PHOTOSPHERIC MACROTURBULENCE IN LATE-TYPE STARS

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I. Why Study Macroturbulence?

It is intimidating to attempt a review of the subject of late-type stars macroturbulence which follows so closely on the heels of David Gray's (1978) fine review in Solar Physics. Therefore this paper will avoid many emphases of his review while filling in some areas where some progress has emerged in the last 1-1/2 years. My slant will come mainly from the standpoint of line broadening analysis.

Each of us has his own reasons for being interested in macroturbulence of late-type stars. A short list of motivations might look like the following:
1) The relation of spectroscopic "macroturbulence" to the general atmospheric turbulence spectrum. Even in the Sun we do not know yet how the resolved velocity fields add up to "spectroscopic macroturbulence". The relationship of this macro-field is still not well defined in terms of microturbulence, and it is far from settled as to how important and unique a mesoturbulent description is. Finally, the cause of macroturbulence, whether convection, granules, nonradial pulsation, or even rotation, is still unspecified and it may be different in different regions of the H-R Diagram.
2) The relevance of macroturbulence to energy dissipation in the chromosphere. Here, at least, it appears that some tentative answers are beginning to emerge (§ III C.).
3) The relationship to chromospheric parameters in stars. These promise to provide us with kinematical models for the chromosphere-corona-solar wind complex both in stars and in the Sun. Adopting the solar-physics-of-stars theme, consider that stars of varying observable characteristics (T_{eff}, log g, composition, rotation, age, are the usual quintet) will help us to see the dependence of upper atmospheric phenomena on fundamental attributes of a star. Even though well observed, the Sun alone cannot provide this dependence. The Wilson-Bappu effect is an excellent historical example of what could have been a relationship between a global parameter and a turbulence, though now it appears that velocity fields are not the culprit after all (Ayres 1979).
4) The relationship of 5-minute-type oscillations to macroturbulence. Analysis of this oscillatory pattern, a consequence of nonradial p-modes (Deubner 1975, Rhodes et al. 1977), has already facilitated probes of interior properties such as the convection zone depth and differential rotation rate. The possibility exists that time-resolved analyses will provide similar information for other late-type stars.

II. Toward the Detection and Modeling of Radial-Tangential Macroturbulence.

In most stars the measurement of macroturbulence is hampered by the presence of a substantial rotational broadening. What makes at all possible the dissection of a profile's broadening into rotational and macroturbulent velocity fields is a combination of high-resolution, high S/N data on one hand and the sharply differing models for the two velocity distributions on the other. Whereas the Unsold "rotation function" is U-shaped, radial-tangential macroturbulence (the appropriateness of which is discussed below) produces profiles with extended wings and a deep, pointed core. Predictably, the Fourier transforms of these two functions are different and these are depicted in Figure 1. The rotation transform can be expressed approximately as a first order Bessel function. This function contains a series of regularly spaced zeroes and sidelobes. As one proceeds to stars of slower rotational velocities, the zeroes shift to higher Fourier frequencies until even the first zero recedes to unobservable frequencies and, ultimately, one is left only with a filtering due to the main lobe of the rotational transform. This lobe is rather square-shaped and for low rotational velocities, the interference from rotation quickly becomes negligible. It is for this reason that most of our information on macroturbulence comes from old, late-type stars. Let us now place these statements on a more quantitative basis: Lines of intermediate strength (~ 100 mÅ) generally offer recovery to the highest Fourier frequency at a fixed S/N (Smith and Gray 1976, Gray 1978). Such a line will have its first natural zero at about 0.14 s km^{-1}. As a practical matter the presence of a macroturbulent broadening agent can be best detected in stars having V_R sin i $\lesssim$ 17 km s^{-1} (Smith 1975, Kurucz et al. 1977). For broadening in these stars, e.g. those occurring in the middle of the H-R Diagram, almost nothing can be said concerning the turbulence distribution. When one passes to V_R sin i = 10 km s^{-1} (see Figure 2), the rotational zero occurs near 0.06 s km^{-1}. One can then perceive a slightly less bowed Fourier main-lobe, which corresponds to extended wings of the profile in

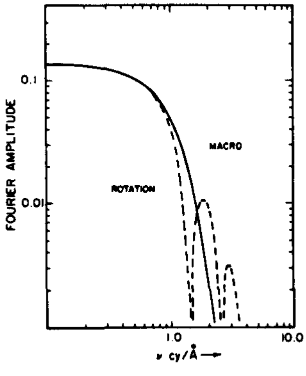

Fig. 1 - Fourier transforms of a model profile at λ6000 broadened by rotation ($V = V_R$ sin i = 22.5 km s^{-1}) and radial tangential macroturbulence (M = 15 km s^{-1}).

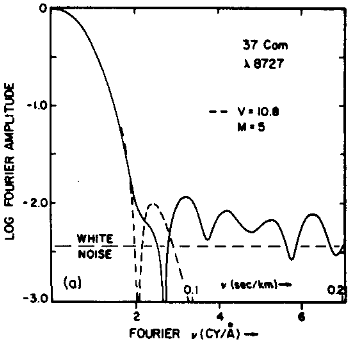

Fig. 2 - Transform of line modeled with rotation and macroturbulence. Rotation dominates, but one can see that R-T is a better turbulence model than is a gaussian.

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the wavelength domain. At this point, corresponding to V_R sin $i/M_{RT} \simeq 2$ in supergiants (Figure 2) and about 3 in giants, one is on the threshold of distinguishing radial-tangential macroturbulence from much different distributions like the gaussian. For V_R sin $i = 3$, i.e. at a velocity ratio near unity, the rotational effects become negligible and a host of other radiative transfer and instrumental parameters become more important (see Smith 1980 for a ranking of sources of error). Included in this velocity range are the ultra-slowly rotating dwarfs like the Sun and the red giants; most of our turbulence information is derived from these sources.

Older studies of macroturbulence used isotropic or single-stream gaussian representations for the lack of anything better. More recently, observers have been forced to a radial-tangential or exponential macroturbulence for certain sharp-lined early-type stars (Smith and Karp 1978), the Sun (Rutten et al. 1974, Gurtevenko et al. 1976, Smith et al. 1976, Gray 1977), solar-type dwarfs (Smith 1976, Smith 1978), and luminous K stars (Lambert and Tomkin 1974, Gray 1975, Luck 1977, Gray and Martin 1979 ("GM79"), Smith and Dominy 1979 ("SD79")). Gray (1975, 1976) first suggested the two-stream, radial-tangential model with internal gaussian dispersion (see Table 1 for definition) because of the similarity of this distribution to Benard cells envisioned in solar granules. Now if these eddies actually followed a circular and not a square pattern, the resulting macroturbulence would be described by an isotropic gaussian distribution. This contrast demonstrates the importance of geometry in the modeling of these motions. Both Gray and Smith have used equal radial/tangential stream areas and velocity dispersions in their macroturbulence modeling. Beckers and Morrison's (1970) results on solar intragranular flow patterns suggest that these adopted equalities appear to be well within a factor of two of reality, but their results also make it clear that granular flows do not turn square corners! An alternate way of representing the observed distribution is with a depth-dependent isotropic gaussian distribution of velocities (Smith et al. 1976). This model is not too physically unreasonable because of the strong depth dependences shown by granular and 5-minute oscillation patterns. In his solar flux-profile study Gray (1977) indeed found a 0.6 km s^{-1} increase in macroturbulence or weak lines formed in the lower photosphere. In sum, both the Benard cell and depth-dependent assumptions seem to have some basis in fact and together contribute toward the radial-tangential model. This conceptual agreement with solar observations also implies that "macroturbulence" as the spectroscopist observes it may well be due to the granulation pattern, perhaps with some residual help from 5-minute-type oscillations.

This reviewer would be remiss in not alluding to other independent techniques of measuring large-scale velocities. One consists of measuring radial velocity shifts (see W. Buscombe's paper) for high and low excitation lines preferentially formed in updraft/downdraft regions. Using this technique Dravins (1974) finds the same result that emerges from line broadening studies: the Sun and α Boo have similar macroturbulent velocities. Line shift studies ought to be encouraged and have a continuing place in photographic work. Finally, Traub et al. (1978) have broken ground in searching for five-minute-type oscillations in spectra of other late-type stars. This work can be most easily extended by time-resolved observations of red giants. These stars are bright and the oscillations are expected to have large amplitudes and periods. Cram and Smith have in progress a pilot investigation of α Boo. The strategy here will be to use a conventional coude system with a Reticon detector and to minimize ultra-small instrumental wavelength shifts by referencing stellar lines with nearby terrestrial features. It is hoped that future reviews on this subject will have less emphasis on line broadening and more on resolved oscillatory patterns.

III. Recent Results.

A. Macroturbulence and the Turbulence Spectrum.

Mesoturbulence - Despite the work done on broadening by finite-sized eddies, there still seems to be disagreement on whether model profiles computed with a correlation-length formulation fit center-to-limb observations, (cf. Auvergne et al. 1973, Frisch 1975 vs. Canfield and Beckers 1976), or the detailed shape of a given profile (Smith and Frisch 1976 vs. Gray 1977), better than a micro-/macro-model does. Most of us observers hope that a micro-/macro-description is an adequate representation of stellar profiles but a decisive answer is not yet forthcoming. Consider that although the solar intensity profile analysis of Smith and Frisch, and the flux analysis of Gray 1977, were each done "correctly", the two studies led to conflicting results. The latter could find no evidence for narrow sidelobes indicative of the dominance of mesoturbulence. Perhaps the fault lies in the assumptions going into the analysis of one or both studies (e.g. inaccurate eddy size distribution, or use of the convolution approximation for rotation and flux profiles) or in systematic errors in the atlases; the matter is not resolved. It may be, as implied from other solar observations (Beckers and Parnell 1969), that mesoturbulence is physically important in a stellar atmosphere but that operationally one can ignore it in a stellar profile, as Gray suggests. Future studies would do well to look for abnormally narrow or broad sidelobes in transforms of intermediate-strong symmetrical lines (~ 200 mÅ). However this approach requires a Fourier noise amplitude of -3 or less in the log. Therefore, only high S/N, completely unblended profiles can be used for studying mesoturbulence.

Microturbulence - The relationship between macro- and micro-turbulence is equally unclear. In his review (Gray 1978) shows an impressive-looking ξ_t - M_{RT} correlation. Contrariwise, our work has not turned up yet any such correlation. For example, the microturbulence values determined by Smith (1978) and Smith and Dominy (1979) increase from 0.5 km s^{-1} to 2.0 km s^{-1} going from dwarfs to giants, but there is no such increase in the macroturbulence values. Perhaps a correlation in broadening does exist, particularly if supergiants are included, but there are reasons to question a turbulence interpretation for any such relation. The quoted values of microturbulence in supergiants (which may include non-LTE effects and/or velocity gradients), on which the Gray correlation largely rests, cannot yet be considered well-documented turbulences. In some cases these values are actually supersonic. In short the turbulence measured in dwarfs and supergiants may arise from totally unrelated phenomena. Thus we seem to be in the same state here as a decade ago. A study of particular lines including effects of non-LTE and asymmetry in the analysis needs to be done to test the turbulence interpretation.

In one important respect progress has been made: the microturbulence values from both profile and curve of growth (e.g. Lambert and Ries 1977) analyses of both dwarfs and giants are finally in good agreement.

B. Macroturbulences of Main Sequence and Luminous Late-Type Stars.

General Survey -- Table 1 is a compilation of recent rotational and macroturbulence velocities obtained by photoelectric means for G type dwarfs and luminous K stars. Note in the table the definition of the M_{RT} velocity-scale used herein; we have scaled Gray's values downwards by $\sqrt{2}$ to put all numbers on a common system.

Where comparison is possible between observers, the agreement in this table is excellent. For the Sun the comparison agrees to within 0.1 km s^{-1}. Note that these turbulence values, even when corrected for velocity scale differences, are perhaps a factor of two larger than the sum of all the resolved solar velocities (e.g. Edmonds 1967). A second comparison can be made from the mean macroturbulence for a group of four giants studied by GM79 and SD79 studies. The mean value in both studies is 3.0 km s^{-1}. Finally, SD79 report a macroturbulence difference of only 0.2 km s^{-1} if the same line is observed and analyzed independently by two investigators (Gray and Smith). This suggests that most errors in the red giant analyses derive from different lines being used in the analyses; that is, errors involving treatment of line blending and radiative transfer are most severe. As main sequence stars tend to have fainter apparent magnitudes, the errors in their analyses are dominated by spectrophotometric errors (Smith 1978).

Main Sequence Stars -- A pair of mid-F and K stars in Table 1 show smaller turbulence values than the G stars do. However, using a scaled solar $T(\tau)$-relation, Smith (1978) found no evidence for a change in the mean macroturbulence values from G0 to K0. It is certainly premature to make a statement on the dependence of turbulence with T_{eff}. Even when more F and K stars are observed, it will be imperative to find a trustworthy model $T(\tau)$-relation in order to carry out an analysis before any results can be related to G stars.

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TABLE 1

Recent Fourier Determined V_R sin i and M_{RT}* Values for Late-Type Stars

Dwarfs --

Star	Sp. Type	V_R sin i	M_{RT}	Ref.
Sun	G2-4 V(?)	---	3.1	S76
		2.2 ± 0.7	3.2 ± 0.2	S78
		1.9	3.1	GM78
Procyon	F5 IV	3.5 ± 0.5	1.2 ± 0.3*	WJ78
59 Vir	F8 V	5.5 ± 0.4	3.8 ± 0.4	S78
β Vir	F8 V	4.1 ± 1.0	4.2 ± 0.5	S78
π^1 UMa	G0 V	10.8 ± 0.4	4.8 ± 0.4	S78
HR 3625	G0 V	6.0 ± 0.2	3.8 ± 0.4	S78
β Com	G0 V	5.8 ± 0.2	3.5 ± 0.3	S78
η Cas A	G0 V	4.3 ± 0.7	2.8 ± 0.7	S78
47 UMa	G0 V	3.3 ± 0.7	3.4 ± 0.5	S78
β CVn	G0 V	4.7 ± 0.7	3.1 ± 0.4	S78
λ Ser	F0 V	5.4 ± 0.2	1.8 ± 0.2	S78
51 Peg	G5 IV	5.0 ± 0.7	2.4 ± 0.5	S78
τ Cet	G8 V	2.2 ± 1.1	2.6 ± 0.5	S78
Gmb 1830	Z8 VI	1.0 ± 1.0	1.8 ± 0.5	S78
70 Oph A	K0 V	3.3	4.1	S78
δ Eri	K0 IV	2.2 ± 0.9	2.9 ± 0.2	SD79
ν^2 CMa	K1 IV	1.5 ± 0.7	3.0 ± 0.1	SD79
γ Cep	K1 IV	2.4 ± 0.4	2.8 ± 0.6	SD79
61 Cyg A	K5 V	2.0	1.8	VF79

*All numbers have been normalized to the following definition of M_{RT}:

$$f(\Delta\lambda) = \frac{1}{2\sqrt{2\pi}\, M_{RT} \sin\theta} \exp(-(\Delta\lambda/\sqrt{2}\, M_{RT} \sin\theta)^2) + \frac{1}{2\sqrt{2\pi}\, M_{RT} \cos\theta} \exp(-(\Delta\lambda)/\sqrt{2}\, M_{RT} \sin\theta)^2)$$

(cf. Gray 1976, eqn. 18-12). My M_{RT} scale is smaller by $\sqrt{2}$ than the "ζ_{RT}" values quoted by Gray; it is 1.5 times larger than those of Wynn-Jones et al.

Giants --

Star	Sp. Type	V_R sin i	M_{RT}	Ref.
γ Leo B	G7 III	1.0 ± 1.3	2.8 ± 0.7	SD79
β Her	G8 III	3.5	4.2	G79
η Dra	G8 III	0.0	4.2	G79
ε Vir	G9 III	2.7 ± 1.1	2.9 ± 0.8	SD79
β Gem	K0 III	0.8 ± 1.3	3.3 ± 1.0	SD79
		2.2	2.8	GM79
α UMa	K0 III	3.2	2.8*	GM79
ε Cyg	K0 III	2.1	2.9*	GM79
β Cet	K1 III	3.3 ± 0.8	4.2 ± 0.2	SD79
β Oph	K2 III	---	4.2*	Gray 1975
α Ari	K2 III	2.9 ± 0.8	2.7 ± 0.8	SD79
		0.0	2.8	
β Oph	K2 III (SMR)	3.0	2.7*	GM79
μ Leo	K2 III (SMR)	2.4	2.8*	GM79
α Boo	K2 III	2.7 ± 0.5	3.2 ± 0.5	SD79
	2.8	3.3*		GM79
α Ser	K2 III (SMR)	2.0 ± 0.3	2.7 ± 0.3	SD79
		2.3	2.8	GM79
α Tau	K5 III	2.7 ± 0.2	3.3 ± 0.5	SD79
γ Dra	K5 III	3.5 ± 0.7	2.7 ± 0.5	SD79
Supergiants --				
37 Com	G9 II-III	10.4 ± 0.3	5.8 ± 0.5	SD79
56 Peg	K0 Ib	3:	5.0 ± 0.3	SD79
α Cas	K0 II_III	3:	6.0 ± 1.2	SD79
ε Peg	K1 Ib	≥ 3	7.4 ± 1.0	SD79
ν^1 And	K3 II	---	4.1*	Gray 1975
ι Pup	K3 Ib	3:	5.3 ± 0.7	SD79
γ Aql	K3 II	---	5.3 ± 0.4*	Gray 1975
ξ Cyg	K5 Ib	3:	6.1 ± 1.3	SD79
ζ Aur	K5 II	3:	4.9 ± 0.6	SD79
HR 8726	K5 Ib	3:	6.9 ± 1.4	SD79

In the same study (Smith 1978), we reported an anticorrelation between macroturbulence and age for G dwarfs. Although this relation is significant only at the 90% level, this relation is still more significant for this sample of stars than the (venerable) correlation between rotation and age. It is likely that age uncertainties have introduced scatter into the turbulence-age relation. A physical explanation for the age correlation effect has not yet been advanced.

Smith and Dominy (1979) found that the mean macroturbulence velocity of early K stars remains constant for five magnitudes along the red giant branch. At $M_{Bol} \simeq -2$, corresponding to the appearance of class II and Ib stars, M_{RT} jumps suddenly from 3 to 6 km s^{-1}. For still brighter supergiants the macroturbulence values appear to increase with luminosity (Luck 1977, Imhoff 1977). This sudden jump is not easily understood, but it is helpful at least to know that stars having the larger macroturbulence values also have larger masses than the fainter K giants. In any case, this step-relation between macroturbulence and luminosity violates the expectation that the Wilson-Bappu

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effect is caused by a chromospheric velocity field. These results and the boundary temperature results of Desikachary and Gray (1978) support the radiative damping model advanced by Ayres (1978).

Of particular significance is the K1 III star β Cet. This star shows a macroturbulence of about 5σ larger than do other K giants of its luminosity. Anomalous broadening for this star has also been noticed by O'Brien (priv. comm.) in the chromospheric λ10830 line (seen in absorption). Moreover, an analysis of I.U.E. spectra of several K giants by Linsky and Haisch (1979) singles out this star as having an anomalous coronal temperature distribution. While it is unclear yet what makes this star so unique, one has to notice that this correlation of peculiar phenomena argues for photospheric and chromospheric velocity fields being correlated. Another argument for correlated velocities, though less convincing, concerns the well-known relation between photospheric and Hα line widths (Bonsack and Culver 1966, Imhoff 1977).

C. The Chromospheric Connection.

Returning to point #2 in § I, one asks: do macroturbulent motions dissipate their energy in the chromosphere? If so, one expects a correlation between chromospheric heating and photospheric macroturbulence. (This assumes the velocities in the chromosphere and photosphere <u>are</u> related, a proposition for which, as just shown, there is some evidence.)

There are several ways to test this idea. Desikachary and Gray (1978) have found that Ca II K1-minima indicate a higher temperature minimum for normal K-type stars than for super-metal rich ("SMR") stars. However, both stellar groups have higher temperature-minima than radiative equilibrium model atmospheres indicate. Therefore one expects dissipation, e.g. by waves, to be more noticeable in the normal stars than in the SMR stars. Finally, one also expects these waves to be observable as (or to be indirectly related to) macroturbulence. Following this reasoning, Gray and Martin (1979) searched for macroturbulence differences between members of these two stellar groups, but found none.

Another test of this concept can be constructed by plotting the macroturbulence values of a large number of luminous K stars against spectral type. Blanco <u>et al.</u> (1976) find that chromospheric K2 emission fluxes peak at spectral type K1. Therefore, in Figure 3 I have plotted the M_{RT} values of the SD79 data against the spectral type difference, (Sp. Type of Star - K1). For reference, the <u>relative</u> K2 emission flux observed by Blanco <u>et al.</u> is included in the diagram. If one omits β Cet from consideration, one sees that neither the turbulence distributions of the giants nor of the supergiants follow the K2-emission relation. Both of these tests imply a lack of observable dissipation of macroturbulent motions in the lower chromosphere.

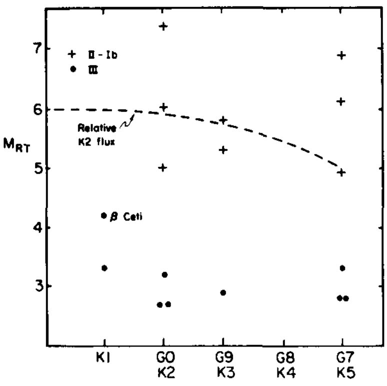

Fig. 3 - The macroturbulence vs. spectral type relation for early K III-IV stars. The K2 emission flux determined by Blanco et al. is shown for comparison.

While neither of the above tests may be sensitive enough, there are additional arguments that M_{RT} and chromospheric emission are related. For example, the K2-emission flux increases by more than a factor of ten between dwarfs and giants (Blanco et al. 1976), but there is no corresponding increase in macroturbulence among them, possibly to within 10%. In the same vein, macroturbulence does not increase from G0 V to K0 V types, whereas the K2-emission flux does. Finally, the macroturbulence value in the Sun does not argue for a detectable turbulence dissipation. One comes to this conclusion because the Sun has been recently reported to be an anomalously slowly rotating and chromospherically quiet star for its age (Smith 1980; Blanco et al. 1974). Despite this reported abnormality, the Sun manages to have a normal macroturbulent value for its age group (Smith 1978). What appears to be a normal photospheric macroturbulence is associated with a quiet chromosphere in the same star; therefore, the turbulence value must not be related to chromospheric activity. In sum, while it cannot yet be stated conclusively that macroturbulent velocities do not correlate with chromospheric heating, "the mood of the jury is perhaps becoming evident". These conclusions support theoretical arguments (e.g. Ulschneider 1974) that the heating of the lower chromosphere is due to dissipation of short-period (~ 30-sec) wave energy. Such waves have too small a wavelength to manifest themselves as macroturbulence. However, the possibility still exists that such waves may be identified in future analyses of strong lines as mesoturbulence, or through wavelength-shifted cores (Gray, priv. comm.).

IV. Prognosis.

Why study macroturbulence in late-type stars in the next few years? Here is one list of problems awaiting our attention:

1) A solar weak-line/strong-line analysis across the limb. Such an analysis has not yet been carried out using all the velocity signatures available in the Fourier domain.

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It begs attention if the relationship between mesoturbulence and large/small scale-length turbulences is ever to be addressed properly. Such a study may also explain why intensity and flux studies can arrive at different answers.

2) Macroturbulence studies in new regions of the H-R Diagram. Values of M_{RT} are needed for KM stars because of their tendency toward complete convective equilibrium in the envelope. The question of M_{RT} increases in supergiants must be investigated too, though only after the non-LTE excitation effects are described for each line and "moving atmosphere" aspects are evaluated.

3) Macroturbulence studies in young clusters. Young stars provide the final, perhaps decisive, test in the search for a correlation between M_{RT}, age, and chromospheric dissipation. One search would be provided by finding a sharp-lined (near pole-on) young star in a cluster. Another would be to dissect velocities in dMe stars. So far one attempt on BY Dra, has led to negative results; the rotational velocity is too large (Vogt and Fekel 1979).

4) Macroturbulence and chromospheric variability. Two chromospheric diagnostics, K2 emission (Wilson 1978) and He I λ10830 (O'Brien and Lambert 1979) are particularly informative chromospheric signatures. Especially with the latter study nearing completion, it should be possible to search for abnormalities in the chromospheres of certain stars (e.g. β Cet) that also betray themselves in the photospheres.

5) The search for 5-minute-type oscillations. If successful, a search for rapid, periodic radial velocity excursions (either of the total line or the line core) promises to lead to a breakthrough in probing the convective envelopes of red giants.

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