QUIET SOLAR PHOTOSPHERE: COMPARISONS OF HIGH RESOLUTION OBSERVATIONS WITH 3-D SIMULATIONS

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ABSTRACT

High resolution observations of a very quiet region of the solar surface have been obtained with IBIS (Interferometric BDimensional Spectrometer) in the non-magnetic photospheric Fe I 7090.4 Å spectral line. We present a first comparison between the observed, spatially resolved, spectral data and the simulated spectra in a 3D snapshot of a radiation-hydrodynamical simulation of the solar atmosphere. Preliminary results indicate that the simulations reproduce quite well many of the observational properties of the high resolution IBIS data, even though the simulations present a velocity distribution that contains values quite larger than the observed ones.

Key words: Sun: photosphere – Sun: granulation – Sun: radiation-hydrodynamical simulations.

1. INTRODUCTION

Realistic 3-D modelling of solar surface convection have been able to reproduce many observed characteristics of the lower solar atmosphere, such as granulation topology and statistics (Stein & Nordlund 1998), helioseismic properties (Rosenthal et al. 1999; Stein & Nordlund 2001) and so on (see review by Stein & Nordlund 2000). Most recently, simulations of magneto-convection have been confronted with the excellent observations obtained at the Swedish Vacuum Tower Telescope on La Palma (Lites et al. 2004), concentrating in particular on the appearance and center-to-limb variation of solar faculae as observed in broad band images (Keller et al. 2004; Carlsson et al. 2004; Shelyag et al. 2004).

Only spectral lines, however, fully encode the whole atmospheric structure. A test of the validity of the simulations hence must necessarily include a comparison of spectral lines characteristics, both observed and synthetized utilizing the simulations as model atmospheres. In this respect, excellent agreement between predicted and observed average shapes, shifts and asymmetries for weak Fe lines in the quiet Sun has been demonstrated by Asplund et al. (2000), but comparisons with spectrally and spatially resolved observations are still scarce (Kiselman & Asplund 2001; Janßen et al. 2003), and often of rather limited spatial resolution (e.g. Khomenko et al. 2005).

Observationally speaking, the task results quite difficult, since both high spectral purity (say, few tens of mÅ) and high spatial resolution (well below 1 arcsec) must be obtained to resolve the characteristic structures of the surface convection, namely the downflows concentrated in the intergranular lanes. These requirements go hand in hand with high temporal cadence, as small structures do evolve rapidly, calling for very efficient instruments. We present here first results obtained with a new instrument capable of satisfying these stringent requirements, the Interferometric BDimensional Spectrometer (IBIS, Cavallini & Reardon 2005). The data will be confronted with spectral lines synthetized using the hydrodynamical simulations of Asplund et al. (2000).

2. OBSERVATIONAL AND SYNTHETIC DATA

IBIS data. IBIS, based on two Fabry-Perot interferometers mounted in a collimated configuration, is installed at the Dunn Solar Telescope of the NSO, and fed with a beam corrected by the high-order adaptive optics system (Rimmele 2004), providing spatial resolution close to the diffraction limit of the 76-cm telescope. The instrumental performances are summarized in Table 1. Given its high efficiency, IBIS allows a full scanning of photospheric lines within the whole field of view in just a few seconds.

The data used in this paper were acquired on June 2, 2004, on a very quiet region at disk center under very good seeing conditions. Scans of the photospheric, non-magnetic Fe I 7090.4 Å line over the 80′ arcsec FOV were obtained in 16 wavelength positions (mean step-size of 30 mÅ). Each scan was performed in about 4 s, with a pixel scale of 0.17′ arcsec, and scans were repeated for about 1 hr. The data and its general reduction is presented
in detail in Janßen & Cauzzi (2005). Figure 1 displays a portion of the observed FOV (50$''$ x 40$''$), for 12 of the 16 sampled wavelengths within the spectral line. Wavelength runs from left to right, top to bottom. Green frames the continuum image, where the granular/intergranular structure is clearly visible, as well as abnormal granulation outlining magnetic features (see, e.g., the upper right corner where a small pore is present). Red frames the (nominal) line core image; here the magnetic structures are well discernable as brighter than the average, and clearly outline a supergranular cell. The intensity structure in the wing images, especially those closer to the line core (second and third in middle row; first and second in bottom row) reflects instead the strong cross talk between convective velocities and intensities, with (blueshifted) granules resulting much darker than average in the blue wing and brighter in the red wing, and vice versa for (redshifted) intergranular lanes (Janßen & Cauzzi 2005).

For a comparison with the non-magnetic simulations, we selected a portion of the FOV clearly not contaminated by magnetic features, corresponding roughly to the central portion of the frames displayed in Fig. 1. The area selected is equivalent to 10 simulation snapshots (see next paragraph). The average spectral profile in this quiet area is plotted with a blue line in Fig. 2.

**Synthetic data.** As a first test, we have performed the spectral synthesis in a single snapshot of the recent 3-D radiation-hydrodynamical simulation of Asplund et al.
Table 1. IBIS instrumental characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>5800 Å ÷ 8600Å</td>
</tr>
<tr>
<td>Available Fraunhofer lines</td>
<td>5896 Å Na D1; 6301, 6302 Å FeI; 7090 Å Fe I; 7224 Å FeII; 8542 Å CaII</td>
</tr>
<tr>
<td>Spectral resolving power</td>
<td>190,000 ÷ 300,000</td>
</tr>
<tr>
<td>Wavelength drift</td>
<td>≤ 10 ms⁻¹ on 10 h</td>
</tr>
<tr>
<td>Field of view (circular)</td>
<td>80 arcsec</td>
</tr>
<tr>
<td>Image scale</td>
<td>0.08 arcsec pixel⁻¹</td>
</tr>
<tr>
<td>Wavelength setting time</td>
<td>≈ 20 ms</td>
</tr>
<tr>
<td>Exposure time (S/N = 100)</td>
<td>25 ÷ 50 ms</td>
</tr>
<tr>
<td>Acquisition rate</td>
<td>≈ 3 frames s⁻¹</td>
</tr>
<tr>
<td>including: wavelength setting,</td>
<td>(1024×1024 pixels);</td>
</tr>
<tr>
<td>exposure, frame reading, storing</td>
<td>≈ 4 frames s⁻¹</td>
</tr>
<tr>
<td></td>
<td>(binning 2×2)</td>
</tr>
</tbody>
</table>

(2000). The volume covered by the grid is 6×6×3.8 Mm, with about 1 Mm located in the atmosphere proper (i.e. above continuum optical depth unity). The horizontal step size is set at 120 km (degraded from the original 30 km, see Asplund et al., 2000), comparable to the resolution of our observations. In order to improve vertical sampling, the snapshot has been interpolated in the vertical direction with a grid size of ~10 km, focussing only in the part of the simulated atmosphere between ~200 km and 800 km, which correctly samples the photospheric region where the 7090 Å line is formed. The synthetic spectral lines were calculated for each spatial position assuming Local Thermodynamical Equilibrium (LTE), with an iron abundance set to the meteoritic value of 7.50 (Shchukina & Trujillo Bueno 2001) and the oscillator strength of the line at log g_f = −1.21 (Nave et al. 1994). The synthesis has been carried out with a spectral sampling of 5 mÅ.

The simulated data have then been degraded to the actual spectral and spatial resolution of the observed data. First, the spectral profiles obtained for each of the spatial points in the computational box have been convolved with the IBIS instrumental profile, as was done for the atlas (see Fig.2). The resulting horizontally averaged spectrum is shown in green in Fig. 2. The synthetic line is too shallow, by about 10%, with respect to the observed one. This could be due either to this particular snapshot, or to a too small value of abundance. The width of the line, however, seems to have been correctly recovered. The spatial resolution of the synthetic data has then been degraded including the PSF of both the telescope and the atmosphere, following the customary approach (Nordlund 1984; Collados & Vázquez 1987). We chose a telescope PSF corresponding to a diffraction limited telescope with a diameter of about 70 cm (true diameter is 76 cm), verifying that this aperture provides a resolution comparable to that obtained from both the (smearred) simulations and the data, as evidenced by the azimuthal average power present in each of the spatial frequencies in the continuum images. The atmosphere contribution has then been set by adjusting the contrast over the synthetic continuum image to match the observed value (as done in, e.g., Shelyag et al. 2004).

3. RESULTS

![Figure 3](image3.png) 6 × 6 Mm synthetic monochromatic images within the FeI 7090.4 Å line, degraded at the spatial and spectral resolution of the actual data. Wavelengths as in Fig. 1.

![Figure 4](image4.png) Same as Fig. 3, for a subset of observations with the same area.

**Morphology.** Fig. 3 represents the synthetic data, degraded as explained above, in the same form as Fig. 1, while Fig. 4 provides the same picture for a portion of the
observed FOV of equal area. The morphological properties of convection, as visible through this photospheric line, seem very well reproduced. In particular, the intensity pattern is quite different in the blue and red wings of the line, with strongly blueshifted portions of granules appearing as dark ‘specks’ in the far blue wing, and “enhanced” granulation appearing in the red wing. The line core is characterized by bright streaks in both the simulations and the observations.

**Brightness distribution.** Fig. 5 provides the synthetic brightness distribution for all wavelengths displayed in Fig. 1. Thick red lines denote the synthetic data, while thin black lines represent 10 different subportions of the observed FOV, each $6 \times 6$ Mm in size (see Sect. 2). Note how for the continuum (upper left panel) the synthetic distribution closely resembles the observed one, even though only the mean value of the contrast has been used to match the two sets of data. The agreement is slightly less satisfactory as we move towards the line core (right panel, middle row): the simulated brightness distribution is usually broader than observed, indicating that there are very brilliant and very dark points in the simulation that are not observed. This might be produced because we have only chosen one snapshot which is not representative of the average simulation. However, it must be noted that the number of points presenting this “anomalous” behavior is very reduced, accounting for about 5% of the total points.

**Reversed granulation.** The good agreement between observations and synthetic data makes us confident that the simulations faithfully describe the physical state of the actual solar atmosphere. In turn, this might allow us to retrieve some important characteristics that are not so easily or unambiguously determined from observations alone. Figs. 6 and 7 are an example of this, applied to the case of “reversed granulation”, i.e. the partial reversal of the continuum intensity pattern, due to a reversal of temperature fluctuations between granules and intergranules, occurring in the low- or mid-photosphere (Nordlund 1985; Rutten et al. 2004).

Fig. 6 shows the continuum and the FeI 7090.4 Å line minimum intensity images for the synthetic data (upper panels) and the actual observations (lower panels). One can see that reversed granulation is clearly visible in the core of the spectral line, and that both synthetic and observational data share a similar morphology. From the synthetic data, it then becomes trivial to determine the height at which this phenomenon appears, for example by determining the layers at which the optical depth $\tau_{\lambda}$ at the core wavelength reaches the value of unity. Fig. 7 (right panel) gives the histogram of such value for the area described by the simulations: the line core forms at a height of about 250 km, although one must be aware that the surface of optical depth unity is quite corrugated. Even more instructive, in this sense, are the same histograms but for two different wavelengths in the line wing: at 60 mÅ from line core in the blue wing (left panel)
the intensity formations peaks around zero (the base of
the photosphere), but large variations are present, with
granules forming much higher than intergranules. At 30
mÅ from line core (middle panel), the distribution is al-
most flat, without any obvious “preferred” height of for-
mation. This strongly cautions against the use of a given
height of formation for a particular line or wavelength
within the line.

Figure 6. A 6 × 6 Mm area displayed at the continuum
wavelength (left panels) and in the line minimum (right
panels). Top panels: simulations; bottom panels: ob-
servations. The line minimum images clearly display the
reversed granulation, i.e., a partial reversal of contrast
between granules and intergranular lanes, occurring in
the mid-photosphere.

Figure 7. Histograms of heights in the photosphere at
which optical depth τ₅ = 1, for the FeI 7090.4 Å. Left:
60 mÅ from line core; middle: 30 mÅ from line core;
right: line core.

Velocities. Finally, Fig. 8 gives the distribution of ver-
tical velocities as retrieved from the simulated data (red)
and the observations (black lines). We note that, although
the exact hydrodynamical velocities are available for the
simulations, the velocity displayed in Figure is calculated
from the emergent synthetic spectrum, completely consis-
tently with what is done for the observations. While
the average value is correctly retrieved, the simulated pro-
files present a broader distribution with respect to the ob-
servations, with about 1/3 of the pixels experiencing ve-
celocities higher than measured in the actual data. This is
related to the extreme intensity values reported in Fig. 5
and could be due to the particular snapshot we are em-
ploying. As an alternative explanation, the PSF correc-
tion applied to the synthetic data might not be optimal for
all wavelengths.

Figure 8. Vertical velocity distribution for the synthetic
data (red) and observed ones (black).

4. CONCLUSIONS

We have presented a first comparison of synthetic spec-
tral data, obtained using a snapshot of recent 3-D hydro-
dynamical simulations of the solar photosphere as model
atmosphere, with high spectral (R∼200,000) and spa-
tial (0.3”) resolution observations of the photospheric FeI
7090.4 Å line. The data have been obtained with the
Interferometric Bidimensional Spectrometer (Cavallini
2005; Cavallini & Reardon 2005), recently installed at
the Dunn Solar Telescope of the NSO (USA).

The simulations seem to closely reproduce many obser-
vational quantities, such as the monochromatic intensity
morphology within the line, the general brightness dis-
bution, and the appearance of reversed granulation in
the minimum intensity image. The velocity distribu-
tion derived from the synthetic data however results quite
broader than observed. We are currently investigating
possible causes of this discrepancies, including perform-
ing an analysis of a more complete set of simulations.

ACKNOWLEDGMENTS

Many thanks are due to the NSO staff for their help and
assistance in acquiring the data. NSO is operated by
AURA, Inc., under cooperative agreement with the NSF.
We are thankful to M. Asplund for providing the sim-
ulations’ snapshot and for friendly encourgement. This
research has been partly funded by the European Solar
Magnetism Network (contract HPRN-CT-2002-00313).
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