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Spectroscopy: The Tool to Study the Stars

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Abstract

Stars are not just useful in the pursuit of astronomy, their importance to us is fundamental. However, the true nature of stars remained a mystery for centuries. Then, through years of hard work we presently do have the tool using which we can actually study and understand the stars. That tool is spectroscopy. For the past few years, intense research in the field of stellar spectroscopy is being carried out at the CHRIST (Deemed to be University) too. This article, written in popular style, provides an understanding of how the exciting field of spectroscopy -- the language of stars -- gradually developed, thus helping humanity to gain a good understanding about stars and astronomy as a whole. The article intends to provide motivation to young students, especially of UG level, who dreams to pursue astronomy research in future to do research in this exciting field.

Keywords: Spectroscopy, stars, spectral classification, Saha Ionization

1. Introduction

During any cloudless night, if you move away from the city lights to some dark place free from light pollution, and if you look up towards the night sky, you will become mesmerized. A spectacular sight of innumerable stars dazzling in the night sky has the power to make a human being wonder with awe, and also think. The beauty of the night sky has indeed captured the imagination of human minds since prehistoric times. Curious by nature, since our

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first awakening, Homo sapiens or humans naturally started asking different questions. As their intellect progressed, the questions also started becoming more curious, more intellectual, more scientific and even more philosophical. Few such curious questions were: Who created the Universe? How and why did it begin? What is the fate of the Universe? Who are we? How do we came from? Are we alone in this vast stretches of the cosmos? Ultimately, such kind of natural curiosity of humanity gave birth to science.

If one looks at the long march of human understanding, one will find that science began with the idea that we can understand our role in the universe using logic and observation. The stars and planets were mysterious objects for most of human history. Yet ancient Greek philosophers were able to use reasoned arguments and simple geometry to estimate the sizes and distances of our neighbors in space. As time passed, with experience and intellect men could understand more and more of the natural phenomenon. Amazingly, in general, stars have acted like pillars for the development of humanity right from the beginning of human awakening.

2. Stars: pillars for understanding the universe

Stars are not just useful in the pursuit of astronomy, their importance to us is fundamental. They provide the universe with light, energy and chemical enrichment. Without them there would be no radiation to supply heat and light to planets. Moreover, without stars there would be no element heavier than hydrogen and helium and life would have not been possible anywhere. Stars also tell us that the chemistry we see around us is not unusual. The elements that make up the planets and people were actually created by generations of stars that lived and died before our own Solar System formed. The same process is going on all over our Galaxy, and in all of the billions of galaxies in the universe. Chemistry is universal. Stars even act as markers to outline the shapes of galaxies. Apart from these, they provided us our first estimation of the matter distribution in the visible universe.

Furthermore, stars provided guidance to early astronomers to form recognizable patterns in the sky, the constellations to track the sky. This ultimately helped in creating calendars, understanding the seasons. Advancement in agriculture, navigation was possible during the ancient days, thanks to those beautiful twinkling stars in the night sky which helped humanity to progress. The list is almost never ending one. We, humans owe a lot to the stars. They have truly played a vital role in the development of our knowledge which gradually gave birth to science and technology.

But, stars are extremely distant objects. They are so far away from us that even the nearest star to us other than the Sun appear as points of light to all but the largest telescopes. The star closest to Earth is the Sun. The next nearest star - Proxima Centauri in the constellation Centauras - is 260,000 times as far from us as we are from the Sun.

Through ages of hard work, early astronomers developed methods to determine the fundamental properties of stars like distance, magnitude, mass, temperature, etc. It became gradually clear that mass is the most fundamental property of a star. A star's entire life cycle is governed primarily by its birth mass. However, the true nature of stars remained a mystery for centuries. It was gradually becoming clear that to know about stars in depth, it is necessary to understand their structure, how they work, what they are made of and how they are powered. The answer lies inside their interiors. But which tool can literally pierce the surface of stars and look into their hidden interiors? Humanity was unaware about any such tool till the first half of the nineteenth century. This obstacle blocked astronomers to probe the stars for centuries.

3. Birth of spectroscopy

In the seventeenth century, Isaac Newton split sunlight into a spectrum of colors using a prism. Then in 1802, the English chemist William Hyde Wollaston detected and noted the appearance of a number of dark lines in the solar spectrum for the first time. Later in 1814, a German optician Joseph von Fraunhofer independently detected and catalogued over 570 of these dark features while observing the Sun through his own invented spectroscope. It was he who started to systematically study and measure the wavelengths where these lines are observed. These lines were named as Fraunhofer lines which are visible in the solar spectrum along with several other features. Fig. 1 shows the solar spectrum exhibiting different Fraunhofer lines as it appears visually.

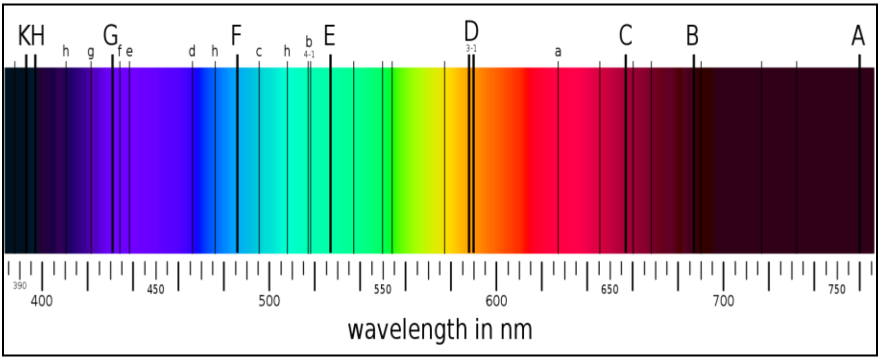


Fig. 1: Solar spectrum exhibiting different Fraunhofer lines as it appears visually. Figure taken from www.wikipedia.org/Fraunhofer lines

Fraunhofer was able to identify sodium by matching the wavelength of one dark line in the solar spectrum with the wavelength of the yellow light emitted when salt is sprinkled in a flame. The realization that dark lines in the solar spectrum is arising from the atoms present in the sun, and that all other stars also show similar line patterns became the first step to decipher the mysteries of the stars. This seminal discovery gave birth to the new science of spectroscopy - the tool to invade the interior of stars.

In 1850s, Gustav Kirchhoff and Robert Bunsen observed that various Fraunhofer lines actually coincide with characteristic emission lines identified in the spectra of heated elements. They correctly demonstrated that the dark lines noticed in the solar spectrum originate from absorption by different chemical elements present in the solar atmosphere. So these are actually atomic absorption lines produced as atoms of certain elements absorb solar (or stellar) radiation (i.e. starlight) at certain wavelengths when the radiation passes through the various outer layers of the Sun (or any star). It was understood that the specific wavelengths at which the radiation gets absorbed act as precise signature of the elements present in the atmosphere of stars. Thus, the works of Kirchhoff and Bunsen laid the foundations of a new branch in astronomy, stellar spectroscopy. Humanity had ultimately found the tool to understand the nature of stars.

Through years of studies, now we know that 3 types of spectra can form: continuous, emission line and absorption line spectra. Kirchhoff (1842–1887) proposed three empirical rules, now known as Kirchhoff's laws which describe the formation of spectra. A diagram demonstrating Kirchhoff's laws and showing the formation of spectrum is depicted in Fig. 2. These 3 laws can be stated simply as below:

1. A hot, dense gas or hot solid object forms a continuous spectrum and does not show any spectral line.
2. A hot, diffuse gas having low density will produce bright spectral lines (emission line spectrum).
3. A cool, diffuse gas in front of any source of a continuous spectrum produces dark spectral lines (absorption lines) superimposed on the continuous spectrum.

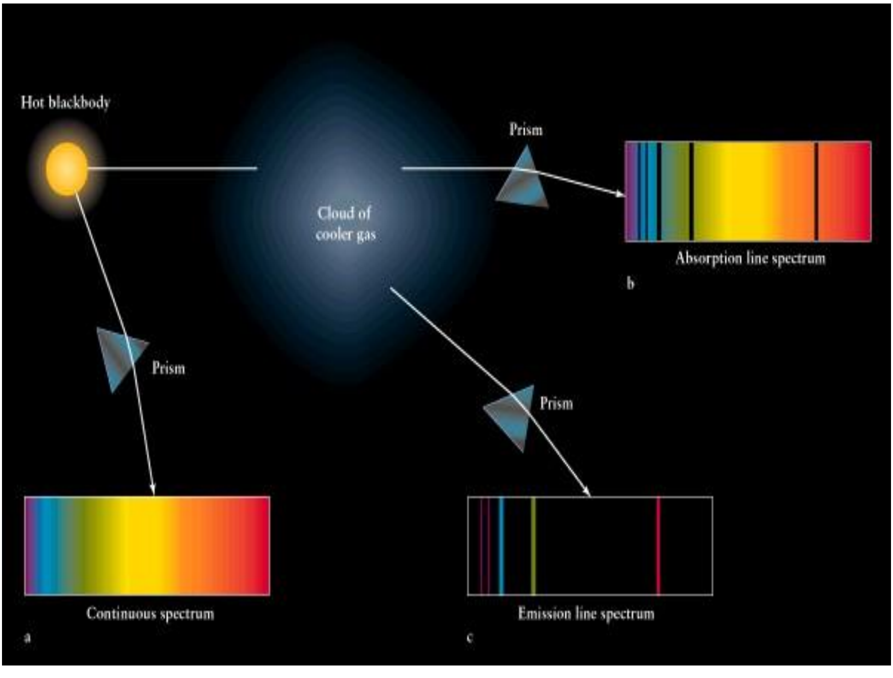


Fig. 2: A diagram demonstrating Kirchhoff's laws and showing the formation of spectrum. Figure credit: http://w3.phys.nthu.edu.tw/~hkchang/ga1/ch05-03.htm

In 1872, it was Henry Draper who first photographed stellar spectra. This was another path-breaking advancement. From now onward astronomers could directly record, compare and measure spectral features instead of only sketching or verbally describing any spectra. Draper then started an ambitious project to photograph and catalog every bright star of the sky. Unfortunately, he passed away long before it was complete. His widow then donated enough money to the Harvard University, USA for continuing the monumental task. The then Harvard Observatory astronomer and pioneer in observational astronomy, Edward C. Pickering headed this historical project to create the Henry Draper Catalog.

4. Spectral classification of stars

Pickering hired a large group of women, who were termed as “computers”, to perform the painstaking work of measuring the spectra of thousands of stars. This started the tiresome job of classifying stars by identifying their spectral properties in the basement of the Harvard College Observatory. Under the leadership of Edward Pickering, the then Director of the Observatory, these dozens of women examined photographic plates on which many stellar images had been smeared out into tiny spectra. They painstakingly measured hundreds of thousands of stellar spectra, noting the wavelength of each of the prominent lines. These photographic plates were taken at the Harvard Observatory many years ago as a part of a large survey of the properties of stars.

Spectroscopic pioneers of the 19th century noticed that few stars had spectra that exactly matched that of the Sun. Some had more powerful lines of hydrogen; in others the hydrogen lines were extremely weak. The chemical composition revealed by the “fingerprint" of spectral lines varied from star to star. Astronomers wondered if the chemical composition related to any other property of a star. One of the lady working at Harvard as a “computer" answered this question.

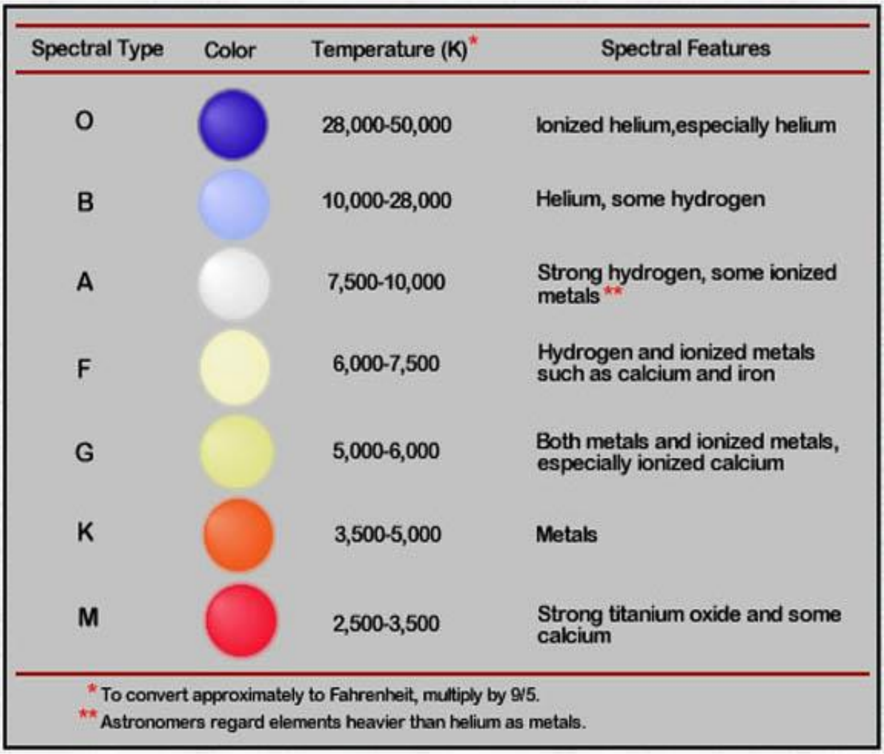
Annie Jump Cannon was one of the most important members of the classification project. Born in 1863, Cannon was among the first women from her state to attend a university. After graduating from Wellesley and Radcliffe, she took a job at Harvard College Observatory as a lowly computer. Working with incredible speed and precision, Cannon proposed a spectral classification system that is still used in astronomy today. Cannon personally classified 225,300 stars, which was a heroic contribution to her subject. She arranged stars by temperature in alphabetical categories. Her sequence runs from white-hot A stars, through yellowish G stars, such as the Sun, to cool red M stars.

Then in 1920s, another woman astronomer Cecilia Payne-Gaposchkin took the data from the classification project and extended it. She realized that the spectral variations among stars are mostly a reflection of temperature in the outer stellar atmosphere. Her unifying idea allowed the apparent diversity of stars to be understood in terms of a temperature sequence.

Cannon and Payne-Gaposchkin initially arranged stars according to the strength of the hydrogen Balmer lines (with A being the strongest). Later, when a physical explanation for spectral line formation was found, the arrangement of the spectral classes was done according to temperature. The sequence that was finally adopted begins with the hottest stars, class O, which show ionized helium lines in their spectra, and proceeds from hot to cool in the order: O, B, A, F, G, K, and M. Most stars of the visible universe can be classified into these groups. Generations of students, researchers and astronomers have created several mnemonics to remember this sequence. One of the most widely used is ‘Oh Be a Fine Girl (Guy) Kiss Me'! The first letter of each word in this sentence depicts the spectral type order from O to M. For finer discrimination each of these classes are further subdivided from 0 to 9 (from hot to cool). The Sun, for example, is classified as a G2 star. Fig. 3 presents the notable characteristics of each category of stars from O to M.

Two other astronomers, Morgan and Keenan later added a luminosity class to this system using Roman numerals. It is useful because stars of very different luminosities may have the same temperature in their photosphere. These designations are 0 for hypergiants, I for supergiants, II for bright giants, III for regular giants, IV for sub-giants, V for main sequence stars, VI for sub-dwarfs, and VII for white dwarfs. Since the Sun is a main sequence star fusing hydrogen into helium, its full designator is G2V.

During the time Cannon was involved in classifying the stars, modern atomic theory had not yet been developed. So astronomers knew little about how spectral lines originate. No one had the idea that emission and absorption lines form depending on the orbital structure of electrons in atoms. Spectra of stars (including the Sun) usually exhibit spectral features of different elements indicating that stellar photospheres are composed of many elements. Each element creates a unique pattern of lines, which help us in deducing which elements are present.



Spectral Type	Color	Temperature (K)*	Spectral Features
O	●	28,000-50,000	Ionized helium,especially helium
B	●	10,000-28,000	Helium, some hydrogen
A	●	7,500-10,000	Strong hydrogen, some ionized metals**
F	●	6,000-7,500	Hydrogen and ionized metals such as calcium and iron
G	●	5,000-6,000	Both metals and ionized metals, especially ionized calcium
K	●	3,500-5,000	Metals
M	●	2,500-3,500	Strong titanium oxide and some calcium

* To convert approximately to Fahrenheit, multiply by 9/5.

** Astronomers regard elements heavier than helium as metals.

Fig. 3: Notable characteristics of each category of stars from O to M. Figure credit: https://skyandtelescope.org/observing/colored-double-stars-real-and-imagined

For example, let us consider the simplest and most abundant element in the universe: the hydrogen atom. The orbits of

Hydrogen atoms can be numbered. Since a neutral hydrogen atom possesses only one electron, an atom in the ground state would have one electron in the orbit n = 1. If this electron somehow jumps to any higher orbit (like n = 2, 3, and so on) then this can only happen if it has somehow gained energy. As a result it absorbs a photon from some incoming radiation, i.e. it has absorbed radiation. For each transition of the electron from any lower to higher orbit will produce an absorption line. Further absorption of energy might cause it to jump from n = 3 to n = 4 and so on, thus creating an absorption line in each case. Each of this line will be produced in a characteristic wavelength. For example, the famous Hydrogen-alpha (Hα) line is produced at 6563 Å, whereas Hydrogen-beta (Hβ) occurs at 4861 Å. It is the Hα line that lends its brilliant red color to several astronomical gases, including the solar chromosphere and numerous nebulae.

Likewise, the electron might spontaneously jump down from any higher to lower orbit (like n = 3 to n = 2, n = 2 to n = 1, and so on) creating an emission line at the same characteristic wavelength where the absorption line was formed for a particular transition. This simply means that if the electron jumps from n = 2 to n = 3, then we observe the famous Hα line in absorption. The same line will be visible in emission if the electron reverts back to n = 2 from n = 3. Similarly, each possible transition of the electron of the hydrogen atom (like 1 to 2, 2 to 3, 4 to 2, and so on) creates a different line, either in absorption or in emission. Transitions between n = 2 and higher levels create the lines prominent in the visible part of the electromagnetic spectrum. This is the same way the electrons of other elements also undergo transitions in favorable conditions (usually present in stellar photospheres depending on several factors), creating spectral lines which become the clear indication of the presence of any particular element in stellar photosphere. For each element, the spectral lines which are visible in the optical spectrum at around 4000 - 7000 Å is shown in Wikipedia if one searches 'Spectral Line'. A schematic diagram of electron transitions and their resulting wavelengths for hydrogen is shown in Fig. 4.

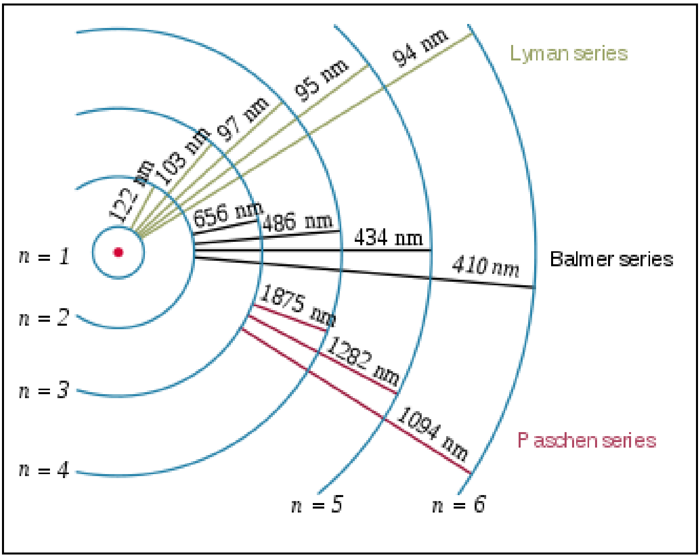


Fig. 4: A schematic diagram of electron transitions and their resulting wavelengths for hydrogen. Figure credit: http://kolibri.teacherinabox.org.au/

5. Saha's historical discovery: stellar spectroscopy gains maturity

At almost the same periods when spectral classification of stars was going on in the early years of the twentieth century, one mysterious question started puzzling the astronomers. Even any casual observation of the twinkling stars in the night sky readily shows that different stars possess of different color. Reddish stars are assumed to have lower surface temperature and bluish stars higher surface temperature. Astronomers noticed that stars of different colors exhibit different kinds of spectral lines. Meanwhile, the brilliant work of Harvard group of women computers, led by E.C. Pickering and A. J. Cannon, have been able to classify a large number of stars majorly in 7 spectral classes: O, B, A, F, G, K and M. Now, does that imply that stars of different colors (i.e. reddish, yellowish and bluish stars) have different chemical composition and hence they show different spectral lines? This was undoubtedly the most outstanding question of stellar astrophysics during early 1900s. There was no answer for this. However, without solving this primary mystery one can never understand the true nature of stars.

This was the time one brilliant Bengali astrophysicist stepped in the drama. He was none other than Dr. Meghnad Saha, one of the greatest physicists India has ever produced. Born on 6 October 1893 in the village Seoratali near Dhaka, Bangladesh (then undivided Bengal), Saha was the son of a small grocery shop owner. There was no academic atmosphere in his immediate family surroundings. But Meghnad was an exceptional student, extremely brilliant. After schooling from Dhaka, he joined the Presidency College in Kolkata in 1911. From here, Saha obtained BSc degree in Mathematics and MSc degree in Mixed Mathematics (this curious name was changed to Applied Mathematics in 1936) in the years 1913 and 1915, respectively. He stood second in both the courses. It is noteworthy to mention that the person who became first in both courses was Dr. Satyendra Nath Bose, who will become one of the greatest physicists in world history in future by formulating the Bose-Einstein statistics. He was the classmate of Saha in Presidency College.

Now, let us come to Saha's own work. Saha started working on the theory of thermal ionization soon after he graduated. He presented his epoch-making work on thermal ionization in a series of four moderately long papers: "Ionisation in the solar chromosphere", "Elements in the Sun", "On the problems of temperature radiation of gases" and "On a physical theory of stellar spectra". Fig. 5 presents a table directly adopted from Saha's first paper. All four were prepared when Saha was a Lecturer at the prestigious Calcutta University and were submitted to the internationally reputed journal 'Philosophical Magazine'. Almost immediately after the submission of these papers, Saha received a scholarship and went to England to work with Alfred Fowler, an expert on spectroscopy. The first three papers appeared one after another in Philosophical Magazine (between October 1920 and February 1921) soon after Saha's arrival in England (the dates of submission of these papers from Calcutta were March 4, 1920; May 22, 1920; and May 25, 1920). However, the fourth and last paper in the series was eventually withdrawn from Philosophical Magazine, expanded in consultation with Fowler and was finally communicated by Fowler to Proceedings of Royal Society, in which it appeared.

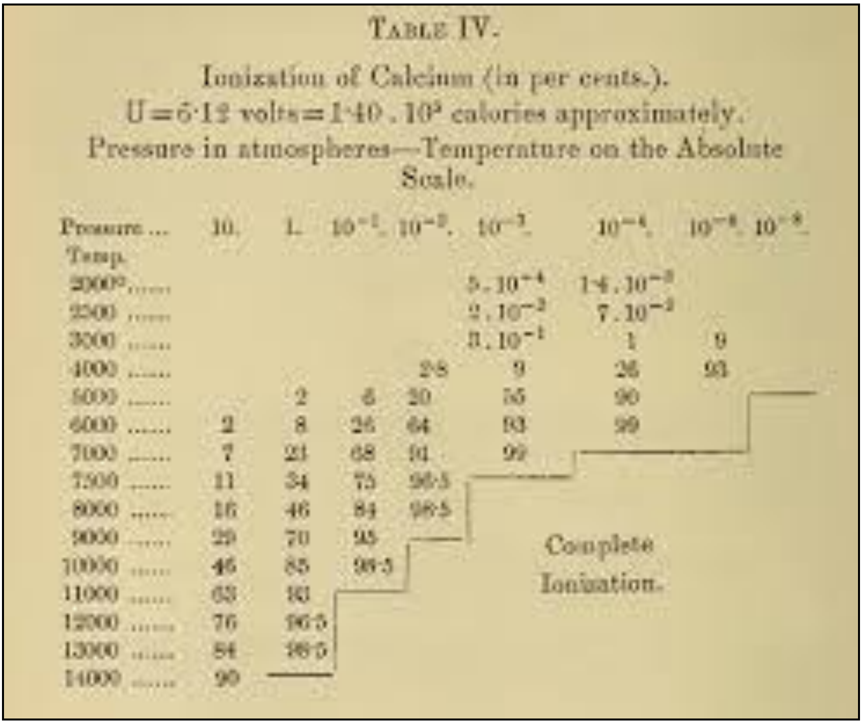


TABLE IV.

Ionization of Calcium (in per cents.).

$U = 6{\cdot}12$ volts $= 1{\cdot}40 \,.\, 10^5$ calories approximately.

Pressure in atmospheres—Temperature on the Absolute Scale.

Pressure ...	10.	1.	10^{-1}.	10^{-2}.	10^{-3}.	10^{-4}.	10^{-6}.	10^{-8}.
Temp.								
2000°					$5 \,.\, 10^{-4}$	$1{\cdot}4 \,.\, 10^{-3}$		
2500					$2 \,.\, 10^{-2}$	$7 \,.\, 10^{-2}$		
3000					$3 \,.\, 10^{-1}$	1	9	
4000				2·8	9	26	93	
5000		2	6	20	55	90		
6000	2	8	26	64	93	99		
7000	7	21	68	91	99			
7500	11	34	75	96·5				
8000	16	46	84	98·5				
9000	29	70	95					
10000	46	85	98·5					
11000	63	93						
12000	76	96·5						
13000	84	98·5						
14000	90							

Complete Ionization.

Fig. 5: A table giving the percentage ionization of calcium at different temperatures and pressures. Figure adopted from the first paper on thermal ionization by Saha (M.N. Saha, Ionisation in the solar chromosphere, 1920, Phil. Mag, 40, 472).

This was the paper where Saha finally turned his attention to one of the most outstanding problems of astrophysics of his day – explaining the spectral sequence of stars. It was already realized at that time that the various spectral types (O, B, A, F, G, K, M) formed a continuous sequence, there being many stars lying between two types. When Saha entered the field, it was already guessed that this sequence might arise from the variation of some physical parameter like the surface temperature of the stars. It was not clear why spectral lines of different elements were present in the different spectral classes. Many astronomers thought that this may imply different compositions. Saha managed to put all the pieces of the jigsaw puzzle together in a single stroke with his theory of thermal ionization. Let us consider the case of calcium. In the spectra of M stars (which are of reddish color and are presumably cooler than other stars), it was found that the g line of normal calcium is very strong, but H and K lines of Ca+ are barely visible. As we move along the spectral sequence towards O stars (bluish and presumably hotter), the g line disappears completely by the time we reach B stars, whereas H and K lines become very strong for A stars. As we move further towards O stars, the H and K lines start becoming weaker and eventually disappear completely in the very hot O stars. In the very first paper on thermal ionization, Saha had already calculated the ionization of calcium by using his ionization formula for different temperatures (Fig. 5). Assuming the pressure to be one atmosphere (the typical pressure expected in a stellar atmosphere), Saha found that calcium becomes completely ionized to Ca+ around temperature 13,000 K (see Fig. 5). Since the g line of calcium is not seen in stars hotter than B stars, he concluded that the surface temperature of those B stars in which the g line is barely seen must be about 13,000 K. On increasing the temperature further, Saha estimated that Ca+ would be ionized further to doubly ionized Ca++, this second-step ionization being nearly complete at about 20,000 K. His argument was that, for those stars in which the H and K lines of Ca+ disappear, the surface temperature should be like this. Considering appearances and disappearances of many spectral lines in different spectral classes, Saha succeeded in mapping the entire spectral classification to a temperature scale.

Finally, the mystery of why stars of different colors show different types of spectra was solved. It became clear that stars of different colors do not have different compositions! Rather, they possess different surface temperatures at which atoms of various elements would be ionized to different extents, causing the resulting spectral lines to be different.

The path breaking work done by Saha became the pillars for understanding the true nature of stars using spectroscopy in later periods. However, it was a truly outstanding achievement. It is great because we need to remember that Saha was only 28 years old when he solved the problem which led stellar spectroscopy to gain maturity. Also, most of his works and ideas already were performed while he was in Kolkata only, without the support of any astronomer, any proper laboratory, any fund or backup. Saha was nominated for the Nobel Prize for this great work. He was the first Indian ever to have been nominated for the Nobel Prize in Physics. However, the Nobel Prize had never been given to any astrophysicist during early half of the twentieth century, until Hans Bethe won it in 1967 for "discoveries concerning energy production in stars". So Saha had very little chance. Interestingly, he was shortlisted and considered seriously in the year 1930 in which C. V. Raman eventually won the Prize.

During the early years, the notion persisted that Saha owed the idea of his groundbreaking work in astrophysics, the Saha equation, to Alfred Fowler, with whom he worked in England in 1920. But this was not true at all. In a letter to Harry Plaskett, Saha clearly mentioned about his works in India (one may read 'Saha-Plaskett Correspondence', Science and Culture, vol. 84 (2018) pg. 285 to check). Plaskett replied Saha saying "(Plaskett to Saha, 6 January 1947): "What was quite new to me was the fact that the early part of your work was done in India, not Germany, before you came to Fowler's laboratory. The knowledge that you had done so much without help and backing in India only serves to increase the admiration I have always felt for your great contribution to astrophysics".

6. Spectra of stars

Stellar radiation originating at their cores reaches us after passing through various outer layers of the star. When light travels outward from the hot, dense interior of a star and passes through the relatively cooler gases near the surface, stellar spectrum is produced. Visible starlight comes from gases present in the stellar outer layer - the photosphere which is much cooler than the inner core. Hence, following Kirchoff's third law, normally a star forms an absorption spectrum. The denser photospheric layers emit blackbody radiation and gases present in the stellar atmosphere absorb their certain wavelengths, producing the so called dark lines (as it appears to us) on a bright background (known as continuum) when we are investigating the emergent starlight. Fig. 6 presents the representative spectra of different stars from a range of spectral classes.

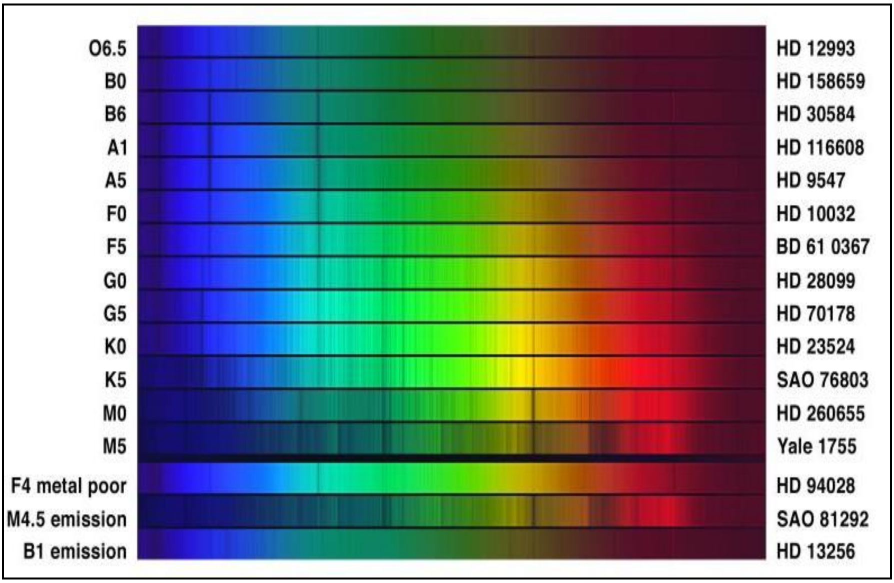


Fig. 6: Representative spectra of different stars from a range of spectral classes. Figure credit: www.teachastronomy.com

Astronomers create a stellar spectrum by spreading starlight into a range of wavelengths (or frequencies) using a spectrograph. A spectrum is usually presented in a graphical form. The graph presents intensity as a function of wavelength. By convention, shorter wavelengths are situated at the left and longer wavelengths remain at the right end of the graph. Absorption lines appear as sharp dips or notches in the spectrum, whereas emission lines appear as sharp peaks. The intensities of the image represent intensities of light, or radiant energy. Usually the blue end is located to the left, whereas the red end to the right.

During the earliest days of spectroscopy, it was only possible to view the spectra by eyes. Later, by the late 1870s, astronomers began to use photographic plates to record spectra observed through any quality telescope. For over a hundred years, astronomical data could only be recorded using photography. The pioneering work on understanding stars using spectroscopy was done in the early 20th Century using photographic plates.

Photographic spectra have now been superseded by spectra taken with sophisticated electronic detectors, or CCDs (Charged Coupled Devices). The wavelength range of the spectrum that can be recorded depends on the wavelength range of sensitivity of the material of the CCD, typically silicon. In present days, it usually covers the range human eye can see and even extends to bluer (UV) and redder (IR) wavelengths.

Modern day technology thus enables astronomers to study digitally recorded spectra which are plotted as graphs of intensity versus wavelength. Here, the 'dark lines' appear as dips in the intensity level. The stellar composition and the corresponding atomic energy levels dictate the wavelengths at which these intensity dips occur. Moreover, the temperature of a star even governs which transitions will occur and also the strength of those transitions. Fig. 7 shows the real spectra of a star in the wavelength range of 3800 - 9000 Å as it appears after data reduction.

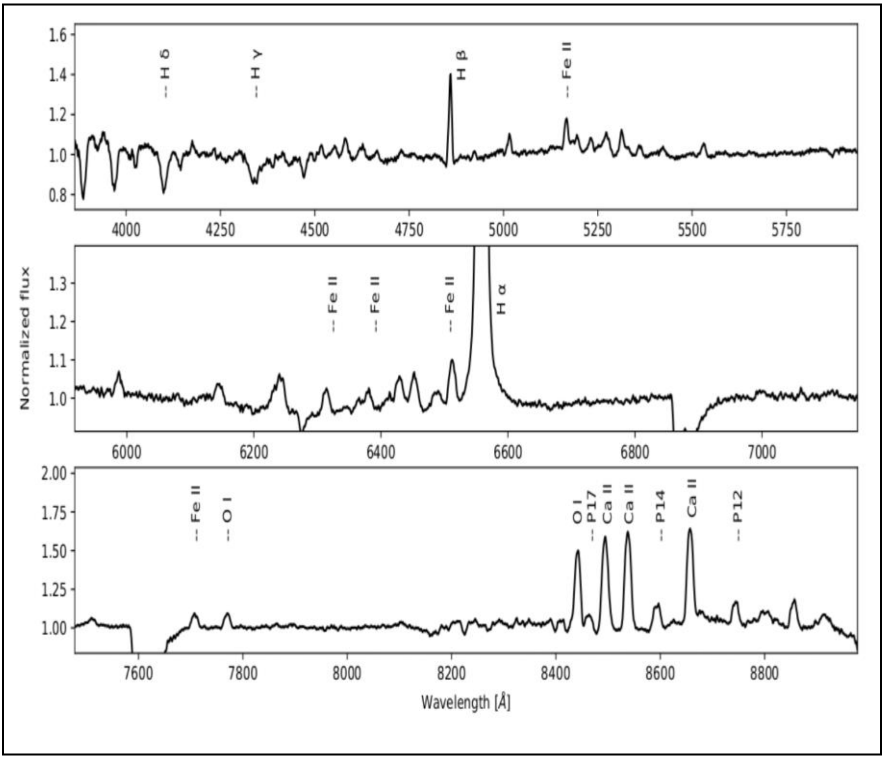


Fig. 7: Representative spectra of the star HD 55606 showing different spectral features in the wavelength range of 3800 - 9000 Å. Figure from Banerjee et al. (2021)

Stars usually show absorption lines in their optical spectra. However, there exist stars which also exhibit emission lines of different elements. Broadly known as ‘emission-line stars', they belong to different categories such as T Tauri, Herbig Ae/Be, Of/ Oe/ Be/ Ae stars, Wolf Rayet (WR) stars, etc.

Extensive studies have revealed that these emission lines originate primarily through three different ways: i) presence of some circumstellar envelope or outer stellar atmospheres, ii) due to some stellar activities like flare outbursts or appearance of bright star spots, and iii) mass exchange in binary systems. Studies of emission-line stars provide tools for understanding the dynamic structure and physical state of circumstellar discs and stellar active regions. Exploring the fine structure of emission phenomenon has become possible through sophisticated ground-based observations combined with space based studies. This has also helped in developing reliable models of stellar activities.

7. Decoding the language of stars

Stellar spectroscopy — the study of spectra of stars — is the primary tool for understanding the physical properties, composition and evolution of stars. Several astronomers devote their entire career to it. They study the spectra of stars, in different wavelength bands, to reveal their physical nature, chemical composition, life cycle, etc. However, one has to keep in mind that identification of spectral lines in a star's spectra tells us what elements are present in the outermost layers of a star. This is because each element shows unique patterns of lines which act like fingerprints. The temperature, density and pressure in a star's photosphere, or surface layer can be derived by measuring the relative line strengths of a particular element. Let me now provide a glimpse of how astronomers use spectroscopy to reveal the secrets of stars.

7.1. Temperature of stars

The word “temperature” can be defined as a measure of the average energy of a molecule of any material. Spectroscopy plays a vital role in understanding the temperature of stars. Analyzing the stellar spectra and measuring which color is the most strongly radiated by a star is a procedure followed to measure the temperature of a star's photosphere (i.e. its surface temperature). Then, a famous law formulated by the German physicist Wilhelm Wien is used to calculate the temperature. Known as the Wien's law, it is a formula which provides the wavelength (W) at which the maximum amount of radiation comes out from anybody having temperature T. The formula is W = 0.0029/T. This is demonstrated graphically in Fig. 8.

Let us see what this figure tells us about a star's temperature. By simply looking at Wien's law, we can say that if one observes a star whose color is peaking in red, then the surface temperature of that star is somewhere around 5000 - 5500 K. In case of the Sun, maximum amount of radiation comes out in a wavelength which provides it the yellow color as observed by us. Hence, we can tell that the surface temperature of Sun is around 6000 K. Although temperature affects spectral lines of different elements, the exact temperature where each spectral line attains the maximum strength differs for every single element. As a result, almost precise determination of the surface temperature of a star is possible by simultaneously examining the relative line strengths of various atoms.

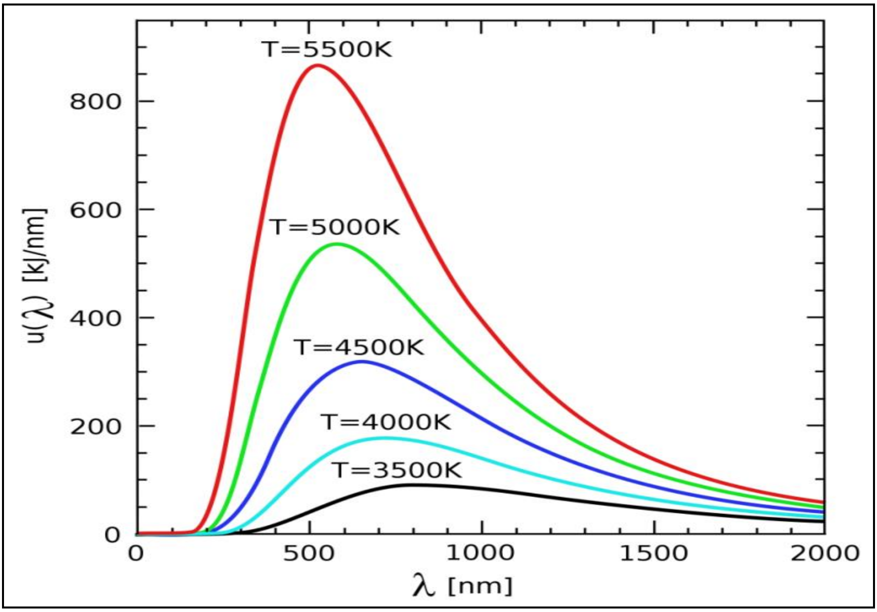


Fig.8: A graphical representation of Wien's law. Figure credit: https://energyeducation.ca/encyclopedia

7.2. Stellar motion

Stars do move. Although stellar motion is not noticeable over any human lifetime, the positions of the stars in the night sky (and also the shapes of the constellations) do change over a long period of time. Spectroscopy helps us to study the motion of stars. A portion of any star's motion - its radial velocity (i.e. the motion along the line of sight of the observer) can be measured using a phenomenon known as Doppler shift. You have definitely noticed how the pitch of any ambulance siren varies as the ambulance approaches your ears, and then passes by. When it approaches, the sound waves from the siren get bunched up, creating a harsh sound with high pitch. When the ambulance moves away from you, the waves get stretched out and you can feel that the pitch of the siren sound gradually diminishes.

Similar phenomenon happens with light waves too. If a star is moving towards or away from us (i.e. the Earth), the starlight (means stellar radiation) will be subjected to Doppler shift. And, astronomers can detect this shift of radiation using spectroscopy. The Doppler shift of a star is proportional to its velocity, expressed as a fraction of the velocity of light. If the spectral lines of a star exhibits a consistent blueshift (meaning the light will be shifted towards the bluer end than the normal wavelength if the star is moving towards us) or redshift (meaning the light will be shifted towards the red end than the normal wavelength if the star is moving away from us), that proves that the star is either moving toward or away from us. For example, say a star is receding at 0.1% the speed of light (or 300 kilometers per second). Then we will notice that its light will be redshifted by 0.1% of its normal wavelength. Any spectral line usually observed at the wavelength 6563 Å would appear near 6569 Å.

However, it has to be understood that any Doppler shift of a star is an indication of motion, not the indication of any change in the temperature of the star. Since the Doppler shift for stars is too small, usually well under 0.1%, we are not able to detect even a slightest change in the color of the star. Instead, sharp spectral features are used as markers to measure the shift.

7.3. Composition of stars

Astronomers can deduce what a star is made of through stellar spectroscopy. The relative proportions of all the different elements give the chemical composition of the star. Classification of huge amount of stellar spectra at the Harvard College Observatory paved the path for understanding what are stars made of. Works of Cecilia Payne-Gaposchkin first showed that nearby stars are primarily composed of hydrogen and helium, making them similar in composition to the Sun.

However, it has to be remembered that the absence of spectral lines of any particular element cannot guarantee that the element is not present in that star. For example, only the hottest O and B type stars exhibit spectral evidence for helium, since the photospheres of cooler stars are not hot enough to ionize helium. Astronomers have to consider several physical conditions, like temperature, density and pressure while determining stellar composition using spectra. Likewise, observing the strength of any spectral feature does not provide any direct indication of the abundance of that element in the star. Conversion of line strength to abundance requires studying a physical model for the star incorporating temperature, density and pressure. The width of the spectral feature is important too. Broader spectral features originate in gas having higher pressure and temperature.

7.4. Stellar interior

We obtain a fair idea about the surface layers of stars using stellar spectroscopy. But to learn about stellar interior composition, we need to look somewhere else - the interstellar medium (ISM). ISM is simply the material and radiation which exist in the space between star systems in any galaxy. A schematic diagram showing the interstellar medium near the Sun is presented in Fig. 9.

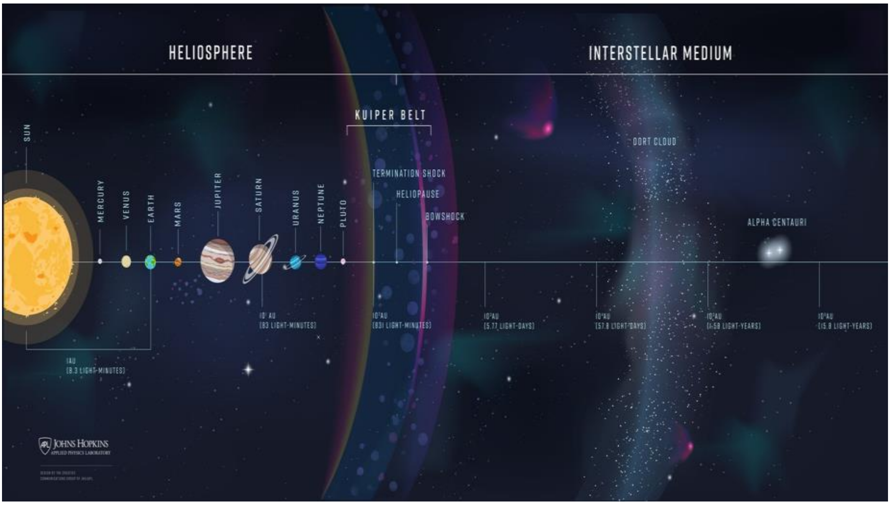


Fig. 9: A schematic diagram showing the heliosphere and the interstellar medium near the Sun. Figure from https://www.azoquantum.com/News.aspx?newsID=7982

Although the cores of stars remain invisible to us, we receive a good idea of their composition by looking at the remnants of stellar explosions. When stars evolve and die, they mix their gas by the churning motions of convection, then they blow off their outer layers, either slowly (for low mass stars like the Sun) or in a violent supernova (in case of massive stars). Then, we can have a look at their interior composition. It is known that hydrogen and helium are the most abundant elements in stars, and thus in the universe. However, we also find heavier elements such as carbon, nitrogen, oxygen, gold, silver, platinum, iron, and all the other elements on the periodic table. Stars produce all these elements, which become the raw material that give rise to new stars. In course of time, many such newborn stars form their own planetary systems. And who knows? Some of those planets might possess conditions to harbor life, even intelligent life too. This is how the life cycle of stars drives the important cycle of creation and destruction in the universe.

8. Conclusion

Through years of hard works of numerous astronomers, scientists and technicians, spectroscopy has emerged to be a powerful tool to understand the true nature of stars. Spectroscopy can be regarded as the ultimate form of remote sensing. We do not have to visit the stars or bring back stellar material into the lab; we can diagnose what they are made of and how they shine purely by gathering light and dispersing it into a spectrum. It appears truly that stars are whispering messengers. They talk to us in whispers and it is the human intellect which was able to decode their language after hundreds of years of struggle, sacrifice and hardest works.

But beyond all, spectroscopy of stars reveals something extremely important about the universe we live in. Helium was a mysterious element when it was first discovered, because it is so rare in our Earth. Now we know that hydrogen and helium are the most abundant elements in the solar system. These two simple elements make up the bulk of the Sun and the giant planets. It is the Earth that is unusual — Earth is a large rock that is rich in carbon, silicon and metals, and is too low in mass to retain the light gases. When astronomers turned their attention towards stars, they had no clue what stars are made of. Would there be strange elements or unusual states of matter at those vast distances? No. Most stars are put together just like the Sun. Hydrogen and helium are the most common elements everywhere in the universe that we have studied so far. This reassures us that the laws of physics and chemistry really are universal.

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