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Highest-resolution spectroscopy at the largest telescopes?

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Abstract. 3-D models of stellar atmospheres predict spectral-line shapes with asymmetries and wavelength shifts, but the confrontation with observations is limited by blends, lack of suitable lines, imprecise laboratory wavelengths, and instrumental imperfections. Limits can be pushed by averaging many similar lines, thus averaging small random blends and wavelength errors. In non-solar cases, any detailed verification of 3-D hydrodynamics requires spectra of resolutions R = $\lambda/\Delta\lambda \approx$ 300,000, soon to become available. An issue is the optical interface of high-resolution spectrometers to [very] large telescopes with their [very] large image scales, possibly requiring adaptive optics. The next observational frontier may be spectroscopy across spatially resolved stellar disks, utilizing optical interferometers and extremely large telescopes.

Key words. Sun: granulation – Convection – Hydrodynamics – Line: profiles – Stars: atmospheres – Techniques: spectroscopic

1. Introduction

Paradigms have changed in the analysis of stellar atmospheres. Contrary to the days of classical 1-D models, it has been realized that it is not possible – not even in principle – to infer detailed stellar properties from analyzing observed line parameters alone, no matter how precisely the spectrum is measured. Any photospheric line is built by great many contributions from a wide variety of temporally variable inhomogeneities across the stellar surface, whose statistical averaging over time and space produce the line shapes and shifts that can be observed in integrated starlight. While it is possible to compute resulting line profiles and bisectors from hydrodynamic models, the opposite is not feasible because the 3-D structure cannot be uniquely deduced from observed line shapes alone (e.g., Asplund 2005).

While hydrodynamic models may predict detailed properties for a hypothetical spectral line, a confrontation with observations may be unfeasible because stellar lines of the desired strength, ionization level, etc., may simply not exist, or be unobservable in practice. In real spectra, lines are frequently blended by stellar rotation, by overlapping telluric lines from the terrestrial atmosphere or else smeared by inadequate instrumental resolution, in practice precluding any detailed studies.

While, in the old days of 1-D models, it may have been sufficient to just resolve the lines, and to determine their strengths, finding line asymmetries implies measurements over smaller fractions of each line-width. Any point on a bisector is obtained from inten-

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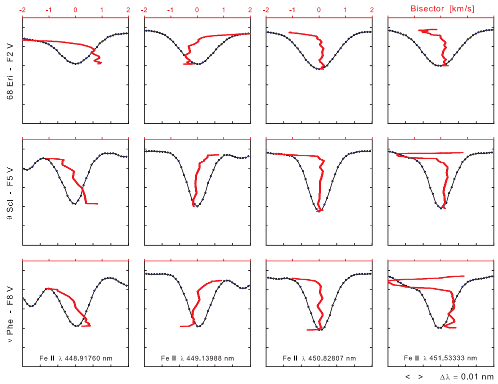


Fig. 1. Examples of individual bisectors, over plotted on the line profiles, for three representative Fe II lines in UVES Paranal spectra of different F-type stars: 68 Eri (F2 V), θ Scl (F5 V), and ν Phe (F9 V). The bisector scale (top) is expanded tenfold.

sities at two wavelength positions on either side of the line center. To define not only the bisector slope, but also its curvature requires at least some five points, implying at least ten measurements across the line profile. Given a width of a typical photospheric line of, say, 12 km s^{-1}, an ordinary resolution of R = 100,000 (3 km s^{-1}) can only indicate the general sense of line asymmetry. Both simulated and observed spectra show how the bisectors degrade when the spectral resolutions decrease towards R = 100,000 (e.g., Dravins & Nordlund 1990b; Allende Prieto et al. 2002; Ramírez et al. 2009).

2. Information limits in stellar spectra

High spectral resolution alone may not suffice to obtain high-fidelity spectra. The desired line may be blended with stellar or telluric ones; its laboratory wavelength could be uncertain; the data may be noisy, and the line might be distorted due to stellar rotation or oscillations.

Fig. 1 illustrates the difficulty of finding truly 'unblended' lines. Visually, all lines selected appear clean but comparing the same line between different stars, it is seen that bisectors often share common features, but that the bisector shapes differ strongly among different lines in the same star (where one would expect them to be similar). Thus, the 'noise' – the cause of bisector deviations from a representative mean – does not originate from photometric errors but instead is largely 'astrophysical' in character, caused by blending lines and similar (Dravins 2008). These spectra represent current high-fidelity spectroscopy, taken from the UVES Paranal Project (Bagnulo et al. 2003), where data of particularly low noise were recorded at resolution R ≈ 80,000 with the UVES spectrometer (Dekker et al. 2000) at the ESO VLT *Kueyen* unit.

3. Limits to line statistics

The omnipresence of weak blends makes it impossible to extract reliable asymmetries or shifts from any single line only. However, effects of slight blends may be circumvented by forming averages over groups of similar lines which can be expected to have similar physical signatures. Fig. 2 shows such average Fe II bisectors for both solar disk center (Delbouille et al. 1989) and for integrated sunlight (Kurucz et al. 1984). The wavelength scale is absolute, using laboratory data from the FERRUM project (Johansson 2002; Dravins 2008). For solar disk center, 104 lines were found to be clean enough, and 93 for integrated sunlight. From such numbers, reasonably well-defined mean bisectors emerge; however, most atomic species have rather fewer lines.

4. Spectra at the largest telescopes

Existing or planned high-resolution stellar spectrometers for the visual at current very large telescopes are summarized in Fig. 3. While some specialized instruments (R ≈ 10^6) have been used to measure interstellar lines (e.g., the Ultra-High-Resolution Facility at the Anglo-Australian Telescope; Diego et al. 1995), the only seriously high-resolution night-time instrument is PEPSI (*Potsdam Echelle Polarimetric and Spectroscopic Instrument*) at the Large Binocular Telescope, reaching R = 300,000 (Strassmeier et al. 2003). Among the PEPSI science cases (Strassmeier et al. 2004), diagnosing 3-D stellar hydrodynamics was ex-

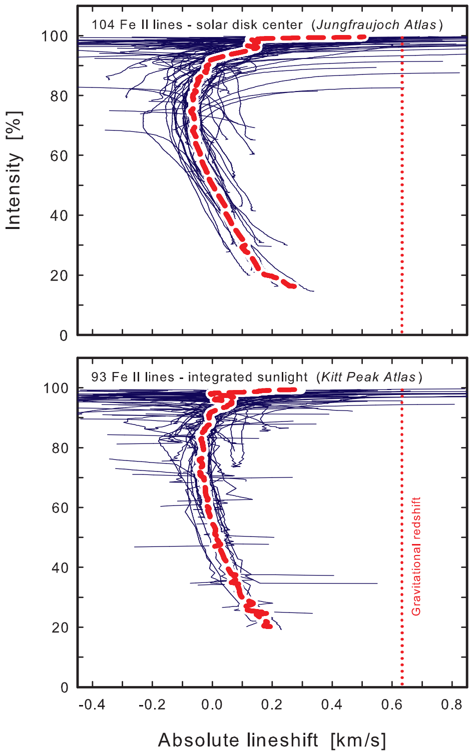


Fig. 2. Fe II bisectors in spectra of solar-disk center and of integrated sunlight. Each thin curve is the bisector of one spectral line; the thick dashed is their average. The vertical scale denotes the intensity in units of the spectral continuum, while the dotted line marks the wavelength expected in a classical 1-D model atmosphere, given by the laboratory wavelength, displaced by the solar gravitational redshift.

amined, noting that studies of bisector curvature indeed require such resolutions. Steffen & Strassmeier (2007) further discuss the PEPSI 'deep spectrum' project for the highest quality spectra for any star other than the Sun.

At the largest telescopes, challenges in highest-resolution spectroscopy stem from the difficulty to optically match realistically-sized grating spectrometers to the large image scales, i.e., to squeeze starlight into a narrow spectrometer entrance slit while avoiding unrealistically large optical elements (Spanò et al. 2006). The use of image slicers would limit the number of measurable spectral orders although some remedy could be offered by adaptive optics (Ge et al. 2002; Sacco et al. 2004).

Pasquini et al. (2005) and D'Odorico et al. (2007) discuss future spectrometers. High efficiency requires large optics: the two-grating mosaic for PEPSI makes up a 20×80 cm R4 echelle, while ESPRESSO for the VLT combined focus, and CODEX for the E-ELT aim at twice that: 20×160 cm (Pasquini et al. 2008; Spanò et al. 2008). Nevertheless, resolutions would not reach much above R = 100,000.

5. Spatially resolved spectroscopy

A major milestone in stellar astronomy will be the observation of stars not as point sources, but as extended surface objects! Already, disks of some large stars are imaged with large telescopes and interferometers, with many more resolvable with future facilities.

3-D models predict spectral changes across stellar disks, differing among various stars and indicating their level of surface 'corrugation' (Dravins & Nordlund 1990a). In stars with 'smooth' surfaces, convective blueshifts decrease from disk center towards the limb, since vertical velocities become perpendicular to the line of sight, and the horizontal ones contributing Doppler shifts appear symmetric. Stars with surface 'hills' and 'valleys' show the opposite, a blueshift increasing towards the limb, where one sees approaching (blueshifted) velocities on the slopes of those 'hills' that are facing the observer. Further effects appear in time variability: on a 'smooth' star, temporal fluctuations are caused by the random evolution of granules. Near the limb of a 'corrugated' star, further variability is added since the swaying stellar surface sometimes hides some granules from direct view.

To realize corresponding observations requires spectrometers with integral-field units and adaptive optics on extremely large telescopes or interferometers. Options for two-dimensional imaging include Fourier transform spectrometers. These provide high resolution for extended objects (e.g., Maillard 2005), although their noise properties have hitherto limited their use for point-source observations. However, it is a fallacy to believe

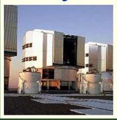
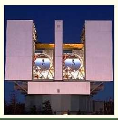
Telescope	SALT	Keck I	VLT Kueyen	HET	Subaru	LBT
						
Diameter [m]	10	10	8.2	9.2	8.2	2 × 8.4
Spectrometer	**HRS**	**HIRES**	**UVES**	**HRS**	**HDS**	**PEPSI**
Maximum R	65,000	84,000	110,000	120,000	160,000	300,000
Wavelengths [μm]	0.37– 0.89	0.3 – 1.0	0.3 – 1.1	0.39 – 1.1	0.3 – 1.0	0.39 – 1.05

Fig. 3. High-resolution spectrometers for the visual at existing 8-10 m class telescopes.

that highest optical efficiency would be crucial to scientific discovery: what is required is *adequate* efficiency. Still, a grand challenge remains in designing an efficient truly high-resolution (R $\approx 10^6$) and high-fidelity spectrometer for future extremely large telescopes!

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