NONRADIAL OSCILLATIONS: THE CAUSE OF MACROTURBULENCE IN LATE-TYPE STARS?

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I. The Problem.

A fundamental problem in contemporary stellar atmospheres research concerns the cause of what the spectroscopist calls "macroturbulence." Even in so well studied a star as the Sun, it is unclear as to which of the many resolved velocity fields is most responsible for the broadening of the disk-integrated spectrum. There are several uncertainties attached to the identification of this primary velocity field. To cite one, Beckers (1980) indicates in a recent review that the two principal contributors to macroturbulence, convective granulation and the five-minute nonradial oscilltion pattern, each add only an r.m.s. velocity of 1/2 km s^{-1} at $\tau_{5000} = 0.1$. According to him, even when they are put together with related unresolved patterns [e.g. subgranulation and short period (<30) oscilltions] the sum of all known velocities seems to fall short of macroturbulence obtained from line broadening studies [~ 3 km s^{-1}; radial-tangential model (Gray 1977, Smith 1978)]. The most recent models of the solar granulation field (Keil 1980) suggest somewhat higher velocities, e.g. 1.1 km s^{-1} at $\tau_{5000} = 0.1$, when revised corrections for terrestrial seeing are taken into account. Nonetheless, such corrections must be added to both the convection and oscillation amplitudes, so it is still not clear whether one of these fields dominates the line formation.

The opposite height dependences of granulation and oscillations complicate this picture still further. The decrease in convective overshooting with atmospheric height may be responsible for an e-folding rate in the vertical component of granulation as steep as 80 km (Keil 1980). In Keil's models the convective transport efficiency is reduced to 3% at depths of interest, $\tau_{5000} = 0.1$. In contrast to this dependence, decreasing atmospheric densities are responsible for an increase in nonradial pulsation amplitudes. For weak solar lines the observed increase in line broadening with depth and the behavior of line-shift asymmetry parameters indicate that convection is probably the dominant velocity field in the lower solar photosphere

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(Gray 1978; Dravins, Lindegren, and Nordlund 1980). However, it not clear that granulation should dominate the broadening of lines in other stars. In fact, the available evidence suggests that as one moves to stars of cooler effective temperatures, the overshooting region is likely to move farther below the line formation region and influence it less. Other arguments can be made for the oscillations dominating. For example, Gray (1978) has presented evidence in cool stars for a correlation of micro- and macro-velocities, both of which increase with height. If this correlation is correct, the high levels of the photosphere sampled by the line core and giving rise to microturbulence are probably more dominated by the nonradial oscillation velocity field than by convection. Moreover, the lines chosen for macroturbulence is samples at layers near $\tau 5000 \approx 0.1$. Thus there are a priori reasons to expect nonradial oscillations to be a very important line broadening agent in luminous late-type stars.

Our motivation for this reinvestigation into macroturbulence stems from unexplained results by Smith and Dominy (1979,"SD") on the dependence of macroturbulence with luminosity among G and K-type stars. Those results are shown in Figure 1. Note that the observed radial-tangential macroturbulence parameter, M_{RT}, is constant for five bolometric magnitudes above the main sequence. At $M_{Bol} \approx -1$ it suddenly exhibits a quantum jump of a factor of two. There is good evidence among supergiants (classes I and II) that macroturbulence increases linearly with luminosity thereafter (Bonsack and Culver 1966, Imhoff 1977). SD were unable to account for this step-function character of macroturbulence nor for the luminosity at which the jump occurs. It will be shown that both characteristics can be explained naturally by existing theory for p-mode nonradial oscillations and by stellar evolution of late-type stars.

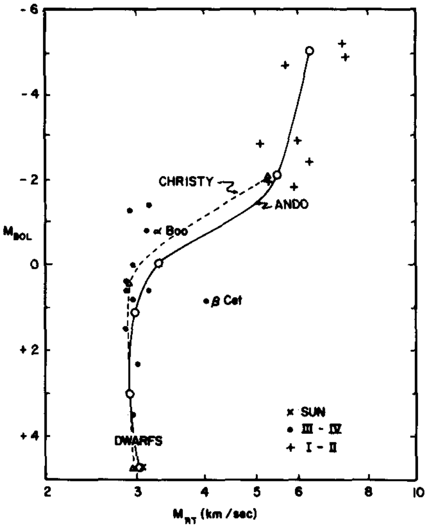

Figure 1. The macroturbulence-luminosity rotation for G Dwarfs and luminous K stars.

II. Predictions of Nonradial Velocity Amplitudes and Macroturbulence.

In this paper we examine published theoretical estimates for relative nonradial pulsation amplitudes in order to see whether this mechanism can account for observed macroturbulences in late-type stars. In order to do so, several aspects of the work of Christy (1962) and Ando (1976) will be briefly summarized.

In a pioneering study, Christy examined the transport of convective flux through the hydrogen-ionization of late-type giant stars. He pointed out that because the mean convective velocity is inversely proportional to the gas density, it will increase with height in the hydrogen convective zone until it saturates at the sound speed [convective velocities may already nearly reach the sound speed in the lower solar photosphere (Keil 1980)]. He then reasoned that the excess convective energy would be transported away as nonradial waves with a characteristic velocity given by the equation.

$$v^2 = \frac{c}{2} \frac{F_c}{P} , \tag{1}$$

where c is the local sound speed, F_c the total convective flux, and P the pressure. By knowing the flux (i.e. luminosity) and the density and temperature in the ionization zone, Christy used equation (1) to compute nonradial velocity amplitudes for various stellar models. It is worth pointing out that equation (1) makes no prediction as to how energy is partitioned among various nonradial modes. However, because macroturbulence itself is a measure of $\sqrt{\langle v^2 \rangle}$ it is of no concern to us in the present context as to how many, or which modes, this energy is distributed among, as long as their wavelengths are longer than the mean free path of a continuum photospheric photon.

Because the convective velocities almost certainly become sonic in the hydrogen ionization zones of luminous, cool stars, Christy's work is important in allowing us to estimate the surplus energy which must be transported by other means. However, it remained a speculation that nonradial modes provide the necessary energy conduit. To check Christy's ideas, Ando (1976) performed a stability analysis in the linear, nonadiabatic regime for a variety of late-type stellar models. He found that the growth rate, η, for unstable modes has the dependence:

$$\eta = \frac{c\,F_c}{P} \tag{2}$$

and therefore, from equation (1),

$$v \sim \surd\,\eta . \tag{3}$$

In short, the similar dependence of the growth rate and Christy's inferred limiting amplitudes on stellar envelope parameters allowed him to equate the two. This is a powerful result because one can utilize his η values from the linear instability analysis to compute relative equilibrium amplitudes that ordinarily cannot be computed. Ando was able to make another simplification from his detailed results, namely that the amplitudes are primarily determined by the stellar gravity and temperature through the following relation:

$$v \sim g^{-0.25} \, T_{eff}^{3} \qquad (4)$$

From this equation one sees that in low gravity stars the velocities will be higher. This is because the lower gas densities will be responsible for convective velocities attaining the sound speed deeper in the envelope; at the same time the total flux generated in such stars is greater. Thus, there will be more excess energy to be carried by nonradial oscillations. Likewise for hotter stars the ionization zone will occur higher in the envelope, ensuring saturation at a lower sound speed, and the velocities will increase in this low density regime.

Utilizing Christy's and Ando's predictions it becomes possible to compare theory with observations. However, because equation 4 is a proportionality we will arbitrarily normalize the results to a 3 km s^{-1} velocity for early G dwarfs (Smith 1978). In addition, we will use the following (T_{eff}, log g) values for Ando's relation: for dwarfs (5780, 4.44), the subgiants (4800, 3.5), for giants (4300, 2.8) and (4200, 2.5), and for supergiants (4000, 1.5) and (3800, 1.0). The results are shown by solid and dotted lines in Figure 1. Moving up the giant branch from the G dwarfs, one sees that the T_{eff} and log g factors in equation 4 cancel one another, and that a large jump occurs between M_{Bol} = 0 and -2. The velocity increase at and above this jump evidently arises due to the nearly vertical evolution of luminous stars in the H-R Diagram.

The quantitative agreement between theory and observations in Figure 1, probably fortuitously good, suggests strongly that nonradial oscillations are either indirectly related to or the direct cause of macroturbulence in strong lines of luminous, late-type stars. This conclusion probably does not hold for weak lines in G dwarfs because granulation effects tend to dominate at great atmospheric depths.

There are several additional aspects of the predicted nonradial velocity behavior that need explanation, the principal one being the jump. Some reflection on this problem demonstrates that this feature can be understood by appealing to conventional evolutionary theory. In particular, the stellar tracks of Iben (1967) for a low mass star (1.0-1.5 $M_{\odot}$) show that the red giant branch terminates with the onset of helium detonation. Upon core exhaustion in the lower luminosity "clump" region, the star evolves quickly to the upper right once again as a double-shell burner and passes near its former red giant termination-point on an asymptotic red giant branch. Such a star is now considerably more evolved than it was in its earlier pre-He detonation state. As a consequence, a number of pulsational properties have been radically altered. The characteristic period is now five days instead of five hours; the mean spherical harmonic index, $\langle \ell \rangle$, and the number of excited modes, are lower by factors of eight or more (Ando 1976). The nearly vertical evolutionary tracks of such stars mean that the nonradial velocities will increase rapidly (equation 4), giving the illusion of a "jump" at $M_{Bol} \approx -1$. A mixture of high mass (fast ascenders) and low mass stars may also contribute to a large scatter in macroturbulence among supergiants, as observed in Figure 1.

Even apart from the success of NRP theory in explaining Fig. 1, it is unlikely that granulation can satisfy the observations. If one compares once again two equal mass stars close together in the H-R Diagram, one prior to and the other subsequent to He-ionization, one expects the stars to have much the same gravities, scale heights, convective fluxes, and convective velocities (sound speed). Therefore the behavior of the two granulation patterns should cause no jump in macroturbulence.

III. Desiderata.

An important test of these ideas would be to search other areas of the H-R Diagram to confirm that other types of stars have macroturbulent values given by equation 4. The K dwarfs provide one such check, but so far very few of them are known to be both slowly rotating and bright enough to permit the accurate determination of macroturbulence values. The G giants are another group to exploit, but most of them are rapid rotators because their antecedents are A or early-F stars. Thus while it is possible in principle to utilize different stellar groups to confirm Ando's relation, it will be difficult to do so until a suitable sharp-lined sample can be isolated from them.

A pivotal test of the Ando relation would come from the direct detection of nonradial pulsation amplitudes through a modulation of radial velocities. One can estimate the amplitude of these oscillations by the relation:

$$K(\mathrm{m\ s^{-1}}) = \frac{2}{\sqrt{N}}\ g^{-0.25}\ T_{eff}^{3} \qquad (5)$$

where N is the number of effective nonradial modes normalized relative to the Sun's (each mode assumed to have the same amplitude), and where the coefficient 2 $\mathrm{m\ s^{-1}}$ comes from a normalization to the amplitude of the solar five-minute oscillations. From Ando and Osaki (1975) and Ando (1976), the number of effective modes is found to be about 250 for dwarfs and giants and 30 for supergiants. From these relations, one can estimate that the mean amplitude of nonradial oscillations in giants is not likely to be much higher in K giants than in the Sun, but that it should be 8 to 10 times higher in the supergiants. These estimates are necessarily crude, first, because Ando's theory is linear, and, second, because it neglects a probably coupling between convection and pulsation. The efficiency of this coupling probably increases as the convective scale approaches the pulsational wavelength, as is expected among the supergiants (cf. Schwarzschild 1975). In that case, then the amplitudes should be even larger than those computed from equation 5.

Can amplitudes as small as 2 or 20 m s^{-1} be detected in other stars? The present instrumental capabilities are such that the 2 m s^{-1}, five-minute oscillation can be detected in bright and integrated sunlight (Traub, Mariska, and Carleton, 1978). Moreover, the r.m.s. errors in stellar radial velocities of K giants can be brought down to the 6 to 12 m s^{-1} level. These errors can be attained by use of an absorption cell in front of the spectrograph slit (B. Campbell, unpubl.) or by monitoring the telluric O_2 lines near λ6300 as a velocity reference system (Smith, unpubl.). Repetitive observations should allow the detection of semi-amplitudes in stars as small as 5 m s^{-1}. This limit certainly ought to recover the supergiant pattern, and can place stringent limits at least on the giant oscillations.

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