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STELLAR CONVECTION: THE OBSERVATIONS

DAVID F. GRAY Department of Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada

ABSTRACT Convection is a major factor in the life of stars. We can observe the top of the convective envelope through the granulation in the photosphere and with the macroturbulence dispersion. Both show increasing strength with increasing effective temperature and luminosity. It is not known if the large velocities inferred for stars on the hot side of the granulation boundary arise from convection or other wise. Temperature inversions are seen to grow rapidly in strength as stars evolve across the H-R diagram between the granulation boundary and the rotation boundary. Possibly convection alone drives this activity. Changes in temperature and granulation are seen on time scales of stellar cycles.

Keywords: Convection; Stellar Cycles

WHY ARE WE INTERESTED IN STELLAR CONVECTION?

Convection affects or controls a remarkably wide range of stellar phenomena. Numerous observations enter the picture, but none give definitive information on the characteristics of convection. Consider the following 'chores' performed by convection.

- convection carries thermal power through the convection zone.
- convection mixes the material, countering settling and diffusion processes.
- convective envelopes cycle material down into hot layers resulting in the destruction of Li and Be.
- convection affects, probably controls, the internal distribution of angular momentum within the envelope.
- convection combines with rotation resulting in dynamo action.
- convection probably winds up magnetic fields above the photo-sphere, resulting in dissipation of magnetic energy into heat.
- convection generates acoustic waves.
- convection generates Alfvén waves.

These last four points are intimately connected with the existence of temperature inversions seen as chromospheres and coronae. In addition,

- convection dominates the shaping of spectral-lines in cool stars.

Further, inhibited convection makes starspots dark, and enhanced convection may be the cause of starpatches. Convection-induced motions at the surface may "comb" the magnetic field into network structures.

No surprise then that we need to know everything we can about convection. And indeed each of the phenomena on the list potentially supplies us with information about convection.

HOW CAN WE FIND OUT ABOUT STELLAR CONVECTION?

We can do hydrodynamical calculations, pushing the best physics we can through the fastest computers. Examples of this kind of work can be seen in papers by Nordlund (1985), Fox & Van der Borght (1985), Stein *et al.* (1989), Steffen *et al.* (1989), Spruit *et al.* (1990), Nordlund & Dravins (1990), and others, especially in the proceedings of the granulation workshop (Rutten and Severino 1989). And some real progress is being made on this front. In particular, we gain insight into what happens below the surface where we cannot see. These topics are the subject of the paper given next by Cattaneo and Stein. The other thing we can do is look at real stars. Observations come in from a number of different directions, but I will concentrate on the surface phenomenon of granulation because in granulation we see directly the top-most layers of the convection zone. Other lines of evidence will be apparent as they come up in this talk. So how can we measure stellar granulation? The most effective way has been to look at the asymmetries of spectral lines. (Systematic differences in radial velocity with excitation potential has proved to be less useful, ref. Glebocki & Stawikowski 1980, Dravins *et al.* 1981). Since the discovery of asymmetries of spectral lines (Gray 1981b, 1982a), several methods of specifying the asymmetry have been tried, but the best one is the line bisector. Line bisectors are constructed by connecting the midpoints of horizontal line segments running between the sides of the line profile. Figure 1 shows this process. A symmetrical profile has a straight vertical line as its bisector, and we see in the example of Figure 1, in the left-hand portion, a bisector that appears to be nearly straight and vertical. Asymmetry of lines are small and requires careful measurement. Signal-to-noise ratios of several hundred are needed along with spectral resolving power $\lambda/\Delta\lambda \approx$ 100,000 or more. Specifically, resolving power $\lesssim$ 50,000 is quite inadequate and results in the asymmetry being lost in the smearing of the instrumental profile.

It is necessary to expand the velocity (wavelength) scale in plots like Figure 1 if we are to see what bisectors have to show us. Expansions of 20-50 times the scale used for line profiles themselves are typical, as shown in Figure 1, on the right. The C shape we see in this example is characteristic of stars on the cool side of the H-R diagram, a point we will return to in the next section. How does granulation cause asymmetries in lines? It does so quite directly because the distribution of its Doppler shifts is the dominant broadener of the spectral lines we are dealing with. That distribution is not symmetric because more photons come from the hotter rising convection cells than come from the cooler material falling back down between the cells. That brings us to the next step.

WHAT DO LINE BISECTORS LOOK LIKE?

Most spectral lines are blended with others to a lesser or greater degree, and so it is important to compare the results of several lines, weeding out those that are strongly blended and therefore unsuited for the task at hand. For those that

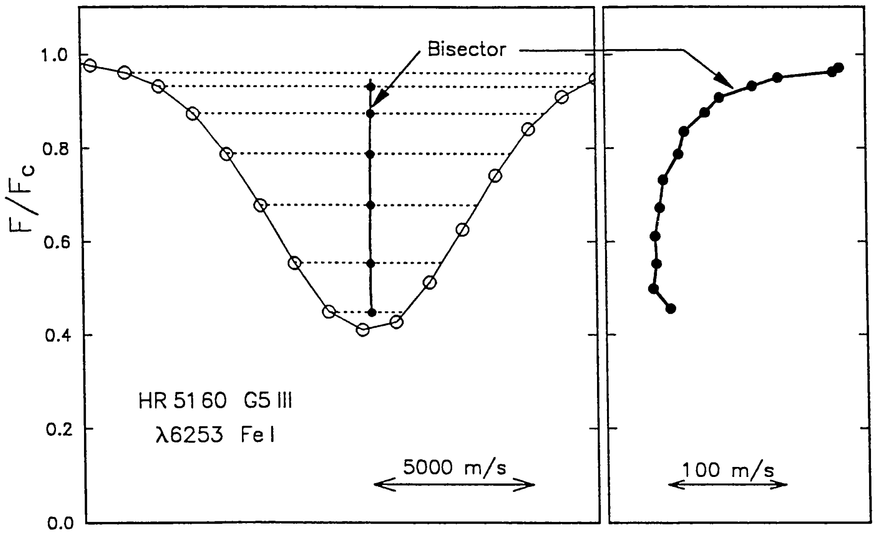

Fig. 1: The bisector is constructed by connecting the midpoints (solid dots) of the dashed horizontal lines. A typical spectral line is very nearly symmetric, and the wavelength (velocity) scale has to be expanded by a factor of 10-50 (note the velocity scales indicated) to see the shape of the bisector. The profile has been interpolated to give the extra points on the expanded version of the bisector on the right.

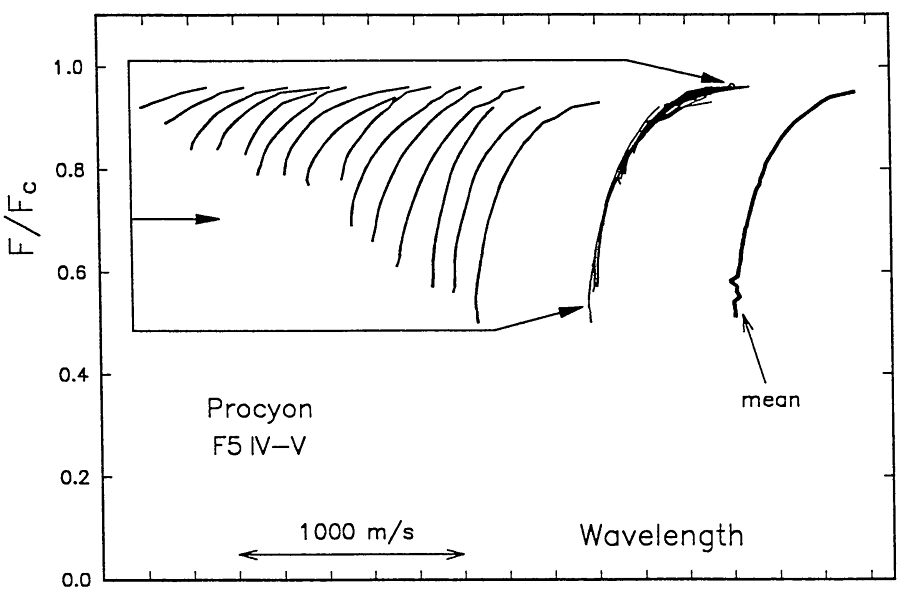

Fig. 2: Line bisectors for lines of different strength are shown on the left with those from the weakest lines left-most. Telescoping these together produces the composite shown in the middle, and the mean of the composite is shown on the right.

are usable, one finds that lines of different strength map out parts of the same bisector within the errors of observation. Consequently, several lines can be put together to form a mean bisector for a star. An example is reproduced here in Figure 2. This makes sense when we reflect on the point that the wings of strong lines and all of weak lines are formed at essentially the same physical depth and should experience the same velocities. Bear in mind, lines formed at distinctly <u>different</u> depths can be expected to have different bisector,*i.e.*, lines having large differences in excitation potential, or those formed in different spectral regions where the continuous opacity is significantly different, because the granulation contrast and velocities vary with depth. Figure 3 shows some typical examples of average line bisectors. A useful way to understand the general "C" shape and the variations they illustrate is as follows. The larger the velocities of granulation and the larger the brightness difference between rising and falling material, the larger the line asymmetry and the larger span in velocity over which the bisector extends. So the velocity span is a measure of how vigorous the granulation is. Because the larger portion of photons comes from the rising granules, the characteristic mean or centroid of the distribution of Doppler shifts is shifted toward shorter wavelengths (which I will refer to as "blue" shifts), and consequently, so is the spectral line it shapes. These displacements can amount to up to 500 m/s, and could be quite significant as systematic errors in precision measurements of radial velocities. We can measure these net line shifts directly and unambiguously in the solar spectrum, but they must be assumed or measured indirectly in stellar spectra because the absolute zero is lost owing to the motion of the star in space. Next consider the displacement of the bottom of the bisector, that part that comes from the core of the line. The core of a strong line is formed higher in the photosphere than the rest of the line. If the granulation penetrates to the height where the core is formed, the bottom of the bisector is blue shifted. If the granulation dies off below that height, the bottom of the bisector is near zero velocity. In Figure 3, Procyon shows strong granulation high up in its photosphere. In contrast, the cooler dwarfs show none. The maximum velocity span goes hand-in-hand with the behavior of the bottom of the line bisector, both features telling different aspects of the same story. Rough estimates of the mean granule velocities are $\approx$ 1.5 km/s (Gray & Toner 1985, Gray 1986) for star similar to the sun. But the strength of convection does depends on the position of the star in the H-R diagram.

<u>HOW DOES CONVECTION CHANGE ACROSS THE H-R DIAGRAM?</u>

We have relatively little information so far. Generally the strength or "vigor" of the granulation increases with effective temperature and with luminosity on the cool half of the H-R diagram. Some general scaling laws are available (Gray 1982), but we urgently need a more complete and a more detailed grid of "standard" bisectors for theoretical interpretation and against which deviant behavior can be compared. Macroturbulence dispersion ζ_{RT} also increases with effective temperature and luminosity (ref. Gray 1988). It would be hard not to suspect that the main component of macroturbulence is granulation. Look at Figure 4, for example. Here the bisector velocity span characterizing line asymmetries of dwarfs is plotted as a function of the macroturbulence dispersion.

Going right along with this pattern of variation are the velocities found in mixing-length calculation (*e.g.*, de Loore 1970, Renzini *et al.* 1977).

A remarkable discovery (Gray & Toner 1986, Gray and Nagel 1989) showed that the nature of photospheric velocity fields changed rather dramatically across a nearly vertical line in the H-R diagram called the "granulation boundary."

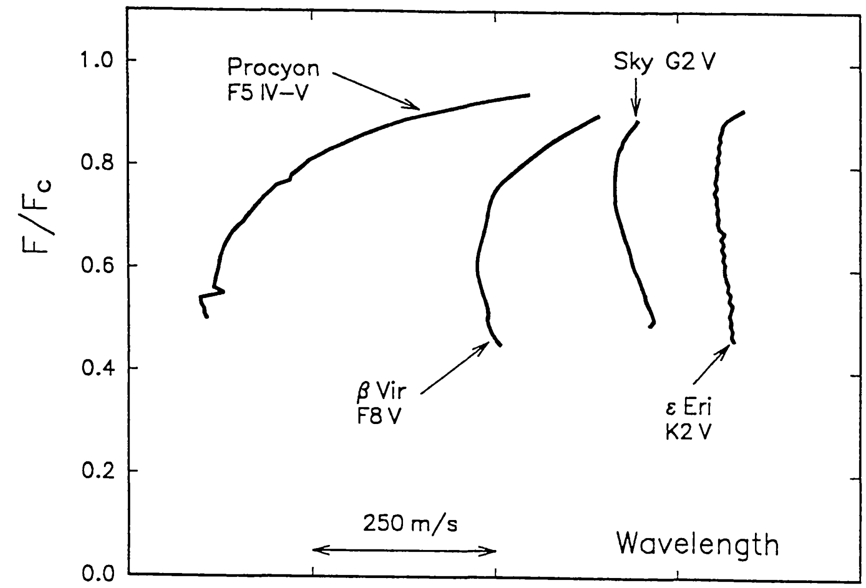

Fig. 3: Mean bisectors are shown for dwarfs having a range in spectral type. Notice the increase in velocity span and the increasing blueward displacement of the lower portion of the bisector with increasing effective temperature.

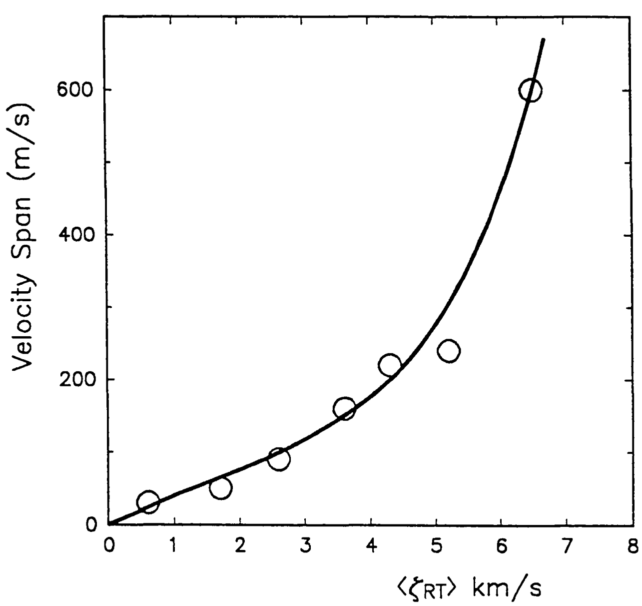

Fig. 4: The granulation strength, as indicated in the velocity span, is closely related to the Doppler broadening of macroturbulence parameterized here by the radial-tangential dispersion. These data are for dwarfs.

Granulation is expected on the cool side of this boundary since these stars have convective envelopes. But "hot" stars are not generally thought of as having convective envelopes. With no convection, we expected little Doppler broadening, and yet velocities inferred from the spectral-line asymmetries are several times larger than for the cool stars. This boundary is truly the separator of "hot" stars from "cool" ones. It runs from G1 Ib down to about F0 on the main sequence. It may be that stars on the hot side of the granulation boundary do have shallow convection zones, but even so, the velocity fields are very different from granulation as we see it in the cooler stars. Not only are the apparent velocities roughly one order of magnitude larger, but the fraction of photons coming from rising material is tiny, running at about 10%. Equally significant is the fact that each line, no matter what its strength, shows the same shape bisector, unlike the behavior in Figure 2 where the bisectors could be telescoped together. The implication is that there is no visible depth dependence in the velocity field. An explanation invoking gravity waves has been offered (de Jager 1990). So, is convection involved here, or should reversed bisectors be discussed in some other talk?

HOW INTIMATE ARE CONVECTION AND MAGNETIC FIELDS?

We all know that rotation and convection are supposed to get together in a process called a dynamo to generate magnetic fields. So perhaps we are not surprised to find that chromospheric activity rises sharply across the granulation boundary. An example of this is shown in Figure 5. Here the carbon emission for class III giants is shown as a function of spectral type (which is essentially a non-linear but monotonic time coordinate since these stars are evolving across the H-R diagram). The position of the granulation boundary is shown by the "GB" at the top of the graphs. The depth of the convection zone grows monotonically after a giant crosses the granulation boundary; one might naturally attribute the growth of the carbon emission to this factor. A short interval later, this chromospheric emission nearly dies out because the rotation drops to a fraction of its previous value as it crosses the rotation boundary (Gray 1981, 1982, 1988, 1989, 1991), labelled "RB" in Figure 5. In a nutshell, add convection to the envelope of a rotating star and you get a chromosphere; add deeper convection, and the chromosphere gets stronger. But take away rotation, and the chromosphere all but disappears. So it behaves just as we would expect for a dynamo. But what is actually happening? I have argued in the references cited in the last paragraph that the rotation boundary is the result of a turn-on of a magnetic brake; the brake resulting from the convection zone having grown deep enough to combine with the rotation to turn on the dynamo. Calculated Rossby/dynamo numbers support this explanation. So also does the observed change in distribution of rotation rates and the rate of decline in rotation seen on the cool side of the rotation boundary. But if dynamos do not turn on until stars reach the rotation boundary, then why do we see magnetic activity between the granulation boundary and the rotation boundary? Although we might think of alternative explanations, might it be that the magnetic field between the boundaries is not a result of dynamo action at all. Could the very appearance of granulation give structure to the photosphere and "comb" an already existing field into something coherent and capable of driving a temperature inversion?

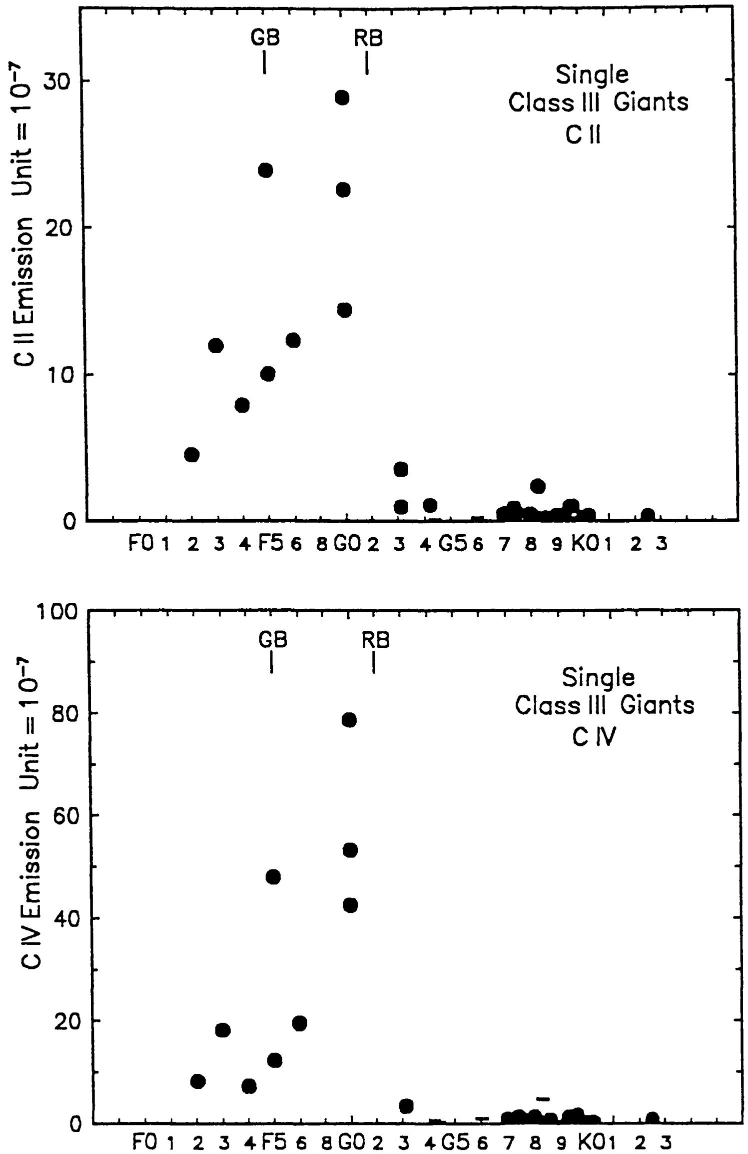

Fig. 5: Non-thermal emission increases rapidly as stars giants evolve across the H-R diagram between the granulation boundary (GB) and the rotation boundary (RB). On the cool side of the rotation boundary, the emission is greatly reduced. Data are from Simon and Drake (1989).

DOES CONVECTION CHANGE DURING A STELLAR CYCLE?

The magnetic field certainly changes during stellar cycles, and we know the magnetic field can alter convection: witness sunspots. There is also clear evidence of granulation being sensitivity to magnetic fields in the solar photosphere (Livingston 1982, 1991, Macri *et al.* 1984, Cavallini *et al.* 1985, Immerschitt & Schrter 1989, Brandt & Solanki 1990). In all cases seen on the sun, granulation seems to be inhibited by the presence of magnetic field. In a spot, one can see how the very large field simply ties up the convective flow trying to cross it. But why is granulation inhibited by much weaker fields? And is it universally true that magnetic fields can never enhance convection?

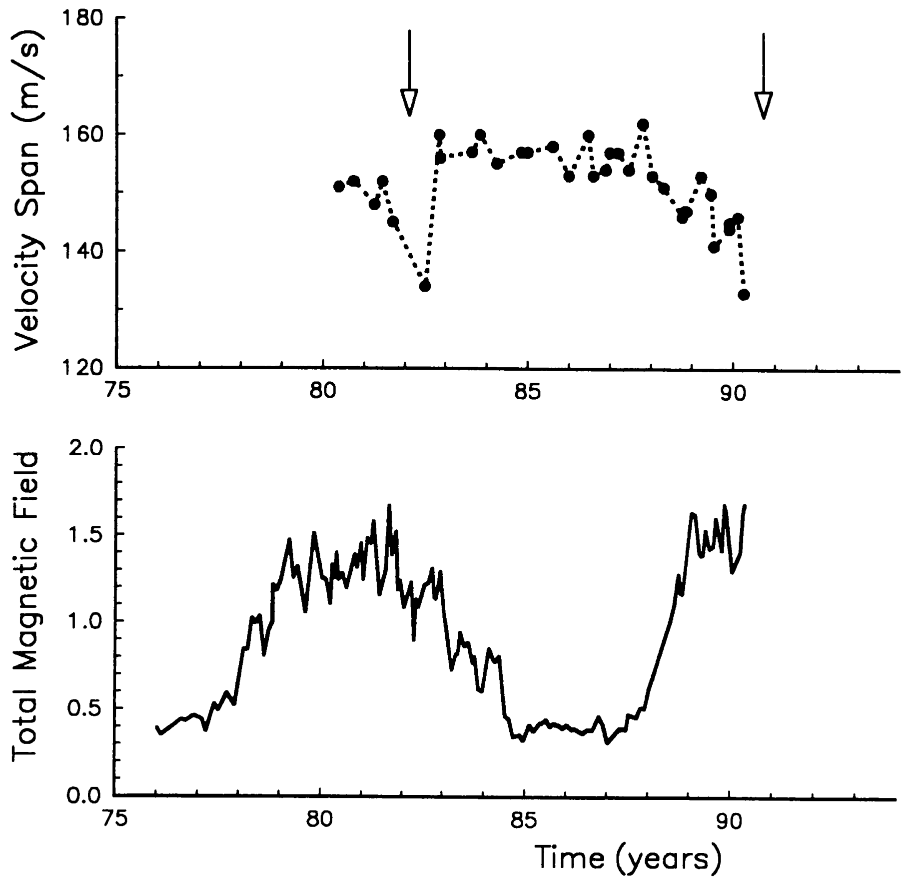

Fig. 6: On top, the solar disk-integrated spectrum show reduced granulation during part of the solar cycle strong strong magnetic activity as indicated by the relative magnetic flux in the lower graph. (Based on data in Livingston 1989.)

Convection carries most of the energy through the envelope. Does the magnetic cycle modulate this flow? Or to state it another way, does the power output vary during a magnetic cycle? And if we were to see variations in the power output, could we muster evidence that the magnetic fields, by altering convection, are the cause of the variation rather than a parametric variable? In Figure 6, you see Livingston's observations of the variation in the strength of solar granulation. Here the velocity span, measured from the bottom of the bisector to the maximum blueward displacement, is plotted as a function of time. It is a strange behavior, not varying in step with the magnetic variation, but showing a more abrupt change over a restricted phase during the time of strong magnetic flux, but not centered on it. The solar power output is slightly reduced during times of stronger magnetic field, presumably because of increased numbers of sunspots (Willson & Hudson 1988, Wolff & Hickey 1987). The sun is a rather weak magnetic star, and so we naturally ask what other stars show us. I want to concentrate on two parameters for stars. The first is a temperature index. I take the ratio of line depths for two lines showing different sensitivity to temperature,

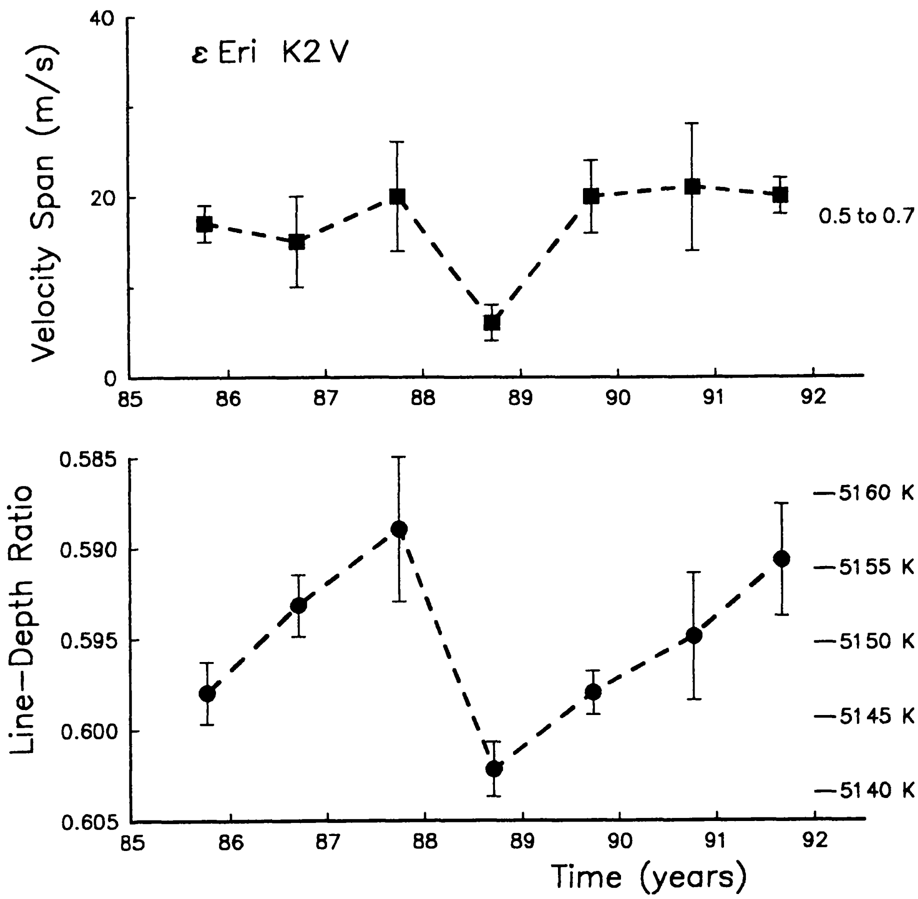

Fig. 7: Granulation and temperature both vary during the 4.15-year cycle of this dwarf (ϵ Eri = HR 10).

in this case, V I λ6261.83 to Fe I λ6252.57. The suitability and sensitivity of this line-depth ratio as a thermometer is discussed elsewhere (Gray & Johanson 1991). Suffice it to say here that a single high-quality exposure allows a star's temperature to be fixed to about $\pm$ 10 K, and combining several exposures together allows the errors to be pushed down to $\approx$ 1-2 K. The second parameter is the granulation strength indicated by the velocity span of the mean line bisector for the star. These particular velocity spans are measured between 0.5 and 0.7 of the continuum, and their yearly means typically have random errors of $\approx \pm$5-10 m/s. First, consider the active K2 dwarf ϵ Eri. The parameters are shown as a function of year in Figure 7. One always wishes the time span were longer and the number of observations were larger. The size of the error bars is largely determined by the number of exposures entering the mean (some 36 exposures over the time span shown). The errors are close to what is expected from the signal-to-noise ratios of the original data. The apparent temperature (temperature scale is on the right) shows a range of $\pm$10 K with a steep drop in the 1988 to 1989 interval and relatively more shallow rise on either side. I say apparent temperature because at the level of a few degrees I can't be sure that

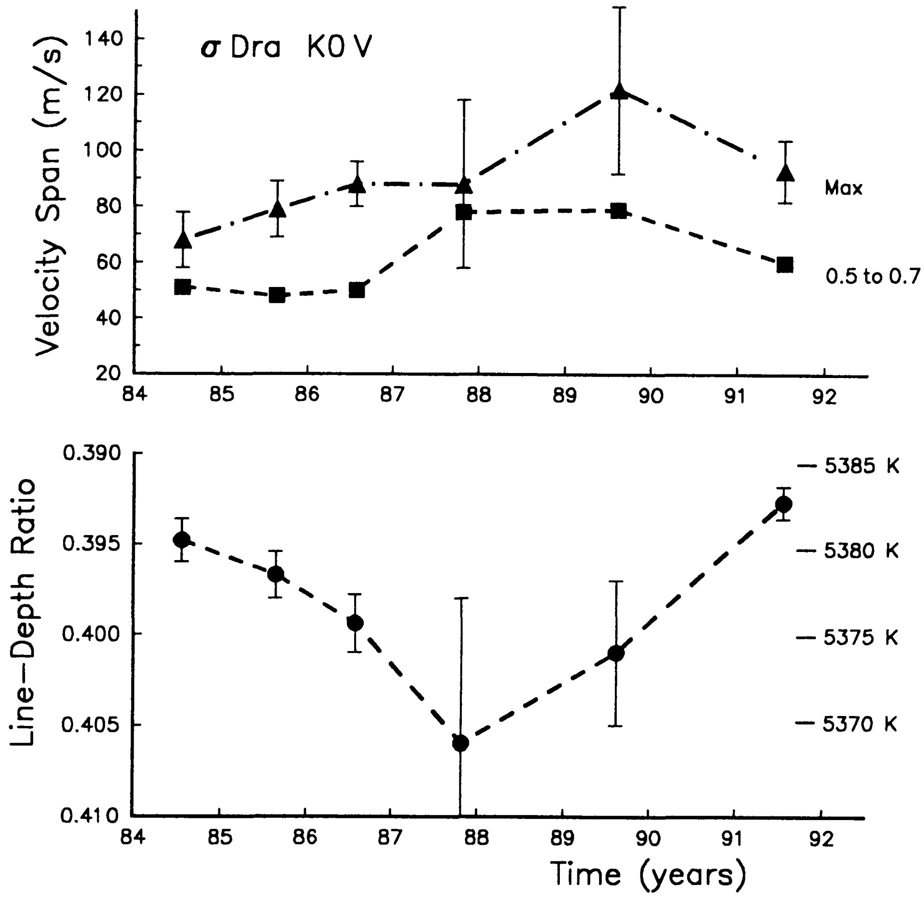

Fig. 8: Both temperature and granulation changes are indicated in σ Dra = HR 7462 = HD 185144 during a cycle of 15 years.

changes in atmospheric structure aren't affecting the line-depth ratio. On the other hand, the flux near 5560Å is approximately proportional to the effective temperature for stars like these, and so we would be talking about a change of about 2% or 0.02 magnitudes. This is not far from the kinds of variations seen in cool stars (Lockwood and Skiff 1988, Radick *et al.* 1990). Phasing of the two linear sections in the figure indicates a cycle period of 4.15 years. The bisector velocity span however is nearly constant except during the small interval near 1989 where a sudden reduction occurs. This is reminiscent of the solar behavior seen in the previous figure. But what is the phase of the magnetic field over this interval? One measure of the chromospheric activity is the one-Å-band equivalent-width measurements of the Ca II λ 8662 published by Campbell *et al.* (1988). These data cover the interval from 1981 to 1987, and they show the same general pattern of a slow build up in chromospheric activity interspersed with relatively short intervals of more rapid decline. There is an increase in chromospheric activity from 1984 right through mid-1987 where the published data end. Looking some 4.15 years earlier in their data, one sees a gap of a full year, and consequently in is not possible to be certain of the relative phasing.

Still, one is tempted to associate the general increase in chromospheric activity shown in their data from 1984 to 1987 with the general increase in temperature seen in this time interval in Figure 7. That would place the maximum magnetic field near 1988.0 at the time of maximum temperature. Immediately thereafter, the temperature dropped and the granulation showed reduced vigor. Can we presume the chromospheric activity and magnetic field also declined at this time? If so, that places the reduced granulation at the phase of magnetic minimum, just opposite the solar behavior. Next, consider the results shown in Figure 8 for σ Dra (K0 V). This stars is generally classes as an "old" star from its H&K line emission, but it is near the boundary between the "old" and "young" categories. A cycle-type variation is seen in both parameters, indicating a period of something like 15 years. The velocity span ranges over tens of meters per second, much larger than for ϵ Eri, but the apparent temperature variation is probably only half as much. Here the granulation is strongest when the temperature is least, just opposite the result for ϵ Eri. There may be a hint of a phase difference between the maximum in granulation strength and the minimum in temperature, but the data are not good enough to be sure. The Campbell *et al.* data show a reduced chromospheric index in 1984 when the temperature is larger. A gradual increase in activity index from late 1984 to 1987 goes with the decline in temperature and the rise in granulation over this same interval. So e Dra may be showing stronger magnetic activity going hand-in-hand with stronger granulation. Puzzling. It was some consolation to my confusion to find that the photometry of stellar cycles (Radick *et al.* 1990) also shows a wide variety of behavior, and in particular, the correlation between photometric brightness and H&K emission reverses sign between "young" and "old" dwarfs. How this ties in with the temperature and granulation changes has yet to be determined.

CONCLUSION AND SPECULATION

We can observe the effects of convection in several different ways. The direct observations of stellar granulation is particularly powerful and is revealing some very basic information not available from solar studies. Understanding what is happening between the granulation and rotation boundaries may open our minds to a different type of magnetic activity, possibly one depending exclusively on convection. Changes in convection apparently occur during the course of stellar cycles. Some interesting physics will have to be worked our to explain it. Does the magnetic field modulate the convective flow of power through the convective envelope, with starspots acting as thermal resistance? Or do magnetic flux tubes physically displace the convective flows inside the envelope enough to lessen the power carried to the surface? Separating cause from effect will be a real challenge. Does reduced convection alter the magnetic field or does the field force reduced convection? Or could it be both? For example, looking at Figures 6, one might wonder if the magnetic field continues to build to a level at which it finally disrupts the convection. The "reduced" convection may then supply too little helicity for regeneration of the field, and that cycle of the dynamo is consequently terminated and winds down. Convection winds up and twists magnetic field high above the photosphere leading to re-connection and flares. With an active dynamo, the internal magnetic field would be substantially stronger than those outside the surface. When convection garbles the internal field, there should be internal "flares." Could these be a significant source of heat at certain restricted phases of a magnetic cycle?

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