High-Fidelity Spectroscopy at the Highest Resolutions

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But why?

Changing paradigms...
AN "IDEAL" STAR?

Solar disk
September 7, 2009
GONG/Teide
Stellar atmosphere theory classics...
Unsöld (1938, 1968); Mihalas (1969, 1978)
Astronomy is the supreme example of the observational, as opposed to experimental, sciences in which the wit of the observer has to be pitted against the difficulties, and in particular the ambiguities, imposed by the need to interpret remotely sensed data. The remote observer finds himself in a situation, akin to that of spectator at a magic show, where he is presented with a limited set of more or less remarkable data emanating from a source, the nature of which he is fascinated to discover but which he is not permitted to handle directly. In the magic show, the basic mechanism of the trick known only to the magician, is convoluted through the unrevealed process of his presentation, before appearing in strongly modified form to the spectator. In astronomy, the unknown basic physics of the observed source is convoluted through the source structure and emission processes (also unknown) before arriving at the observer’s instrument. Mathematically this process can be described in terms of an integral operator relationship between the required source distribution and the observable data. The very essence of interpretation of astronomical observations in many cases, therefore, reduces essentially to the analysis (or ‘inversion’) of data which have been subject to integral convolution processes.
Granulation near the limb (towards the top) at 488 nm; Swedish 1-m solar telescope, La Palma
Spatially resolved line profiles of the Fe I 608.27 nm line in a 3-D solar simulation.
Thick red line is the spatially averaged profile.
Steeper temperature gradients in upflows tend to make their blue-shifted lines stronger

CHANGING STELLAR PARADIGMS

- **PAST**: “Inversion” of line profiles; “any part of a profile corresponds to some height of formation”

- **NOW**: Stellar line profiles reflect distribution of lateral inhomogeneities across stellar surfaces

- Not possible, *not even in principle*, to “invert” observed profiles into atmospheric parameters

- Confrontation with theory through “forward modeling” – computations versus observables
Limits to information content in high-resolution spectra?
3-D models predict detailed line shapes and shifts

... but ...

their predictions may not be verifiable due to:

- Uncertain laboratory wavelengths
- Absence of relevant stellar lines
- Blends with stellar or telluric lines
- Data noisy, low resolution, poor wavelengths
- Line-broadening: rotation, oscillations
Spectral complexity
Pr II HYPERFINE STRUCTURE

Pr II 422.29 nm hyperfine multiplet; 11 components (Hans-Günter Ludwig)
Blended lines
Individual bisectors (red), overplotted on line profiles, for Fe II lines in UVES Paranal spectra of 68 Eri (F2 V), θ Scl (F5 V), and ν Phe (F9 V).

Limits to line statistics?

Fe II bisectors at solar disk center, and of integrated sunlight, on an absolute wavelength scale. Thin curves are individual bisectors; thick dashed is their average.

Finite spectral resolution
Limits to spectral fidelity?

Different line profiles in different recordings of solar spectra.
Solar disk center (Jungfraujoch & Hamburg); Integrated sunlight (Kitt Peak); Moonlight (UVES).
Fe I-line bisectors in Sun and Procyon (F5 IV–V)

Average bisectors for Fe I lines of different strength, produced from a time-dependent 3-D model

Fe II bisectors in Procyon, measured with successively higher spectral resolution. Left: $R = 80,000$; Middle: $R = 160,000$; Right: $R = 200,000$.

Absorption in the Earth’s atmosphere
KITT PEAK IRRADIANCE ATLAS NORMALIZED TO CONTINUUM OF KURUCZ MODEL ASUN  TOP = 2.6 W/M²/NM, VACUUM WAVELENGTH IN NM
Limits from telluric absorption?

Spectrum of *Sirius* (A1 V) from space (R.Kurucz; Hubble Space Telescope), and from the ground (E.Griffin; Mt.Wilson), showing atmospheric ozone absorption in near-UV.
Wavelength noise
MODELING SPECTRA (not only single lines)

LTE solar 3-D spectra, assuming [O]=8.86 for two different van der Waals damping constant (black lines). Blue line: observed disk center FTS spectrum by Neckel (“Hamburg photosphere”), slightly blueshifted.

Hans-Günter Ludwig
LTE solar 3-D hydrodynamic spectra, assuming [O]=8.86, for two different damping constants (black lines).
Blue line: observed disk-center FTS spectrum, slightly blueshifted.
Limits from wavelength noise?

Ti II bisectors at solar disk center from the Jungfraujoch grating spectrometer, and as recorded with the Kitt Peak FTS. Bisectors have similar shapes but differ in average lineshift, and scatter about their average. Dravins, A&A 492, 199 (2008)
Lineshifts from intergalactic convection
Perseus cluster core in X-rays (Chandra), overlaid with Hα image (WYIN).

Arc-shaped Hα filaments suggest vortex-like flows. Image is 4.3 arcmin (96 kpc) on the side.

Density slices (top) and simulated X-ray brightness maps (bottom) at three times. Arrows indicate fluid velocity. Viscosity stabilizes the bubble, allowing a flattened buoyant “cap” to form. X-ray brightness and inferred velocity field in Per-A can be reproduced.
Density map (inner 254 kpc of simulation): 3-D hydrodynamic simulations of jetted active galaxies responding to accretion of an intracluster-medium atmosphere.

Cosmic-ray pressure divided by the plasma pressure and the rms turbulent velocity in model solutions for the Virgo Cluster (left), the Perseus Cluster (middle), and Abell 478 (right)

OBSERVING THE INTERGALACTIC MEDIUM

Cosmological 3-D hydrodynamic simulation (512^3 gas & 512^3 dark). Density map: each bright point is a group of galaxies evolved within a cold-dark-matter cosmology. Image width = 400 Mpc. (James Wadsley)
INTERGALACTIC SPECTRAL LINES

Spectra of $z > 2$ quasar, recorded with Keck HIRES spectrograph (A.S. Cowie, Univ. of Hawaii)
**LINESHIFTS FROM INTERGALACTIC CONVECTION?**

**INTERGALACTIC LINE ASYMMETRIES AND SHIFTS: ANALOGIES AND DIFFERENCES TO STELLAR CONVECTION:**

- Plausible amount: 1% of “turbulent” broadening = 0.5–1 km/s?
- Lines closer to cluster centers gravitationally more redshifted
- Need line synthesis from 3-D hydrodynamic models!
- Mapping depth structure from multiple line components
- Mapping lateral structure from secular time changes?
- Need resolving power approaching 1,000,000?
- Need very high S/N, i.e. Extremely Large Telescopes!
- CODEX-like instrumentation?
- **Line formation must be understood before new physics implied!**
Visual high-resolution spectrometers at 8–10 m telescopes

<table>
<thead>
<tr>
<th>Telescope</th>
<th>SALT</th>
<th>Keck I</th>
<th>VLT Kueyen</th>
<th>HET</th>
<th>Subaru</th>
<th>LBT</th>
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<tbody>
<tr>
<td>Diameter [m]</td>
<td>10</td>
<td>10</td>
<td>8.2</td>
<td>9.2</td>
<td>8.2</td>
<td>2 × 8.4</td>
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<tr>
<td>Spectrometer</td>
<td>HRS</td>
<td>HIRES</td>
<td>UVES</td>
<td>HRS</td>
<td>HDS</td>
<td>PEPSI</td>
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<tr>
<td>Maximum R</td>
<td>65,000</td>
<td>84,000</td>
<td>110,000</td>
<td>120,000</td>
<td>160,000</td>
<td>300,000</td>
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<tr>
<td>Wavelengths [µm]</td>
<td>0.37–0.89</td>
<td>0.3–1.0</td>
<td>0.3–1.1</td>
<td>0.39–1.1</td>
<td>0.3–1.0</td>
<td>0.39–1.05</td>
</tr>
</tbody>
</table>
Potsdam Echelle Polarimetric and Spectroscopic Instrument @ Large Binocular Telescope
20\times80 \text{ cm} 
R4 echelle grating for PEPSI
Optical arrangement of multi-camera CODEX design

Pasquini et al.: CODEX: the high resolution visual spectrograph for the E-ELT
Resolving power and spectral range of proposed 42-m E-ELT spectrographs
Beyond CODEX: Spatially resolved stellar spectroscopy

Simulated intensities approaching the solar limb

Mats Carlsson, Oslo;
in Å.Nordlund, R.F.Stein, M.Asplund:
Solar Surface Convection,
Living Reviews in Solar Physics, 2009
Granulation on stars

Synthetic images [negative] of granulation in four stellar models

From top: Procyon (F5 IV-V), Alpha Cen A (G2 V), Beta Hyi (G2 IV), & Alpha Cen B (K1 V).

Disk center (μ=1), and two positions towards the limb.

D. Dravins & Å. Nordlund
Stellar Granulation IV. Line Formation in Inhomogeneous Stellar Photospheres
A&A 228, 84
Bisectors of the same spectral line in different stars

Adapted from Dravins & Nordlund, A&A 228, 203

From left: Procyon (F5 IV-V), Beta Hyi (G2 IV), Alpha Cen A (G2 V), & Alpha Cen B (K1 V).
Really high resolution:

Special grating spectrometers
$(R \approx 1,000,000)$

Fourier Transform Spectrometers
$(R \approx 1,000,000)$

Heterodyne IR lasers
$(R \approx 10,000,000)$
1-meter FTS; \( R = 3,000,000 \)
National Solar Observatory, Kitt Peak
Spectra of Martian $CO_2$ emission line as a function of frequency difference from line center (in MHz). Blue profile is the total emergent intensity in the absence of laser emission. Red profile is Gaussian fit to laser emission line. Radiation is from a 1.7 arc second beam (half-power width) centered on Chryse Planitia. (Mumma et al., 1981)
Outrageously high resolution:

Photon correlation spectroscopy

($R \approx 100,000,000$)
Eta Carinae
5.5 year cyclic variation at 6 cm (Stephen White, ANTF)
Natural lasers result when atomic energy levels become overpopulated.

A known case is the ultraluminous star $\eta$ Car; other sources might be symbiotic, Wolf-Rayet & Be stars.
HST/STIS spectrum of the η Carinae central star, and a condensation blob outside. Emission around 2507 and 2509 Å are identified as Fe II lasers.
Model of a compact gas condensation near η Car with its Strömgren boundary between photoionized (H II) and neutral (H I) regions

S. Johansson & V. S. Letokhov
Laser Action in a Gas Condensation in the Vicinity of a Hot Star
Narrow (4 pm = 40 mÅ) laboratory line profile & expected very narrow natural laser line (0.15 pm = 1.5 mÅ)
PHOTON CORRELATION SPECTROSCOPY: SPECTROMETER LENGTH AND EQUIVALENT LIGHT-TRAVEL-TIME REQUIREMENTS FOR DIFFERENT RESOLVING POWERS AT \( \lambda \) 600 nm

<table>
<thead>
<tr>
<th>Spectral resolution ( R )</th>
<th>Length</th>
<th>Time</th>
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</thead>
<tbody>
<tr>
<td>100,000</td>
<td>6 cm</td>
<td>200 ps</td>
</tr>
<tr>
<td>1,000,000</td>
<td>60 cm</td>
<td>2 ns</td>
</tr>
<tr>
<td>10,000,000</td>
<td>6 m</td>
<td>20 ns</td>
</tr>
<tr>
<td>100,000,000</td>
<td>60 m</td>
<td>200 ns</td>
</tr>
<tr>
<td>1,000,000,000</td>
<td>600 m</td>
<td>2 ( \mu )s</td>
</tr>
</tbody>
</table>

\( \lambda \) represents the wavelength, typically 600 nm in this context.
Common fallacy:
Belief that high optical efficiency is crucial to scientific discovery
Still ... A grand challenge:

Design an efficient high-fidelity spectrometer for ELTs!