Session B

Observational probes of convection

Convection in Astrophysics
Proceedings IAU Symposium No. 239, 2006
F. Kupka, I. W. Roxburgh & K. L. Chan, eds.

doi:10.1017/S1743921307000245

Observing convection in stellar atmospheres

John D. Landstreet[1]

[1]Department of Physics & Astronomy, UWO, London, ON N6G 1P7, Canada
email: jlandstr@astro.uwo.ca

Abstract. Convection occurs in the visible photospheric layers of most stars having T_{e} less than about 10 000 K, and in some hotter stars. The solar granulation pattern is a symptom of this, as is the non-zero microturbulent velocity often required in abundance analysis to make both weak and strong lines yield the same abundance.

In very sharp-lined stars, the presence of a non-thermal velocity field in the visible stellar atmosphere leads to several other effects which may be detected in spectral line profiles. These include radial velocities that vary systematically with equivalent width, distortions of the line profile as compared to a profile computed with a Voigt profile and rotational broadening ("macroturbulence"), and asymmetries with respect to the line centre ("bisector curvature").

Detection and interpretation of these effects, with the goal of obtaining empirical information about a velocity field present in the visible layers, requires comparison with calculated synthetic spectra which incorporate model velocity fields. Thus, this review will summarize some of the observational clues concerning photospheric velocity fields, as well as modelling aimed at interpreting these data.

Keywords. Convection, Sun: atmosphere, stars: atmospheres, line: profiles, line: formation

1. Granulation and microturbulence

Photographic observations of solar granulation starting in the late 19th century by Janssen and others encouraged the view that the observed bright granules are convective cells. The persistence of granules over time scales of order 10 min, typical granule sizes of $\sim 10^3$ km, and bulk velocities of ~ 1 km s^{-1} suggest that we are observing a kind of coherent overturning flow, perhaps analogous to Bénard cells. Solar granulation provided the first indication that convection may be directly visible in stellar atmospheres.

Unfortunately, atmospheres of other stars are at best barely spatially resolved, and in general convective structures in the atmosphere cannot be directly imaged. However, the presence of a velocity field with velocities of the order of atomic thermal velocities of a few km s^{-1} will influence the formation of spectral lines significantly, and this effect offers us a wide range of possibilities for detecting the presence of the velocity field and establishing at least some of its characteristics. However, beyond simple recognition of symptoms of the velocity field in line shapes, obtaining quantitative information about the velocity field present requires comparison of calculated line profiles with observed ones, and so this review will discuss both aspects of observing photospheric convection together.

Perhaps the simplest example of the effect of a velocity field on line profiles is provided by stellar rotation, which greatly broadens lines in early-type stars. This broadening not only allows one to detect stellar rotation, but to measure the line-of-sight component of the equatorial rotation velocity, $v_{\mathrm{e}} \sin i$. An unfortunate feature of this particular velocity field is that when $v_{\mathrm{e}} \sin i$ exceeds a few km s^{-1}, the rotational line broadening masks most of the effects of other velocity fields that may be present. This is not a severe problem with late-type stars (cooler than mid-F), but is an important limitation for studies of A and B stars.

Other examples of large-scale velocity fields that affect line profiles are provided by binary motion and low-order pulsation. In these cases, the velocity field usually has a length scale of the order of the stellar radius.

However, judging by the solar case, the length scale of convective motions is likely to be much smaller than the size of the star as a whole, and may even be small compared to the mean free path of a photon in a spectral line. The first detection of a small scale stellar velocity field was provided by *microturbulence*. It was found (Struve & Elvey 1934) that modelling weak spectral lines for abundance analysis yielded systematically lower abundances than strong lines, and that this discrepancy could be removed, and consistent abundances derived, by assuming the presence of a Gaussian velocity field – in addition to thermal broadening – of scale small compared to the atmospheric scale height, and amplitude ξ of the order of 1 $\mathrm{km\,s^{-1}}$. Physically, the additional velocity broadening provided by the microturbulence parameter allows strong lines to spread their absorption over a wider wavelength interval, and to saturate at a larger equivalent width, than without microturbulence. This in turn increases the strength of saturated lines relative to weak lines for a given abundance, as required by observations.

A non-zero microturbulent velocity ξ is required for most stars with atmospheres cooler than about $1\,10^4$ K. Because this temperature range coincides roughly with the part of the HR Diagram in which surface or near-surface convective instability is expected, due to the high opacity of partially ionized H, it seems plausible that the microturbulent velocity is in fact a rough measure of typical convective velocity dispersion along lines of sight in the photosphere. As there are now thousands of stars for which chemical abundances have been determined in a reasonably modern way, and almost all of these analyses yield values of ξ, there is a very large pool of available (and so far mostly unexploited) data concerning this symptom of atmospheric motions.

Microturbulent line broadening can also be detected directly in stars of sufficiently slow rotation and large convective velocities. For example, modelling of individual photospheric lines in G and K giants, where microturbulence of the order of 2 $\mathrm{km\,s^{-1}}$ is found, reveals directly the additional Gaussian broadening in excess of the thermal value (Gray 1982). In general, direct determination of ξ from line profile shapes and indirect determination from abundance studies give similar results.

Non-zero microturbulent velocities are found throughout the cool part of the HR Diagram, among spectral types A, F, G, K, and M. The typical values of ξ do not vary much with T_{e} in a given luminosity class among cooler stars (late F and cooler). Among F and later stars, ξ increase with luminosity class from roughly 1 $\mathrm{km\,s^{-1}}$ on the main sequence to 2 or 3 $\mathrm{km\,s^{-1}}$among supergiants (see e.g. Gray 1988). However, it appears that ξ rises to a larger value in main sequence A stars and then declines to near zero in late B stars (e.g. Hill 1995; Varenne & Monier 1999; Landstreet 1998). The maximum value of ξ is around 4 $\mathrm{km\,s^{-1}}$ for stars of $T_{\mathrm{e}} \sim 8000$ K.

Amongst the hotter stars, with T_{e} above about 12000 K, the situation is rather confusing. Many abundance analyses have been carried out, yielding values of ξ (e.g. Gies & Lambert 1992; Fitzpatrick & Massa 1999; Lyubimkov, Rostopchin & Lambert 2004). For main sequence stars, ξ values between 0 and a few $\mathrm{km\,s^{-1}}$ are found, rising to 10 $\mathrm{km\,s^{-1}}$ or more for stars with T_{e} above about 30000 K. However, no obvious pattern is discernible in the data, with similar stars having $\xi \sim 0$ and $\xi > 0$. It is not clear what ξ measures in this temperature range; for the hottest stars, the non-zero value of ξ may even be produced by mass loss rather than convection. For hot giants and supergiants, the values of ξ found are larger than for dwarfs (up to 20 $\mathrm{km\,s^{-1}}$ for supergiants); again this number may provide information about a variety of effects such as non-LTE line formation and mass loss, so it should be interpreted with caution.

2. Radial velocities, macroturbulence and bisector curvature

In recent years, observational studies of convective velocity fields in stellar atmospheres have increasingly focussed on three other observable effects of convection: (1) systematic variations in measured stellar radial velocity with equivalent width (or depth) of lines; (2) the departure of line profiles (particularly of strong lines) from the shapes predicted by simple Voigt profiles ("macroturbulence"); and (3) the asymmetry introduced into line profiles which are formed by columns of rising and descending gas under circumstances where the two kinds of flows have different morphology ("bisector curvature").

In a convecting atmosphere, we expect that in general the regions of upward flow will not have the same areal coverage as the downflow. In addition, the effective temperature at $\tau \sim 1$ in a region of upward flow may well be somewhat higher than in a sinking region. (Both these effects are observed in solar granulation.) The part of the observed spectral line that is formed in the upward moving gas will be blue-shifted; in the downward flow, red-shifted. If, as we expect, the flux from the two directions of flow is not equal, observed spectral lines will be produced more by one region than the other, and the observable line, integrated over the stellar disk, will be somewhat shifted in wavelength from the rest velocity of the star. It will also be asymmetric; the weaker contributor will tend to form a depressed wing on the stronger contributor. This effect is the origin of bisector curvature in spectral lines, and probably also of the various line profile shapes observed, which are different from those predicted by a single Voigt function, and that we describe empirically by macroturbulence (Gray 1982).

Furthermore, we may expect that the flow velocities are a function of depth in the atmosphere. It is not unreasonable to guess that (as in the Sun) the vertical flow will be more rapid at greater depths, and die out, or at least diminish, at small optical depth. If this is true, the typical velocity of lines formed close to $\tau \sim 1$ in the continuum will be different from the velocity of lines formed high in the atmosphere. Since weak lines are (usually) formed deep in the atmosphere, while the cores of strong lines (which we use to measure the radial velocity of these lines) are formed high in the atmosphere, we expect to find a systematic *variation* of radial velocity with line strength (or line depth).

For more than two decades, empirical modelling of lines has been used to try to extract some basic information about the atmospheric velocity field from the observations. In early studies, the modelling tended to be focussed on a single line profile indicator; more recently, more comprehensive models have been developed which extract a more complete picture of the underlying flows.

2.1. *Macroturbulence*

The most easily recognized feature of observed line profiles that carries information about the surface velocity field is the overall shape of a line. The line profiles of most main sequence stars of all masses (up to the mass at which non-LTE effects become important and emission lines appear) can be approximately modelled using Voigt profiles with the addition of some microturbulence and stellar rotation. However, as one looks at higher luminosity stars, the line profiles of the stronger lines of slow rotators change to looking more like a Lorentz profile, with fairly narrow central cores and broad, shallow wings. It was found in the 1970's (see Gray 1988 for references) that these line profiles could be fit approximately with a simple model in which the surface of the star is divided into two areal fractions. In one fraction (A_R) the bulk gas motions are assumed to be purely vertical (radial), with a Gaussian velocity dispersion ζ_R; in the other fraction (A_T, with $A_R + A_T = 1$), the gas flow is horizontal (tangential) and in the plane containing the line of sight, with Gaussian dispersion ζ_T. Usually, to reduce the number of free parameters, it is assumed that $A_R = A_T = 0.5$, and $\zeta_R = \zeta_T = \zeta_{RT}$. Thus in most modelling using the "radial-tangential macroturbulence" model, the single free parameter is the characteristic velocity dispersion of the bulk flow, ζ_{RT}. (For an example of modelling using these ideas, see Gray 1982.)

Essentially, modelling using the radial-tangential macroturbulence model provides two valuable pieces of information. First, a non-zero value of ζ_{RT} indicates that a relatively large-scale macroscopic velocity field has been detected in the star. Secondly, the value of ζ_{RT} provides a rough estimate of some characteristic velocity of this flow, although the level in the atmosphere which this velocity characterises is unclear. (In fact, Gray 1982 has suggested that different values of ζ_{RT} derived from weak and strong lines in G and K giants may characterise the velocity field at different optical depths.)

The variations of ζ_{RT} over the cool part of the HR diagramme (below $T_{\mathrm{e}} \sim 7000$ K) have been studied (they are summarized by Gray 1988). It is found that among main sequence stars ζ_{RT} declines from about 7 $\mathrm{km\,s^{-1}}$ among early F stars to only 1 or 2 $\mathrm{km\,s^{-1}}$at early K. Ib Supergiants range between 12–15 $\mathrm{km\,s^{-1}}$ for late F stars to about 8–10 $\mathrm{km\,s^{-1}}$ at mid-K. Intermediate luminosity classes fall between these two trends. A remarkable feature of the large values of ζ_{RT} found for supergiants is that the values are not far below the speed of sound in the atmospheres of these stars, as is also often the case for the microturbulence parameter ξ.

2.2. *Radial velocities*

Studies of the variations in radial velocity with line strength or depth were pioneered by Dravins (see Dravins 1999 for a useful review). The expected effect is certainly found. In both the Sun and in Procyon, which have been studied intensively, the weak lines are shifted blueward of the strong lines by a few hundred $\mathrm{m\,s^{-1}}$(Hamilton & Lester 1999; Allende Prieto, Asplund, López & Lambert 2002b). A larger sample, representing stars with spectral types between F5 and K2, with luminosity classes III – V, shows very similar behaviour (Allende Prieto, Lambert, Tull & MacQueen 2002a).

This phenomenon is rather difficult to study observationally, as very precise line wavelengths are required for a substantial sample of lines; recent work (Nave, Johanssen, Learner 1994) has provided an excellent reference framework for Fe I lines. The phenomenon of radial velocity shifts as a function of line strength has been observed in a number of cool stars, mainly of luminosity classes III – V (see especially Allende Prieto, Lambert, Tull & MacQueen 2002a), but has not been studied systematically over the HR diagramme.

2.3. *Bisector curvature*

Line asymmetries (bisector curvature) are also rather difficult to study observationally. Spectra need to be taken with a resolving power of more than about 10^5, and the signal-to-noise ratio needs to be of order $3\,10^2$ or more (although this last requirement can be reduced by suitably combining many line profiles together). The usual method of characterising the observations is to present graphically the variation with depth in one or many lines of the wavelength of the line bisector. For the Sun, such a graph has approximately the form of a "C", or perhaps a "(“, with the top and bottom of the bisector at longer wavelength than the middle. As discussed above, this is generally interpreted as revealing relatively bright, slow upflow over large areas (the granules), together with faster downflow in cooler, darker and smaller regions (the inter-granular network). Since the observed variation of radial velocity with depth traces the mean velocity shift of the line at various optical depths, it carries much the same information as the line bisector of a strong line (Hamilton & Lester 1999).

The shapes of line bisectors appear to vary fairly systematically over the cool half of the HR diagramme. Gray 2005 reports a large number of high-precision measurements and shows the variation with spectral type for cool stars. Bisectors for two cool metal-poor stars have also been published (Allende Prieto, García López, Lambert & Gustafsson 1999).

Perhaps the most surprising result of the study of bisectors was the discovery (Gray & Toner 1986, Dravins 1987, Gray & Nagel 1989, Gray 1989) that among hotter stars the bisectors are *reversed*: that is, the depressed wing is the short-wavelength wing rather than the long-wavelength wing as is found in G and K stars. The transition boundary (the "granulation boundary") separating one form from the other in the HR diagramme runs from about F0 V on the main sequence to about G1 Ib among supergiants. An obvious interpretation of this discovery is that the nature of the atmospheric convection pattern in stars on the hotter side of the granulation boundary is qualitatively different in form from that prevailing on the cool side of the boundary: it seems to be a convection in which most of the observed spectral line is formed in a slow, cool downflow, with a minor contribution from a more rapid upflow that is confined to a smaller areal fraction of the surface.

This surprising result has been confirmed and extended on the main sequence (Landstreet 1998). The main difficulty in studying bisector shape above F0 V is the generally rapid rotation of A and B stars, but among the very small number of sufficiently sharp-lined stars studied, it is found that reversed bisectors occur up to about A0 V ($T_\mathrm{e} \sim 10500$ K). Late B stars show no sign of bisector curvature at all, a result that is not surprising, as atmosphere models for temperatures somewhat above 10500 K are stable (or nearly so) according to the Schwarzschild criterion, while main sequence atmospheres below this temperature have significant unstable regions above $\tau \sim 1$ (Landstreet 1998).

Pioneering work on empirical modelling of bisector shapes with parametrized flows (Dravins 1990) has supported the qualitative interpretation of bisector curvature discussed above. Dravins used a model with two kinds of hot vertical upflows, stationary neutral areas, and cool downflows, each with a height-independent velocity, to model bisectors in several stars for which he had obtained very high quality line profiles. His best fits suggest that indeed the solar type of bisectors reveal slow, hot upflows over with relatively large areal coverage, together with more confined, rapid downflows. The reversed bisector of hotter stars appear to have a flow structure reversed from this pattern, with rapidly rising granules covering only a small areal fraction.

3. Recent advances

3.1. *Multi-parameter granulation models of observed line profiles*

An important recent development has been more elaborate empirical modelling of all available characteristics of several line profiles simultaneously. Although even multiparameter models are only quite approximate descriptions of the actual visible flows, such models are quick enough to compute that they allow one to consider easily such questions as the amount of information contained in a particular set of observations, and the uniqueness (or not) of various types of models that fit the data. Two very interesting examples of this approach concern solar granulation (studied as a test case) and the photospheric convection of the G2 IV and K1 V stars α Cen A and B (Frutiger, Solanki, Fligge & Bruls 2000; Frutiger, Solanki & Mathys 2005). These authors have used multi-component granulation models with coarse depth-dependence of flow speeds. The resulting models show flows rather similar to those observed more directly on the Sun, with granulation patterns similar to the solar pattern, and flow velocities that decrease with height in the atmospheres. The models also yield a semi-empirical temperature structure for each flow component. The fits to the observed spectral lines from which the models are derived are impressive, but the question of uniqueness is not discussed in detail.

3.2. *3D numerical hydrodynamical models*

Another very important approach to studying the information about photospheric convective flows, pioneered by Nordlund and Dravins, has been to compare observed line profiles with those predicted from relaxed 3D hydrodynamic calculations of the detailed velocity fields in numerically modelled stellar surface regions (Nordlund & Dravins 1990; Dravins & Nordlund 1990a; Dravins & Nordlund 1990b). Such models are of course much more physically realistic than simple parametrized “geometric” models based on hydrostatic 1D atmospheres. The 3D hydrodynamical models replace the parameters (such as macroturbulence, microturbulence, areal coverages, etc.), which one hopes will describe the photospheric flows approximately, with a much more realistic description of the actual flow, including inhomogeneous rising and falling streams of a variety of sizes and speeds that satisfy the (approximate) equations of mass, momentum, and energy conservation as well as of radiative transfer.

Such numerical models are however very difficult to compute, even with current computing power. Limited memory results in turn in limited spatial resolution (typical computation grids have at most a few hundred grid points along each dimension) which in turn requires assumptions about subgrid phenomena such as eddy decay and viscosity. Radiative transfer occurs in all directions, and couples grid points that are far from one another. In practice, only a limited number of directions and wavelengths can be considered; and sometimes radiative transfer is limited to the gray approximation. In a stratified gas, the time and length scales may be quite different at the top and bottom of the computational volume.The initial assumed gross structure may not be close to the final relaxed state, and the computing time required to relax the initial model may be very large. All of these difficulties mean that such 3D models can realistically only be computed for a few specific cases at present. Nevertheless they are very illuminating, and several such models that have been compared with observed line profiles have been published recently.

Hydrodynamic 3D models of two metal-poor stars have been computed (Asplund & García Pérez 2001), primarily to study the effects of convection on the temperature stratification in the photosphere of these stars. These models were computed using a detailed equation of state, assuming LTE and employing opacity binning for the radiative transfer. In 3D, the temperature in the outer atmosphere is determined by a competition between adiabatic cooling, and heating by line absorption of continuum radiation emitted at $\tau \sim 1$. The result is then that the outer atmosphere of a metal-poor star, with less line absorption, is cooler than the outer layers of a star of the same $T_{\rm e}$ value but solar metallicity. This effect potentially provides another means of observing consequences of convection, through the effects on the observed ionization balance, but it may also be necessary to consider non-LTE effects or the detailed effects of atmospheric velocity gradients on local heating. The authors report that the computed line bisectors agree reasonably with observed bisectors of the stars modelled.

A detailed model of Procyon A (α CMi) has been computed (Allende Prieto, Asplund, López & Lambert 2002b) using the same computer code that was employed for the Sun and stellar granulation (Stein & Nordlund 1998; Asplund & García Pérez 2001). The computational grid is 13 Mm deep, with about 3 Mm in the observable atmosphere. The resulting line profiles are compared both to the observed profiles and to profiles computed from a hydrostatic 1D model (for which both microturbulence and macroturbulence parameters were fit). The agreement of lines predicted by the 3D model with observed lines is several times better than the agreement of the best 1D model with observations, even though this latter model is already rather good. This certainly suggests that the 3D hydrodynamic model captures many essential features of the actual stellar convection.

A second hydrodynamic code ("CO^{5}BOLD") has been developed which not only has the capability to model a convecting slab near the surface of a star, but can even model the hydrodynamic behaviour of an entire star in a cubic mesh ("star-in-a-box"), although at present with only about 200 mesh points in each dimension. This code has been used to model the large-scale convective behaviour of the M2 supergiant Betelgeuse (α Ori; Freytag, Steffen & Dorch 2002). In agreement with interferometric images and the hypothesis (Schwarzschild 1975) of giant convection cells, the best model reported so far is indeed dominated by a few giant cells, with a stochastically varying spottedness and integrated surface brightness.

The same CO^{5}BOLD code has been used to produce models of mid-A stars (Steffen, Freytag & Ludwig 2005). These models have been aimed particularly at studying the interaction between the H + He I and He II convection zones, but synthetic line profiles of one red Fe I line have been produced. Although the span of the computed bisector is similar to that observed in such stars (Landstreet 1998), the models predict bisectors curved in the same sense as the solar bisectors instead of the reversed bisectors actually observed. The physical origin of the reversed bisectors remains elusive.

One might be tempted to think that with the advent of 3D models, the usefulness of simple parametrized models is at an end. In my opinion, we are still some years from a situation in which the 3D models reproduce observational data over the whole HR diagramme; at present their success is largely limited to the lower main sequence. In addition, the parameters of the simple models describe a very large sample of stars, much larger than is likely to be modelled in detail in the near future. Parameters such as ξ and ζ_{RT} may be expected to continue to be useful for statistical studies, and for identifying particularly interesting objects for detailed study, for some years to come.

3.3. *Other observational consequences of convection*

Simple, idealized geometrical models of single convection cells tiled over the stellar surface, and full 3D hydrodynamical simulations, represent two possible descriptions of convection that may be compared with observations. Another class of descriptions available is drawn from the mixing-length theory and its extensions to full-spectrum turbulence models and to non-local models based on moment equations (e.g. Kupka & Montgomery 2002; Montalbán, D'Antona, Kupka & Heiter 2004). Such models are attractive because they are based on physical principles (which the simple geometrical descriptions are not), but require enormously less computational effort than full numerical simulations, and thus are used extensively in, for example, stellar evolution computations. These models generally predict a characteristic convective velocity as a function of position in the convective region (and for the non-local models, in the overshoot region as well). The non-local models go farther, and may predict velocity dispersions and kinetic energy fluxes (and thus areal fractions of rising and descending streams).

One way to compare such models to observations is to see if they predict convective velocities in the lower photosphere that are of the same order of magnitude as bisector spans, or microturbulent or macroturbulent velocity parameters. A series of models of A star envelopes (Kupka & Montgomery 2002) provides an example of such a comparison; in this case, it is found that the non-local theory gives photospheric velocities of about the right size, while the mixing-length theory (when the mixing length parameter is tuned to give the correct flux) predicts velocities that are much too small. It is also found that the kinetic energy flux in the photosphere is positive (outward), suggesting that the filling factor for upward gas movements is less than 1/2, in apparent agreement with the observations discussed above.

Comparisons may also be carried out between such convection models and other aspects of a stellar energy distribution, because different convection theories lead to changes in the temperature and density stratification in the visible atmosphere. The effects of various descriptions of convection on Strømgren *uvby* colours have been calculated for several convection models (Smalley & Kupka 1997), and it is found that different models give results which are different enough from one another that this kind of comparison provides a valuable test of convective models. Similarly, the effects of various convection models on Balmer line profiles (Gardiner, Kupka & Smalley 1999) also provides a useful discriminant among models.

4. Conclusions

Stellar photospheric velocity fields are clearly detectable in the line spectra of many stars through such effects as microturbulence, macroturbulence, and bisector curvature. These velocity fields also appear to have detectable effects on stellar energy distributions and H line profiles.

The behaviour of the various model parameters used to describe these effects has been partially mapped over the HR diagramme. In temperature ranges where the parameters are non-zero, they tend to increase from modest values on the main sequence to surprisingly large values for supergiants. There are also regions (e.g. late B main sequence stars) where the atmospheres appear to be quiescent.

Modelling of the observable symptoms of atmospheric convection is presently proceeding on a variety of fronts, including determination of simple model parameters, more comprehensive empirical characterisation of flows, numerical 3D simulations without any free parameters for the velocity field, and models such as non-local extensions of the mixing length description. We can look forward to a continually expanding body of knowledge about the visible manifestations of convection in stars.

Acknowledgements

I acknowledge ongoing and generous support from the Natural Sciences and Engineering Research Council of Canada.

References

Allende Prieto, C., Asplund, M., García López, R. J. & Lambert, D. L. 2002, *ApJ* 567, 544
Allende Prieto, C., Lambert, D. L., Tull, R. G. & MacQueen, P. J. 2002, *ApJ* 566, L93
Allende Prieto, C., García López, R. J., Lambert, D. L. & Gustafsson, B. 1999, *ApJ* 526, 1000
Asplund, M. & García Pérez 2001, *A&A* 372, 601
Asplund, M., Nordlund, Å., Trampedach, R. & Stein, R. F. 1999, *A&A* 346, L17
Dravins, D. 1987, *A&A* 172, 211

Dravins, D. 1990, *A&A* 228, 218

Dravins, D. 1999, in J. B.Hearnshaw & C. D. Scarfe (eds.), *Precise Stellar Radial Velocities*, ASP Conference Series, Vol. 185, p. 268

Dravins, D. & Nordlund, Å. 1990a, *A&A* 228, 184

Dravins, D. & Nordlund, Å. 1990b, *A&A* 228, 203

Fitzpatrick, E. L. & Massa, D. 1999, *ApJ* 525, 1011

Freytag, B., Steffen, M. & Dorch, B. 2002, *AN* 323, 213

Frutiger, C., Solanki, S. K., Fligge, M. & Bruls, J. H. M. J. 2000, *A&A* 358, 1109

Frutiger, C., Solanki, S. K. & Mathys, G. 2005, *A&A* 444, 549

Gardiner, R. B., Kupka, F. & Smalley, B. 1999, *A&A* 347, 876

Gies, D. R. & Lambert, D. L. 1992, *ApJ* 387, 673

Gray, D. F. 1982, *ApJ* 262, 682

Gray, D. F. 1988, *Lectures on Spectral-line Analysis: F, G and K Stars* (Arva, ON, Canada: The Publisher)

Gray, D. F. 1989, *PASP* 101, 832

Gray, D. F. 2005, *PASP* 117, 711

Gray, D. F. & Toner, C. G. 1986, *PASP* 98, 499

Gray, D. F. & Nagel, T. 1989, *ApJ* 341, 421

Hamilton, D. & Lester, J. B. 1999, *PASP* 111, 1132

Hill, G. M. 1995, *A&A* 294, 536

Kupka, F. & Montgomery, M. H. 2002, *MNRAS* 330, L6

Landstreet, J. D. 1998, *A&A* 338, 1041

Lyubimkov, L. S., Rostopchin, S. I. & Lambert, D. L. 2004, *MNRAS* 351, 745

Montalbán, J., D'Antona, F., Kupka, F. & Heiter, U. 2004, *A&A* 416, 1081

Nave, G, Johanssen, S., Learner, R. C. M., Thorne, A. P. & Brault, J. W. 1994, *ApJS* 94, 221

Nordlund, Å., & Dravins, D. 1990, *A&A* 228, 155

Schwarzschild, M. 1975, *ApJ* 195, 137

Smalley, B. & Kupka, F. 1997, *A&A* 328, 349

Steffen, M., Freytag, B. & Ludwig, H.-G. 2005, in F. Favata *et al.* (eds.), *Proceedings 13th Cool Star Workshop*, in press

Stein, R. F. & Nordlund, Å. 1998, *ApJ* 499, 914

Struve, O. & Elvey, C. T. 1934, *ApJ* 79, 409

Varenne, O. & Monier, R. 1999, *A&A* 351, 247

Discussion

Myron Smith: With regard to line bisector in B stars there are two empirical problems in assessing them:

(*a*) as you mentioned, effects of non-radial pulsations are commonly present in the line profiles, so if one looks at a single snapshot in time one can't be too sure of the physical diagnosis.

(*b*) line profile bisector distortions are actually amplified by rotation, so in comparing their effects among different spectral classes one has to be careful to compare stars with like rotational velocities (hopefully near zero!).

John Landstreet: Yes, it seems clear that interpreting line profiles in hot stars requires consideration of a number of possible velocity fields. This may be behind the presently rather incoherent situation one observes.

Juri Toomre: What types of flows do you imagine contribute to macroturbulence - streaming flow, differential rotation?

John Landstreet: To be visible as macroturbulence, it is necessary for a velocity field to have a characteristic velocity of at least a couple of km s^{-1}. A differential rotation pattern with a velocity difference of this magnitude between, say, equator and mid-latitudes, would complete one extra rotation in the faster region in less than one month. This is an order of magnitude faster than the solar differential rotation, so only a pretty rapid differential rotation could be detected in this way. My own guess would be that macroturbulence might be more like solar supergranulation, or perhaps even like granulation, which does occur on a scale comparable to the thickness of one optical depth in the atmosphere.

Bob Stein: Martin Asplund has compared Fe line profiles from 3D convection simulations with observed solar profiles and gets excellent fits without any micro- or macroturbulence. These simulations had no large scale flows or meridional circulation, so that clearly the macroturbulence is due only to the granule flows which are on scales larger than the scale height. Mats Carlsson and Øystein Langansen have observed Fe line bisectors in the quiet sun and compared with bisectors calculated from both non-magnetic convection and plage convection simulations. There is excellent agreement between the quiet sun and non-magnetic simulations, while line bisectors for the plage simulation are shifted by a few hundred m/s.