DISCUSSION

COWLEY: I completely agree about the importance of blends. On occasion it is useful to know what the dominant contributor is to a given feature. This is especially useful when you make comparisons of stars with different spectra. It is like having a map of the city. In this case it is not necessary to have all the details on the map, but only a selection of the important features.
KURUCZ: I have been trying for years to get money for a color laser printer. When I get one, I will be able to produce your "map" by coloring specific contributors to the spectrum, and I will still be able to indicate what they are blended with.
TABISZ: In the case where there are dominant contributors or pure lines, are the line shapes understood?
KURUCZ: I do not know yet from my own experience. Everyone says no, but there are uncertainties in determining the continuum shape, and there are blending effects that have not been considered. For example, Ti has 5 isotopes, ^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti, and ^{50}Ti. ^{48}Ti is the strongest and the other isotopes tend to appear symmetrically in the wings. A naive analysis would assume that there is a single line with extra damping. In fact, there are 5 lines with normal damping.
de la REZA: What is the behavior of the Chappuis bands with airmass?
KURUCZ: Linear. The O_2 "dimer" features are quadratic so they are strongly enhanced at large airmasses observed from low altitudes.
GRIFFIN: Given that this is an age of computer dominance and digital analysis, would you like to say why you feel it is nevertheless still important to produce analogue versions of spectral atlases?
KURUCZ: There is a psychological problem. Astronomers are used to working with reduction programs on small sections of low-resolution, low signal-to-noise spectrum, such as echelle orders, on workstations with resolution about 1000 x 1000. Then they make small paper plots with the same resolution. Astronomers tend to think that the spectra on their workstations are like the stars! But the physics of stars works at high resolution and high signal-to-noise. A workstation with resolution 10000 x 10000 is required. The pages I use for laser printer plots have resolution 3000 x 5000, which is still not good enough, but they do give an indication of the detail that is important. If I give out only the digital spectrum, most people would throw out the detail and the physics and just plot it at low resolution on their workstations.

Fig. 5. A small section of the solar central intensity spectrum at 599 nm plotted at full scale and at 10 times scale. The heavy lines show the observed FTS spectrum from James Brault at Kitt Peak. The resolution is 522000 and the signal-to-noise is about 3500 which is poor for this work. The continuum level is very uncertain due to atmospheric ozone. The thin lines are the computed spectrum. There are solar lines of Ca I, Ti I, Cr I, Cr II, Fe I, Fe II, Co I, Yb II, C_2, and terrestrial lines of H_2O. The first number in each line label is the last 3 digits of the wavelength and the 4th number is the per mil central intensity if the line were computed in isolation. The Co I line at 599.1866 has been divided into 15 hyperfine components. The hyperfine splitting is not known for the two other Co I lines. There are many missing lines.

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Fig. 4. Far infrared central intensity atlas by Farmer, Delbouille, Roland, and Servais (1994). The upper plot shows the whole atlas. The small plots show interesting features.

Fig. 3. *An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm^{-1} (1.1 to 5.4 μm)* by Livingston and Wallace (1991). The atlas shows the transmitted spectrum, the transmission spectrum, and the derived solar spectrum.

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Fig. 2. Extreme ultraviolet (23-45 nm) spectrum of an active region by Thomas and Neupert (1994).

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Fig. 7. Resolved isotopic splitting profiles for Fe II and Ni II redrawn after Rosberg, Litzen, and Johansson (1993). The indications for ^{61}Ni and ^{57}Fe, which are hyperfine split, were added because of excess emission at those wavelengths.

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Moe, O.K., Van Hoosier, M.E., Bartoe, J.-D.F., and Brueckner, G.E. 1976. *A Spectral Atlas of the Sun between 1175 and 2100 Angstroms.* Naval Research Laboratory Report 8057.

Moore, C.E., Minnaert, M.G.J., and Houtgast, J. 1966. *The Solar Spectrum 2935Å to 8770Å.* NBS Monograph 61.

Moore, C.E., Tousey, R., and Brown, C.M. 1982. *The Solar Spectrum 3069Åto 2095Å.* Naval Research Laboratory Report 8653.

It is imperative that laboratory measurements be made to determine the isotopic splitting of every energy level of every stable isotope of every atom and ion as is now routinely done for actinides and for diatomic molecules. The hyperfine splitting should be measured as well for those isotopes with nuclear spin. The data should be presented in a form that is directly usable. Energy level publications should list the energy levels for each isotope and for each hyperfine component when they exist.

At the present time I am including hyperfine and isotopic splitting in my spectrum calculations, one level at a time, from whatever laboratory data I can find. Given enough laboratory data, it should be possible to work semiempiricially to generate the splittings for whole computed transition arrays, including all the predicted lines. Unfortunately, this will produce ten times as many lines and ten times as many identifications.

I plan to publish or republish atlases with the lines labelled, including terrestrial lines from the Air Force HITRAN line list (Rothman et al. 1987) and those I have determined from the spectra themselves. I am synthesizing each spectrum and should be able eventually to deconvolve the blends and to deconvolve the atmospheric transmission where it is not near zero.

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SPECTRUM SYNTHESIS LINE IDENTIFICATION

The spectrum of the sun consists of many thousands of lines blended together. Even at infinite resolution and signal-to-noise the blends are difficult to interpret. It is possible to observe the solar spectrum with a signal-to-noise ratio of 10^4 and a resolving power of 10^6. But no one has done so yet. In the sun we can study contributions to blends at the 1 per mil level. There are many cases where lines can be seen in the sun that have been difficult or impossible to see in the laboratory. The sun is a unique spectroscopic source for studying atoms and molecules.

The quality of solar observations is now high enough that we can see physical effects that have been assumed to be insignificant. As discussed above, I am reducing the solar central intensity spectra taken by James Brault with the FTS on the McMath telescope at Kitt Peak. The spectra were observed with resolving power greater than 522000 in the visible and signal-to-noise greater than 3000. I typically plot the observed and computed spectra at a wavelength scale of 2 m/nm and a residual intensity scale of 2 m. Wavelengths can be read by eye to 0.0001 nm. All lines in the spectra are blended. When the observed spectra are compared with computed spectra (Kurucz 1993), they do not look "right": the damping wings do not look like Voigt profiles and the lines seem to be asymmetric. Because of blending and missing lines and uncertainties in continuum placement, however, this is difficult to demonstrate from the comparison. Also there are Doppler shifts and asymmetries from mass motions in the solar atmosphere on the order of 100 m/s, and many of the lines are naturally asymmetric due to hyperfine splitting. I have included hyperfine splitting in my spectrum calculations for Sc, V, Mn, and Co for lines that have laboratory data available. Removing those lines from consideration, the remaining lines still give the same impression. I investigated isotopic splitting in Ti, Cr, Fe, and Ni and found that they are indeed asymmetrically split. Very little data has been published on isotope splitting in the iron group. However when I went into James Brault's office at Kitt Peak and I looked through the files of infrared FTS spectra, isotopic splittings were clearly visible in the even elements and hyperfine splittings were clearly visible in the odd elements. Analysis of Brault's spectra and new laboratory measurements are urgently needed and are underway in London and Lund. Figure 7 is based on paper by Rosberg, Litzén, and Johansson (1993) in which they show the first isotopic splitting data for Fe II and Ni II. As both hyperfine splitting and the isotope shift vary roughly as Z^3 (Huhnermann 1992), higher ions can have much larger splittings.

In natural isotopic mixtures essentially all atomic lines are asymmetric because of isotopic and hyperfine components. I have a review (Kurucz 1993) that lists all the stable isotopes of all the elements, isotopic abundances, nuclear spins, nuclear magnetic moments, and nuclear electric quadrupole moments. The isotopes with nuclear spin have hyperfine splitting, and almost every element has at least one isotope with hyperfine splitting. The magnitudes of the magnetic moment and the spin give an indication of the strength of the hyperfine splitting. The only element that does not have isotopic or hyperfine splitting is thorium. The review discusses the errors that are made if the splittings are not considered when interpretting spectra.

FUTURE IRRADIANCE ATLAS

Why are there no atlases of the solar irradiance? Why do NASA and ESA show no interest in the radiation that illuminates every body in the solar system?

I am now able to compute a purely theoretical model photosphere (Kurucz 1992a;b;c) that reproduces the irradiance measurements of Neckel and Labs (1984) in the visible for bandpasses of approximately 2 nm. That model, and Avrett's empirical quiet sun model (Fontenla, Avrett, and Loeser 1993) that includes the chromosphere, can be used to predict the irradiance out to 200 μm at low resolution. I have computed the spectrum from 150 nm to 200 μm for both models at a resolving power of 500000 using 58 million lines, both predicted and observed. If this spectrum is degraded to the resolution of the theoretical model, it looks like the model. At any given wavelength the spectrum is not reliable. But at a resolving power of 10000, say, it approaches measurement accuracy. In regions of low transmission it is more reliable than existing measurements. I will publish tables of these low resolution irradiance spectra for use in terrestrial atmospheric modelling.

Parts of the flux atlases directly give the residual irradiance spectrum, but much is confused or obscured by terrestrial lines. I will compute the terrrestrial lines and remove them except where the transmission is too low. Then I will fill in with the purely theoretical solar spectrum, which is continually being improved, hopefully to the point of being realistic. In this way I expect eventually to produce an atlas showing the solar spectrum above the atmosphere.

CLASSICAL LINE IDENTIFICATION

The standard for line identifications in the visible is still the Rowland Table, *The Solar Spectrum 2935Å to 8770Å*, by Moore, Minnaert, and Houtgast (1966). Improved identifications in the 3000 Åregion have been made by Mitchell and Mohler (1969). In the ultraviolet Moore, Tousey, and Brown (1982) have extended the identifications down to 2095Åusing NRL photographic spectra (Tousey et al. 1974). Line identifications in the near infrared are given by Swensson et al. (1970), *The Solar Spectrum from λ7498 to λ12016*. There are a number of papers by Biemont et al. (1985, for example) where he identifies infrared lines of iron group atoms. Those papers and similar papers are listed by Livingston and Wallace (1991) and Geller (1992). The Sac Peak flux atlas (Beckers, Bridges, and Gilliam 1976) was the predecessor to the Kitt Peak flux atlas. The Kitt Peak atlas has higher resolution and higher signal-to-noise and greater wavelength coverage, but the printed copy of the Sac Peak atlas does have the advantage of line labels from the Rowland Table.

Geller (1992) has almost single-handedly identified most of the solar lines in the ATMOS infrared spectra. Some of these identifications are for atomic lines that had not been seen on the laboratory so have led to new energy level determinations.

Much more effort is required still because one half of the lines in the overall solar spectrum are not identified.

over Vernazza and Reeves (1978) in that region. The spectrum is shown in Figure 2.

Wallace and Livingston at Kitt Peak have been producing spiral-bound atlases distinguished by the color of their covers. They can be requested from Livingston at wcl@noao.edu. These atlases include many useful line identifications. Yellow is *An Atlas of the Solar Spectrum in the Infrared from 1850 to 9000 cm^{-1} (1.1 to 5.4 μm)* by Livingston and Wallace (1991). It was produced by ratioing two scans at different airmasses to obtain the central intensity above the atmosphere for wavelengths where the atmosphere is not too strongly absorbing. Figure 3 gives an example. Many of the lines are labelled.

Orange is *An Atlas of a Dark Sunspot Umbral Spectrum from 1970 to 8640 cm^{-1} (1.16 to 5.1 μm)* by Wallace and Livingston (1992). Blue is *An Atlas of the Sunspot Spectrum from 470 to 1233 cm^{-1} (8.1 to 21 μm) and the Photospheric Spectrum from 460 to 630 cm^{-1} (16 to 22 μm)* by Wallace, Livingston, and Bernath (1994).

Finally Farmer, Delbouille, Roland, and Servais (1994) have produced *The Solar Spectrum between 16 and 40 microns* from Jungfraujoch with conditions of minimal water vapor. Maximum signal-to-noise is 1500. It nicely shows rotational lines of hydrides as displayed in Figure 4. The atlas can be obtained from Farmer via farmer@atmosmips.jpl.nasa.gov.

FUTURE BRAULT ATLASES

I am producing atlases of the solar flux, central intensity, and limb intensity from 0.3 to 5 μm using FTS spectra taken by James Brault at Kitt Peak. For these, and for all the other published atlases, I will produce print-on-demand atlases that include a computed spectrum and the line identifications. Each page will show the observed spectrum normalized to a continuum, the state-of-the art computed transmitted spectrum at the time the atlas is printed, and line identifications. Note that the calculated spectrum cannot yet reproduce the observed spectrum. Each section (about 500 pages) will cost \$100, plus shipping if outside North America. If I can obtain a color laser printer, I will make a \$200 version with color coded solar spectrum, transmission spectrum, transmitted spectrum, and the line indentifications. The line data will be available as computer files. These atlases are not yet ready for distribution because I am still trying to clear up problems with atmospheric transmission and continuum fitting.

I use the atlases described here to test the pure calculations of solar spectra and transmission spectra as shown in Figure 5. I identify problems with the line data and I try to make generic corrections that improve hundreds or thousands of lines at a time. If the spectrum calculations look good in the regions of high transmission, I can have some confidence that the regions of low transmission are computed accurately. The main problem has been continuum placement which affects the appearance of line wings and the apparent depth of weak features. Ozone and O_2 "dimer" features are difficult to determine because the Brault atlases are each made up of a number of sharply peaked FTS scans. The features are shown in Figure 6.

OLD ATLASES

Earlier work has been thoroughly discussed in Kurucz (1991) including plots of the spectra. Following is a list of atlases discussed in that review:

Solar Flux Atlas from 296 to 1300 nm by Kurucz, Furenlid, Brault, and Testerman (1984);

The Jungfraujoch central intensity atlas, *Spectrophotometric Atlas of the Solar Spectrum from λ3000 to λ10000* by Delbouille, Roland, and Neven (1973);

The Kitt Peak infrared central intensity atlas by Delbouille, Roland, Brault, and Testerman (1981), *Photometric Atlas of the Solar Spectrum from 1,850 to 10,000 cm^{-1}*;

The JPL ATMOS experiment was flown on the space shuttle to produce *A High-Resolution Atlas of the Infrared Spectrum of the Sun and the Earth Atmosphere from Space*, Farmer and Norton (1989);

The central intensity spectra taken by the Ultraviolet Spectrometer and Polarimeter on the Solar Maximum Mission spacecraft (SMM/UVSP). The region from 129 to 177 nm has been reduced by Shine et al. (1989) at Lockheed. I am working on the region from 180 to 300 nm. To produce a continuous spectrum I expect to fill in gaps in the SMM spectra using Harvard data (Kohl, Parkinson, and Reeves 1975), and data from NRL (Moe, van Hoosier, Bartoe, and Brueckner 1976) and OSO-8 (Chipman 1981);

There are three atlases available now in the 220 to 300 nm region. The Harvard rocket atlas, *Center and Limb Solar Spectrum in High Spectral Resolution: 225.2 to 319.6 nm.* (Kohl, Parkinson, and Kurucz 1978); The NRL atlas, *An Atlas of the Solar Ultraviolet Spectrum between 2226 and 2992 Angstroms* by Tousey, Milone, Purcell, Schneider, and Tilford (1974); and *High Resolution Atlas of the Solar Spectrum 2678-2931Å* by Allen, McAllister, and Jefferies (1978);

Vernazza and Reeves (1978) show the spectrum taken from Skylab at low resolution and short wavelengths from 26 nm to 136 nm;

A few other atlases were cited but not discussed in the review.

NEW ATLASES

The NRL HRTS (High Resolution Telescope and Spectrograph) photographic spectra have finally been reduced and published by Brekke (1993) as *An Ultraviolet Spectral Atlas of the Sun between 1190 - 1730Å*. The spectrum is the image of a long slit that intercepted many features on the solar surface from near disk center to off the limb. Pixels for each type of feature were coadded to produce 11 spectra enumerated by type and μ value: 1) active region, 0.85; 2) active region limb, 0.25-0.36; 3) explosive event, 0.62; 4) prominence, off limb; 5) light bridge, 0.79; 6) quiet region A, 0.92-0.98; 7) quiet region B, 0.65-0.70; 8) quiet region limb, 0.17-0.20; 9) quiet region, 0.85-0.86; 10) sunspot A, 0.78; 11) sunspot B, 0.76.

The quiet region A, which is nearly central intensity, is shown in Figure 1. The resolution is not sufficient to resolve line profiles in the spectra, The data can be obtained by electronic mail from Brekke at paalb@astro.uio.no.

Thomas and Neupert (1994) have obtained a relatively high resolution spectrum of a solar active region from 23 to 45 nm that is a great improvement

THE SOLAR SPECTRUM: ATLASES AND LINE IDENTIFICATIONS

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ABSTRACT High resolution solar atlases are reviewed and the problem of line identification is made more complicated.

INTRODUCTION

There are several different reasons for studying the solar spectrum. In every case we want high signal-to-noise and high resolution, resolving power of one half million or so if there are no telluric lines, or resolving power of two million if there are. One reason is obviously to study the sun itself. Then we want spectra that also have high spatial and temporal resolution. A second reason for studying the solar spectrum is that the sun is the brightest star so that we can study it the same way that we study other stars, but at higher resolution and higher signal-to-noise. We want a spectrum with no spatial or temporal resolution, a A reproducible flux spectrum. This is also the spectrum seen by all the bodies in the solar system and that determines their atmospheric chemistry. However, the high-resolution flux spectrum has not been observed above the atmosphere. The available flux atlases have been made through the earth's atmosphere and include the telluric absorption. The third reason for studying the solar spectrum is that it serves as a spectroscopic data source for atoms and molecules that goes beyond what is available in the laboratory. It also provides a test of the predictions of theoretical calculations.

Here I mention the atlases discussed in my last review (Kurucz 1991), review newly available atlases, and discuss work in progress on Brault's spectra and on an irradiance atlas.

Except for the far infrared, where some lines are isolated, lists of line identifications do not very useful because the features we see in the solar spectrum are not single lines. They are blends of many lines, lines of different species, lines of isotopes, and hyperfine component lines. Only a synthetic spectrum can indicate in any meaningful way what are the components of the blends. I will give examples of these various complications and discuss atlases with line identifications included.