How we know what we know

Steve Crawford explains how astronomers use spectroscopy to unlock the secrets of the Universe

Astronomers will describe the composition of a galaxy or report the discovery of a planet around our closest neighbour or measure the temperature of a star – but how do they learn these things? How do astronomers carry out the experiments that allow them to explore and investigate even the most distant objects or objects far too faint to ever be seen by the naked eye? The workhorse instrument of astronomers is the spectrograph, which separates light into its different components and revealing the underlying physics of the Universe.

Capturing dispersed light

Spectrographs are instruments that disperse light into its different components, allowing astronomers to measure the spectrum of objects. For anyone who has seen a rainbow, the basic phenomenon of spectra should be familiar to you: the light we see is composed of light at many different wavelengths and these wavelengths correspond to different colours. Red light has a wavelength around 700 nanometres, while blue light is around 300 nanometres. As sunlight is passed through water particles in the sky, light of different wavelengths is refracted (bent at different angles) and appears to be dispersed. Early spectrographs used prisms, that work on a similar principle, to make measurements of the spectra of different objects.

Today astronomers primarily use diffraction gratings to disperse the light: these are surfaces with small grooves in them (often hundreds of grooves per millimeter) that cause light of different wavelengths to reflect at different angles. The most modern spectrographs, like the Robert Stobie spectrograph on the Southern African Large Telescope, use volume phase holographic gratings, where the grooves are burnt into a gel by lasers.

In addition to the grating, a spectrograph usually includes several other components. Light from the telescope is fed to a slit or an optical fibre. This limits the amount of light being passed to the spectrograph and allows the astronomer to select the object they are targeting. Next, the light is collimated, which helps control how the light will be dispersed. The light is then passed to a prism or a grating where it is dispersed into its components. The highest dispersion spectrographs will resolve features in an optical spectrum to a hundred of a nanometre. This dispersed light is passed to a camera where it is then recorded electronically so it can be analysed.

Dispersed spectra can usually be broken into two components: a continuum and line component. From these different components, we can learn about the temperature, composition, and motions in different astronomical objects, which can lead us to know about the temperature, density, and size of these objects.

Continuum emission

For most objects, the continuum emission is dominated by blackbody radiation – the transformation of thermal energy into light. Essentially, any object that is opaque will emit blackbody radiation. The intensity of blackbody radiation peaks at a wavelength corresponding to a specific temperature. The peak wavelength is inversely proportional to the temperature. For example, the
Sun with a temperature of 6050°C peaks at 501 nanometres, whereas humans, with a typical temperature of 37°C, peak at 9.35 micrometres, corresponding to infrared light. Blackbody radiation becomes slowly less intense at wavelengths longer than its peak wavelength whereas the intensity diminishes rapidly at shorter wavelengths. The overall intensity depends on the temperature and surface area of the object.

Example of a blackbody spectrum with a temperature of 6050°C, similar to our Sun. The peak of the blackbody occurs in the optical wavelengths around 500 nanometres.

The continuum emission from stars is primarily blackbody radiation. As such, the temperature of stars can be determined from the shape of its spectra. If the distance to the stars is known and the measured flux can be converted into an intensity, then an estimate of the size of the star can also be made.

In addition to blackbody radiation, there are also other sources of continuum emission such as Bremsstrahlung emission (caused by the de-acceleration of a charged particle) and synchrotron emission (caused by a charged particle rotating in a magnetic field). These typically dominate the emission seen in the X-rays or radio waves, respectively, whereas blackbody radiation is usually the main source of continuum emission in the optical and infrared. These different types of emission reveal different properties about the objects being studied, like temperature, density, or the strength of the magnetic field.

Line emission

When an electron moves from a higher-energy orbit to a lower-energy orbit in an atom, a photon will be emitted with an energy corresponding to the difference in energy between the two orbits. Likewise, an atom can also absorb a photon moving the electron from a lower-energy orbit to a higher-energy orbit. Due to the quantisation of energy at small sizes, only orbitals with certain energies are allowed around an atom. As the energy of a photon is inversely proportional to its wavelength, the photons will have distinct wavelengths corresponding to the energy difference between these levels. In a spectra, this transition of an electron will show up as lines at a given wavelength.

The allowed orbitals around an atom are set by how many protons, neutrons, and electrons the atom has. For example, the energy levels of an electron orbiting deuterium, a nucleus composed of one proton and one neutron, are slightly different to the ones around a hydrogen atom, which has only a single proton. Following the same principles, the energy levels of the orbits around helium, with two protons and two neutrons, are approximately four times that of hydrogen. However, the energy level of the orbitals of neutral helium, with two electrons orbiting around it, are different from previously ionised helium, with only one electron orbiting around it. So, each element, and different configurations of an element, has a unique set of spectral lines, and these spectral lines act as ‘fingerprints’, allowing an element to be identified. This is how astronomers can determine the abundance of different elements in an object from the lines in its spectra obtained from optical telescopes.

From measurements of the abundance of elements in stars, astronomers can trace the evolution of our galaxy. The abundance of different elements in a star is related to the fraction of those elements in the gas cloud from which that star formed. Heavier elements are formed in the cores of stars and are ejected into the interstellar medium when a star dies as a supernova – the abundance of heavy elements in the gas clouds increases with each generation of stars. Stars that have formed recently are rich in heavy elements like carbon, oxygen, and iron, whereas the oldest stars have only trace amounts of the heaviest elements. Astronomers are still looking for the very first stars, if any should still exist, as those stars should not have any heavy elements at all.
Temperature and density
The strength of spectral lines is determined by a number of different factors. Some are set by quantum mechanics, such as how likely a transition is to occur, while others are determined by the density and temperature of the gas. For example, the hotter a gas is, the more likely its atoms will be ionised, which will result in a different set of emission lines from a cloud filled with neutral gas. The denser the gas is, the more likely it is that transitions are caused by collisions between atoms and not by the emission of a photon.

For example, the ratio of different oxygen lines in a spectrum of a planetary nebula reveals its density and temperature. If the density of the gas is high, then the collisions between the particles would further excite the electrons so that the electrons would never make the transitions that cause these lines. In the same way, temperature can regulate the number of collisions that occur and how likely we are to observe certain lines, which will give an idea of the temperature.

Motion of objects
Due to the Doppler effect, the spectrum of an object will shift with its velocity. For motions toward the observer, spectra will shift towards the blue and shorter wavelengths, while motions away from the observer will shift the spectra towards the red and longer wavelengths. By knowing the wavelengths of spectral lines to high precision and being able to measure their positions with high-resolution spectrographs, the velocity of objects can be measured to incredibly high precision. For example, the highest precision spectrographs today can measure velocities of objects to 1 m per second – comparable with walking speed.

The apparent motion of objects can be due to many different things – winds blowing material away from stars, outflows from the explosion of a supernova, the expansion of space – but for many objects this motion balances the force of gravity. For example, astronomers can measure the rotation of galaxies to measure the mass of the galaxy. For example, observations by Vera Rubin of rotating spiral galaxies were some of the first evidence for dark matter in galaxies: that galaxies were rotating far too fast for the amount of visible matter that could be observed.

One of the most exciting applications of spectroscopy is discovering new planets around other stars. Just as the Earth feels the pull of gravity from the Sun, the Sun feels the pull of gravity from the Earth. This causes a small wobble and the motion of this wobble can be measured using very precise, very stable spectrographs. Often kept in vacuum-sealed tanks to maintain a constant temperature and pressure and with resolutions of a hundredth or less of a nanometer, these spectrographs detect motions down to a level of centimeters per second. Recent radial velocity observations allowed the discovery of a planet orbiting around the habitable zone of Proxima Centauri, the nearest star to our own. The next generation of spectrographs will use even more advanced technology to provide even greater stability. This will allow the discovery of Earth-like planets around stars like our Sun.

Future of spectroscopy
These are just the some of the ways astronomers use spectroscopy to learn about our Universe. Future spectrographs and telescopes will further extend our knowledge by studying larger numbers of objects, fainter sources, higher resolutions, more precise velocities, and unlock wavelength regimes that have been unstudied. Currently, spectroscopy from SALT is helping to measure the mass of black holes, search for new planets, classify distant supernova, and measure the star formation in colliding galaxies. Future spectroscopy from the SKA will map even the farthest reaches of the Universe. While imaging produces some of the most beautiful images of our Universe, it is spectroscopy that lets us understand what we are seeing.

Steve Crawford completed his PhD at the University of Wisconsin in 2006, after which, he took up a research fellowship at the South African Astronomical Observatory that led to his current post as the SALT Science Data Manager. His research interests include galaxy evolution, observational cosmology, and developments for improving astronomical research. His early work has focused on observations of different populations in galaxy clusters. Currently he is working on a variety of different projects but most of his recent work has focused on the Southern African Large Telescope. He is also interested in site testing and adaptive optics, spectrograph design, and software development for astronomy.

Example of a spectra of a galaxy from the Sloan Digital Sky Survey. Different elements are labelled in the plot include hydrogen (H), oxygen (O), helium (He), nitrogen (N), and silicon (Si). Sloan Digital Sky Survey

Curriculum corner
Physical Sciences grade 10–12
Transverse pulses on a string or spring (pulse, amplitude superposition of pulses), Transverse waves (wavelength, frequency, amplitude, period, wave speed, Longitudinal waves (on a spring, wavelength, frequency, amplitude, period, wave speed, sound waves), Electromagnetic radiation (dual (particle/wave) nature of electromagnetic (EM) radiation, nature of EM radiation, EM spectrum, nature of EM as particle–energy of a photon related to frequency and wavelength)