ray flux varies with the square of the rotational velocity. The Ca H and K line emission seems to vary proportional to the rotational velocity in dwarfs. Other chromospheric and transition-region lines appear to be correlated with rotation, but show no simple functional dependence. We will have to look into this further.

SIMON: (1) Comment in response to Schüssler's question: Ultraviolet observations of G-K giants do show an apparent break in transition-region properties near G5 III, but the observational situation is very complex. In particular, transition-region lines among early G giants show a wide range in strength (Simon, Linsky, and Stencel: 1982, *Astrophys. J.* 257, p. 225). (2) I am puzzled by your remark that the existence of a rotational brake in the Hertzsprung gap was previously unknown, since R. Kraft published a classic paper on this question more than 15 years ago in the *Astrophysical Journal*. I would like to know how your results differ from Kraft's. Moreover, since Kraft, and later Alschuler, showed that 75-90% of G5-K2 giants are likely to be second crossers, travelling from right to left across the H-R diagram, how can we be sure that the apparent drop in surface velocity occurs *at* G5 rather than elsewhere in the H-R diagram, say in the red giant region?

GRAY: Kraft measured a few Hyades giants (K0 III) and found upper limits of 5 or 6 km s^{-1}. From this he concluded that angular momentum loss must have occurred. Using these upper limits, Endal and Sofia (1979, *Astrophys. J.* 232, p. 531) reversed this conclusion on the basis of their ability to calculate fairly realistic models, which met the 5–6 km s^{-1} upper bound. My measured values are half of Kraft's upper limits and reinstate the original conclusion of mass loss being needed. To my knowledge, Kraft made no measurements of G5 - K0 giants and so did not see the discontinuity. Similarly, if my memory is correct, Alschuler's work (1975, *Astrophys. J.*) extended only as late as G5 III and was really mainly concerned with F stars. So he did not see the discontinuity either.

The question of first vs. second vs. third crossing is unresolved. Most evolutionary calculations in this mass range seem to show loops extending to ~G8 but not to G5. Similarly, color-magnitude diagrams of globular clusters seem to support the G8 position for the blue end of the loop. Even if the K0 III and K2 III stars I have measured are on the second or third crossing, it does not destroy the picture I have presented, but of course you are free to develop your own interpretation of the G5 III discontinuity.

WALTER: I grant you that the rapidly rotating G giants are likely to have evolved from rapidly rotating upper main sequence stars. However, by the time that you reach K0, this

is no longer necessarily true: many may be low-mass stars like Arcturus. If so, the K giant population, or some proportion thereof, began as slow rotators. Could your alleged break be due to selection effects, primarily sampling low-mass K0 giants, as well as second crossing stars?

GRAY: It seems to me very unlikely that all of the G5 - K2 giants of my sample should be low-mass stars. If some low-mass stars were intermixed with others having evolved horizontally across the H-R diagram, then I would expect to see a wide spread of rotational velocities. Instead, the G5 III to K2 III observations are indicative of a rather homogeneous group. Further, the evolutionary tracks that I have seen remain basically horizontal until at least K0 III. Certainly by K5 III more vertical-like tracks are computed, but that is well to the cool side of my stars.

SODERBLOM: Let me comment on this question: Although I am skeptical of your evolutionary interpretation, I remind you that four of your stars are the Hyades giants, which rotate just as slowly as the other K0 III's. These are definitely not low mass stars, in fact they have about $3M_{\odot}$.

MOUSCHOVIAS: The quantity $\bar{\rho}_*^{2/3}R_*/R_{\odot}$ is close to unity for stars earlier than F5. Does any observer here know whether this quantity is significantly smaller than unity for later-type stars? (If it is, the break in the rotational velocity with spectral type can be understood very simply.)

GRAY: I don't know.

ENDAL: In reply to Ted Simon's remark about older observations, I would note the following: The Endal and Sofia (1971) paper showed that Kraft's observations (upper limits) could be explained without angular momentum loss. Gray's results, by contrast, definitely require angular momentum loss.

GRAY: Yes, my observations show the rotation to be about half of Kraft's upper limit.

SODERBLOM: I wish to take issue with your claim that the distribution of velocities that is present before the braking is completely eliminated, resulting in a single rotational velocity for each spectral type, G5 and later. Your data appear to me to show the same proportionate spread after G5 as before. Given these modest $v \sin i$'s and observational error, how can you rule out a similar Maxwell-Boltzmann distribution among the slow rotators?

GRAY: Let us go back and look at Figure 1. The individual measurements are shown by the solid dots. If I take means for the four obvious spectral groups, and then increase this mean by $4/\pi$ to statistically account for the average $\sin i$ value, I get the crosses you see. Notice how these crosses fall near the top of each set of dots, at least for the G5, G8, and K0 groups. This is what you would expect for a $\sin i$ distribution, and what you would not expect for a Maxwell-Boltzmann distribution. I have done a more complete analysis (1982, *Astrophys. J.* **262**, pp. 682 – 699), from which I conclude that a $\sin i$ distribution is the better representation of the observations. With statistics on about two dozen points, the conclusions of this sort are obviously not firm.

NORDLUND: If you read off the upper envelope on your slide with the main sequence stars, you get approximately the same 5 km s^{-1} as for the giants. Do you consider this significant?

GRAY: I suspect that the main sequence velocities of the brake turn-off need to be scaled up so that they correspond to an earlier age (as I indicated in my talk). In such a case, the 5 km s^{-1} correspondence between giants and dwarfs is coincidental.