Astronomical spectroscopy

Spectroscopy is the analysis of light as a function of wavelength; astronomical spectroscopy is the use of spectroscopy as a tool for obtaining observational data on the chemical compositions, physical conditions, and radial velocities of astronomical objects. Astronomical applications of optical spectroscopy from ground-based observatories cover the electromagnetic spectrum from the near-ultraviolet (0.3 μm) through the visible (0.4-0.7 μm) and into the near-infrared (2 μm). Space-based observatories, such as the *Hubble Space Telescope*, the *Far Ultraviolet Spectroscopic Explorer*, and the impending *Space Infrared Telescope Facility* extend spectroscopic observations from the far-ultraviolet (0.1 μm) to the far-infrared (100 μm). [In electronic version: insert the URLs:" http://www.stsci.edu" for *Hubble Space Telescope*, "http://fuse.pha.jhu.edu" for *Far Ultraviolet Spectroscopic Explorer*, and "http://sirtf.caltech.edu" for *Space Infrared Telescope Facility.*] Work at shorter wavelengths (x-ray and gamma-ray spectroscopy) and longer wavelengths (sub-millimeter and radio wavelengths) requires techniques other than those discussed here.

Usually a spectrograph is fitted to a reflecting telescope, which serves as a light collector. The image of the celestial body being studied is focused on the spectrograph slit, which limits the region under study (thus improving the spectral resolution) and reducing the contribution by the night sky. The diverging light beam then passes from the slit to a collimator (either a lens or mirror). This produces parallel light, which is then dispersed by a diffraction grating or prism. The dispersed light enters a camera, which focuses the spectrum on to a detector, either a charge-coupled device (CCD) in the case of an optical spectrograph, or an electronic array sensitive to infrared light.

Resolving power. The resolving power of a spectrograph is usually denoted by R, and is equal to the wavelength of light divided by the spectral resolution; e.g., $R = \lambda/\Delta\lambda$. The size of the spectral resolution element is set by the width of the slit, the grating, the focal length of the camera, and the detector resolution. Typically $R \approx 200$ for low-dispersion survey work, $R \approx 5000$ for "classical" spectroscopy, and $R \approx 50,000 - 100,000$ for the highest resolution work.

Multi-object spectroscopy. It is often desirable to obtain spectroscopy of many of the objects within a telescope's field-of-view in a single exposure. There are a variety of methods to accomplish such surveys.

Slitless spectroscopy. It is possible to take spectra of *all* of the brighter objects within the field-of-view by not using a spectrograph at all, but rather a low-dispersion dispersing element may be combined directly with the telescope. For instance, an objective prism may be placed in front of the telescope, which is often a Schmidt camera. Historically, slitless spectroscopy was used for large stellar surveys, e.g., the Henry Draper Catalogue and, more recently, the Case Michican Survey. Alternatively, a "grism" or "grens" (a hybrid between a prism and a grating) may be placed in the converging beam near the focal plane. Such spectroscopy is usually of low resolving power ($R \approx 100-500$), and is limited to the objects brighter than the sky background, as slitless spectroscopy has no way of attenuating the amount of sky seen by the detector. Nevertheless, the use of large-format arrays of CCDs which can minimize the effects of the sky background opens new, engaging possibilities in searches for faint, interesting objects.

Slitlet masks. Usually a picture is first taken of a region containing several astronomical objects of interest; the exact locations of these objects are then determined and small slits ("slitlets") are then milled in the corresponding locations in a metal plate. This plate is then substituted for the slit in a conventional spectrograph. Care must be taken that the spectra do not overlap; this usually limits the number of objects to 10 or so. Such systems have the advantage of good subtraction of the night sky, and very high efficiency.

Fiber-fed spectroscopy. Rather than milling slitlets in a plate, holes may be drilled instead, which are then pluged with optical fibers. (Such an arrangement is often referred to as a "plugboard".) The light is then transported via the fibers to a spectrograph mounted on an optical bench in a laboratory-like environment adjacent to the telescope. Alternatively, robotics may be used to position fibers in the focal plane; the fibers are then anchored to a metal plate via magnets. At the spectrograph, the fibers are arrayed in a line, and act as the spectrograph slit. Although significant light-losses may occur in this scheme (typically factors of 2-3), hundreds of objects can be observed simultaneously, leading to very effective use of the telescope. The faintest object that can be usefully observed is dependent upon how well one can calibrate the fiber-to-fiber transmissions, as separate fibers must be used to observe the night-sky.

Echelle spectroscopy. Normal spectrographs employ diffraction gratings that are intended to be used in low order (n =1, 2, or 3), with colored glass filters used to prevent overlap of adjacent orders. Echelle spectrographs differ from conventional systems in that they employ gratings intended to be used in very high orders ($n > 10$), resulting in very high resolving power. Normally these orders would fall on top of one another rendering the data useless. An echelle uses a second dispersal element, usually another grating but sometimes a prism, at right angles to the first, in order to separate the successive spectral strips from each other. A large range of wavelengths can be obtained in the format of nearly parallel segments, well suited for CCDs.

Coudé spectroscopy. Historically, high resolving power was achieved primarily by using a large, stationary spectrograph located off the polar axis of an equatorial telescope. Light would be brought through the hollow axis of the telescope by a series of flat mirrors (the coudé train). Coudé spectrographs are very stable, as they are located off the telescope, and the optics and gratings can be quite large as they did not need to be attached to the telescope. The use of echelles and fiber-fed bench-mounted spectrographs have largely replaced the coudé spectrograph; most modern telescopes are now built with altitude-azimuth mounts rather than equatorial mounts, leading to the further decline of coudé systems.

Integral field spectroscopy. In this application, a close-knit bundle of optical fibers is placed in the focal plane and is used to observe an extended astronomical object, such as a gaseous nebula or a galaxy. The light is transmitted via the fibers to a bench-mounted spectrograph. Although the fibers are arrayed in a linear array at the spectrograph, their locations in the focal plane are known, and sophisticated data reduction techniques allows the astronomer to reconstruct a spectral "image" of the object.

Fourier transform spectroscopy. Fourier transform spectroscopy, used particularly in the near-infrared, employs a concept entirely different from the spectrographs described above. Instead of being dispersed in a spectrograph, the light of a wide band of wavelengths is passed through a Michelson interferometer with variable spacing of its two apertures. The resulting interferogram, which is an electronic record of the interference signal produced by the interferometer as the separation of the apertures is varied, is converted into a record of intensity versus wavelength by a computer, and is of extremely high spectral resolution.

Spectrophotometry. Care can be taken to account for atmospheric light losses, and the resulting spectrum calibrated into physical flux units via observations of "spectrophotometric standard stars"—stars whose spectral energy distribution is known via comparison to laboratory sources. Such calibration removes the wavelength-dependence response of the telescope, spectrograph, and detector, and hence allows a direct comparison with model calculations, providing complementary information to that determined from analysis of spectral lines.

Spectropolarimetry. Measurements of polarization in continuum and line spectra often enable the recognition of nonthermal processes (such as synchrotron radiation) in the source. In many instances, they make it possible to assess the importance of light scattering by electrons or small solid grains.

Precision radial velocities. Measurements of the wavelength displacement, due to the Doppler effect, between the spectral lines in a celestial object and a laboratory source give the line-of-sight velocity of the source with respect to the observer. With conventional comparison sources (discharge tubes) and standard spectrographs, the precision of radial velocities is generally of order 1 – 3 km s^{-1}. However, recent improvements have pushed this to 15 m s^{-1} or better by using fiber-fed bench-mounted spectrographs, and/or by using absorption cells of gas (such as iodine) through which the starlight passes to provide an excellent internal reference system. The use of precision radial velocities, combined with dedicated observational programs, have resulted in the detection of planets around nearby stars, evidenced by small, periodic radial velocity variations in their parent stars. [In electronic version insert the following URL: http://www.physics.sfsu.edu/ gmarcy/planetsearch/planetsearch.html on "planets around nearby stars"]

Examples of astronomical spectroscopy. Here we will briefly discuss emission-line sources, absorption-line sources, reflection spectra, and the study of continuum energy distributions. The application of astronomical spectroscopy extends from solar system objects (the sun, planets, and comets) to Milky Way objects (stars, including binary stars, ordinary novae and cataclysmic variables; and gaseous nebulae, such as supernova remnants, H II regions, and planetary nebulae) to distant galaxies and quasars.

Emission-line spectroscopy. Rarefied gas seen against a cooler background will produce an emission-line spectrum. In gaseous nebulae, such as H II regions and planetary nebulae, gas is ionized by the extreme ultraviolet emission of hot stars. As the electrons recombine with atomic nuclei, emission-lines are produced. Spectroscopy of the gas reveals physical conditions (density, electron temperatures) as well as chemical composition. The strongest optical nebular lines are the hydrogen Balmer lines, plus forbidden lines of doubly ionized oxygen ("forbidden" in that these lines would not be seen at higher densities); forbidden lines of other elements are also usually present, in addition to neutral helium lines (Fig. 1).

Some stars also show emission-lines in their spectra, indicative of hot gas seen in extended envelopes or disks around these stars. Examples include Be stars and Wolf-Rayet stars.

Absorption-line spectroscopy. More commonly gas is seen projected against a hotter source, as is the case in a stellar atmosphere or in gas found in interstellar space seen against stars or galaxies. In this situation an absorption-line spectrum is produced.

The sun was the first astronomical object whose spectrum was analyzed; Joseph Fraunhofer discovered hundreds of dark bands superposed on an otherwise continuous range of colors in 1815. Subsequent analysis of the dark-line Fraunhofer spectrum allowed astronomers to deduce the solar chemical composition, the temperature, density values, and their variation with depth in the solar photosphere. Later discovery of the splitting of spectral lines due to the "Zeeman effect" demonstrated the existence of magnetic fields on the sun. The attenuated outer envelopes of the sun, the chromosphere and corona, require special instrumentation, as they are very faint compared to the bright surface of the sun.

Differences in the spectral appearance of stars is due first and foremost to differences in the effective temperature of stars (the temperature at the surface), and only secondarily due to surface gravity (pressure). Differences in chemical compositions are usually a tertiary effect, except for stars with significant chemical peculiarities. The spectra of most stars can be classified in a two-parameter spectral class and luminosity system. Strengths and appearance of different spectra lines supply classification criteria. Classification indices are usually temperature-sensitive lines; luminosity criteria are usually density-sensitive lines. Stars of high luminosity have lower atmospheric densities. The spectral sequence is described by letters O, B, A, F, G, K, and M, ranging from hot, about 90,000 °F or 50,000 °K to 4000 °F or 2000 °K, with decimal subdivisions. Luminosity classes range from I (very luminous) to V (main-sequence dwarf stars). The Sun's spectral class is G2 V, which means it is closer to G0 than to K0 and is a dwarf star. We illustrate here the spectrum of one of the hottest, most luminous stars known (Fig. 2).

Certain stars, particularly white dwarfs, have intense magnetic fields, whose strength can be measured by the splitting of spectral lines similar to that done for the sun, although without the possibility of spatial resolution over the disk of the star. In fact our appreciation of the importance of magnetic fields in astrophysics derives largely from spectroscopic data!

The presence of matter in interstellar space manifests itself in sharp, strong absorption lines. Despite the incredibly low density of gas found between stars, the distances to some stars are so great that the effective column depth can be appreciable. Among the strongest interstellar lines in the optical are the Ca II H and K resonance lines. Broad, diffuse interstellar bands are also seen, the strongest of which in the optical occurs at 0.443 μm. Both of these can be seen in the spectrum of the hot O3 I star above (Fig. 2). Incredibly luminous, distant quasars allow us to probe the conditions of the interstellar medium back when the universe was quite young, as their light passes through the interstellar media of a number of intervening galaxies.

Spectroscopy can be obtained of the resolved, luminous members of the very nearest galaxies; for all but this handful, the spectrum of a galaxy is a composite of its typically trillion stellar members. Such integrated spectroscopy can be analyzed by "population synthesis", in which a library of stars is mixed in appropriate proportions until something similar to the observed spectrum is seen. Such studies can place useful limits on the relative numbers of various types of stars, but whether the mix is a unique match to the integrated spectrum is often open to question without additional information.

Reflection spectroscopy. The spectra of solar system objects (other than the sun) are primarily reflected sunlight. Spectra of planets with atmospheres also show tell-tale lines of and bands of molecules which enabled us to assess atmospheric temperatures and densities in favorable circumstances. For instance, the presence of CO_2 in the atmosphere of Venus was established in 1932 from spectroscopic observations. The spectrum of comets show a reflection spectrum of the sun upon which are superposed bright bands of CN, molecular carbon, and other molecules. They also show intense fluorescence effects.

Continuous energy distributions. In addition to the spectral lines, the energy distribution of the continuum—the light between the spectral lines—often provides information about the physical conditions which is highly complementary to the information that can be gleaned from the spectral lines themselves. Measurement of the intrinsic continuum shape requires use of spectrophotometry (discussed above), and the ability to correct for any reddening due to interstellar material. The continuous energy distribution will sometimes reveal limitations in stellar atmosphere models that would otherwise cause analysis of the spectral lines to yield misleading results. In addition, the continuous energy distribution, particularly over a large wavelength interval, is necessary for population synthesis to produce unique results. **Philip Massey and Lawrence H. Aller**

Bibliography: L. H. Aller, *The Atmospheres of the Sun and Stars*, New York, Ronald Press, 2nd ed., 1963; P. M. Gray, (ed.), *Fiber Optics in Astronomy II*, San Francisco, Astronomical Society of the Pacific, 1993; C. R. Kitchin, *Optical Astronomical Spectroscopy*, Bristol, Institute of Physics Publishing, 1995; A. D. Thackeray, *Astronomical Spectroscopy*, New York, Macmillan Company, 1961.

Additional reading list:

L. H. Aller, *Atoms, Stars, and Nebulae*, Cambridge, Cambridge University Press, 3rd ed., 1991

L. H. Aller, *The Physics of Thermal Gaseous Nebulae*, Dordrecht, Kluwer, 1984

A. Aparicio, A. Herrero, and F. Sanchez (eds), *Stellar Astrophysics for the Local Group*, Cambridge, Cambridge University Press, 1998

S. C. Barden, *Fiber Optics in Astronomy I*, San Francisco, Astronomical Society of the Pacific, 1988

D. F. Grey, *The Observation and Analysis of Stellar Photospheres*, Cambridge, Cambridge University Press, 1992

J. B. Kaler, *Stars and their Spectra: An Introduction to the Spectral Sequence*, Cambridge, Cambridge University Press, 1989

G. Kuiper and B. Middlehurst (eds.), *Telescopes: Stars and Stellar Systems*, vol. 1, Chicago, University Press, 1960

W. A. Hiltner, ed., *Astronomical Techniques: Stars and Stellar Systems*, vol. 2, Chicago, University Press, 1962

C. Jaschek and M. Jaschek, *The Classification of Stars*, Cambridge, Cambridge University Press, 1987

G. W. Marcy and R. P. Butler, "Detection of Extrasolar Planets", *Annual Reviews of Astronomy and Astrophysics*, Vol. 36, pp.57-98

D. Mihalas, *Stellar Atmospheres*, San Francisco, W. H. Freeman, 1970

D. E. Osterbrock, *Astrophysics of Gaseous Nebulae*, Mill Valley, University Science Books, 1989.

D. J. Schroeder, *Astronomical Optics*, Orlando, Academic Press, 1987

G. Walker, Astronomical Observations, Cambridge, Cambridge University Press, 1987

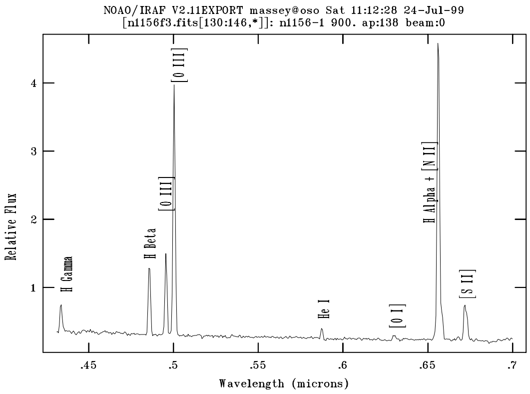
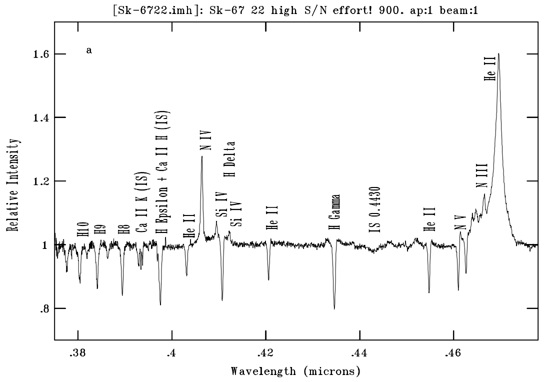


Fig. 1.— The spectrum of the largest H II region in the irregular galaxy NGC 1156. The continuum comes from the underlying stellar population. Forbidden lines of neutral and doubly ionized oxygen ([O I], [O III]), singly ionized nitrogen ([N II]), and singly ionized sulphur ([S II]) are visible.



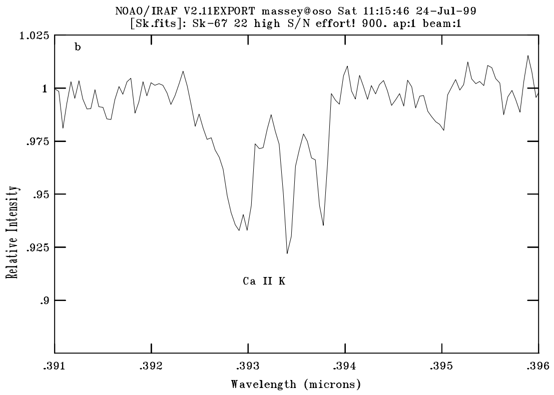


Fig. 2.— (a) The spectrum of the star Sk-69° 22, one of the hottest, most luminous and massive stars known, with a spectral type of O3 I. This star is located in the Large Magellanic Cloud (LMC), the nearest galaxy to our own. Absorption lines of hydrogen (H) and singly ionized helium (He II) dominate. The lack of neutral helium (He I), and the presence of four-times ionized nitrogen (N V), requires that the star's temperature be at least 50,000°K. The presence of emission lines of N III, N IV, Si IV, and the very strong, broad emission line of He II at 0.4686 μm, indicates that this star is of extremely high luminosity; these emission lines are formed in an expanding outer envelope of the star. Both the diffuse interstellar band at 0.443 μm and the Ca II H and K resonance lines are due to gas in the interstellar medium. (b) Detailed inspection of the Ca II K line shows multiple components, with radial velocities corresponding both to gas in our own galaxy and to gas in the LMC.

Figure Captions