STELLAR GRANULATION AND PHOTOSPHERIC LINE ASYMMETRIES

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ABSTRACT. The fine structure of stellar photospheric convection (the stellar equivalent of solar granulation) can be analyzed with the aid of high-resolution spectroscopy. Photospheric absorption lines are slightly asymmetric and wavelength-shifted due to unequal photon contributions from bright and systematically Doppler-shifted granules and from darker intergranular areas. Numerical simulations of stellar surface convection in different stars have now been carried out, and such three-dimensional and time-dependent models predict the detailed stellar line profiles (including asymmetries and wavelength shifts), thus enabling a direct confrontation between observations and theory.

1. WHY STUDY STELLAR GRANULATION?

The study of stellar granulation, physical processes in stellar convection, and the ensuing inhomogeneities on stellar surfaces has considerable potential not only for the analysis of stellar atmospheres *per se*, but also in applications for other astrophysical problems. Examples of relevant topics are:

- Structure of stellar surfaces. How do stars look like? One very important goal for stellar astrophysics is to obtain high resolution images of stellar surfaces, to ultimately enable studies of stars as surface objects. Until such images are available, one should at least deduce the statistical properties of stellar surface features.

- Physical processes in stellar convection. Convection is a central but poorly understood parameter in the construction of stellar models and the determination of stellar ages, influencing both the energy transport through the atmosphere, and the replenishment of nuclear fuels in the core. What is the validity (if any) of the classical 'mixing-length' concept and other approximations in stellar atmosphere theory?

- Spectral line broadening. The understanding of small-scale motions in stellar photospheres will elucidate the mechanisms of spectral line

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broadening and show the relation (if any) to the classical 'micro-' and 'macro-turbulence' parameters.

- Accurate radial velocities. Since photospheric spectral lines are asymmetric and wavelength shifted due to unequal photon contributions from rising and sinking elements, spectroscopic determinations of stellar motions require a correction for granulation effects if accuracies much better than 1 km/s are required. Such effects constrain studies of e.g. the velocity dispersion in open galactic clusters.

- Radial velocity variations. Activity-cycle variations may modulate the structure of stellar granulation analogous to what is seen on the Sun during its 11-year activity cycle. Such variations may change somewhat the asymmetry of photospheric lines and thus mimic e.g. radial velocity variations expected from the star's motion in conjunction with a low-mass companion.

- Stellar photometric variability. The finite number of evolving granules on a stellar surface induces photometric variability in integrated starlight, and sets physical limits to the interpretation of very accurate stellar photometry. This may complicate critical photometric tasks such as the identification of planetary transits across stellar disks.

- Accurate abundance determinations. Models that assume homogeneous photospheres may yield inaccurate abundances. This will result from the circumstance that the population of a particular atomic or molecular species in a certain stage of excitation or ionization is a nonlinear function of temperature, and hence an atmosphere with temperature fluctuations will produce lines of different strength than an atmosphere without such fluctuations. Further, there may well be real abundance inhomogeneities across a normal star, where molecules dissociate in the hotter regions. Significant effects may be expected for lines of high excitation potential and for molecular ones.

- Magnetic flux density in stellar photospheres. Irrespective of how stellar magnetic fields originate, their flux density at the surface will be strongly dependent on the horizontal velocity fields and the associated horizontal pressure fluctuations in stellar granulation. These constrain the magnetic flux density to which magnetic fields can be compressed in the photosphere. Knowledge of magnetic flux densities is a prerequisite for further analysis of e.g. magnetohydrodynamic wave generation and propagation into higher atmospheric layers.

- Acoustic energy flux. The motions in stellar granulation generate pressure waves with probable effects both above and beneath the photosphere. In higher layers one may expect acoustic waves to dissipate, thus contributing to e.g. chromospheric heating. In deeper layers one should expect an interaction with large-scale oscillations, perhaps even global pressure modes.

- Comparisons to solar granulation. Last (but perhaps not least), studies of stellar granulation enable comparisons to be made with the much-studied solar counterpart. Credible theories of solar granulation should be able to predict not only observed solar properties, but also those of other (at least solar-type) stars.

2. HOW TO DETECT STELLAR GRANULATION?

Since, at the present time, it is not yet possible to obtain high spatial resolution images and spectra of stellar surfaces, we have to rely on more indirect methods to detect effects of stellar granulation. The visibility of solar granulation in integrated sunlight (the Sun seen as a star) gives a first indication of the magnitude of the effects likely to be encountered in other stars. A number of different methods should allow one to observe effects of stellar granulation:

- Photospheric line asymmetries. The different amplitudes and area coverages of upward and downward atmospheric motions, coupled with the correlation between photospheric temperature (brightness) and the sign of vertical motion (hot elements are rising) cause an intrinsic asymmetry of photospheric absorption lines. Such asymmetries are perhaps best described by the line bisector (median), which shows the apparent radial velocity at each depth in the line. For integrated sunlight, the amplitude of this bisector corresponds to some 200 m/s, only some percent of the line-width. Consequently, very high resolution observations of unblended lines are required to reveal these effects. The bisector shapes differ for lines of different parameters, reflecting different conditions and heights of formation. The asymmetries depend in particular on line strength, excitation potential, and ionization level.

- Photospheric line wavelength shifts. This has proven to be a useful tool for solar studies, although its stellar application is somewhat more complicated. The larger and brighter ascending granules give a slightly larger photon contribution than the darker and smaller intergranular lanes. This statistical bias of blueshifted photons causes a convective blueshift such that the wavelengths of solar lines (after corrections for solar motion and gravitational redshift) are slightly shorter than the corresponding laboratory values. The magnitude of this effect depends on the line parameters but is typically some 300 m/s or a few percent of the line-width. To study differential apparent radial velocities among lines of different parameters in one star requires high-quality spectra, a very accurate stellar wavelength calibration, and accurate laboratory wavelengths. For a determination of the absolute value of such convective lineshifts, the true stellar radial motion must also be known, as well as its gravitational redshift.

- Time variability of photometric irradiance. The finite number of granules on a stellar surface implies that random changes in the granulation structure will be accompanied by some finite change in the integral properties of the star, such as its bolometric irradiance.

In the solar case, with ≃ 20% intensity contrast per granule, and assuming all granules independent, the variability in integrated sunlight should be roughly this number divided by the square root of the number of solar granules (≃ 10^6), which comes out to a few times 10^{-4}. Such variations are observable from space and have probably already been measured as part of the variations of solar irradiance, although not yet conclusively identified as granular in origin. In giant stars, the increased pressure scale heights may cause there to be only a modest number of granules on the stellar surface, and the resulting effects from their time evolution could be greater. Such irradiance fluctuations might well be correlated with line-profile changes and could also include polarization effects.

- Interferometric imaging of stellar surfaces. The disks of a few giant stars can be resolved already with existing large telescopes or interferometers. Since convection cells on some giant stars might subtend a significant fraction of a stellar diameter, their spectral features should soon be detectable through e.g. speckle spectroscopy. Solar-type granules, however, have sizes only about one thousandth of the solar diameter, and their imaging requires optical baselines a thousand times longer than those required to resolve the stellar disk. To achieve this might require space-based interferometers and remains an interesting challenge for the future.

A more detailed discussion of different plausible schemes to detect stellar granulation is in Dravins (1987a). For a general review of in particular solar granulation signatures in the spectrum of integrated sunlight, see Dravins (1982). Solar granulation is reviewed in the monograph by Bray et al. (1984).

Among these different schemes to detect stellar granulation, the most promising seems to be the study of photospheric line asymmetries. In spectra of very high photometric quality and a spectral resolution $\lambda/\Delta\lambda$ at least about 100,000, the signature of (at least solar amplitude) granulation will appear. Such studies of line asymmetries indeed form the current basis for analysis of stellar granulation.

3. STELLAR PHOTOSPHERIC LINE ASYMMETRIES

A fair number of stars has now been observed for photospheric line asymmetries by different authors, revealing considerable asymmetry changes across the Hertzsprung-Russell diagram. The asymmetry of typical solar lines is characterized by a bisector in the shape of the letter 'C' (in spectral plots with wavelength increasing to the right), i.e. the middle part of the line is somewhat blueshifted relative to its top and bottom portions. Gray (1980) identified the sense of line asymmetry in the K giant Arcturus to be opposite that in the Sun, and similar lineshapes in other cool giants were seen by Ridgway and Friel (1981). In a survey of F, G, and K stars, Gray (1982) found line asymmetries to be generally present. More detailed lineshape observations for several stars are in Dravins (1987b). Particularly large asymmetries (with the asymmetry opposite to the Sun's) are seen in F giants (Gray and Toner 1986; Dravins 1987b).

To reliably measure these subtle line asymmetries requires a good understanding of the instrumental profile in the spectrometer, a careful selection of as unblended lines as possible, and (in general) an averaging over several lines to take away residual noise. In Figures 1 - 2, examples of line asymmetry patterns are shown for two G2 V stars: the Sun (central main sequence) and α Cen A (upper main sequence).

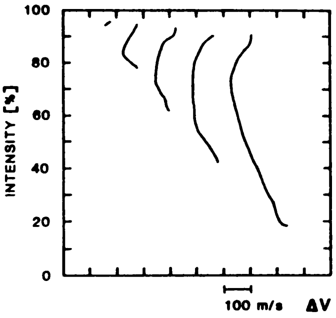

Figure 1. A signature of solar granulation in integrated sunlight. Each curve is the average of bisectors for Fe I absorption lines, grouped according to line-depth. Intensity is in units of the spectral continuum (100%) while wavelength increases to the right. Adopted from Dravins et al. (1981).

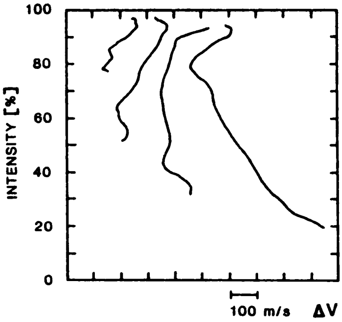

Figure 2. Bisectors for differently strong Fe I lines in α Cen A (G2 V), recorded with the coudé echelle spectrometer of ESO at La Silla using a double-pass scanner mode at spectral resolution λ/Δλ ≈ 200,000 (Dravins, 1987b). Although generally similar to the Sun, there is a clear difference in bisector slope for the strongest lines.

4. NUMERICAL SIMULATIONS OF STELLAR GRANULATION

Numerical supercomputer simulations of stellar surface convection in different stars have now been carried out (Nordlund and Dravins, 1988). These time-dependent models of the 3-dimensional, radiation-coupled compressible convection contain only three free physical parameters: effective temperature, stellar surface gravity, and chemical abundance. The models are stepped forward in time to reveal the properties of the convective elements (granules) in stellar photospheres: their sizes, the patterns in their gas flows, and their time evolution. These models are based upon the experience from the solar case (e.g. Nordlund 1985a), and have been completed for four different non-solar cases: $T_{eff} = 6600$ K, corresponding to Procyon (F5 IV-V); $T_{eff} = 5800$ K, one half solar surface gravity, corresponding to α Cen A; $T_{eff} = 5800$ K, one quarter solar surface gravity, corresponding to β Hyi (G2 IV), and $T_{eff} = 5200$ K, corresponding to α Cen B (K1 V).

By using these models as a set of spatially and temporally varying model atmospheres, synthetic spectral line profiles have been computed as averages over the simulation sequence (Dravins and Nordlund, 1988), analogous to previous solar work (Dravins et al., 1981, 1986). These profiles do *not* contain any arbitrary fitting parameters such as 'micro-' or 'macro-turbulence' and can thus be directly compared to observations to verify the degree of realism in the models. There is a very satisfactory agreement concerning the line asymmetry patterns in α Cen A and Procyon (the only stars for which extensive high-quality observations are available). For example, the large bisector curvature in α Cen A is predicted for the deepest lines only, as observed in Figure 2. Compared to the Sun, this effect can be traced back to the larger velocity amplitudes that develop on α Cen A due to its lower surface gravity. Such examples demonstrate the sensitivity of line asymmetries to minute changes in stellar atmospheric structure.

Other theoretical granulation models, including spectral line synthesis for both solar and non-solar conditions, are being pursued by a number of other authors, e.g. Steffen (1987). Besides more detailed simulations, there is a strong need for simpler parametrized models in order to understand basic properties in stars of spectral types that are not yet accessible to detailed modelling, to give guidance to observers as to what types of effects to look for, and also to give a connection to classical stellar model atmospheres (involving fitting parameters such as 'mixing-length', 'turbulence', etc.). Such work is being pursued by several authors.

5. OUTSTANDING PROBLEMS

New methods have now made stellar surface structure accessible to detailed observational and theoretical investigation. However, none of these methods is trivial. As can be seen in numerical experiments of gradually degrading the spectral resolution of solar spectra, already a spectral resolution $\lambda/\Delta\lambda$ = 100,000 (a resolution often considered 'high') is actually only marginally adequate to permit meaningful studies of bisector shapes in normal stars (Livingston and Huang, 1986; Dravins, 1987a). Rather, a resolution of 200,000 or 300,000 or even more is desirable to analyze line asymmetry patterns in different types of spectral lines. The numerical simulations of granulation predict a series of line asymmetry and wavelength shift phenomena in different stars (as function of excitation potential, wavelength region, etc.) that are beyond current observational capability, and that probably will require such resolutions for reliable detection. An ideal instrument should combine this very high resolution with a very low straylight level, a very high wavelength accuracy, and an extended spectral coverage. For brighter stars, such an instrument would by far not be limited by the photon flux collected by any reasonable telescope, but rather by inefficiencies in the spectrometer. Since neither current double-pass spectrometer scanners, nor Fourier transform spectrometers appear to give adequate performance, this remains an important instrumental and observational challenge for the future.

Current theoretical models suffer limitations in particular due to the physical approximations enforced by the finite computing power available. Future models should not be limited to a small volume near the stellar surface, but rather embrace a large fraction of the star. Computer codes that allow waves to propagate should allow an examination of e.g. the interaction between events in the granulation and excitation of large-scale pressure waves. Granulation in chromospherically active stars and in stellar active regions will further require inclusion of effects from magnetic fields (Nordlund, 1985b). This probably will require computations to be carried out to smaller spatial scales than in the non-magnetic case. Since already some of the present models need several tens of supercomputer hours for each run, the inclusion of all desired parameters seems difficult as a simple extrapolation of present methods. Either vastly more efficient algorithms are to be found, or computing power is to be enhanced by many orders of magnitude. Possibly, the most promising way to achieve such increased performance would be to use novel computer architecture, custom-designed for the stellar convection problem.

ACKNOWLEDGEMENT

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DISCUSSION

MARCY How are your models affected by the lack of magnetic fields, especially those between the granules ?

DRAVINS Such effects can be studied on the Sun : granulation in active regions (in so-called plage or facular areas) is penetrated by magnetic fields which are largely concentrated to inter-granular regions. In such regions, the photospheric line asymmetries are indeed different from those in quiet areas. For solar levels of activity, however, the area coverage of such active regions is small enough not to influence the average line profile very much : it is a second-order effect. Nevertheless, the periodic variation of active region area coverage over a stellar activity cycle is likely to induce a periodic variation in line profile parameters that might mimic the expected periodic radial velocity variation induced by an extrasolar planet. High-activity stars might be dominated by magnetic regions, and the study of convection in magnetic fields will probably be required to understand their photospheric line profiles. Some theoretical work has been done for solar conditions by Nordlund, but the stellar area is unexplored as yet.

VOGT From your detailed simulations, will you now be able to give those of us who do line profile synthesis a better parameterization for micro and macroturbulence ?

DRAVINS One of the aims of the detailed simulations is indeed to understand which parameters are important for simpler line profile modelling, and what relation there is between deduced 'turbulence' parameters and physical gas velocities in the stellar atmosphere. This work is in progress.

APPENZELLER You correctly stressed that your method avoids arbitrary and unphysical assumptions. However, does not the limited volume (of the star) which can be handled by the computer restrict the manifold of solutions which you can obtain, excluding e.g. all effects having large scales, such as larger scale motions or effects of global oscillations ?

DRAVINS Yes, the present simulations cover only a small volume near the stellar surface. A long-term goal is indeed to have models that embrace the entire star, and include processes such as wave generation and dissipation. With such models one should ultimately be capable of studying e.g. the excitation of global oscillations by events in the convective motions. The present simulations aim at understanding the origin of photospheric line profiles for solar-type stars. As observed on the Sun, the most significant line fluctuations occur on granular scales, and these are the only ones presently modelled.

RUTTEN I want to rephrase Appenzeller's question. Of course, while your simulations are free of fudge parameters as turbulence and mixing length, they do contain implicit limitations on which the results may sensitively depend. Apart from the neglect of waves and magnetic field that you mentioned, there are intricate assumptions in the radiative transfer that we perhaps shouldn't go into here, and there is the important choice of your Fourier grid. With regard to the solar simulation the comment has been raised that its largest scale is yet too small, effectively forcing all of the mechanical energy flux to flow upward at granular scales, so that the computed granulation is too vigorous.

Now, how did you select the largest scale or smallest spatial frequency of the stellar grids ? And can you test whether it is sufficient ?

DRAVINS The present computations were made for a spatial grid of 32x32 Fourier coefficients on the stellar surface. Scaled to solar conditions, these cover linear scales between approximately 100-3000 km. This range was chosen to correspond to granular features as observed on the Sun. For a given stellar luminosity and surface gravity, there will be one characteristic scale of granulation, constrained by energy considerations (too small granules would not transport enough energy ; too large granules would break apart under their own pressure). This scale can be roughly estimated for modest departures from solar conditions but, due to the complexity of the problem, such estimates become very uncertain elsewhere in the Hertzsprung-Russell diagram. This is one of the main reasons why the present simulations have been carried out for solar-type stars only. There is no known reason why the present computer programs could not be applied also for other stars, if only the computing power was available. The present 32x32 resolution is a significant improvement over the early solar work with 16x16 resolution (Dravins, Lindegren and Nordlund, 1981), but significant increases in this resolution become very expensive in computing time due to the four-dimensional nature of the problem (3-dimensional space, and time).

The crucial test of whether the models are adequate comes from comparisons with observed line profiles, asymmetries, and wavelength shifts. Taken together, these form very sensitive tools for segregating different types of granular motion. Of particular interest would be the availability of very accurate wavelength measurements for stellar lines : a parameter that hitherto has been lacking.