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Stellar Surface Convection, Line Asymmetries, and Wavelength Shifts

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Abstract. Wavelength positions of photospheric absorption lines may be affected by surface convection (stellar granulation). Asymmetries and wavelength shifts originate from correlated velocity and brightness patterns: rising (blueshifted) elements are hot (bright), and convective blueshifts result from a larger contribution of such blueshifted photons than of redshifted ones from the sinking and cooler (darker) gas. For the Sun, the effect is around 300 m s^{-1}, expected to increase in F-type stars, and in giants. Magnetic fields affect convection and induce lineshift variations over stellar activity cycles. A sufficient measuring precision reveals also the temporal variability of line wavelengths (due to the evolution of granules on the stellar surface). A major future development to come from adaptive optics and optical interferometry will be the study of wavelength variations across spatially resolved stars, together with their spatially resolved time variability. Thus, precise radial velocities should soon open up new vistas in stellar atmospheric physics.

1. Solar Line Asymmetries and Shifts

The only star whose surface can be observed in any detail is the Sun. In visual light, its surface is characterized by the granulation pattern of convective features, intermingled with occasional dark spots. Sunspots, however, occupy only a very small fraction of the surface and (being dark) contribute only negligibly to the shape of ordinary absorption lines in integrated sunlight. For a review of solar granulation, see Spruit, Nordlund, & Title (1990).

The (spatially resolved) spectrum of solar granulation is characterized by "wiggly" spectral lines, i.e. the line wavelength undulates back and forth between bright granules and dark intergranular lanes. Granules correlate with local blueshifts (rising motion), and intergranular lanes with local redshifts (sinking motion), as naturally expected in convective energy transfer. Since the spatial scale of granulation falls close to telescopic angular resolutions, the observed velocity amplitudes depend sensitively on the resolution achieved, but may well reach 2 km s^{-1}. For observed differences between spectra from granular and intergranular regions, see Kiselman (1994); the effect of finite spatial resolution is illustrated by Lites, Nordlund, & Scharmer (1989).

When averaged over the solar surface, a net wavelength shift results from the statistical bias of a larger photon contribution from bright and blueshifted areas. Photospheric absorption lines generally become distorted and asymmet-

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ric, their central positions wavelength shifted relative to the case of a static atmosphere. This convective shift is an order of magnitude smaller than the full velocity amplitude, reaching some 300 m s^{-1} in typical photospheric lines. The exact amount depends on precisely how the shift is defined for the asymmetric line profile, and differs among lines with different conditions of formation. For example, high-excitation lines may form predominantly in the hottest (also the most rapidly rising, and most blueshifted) elements, and thus show a more pronounced blueshift.

For an introductions to observed solar line asymmetries and shifts, see Dravins (1982). Wavelength shifts for lines in the visual have been studied by Allende Prieto & García López (1998), Dravins, Lindegren, & Nordlund (1981), and Dravins, Larsson, & Nordlund (1986). Infrared lines were analyzed by Hamilton & Lester (1998), Nadeau (1988) and Puschmann, Hanslmeier, & Solanki (1995). The atmospheric opacity reaches a minimum around 1.65 μm, and in such regions one may expect to see signatures of deeper granulation layers, even if the diminished granulation contrast in the infrared does not lead to increased amounts of shift.

The greatest blueshifts are generally observed for weak lines, formed deep into the atmosphere, where solar convective motions are more vigorous. Strong lines form at higher layers, and show smaller shifts. Lines formed in the very uppermost photosphere begin to form in regions of convective overshoot, i.e. regions where the gases continue in the same direction of motion as deeper down, although they have already cooled off. An interplay between cooling and heating through radiation and adiabatic expansion and compression causes the rising elements to become locally cooler than the sinking ones, and the net convective flux (although small) is here directed downwards, i.e. into the Sun (Stein & Nordlund 1989). Lines forming in these regions therefore show an inverse correlation between brightness and local lineshift, resulting in a convective redshift. In the visual, this inverse correlation appears near the bottoms of the very strongest absorption lines (e.g. the flanks of Ca II K), and apparently is the cause of redshifts for lines in the ultraviolet (Samain 1991). The same inverse brightness correlation appears in the far infrared (Kiselman & Nordlund 1995).

It must be stressed that the "wavelength" of an asymmetric spectral line is not a uniquely determined quantity. Its exact value depends on the precise definition used (Neckel & Labs 1990) and on the spectral resolution achieved (Dravins 1987a; Dravins & Nordlund 1990b). It also changes with the velocity of stellar rotation, including the angle under which a given star is observed. Further, the deduced wavelength shifts depend on the corresponding laboratory values. Their accurate determination also has limitations, especially for weak lines, high-excitation ones, lines in the infrared, and such from ionized species. Therefore, different laboratory data sets may show systematic differences, as illustrated for lines in the infrared by Nadeau (1988). And finally, it should not be forgotten that wavelengths in the spectrum of the solar disk center are systematically different from those at other center-to-limb positions, as well as from those in integrated sunlight.

2. Stellar Line Asymmetries and Shifts

When observed under sufficient resolution, practically all stellar spectral lines prove to be slightly asymmetric. As in the Sun, absorption lines in cooler stars form in inhomogeneous atmospheres, affected by surface convection.

A new generation of stellar model atmospheres is now able to model stellar granulation structure, and its time evolution (Atroshchenko & Gadun 1994; Dravins et al. 1993; Freytag, Ludwig & Steffen 1996; Freytag & Steffen 1995; Ludwig, Jordan & Steffen 1994; Nordlund 1985; Nordlund & Dravins 1990; Spruit et al. 1990; Stein & Nordlund 1989, 1998).

Line asymmetries and shifts are an important observational parameter for constraining such two– or three-dimensional [magneto-]hydrodynamic models. These are capable of predicting not only line-widths and shapes, but also asymmetries and shifts at different center–to–limb distances on the stellar disk. The differential behavior between lines of different excitation potential, ionization stage, and height of formation, as well as the time dependence in all these quantities, reflects further details of the atmospheric structure.

Compared to the Sun, the vigor of surface convection, and the magnitude of convective lineshift is predicted to increase in earlier-type stars, and in evolved ones. The latter can be easily understood: if a dwarf and a giant share the same effective temperature, the same thermal power per unit area must be carried by convection. The atmosphere in the giant star is more tenuous, and has a lower heat capacity. In order to carry the same amount of energy (while preserving the same average temperature), the convection in the giant must have a larger velocity amplitude and/or higher temperature contrast. And the result of either of the latter is a more pronounced blueshift.

In order to constrain and guide the development of such models, diagnostic tools beyond classical line profiles are needed. Since (except for the Sun) most of the stellar surface structure will likely remain unresolved for the nearest future, spatially averaged tools must be used, e.g. spectra integrated over the full stellar disk (Atroshchenko, Gadun, & Kostyk 1990; Dravins 1990; Dravins & Nordlund 1990a, 1990b; Kiselman & Nordlund 1995; Ludwig & Steffen 1995; Steffen, Ludwig, & Freytag 1995).

To observe subtle details in line profiles requires very high spectral resolution, and data with very low noise. However, since a given atmospheric structure imprints similar signatures on lines with similar conditions of formation, line asymmetries and shifts can be measured as averages over many similar lines, thus [statistically] diminishing the problem of line blends, and permitting the study also of fainter stars.

3. Lineshift Dependence on Magnetic Activity

The presence of magnetic fields disturbs the photospheric convection, and granules do then not grow to equally large size nor velocity amplitude. The observed difference between images of granulation in non–magnetic and magnetic regions is shown by Spruit et al. (1990), while corresponding synthetic images are in Stein, Brandenburg & Nordlund (1992), and Bercik et al. (1998). Granules in solar active regions appear smaller and more fragmented. Early observations (spatially not fully resolving these features) often denoted these as "abnormal granulation". Corresponding spatially resolved spectra clearly show the changing velocity scale and/or amplitude in such magnetic regions.

There is a continuous change of line asymmetry and wavelength shift when going from non–magnetic into magnetic areas (Cavallini, Ceppatelli, & Righini 1985a; Immerschitt & Schröter 1989). Since the area subtended by magnetic regions changes during the solar 11–year cycle, also the line asymmetry and shift will be modulated with such a period. Although the spatially local bisector shift and curvature may well change by a factor of two, the magnetic area modulation does not exceed perhaps 20%, and thus the global changes can be expected to be on the order of 10% of the total convective shift, i.e. perhaps 30 m s^{-1}. Such an 11–year modulation is probably in phase with the Ca II K chromospheric emission measure or plage area coverage, but lagging a few years behind the sunspot number. Such secular changes have been sought (e.g., Deming et al. 1987; Wallace, Huang, & Livingston 1988), although convincing measurements in integrated sunlight over a full solar cycle appear to be lacking. The stellar analogues must of course be segregated from stellar velocity signals in searches for exoplanets with comparable periods.

Activity–cycle variability has been sought in some stars (Gray & Baliunas 1994; 1995; Gray et al. 1992; 1996a; 1996b). Indications for granulation (and perhaps other) inhomogeneities across a stellar surface can be seen in the rotational and temporal modulation of stellar bisector shapes and wavelength shifts (Toner & Gray 1988). As could be expected, there is a clear increase of the wavelength variability in magnetically more active stars (Saar, Butler, & Marcy 1998).

4. Synthetic Line Asymmetries and Wavelength Shifts

Sequences of synthetic spectral line profiles, computed from time–dependent and 3–dimensional hydrodynamic model atmospheres offer insights into the expected dependence of spectral line wavelengths on parameters such as line–strength, excitation and ionization level, wavelength region, etc., as well as the difference among different stars. Fig. 1 illustrates the significant change in bisector shapes and wavelength shifts already for stars quite close to the Sun in the Hertzsprung–Russell diagram. The top row is for integrated starlight (assuming zero stellar rotation), the center row for the spectrum at stellar disk center, and the bottom one near the stellar limb.

The left panels in Fig. 1 show bisectors for a strong Fe I line, and those at right for a weak one, both with lower excitation potential $\chi = 3$ eV. The horizontal wavelength scale is *absolute*, shown as apparent velocity. Thus, "0 m s^{-1}" denotes a wavelength equal to the laboratory one, corresponding to the true velocity of the stellar center of mass (unaffected by gravitational redshift). The vertical scale is spectral intensity. In the two lower rows that is in units of that at stellar disk center; the somewhat varying intensity levels for the lines near the stellar limb reflect different limb darkening in different stars.

It is seen that (a) convective blueshifts differ substantially between different spectral types; (b) shifts differ somewhat between lines of different strength; (c) the amount of shift depends on precisely which line portion is measured; and

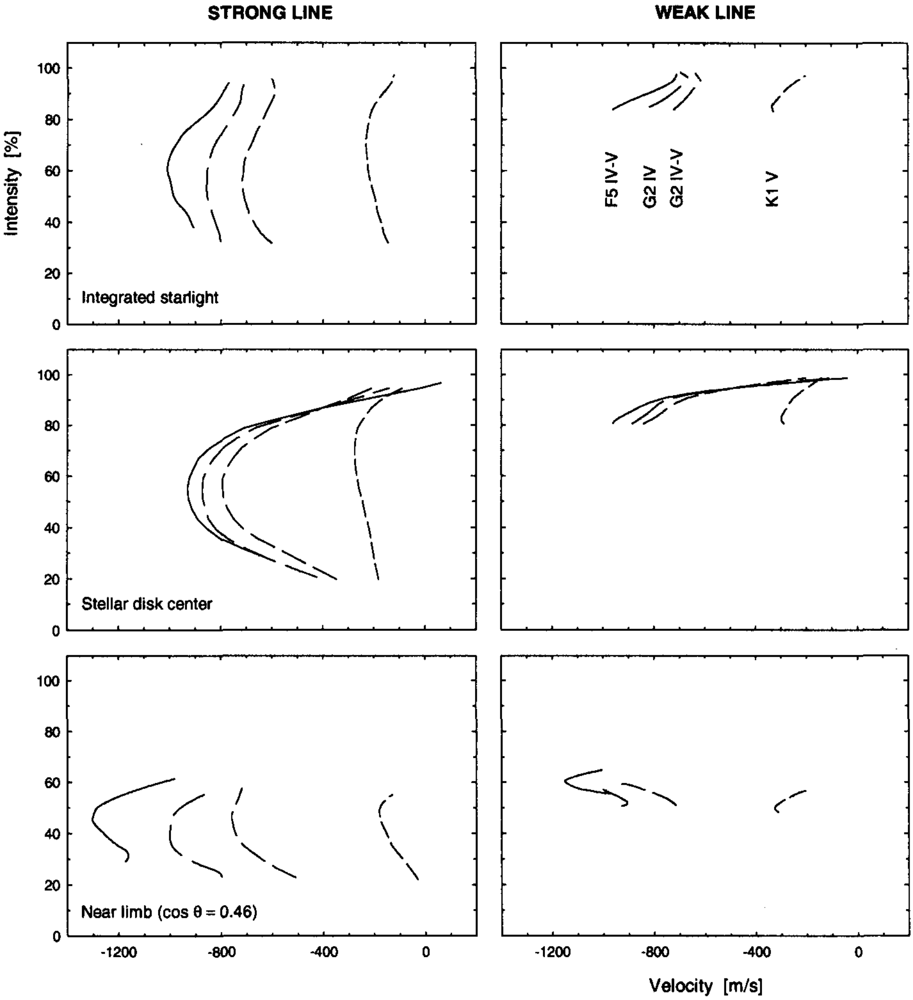

Figure 1. Bisectors for photospheric spectral lines in different solar-type stars, computed from hydrodynamic models of stellar granulation.

(d) the change in shift between stellar disk center toward the limb may differ in both size and sign between different stars. In order of decreasing lineshift, the four stellar models correspond to Procyon (F5 IV–V); β Hydri (G2 IV); α Cen A (slightly evolved G2 V), and α Cen B (K1 V). The bisectors for the Sun are similar in shape but slightly less shifted than those of α Cen A. These data were adopted from the models in Nordlund & Dravins (1990) and Dravins & Nordlund (1990a, 1990b).

5. Observed Asymmetries and Wavelength Shifts

Spectra of sufficient quality reveal the intrinsic asymmetries of spectral lines, conveniently shown by their bisectors. Observations of wavelength shifts in stars may be either relative within the same star, i.e. between [groups of] different lines with known laboratory wavelengths, or absolute, i.e. relative to a rest frame defined by the motion of the stellar center–of–mass. Also, relative shifts between lines in spectra of different stars may be measured if the stars are members of a binary or a cluster whose common system velocity is known.

Bisectors in various spectral types have been measured by Allende Prieto et al. (1995), Dravins (1987b), Gray (1982), Gray & Nagel (1989), and others. Differential lineshifts between different groups of lines were detected in some stars by Gullberg (1998), Nadeau & Maillard (1988) and Nadeau, Bédard, & Maillard (1989). The most information is contained in line profiles placed on an absolute wavelength scale, but this information is also the most difficult to obtain. In the past, such data were only available for the Sun, whose relative motion is accurately known from planetary system dynamics. The accuracies now realized in space astrometry now permit similar data to be obtained also for other stars via astrometric radial velocities, i.e. such determined purely from geometric projection effects, not involving spectroscopy (Dravins et al. 1997; Madsen, Lindegren, & Dravins 1999). The comparison of such velocity values with those deduced from spectroscopy permits the identification of spectroscopic lineshift components due to causes other than stellar motion (Dravins et al. 1999).

6. Temporal Signatures of Granulation

A sufficiently high measuring precision reveals properties of the stellar surface structure also through the temporal variability of stellar line bisectors and wavelength shifts. On the visible solar disk, there are on the order of one million granules, each with a velocity amplitude of perhaps 2 km s^{-1}, evolving over some 10 min. Assuming the granules to have the character of random noise (not true, but probably adequate for order–of–magnitude estimates), this amplitude is reduced in integrated sunlight by a factor of the square root of a million, to perhaps 2 m s^{-1}. Stars with larger velocity amplitudes and/or fewer granules will show correspondingly greater fluctuations. Quite probably, such changes have already been observed, although (since detailed hydrodynamic models for entire stellar envelopes are not yet available) such measurements are still awkward to interpret.

The measuring precision reached by solar oscillation networks has permitted the solar "background" velocity power spectrum to be measured also in integrated sunlight (Elsworth et al. 1994; Pallé et al. 1995). The wavelength variability over small areas can be readily measured on the Sun (Roca Cortes, Vazquez, & Wöhl, 1983), and modeled also for other stars (Dravins & Nordlund 1990a).

7. Spatially Resolved Spectroscopy across Stellar Surfaces

Until the present, "stellar radial velocities" have implied wavelength-shift observations for unresolved stellar disks. A major development that can be awaited in the near future is the study of wavelength variations across *spatially resolved stars*, e.g. the center–to–limb changes along the equatorial and polar diameters, and their spatially-resolved time variability.

Fig. 1 above illustrated the center–to–limb changes expected for different types of stars (after removing effects from stellar rotation). For the Sun, this has been known as the "limb effect" since a long time ago, although its origin was understood only more recently (Dravins 1982; Cavallini, Ceppatelli, & Righini 1985b).

The magnitude and sign of the limb effect is expected to differ among different spectral types (Dravins & Nordlund 1990a). In stars with a "smooth" photospheric surface (in the optical–depth sense), one may expect the convective blueshift to decrease near the limb, since the vertical convective velocities are then perpendicular to the line of sight, and the horizontal velocities which contribute Doppler shifts appear symmetric. However, stars with a "corrugated" surface with "hills" and "valleys" should show an increased blueshift toward the limb. Although the velocities on the star are horizontally symmetric, one will predominantly see the horizontal velocities on those slopes of the "hills" facing the observer. These velocities are approaching the observer and thus appear blueshifted. The equivalent redshifted components remain invisible behind these "hills", and an enhanced blueshift results. In Fig. 1, this effect is seen for the F–star model. Further effects appear in the time variability: On a "smooth" star, the temporal fluctuations are caused by the random evolution of granular features, all of which can be reached by the observer's line of sight. On a "corrugated" star, observed near its limb, there enters another element of variability in the sense that the changing "corrugations" of the stellar surface sometimes hide some granules from direct view. The result is an enhanced temporal variability of line wavelengths and bisectors, another observational parameter for constraining the hydrodynamics of stellar atmospheres.

Adaptive optics on very large telescopes, long-baseline optical interferometry, and optical aperture synthesis will soon permit such novel types of studies of stellar atmospheres through radial-velocity observations. Already an 8–10 m class telescope, operated at its diffraction limit, gives on the order of 10 resolution elements across the diameter of the largest (supergiant) stars, while optical interferometers with baselines of 100–1000 m are capable of resolving the disks of great many stars. These developments are likely to vitalize stellar physics in general, and precise radial-velocity studies across spatially resolved stellar disks should in particular open up the fine structure of stellar atmospheres to detailed study.

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Discussion

Noyes: Given the existence of the "convective redshift" in solar lines formed at higher altitudes (as seen in the infrared or ultraviolet regions of the spectrum), would it be possible to combine information from lines showing convective blueshifts and those showing convective redshifts to develop a radial-velocity measure which is relatively less dependent on magnetic activity-induced variations in apparent radial velocity than can be obtained without considering these effects?

Dravins: Yes, indeed. For the sun it is possible to select optimal spectral features that are minimally affexted by convective shifts. These include the near-bottoms of very strong photospheric lines, such as the Na I D_1 and D_2 lines. When viewed through a monochromatic filter tuned to those wavelengths, the solar surface shows quite low contrast. The level of line formation is already above the layers of vigorous granulation, yet not as high as the region of convective overshoot. However, the optimum choice of spectral lines may be quite different for other stars, where the relationship between optical depth and granulation contrast could be very different.

Hearnshaw: Your models are for dwarfs and subgiants. Have you also done any work on giant stars? And if not, would you care to speculate about convective line shifts and timescales for giants?

Dravins: Detailed simulations are, so far, not available for stars much off the main sequence. In order to make such simulations, some observational guidance would be needed, e.g. concerning the spatial scales of convective features on the stellar surface. From various dimensional arguments, their linear scale is expected to increase with the pressure scale height in the stellar atmosphere, thus becoming much greater in giants. However, there are also other issues, e.g. the question of whether the convective temperature fluctuations reach the very stellar surface, or whether they remain hidden at large optical depths.