Essentials of Optical Astronomical Spectroscopy

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1 Overview

Our knowledge of the universe, indeed even of our immediate surroundings, comes through interactions with it based on the fundamental forces: gravity, electromagnetism, the strong and weak nuclear forces, and perhaps dark energy.

It is almost exclusively through information conveyed in light and detected by light-matter interactions that astrophysics has developed a self-consistent understanding of our universe over unimaginable distances, looking back almost to its origin, and projecting its ultimate fate. There are four key resources for the analysis of light based on the detection of the properties of photons

Astrometry determining the direction from which the light comes

Chronometry determining the precise time of signals in light

Photometry determining the flux across broad spectral bands

Spectroscopy determining flux of light versus wavelength, frequency or photon energy

Polarimetry determining polarization of light

Astrometry enabled chronometry through the use of Earth's rotation as a time keeper, and it yielded parallaxes that gave the distances to stars. It remains an essential component today, exemplified by efforts to resolve very fine detail at planetary, stellar, and extragalactic distances.

Chronometry is easily dismissed as time keeping, but it is really the addition of time to every measurement of a property that we make. Thus it is the measurement of extragalactic redshifts, the variations in apparent wavelengths due to velocities of planets orbiting stars, and the sudden events which occur in the interplanetary medium and on our Sun that are encompassed by this category. Measurement of time and temporal correlation is the basis of understanding patterns and connecting the present here with the past elsewhere and the future someplace else.

Photometry enabled determination of star temperatures, the size of the Milky Way, and distances to galaxies. It could be dismissed as a cousin of spectroscopy, but the intent of giving it a category of its own is to emphasize its broad sweep. For those searching for extrasolar planets, it is the most productive method we have of finding them and measuring their sizes. It is a key to unlocking the evolution of stars and characteristics of clusters and groups of stars, of identifying interstellar dust, and of measuring the expansion of the universe at its detectable edge. Furthermore, photometry can be calibrated across the entire spectrum, yield a spectral energy distribution (SED) which on its own may reveal otherwise hidden secrets about the source.

Spectroscopy provided the compositions of stars and galaxies, their line of sight velocities, and the size and age of the universe. This category emphasizes precision in the details, while photometry is big picture. The current technology can find the reflex motion of a star as a consequence of the tug of a companion planet that changes its speed by less than 1 m/s. That's the speed of a fast walk, and improvements are being developed to reduce the error to cm/s where there is enough light to make the measurement. It tells us precisely how much of which elements and molecules are present, and with physics validated in the laboratory, also can tell us the degree of ionization, the temperature, the density, and the magnetic field in the source.

Polarimetry, while less often used because of technical difficulty, yielded measurements of magnetic fields, stellar environments, dust, and starbirth. The causes of polarization of light from astronomical sources are the dependence of scattering efficiency on polarization, and the Zeeman effect which splits energy levels of atoms and molecules in the presence of magnetic fields. Both are very well understood at a fundamental level, and have subtle but detectable consequences for photometry and spectroscopy. The combination of methods, sometimes termed *spectropolarimetry*, allows mapping of the surface of a star and measurement of the spaceweather affecting the planets that it hosts.

Each of these, along with other categories such as gravitational wave, cosmic ray, and now in situ planetary science, deserve a focused review. Here we look at the essential elements of astronomical spectroscopy, especially of stars.

2 Physics of spectroscopy

While spectroscopy is ubiquitous throughout many fields of astrophysics, it is fundamentally physics, with applications including these that may already be familiar

- measuring time
- determination of atomic structure and its implications for electrodynamics and quantum mechanics
- elucidating how atoms interact
- identifying the structure of molecules and their vibration, rotation and dissociation

- measuring the density, temperature, and turbulence in plasmas
- determining magnetic fields through the Zeeman effect
- determining velocities through the Doppler effect
- determining composition through spectrochemical analysis

Each of these would depend on the dual nature of light, which is to say that it can have wave properties associated with time dependence

$$\lambda = c/\nu \tag{1}$$

while also having particle properties of photons with energy

$$E = h\nu \tag{2}$$

and momentum

$$p = h\nu/c \tag{3}$$

Its quantum nature depends on Planck's constant h, one of the universal constants on which our understanding of nature rests. The speed of light c is the same for every observer, everywhere in the universe, for all time. In our Systeme International of fundamental constants and units, c is no longer a measured quantity and it is set to a fixed value while other constants are adjusted based on experiments to establish a consistent framework for physics. This encompassing and interconnected system is highly dependent on spectroscopy because it connects time, space, and energy at a fundamental level. A consequence is that wavelength and frequency are equivalent measurements in the laboratory. That is why "measuring time" is first on my list above. The time unit of a second is based on the frequency of an atomic state transition in cesium, and consequently spectroscopy is a key but unseen component of daily life. One cycle of a constant amplitude, single-frequency, monochromatic electromagnetic radiation that lasts forever has a period $\tau = 1/\nu = \lambda/c$ from the frequency of that radiation.

More generally, there is a distribution of frequencies in light because, on a time scale of the period, the phases of the sources are disrupted by atomic collisions, and because we observe an ensemble of atoms that are in motion relative us and to one another. The spectrum we see is then a sum of components taken over the duration of the observation. There is more on this below in the context of Fourier analysis. Conceptually we treat all but the emission and absorption of light classically in the context of electromagnetic radiation theory while treating the process of emission, interaction with matter, and detection quantum mechanically. This semiclassical approach remains the basis for most treatments of radiative processes in astrophysics. Nevertheless, a complete theory of quantum electrodynamics exists and is used for many applications of spectroscopy, including quantum computing and other instances of "spooky action at a distance."

In optical spectroscopy, broadly from the far ultraviolet to the near infrared, the standard physics unit of wavelength is the nanometer, nm. Historically, and still widely used, it is the

Angstrom, Å. So the green spectral line of mercury atoms has a wavelength of 546.1 nm or 5461 Å. Here are a few others you should know too [1]:

5461 Å Mercury green line

4358 Å Mercury blue line

2537 Å Mercury near UV line (ionizing or germicidal light)

1850 Å Mercury resonance line (strongest transition to the ground or lowest energy state of the atom)

The paper by Saloman (2006) which is available online is an example of how much research has gone into determining the spectra of atoms, their energy levels, and transition probabilities. Much of it was done throughout the 20th century in parallel with the development of quantum mechanics. Consequently we know the spectra of neutral atoms very well, and also the spectra of singly ionized atoms. Optical spectra are largely a consequence of transitions of the valence electrons, the ones most easily removed from an atom. At elevated temperatures one or more of them may be lost, and the species emitting most of the spectrum of that element will be its ion. Typically the strongest spectral features will be from the neutral atoms except when the temperature of the gas is high enough to ionize that species.

Other neutral atom spectral lines of note in astrophysics are these for hydrogen

6562.8 Å Balmer α of atomic hydrogen

4861.4 Å Balmer β of atomic hydrogen

1215.7 Å Lyman α the resonance line of atomic hydrogen

1025.7 Å Lyman β the second member of the principle series of atomic hydrogen

and these for other elements

10830 Å Infrared line of atomic helium

5875 Å Yellow line of atomic helium

5895.1 Å Sodium D1 resonance line

5890.0 Å Sodium D2 resonance line

5183.6 Å Magnesium b1 resonance line

5172.70 Å Magnesium b2 resonance line

5167.33 Å Magnesium b4 resonance line

584 Å Resonance line of atomic helium

Calcium ion are prominent in stars [2]

8662.1 Å Calcium II infrared triplet

8542.1 Å Calcium II infrared triplet

8498.0 Å Calcium II infrared triplet

3968.47 Å Calcium II H line

3933.66 Å Calcium II K line

and lines of ions, some highly ionized are seen in the gaseous nebulae and elsewhere

6716 Å S II in nebulae

6731 Å S II in nebulae

5007 Å Oxygen III forbidden line in airglow and nebulae

Two books that cover spectroscopy from the physics and the astronomical sides of the field are Anne Thorne's *Spectrophysics* [3] which is now old but still in print and relevant, and Hearnshaw's history of astronomical spectroscopy [4] that provides a remarkable overview of how spectroscopy evolved as astrophysics' leading analytical too. For the spectra and physics of nebulae and active galaxies, the standard reference is Osterbrock and Ferland's study [5]

Nomenclature

At this point, if you are not a spectroscopist yet, you will be puzzling about the labels and terms already. For neutral atoms we speak of the "first spectrum" and designate it with a Roman numeral "I" to indicate it is from the neutral atom. The wavelengths given above for mercury would be labelled as Hg I, for example. The wavelengths of singly ionized He, that is of He^+, would be He II. Each step of the ionization is called a "stage", and the spectra of the ion would be said to be from the first stage of ionization.

In neutral atomic hydrogen, the different series of lines have patterns that led to the Bohr model of the atom and from that to quantum mechanics. The visible spectrum was discovered and analyzed first. That series is named after Johann Balmer who figured out the pattern. In order, the hydrogenic series are Lyman, Balmer, Paschen, Brackett and Pfund, all named after the physicists who first worked on them. The Lyman series is in the vacuum ultraviolet; the Balmer series is in the visible, and the Paschen series is in the near-infrared.

The strongest line in spectrum is called the resonance line because it is classically associated with a resonant oscillation though today we know it is simply the most probable transition between atomic states. The resonance lines of atoms are those that end on the lowest energy state, the ground state, and make an allowed transition to the next highest state. The sequence of lines within a series identifies the member and starts with the label

α. Balmer α is the first member of the Balmer series. Higher series members are transitions from the same lower state to higher excited states and have shorter wavelengths than the first member of the series.

The letter designations are the Fraunhofer line names, the ones that Joseph von Fraunhofer assigned when he discovered that they were intrinsic in the solar spectrum and could be associated known atomic spectra. For the most part, these are not often used anymore, except a few prominent ones. The sodium D doublet and the calcium H and K lines are examples of naming you will see in the astrophysics literature.

3 Vacuum wavelengths and energy

Often unsaid in astronomy, wavelengths of visible light are usually measured in air, but the fundamental wavelength of interest in physics is the one light would have in a vacuum. The connection between them is the index of refraction of air, the ratio of the speed of light in a vacuum to its speed in air where it is usually slower.

$$n = c/v \tag{4}$$

Because light slows in air while keeping its frequency constant, the wavlength shortens

$$\lambda_{air} = \lambda_{vacuum}/(1.0 + 2.735182 \times 10^{-4} + 131.4182/\lambda_{vacuum}^2 + 2.76249 \times 10^8/\lambda_{vacuum}^4) \tag{5}$$

This is a variation of an equation known as "Edlen's formula" which also includes the atmospheric pressure, temperature, and humidity at the time of the measurement. It is important to realize that a measured wavelength in air does depend on the environment, notably on atmospheric pressure. This factor has to be allowed for when comparing observed and known wavelengths, and making precision measurements of velocities from the Doppler effect. Expressions for the index of refraction of are discussed by Morton in his paper on wavelengths of resonance lines [6]. Wavelengths given in research papers are usually in standard air when they are above 2000 Å, unless otherwise noted.

For a wavelength in vacuum, there is a connection with the energy of the photon and the change in the energy of the emitting atom. The two energies are not the same because of the Doppler effect and atomic recoil to conserve momentum. The energy of the photon for which the measured wavelength is λ in a vacuum is

$$E = h\nu = hc/\lambda \tag{6}$$

The value of $1/\lambda$ is proportional to the energy and does not depend on the constants h and c. It is called the "wavenumber" because it is really the number of wavelengths per unit length. For example, light with a wavelength of 5000 Å, 500 nm, has a wavenumber of 20,000 cm^{-1}. Atomic physicists use the symbol

$$\overline{\nu} = 1/\lambda \tag{7}$$

for it.

4 Doppler shifts

Each frequency that we observe is affected by our motion relative to the source. This is termed the Doppler effect, named for the scientist credited with explaining it for light. The explanation for light is much more complex than for sound, though the usual one for sound works at velocities small relative to the speed of light. Dopplers work was pre-relativistic in the first part of the 19th century. The derivation should recognize that light travels at the same speed seen by the observer and the source, and the solution requires consideration of special relativity. Add quantum theory, and it turns into a conservation of momentum problem in which the emitted photon carries momentum and its conservation requires a minuscule recoil of the source. The Doppler shift we observe, in the quantum picture of light, is the loss of photon energy compared to the energy difference of the atomic states, to provide that recoil energy. Our observation of this effect depends on our velocity, and somewhat amazingly, at low v/c it matches the classical wave theory Doppler formula that also works for any wave, including sound, if its speed is c in this formula

$$\Delta\nu/\nu = -v/c \tag{8}$$

The sign is such that v is positive for motions of the source away from us. Frequencies decrease and wavelength increase in proportion to v/c

$$\Delta\lambda/\lambda = +v/c \tag{9}$$

At larger v the correct relativistic relationship is

$$\nu = \sqrt{\frac{c-v}{c+v}}\,\nu_0 \tag{10}$$

5 Transition probabilities and symmetry

An electronically excited state of an atom or molecule is not usually stable. When an atom in its lowest energy level absorbs light and goes into a higher energy level it will not stay there for long. Similarly, an atom that has an inelastic collision with an electron and leaves that event in an electronically excited state, will soon radiate away some or all of that energy as a photon. The transitions between states is governed by conservation laws of energy, parity, charge, momentum, and angular momentum. The conservation laws are in turn related to symmetries and some transitions that would seem likely because of the energy change are not possible because they would break the symmetry of the system. The strength of an observed spectral line is proportional to the probability of a transition in the quantum since of one atom at time, which determines the lifetime of the state. Resonance lines arise in transitions that have excited state lifetimes of nanosecond (10^{-9}s) scale. Higher lines of of a series have longer lifetimes and are weaker in spectrum.

Angular momentum and parity conservation requires that atoms change their total orbital angular momentum when they emit a photon, in part because a photon carries away $1\hbar$ of angular momentum from the atom as well as the energy change. This simple rule means that there are other series of patterns in spectra that make a transition to the ground state. For sodium as an example, the one active electron will be an s, p, d or f electron if it has 0, 1, 2 or 3 $\hbar$ angular momentum. Its lowest energy state is 3s, the next highest is 3p and then the others – 3d, 4s, 4p, 4d, 4f, and so on. The "principle series" of spectral lines is for transitions to the 3s state from every possible excited np state, and it begins at the resonance line (the Na D-lines) extending to short wavelengths with diminishing line strength until the series limit at which the atom is ionized. The ionization energy of sodium is 41449.451 cm^{-1} and the wavelength of the series limit for which the D-lines are the first member would be 2413 Å. Also in the case of sodium atoms the valence electron has a spin of 1/2 and in a p state it has an orbital angular momentum of 1. The combined total angular momentum of the electron is either 3/2 or 1/2, summing the to components of angular momentum using the rules of quantum mechanics. This means there are actually two first excited states for a p electron, with two different total angular momenta. They have slightly different energies because of the energy associated with the magnetic coupling of the spin and orbital magnetic moments. The result is two spectral lines, and the doublet with D1 and D2 components in the spectrum of the Sun.

The hydrogen lines also have fine structure, and the Lyman series of atomic hydrogen is analogous to the sodium principle series that we see in the visible. The Balmer series with higher states is more complex with components for both p and d states, but these blend with the observed spectra line in stars. Two series limits for hydrogen affect what we observe in stars and galaxies greatly. The Lyman series converges to a limit at the ionization energy of the hydrogen atom, 109678.7717 cm^{-1} or 911.7 Åin the extreme ultraviolet. Photons energy higher than that, wavelengths shorter than that, will remove the electron from any free hydrogen atom they find. Radiation with shorter wavelengths or high energies is absorbed by atomic hydrogen in a galaxy, creating a distinctive signature in the spectrum. The other limit for hydrogen that is important for stars is the Balmer series, which ends on the first excited state, rather than the ground state. Since that state is at about 82559 cm^{-1} for 2s and 2p, the allowed transitions from the ns, np, and nd states with $n \geq 3$ have energies up to $109679 - 82559 = 27120$ cm^{-1}, a wavelength of 3687 Å for the Balmer series limit. Light more energetic than that limit will be absorbed by hot hydrogen gas that has many excited atoms, a condition found in stars like the Sun.

6 Fourier transforms briefly

You may have covered this topic in a calculus class, a separate math class on Fourier analysis, or in math physics classes. Or, you may have not seen it at all yet. Since this is written for the observational astrophysics class and is not meant to be a comprehensive treatment, let us take an aside moment and consider the analysis of frequencies in time-dependent data. For example, it is obvious that an oscillating electric field might be presented by $E_0 \cos(2\pi\nu_0 t + \phi_0)$ if it had a frequency f_0, an amplitude E_0 forever, and a fixed phase ϕ_0. The energy conveyed by this field is proportional to its square and would be observed averaged over many cycles of the oscillation. That is what we detect in a classical sense, but in the quantum sense we detect a number of discrete photons at distinct arrival times, each with an energy $h\nu$. The number we count, multiplied by $h\nu$ must be the same, on average, that classical electromagnetic theory predicts for the energy in the wave.

If we take the spectrum of the light and sort it by wavelength, we are sorting photons by energy. The distribution of photons across the spectrum will be that of the distribution of energy by frequency or by wavelength $\lambda = c/\nu$. A spectrum of amplitudes as a function of frequency is the *Fourier transform* of the time-dependent process. However we since observe energy, not amplitudes, in optical spectra, the description has added factors. In a real light source like a stellar atmosphere, there are many atoms contributing to the total flux of photons we observe, those atoms are not emitting in step, that is the light is incoherent, and they are subject to random processes of collision that jostle them into emitting light with phases that are interrupted, frequencies that are interrupted by subtle changes in the energies of interacting atoms, and Doppler shifts due to motions on a microscopic, macroscopic, or total object scale.

The outcome of these treatments is that the observed spectrum is the Fourier transform of a correlation function. Here, briefly, is a way to see how that happens. Take one atom emitting a frequency ν_0. Its phase may vary with time because of external influences and the power it radiates would be

$$P(\nu) = \frac{4(2\pi\nu)^4}{3c^3} I(\nu) \tag{11}$$

where

$$I(\nu) = \sum \delta(\nu - \nu_{if}) \langle f|d|i\rangle^2 p_i \tag{12}$$

The frequency of the transition is ν_{if}. The delta-function δ is zero unless the frequency emitted matches the transition frequency. The electric dipole moment of the radiating atom is d. There is a probability p_i that the atom is in the initial state weighting each contribution, and a sum over all the atomic states that can contribute. In semiclassical radiation theory we can only find an emission spectrum. In stars we observer absorption too, and that is found by using the Einstein relations that govern radiative equilibrium. There is an implied average over the ensemble of atoms contributing to the spectrum. It is clearly getting complicated quickly, yet this is the complete emission of the source and is what we will observe. It is also given by a Fourier transform

$$I(\nu) = \int_{-\infty}^{+\infty} \Phi(s) \exp(-i\, 2\pi\nu s) ds \tag{13}$$

which will tell what frequencies are present [7]. That is what spectroscopy does, experimentally. It gives us the Fourier transform of the autocorrelation function of the light source. Conceptually, it provides a sequence of discrete frequencies corresponding to the atomic or molecular transitions that contribute to the spectrum, adding the continuum from the thermal blackbody radiation. In stars we see dark missing frequencies because the light is absorbed on the way to us, and scattered off in another direction. In nebulae we see the emitted light because the gas is thin and absorption is not consequential.

There is more. The correlation function depends on the ensemble average of all the atoms and is affected by how they are disturbed while they radiate, and by their individual Doppler shifts because of the relative motions of the atoms with respect to the observer. These two contributions redistribute the initially monochromatic radiation and broaden the spectral features. Rather than pure discrete frequencies missing from the spectrum of a star there are a wider absorption features, the breadths of which are determined by the temperature and pressure in the star. Of course if there is also a magnetic field present, then the energy levels of the atoms and molecules are split too, removing a an energy degeneracy in the projected angular momentum on a direction determined by the magnetic field. The spectrum in this case conveys information on both the field strength and its orientation with respect to the line of sight. In cases where the gravity is also very high, the slowing of time by general relativity creates a decrease in frequencies dependent on the location of the sources in the deep gravitational potential well.

To learn more about this you would likely study stellar physics and the atomic physics of spectral line formation. The book Stellar Photospheres by David Gray is recommended if you are interested in self-study [8].

7 Fraunhofer in 1814

Joseph Fraunhofer is remembered today for his discovery of the nature of the dark lines in the solar spectrum, for the development of precision telescopes that imaged stars without chromatic aberration, for observing diffraction of light by apertures, and for using interference in a grid of wires to create spectra - the diffraction grating that is the heart of many astronomical spectrographs. Early in the 19th century he was studying glasses and measuring refractive power, that is index of refraction. He knew that by taking two different glasses with selected properties he could manufacture lenses that focused both red and blue light to the same spot. The key to this was to measure how the glasses refracted light for precisely repeatable wavelengths, and he found that dark lines in the solar spectrum were ideal for this. In 1814 he published a map of the lines, labeled with letters for each distinctive feature. It is reproduced in Fig. 1 from his paper [9].

This illustration, engraved in the publication, is remarkable in its detail. Notice how finely mapped the spectral features are, with the letters we still use today. From long wavelengths on the left in the near-infrared they start with A which is due to O_2 in Earth's atmosphere. C is hydrogen Balmer α in the red. D is the sodium doublet in the yellow. E is due to iron while b is from magnesium. F is hydrogen Balmer β. H is one of the two lines of ionized calcium in the near-ultraviolet. He has annotated the perceived colors below the drawing of the spectrum. At the far left where the wavelengths are above 7500 Å he writed "red", but he is actually perceiving infrared. Most observers would describe the hydrogen Balmer α as red, and he write "orange". Notably he sees into the ultraviolet too, with the H line below 4000 Å. Young eyes can see ultraviolet at these wavelengths, and Fraunhofer

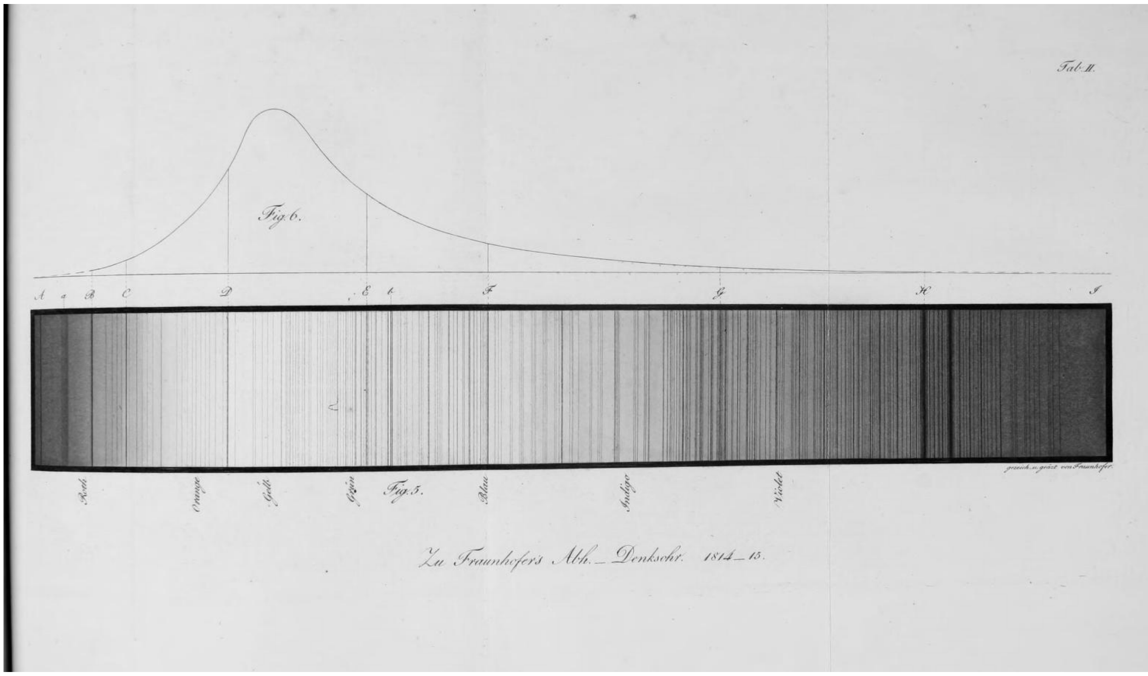

Figure 1: Fraunhofer's drawing of the solar spectrum.

was 27 years old at the time he did this work. The Sun as a light source provided enough light at the extremes of the spectrum to detect lines beyond the usual range of vision. The strength of the underlying continuum plotted above the spectrum and it too is remarkable for its accurate representation of the Sun's blackbody radiation which is absorbed by the atoms in its out atmosphere that redistribute the continuum and leave an absence of light where they have natural atomic transitions.

A modern version of the solar spectrum is shown in Fig. 2 rendered with color, and illustrating the use of a echelle spectrum that covers the full visible range with great detail.

This image is a digital recreation based on a solar spectral flux atlas made with a Fourier Transform spectrometer. That is, the color and the pattern of slices have been added to recreate a spectrum such as would be recorded by an echelle spectrograph. Wavelengths are increasing from left to right along each strip, and from bottom to top. Each of the 50 slices covers 60 angstroms, for a complete spectrum across the visual range from 4000 to 7000 angstroms. The Sun is a G2 star, and this image covers the same wavelength range in the same format as the spectrum of Procyon, type F5, and the spectrum of Arcturus, type K1 (or K2) that we will show below. At the center of the image, about 15 slices from the top, the dark pair of lines in the yellow are D1 and D2. The Balmer α Fraunhofer C line is the dark feature in the red at the upper right.

Figure 3 is a high resolution version of the spectrum of the sub-giant star Procyon, also known as Alpha Canis Minoris (spectral type F5). This image was created from a digital version of the an atlas created by photography with the Mount Wilson 100-inch reflector

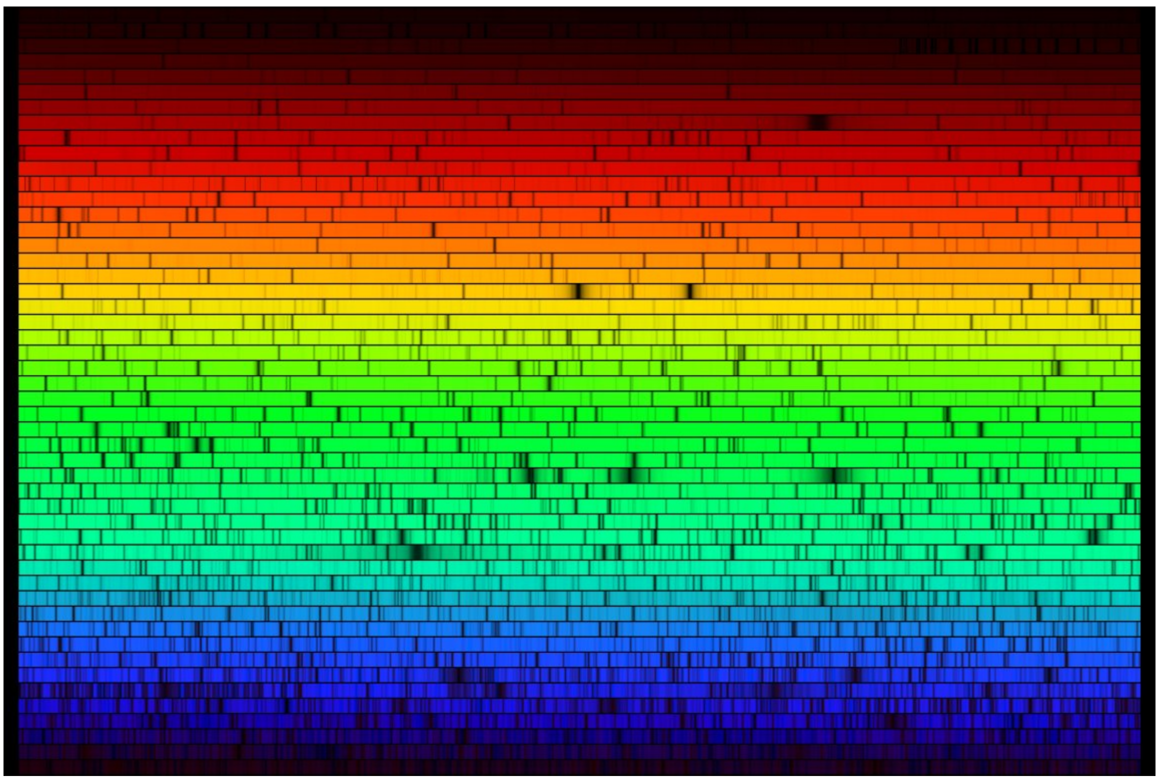

Figure 2: The solar spectrum. Credit: N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NST

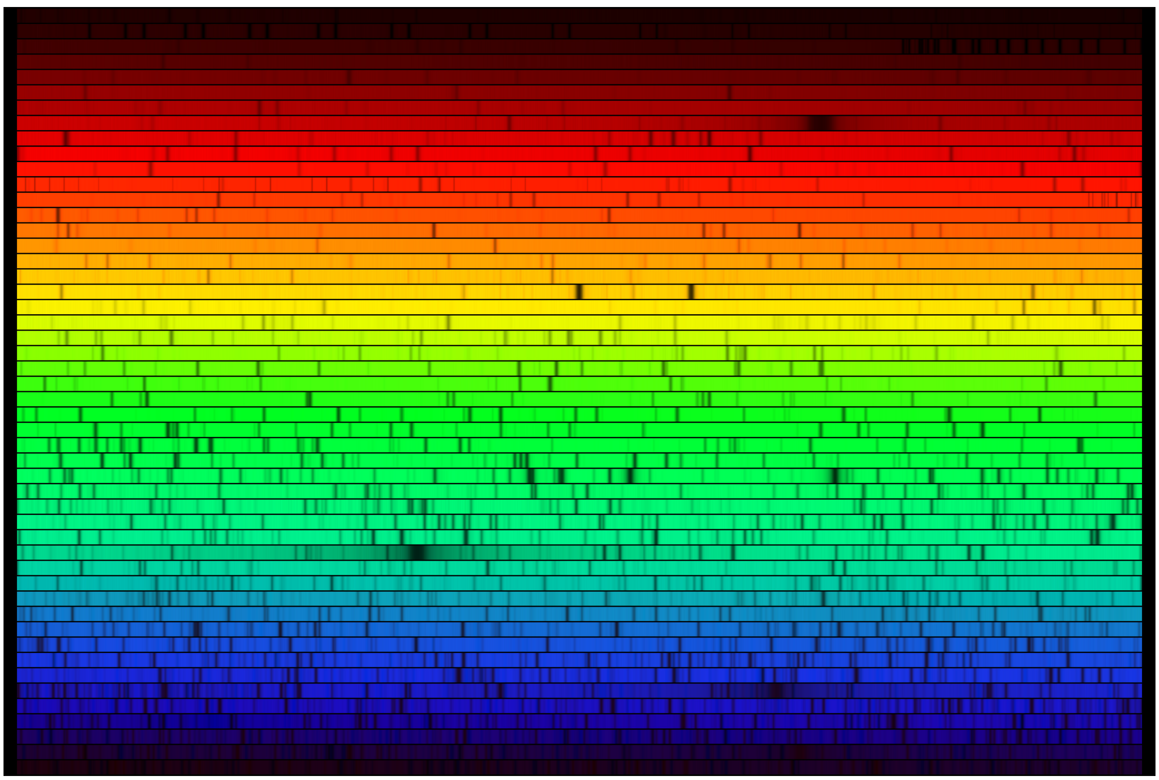

Figure 3: Spectrum of Procyon. Credit: R.E. and R. Griffin, N.A. Sharp, NOIR-Lab/NSF/AURA

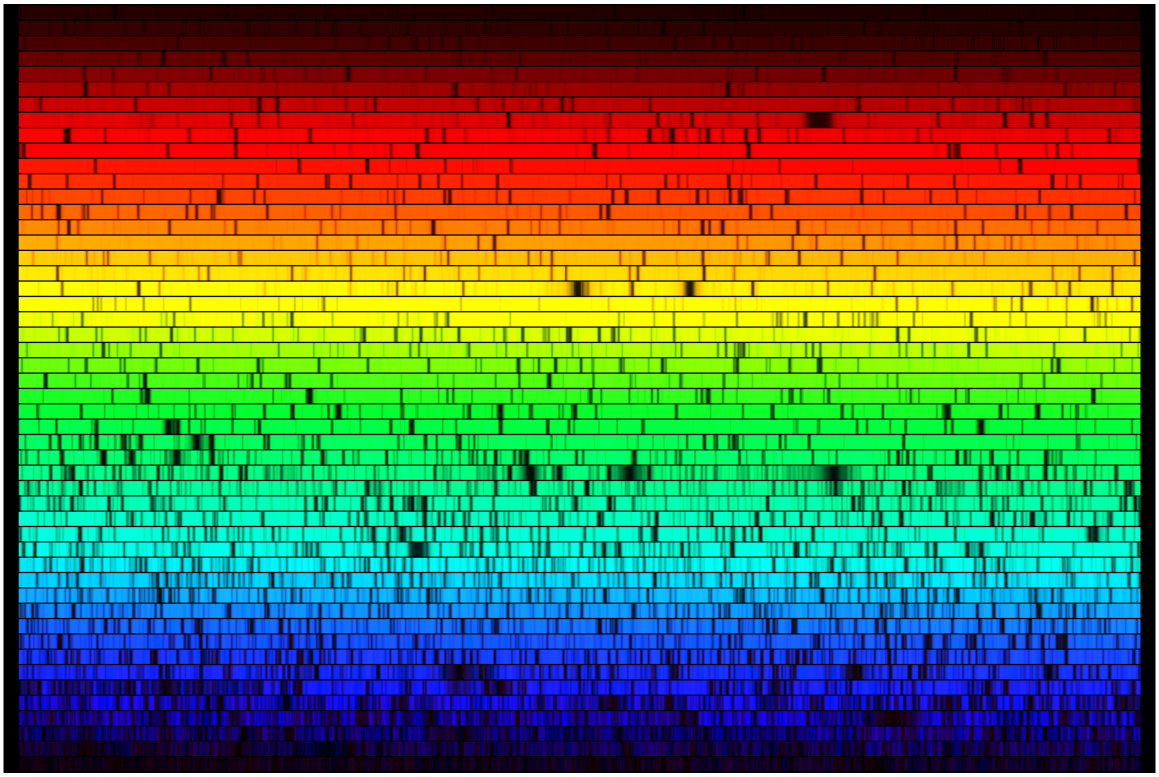

Figure 4: Spectrum of Arcturus. Credit: N.A. Sharp, NOIRLab/NSF/AURA

and published in 1979 [10]. As in the solar spectrum, the image mimics an echelle spectrum, with wavelength increasing from left to right along each strip, and from bottom to top. Each of the 50 slices covers 60 angstroms, for a complete spectrum across the visual range from 4000 to 7000 angstroms. The differences between the G2 star and F5 star spectra are subtle. Note the breadth and depth of the sodium and hydrogen lines.

Figure 4 is the spectrum of the prototypical cool giant star Arcturus, also known as alpha Boo (spectral type K1 III). This image was created from a digital atlas observed with the Coudé Feed telescope at Kitt Peak National Observatory, near Tucson, Arizona [11, 12]. As in the others, the image has wavelength increasing from left to right along each strip, and from bottom to top. Each of the 50 slices covers 60 angstroms, for a complete spectrum across the visual range from 4000 to 7000 angstroms.

Stellar spectra libraries

There are a few digital libraries of high resolution stellar spectra available. Although it is feasible to provide archival spectra of stars, it is rarely done except for examples of spectral types and selected bright stars. Extremely high quality spectra of Arcturus and Procyon were obtained by R. and R.E. Griffin and published as paper atlases. The images shown above are in part derived from that work. Contemporary high resolution stellar spectra are used for abundance determinations and radial velocity measurements. The data products are published but usually not the original spectra. This partial list of those available in October 2021 includes primarily the cooler spectral types that have rich spectra. The MAST archive has Hubble Telescope spectra in its database as well.

UVES POP ESO's UVES Paranal Observatory Project (POP), is an on-going program of acquisition, reduction, and public release of stellar spectra obtained with UVES at the VLT unit Kueyen.

ESO Bright Stars A compilation of high resolution spectra of bright stars in the southern sky was developed in 2002 and is static now.

Coudé Feed Library The Indo-US Library of Coudé Feed Stellar Spectra from Kitt Peak.

Elodie Archive This is the instrument at Haute Provence observatory with which Didier Queloz found the extasolar planet around 51 Pegasi. In 2019 he and and his doctoral advisor Michael Mayor received the Nobel Prize for their discoveries. Elodie was decommissioned in 2006.

References

[1] E. B. Saloman. "Wavelengths, Energy Level Classifications, and Energy Levels for the Spectrum of Neutral Mercury". In: *Journal of Physical and Chemical Reference Data* 35.4 (Dec. 2006), pp. 1519–1548. DOI: 10.1063/1.2204960.

[2] G. Smith and J. J. Drake. "Collisional broadening of the calcium infrared triplet lines by atomic hydrogen". In: *Monthly Notices of the Royal Astronomical Society* 231 (Mar. 1988), pp. 115–123. DOI: 10.1093/mnras/231.1.115.

[3] Anne P. Thorne. *Spectrophysics*. Dordrecht: Springer, 1999. DOI: doi.org/10.1007/978-94-009-1193-2.

[4] J. B. Hearnshaw. *The analysis of starlight : one hundred and fifty years of astronomical spectroscopy*. Cambridge University Press, 2014. DOI: doi.org/10.1017/CBO9781139382779.

[5] Donald E. Osterbrock and Gary J. Ferland. *Astrophysics of gaseous nebulae and active galactic nuclei*. University Science Books, 2006.

[6] Donald C. Morton. "Atomic Data for Resonance Absorption Lines. I. Wavelengths Longward of the Lyman Limit". In: *Astrophysical Journal Supplement Series* 77 (1991), p. 119. DOI: 10.1086/191601.

[7] Nicole Allard and John Kielkopf. "The effect of neutral nonresonant collisions on atomic spectral lines". In: *Reviews of Modern Physics* 54.4 (Oct. 1982), pp. 1103–1182. DOI: 10.1103/RevModPhys.54.1103.

[8] David F. Gray. *The Observation and Analysis of Stellar Photospheres*. New York: Cambridge University Press, 2005.

[9] Joseph Fraunhofer. "Bestimmung des Brechungs und Farbezerstreuungs Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre". In: *Denkschriften der Königlichen Akademie der Wissenschaften zu München.* 231 (1817), pp. 193–226.

[10] R. Griffin and R.E. Griffin. *A photometric atlas of the spectrum of Procyon, λ 3140 - 7470 Å*. Cambridge, England: Cambridge: Institute of Astronomy, 1979.

[11] R. Griffin. *A photometric atlas of the spectrum of Arcturus, λ 3600 - 8825 Å*. Cambridge, England: Cambridge Philosophical Society, 1968.

[12] Kenneth Hinkle et al. *Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 Å*. San Francisco: Astronomical Society of the Pacific, 2000.