From stars to abundances

How can we learn ?

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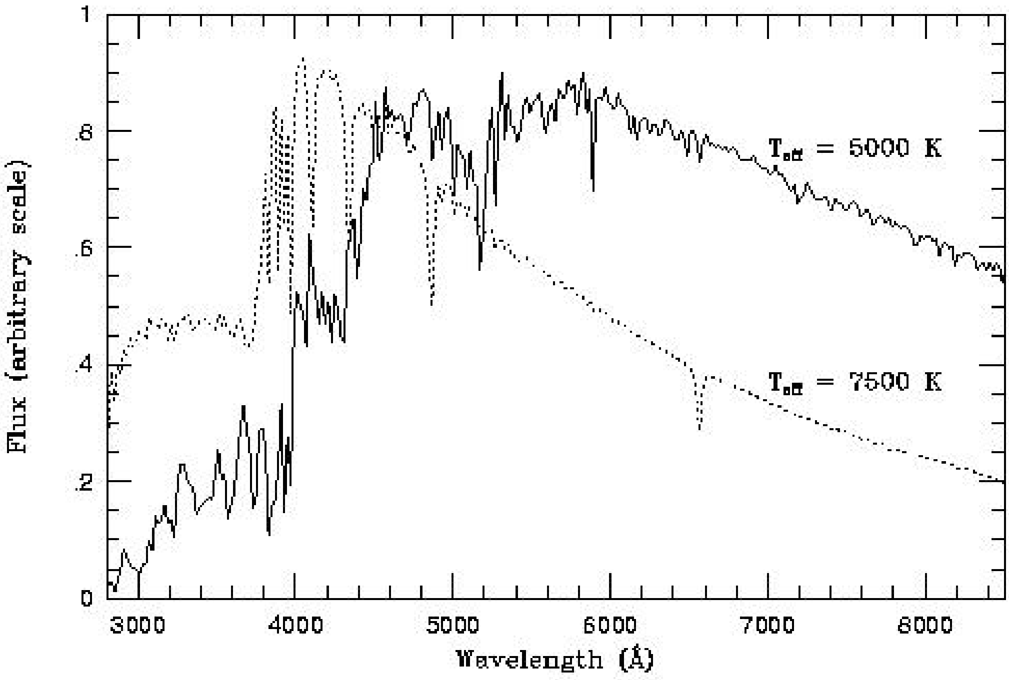
The usefulness of stars

- Stars are common and bright and supply most of the light in the Universe
- Stars consist of the matter of the place and time that they were formed
- Stellar spectra contain a lot of information, for example of the surface composition
- Well-chosen stars show their original chemical composition at their surfaces

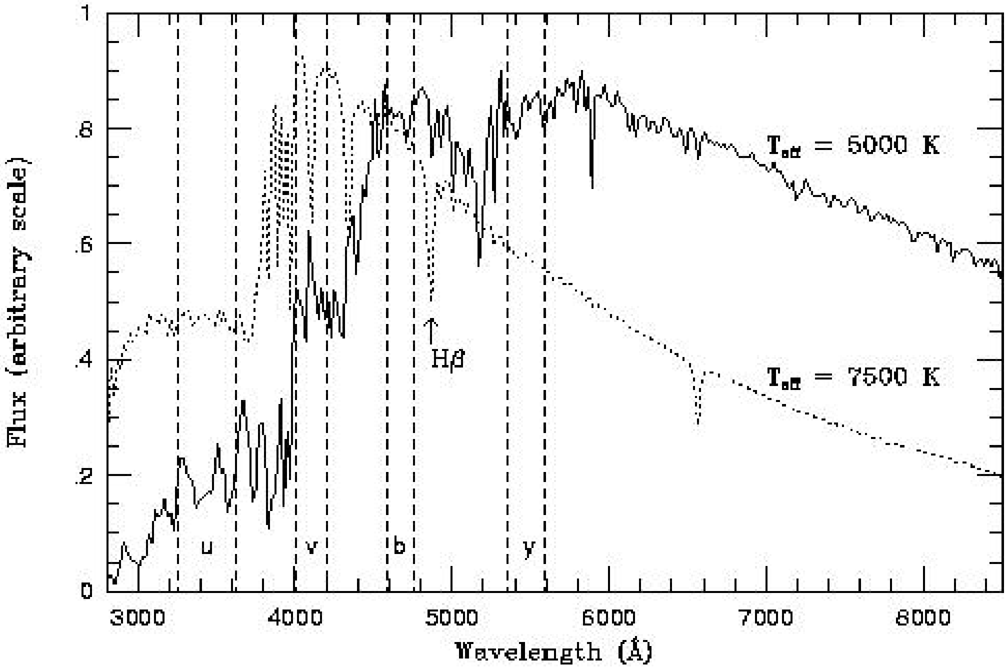
Surveys give rough classifications with a limited number of photons per star

- Photometric catalogues(page 4 & 5)
- Objective prism surveys (page 6)
- Dedicated telescopes, automated surveys (page 7)
- Sometimes you have to design your own survey for addressing a new question



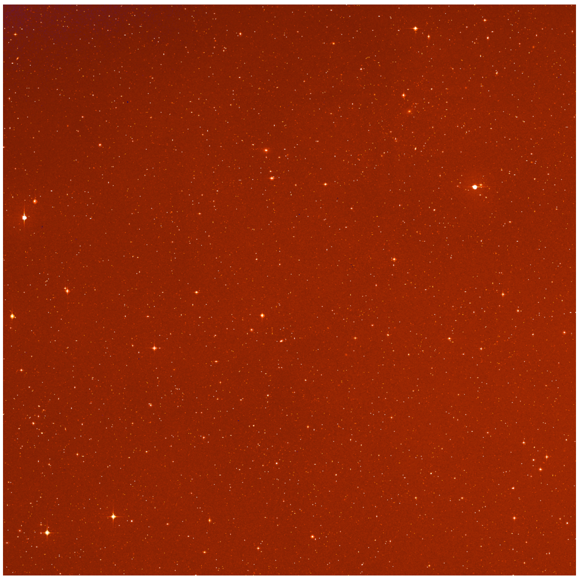
The general shape of a stellar spectrum depends primarily on the effective temperature. Smaller effects are caused by differences in the surace gravity (via prssures), and overall metallicity.

In astronomical nomenclature ”metals” are all elements heavier than H and He, thus oxygen ist the most common ”metal” in the Universe. The historical reasons for this is that almost all absorption lines in stars like the Sun are formed by ”true” metals, and that all ”metals” are barely trace elements in normal stars.



”u”, ”v”, ”b”, and ”y” show the Full Widths at Half Maximum of the Stromgren photometric pass bands. The flux in the y band divided by that in b is sensitive mainly to the stellar effective temperature (and independent of stellar distance) via the temperature sensitivity of the position of the stellar peak flux. The ”second-derivative” index (y/b)/(b/v) is quite sensitive to the stellar overall metallicity by the increasing blocking effect of absorption lines towards shorter wavelengths. (b/v)/(v/u) is sensitive to the gas and electron pressures via its effect on the ionisation of neutral hydrogen in its first excited state, the ”Balmer continuum”. Such photometric indices are also sensitive to the possible and sometimes dramatic effect of interstellar dust extinction which increases towards short wavelengths. Therefore also an extinction free measure of the effective temperature is used. This is measures the strength of the hydrogen H (beta) line as a ratio between the fluxes of a narrow and a wider band over the line. Via comparison with y/b the effect of extinction can be estimated and numerically compensated for.

A HES objective-prism plate



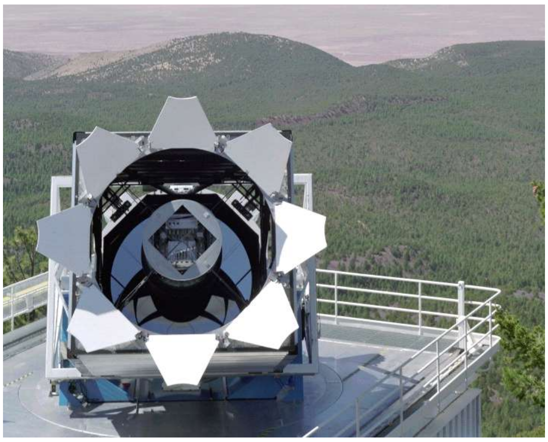
- 5 x 5 deg on the sky
- Mag. range: approx. 10 mag < B_J < 17.5 mag
- Typically 10,000 objects per plate
- HES: 380 plates => ~4,000,000 spectra
- Kodak IIIa-J emulsion => 3200–5300Å
- Resolving power $R = \lambda/\Delta\lambda = 400$

Slide courtesy Norbert Christlieb http://www.astro.uu.se/~norbert/ .

(The second page of this image which does not show up in this comented version shows each star image as a short spectrum.)

The short computer-scanned spectra in the Hamburg-ESO Survey objective-prism plates may be used in a manner similar to that of a photometric system. To find very metal-poor stars specifically the strengths of the 2 strongest absorption lines (of Ca II) near 3950 Angstrom are measured.

Sloan Digital Sky Survey



- Apache Point, NM
- 2.5m diameter
- 120 Mpix camera
- 2 Fiber-fed spectrographs
- 200 M galaxies, quasars, stars
- Huge archive

http://www.sdss.org/

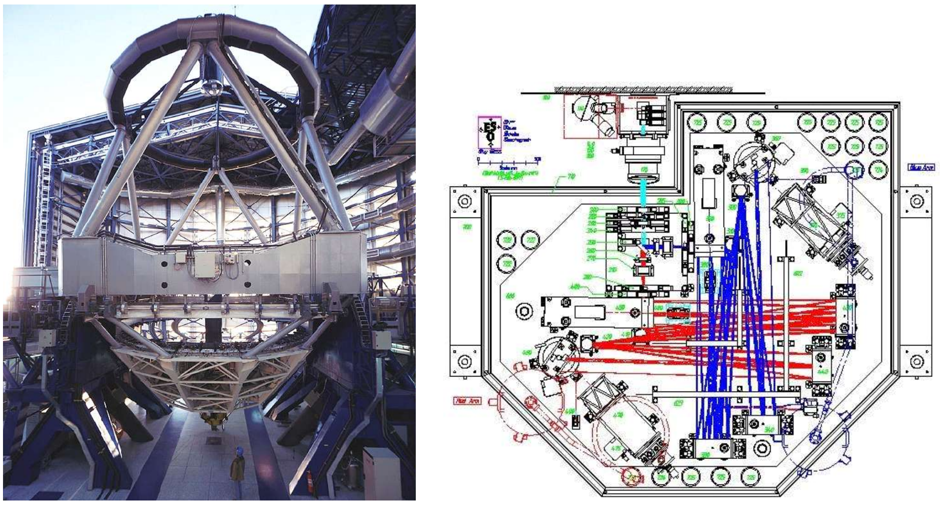
Although SDSS was designed as a survey for galaxies and quasars very many stars of the Milky Way are found in the foreground. The photometric passbands can be used to classify stars analogously to the Stromgren system.

Solar-type main-sequence stars

- Come with all different ages
- Very common, many nearby us
- Have surface-convection zones, well mixed
- Surfaces not affected by internal processes
- Relatively uncrowded spectra
- Easy to analyse relative to the Sun
- Major drawback: they are faint, need for brighter stars in distant locations and in other galaxies

A single star formed with a mass smaller than about 0.8 solar masses is still a well-behaved core-hydrogen-burning dwarf star even if it was one of the first stars in the Universe.

Spectroscopic observations



The VLT Kueyen telescope and a sketch of the UVES echelle spectrograph which is permanently situated at one of the telescopes' Nasmyth platforms. For more details see http://www.eso.org/instruments/ . The width of UVES is about 2 meters.

Spectroscopic data reductions

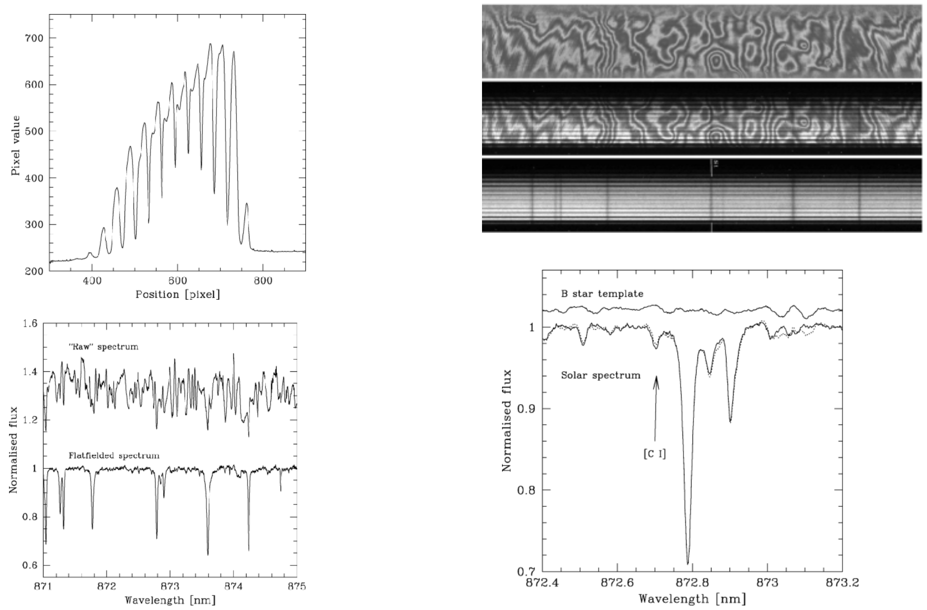


Image courtesy Thomas Bensby, http://www.astro.lsa.umich.edu/~tbensby/

Top left: Since the image of the star is larger than the spectrograph entrance slit an “image slicer” puts slices of the image along the slit to avoid waste of light collected by the large telescope primary mirror.

Top right: Fringe removal. In the near infrared wavelength region high-sensitivity scientific CCDs often suffer from “fringing effects” illustrated by the wood-like response of homogeneous illumination by a white lamp seen in the upper 1/3 of the image. The middle third shows the “raw image” of one order of a stellar spectrum obtained with an image slicer. The division of this image by the upper frame results in the bottom image where the spectral lines are clearly seen.

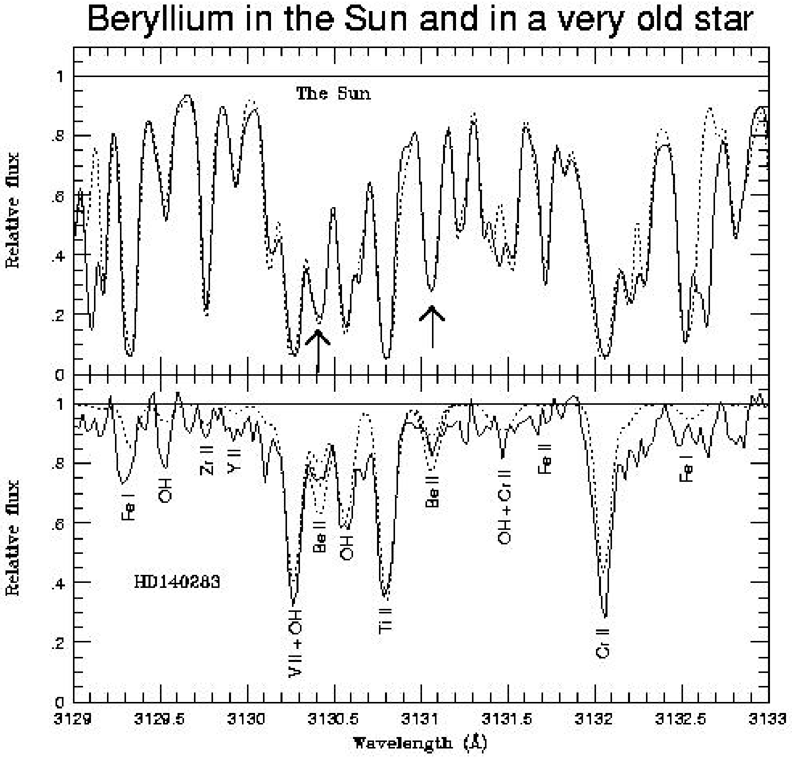
Bottom left: Summation of all the slices in the middle and the bottom frames of the top right image result in the spectra seen here. Without the fringe removal the spectrum would be virtually useless.

Bottom right: A white (quartz-iodine) lamp does not illuminate the CCD in precisely the same way as a stellar image. Therefore a spectrum of a “line-free” star (quickly-rotating B star) is obtained and reduced in the same way as a target star. A final division by this spectrum further reduces the effects of detector nonlinearities.

Other non-illustrated data reduction procedures include the subtraction of read-out noise and dark-current and wavelength-calibration by measurement of consistently obtained spectra of emission-line lamps (often Th-Ar).

Chemical abundance analysis

- Interpretation of observed absorption line profiles in terms of elemental abundances
- Either direct comparison with a synthetic spectrum (page 12)
- or, alternatively, by means of a simple line-strength measure – the ``equivalent width´´ (easily automated for large data sets) (page 13)



Beryllium in the Sun and in a very old star

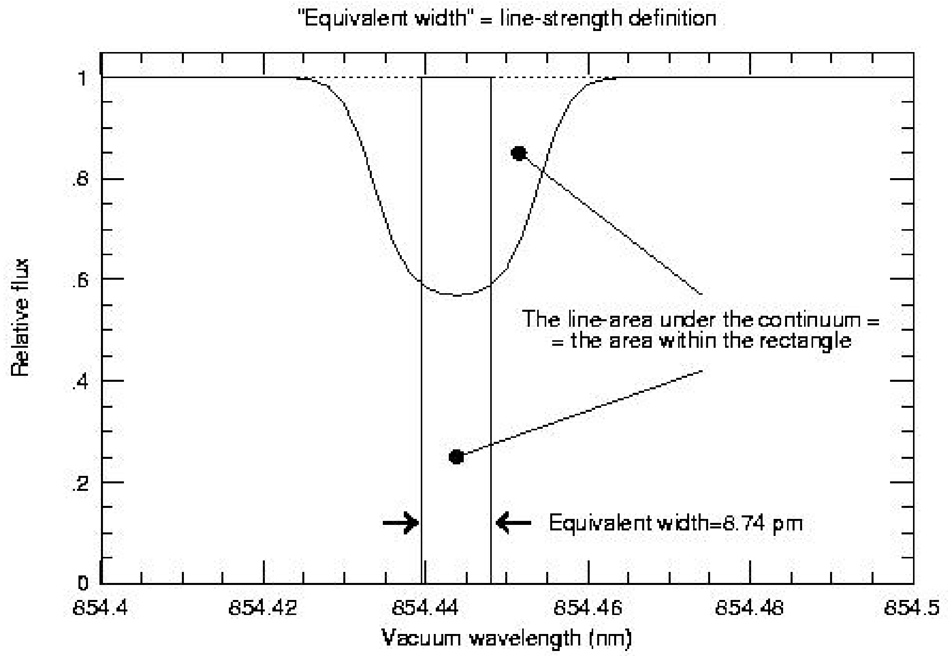
Ref: Gilmore G., Edvardsson B., Nissen P.E. 1991, Astrophysical Journal 378, 17-21

Relative-flux spectra obtained by division with the ”continuous spectrum”, which is the theoretical flux level if there were no absorption lines. For solar-type stars the continuous opacity is dominated by bound-free and free-free absorption of the negative hydrogen ion.

The top panel shows a short strech of the near UV solar spectrum includng two resonance lines of singly ionised beryllium marked by arrows. The solid line shows the NSO solar atlas observationd (R. Kurucz et al. 1984) and the dotted line a synthetic spectrum with line data collected from various sources. The oscillator strengths of many of these are adjusted to fit the observations (so-called astrophysical gf values). Nevertheless the fit i´s far from perfect and many features are unidentified or probably erroneously identified.

The bottom panel shows the well known very metal-poor halo star HD140283 which has only about one fivehundredth of the solar metallicity. The spectrum obtained in the early 1990s with the Anglo-Australian telescope is very noisy and the synthetic spectrum fit poor. The two beryllium lines are best fit by an abundance of 1 beryllium atom per about 10^13 hydrogen atoms. The result sparked an intense debate and much work concerning the possible Be production in an inhomogeneous Big Bang.

Later it has been found that the beryllium was instead produced by a much more efficient production by interstellar spallation in the Early Galaxy. If the synthetic spectrum does not agree with the observed one try to change the abundance(s) and rerun the synthesis and compare again.



The equivalent widths of observed lines can be measured by direct integration or fitting of a Gaussian or Lorenzian profile. The programme used for abundance determination iterates for each line by adjusting the element abundance and recalculating the line profile until the synthetic equivalent width agrees with the measured one. The shape of the line can with this method not be used to derive futher information.

How does one compute synthetic spectra and line profiles?

- Model atmosphere (Teff, gravity, metallicity from a survey or complementary observations)
- Chemical abundances
- Continuous opacities at each wavelength point
- Accurate line data for the wavelength interval
- Solve eq. of radiative transfer (wavel., angles)
- Integrate surface fluxes over half sphere
- Convolve output spectrum (for rotation, macroturbulence , instrumental profile)
- Compare with observed spectrum

Stellar rotation and macroturbulence

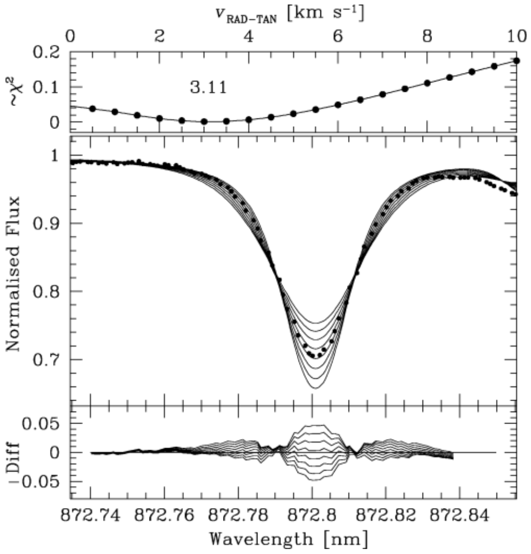


Image courtesy Thomas Bensby, http://www.astro.lsa.umich.edu/~tbensby/

Can be simulated by convolution of the synthetic spectrum with appropriate normalised profiles. These effects do not alter the equivalent width of lines, only their shapes. The same is true of the spectrograph “instrumental profile” which will also have to be accounted for when the lines are not fully resolved.

Atomic and molecular line data

- Wavelengths
- Energy levels
- Oscillator strengths
- Radiative broadening
- Pressure broadening
- Hyperfine structure
- Isotopic shifts
- Zeeman splitting
- …

Examples of sources

- NIST
  physics.nist.gov/PhysRefData
- Robert Kurucz
  kurucz.harvard.edu
- VALD
  ams.astro.univie.ac.at/vald
- Individual publications and special data bases

Sometimes better to define "astrophysical" oscilllator strengths

”Astrophysical oscillator strength”: Since the strength of a line is a function of the product of the atomic oscillator strength and the abundance of the line forming element the actual oscillator strength (or equivalently the Einstein A value) which is rarely very well known is of little importance when the same line is used in the target star and in a comparison star and only the relative abundance of the target star to the comparison star is determined.

(Version 3 of VALD is presently being reviewed for release. It will contain also data for molecular lines.)

What is a model atmosphere ?

Most commonly a 1-dimensional table describing the run of physical parameters with depth

Created iteratively by requiring physical self-consistency among selected properties such as hydrostatic equilibrium and flux constancy

Using several simplifying assumptions

Common simplifying assumptions

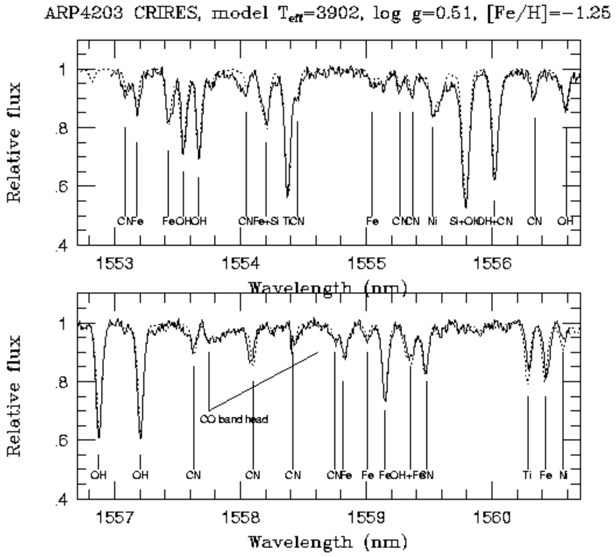
- 1-dimensionality (plane-parallel or spherical)
- Hydrostatic equilibrium
- Local thermodynamic equilibrium,“LTE”
- No magnetic fields
- No stellar rotation
- more …
- There are exceptions to all of these

LTE assumes that at each model atmosphere depth point isotropic collisions determine the (only) temperature. (Maxwellian distributed) collisions determine the total Equation of state: the (Botzmann distributed) excitation of atoms and molecules and the (Saha) ionisation distribution of each element and the corresponding properties for molecules. The same temperature determines the (black body) spectrum of emission. There are models relaxing one or two of these assumptions at the expense of spectral detail and computational speed. These models are usually individually produced to match a single star and lagre general-purpose grids are still not available.

Model calculations

- Chemical composition
- Effective temperature
- Surface gravity
- Starting T-Tau relation
- 50-100 discrete layers
- Equation of state, rho, Pe, Pg, Prad, Pturb…
- Hydrostatic equilibrium
- Opacities at MANY wavelengths
- Solve energy transport by radiation (at many wavel. and several directional angles), convection, …
- Check for flux constancy
- Iterate until T corrections are small
- Requires enormous amounts of opacity data from atoms, ions and molecules

Abundance accuracy ?



Looks nice but there are many uncertainties, both in the observations (solid line) and in the synthetic spectrum (dotted). Considering all uncertainties there may well be errors of a factor of two or more in absolute abundances derived in an evolved, luminous, and cool star like this one.

Uncertainties

- Data reductions
- Model fundamental parameters: effective temperature, surface gravity, overall metallicity
- Unjustified model assumptions
- Undetected stellar binarity
- Atomic/molecular data
- Too simple spectrum calculations
- Programming errors
- …

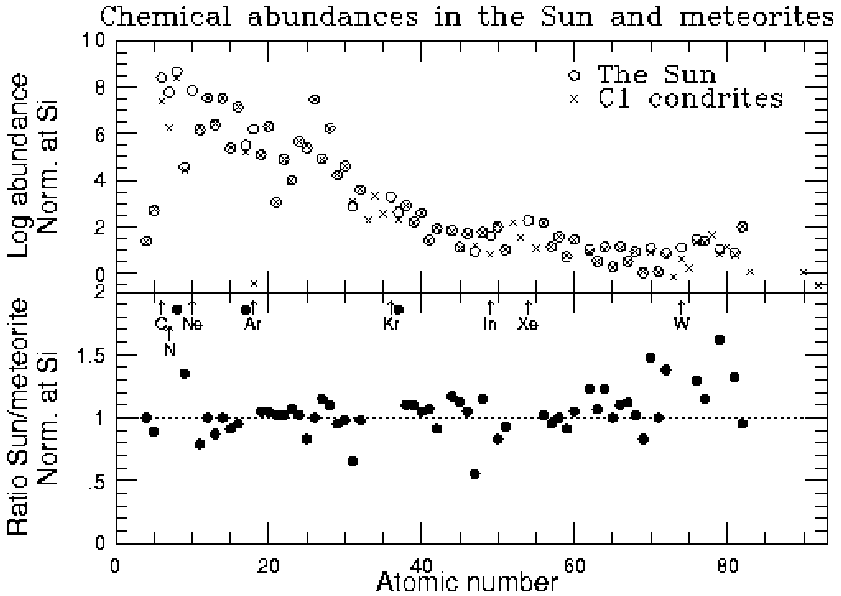
Consistency checks

- Compare different measurements of the same element; atoms, ions, molecules…
- Compare with other peoples´ results; observe some of “their” stars
- Try another synthesis code
- Make your analysis “differential”
- For the Sun: compare with meteorites

Also: if there are systematic trends in abundances derived from lines of a single species, e.g. as a function of excitation energy, wavelength or line strength, this may indicate errors in the assumed effective temperature, the model atmospheric structure, the data reductions, or the ”microturbulence” parameter.

”Diferential” means that it is preferable to seek ”differential” abundances relative to a (well known) star with similar properties: Use the same spectrograph and data reductions, use the same spectral lines, do the analysis with the same line data and model atmosphere using the same programmes. Present the abundances relative to the reference object, since errors and uncertainties will be similar and probably go in the same direction for both objects and be largely cancelled out in the comparison.

The best we can do: The Sun



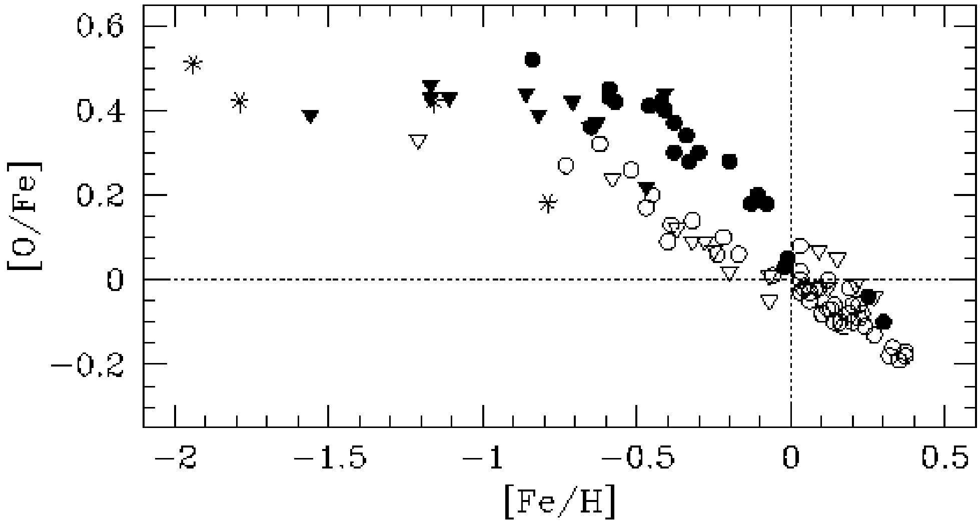
Ref. Asplund et al. 2006, Nucl. Phys. A, in press

Volatile elements like H, He, noble gases, C, N and O readily escape from and were often hardly included in meteorites. Therefore some more refractory element (here Si) has to be used for normalization between the two data sources. We can not say whether the differences are errors in the analysis or actual differences: The formation of the C1 condrites in the protosolar disk is not a very well-known process, and there may be small effects of diffusion in the Sun whuch have accumulated for 4.5 Gyr. Over the years, however, the differences between meteorites and the Sun have generaly diminished for refractory elements.

Spectroscopically almost exclusively element abundances are reported. For a few elements atomic or ionic line profiles may be used with very high spectral-resolution observations to determine isotopic abundances. In several other cases molecular lines show large isotopic wavelength differences which may be utilised for isotopic abundance determnations.

Oxygen in the thin and thick disks

Bensby et al. 2004, Astr. Astrophys. 415, 155,
Nissen et al. 2002, Astr. Astrophys. 390, 235.



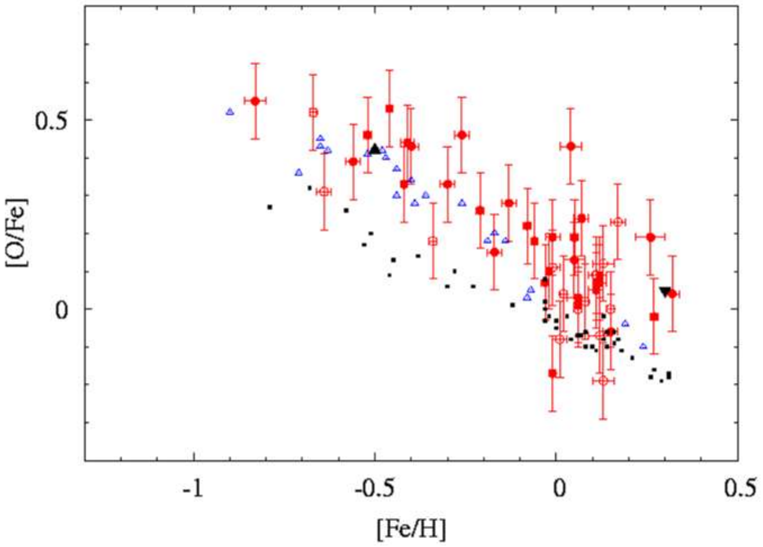
Oxygen abundances from the weak forbidden [O I] line at 630.0 nm in stars similar to the Sun. Spectroscopic abundances measure the number of atoms of an element rather than the mass. The standard spectroscopic notation [X/Y] is the logarithm of the ratio of element X over Y normalised to zero for the (reference) ratio in the Sun; the Sun is implicitly at the origin. The horizontal dotted line indicates a (not observed) solar ratio of oxygen to iron independent of the iron abundance (which is often used as a readily measurable proxy for the overall stellar metallicity).

Since these analyses were made differentially to the Sun which is of the same stellar type, these are among the most reliable stellar abundances available. The solid and open circles, respectively, represent abundances in individual stars of the “thick” and the “thin” disks of the Galaxy in the immediate solar vicinity. The error bars are extensively discussed in the references.

- Good for nearby sun-like stars
- More difficult for luminous giants: Barbuy et al. (2003, Astrophys. J. 588, 1072) for the nearby "template giant" HD122563 found abundances differing by factors of 2 and 3 using three different oxygen abundance criteria

Oxygen in the galactic bulge

Zoccali et al. 2006, Astr. Astrophys. L., submitted



The red symbols with error bars show oxygen abundances derived from the [O I] 630.0 nm line for luminous red giant stars in the bulge of the Milky Way. The blue triangles and the black dots are basically the thin and thick disk star abundances shown in the previous figure. Since the Bulge stars are quite different from the solar type stars used for the disk studies, the absolute level of the (red) Bulge star abundances have a considerable systematic uncertainty relative to the disk stars. The line is sensitive to the surface gravity which is uncertain due to uncertainties in the relevant turbulent pressures to use for luminous stars. Differentially, however, the Bulge stars are probably rather well positioned relative to each other.

Conclusions

- Be cautious in using abundance results
- "Differential" abundances most reliable
- There are many really excellent studies
- The observations are improving rapidly
- On the analysis side the progress is in many ways impressive but slower due to a rather small number of (small)active research groups