Astronomical Spectroscopy

2. The Light From the Stars

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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.

The spectrum of light emitted by a star holds deep secrets about it. In particular it gives the temperature of a star. It can also reveal the abundances of elements and whether they are in atomic or ionised states. This part of the series dwells upon some of the riddles associated with stellar spectra and their implications.

Let us return to the question of the determination of the chemical composition of stars by spectral analysis. In the sixth decade of the nineteenth century, the French scientist, Jean Foucault, and the American scientist, Tom Alter, studied the spectral characteristics of laboratory sources. Kirchhoff and Bunsen started their famous series of experiments in an attempt to unfold the mysteries behind line emission; similar searches were conducted in other laboratories in Europe and the USA. The Swedish scientist Angstrom invented an improved version of the spectroscope which revealed more than a thousand lines in the solar spectrum. Almost all these lines could be traced to known elements found on earth: hydrogen, sodium, iron, etc.; then, one day, an unknown line was discovered.

The event happened during a total solar eclipse, which could be seen on August 18, 1868, from India. Near the town of Guntur in present-day Andhra Pradesh, two camps were set up for observation of the eclipse. The British team led by Tennant of the Survey of India was in one camp, while the other team was led by the famous French astronomer, Pierre Janssen. Both were conducting pioneering spectroscopic observations of the eclipsed sun. They were particularly interested in the spectrum of the chromosphere, which flashes out at the beginning and the end of totality. They noticed many lines due to known elements, e.g. hydrogen, sodium, etc, but among them was a bright yellow line (λ 5876) which could not be identified as being due to any known element.

The line was noticed by both teams; Janssen wrote to the famous British scientist, Norman Lockyer, in England, seeking an explanation. The report by Tennant also reached him. After considering all features, he arrived at the conclusion that the line must be due to a new element; because it was found on the sun, a name was suggested: helium, from the Greek word 'helios' meaning the sun. But it remained a wild guess; the scientific community was not prepared to accept the existence of a new element. Twenty seven years later, the British chemist, William Ramsey, discovered a new gas liberated from radioactive decay products of some minerals. The yellow line was clearly seen in its spectrum; other lines matched exactly some of the solar Fraunhofer lines which had remained unidentified. Helium had finally been discovered. It was later proved that, after hydrogen, this element is the most abundant one in the universe.

It is somewhat fortunate that an element first seen in solar spectra was later discovered on earth. Certain other speculations about new elements based on spectral signatures could not be verified. In the spectrum of the solar corona, a bright green line (λ5303) may be seen during a total eclipse; following the established practice, they even named it 'coronium'. But searches over three-quarters of a century did not yield any proof of the existence of this element; ultimately, in 1940, the Swedish scientist, Bengt Edlen, proved that, at very high temperatures, when iron atoms become multiply-ionised, they produce this line.

Another bright green line (λ 5007) is seen in the spectra of nebulae; it was speculated that this corresponded to a new element, 'Nebulium', which again proved elusive. It was later shown that, at high temperatures, rarefied oxygen ions emit this particular line; 'nebulium' is non-existent. But in the case of helium, the speculation was proved correct.

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According to many astronomers, a new branch of science, astrophysics, was born during the total eclipse of August 1868, because, from that day onwards the new technique of spectroscopy began revealing new information about the cosmos. The most brilliant proof of the ideas of Bunsen and Kirchhoff was obtained during another solar eclipse, in 1870; the track of totality passed over the northernmost parts of Africa, and Charles Young of Princeton University had set up instruments for a very special observation. He kept watching through a spectroscope the eastern edge of the sun about to be eclipsed. He wanted to verify Kirchhoff's hypothesis[1] and the experiment confirmed the hypothesis, but with such magical suddenness that the observer was left spellbound. More than a century has passed since that pioneering experiment, but the experiment of observing the 'flash-spectrum' is repeated during almost all eclipses. More refined instruments have definitely added new information, but, more importantly, the indescribable beauty of the event fascinates all observers. Young's experiment has silenced all doubts about the ideas of Kirchhoff and Bunsen.

Ever since that time, spectroscopy became the main tool for astrophysical research. I have already discussed early experiments by Huggins; a few other scientists continued the search. An Italian astronomer, Pietro Angelo Secchi, started classifying stars according to the patterns of their spectra. Photography had been invented about twenty five years before the first photograph of the moon was obtained in 1840. The sensitivity of detection was rather low, but rapid progress in the technique was achieved. The photography of celestial objects became quite common, and efforts were now made to photographically record stellar spectra. The Harvard Observatory in the USA took on a leading role; Henry Draper, from this group, started a very ambitious programme of photographing the spectra of all stars that were accessible to their equipment. He started the programme in 1872, and by 1884, when Henry Draper died, only about twenty percent of all stars had been covered. Members of the Draper family requested the observatory not to stop the programme; they promised to provide

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[1] The origin of the Fraunhofer lines is in the chromosphere; in that case, when the last trace of the sun's photosphere was covered, the dark Fraunhofer lines would suddenly change into bright emission lines.

h financial assistance to continue the work. The new r, Edward Pickering, carried on the programme; by 1920, 200,000 stellar spectra had been collected; the present r is about 250,000. In astronomical literature, this collection tra is known as the Henry Draper Catalogue; each star in talogue is designated by a number starting with the letters he initials of Henry Draper. This collection proved vital, a critical stage in the evolution of astrophysics, it provided sential raw data to help the advancement of the young e. The main hero of this drama was a young Indian ist, Meghnad Saha; I shall come to his story a little later.

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beginning of this century, two kinds of information came f the analysis of astronomical spectra: the chemical osition of the heavenly bodies, and the details of their ns. In 1908, a clever application of a newly discovered effect oratory physics resulted in the opening up of another el: the magnetic fields of distant bodies could be measured. e Ellery Hale, at Mount Wilson, USA, applied the principle Zeeman effect,[2] to the analysis of the light from sunspots iscovered the existence of strong magnetic fields there. A onths later, John Evershed, at Kodaikanal Observatory in discovered vortical motions in solar gases in areas unding sunspots. The foundations of a new branch of cs, magnetohydrodynamics, were laid by these two early iments.

more advancements in the techniques of spectroscopy, features of astronomical spectra came to light. Many new cteristics of the profiles of spectral lines could now be nguished, which conveyed new information about the es of these lines. Let us take the case of solar spectra, for ple: some very fine lines were noticed which did not appear ve their origins in the sun. These are, in fact, created by in the atmosphere of the earth and were termed 'telluric . I have already mentioned that small Doppler shifts are ed when light from different parts of the sun are analysed;

[2] The spectral lines of sources placed in a magnetic field split up into two or more polarised components leading to the determination of celestial magnetic fields.

telluric lines do not show any such shifts. They are also very narrow, almost down to instrumental limits. The reason for this narrowness lies in the relatively low temperatures in the earth's atmosphere. In the solar atmosphere, higher temperatures result in the random thermal motion of constituent atoms, which broadens the spectral lines. This is known as thermal broadening and is utilised for determining the temperatures of sources.

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But temperature is not the only factor that broadens spectral lines; in the solar atmosphere, microturbulence also considerably broadens them. For stars, whose surface features cannot be resolved, rotation also broadens spectral lines. The characteristics of the absorbing materials also affect the width, particularly in thick atmospheres. But all these effects have subtle differences which can be recognised by high-dispersion, high-resolution spectroscopy.

Many patterns of spectra were noticed in the Henry Draper collection, but no physical explanations were forthcoming. It was only known, from earlier experiments, that different materials produce their characteristic patterns of spectra; how the properties of the material and the emission of radiation are linked was not clear. The time was ripe for the appearance of a genius who would solve that riddle.

At the turn of the twentieth century, a radically new idea was introduced by a German professor, Max Planck. It was known that matter is composed of smaller units called atoms; it was now speculated that when radiation is emitted, it comes in small bundles. It was a novel idea and was not easily accepted by the scientific community, but several experimental observations were beautifully explained by the application of this hypothesis; this idea led to what is known as the quantum theory.

In 1913, a young Danish Professor, Niels Bohr, published a paper in which he put forward a solution to the riddle of line spectra. If hydrogen is enclosed in a closed tube and an electrical discharge is passed through it, a reddish light is emitted whose spectrum consists of a series of lines; this had been known for more than half a century. Even a remarkable order had been discovered in spacing of these lines. In Niels Bohr's paper, it was shown that the lines are created by electronic transitions within the atom, and that the process occurs according to the quantum theory. His calculations exactly determined the spacings of the lines.

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Bohr's idea can be described by a simple classical model. He chose the simplest of atoms, hydrogen, with a positively charged proton at the centre and a negatively charged electron orbiting around it, somewhat like a planetary system with a single planet orbiting around a central star. If a bundle of radiation is captured while passing through it, the energy of the atom increases and this manifests itself in the electron jumping to a higher orbit. But unlike a classical dynamical case, the next higher orbit can have only fixed sizes, strictly according to the quantum theory. Again, when the electron jumps back to the lower orbit, its extra energy is radiated away as a new photon. Since the orbital sizes are fixed, the energies of the emitted photons are also fixed, and, according to Planck's postulate, their frequencies are also fixed. These are the emitted photons distributed over the series which give the line spectrum. From experimentally determined parameters of the hydrogen atom, these line frequencies can be precisely calculated, and these match the observed frequencies of the various lines perfectly.

The observed frequencies of the lines in the hydrogen spectrum matched Bohr's calculations, but when the same idea was applied to heavier atoms, large discrepancies were noticed. The riddle was ultimately solved by Sommerfeld and a few other scientists, who introduced modifications in the structure and dynamics of the electrons; after these modifications had been introduced, it was possible to calculate the frequencies of line emissions for all atoms quite precisely. Fifty years after Kirchhoff's discovery, it had become clear that the patterns of line emissions characterising different materials are due to the internal structure of the atoms involved.

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Laboratory experiments also revealed that even small changes in the orbiting electron cloud could alter the emitted spectrum drastically. Let us take, for example, the case of a laboratory argon lamp. If a lamp is ignited by discontinuous sparks, its light is different from another operated with a steady arc. It was found that, in the first case, one or two outer orbital electrons are expelled and the gas becomes ionised; the internal structure and energy levels of the ions are different from those of neutral argon atoms. It was also known that, at high temperatures, a large number of atoms becomes ionised, and the emitted light has a different spectral pattern. This property of light emission was fully comprehended by M N Saha, and he applied his principle to understanding the spectra of the sun and the stars. It happened in 1920 and he was a lecturer in Calcutta University at that time; I shall now deal with his story.

At the time, Henry Draper's programme had been in existence for almost half a century, about 200,000 spectra had been collected, but stellar spectra were becoming more enigmatic. It was realised that the line patterns vary; in some stars only a few lines were visible, while in others, numerous lines could be seen. The spectra of some stars were bright in the blue-violet region while others were distinctly red. Some stars appeared to be filled with metal vapours, while others appeared to contain nothing but hydrogen. What did all these observations indicate? Were the stars composed of different materials than the rest of the universe? Or was it the stellar evolutionary process that created new materials? All these questions were crowding scientists minds.

Some rough guesses could be made from the spectra; blue stars are probably high temperature ones, and the rest can be arranged in order of progressively decreasing temperatures according to their colours (from white to red). But that poses another riddle. Blue stars appear to contain nothing but hydrogen; as one moves to lower temperatures the hydrogen lines become stronger at first, reach a maximum intensity, and then slowly fade out; in their place, metallic lines appear to grow stronger. In most low-temperature red stars, one finds many fine metallic lines. How is such a variety of lines possible?

Many weird ideas were expressed at that time. According to some, when new stars are born out of clouds consisting of the primeval material of the universe, all the elements are present; this is why metal lines are seen in some stars; but, as they start to heat up, bigger atoms are broken down to smaller ones like hydrogen, and that is why the hotter stars show the presence of more hydrogen. But the idea did not convince many scientists; the temperatures needed for breaking up atoms are much, much higher than those that are found on stellar surfaces. Besides, in certain high-temperature stars, no hydrogen is seen, but lines due to ionised helium are very strong; this does not conform to the scenario of fragmentation of large atoms.

The riddle was cleared in a series of papers which was published in successive issues of the *Philosophical Magazine* in 1920; satisfactory answers to all these questions could be found in them. The central idea was that to extinguish a line from the spectrum one does not need to break an atom, the removal of an outer electron is sufficient, and this does not require very high temperatures. The outer electrons in metal atoms are rather loosely bound; a relatively low temperature easily removes them, and the metal-indicating lines fade out. New lines due to ionised metals appear in other parts of the spectrum, but these may fall outside the visible band. It may appear that metal atoms are not present in the star, but, in fact, they remain in an ionised condition.

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The enigmatic behaviour of hydrogen lines in stellar spectra was easily explained. Hydrogen atoms have only one electron each, and, at high temperatures, this electron gets detached and the atom loses the capability of line emission. Lines due to ionised helium are seen because the second electron of helium is relatively strongly bound and it continues to emit line radiation. At lower temperatures, the electron descends to near the ground level, and no radiation results. This is why medium temperature stars show strong hydrogen lines; too high or too low a temperature inhibits the emission of characteristic line series.

The Saha ionisation equation[3] made possible detailed calculations of the expected changes in stellar spectra at different temperatures and pressures. This not only solved the many riddles of stellar spectra, but opened up new channels of information in astrophysics. Earlier, only broad hints about the physical conditions in distant stars could be guessed, but the Saha equation ushered in a flood of new information. Temperatures, pressures, abundances, etc., could now be precisely determined from the analysis of spectra; a new and powerful tool for astrophysical research was placed in the hands of scientists. According to Arthur Eddington, some discoveries have ushered in a revolution in astronomy, and the Saha equation is one of the most important.

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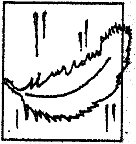
[3] See 'Article-in-a-box' in the previous issue.

The Sad Story of Heisenberg's Doctorate



> In the handling of the present problem, Heisenberg shows once again his extraordinary abilities: complete command of the mathematical apparatus and daring physical insight.
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> —*Arnold Sommerfeld*

In May 1923 Heisenberg returned to Munich from Göttingen, where he had been a visiting student, to finish out his last semester while writing his doctoral dissertation. Knowing Heisenberg's reputation for controversial solutions to problems in quantum theory, Heisenberg's Munich mentor, Arnold Sommerfeld, suggested that he write his dissertation in the more traditional field of hydrodynamics. The title in English is: "On the stability and turbulence of liquid currents." Heisenberg also had to take the four-hour laboratory course in experimental physics offered by Prof. Willy Wien. Wien insisted that any physicist, including Sommerfeld's brilliant theorists, must be fully prepared in experimental physics. Wien and Sommerfeld both sat on the candidate's final oral exam and both had to agree on a single grade in physics.

While Heisenberg struggled through Wien's lab course (much to Wien's displeasure at the results), Heisenberg prepared his dissertation. He submitted his dissertation, a 59-page calculation titled "On the stability and turbulence of liquid currents," to the Munich faculty on July 10, 1923. The topic arose from an earlier research contract Sommerfeld had received from a company channelling the Isar River through Munich. The problem was to determine the precise transition of a smoothly flowing liquid (laminar flow) to turbulent flow. It was an extremely difficult mathematical problem; in fact, it was so difficult that Heisenberg offered only an approximate solution.

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