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New atlases for solar flux, irradiance, central intensity, and limb intensity

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Abstract. I have produced a revised FTS Kitt Peak Solar Flux Atlas for 300 to 1000 nm (Kurucz 2005) and a new high resolution Kitt Peak Irradiance Atlas from 300 to 1000 nm with the telluric lines removed. I am now working on central intensity and limb intensity atlases for the same region. If I can get funding I will extend these atlases to 5.5 μm. I will also produce atlases with the observed and computed spectra and line identifications.

Key words. Stars: atmospheres – Stars: abundances – Atmospheric effects – Atomic data – Molecular data – Techniques: spectroscopic

1. Introduction

The low resolution, low-signal-to-noise spectra that astronomers normally work with do not contain enough information, in themselves, for interpretation. Without a priori knowledge of the atomic and molecular line data for each significant line in the blended features any inferences about abundances have large uncertainties. Reliable atomic and molecular data are not available from the laboratory or from theory except for a small fraction of the lines. Atlases of high-resolution, high signal-to-noise spectra of stars with low projected rotation velocity provide information about details and blending in the spectra. People who work with stellar spectra should always check their wavelength region in high quality atlases. If the atlas was taken from the ground, it will also show the telluric lines and their contribution to blends.

I have been trying to make atlases with line identifications for the sun for 25 yeers so that I could check my calculated spectra against reality. When I can find patterns in the errors, I try to correct the physics. However, the calculated spectra have been so poor that almost every line needs to be adjusted to match the observed spectra. Many of the lines in the observed spectra are missing altogether from the line list. The calculations are also needed for the reduction of the observed spectra themselves because the continuum placement depends on many weak blends and on the damping treatment of the wings of many lines.

Matching observed spectra seems to be hopeless, at least in the near future. I have finally decided that the continuum placement is good enough, and that I should publish the spectra with only "suggestive" calculations and identifications to give the user an idea of where to begin and what the problems are.

2. New atlases

I have fifty solar FTS scans taken by James Brault and Larry Testerman at Kitt Peak.

The scans cover the central intensity, limb (μ=0.2), and flux spectrum from 0.3 to 5.5 μm. The central intensity for 1.0 to 5.5 μm was published by Delbuille, Roland, Brault, & Testerman (1981). The flux spectrum from 0.3 to 1.3 μm was published as Solar Flux Atlas (Kurucz, Furenlid, Brault, & Testerman 1984). However, since then I have learned that broad O_3 and O_2 dimer (or $[O_2]_2$) features are present in the spectrum, and I have improved the line data and the continuum treatment. I have produced an improved version of the flux atlas (Kurucz 2005a) that is available on my web site KURUCZ.HARVARD.EDU. I have merged the scans into a single spectrum, but I also present each scan separately because each FTS scan has its own atmospheric model, air mass, telluric spectrum, and radial velocity. The resolving power and signal-to-noise vary from scan to scan and are on the order of 300000 and 3000, respectively. I am now working on similar atlases for central intensity and limb spectra. If I get funding, I will continue the atlases into the infrared to 5.5μm. I will produce atlases plotted at one Å/page that include the computed spectrum and line identifications. If I can get funding, I will distribute paper and DVD copies.

The telluric line spectrum was computed using HITRAN (Rothman et al. 2005) and other line data for H_2O, O_2, and CO_2. The line parameters were adjusted for an approximate match to the observed spectra. I was able, through many hand adjustments, to remove the telluric absorption spectrum for the flux atlas and to recover the residual irradiance spectrum above the atmosphere for the region from 0.3 to 1.0 μm. Figure captions 1 to 13 outline the reduction procedure. In wavelength regions with heavy absorption the quality has been compromised by more than an order of magnitude. I have produced a continuous atlas of this irradiance spectrum (Kurucz 2005b). Most of the irradiance atlas has the same resolution and signal-to-noise as the flux atlas.

Given a calculated or semiempirical solar model, the continuum level can be computed and multiplied by the residual irradiance spectrum to produce the absolute irradiance spectrum at high resolution. Alternatively, the high resolution residual irradiance spectrum can be broadened and smoothed to match the resolution of any low resolution irradiance spectrum and normalized to the low resolution spectrum. That normalization can be applied to the high resolution spectrum to obtain a high resolution absolute irradiance spectrum. An example for each method is presented below. This is the spectrum that illuminates the Earth and all other bodies in the solar system. This is a typical G star spectrum like those that illuminate extra-solar planets.

3. Figure captions

The figures are in color, are ledger size, and are published in electronic form only, together with a table of the observations. The figures and a table of the observations are also on my web site http://KURUCZ. HARVARD.EDU/PAPERS/ TRANSMISSION. They are large files. I will send paper copies of a poster on the irradiance atlas (Kurucz 2005c) by post on request. The figure captions, in themselves, provide an explanation of the reduction procedure.

Table 1. Record of the observations.

Fig. 1. The old Kitt Peak Solar Flux Atlas. There are eight overlapping FTS scans that were normalized and pieced together to form a continuous residual spectrum. The observational data for the scans is listed in Table 1. (There are only seven scans in this figure because the eighth is beyond 1000 nm.) The next figures show the re-reduction of these scans.

Fig. 2. Broad atmospheric features of O_3 and $[O_2]_2$ that were present in the scans but not considered. Each scan was assigned to an atmospheric model listed in Table 1. The O_3 and $[O_2]_2$ transmission was computed using programs available on my website, kurucz.harvard.edu, and divided out. (The transmissions for the seven scans were pieced together for the plot.)

Fig. 3. The blue end of one of the FTS scans is shown in green. A continuum, smooth green line, is subjectively fitted to the scans by comparing to predictions from calculations of the solar spectrum and the telluric spectrum. When a reasonable looking fit has been obtained

through iteration, the spectrum is divided by the continuum value to produce a residual spectrum shown in red. The top 1 percent of the residual spectrum is replotted in red as well. The blue curve is the the transmission curve for O_3 and $[O_2]_2$ that has already been divided out.

In **Fig. 4.** The scans were blue shifted to remove the gravitational red shift and pieced together in the solar laboratory frame in air. This is the revised spectrum of the Kitt Peak Solar Flux Atlas.

Fig. 5. Telluric lines of O_2 and H_2O that were computed from the atmospheric model for each scan in the solar laboratory frame with gravitational red shift removed. (The seven scans are pieced together.)

Fig. 6. A sample calculation of the spectrum for a relatively empty angstrom at 599.1 nm in the Solar Flux Atlas shown in Figure 4. The telluric, solar, and observed spectra are labelled at normal scale and 10 times scale.

Fig. 7. Shows the irradiance spectrum obtained from the spectra in Figure 6 by dividing out the telluric spectrum. For stronger telluric lines and lines with incorrect wavelengths, there are artifacts that appear in the irradiance spectrum that were removed by hand and replaced with a linear interpolation.

Fig. 8. The residual irradiance spectrum after all the scans have been processed and pieced together in the solar laboratory frame in vacuum with gravitational red shift included.

Fig. 9. The predicted level of the continuum for theoretical solar model ASUN (Kurucz 1992).

Fig. 10. The absolute irradiance spectrum obtained by normalizing the residual irradiance spectrum shown in Figure 8 to the continuum level shown in Fig. 9.

Fig. 11. The reference irradiance spectrum proposed by Thuillier et al. (2004).

Fig. 12. The Kitt Peak absolute irradiance spectrum smoothed using a 0.5 nm triangular bandpass that approximates the resolution of Thuillier et al. and then compares the two spectra. Note the probable overestimation of the ozone below 320 nm and around 600 nm in the Kitt Peak atlas. (Remember that ozone has been divided out.) I will probably have to reduce those scans. Note the flux discrepency in the G band. It appears that model ASUN does not produce enough flux, perhaps becase of insufficient opacity below 300 nm that results in too low a temperature gradient. I am adding more line opacity. I will try to produce a better model. Of course, there may also be errors in Thuillier et al. as well.

Fig. 13. The Kitt Peak irradiance spectrum subjectively normalized to the Thuillier et al. irradiance spectrum. I recommend this spectrum as the high resolution irradiance spectrum. The procedure for removing telluric lines introduces noise into the irradiance spectrum where there were telluric lines. The flux atlas itself should be used for abundance analysis or other critical work.

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