Quantitative Astronomical Spectroscopy in the Post Saha Equation Period

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Abstract

Several new questions of quantitatively estimating physical conditions on astronomical bodies had opened up after formulation of Saha Ionization Equation. The article first reviews the step by step progress in the establishment of a stellar temperature scale. The second point reviewed is the efforts by many groups for determining elemental abundances and finding the solution to the Hydrogen problem. Finally some current efforts to read the magnetic field characteristics from polarization profiles of Zeeman affected spectral lines have been described.

From the days of discovery of spectral features in the light of stars, the main advantage was the ability to form an idea of the chemical composition of the distant bodies. The patterns of emission and absorption lines, closely matched those obtained from known materials in the laboratory, so that scientists could make convincing guesses about the presence of such substances. But still there were important differences ; besides having confusing mixture of line sets ascribable to materials, the ratios of strengths of different lines did not always show same values as one could get from laboratory measurements. The exact process of formation of lines in the stellar atmospheres was ill understood ; it was speculated that the pattern changes with change of physical conditions, but no consistent theory explaining such changes were available, until Saha's theory of ionization equilibrium was formulated. This was the first important step of transformation of stellar spectroscopy from the qualitative to the quantitative era.

Even in the qualitative era, some quantitative deductions could be made from analysis of stellar spectra. Doppler shifts of Fraunhofer lines could be interpreted in terms of motions, and such measurements could confirm solar rotation as early as 1871. More complicated cases of spectroscopic binaries were solved by H. C. Vogel from Germany, and E. C. Pickering in the United States, almost simultaneously in 1889 through efforts which were independent of each other. The models for the line sources used in these cases were somewhat crude and limited by unknown processes in the formation of line profiles. Even Hale's discovery of strong sunspot magnetic fields from Zeeman splitting of certain spectral lines suffered from this limitation. In the period after Saha's formulation of Ionization equation several improvements in astrophysical theories could be affected, which gradually removed the uncertainties in our understanding of the radiation mechanism in stellar atmopheres.

Besides finding solutions to a few puzzling observations, Saha equation opened up new lines of investigation in stellar astrophysics. In this article some of these are reviewed.

1. Stellar temperature scale

Determination of temperatures of the stars were fraught with several uncertainties. Only physical laws known in the nineteenth century were Newton's law of cooling, and the modified Dulong and Petit's law ; an attempt to determine the solar surface temperature by employing these and a few new ideas resulted in widely discordant values ranging from below 1000°C to higher than 40000°C. By end of the century Stefan's fourth power law had been formulated, but took a long time in being accepted by the scientific community, which yielded solar photospheric temperatures around 60000°c. Although the fourth power idea was later confirmed to be consistent with the Planck function describing energy distribution in a black body spectrum, the astronomers were concerned that solar spectral shape does not wholly match with Planckian curves. Development of the technique of photographic spectrophotometry, enabled stellar spectral curves to be examined by similar methods, the departure of the observed curves from theoretical Planckian profiles still bothered astronomers.

By about 1920 Harvard sequence of stellar spectra had been compared with some of the spectrophotometric determination, and a rough idea of the temperatures have been arrived at. Saha in his paper had compared these values with computations based on his

Table I

Stellar class	Typical star	Secchi's classification	Temperature		Remarks
			Wilsing and Scheiner	Saha	
Pb	The Great Orion Nebula	—	15,000 K†		
Pc	I.C., 4997	—	30,000 K	—	Gaseous nubulae with bright lines.
Oa	B.D. + 35^0, 4013		23,000	23,000-24,000	
Ob	B.D. + 35^0, 4001	Type V including Wolf-Rayet stars	—	+ 22,000	
Od	ζ Puppis.				Henceforth all lines are dark
Oe	29 Canis Majoris				
Oe5	τ Canis Majoris				
Bo	ε Orionis	—	20,000	18,000	
B5A	*q* Tauri	Type I, Helium and hydrogen stars	14,000	14,000	
Ao	α Canis Majoris		11,000	12,000	
A5F	β Trianguli		9,000		
Fo	*a* Carinae				
F5A	α Canis Minor	Type II, Yellow-red Stars	7,500	9,000	
Go	*a* Aurigae		6,000		
G5K	a Reticuli		5,000	7,000	The sun is a dwarf star of this class
Ko	a Bootis		4,500		
K5M	a Tauri		4,200		
Ma	a orionis	Type III, Red stars	3,200		
Md	o Ceti		3,100	5,000	
N	—	Type IV	2,950	4,000	
R	—		2,300		

own theory, (Saha 1921) (Table I) which is seen to provide a totally new method of determining stellar temperatures.

Saha himself had realised that his equation was approximate being only a first attempt in determining properties of matter at high temperatures for which experimental data were lacking. Some of the approximations were removed by Fowler and Milne, and they rederived Saha's temperature scale (Fowler & Milne 1923). One important deviation they introduced, was instead taking the points of marginal appearance and disappearance of selected lines in the sequence, they considered the places where particular lines reach their maximum intensities. This criterion, they argued, avoided the uncertainties in determining the total concentration of relevant absorbing atoms, and depended only on temperature and pressure. By employing the modified ionization equation, they recalculated the temperature scale for the stellar sequence. In course of their calculations it came to light that the pressure of 1 atmosphere assumed by Saha for the reversing layers of sun and stars was too high, and a value 10^{-4} of this is typical.

Fowler and Milne presented their results in a graphical form. They calculated the fractional concentration of particular atoms or ions at different temperatures, assuming a constant partial pressure of electrons. The visibility curves for different spectral lines, which were assumed to be proportional to the fractional concentration were seen to peak at different temperatures, and these were related to Harvard Spectral classes ; thus a provisional stellar temperature scale was drawn up. (Fig. 1) summarizes Fowler & Milne's calculations. They admitted that the electron pressure may alter the scale ; but since they found good consistency over much of the temperature range, no necessity of making this adjustment was felt.

Further improvements in the stellar temperature scale were left to future investigators. The hurdles remaining at that time were many, biggest one being understanding the process of actual line formation in stellar atmospheres. This in its turn, required the knowledge of relative abundances, the statistical distribution of the atoms in their various stages of ionization and excitation, their relative efficiencies in the photon capture process, reliable values of their ionization and excitation potentials etc. The entire line of investigations was thrown open after these initial developments.

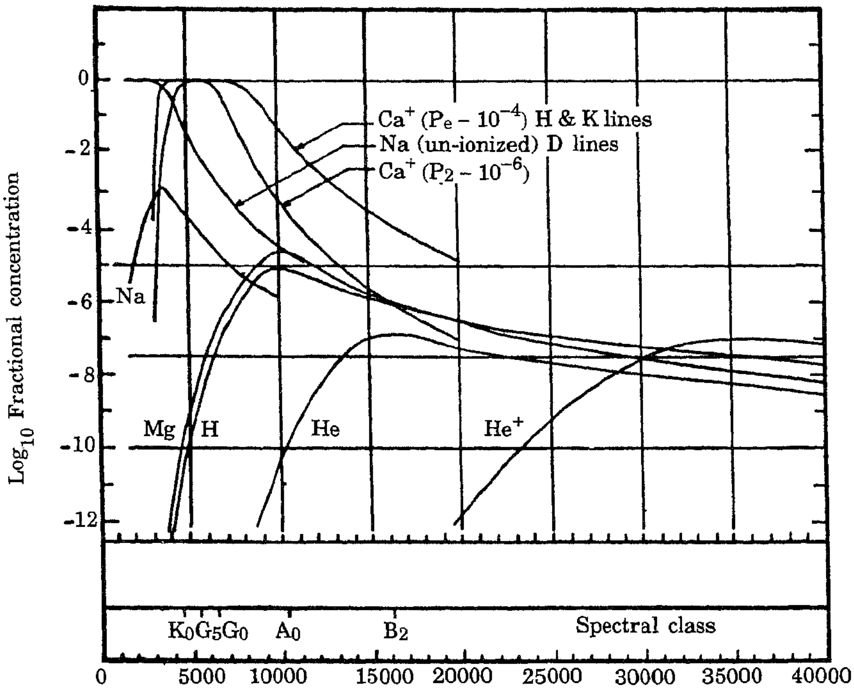

Fig. 1 Temperature°k
Fowler and milnes calculation of fractional concentrations

Two young Ph.D students, who had access to the necessary observational materials took up the challenge. The first was Donald Menzel, a student of Russel at Princeton, and the second Cecilia Payne, a student of Fowler & Milne in Cambridge, England ; both came to Harvard for using the collection of stellar spectral plates for their theses work. Menzel measured the intensities of the lines, which were identified to be due to twelve elements known on the stars. His aim was to standardize the different photographic plates, so that an absolute measurement of the line intensities could be found. He developed a new technique for deriving ionization potentials for elements from stellar spectra ; he also noted a qualitative agreement in the strengths of sub-ordinate lines following Saha's idea : They reach maxima practically in the order of the ionization potentials of the respective elements.

Cecilia Payne delved a bit deeper into the problem ; she derived a refined temperature scale for stars in the Harvard spectral sequence. Fractional concentrations of atoms and ions were calculated by her following the Fowler-Milne modifications of Saha Equation, and with better values of ionization and excitation potentials. She also extracted the strengths of several lines along the sequence from the Harvard plate collections. These two sets of curves when placed side by side showed remarkable resemblance (fig. 2). The link between the strengths of spectral lines and temperatures were clearly demonstrated. Summarizing her work she expressed "what the Draper system classifies is essentially the degree of thermal ionization". A reliable scale of stellar temperatures was at last discovered.

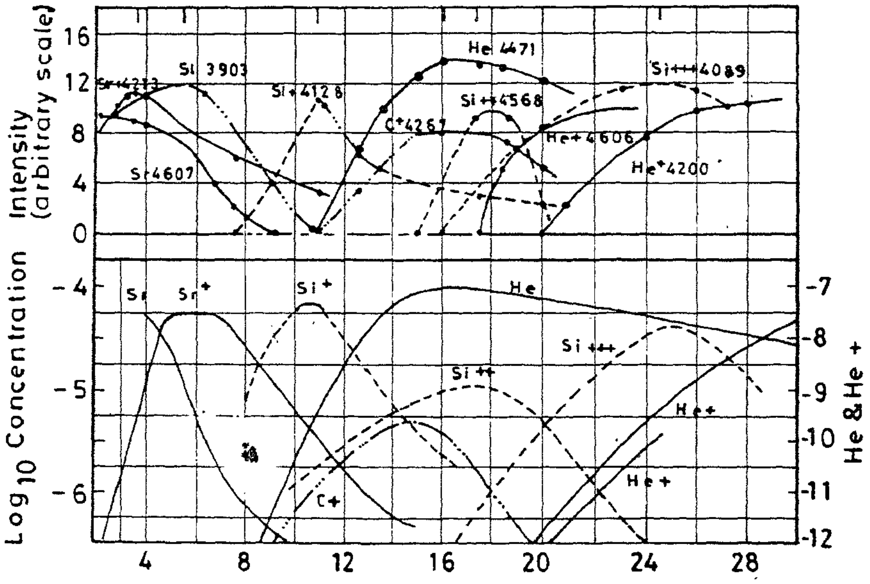

Fig. 2 Temperature 10^3k

2. Relative Abundances

Fowler & Milne while modifying the Saha Ionization Equation pointed out that the criterion of marginal appearances is dependent on the relative abundances of the involved atoms. Any temperature scale derived from this feature then will be uncertain. But if the temperature scale can be fixed, from other features, such as, the points of intensity maxima of different lines with known physical characteristics, then the marginal appearances will be a very sensitive method for determining relative abundances.

The clue was taken up by Cecilia Payne who first calculated relative abundances in some stellar atmospheres. She was convinced that the stellar temperature scale determined was quite accurate, and therefore, the intensity of a given spectral line was proportional to the concentration of the atoms producing it. Accordingly, she argued that relative abundances should be given by the reciprocals of the fractional concentrations at marginal appearance—She calculated the fractional contribution of several elements in stars around points of marginal appearance, and hence the relative abundances, and presented in her thesis. She found H and He to be overabundant by several orders of magnitude and rejected them as the values went against the then existing conviction of scientists.

Earlier it was believed that relative abundances of all elements were similar to those on the earth's crust. Rowland had made a statement that if the earth was raised to the temperature of the sun, its spectrum would most probably resemble the solar one (Rowland 1891). But in the Harvard sequence, many stars were found to have exceptionally strong metal lines, and some scientists believed that there were overabundances of those elements. Saha, in his paper had laid all those speculations to rest when he explained that spectral features can all be explained by temperatures ; there was no need to assumed peculiar abundances.

When Cecilia Payne's abundance calculations showed high H and He abundance, she refused to accept it and deleted the results from her list. The case had further been complicated because Eddington in his theory of the internal constitution of the stars, had speculated very low abundance for H, and persistently resisted any results showing high H-abundance. But indications of high hydrogen abundance kept coming up from several investigations ; efforts were made to explain these by ad-hoc theories.

Russel had been playing the important role of defending Eddington's idea of low hydrogen abundance in stars, but gradually he was won over by new young investigators who started proving that hydrogen is the most abundant element in the universe.

One of the pioneers in a new approach to understanding the physics of line formation was Albrecht Unsöld, who introduced ideas of radiation damping, and transition probabilities in an effort to devise a quantitative method of estimating line strengths (Unsöld 1928). His estimation of elemental abundances tallied with the results of Cecilia Payne. He found that in the solar atmosphere Hydrogen was more than a million times abundant than metals, a result which left him equally confused.

Donald Menzel, who had joined Lick Observatory was trying to work out the composition of solar chromospheres from a valuable collection of flash spectra taken during several solar eclipses. He developed a new method of computing profiles of emission lines from the composition of emitting gases very similar to the "curve of growth" method, devised by Minnaert and his students about a year later, but independent of Menzel's effort. Menzel found that in the solar atmosphere Hydrogen is the dominant element, and convinced Russel that the "Hydrogen problem" as it was existing then needed a closer re-examination.

Russel put forth his altered views in a paper on sun's atmosphere, (Russel 1929) which still attracted a lot of criticism from Unsöld, Plasket, Milne and others, but strongly backed by Menzel, Atkinson and a few other scientists who considered that the new view solved many outstanding problems in Astrophysics. Gradually the opinion started tilting towards dominant hydrogen abundance, and even Eddington admitted that this new idea did not clash with his equations for stellar interiors (De Vorkin & Kenat 1983).

3. More Recent Problems

Development of quantitative techniques which followed Saha Equation, still influence several lines of investigation in Astrophysics.

One such case concerning measurement of solar vector magnetic fields is included as an example.

The original application of Zeeman effect on solar surface was done with a highly simplified model where only the longitudinal components could be estimated (Hale 1908). Sears tried to extend the idea for measurement of total magnetic fields, with all the vector informations (strengths, directions, orientations) without going deep into the basic processes (Sears 1913). Not much success in this direction could be achieved until Unno tried to calculate the polarization line profiles formed in solar gases traversed by magnetic fields (Unno 1956). All bits of knowledge about Fraunhofer line formations in stellar atmospheres had to be applied to achieve this.

Unno's approach followed efforts towards estimation of line profiles ; he tried to calculate the effect of magnetic field on the radiative transfer process ; line profiles without magnetic field had already been computed by several refined methods. He formed the polarization matrix of Stokes parameters, and computed changes for true absorption according to magneto-optical theory. He thus was able to compute the profiles of all Stoke's vectors along the line profile. Actual measurement of the vectors along the line profile could thus yield the total magnetic field.

All these efforts were directed to estimate true magnetic field strengths from their spectral signatures. Efforts to construct solar vector magnetographs at a few observatories of the world are being made. These will provide the vital information about the complex plasma processes happening on the spot regions of the sun. K. S. Balasubramanian at Kodaikanal have recently developed a process to extract this information (Balasubramanian 1988) ; a prototype instruments utilizing these principles has also been built (Bhattacharyya et. al 1992).

The methods of quantitative spectroscopy introduced three quarters of a century ago are still being employed in experimental astrophysics.

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