Astronomical Spectroscopy

1. A Short History

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Bhattacharyya retired as the Director of Indian Institute of Astrophysics in 1990 but continues to be associated with the organisation. His specialisation is in experiments where he has devised, designed and constructed many new instruments and employed them in studies of various manifestations in nature. The subjects covered in his researches stretch over meteorology, aeronomy, sun and the solar system and stars. He is a regular contributor to many popular science journals in English and Bengali.

This article surveys important developments in the growth of spectroscopy and its application to the study of stellar spectra. Among others, the contributions of Wollaston, Fraunhofer, Kirchhoff, Bunsen and Doppler are highlighted.

It was Isaac Newton in the latter half of the 17th century who first produced a white light spectrum of the sun using a glass prism. The arrangement was crude by today's standards and many features of the solar spectrum were missed. Newton did not use a fine slit, nor imaging optics, and the spectrum did not reveal the fine features which later formed the foundations of spectroscopy. In one of his later papers, he suggested the use of imaging optics for producing better spectra, but he himself did not carry out the experiment. It was left to the British scientist, W Wollaston, to produce a spectrum of sunlight with an arrangement in which a pinhole was imaged in sunlight dispersed by a prism. The spectrum, which was in the form of a streak of coloured light, showed prominent gaps at several places. This was in 1804, more than a hundred years after Newton.

The arrangement was perfected by Joseph Von Fraunhofer (1787–1826) who constructed the first real spectroscope. The light passing through a pin-hole was minimal and the dispersed spectrum was very faint; Fraunhofer therefore replaced the pinhole with a slit, which admitted much more light into his instrument and, its orientation being perpendicular to the direction of dispersion, it did not interfere with the details of the spectrum produced. He could now see many dark lines in the solar spectrum; there were a few broad ones which were earlier detected by Wollaston as gaps. This may be described as the beginning of spectroscopy.

If we look at the sun through a spectroscope, we find a spread of colours from red to violet, interspersed with numerous dark lines. These were first seen by Fraunhofer through his new instrument and are known by his name. Some are quite prominent, and these were labelled with the letters of the Roman alphabet (A, B, C, D, etc.) by him; the nomenclature is still used. Fainter lines are known by their wavelengths in Angstrom units (1Å = 10^{-10} m) (λ 5250, λ 4471, etc.)

It was only after a few decades that the origin of these lines was understood, but it was noticed even by Fraunhofer that the lines remain in fixed positions among the spread of colours. He also performed one more experiment. Common salt (sodium chloride) emits yellow light when heated in a flame. If this light is observed through a spectroscope, no continuous spread of colours is seen. Instead, one sees a bright yellow line. (Later by using improved instruments, it was found that this yellow line really consists of two closely-spaced lines.) In any case, Fraunhofer noticed that the position of this line coincides with the position of a dark line which was earlier designated by him the D-line of the solar spectrum. We know now that both indicate the presence of sodium in the source; I shall come to this point shortly.

The dark lines in the solar spectrum are not totally dark; because of lower emission at those wavelengths, they appear dark compared to their surroundings. A sunspot is an example of a similar illusion; if all the bright areas of the solar disc were covered and only a sunspot was viewed, it would appear like a red star in the night sky. If one scans through the solar spectrum with a spectrophotometer[1], one will notice that the intensity within the lines is lower than that in the nearby continuum region but never totally zero.

[1] This is an instrument which records the intensity of light at different points in the spectrum, i.e. at different wavelengths. In older instruments this was done by moving one detector; modern detectors operate in parallel and record the entire spectrum in some range.

The plain indication is that, for some reason, the radiation received from the sun is low at certain wavelengths; if sunlight is viewed after spreading the colours, those parts appear dark. Usually, this reduced radiation is restricted to very narrow bands of wavelengths; that is why they appear as narrow lines in the spectrum. But why does this absorption take place? The answer came from laboratory experiments conducted by the German scientists, Gustav Kirchhoff and Robert Bunsen.

The experiments were done quite independently; they noticed that any substance heated in a flame gives off light whose spectrum is a series of coloured lines. Different substances give different series of lines; it does not matter whether the substance is an element or a compound. In the case of compounds, line series due to the components of the compound are seen together. They experimented with different salts and identified many elements from their spectra; then, in one sample, they noticed a new series of lines. Chemical analysis of the sample revealed the existence of a new element; it was named cesium. It filled up an important slot in Mendeleev's Periodic Table when the latter was formulated in 1869. Cesium was discovered ten years earlier, in 1859; it is the first element discovered by spectroscopy. Kirchhoff and Bunsen continued their search; another new element was discovered in 1860. It was named rubidium, and it filled up another slot in the Periodic Table. A new method of chemical analysis had been discovered. [2]

[2] The familiar 'flame test' of the chemical laboratory is a simplified version which uses the human eye to detect changes of colour.

Kirchoff and Bunsen suggested an explanation for the Fraunhofer lines. The sun and the stars must have an envelope of gases composed of vapourised matter, and white light from their photospheres suffers selective absorption while passing through these envelopes. It was known that any material which emits a particular colour when heated, tends to absorb the same colour strongly. It was established from laboratory experiments that vapours of different materials emit line-radiation; when white light is passed through these vapours, the colours corresponding to the emission lines are absorbed and the emergent light is poorer in those wavelengths [3]. This phenomenon gives rise to dark lines in spectra. Comparing the Fraunhofer lines with the laboratory spectra of known materials, it is thus possible to know the composition of the sun and the stars.

[3] It is assumed here that the material in the outer layer is cooler than in the layer which emits from behind it. Only then will the removal of light be greater than what the outer layer itself emits.

This discovery struck a death blow to a popular conviction held earlier. In 1835, the famous French philosopher August Comté emphatically stated that no matter what advancements in science man achieved, he would never be able to know the chemical composition of the stars. The discovery by Kirchhoff and Bunsen totally demolished this dogma. In fact, it is impossible to limit the inventive genius of the human mind; nothing appears to be beyond its grasp. Fortunately Comté died a couple of years before Kirchhoff and Bunsen's discovery; he was spared the pain of seeing a total demolition of his conviction!

Thus began the spectroscopic method of estimating the chemical composition of celestial bodies. More information about astronomical objects became accessible to scientists with the advent of spectroscopy; their spectra conveyed a precise idea of their motions as well. We will have to go back about twenty years from the date of the discovery just discussed to understand the method.

In 1842, the railways had just come into existence; the sight of steam locomotives pulling rows of box cars had become very common. When a train went by, people gathered to look at the new invention from the sides of the track. It was noticed at this time that the pitch of the whistle of a stationary or receding engine was different from that of an approaching engine. It was also observed that the pitch changed sharply when the engine passed the observer.

These phenomena were explained by an Austrian physicist, Johann Christian Doppler. He determined how the change in pitch depends on the velocity of the source. Sound from an approaching source will be higher in pitch; that from receding ones will be lower. This is due to the sound wave-train being compressed or stretched. The same is true, in principle ,for light waves. The fractional change in frequency would equal the ratio of the relative velocity between source or observer, to the speed of light; of course this ratio could be small in practice.

The French scientist, Armand Fizeau, was aware that the Fraunhofer lines remain in sharply fixed positions in the spectrum. If small frequency changes occur due to the Doppler effect, the Fraunhofer lines will be shifted, and these shifts can be measured. The speed of light had already been measured quite precisely; the motion of any heavenly body could be estimated by combining the observed shifts with the value of the velocity of light.

The English scientist, William Huggins, started his search for Doppler-shifted Fraunhofer lines in Sirius, the brightest star in the sky. After about five years' effort, he announced that all the lines in the spectrum of Sirius are shifted slightly towards the red side. From the measurements of the shifts, he estimated that the star is receding from us with a velocity of 50 km sec^{-1}.

We know now, from later experiments with improved instruments, that Sirius is really receding but with a velocity of about 10 km/sec^{-1}. Besides, we also know that Sirius has a faint but heavy companion and that the two stars are going around each other; as a result, there are regular periodic changes in the velocity of recession of Sirius. But it took about twenty-five more years to improve the techniques of measurement to be able to detect such small velocities.

More evidence of Doppler shifts was soon found with improved techniques. In 1871, a German scientist, Hermann Carl Vogel, showed that the east limb of the sun is approaching us with a velocity of about 2 km/sec^{-1}, and that the west limb is receding with the same velocity, a clear indication that the sun is rotating on its own axis. This fact was, of course, well known, for beginning with Galileo many scientists had measured the rotation of the sun from the movement of visible features like spots, faculae, etc. But Vogel's findings were definite proof of the conjecture that Doppler shifts are indeed indications of the motion of celestial sources.

A fascinating discovery using Doppler effect measurements was made in 1889. Two scientists, Vogel from Germany, and

Edward Pickering from the USA, were trying to understand the peculiar behaviour of a star, Mizar, in the northern constellation of the Great Bear. Sometimes its spectrum looked like that of a normal star, but sometimes all the lines were doubled. They proved (almost simultaneously) that Mizar is a binary star consisting of two stars revolving around each other. The two stars are so close that it is impossible to see them separately with terrestrial telescopes. In some locations in their orbit, one of them approaches us, while the other recedes; at these moments, the spectra from the two are shifted in opposite directions so that the combined spectrum appears doubled. The total period of revolution is about twenty days, and twice within this span the spectrum becomes double, confirming the speculation. This was the discovery of the first member of a class of stars known as spectroscopic binaries. These are of great astronomical importance as they allow stellar masses to be measured.

There have been many more applications of the Doppler-Fizeau effect in astronomical spectroscopy. Both the rotations and orbital motions of solar system objects and the velocities of recession of galaxies and other objects at the farthest ends of the known universe have been measured. In India, in the first decade of the present century, John Evershed at Kodaikanal Observatory in the Palani Hills of Tamil Nadu discovered the motions of gas around sunspots from studies of fine Doppler shifts in the spectral lines. This is the famous 'Evershed effect' in solar physics.

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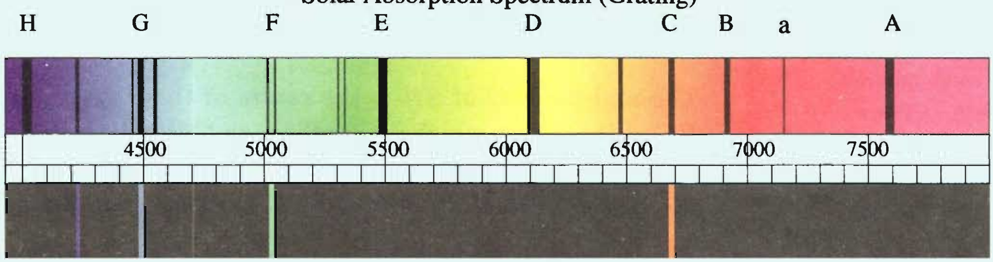
Solar Absorption Spectrum (Grating)



Emission Spectrum of hydrogen showing Balmer lines

Reproduced from *A Treatise on Heat* by M N Saha and B N Srivastava, 2nd edn, p.560, 1935.