Cosmic Fingerprinting: The Key to Understanding the Universe

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Spectacular astronomical images such as those obtained by the Hubble Space Telescope (HST) often appear in the news. Amazing detail is revealed and the light and shadow give the 2-dimensional image an almost 3-dimensional quality. However, in creating the image important information is being discarded that could be used to give a deeper insight into the physical processes at work in the object. This paper will outline how astronomers use the technique of spectroscopy to dig out this information, applying a range of the fundamental physical principles to interpret their data. Some specific examples of how spectroscopy is applied to understanding the Universe are presented.

The nature of light

Isaac Newton was the first person to demonstrate what we now know, that white light is not a pure and indivisible form of radiation. We most often experience this fact when viewing the colours of a rainbow, produced by refraction of light in water droplets in the atmosphere, but we can also recreate the effect artificially by passing white light through a prism. As Newton noted, when the light is passed through a second prism no further dispersion of the light is seen and recombined, with a lens, the individual colours produce white light.

All Newton's studies were applied to visible light. However, in 1800, Sir William Herschel (better known for his discovery of Uranus) carried out further experiments on sunlight. He was interested in how much heat passed through different coloured filters and set up an experiment to measure this, directing sunlight through a glass prism to create a spectrum. He then measured the temperature of each colour using a thermometer, placing two others beyond the spectrum as control samples. Measuring the temperatures from violet through to red he noticed that temperature increased towards the red end of the spectrum. He then decided to measure the temperature just outside the red portion of the spectrum, in a region apparently devoid of sunlight, and obtained an even higher temperature. With further experiments Herschel found that these "calorific rays" were refracted and reflected exactly like visible light. He had discovered infra-red radiation and established that the spectrum extended beyond the range of the human eye.

In the late 19th century, James Clerk Maxwell's theory of "Electricity and Magnetism" (published in 1873), proposed that light is an electromagnetic (wave) phenomenon and that visible light formed only a small part of the entire spectrum possible. Before the end of the 19th century, other forms of electromagnetic radiation (X-rays and radio waves) had been discovered and astronomers have now detected and regularly use "light" that spans around 18 factors of 10 in wavelength (see figure 1).

Even in Newton's time there was considerable debate about the nature of light, whether it existed as a wave or a "corpuscle" (=particle, Newton's view), and this continued for several centuries until the twentieth century and the birth of quantum theory. Even so, we have not decided between these two choices, but arrived at a kind of compromise, which is called wave-particle duality, where light can be represented by either or both descriptions. Hence, we can consider that light has the properties of both a wave and a particle, called a photon.

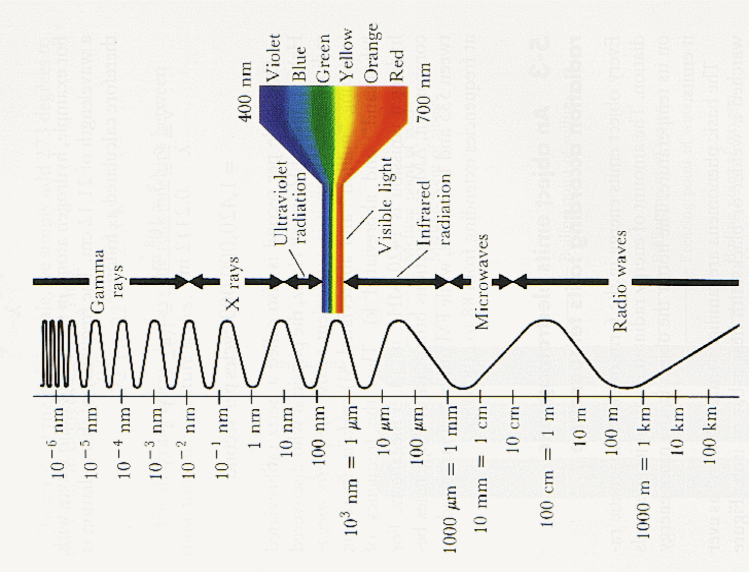

Figure 1. Schematic diagram of the electromagnetic spectrum showing the main distinct ranges and their wavelengths.

“Fingerprints” of the elements

At first sight a spectrum appears to convey little information. However, even in the basic “rainbow” we get from sunlight, we can see that the light is most intense in the central green/yellow colours and fainter in both the red and blue/violet regions. This is related directly to the 5,800K surface temperature of the Sun. We can simply estimate the temperatures of other stars by looking to see where in their spectra, the brightness peaks.

If we examine a spectrum of the Sun more closely, however, we will see much more information in the form of dark “bands” and “lines” at particular wavelengths, where there is little or no light present. For example, figure 2 shows a small section of the solar spectrum covering blue, green and yellow light, wavelengths from 4700Å to 5100Å. These features were first studied definitively in 1814, by Joseph von Fraunhofer. Not understanding their origin he labelled them with letter names, but he did notice the wavelength coincidence between his D line and a prominent line in a laboratory flame spectrum (now known to be due to sodium).

From work on flame spectra it was eventually realised that individual lines or groups of lines were associated with specific elements and that the dark (absorption) lines in the solar spectrum were due to the presence of such elements in the Sun’s atmosphere. Thus the main constituents of the Sun, and eventually other stars, could be identified. Indeed, the element helium was first found in the Sun, rather than on Earth, through several unidentified lines in the spectrum.

This “stamp collecting” approach to identifying absorption lines can only get us so far. An understanding of the physics underlying the line identifications was developed through the ideas of quantum theory, in the early part of the 20th century, and in which the idea of the particle nature of light is crucial. The basic ideas are encapsulated in the nuclear model of the atom, visualised to have a central nucleus with one or more electrons “in orbit” around it. However, the electrons bound in an atom can only have certain energies, which are known as electronic energy levels. Transitions between these levels lead to emission (electron moves from a higher to a lower level) or absorption of photons (electron moves from a lower to a higher level).

Containing just one electron, hydrogen is the simplest element and its line spectrum is the easiest to calculate. Some of the calculated energy levels, some possible transitions and an example spectrum are shown in figure 3. The more complex the atom (i.e. the more electrons it has), the more energy levels are available and, therefore, a greater variety of transitions can take place. So, while we see only a few spectral lines associated with hydrogen, we see many more for complex atoms such as iron. These patterns of lines are a unique “cosmic fingerprint”, from which we can identify each element.

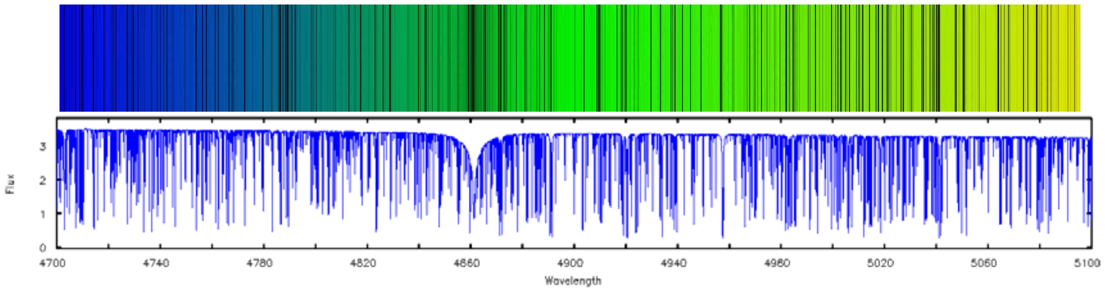

Figure 2. Part of the Solar spectrum, covering blue, green and yellow regions of the visible band, from 4700Å to 5100Å. The information is displayed a (top) a colour coded section of a rainbow, with the dark lines indicating the absorption lines present and (bottom) as a graph of the measured brightness of the Sun at each wavelength. It can be seen that the dips in the flux correspond to the dark lines. The broad absorption at 4860Å is a hydrogen line and two strongest lines between 4780Å and 4800Å are the calcium H and K lines (labelled by Fraunhofer).

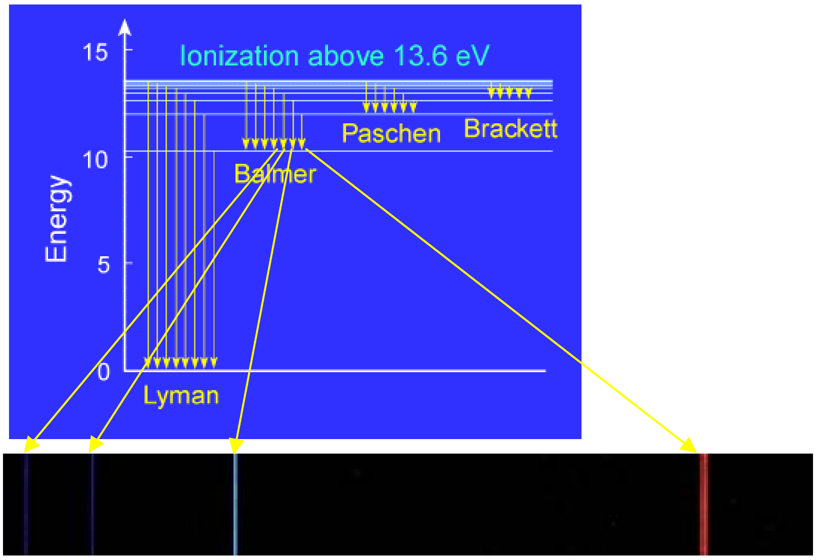

Figure 3. (Top) Energy level diagram of the hydrogen atom, showing some of the possible transitions that can take place between levels. (Bottom) The distinctive pattern of the hydrogen emission lines that appear in visible light.

White dwarfs and interstellar space

White dwarf stars are the end stage of the life cycles of most stars. They are the remnant cores of stars that were once like the Sun and have collapsed to become extremely compact, typically around the same radius as the Earth, and very dense (10^8 kg m^{-3}, compared to 5,400 kg m^{-3} for the Earth). Study of these stars allows us to observe matter under conditions that cannot be reproduced on Earth. White dwarfs are also among the oldest objects in the galaxy. As the nuclear reactions that powered the original star have ended, their temperature is determined entirely by their cooling, which takes billions of years. Measuring the temperature of the coolest white dwarfs can give us an estimate of the age of the galaxy and a limit on the age of the Universe. In addition, the production of white dwarfs gives rise to a large fraction of the dust and gas present in interstellar space, from which our own solar system formed.

To understand white dwarfs, we need to make measurements of their temperature, density and composition. This information can only be obtained from spectroscopy of these stars. Young white dwarfs are very hot and emit most of their light in the X-ray and ultraviolet regions of the electromagnetic spectrum. Apart from studying the stars themselves, they are also useful probes of the gas in interstellar space. For example, figure 4 shows the ultraviolet spectrum of a typical hot white dwarf. Almost all the weak absorption lines seen are produced by nickel in the atmosphere of the star. Three strong lines are also present. Two of these are from stellar nitrogen but the third is from interstellar silicon.

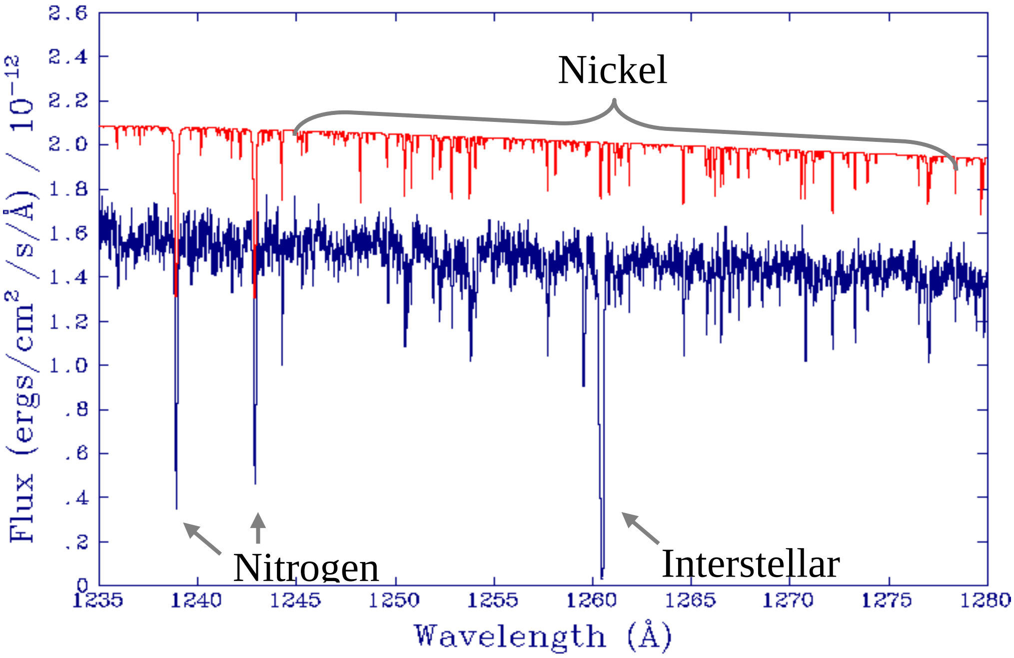

Figure 4. Ultraviolet spectrum of a white dwarf star (blue) compared to a theoretical calculation of the expected appearance (red). Most of the weak absorption lines are from nickel present in the white dwarf atmosphere. The two strong lines at 1238Å and 1243Å are from nitrogen, also in the star, while the strong line at 1261Å is from silicon gas in interstellar space.

The fate of the Universe

The ability to recognise patterns of lines from a particular element is crucial to our understanding of the history and possible future of the Universe. In the 1920s and 1930s, the American astronomer Edwin Hubble used the 100 inch telescope on Mount Wilson (the largest in the world at the time) to record the spectra of distant galaxies. He noted that, while the spectra were generally similar to those of nearby galaxies, the spectral lines he observed did not appear at the expected wavelengths but were shifted towards the red end of the spectrum. Hubble interpreted this “red shift” as a Doppler shift of the light emitted due to the more distant galaxies moving away from us. He also realised that the size of the red shift, and the implied speed, increased with the estimated galaxy distance – Hubble’s Law, providing the first evidence for the expansion of the Universe and its origin in the Big Bang.

Figure 5 shows modern spectra of two distant galaxies with red shifts of 2.0 and 2.66, showing emission lines that appear in the UV, rather than the visible band, when the red shift is zero. Large scale surveys of the sky are discovering ever more distant objects and the current record for a measured red shift is around 7. However, the most distant galaxies do not behave as expected. The most recent results indicate that the expansion of the Universe is not slowing down, as would be expected if gravity is the dominant force, but accelerating. This has led astronomers to propose the existence of “dark energy” which produces a repulsive force opposing gravity. The nature of the “dark energy” and whether or not it really exists has still to be determined.

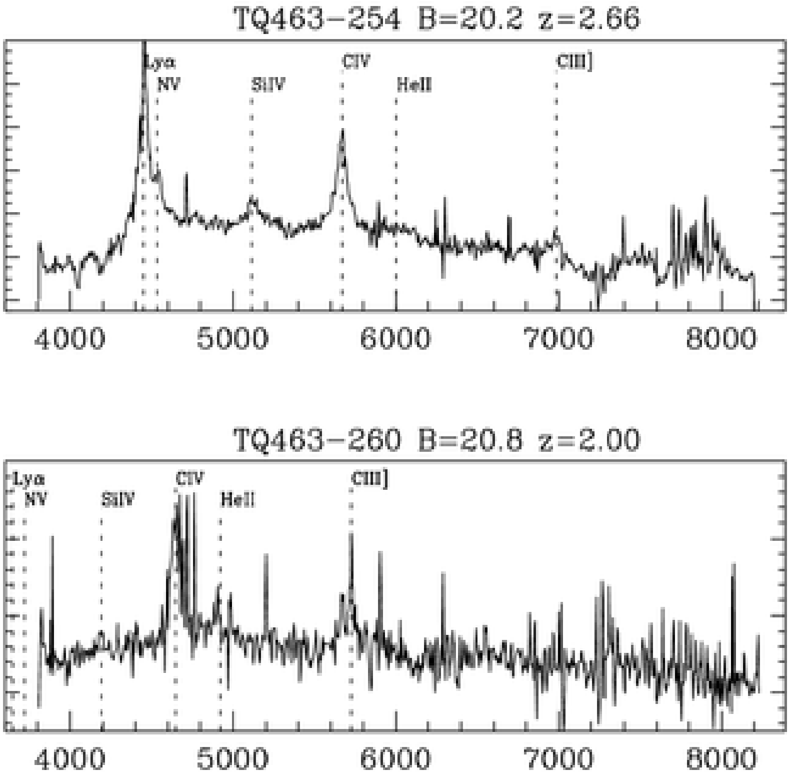
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Figure 5. Spectra of two distant galaxies with red shifts of 2.66 (top) and 2.0 (bottom), showing emission lines from hydrogen, helium, carbon, nitrogen and silicon, shifted from ultraviolet wavelengths.

Conclusion

Spectroscopy is one of the most important techniques of astrophysics. If a picture is worth 1000 words, then a spectrum is worth 1000 pictures. Spectroscopy allows us to make important measurements of the fundamental properties of stars and galaxies and helps us understand the important physics of the Universe. It is an essential tool for astronomers to discover where we came from and what our ultimate fate will be

Further information

A colour version of this paper and slides from the lecture can be viewed on-line at http://www.star.le.ac.uk/~mab, by following the Education and Outreach link from the home page.