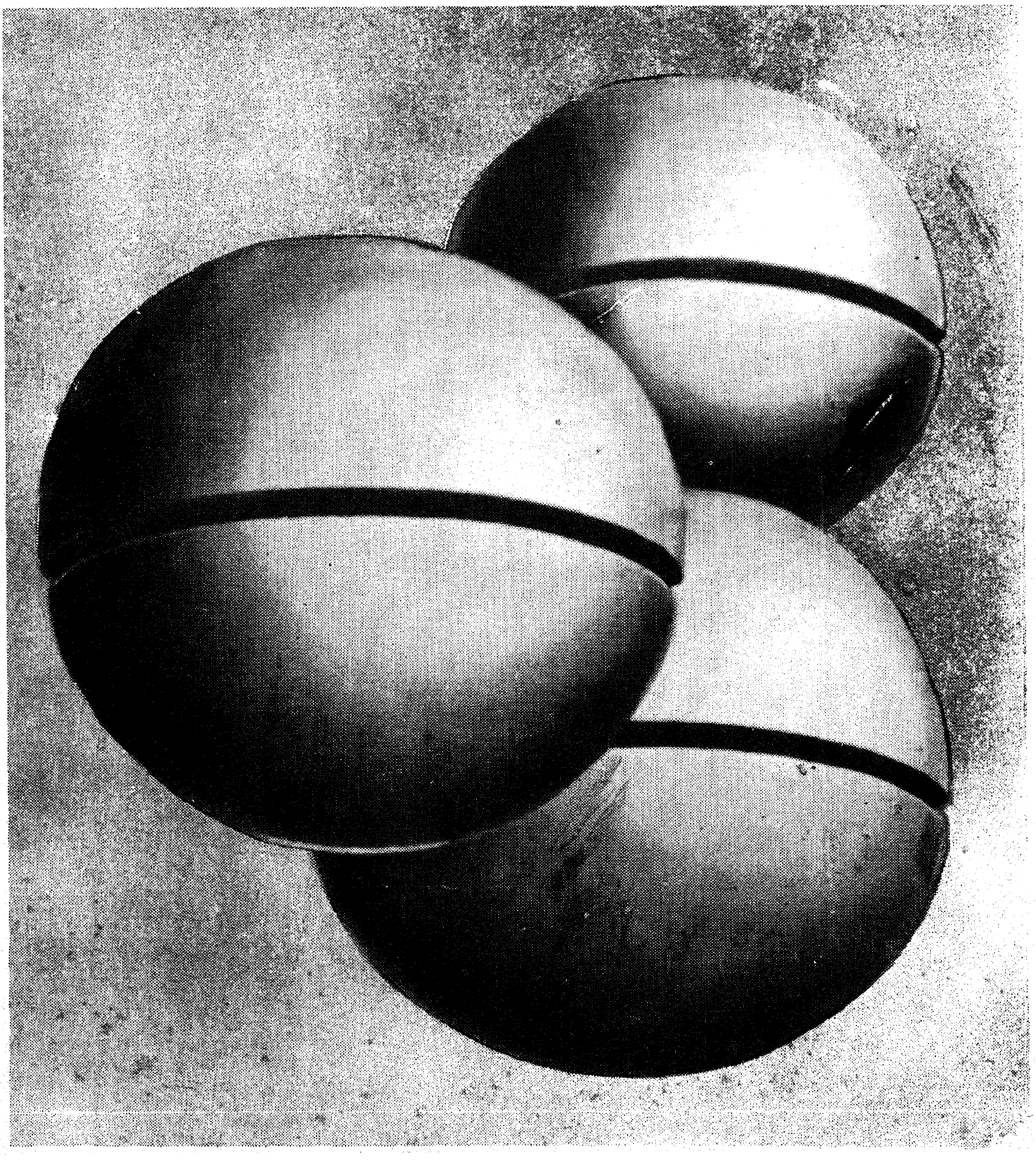
The Sun Is A Star

M. K. V. Bappu

Vikram Sarabhai Memorial
Lectures

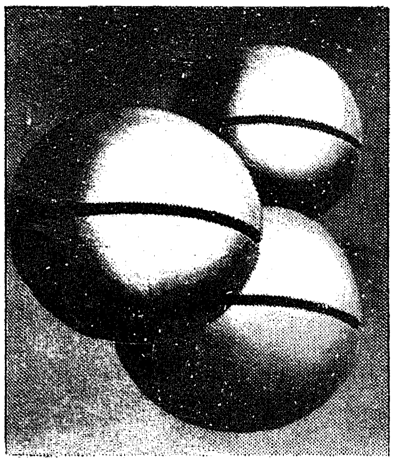


PRL

THE SUN IS A STAR

M.K.V. BAPPU

Front Cover



The Voice of the Wind
by Rene Magritte
Torino Public Gallery
of Modern Art

About the Vikram A. Sarabhai Professership

To stimulate further the research activities initiated by Prof. Vikram Ambalal Sarabhai in the field of Space and Earth Sciences, and to continuously generate winds of change in the scientific environment, a Vikram Ambalal Sarabhai Professorship (VASP) has been instituted at the Physical Research Laboratory. This has been possible due to the endowment funds generously provided by the Sarabhai Foundation and Karmakshetra Charity Trust No. 2 as well as by Late Sheth Shri Kasturbhai Lalbhai. Under this scheme, each year a distinguished physicist is invited to spend some time at the Physical Research Laboratory to deliver lectures and to participate in the research programmes, to visit sister academic institutions in India, and to participate in national scientific meetings, according to his convenience.

Prof. M.K.V. Bappu (1927-1982)

> *"It is better to live for a moment in the brilliant sunlight of victory or die in the dark midnight of defeat than to live for ever in the dim twilight which knows neither victory nor any defeat".*

(excerpt from a public lecture
given by M.K.V. Bappu at Jai-
sankar Sundari Hall, Ahmedabad,
on 8th January, 1982)

In resonance with his words, Prof. Bappu made an enormous contribution to the astronomy and astrophysics within such a short span of life. He passed away at Munich, at the peak of his glory, as the President of the International Astronomical Union, at a time when he was to preside over the eighteenth IAU General Assembly held at Patras, Greece.

Foreword

The Physical Research Laboratory was fortunate to have Professor M.K.Vainu Bappu, Director, Indian Institute of Astrophysics and President of the International Astronomical Union (1979-82), as Vikram Sarabhai Professor from December 1981 to February 1982. Besides holding numerous discussions with the Faculty, he gave a course of lectures on Astronomy and Astrophysics, in which he elucidated the interplay between stellar and solar astronomy, brilliantly showing how each gains from the other. He expounded the subject in a masterly erudite fashion. Those who were privileged to hear them were charmed by the brilliance of the manner in which they were delivered as well as by their scientific content and research outlook. Those lectures are reproduced here. It is hoped that they would convey even in cold print some of the charm and inspiration received by those who heard those lectures.

These lectures practically represent the last series of public scientific discourses that Professor Vainu Bappu delivered with his usual dignity and authority. He passed away on 19 August 1982 at Munich a few days before he could deliver the Presidential Address at the 18th General Assembly of the International Astronomical Union at Patras, Greece.

In a short span of life of 55 years, Dr.Vainu Bappu made enormous contributions to the furtherance of Astrophysics not only in India but internationally as well.

Manali Kalath Vainu Bappu was born on 10 August 1927. He graduated from the Nizamia College, Hyderabad in 1946, and obtained his Master's degree in Physics in 1949 from the University of Madras through his work at Hyderabad. Thus he bloomed into an active young scientist around the same time as India gained her independence. After a brilliant post graduate career, 1949-1952 at Harvard and Caltech in the United States, where he also obtained his Ph. D. degree in record time, his deep sense of patriotism made him return to India in 1952. As he himself remarked : "I was returning to a country with facilities which were primitive compared with those in the United States ..... My principal encouragement was some advice from Plaskett on how it was possible to do good work even with limited resources if the topics were chosen carefully".

In July 1949, while at Harvard, he discovered a comet and worked out its orbit sooner than more experienced people could do. It is now known as comet Bappu - Bok - Newkirk. In 1957, he published a paper which established a relation between the line width of ionised calcium lines emitted by a star and the absolute visual magnitude of the star over a very wide range of magnitudes. This is known as 'Wilson-Bappu effect'. It has triggered developments of a number of areas in astrophysics all over the world.

Dr. Bappu's scientific activity covered a wide variety of topics : solar and stellar chromospheres, comets, planetary rings, Wolf-Rayet stars, galactic structure, red-stars in the Magellanic Clouds, ultra low dispersion spectroscopy of stars and galaxies, instrumentation and techniques and above all, solar eclipses. He was a great builder of astronomical observatories. He built and equipped the Nainital Observatory in its formative period; he made considerable improvements in the Kodaikanal Observatory. He built and equipped the Kavalur Observatory into one of the best in the world. The buildings and the scientific work at the Institute of Astrophysics, Bangalore, are the result of his imagination and drive. His dream of equipping the Kavalur Observatory with a 2. 3 metre telescope was nearing its realisation when he passed away. Dr. Vainu Bappu demonstrated how much a dedicated individual can accomplish in twenty five years, even when conditions in a developing country are not quite favourable.

It is India's tragedy that Bhabha, Sarabhai and Bappu were all snatched away by a cruel fate, when a further lease of a decade or two of life would have made a tremendous difference to the advancement of science in this country.

It is felt that these printed lectures of Professor M. K. Vainu Bappu would contribute to the continuation of his inspiring spirit among us.

वाण्येका समलंकरोति पुरुषं या संस्कृता धार्यते ।

Only erudite and chiselled speech can properly adorn a person.

- P.R. Pisharoty

A Word From the Editors

After Prof. Bappu had delivered these lectures at PRL in December 1981, they were edited and the edited version was taken by one of us to Prof. Bappu for the necessary corrections to be made by him. When asked as to when we could expect to get the final version of the lecture notes, Prof. Bappu said, with authority and confidence, which were so typical of him, "You give me the tapes, the notes and everything and I am going to do a lot of changes in these notes. PRL will be lucky if it gets the final version by June 1982". Definitely, he meant to complete this work before June 1982 but because of the pressing involvements at hand, as the President of International Astronomical Union, it was impossible for him to complete the job before the IAU General Assembly held in August 1982 and the rest of the unfortunate story, we all know.

So the task of making the final version of the "lecture notes" had to be undertaken by us and here we had a little difficulty.

An excellent and a very coherent speaker Prof. Bappu was; however, he had often to depart from the main text in response to the many questions and interruptions from the audience. As a result, there were a few links missing at some places of the series and now that Prof. Bappu is physically no more with us, we had to make up for this deficiency. Hence, in the course of this venture of ours, though we have most probably not missed any important point, we have certainly added many things at many places. This was done essentially to maintain the coherence and continuity of the series and we have tried our best to do it in the way Prof. Bappu would have done it.

We trust Prof. Bappu will forgive us for the liberty we are taking, but the best we can do is to write, in the way we imagine what he had in his mind.

K.C. SAHU
J.N. DESAI

CONTENTS

LECTURE-I

1. 1 INTRODUCTION

1.2 THE SOLAR-STELLAR CONNECTIONS

LECTURE-II

2. 1 THE SOLAR/STELLAR ATMOSPHERE

2. 2 THE SOLAR CHROMOSPHERE

2.3 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

LECTURE-III

3.1 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

3.2 AGE CHARACTERISTICS OF CALCIUM EMISSION

3.3 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

LECTURE-I

1.1. INTRODUCTION

1.1.1. Recent Improvements in Solar 'Seeing'

Due to the recent technological advancements, the world has seen a lot of improvements in all astronomical observations in the last few years, and this has been more dramatic in case of solar observations, so far as accuracy of information is concerned.

One of the serious handicaps that an observer located on earth suffers from is that his 'seeing' is limited by the restrictions imposed by the earth's atmosphere. In case of solar observations, the handicap is more serious because here the 'seeing' is not only affected by the layers of atmosphere high above, that contribute to the success or failure of the day, but the conditions within the dome and the telescope play a very significant role. So, one of the prime requirements in solar observations is to avoid this poor 'seeing' and increase the spatial resolution as much as possible. Astronomers have tried to achieve this by going to exotic places like the middle of a large expanse of water etc. where the disturbance in the local 'seeing' is controlled to a good extent. Also, one can control this local 'seeing' effect by flying a telescope up in the air where a good bit of the atmosphere is below it and indeed stratoscopic balloons have produced very fine pictures which confirm this possibility. The idea of simulating such a situation on the ground has led to the concept of a vacuum telescope where the whole telescope is enclosed in a low pressure of one to two millimeters of Hg which is sufficient to eliminate the major factor that contributes to poor local 'seeing'. So it is possible to minimise some of these harmful effects that upset the spatial resolution by proper choice of a telescope.

The proper choice of a telescope is rather a serious requirement for many kinds of works. We recognised this problem in Kodaikanal a long time ago. Kodaikanal is a place where there is a very fine definition of the Sun within an hour of the sunrise. And as soon as the mountain slopes start getting heated up, the convection currents rise, and the simmering of the Sun starts, and that is the end of our work if our work calls for an extremely good definition of one to two seconds of arc. Therefore, there have been days, nay, there have been months, when we have failed on continuous occasions to have spells of good 'seeing' that would permit long time sequence photographs - the kind that the present day solar physics calls for, to be taken with any degree of success.

1.1.2. The Sun Does Not Have Enough Flux !

If we want to make any advancement in solar physics, then it is essential that we think in terms of a large telescope that has not only the aspect of good definition but also the aspect of good light collection. Good light-collection is a necessity because even the Sun does not have enough flux for the present day solar physics. This looks to be a rather difficult statement to accept but the fact remains that it is very much true because of the following reason.

Present day solar physics calls for an extremely good definition and you can achieve this in two ways: (i) by actually having a very good definition or (ii) by having it for very limited spells of time during which a complete sequence of exposures has to be taken. Now, since the former is restricted by the constraints imposed by earth's atmosphere, we have to resort to the second alternative. Here, since the exposure time has to be very small, it is necessary to have a large aperture telescope so that enough number of photons go through the slit of the spectrograph during that brief spell of time to give a good picture. Hence, a large aperture vacuum telescope becomes a necessity.

1.1.3. Recent Major Discoveries

Granules: Granules are known since the middle of nineteenth century, as these are rather gross features on the surface of the Sun. These are small scale (one to three arc seconds) intensity patterns and if you have a good 'seeing', it is possible, by using a solar eyepiece, to observe these beautiful fine structures in fleeting glimpses.

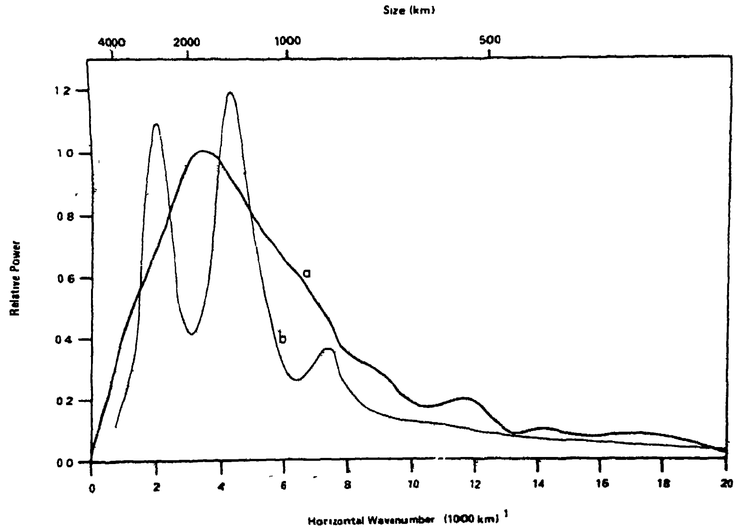


Fig.1.1 Power spectrum of granular intensity fluctuations. Curve 'a' is the average of many observations. Curve 'b' is the power spectrum of limited sample, which accentuates possible fine structures.

An objective way of describing solar granulation is the intensity power spectrum shown in fig.1.1. The mean size of a granule is about 1000 kilometers and the mean spacing between the granules is about 1500 kilometers. The life time of a granule is typically 6 minutes, but sometimes they last for as long as one hour.

Supergranules: Supergranulation is essentially a discovery made from velocity pictures.

For spectral studies, when we place the slit of the spectrograph along the granules, it also covers some intergranular space. This is the problem one faces in studying some of these features. As a step to overcome this problem, the technique of photographic subtraction was introduced. Here, one picture is taken in the light of the shortward component of the line, another picture is taken in the longward component of the line and a photographic subtraction is applied. So this, essentially, is a velocity picture and when a two dimensional picture of this kind was taken and a spatial autocorrelation was made (Hart 1954, 1956), the existence of systematic horizontal velocity patterns were discovered which lasted for longer than an hour and had a size of about 26,000 kilometers. Leighton et al. (1962) later showed that these consist of cells which they called "supergranules". In the supergranules the flow of matter in any cell is along the surface from the centre towards the periphery. The life time of a cell is typically one day but longer life times (two to three days) have also been found.

Five-minute Oscillations:

Another important step in solar physics was the discovery of five-minute oscillations. Now, if the slit of the spectrograph is placed on any part of the Sun and a Doppler signal is taken (for this, the shortward component of the absorption line is fed to one photomultiplier, the longward component is fed to another photomultiplier and a difference signal is taken) then, if there is a velocity, we get a signal. If such a signal is monitored on any part of the Sun, particularly at the centre, then we get a form which has a periodicity of 300 seconds. This is called the five-minute oscillations.

The above three major discoveries marked a very active era in solar physics starting from mid 1960's. Now let us look into some details.

1.1.4. 'The Sun Is a Star' vs. 'The Sun as a Star':

As is the title of the series, when we say that 'The Sun is a Star', it is essentially an exploration from the observatory and there is, of course, no ambiguity about it. But the question is, why don't we enumerate ' The Sun as a Star' rather than say, 'The Sun Is a Star' ?

We know that the Sun is the only star which not only allows for spatial resolution but gives enough flux for detailed analyses of such spatial studies. Now, if we were to describe the Sun as a Star, then we would try to dilute the findings that we make on the solar surface to the standards of meagre data that we are accustomed to see from the stars by virtue of the fact that we have neither spatial resolution nor enough photons from the stellar sources.

It has always been a statement which every astrophysics teacher imparts to his students that the Sun is a typical star and, therefore, it is essential to use the Sun as a testing ground for all kinds of theories. Unfortunately this is basically a theoretically induced statement which apparently seldom holds in practice because in these days of specialisation, we have reached a stage where there are so many things that we have been able to see only in the Sun which we would like to see in the stars; and there are so many things in the stars which we would like to see and verify in the Sun. Hence, at this moment, establishing the close interplay between the Sun and the stars is the task that we set upon and this interplay between the Sun and the stars is really what I hope I would be able to demonstrate in the course of this series of lectures. Hence, instead of describing "the Sun as a Star" we call "The Sun Is a Star" as the title of this series of lectures.

1.2. THE SOLAR-STELLAR CONNECTIONS

1.2.1. Other Stars too Have Granules:

In this task of our establishing a correlation between the Sun and other stars let us start out with finding out the possibility of observing granules in other stars. We know that granules are one of the smallest features that are seen on the surface of the Sun. Of course, the smallest feature seen on the Sun is the filigrees (a discovery from the vacuum telescope) which are extremely small in size (about 200 to 300 kilometers) and are seen scrambled in clumps around the granules. Nevertheless, the discovery of granules, though they are much bigger compared to filigrees, was not an easy one and was possible because of rather larger contrast (about 1.25) between granules and intergranular spaces. So, when it is so difficult to see granules even in the Sun, and the granules are not possible to be seen unless you have very good 'seeing', is it not too much of a fantasy to hope to detect them in stars? Let us see.

We know that (i) about 50% of the solar surface is covered by granules, (ii) in granules there is an upflow of matter with a velocity of about 1.5 kilometers per second and in intergranular space there is a downward flow of matter with a velocity of about 3 kilometers per second and (iii) the granules are brighter than intergranular spaces. Net effect is that if a line profile is obtained for a region covering many granules and intergranular spaces, there is more of a shift towards violet by virtue of the granules than the shift towards red by virtue of the intergranular spaces.

Now, we know that since the temperature increases as we go from the surface towards the centre and there is radiation at the surface which is an efficient means of cooling, there is a convection zone near the surface and it is the manifestation of this convection zone that shows up in the nature of granules. Since the high excitation lines are favoured by higher temperatures, these lines are formed deeper down, and since these lines pass through a greater optical depth, they are weak. Hence a weak line, in contrast to a strong line, is an effective means of probing deeper. So, if we observe a weak line, we find the convection neatly demonstrated in the profile and these lines have, principally, a tendency to have a blue shift for the above mentioned reasons. To be able to observe the blue shifts, we must choose suitable good lines like the iron-lines. It is worthwhile noting here that good laboratory wavelengths just do not exist within the precision required for this purpose. Laboratory wavelengths are good enough for precision of the order of 500 meters per second where as what we are now talking of is of the order of 200 meters per second and what we would like to observe are very subtle differences of velocity of the order of 100 meters per second. Now, with the precision required, if you take spectra at different portions of the solar disc,

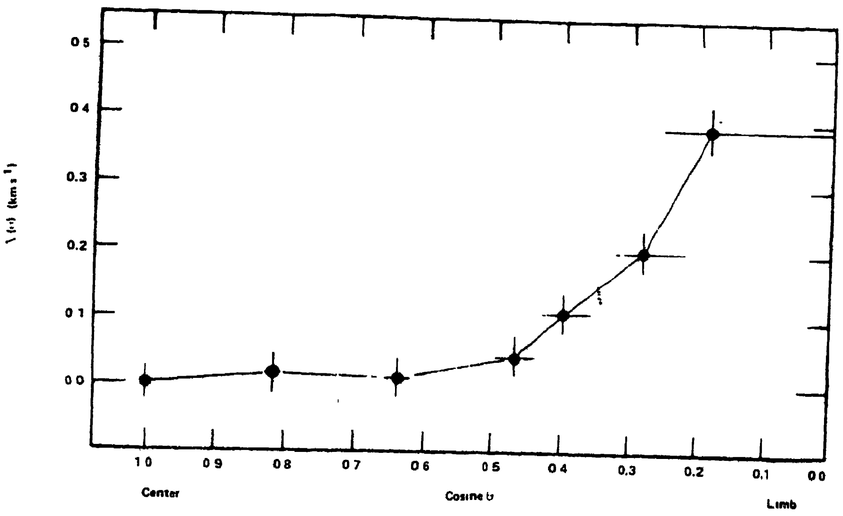


Fig 1.2 Solar limb shift as measured by Adam (1959). The velocities are relative to the line position at the disk center. Zero velocity on an absolute scale occurs at $\Lambda(\theta) \simeq 0.4$ kilometers per sec. Increasing Λ (θ) is increasing velocity away from the observer.

you get a velocity curve as shown in figure 1.2 where the velocities are plotted with reference to the line position at the disc centre which actually is blue shifted by about 400 meters per second compared to the laboratory wavelength. (Note that the observed line centre has a red shift of about 200 meters per second but when we consider the red shift of 636 meters per second dictated by the theory of relativity at the centre of the solar disc, we get a blue shift of about 400 meters per second as the effect of granulation). We see here that, as we go towards the limb, the blue shift decreases which is just what we would expect since what we are seeing is just the line of sight component. When we take a spectrum of the integrated Sun this effect can not be escaped and hence what we find is a blue shift of about 400 meters per second at the centre diluted by the limb effect. Net result would be a blue shift of probably about 200 meters per second (I say 'probably' because this has not confirmatively been observed, but it can be observed because when one has the precision required it is possible to observe this blue shift with respect to the intrinsic velocity of the star; the method of finding the intrinsic velocity will be discussed shortly).

Now, we can extend this argument to other stars. We know that the stellar spectrum would be equivalent to that of the integrated Sun and hence in the spectrum of the star if we find a blue shift of the order of about 200 meters per second for the high-excitation lines with respect to the peak position for the low excitation lines then we can say, with some degree of certainty, that there is some evidence of granulation. It is useful to recall here that one can consider some molecular lines like that of carbon monoxide which are formed at the top of the atmosphere where there is no convection effect, to find out the intrinsic velocity of the star. The shift of the other lines with respect to this line may be considered as the effect of the granulation.

Another Approach (the Bisector Technique):

There is another approach to this problem which is a little more refined though it is also a little more empirical. Since an absorption line is formed over a certain depth and since the convection properties would range over the depth, there is likely to be an asymmetry in the line. If you draw the locus of the mid points, you would find a certain distinct asymmetry in the line. You can describe this asymmetry mathematically by taking a Fourier Transform of the spectrum and describe the skewness of the line mathematically. However, a very convenient way of handling this is to draw a bisector of the profile which, if there is granulation, has the tendency to have the shape of a 'C'. The 'C' shape is more pronounced for the weaker lines and become less pronounced as you consider the stronger lines as expected (see fig. 1. 3). The bisector changes its shape as one comes towards the limb.

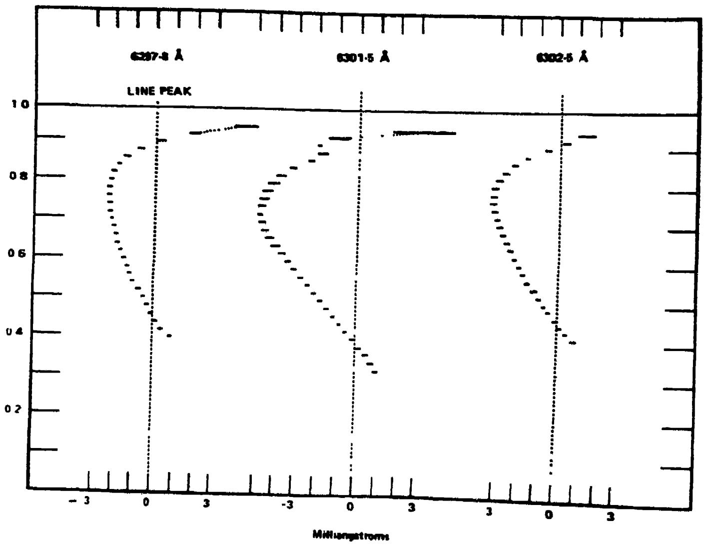


Fig. 1. 3 The bisectors for three Fraunhofer lines showing the 'C'shaped characteristics. The 'C' shape becomes more pronounced for weaker lines (Adam et al. 1976).

So, here is a diagnostic approach which can quite effectively be utilised to detect the degree of asymmetry that one finds in the spectrum and thereby draw the inference of the presence of a granular component, and indeed this is a method which has been successfully used by Dravins, a young scientist from Sweden, in recent times (Dravins et al. 1981). Employing this technique he has shown (Dravins, 1982) that stars like Aldebaran (alpha-Tau) show granulation phenomena.

From the above arguments it is clear that it is quite possible to see the effects of granulation in stars if you have the following requirements satisfied:

(i) A few hundred good laboratory lines; the exact wavelengths of which are known to a precision of less than 200 meters per second.

(ii) Selected lines of different excitation, essentially coming from different depths of the stellar atmosphere.

(iii) Line spectra with a resolution comparable to what we have in present day solar observations.

The demand of these requirements in general and the third one in particular, seems to be quite exorbitant. But let us remember that today our standards of stellar spectroscopy are just what the solar spectroscopy had twenty years ago and so it is not unlikely that the stellar spectroscopy will soon achieve the standards of present day solar spectroscopy and if it is so, we will be able to learn much more about the granulation phenomena in other stars.

1.2.2. Possibility of Finding Supergranules in Other Stars:

Unfortunately, the presence of supergranules is not as striking as the granules and the supergranules are difficult to observe even in the Sun unless you have a different way of looking at them. Supergranules can be detected only in an indirect way with the aid of velocity pictures where you have to go through the tedius task of photographic or electronic subtraction to have the whole picture in front of you.

Fortunately however, supergranules can be outlined quite easily, because of their association with the network that is seen in a calcium spectroheliogram. Here, it is quite suggestive that there is a flow from above the centre towards the periphery and the velocity flow is parallel to the surface all over. There is also a large down flow of matter at some of the localised points at the boundary which outline the supergranular cells. Now, precisely at these regions, there is a weak calcium intensity seen and this calcium intensity must have been formed by virtue of the magnetic field which had been pushed along with the flow and brought to the boundary. There is a piling up of the magnetic field at the boundary which gives rise to enhanced calcium intensity. So it is possible to locate the supergranular cells by virtue of the calcium picture. However, it is not quite like being able to locate the supergranule itself; it is still a very indirect means. So recognizing a supergranule by this method is a difficult task and it is going to remain difficult to recognise a supergranule in the star-light, until it is possible for us to get a two dimensional picture of the disc of a star. Probably that is not too far off. In the near future one may see a space telescope of 20 to 25 meters diameter, floating around in space and then it will certainly be easy to have two dimensional pictures of the stars and then supergranules in other stars can easily be picked up.

1.2.3. Spots : Magnetic Field Is Not the Way

One of the most striking features that one sees in case of the Sun is the presence of sunspots. Now, do we have any evidence of having spots in stars?

The answer certainly would be 'yes'. Recently we have seen several such cases and one of the 'much talked of' kind is the case of RS CVn stars. In these stars, an integrated brightness variation in white light has been observed and one invokes the spottiness of the surface to explain this light change. We know that, if we were to examine the Sun as a variable star, the total contribution to the blocking of white light radiation caused by the sunspots is trivial and we would need very fanciful means of measuring brightness to detect these subtle changes. But in case of RS CVn stars the spottiness is extremely significant and hence it is possible to detect them in white light.

Now, let us examine the possibility of detecting the spots by virtue of their magnetic fields. If we can have a two dimensional picture, it is possible to pick out the spots by their high magnetic fields. Otherwise, since the spots are generally found in bipolar forms, the balance field in the integrated case is less than one Gauss even though the magnetic field in individual spots is 3000 to 4000 Gauss. So, in the integrated case, using the magnetic fields of the spots as the criterion does not seem to be a very useful means of identification of spots in the stars.

There are other means of inferring the presence of sunspots, and one of the most efficient means is to use the spectral aspects. We know that the spots are comparatively cooler regions on the surface of the Sun and hence favour molecular absorption features like that of titanium oxide. So the presence of such types of absorption features in other stars may indicate the presence of spots. Now, if we consider RS CVn stars, the observations taken at two different phases show strikingly different features. In the first phase there is an enhanced spottiness and in the second phase there is none. Also it is found that, in the first phase, there is enhanced titanium oxide absorption feature and in the second phase there is no titanium oxide absorption. This is an illustration where different features are consistent in indicating the spots and go to show the authenticity in assuming that there is a certain degree of spottiness on the surface of other stars.

1.2.4. Five Minute Oscillations: Possibility of Solar like Stellar Oscillations

Five-minute oscillations is one of the few experimental findings that have very satisfactory theoretical explanations; the explanation for the five minute oscillations being that it is the manifestation of the trapped acoustic waves in the convection zone. The various diagnoses of this in the various diagnostic diagrams uniquely confirm that it is indeed an acoustic wave phenomenon which occurs in the solar atmosphere. Now, if it is so, it is certainly of interest to be able to detect this in other stars.

Very recently, by using techniques which are extremely sophisticated (like the method of potassium resonance cell of Blamont; Blamont, 1961 & 1977) and by making very refined measurements, it has been possible to determine the total overall oscillations seen in the integrated light. Sure enough, the Sun has these oscillations with a periodicity of about 300 seconds. This is a very important aspect because it is a powerful means of probing various depths of the atmosphere. Also, it provides a means of studying certain features which, at present, are confirmed only by the photospheric observations where we find the absorption lines. If one is interested in studying how the velocity of rotation at different depths increases below the photosphere, the only means of doing this is to study on a diagnostic diagram these oscillatory modes and then couple this information to find the rotational velocity. Employing this method, indeed it has been shown in recent times that at a depth of about 20,000 kilometers the Sun rotates faster by approximately 80 meters per second.

1.2.5. One Sixty Minute Oscillations: Detection of Stellar like Solar Oscillations

Now, we come to an example where we have a feedback in the reverse sense. For a long time we have recognised that stars have pulsation phenomena well demonstrated in case of cepheids etc. which are very useful in determining various factors, the most important of them being, perhaps, the distance scale. The question is, can we expect a pulsation feature to manifest itself in case of the Sun and if so, is it possible to measure this? Theory has shown that this can be done. Indeed there are certain modes of oscillations which permit the Sun to show up a slight degree of pulsation and recently a pulsation with a period of one hundred sixty minutes has been measured. The amplitude of oscillation is surprisingly low, of the order of a few meters per second. To be able to unscramble this little message from the noise is in itself a feat of the present-day technology. Nevertheless, this has been done. This has been confirmed by several groups working over three to four years, continuously monitoring these oscillations; the groups have been spaced two continents apart and they have been able to find an appropriate phase difference. So, definitely this is not a terrestrial phenomena that is superposed on this aspect of study. A IAU colloquium on this aspect (sixty-sixth colloquium of International Astronomical Union on "Problems of Solar and Stellar Oscillations") was held at Cremean Astrophysical Observatory, 1-5 September 1981, where even higher modes of solar oscillations might have been reported.* While there are no serious disbelievers on this one hundred sixty minute oscillations, a good theoretical explanation of this phenomenon is still lacking.

---

* Proceedings of the sixty-sixth IAU colloquium on "Problems of Solar and Stellar Oscillations" have been published, as a special issue, in Solar Physics Vol. 82, 1983. Though there was no report of any solar oscillations with periodicity larger than 160 minutes in this colloquium, higher mode solar oscillations of about 13 day periodicity have recently been reported by A. Claverie and his collaborators. For details, the reader is referred to the articles by Claverie et al. (1982), Dicke (1983) and Duval & Jones (1983).

LECTURE-II

2.1 THE SOLAR/STELLAR ATMOSPHERE

Before proceeding further with our solar-stellar connections it is now necessary to look, in some detail, into the atmosphere of the Sun/star.

2.1.1. What Constitutes the Atmosphere:

In the interior of the Sun, we have a reservoir of energy where the energy is predominantly flowing towards the outer surface and the material in this volume is completely opaque. Then, as we go outwards from the interior, the temperature decreases and at the photospheric values, not only do electrons and hydrogen ions recombine to form neutral hydrogen but electrons also attach themselves to neutral hydrogen atoms through

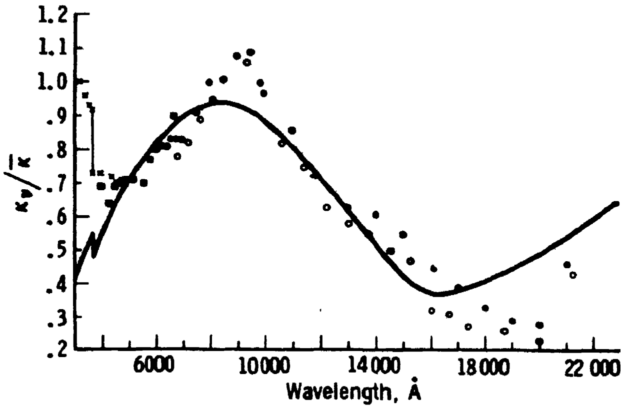


Fig. 2.1 Monochromatic continuous absorption coefficient of H^- relative to the mean absorption coefficient calculated for 5740 K (Chandrasekhar, 1960).

relatively weak bonding to form negative hydrogen ions, H^-. Since this ion has a relatively large interaction probability with photons (see fig. 2.1. where $\bar{K}$ is the monochromatic opacity averaged over flux), this is one of the principal sources of opacity in the solar atmosphere. The other principal source of opacity, of course, is the Bremsstrahlung absorption in the far infrared. As shown in fig. 2.1, the minimum of opacity due to the H^- source falls in the near infrared region at about 1.6 micrometers. So, this is perhaps the region where you would be able to first see the atmosphere as a transparent window to the opaque reservoir of energy deep inside. And then, as you go higher up from the boundary of this reservoir, you gradually begin to have increasing transparencies into the atmosphere and hence you have more and more radiant energy flowing out into the interstellar medium.

The region that lies between the lower boundary of the interstellar medium and the boundary where the radial optical depth becomes one at 1.6 micrometers, is what we call the atmosphere and this is the region which is now of considerable interest to us. However, if the star happens to be a hot star, our above definition needs a little modification because it is not at the minimum of the H^- curve that we will have the maximum transparency but at the Lyman continuum of the star and hence we have to consider the optical depth at Lyman continuum instead of at 1.6 micrometers.

2.1.2. TE, LTE and NLTE:

We know that thermodynamic equilibrium is a situation where the distributions of the gas particles and photons over the various energy states available to them are statistically the most probable ones. In such a case, once the total gas composition and the total energy are specified, the state is uniquely defined. Close to the stellar boundary the radiation is predominantly flowing in an isotropic way and here the matter is in a state of thermal equilibrium (TE).

As we go into the atmosphere, since there is a temperature gradient, a little deviation from TE occurs, but we try to retain the TE assumption on a local scale. So we have the distribution of the various atoms in different stages of excitation and ionization as a characteristic of a region and at the same time the kinetic temperature is defined by the electrons. Also, flow of radiation is predominantly in one direction which is anisotropic but still we can say that the atmosphere in this portion is roughly in radiative equilibrium. This is what we call the condition of local thermodynamic equilibrium (LTE). And as we go further up, we come across a situation where a deviation from thermal equilibrium exists. One of the main features here is that we cannot define the population of the various atomic levels in accordance with the Planckian temperature of the volume element. This is the nonlocal thermodynamic equilibrium (NLTE) situation which is dominant in the outer layers of the atmosphere i. e. in the upper photosphere, chromosphere and the corona. This NLTE situation manifests itself in abnormal population characateristics of the atomic levels and this is one of the principal problems that we have in studying any stellar atmosphere, in detail.

2.1.3 Different Lines Act as Probes for Different Layers of the Atmosphere:

High excitation lines like those of neutral carbon (C I) etc. are formed deep down in the atmosphere and hence by studying these line configurations one can essentially study the lower levels of the atmosphere where the situation is closer to the assumptions of LTE. On the other hand, some of the resonance lines are formed in the regions where we have the NLTE situation and hence by studying these resonance lines we can study the higher levels of the atmosphere. Again, in the core of the line there may be some contribution coming from the chromosphere as, for instance, in Na-lines. These lines are basically found in absorption but we do find a chromospheric emission component right in the very core. Hence by studying these emission cores of the absorption lines we can study the chromospheres of the stars.

2.2 THE SOLAR CHROMOSPHERE

2.2.1. General Observations:

It is interesting to note that the existence of the chromosphere was known from the observations of the total solar eclipses and the term 'chromosphere' owes its origin to the same. At the time of a total solar eclipse, when the moon just covers the Sun's disc, one observes a thin fringe of ruddy colour around the moon which comes by virtue of the fact that the radiation from the Sun is essentially in H-alpha which is red. It is essentially because of its ruddy colour that this region is named chromosphere (chroma = colour; Greek).

Now, let us look at this region in high magnifications (fig. 2.2). What we find here is the chromospheric background with fine spike-like features known as spicules at the very top of a general background. Note that, as we come to the centre of the H-alpha line profile spicules in the line-of-sight become so abundant that there is the appearance of a diffuse chromospheric limb above the inner sharp photospheric limb. Typical

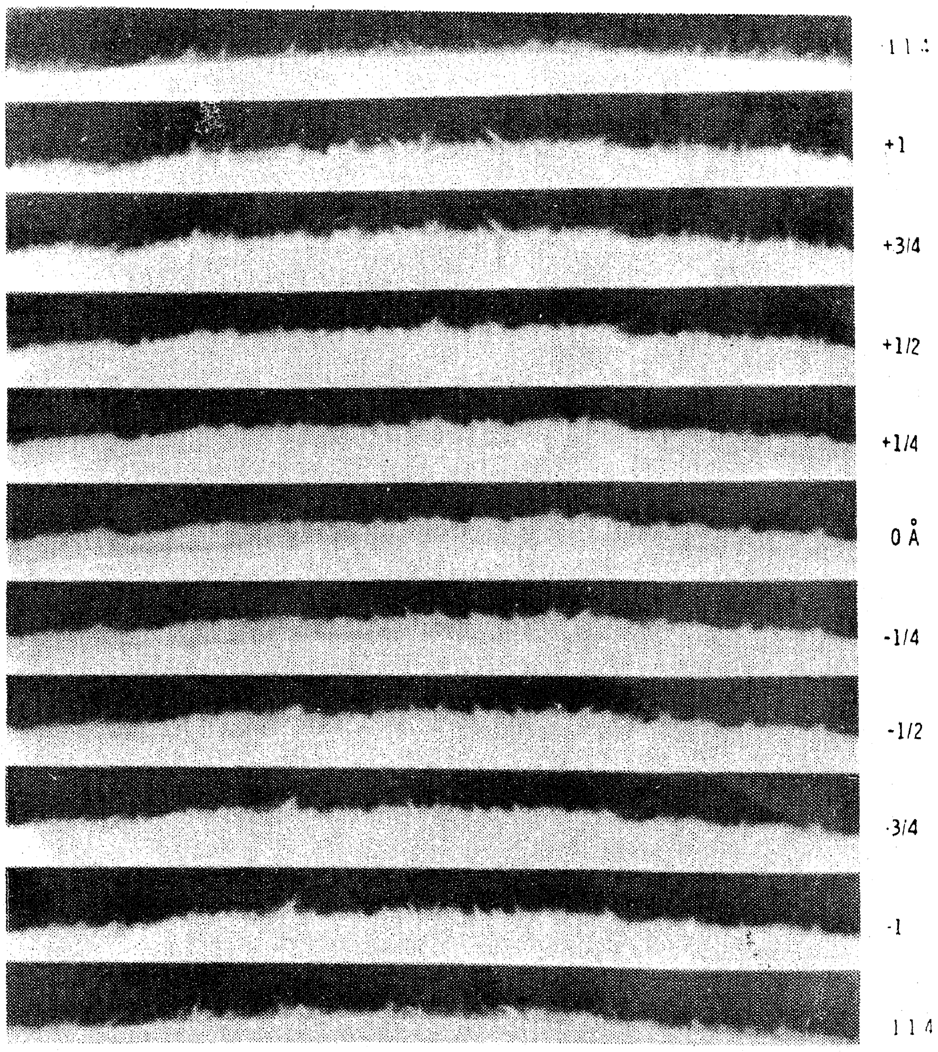


Fig. 2. 2 Spicules at the limb observed in H-alpha. This is a series of photographs taken from Sacramento Peak Vacuum Telescope where the effects on seeing of turbulence in the earth's atmosphere is very less thereby allowing for a relatively high spatial resolution. Individual spicules are easily resolved.

height of the spicules is about 5,000 kilometers and some go to heights as large as 10,000 kilometers. It is this layer which contains the spicules, that gives rise to the 'flash spectrum' that is seen at the time of total solar eclipse. The term 'flash spectrum' derives its name from the following fact.

At the time of a total solar eclipse, as the moon keeps covering the bright photospheric radiation, in the last few seconds before totality, the chromospheric component comes about in the form of bright emission lines which is characteristic of the chromosphere and it is this sudden transition from absorption to emission phase that gives rise to a flash like appearance and hence the name 'flash spectrum .

This flash spectrum lasts for a few seconds; the exact time that it lasts depends on the element that is examined. H-alpha, for instance, since it is visible out to about 5000 kilometers and the moon covers at a rate of about 300 kilometers per second on the face of the solar surface, would persist for about fifteen to twenty seconds. At the same time, some metallic lines like those of iron or titanium which originate from regions which are quite low down in the chromosphere would be visible for just about four to five seconds.

Consequently, the very small duration that one gets for making these observations is the principal reason why it is so difficult to get good observations of the flash spectrum of the chromosphere and it is a process which is accumulated from eclipse to eclipse and that is why chromospheric analysis, by and large, is a rather slow process.

2.2.2. Temperature Profile in the Chromosphere:

The characteristics of the variation of temperature with height are shown in fig. 2.3. The low chromosphere has a temperature of about 6000 K and the temperature decreases as we go higher up because H^-, which is a predominant species here, acts as a very good absorber and emitter of continuum radiation. But as we go higher up the density of H^-

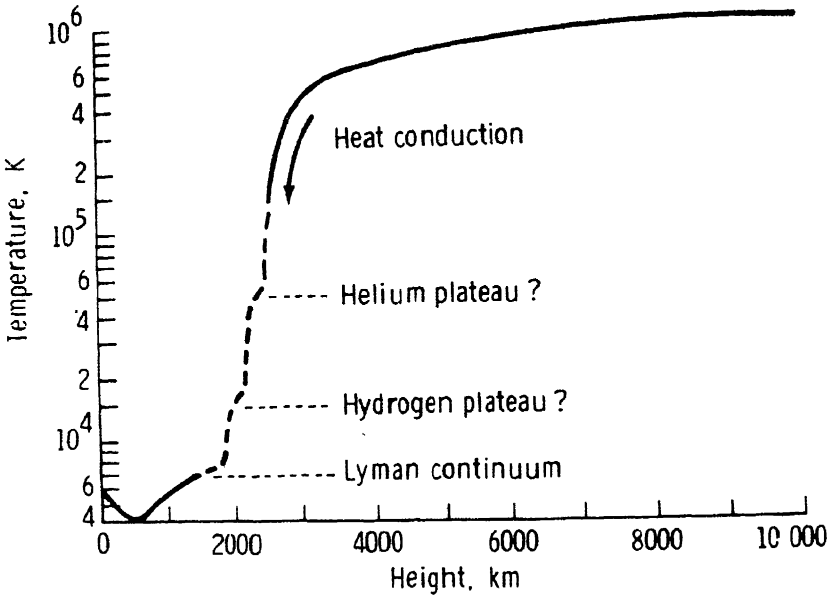


Fig. 2.3 A hypthetical temperature profile of the solar atmosphere. Because of the large uncertainties that presently exist in our knowledge of this profile and the invalid assumption of a spherically symmetric outer atmosphere, the location of the transition region and the shape of the profile above the temperature minimum are approximations only (Gibson, 1972).

reduces greatly and hence we reach a temperature minimum of about 4100 K, after which the temperature rises up steeply until the emission from excited and ionized states of H I is sufficient to balance the energy input. That is how we get the first plateau and similarly the second and the third plateaus as shown in the figure. Then there is a sudden transition in temperature from 10^5 K to 10^6 K with the transition region being confined to a very limited region in the atmosphere - only a few hundred kilometers. Beyond the transition zone, one finds the coronal characteristics.

In the lower levels of the chromosphere, where we find a comparatively lower value of the temperature which is, of course, higher than the temperature minimum of about 4100 K, we find many of the molecular species appearing in emission. So, this is a very nice region to examine the fundamental vibrational-rotational band of carbon monoxide which arises from this lower region of the chromosphere. Also, cyanogen bands are found in emission in this region - an observation which has been recorded in the first few seconds of the flash spectrum.

2.2.3. Line Emissions from the Chromosphere:

One of the strongest lines that is seen in the solar spectrum is the calcium K line at 3934 Å and if one can go to ultraviolet, one finds another strong line due to magnesium which comes around 2800 Å. The absorption feature is more or less like that shown in fig. 2.4. The notations K1V, K2V K3, K2R and K1R are as shown in the figure. When we isolate the emission

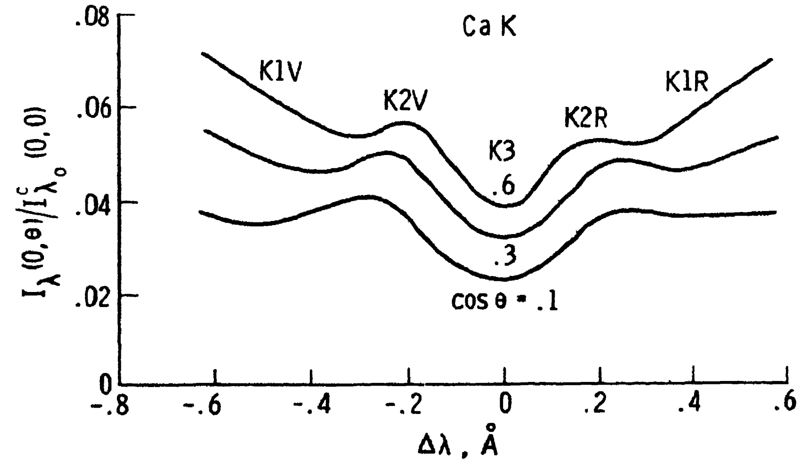


Fig. 2.4 Self reversed emission cores of Ca K. The notations 1V, 1 R etc. are alternatively written as subscripts also. Note the very low central intensities, 0.02 to 0.04 and the emission peaks at ± 0.2 Å from the line center.

feature by the slit of the spectrograph and get a distribution of this weak emission feature over the solar surface we get what is called a spectroheliogram. With the help of a high dispersion instrument, one can keep the slit right in the middle of the line i.e. in K_3 which looks like a reversa of an emission line. This is known as the K_3 spectroheliogram. Note that, according to our current theories, the emission can be formed anywhere between 200 kilometers above the temperature minimum position to 1300 kilometers above it but since K_3 is formed at larger heights, by studying K_3 line it is possible to study the upper levels of the atmosphere. On the other hand, if we are taking a picture in K_1 then, since this comes from the temperature minimum region, we are essentially studying the temperature minimum characteristics in a two-dimensional way over the solar surface. And the centre of the line tells the story at the greatest heights. A similar phenomenon occurs with Lyman-alpha. The centre of Lyman-alpha takes us to a height of about 2200 kilometers whereas, when we are 5 Å away from the centre, we penetrate into the atmosphere down to a height of about 1000 kilometers. Some of the lines of iron, silicon, carbon etc. are formed deep below and hence tell the story at much lower heights.

2.2.4. Mechanism of Line Formation:

Now, obviously it would be of considerable help and interest to us to look, at a glance, into some theoretical aspects as to how the chromosphere comes into existence and how these different features are formed. In this connection, it is very important to note that

(i) the chromosphere is not in a state of thermal equilibrium,

(ii) there is evidence of mass motion and

(iii) this mass motion is, to some extent, responsible for the inversion of temperature (i.e. the gradual decrease in temperature which would have dropped off to very low values at great heights instead experiences a sudden reversal).

The entire phenomenon is due to the fact that, there is a dissipation of mechanical energy in the solar atmosphere which excites the different species in this region. This excitation has many different aspects and the manifestation of the line profiles is one of them. In the evaluation of the line profile, it would be of interest to consider the relative role of the source function, which is given by

$$S = j/k$$

where j = emission coefficient
and k = absorption coefficient.

The contributions for the line source function S_L can be divided into four components A, B, C and D.

where A = population of the levels stimulated by radiation
B = collisional de-excitation
C = other processes responsible for filling up the upper level
D = other processes for increasing the number in the lower level.

Here the collisional de-excitation term B reduces the population of the upper level. It is the sensitivity of the line to these four factors that decides the type of the emission feature that we would come across.

Therefore when B is greater than C, we will have a high degree of sensitivity to the temperature and vice versa when C is greater than B. These two procedures would indicate the possibility of collision dominated lines and photoelectrically dominated lines respectively, this of course, being also dependent on the parameters of the line. Typical of the first category are calcium-II resonance line (around 3950 Å) and magnesium- II resonance line (around 2800 Å) (Linsky and Avrett, 1970). Also the resonance lines of some neutral atoms, typical of which are in Balmer series,e.g. H-alpha etc.,come in the latter category.

It is very difficult for H-alpha to come up in emission not only because it is a photoelectrically controlled line and hence less sensitive to the temperature but also because it is formed at greater depths of the solar atmosphere. Hence, whenever there is a slight enhancement of the temperature, the calcium resonance line shows up the emission feature much better and in a more striking way than the H -alpha line. On the other hand H-alpha, while it is photoelectrically dominated in the type of gravity and temperature that one encounters in the solar surface, begins to behave very much like a collisionally dominated line in M-dwarfs where the temperature and gravity that one encounters are quite different. The process of collision-dominance or photoelectric-dominance is very much related to the nature of the physical parameters in the atmosphere that one is considering and so one finds a wide range of features that typify a chromosphere.

3.3 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

2.3.1. Search for and Detection of Chromospheres in Other Stars

Now, in our search for chromosphere in the stars, we are ready to pick out the typical chromospheric indicators and from this point of view we must remember the resonance lines of ionised and neutral atoms and subordinate lines which we find in the solar chromosphere. From our knowledge of the Sun, we know that, in the ultraviolet or visible region, there is a whole range of lines which indicates the presence of the chromosphere of the Sun. In the visible region, there are CaII-K (around 3950 Å) and sodium lines (at 5890 Å) which are weak emitters. Also, there is the calcium triplet at 8498 Å which is a very good indicator in the near IR. Then there is the magnesium resonance line around 2800 Å which is the strongest line in the ultraviolet region. In some way, magnesium line is superior to calcium-line and in some way, the superiority role is reversed. For instance, for calcium-line, the maximum of the emission feature in case of the Sun is 7%, whereas in case of magnesium, it is a clean 30% of the continuum. In other words, the emission feature is more striking in magnesium. This is, to some extent, because of the fact that the boundary temperature of the Sun is in the neighbourhood of 5000 K, and hence it has a higher flux of radiation around 3950 Å than around 2800 Å, in the continuum.

On the other hand, calcium-line has its own advantages: calcium is most abundant of the elements in the solar atmosphere which give rise to ne of these chromospheric features and therefore, obviously, the olute intensity of the emission feature is appreciable.

Some of the other features lie in the ultraviolet, the principal among n being the Lyman series, carbon-II at 1335 Å and silicon-II at 1264 Å. Also, one finds oxygen-I line near 1300 Å and this being esonance feature, is of interest to us. Then, there is the Lyman-alpha ch excites the oxygen atom from ground state to a higher excited state r which it gives rise to a radiation at wavelength 1027 Å and then another nother wavelength, 8446 Å which are easily seen as chromospheric features. However, since this is a case of photoelectric dominance, these two lines are not sensitive to temperature.

These are, in essence, chromospheric indicators which can effectively be used in identifying the chromospheres in other stars and we know that some of them have been successfully used resulting in a positive identification of chromospheres in other stars.

LECTURE-III

3.1 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

3.1.1. K-Line Width-Absolute Magnitude Relationship[*]: A Common Rule for the Sun and the Stars Cause and Characteristics:

Fig. 3.2 shows a part of a high quality spectroheliogram where we notice that the solar surface is quite heavily populated by bright points

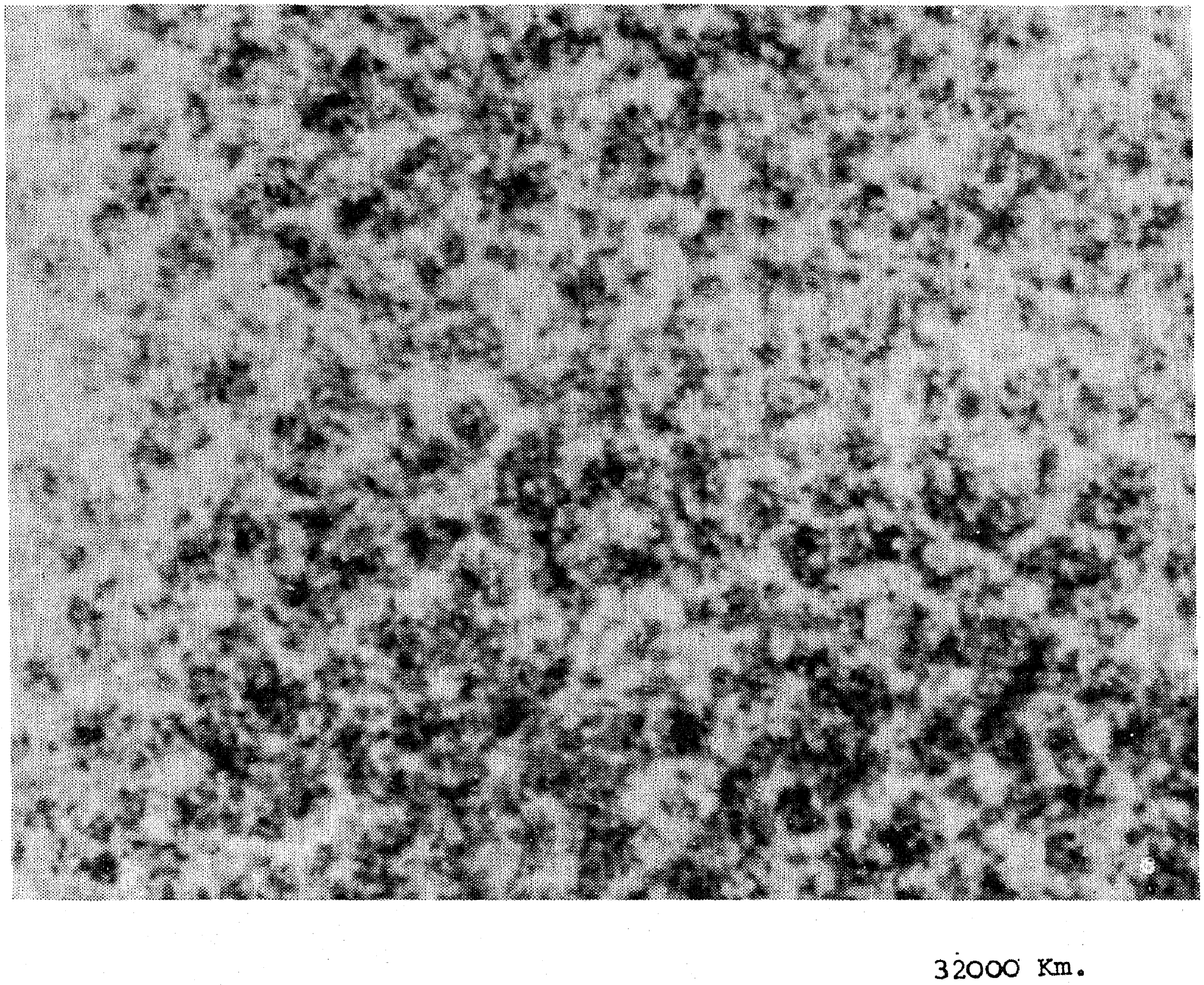


Fig. 3.2 Part of a high quality K_{232} spectroheliogram obtained at Kodaikanal. The image shows the bright points or fine mottles, the coarse mottles, the network and the dark condensations (Bappu and Sivaraman, 1971).

[*] See page 53

and the brightness varies from one bright point to another. So when the slit of the spectrograph is placed on the solar surface and a picture is taken, what one obtains is a streaky pattern as shown in fig. 3. 3 where each streak corresponds to a bright point. Let us look at some statistics of these features.

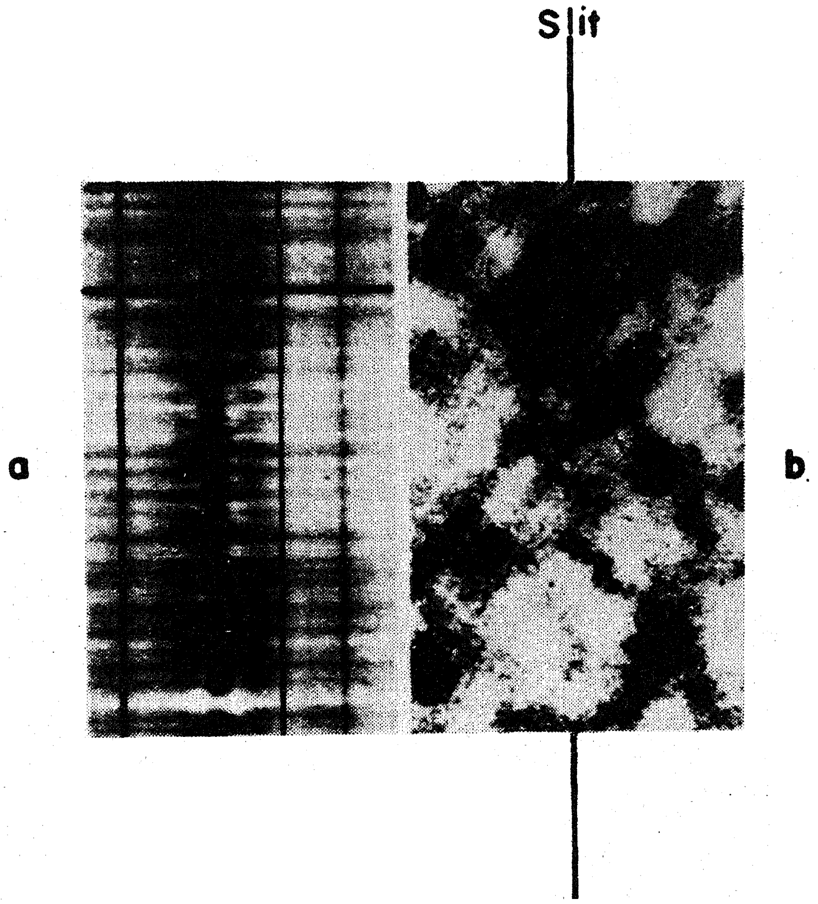


Fig. 3. 3 (a) The K-line spectroheliogram taken from Kodaikanal.
(b) K_{232} spectroheliogram taken within four minutes of the spectrogram and enlarged to the scale of fig. 'a'. The supergranules intersected by the slit can be identified with the help of the spectroheliogram (Bappu and Sivaraman, 1971).

(i) If a spectral sequence is taken and the time versus intensity characteristics of several of these bright points are looked at, then one finds that there is almost no correlation between these characteristics of different bright points. In other words, each bright point performs independantly of its own, totally unrelated to the performance of the other.

(ii) Another interesting feature to note is that, the intensity in the violet core of the emission feature has an oscillation of a period of about 200 seconds. We have seen this type of oscillation in the photosphere which has a period of about 300 seconds and now it is seen that, by the time it comes to the chromosphere it attains a periodicity of about 200 seconds. This shows that fluctuation in intensity in the chromosphere go along in a periodic fashion very much like the acoustic features that are seen in the photosphere.

(iii) Fig. 3.4 shows some observations of the location of the core between the two emission peaks and the displacement of this core is what is called K_3 velocity. In a spectral sequence one finds a periodic displacement of the core. Fig. 3.5 shows the ratio of the violet to the red correlated against the K_3 velocity which indicates that, at least to some extent, Doppler shift of an absorbing core is responsible for the brightness ratio.

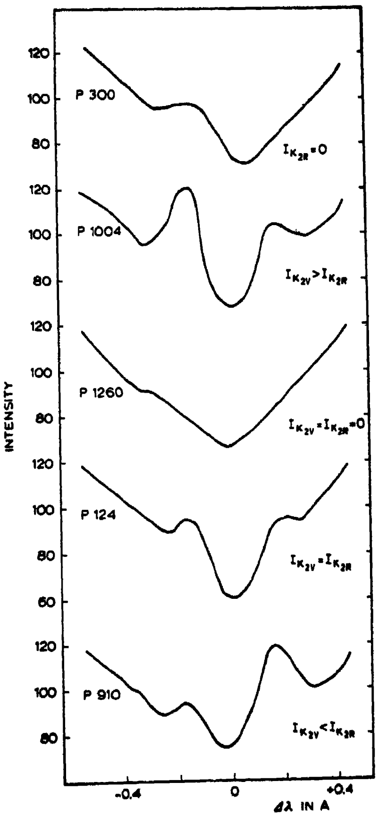


Fig. 3.4 Samples of the K-line profiles at five points along the slit of the spectrograph showing the locations of the emission core and different ratios of $I_{K_{2V}}$ and $I_{K_{2R}}$. The numbers P 300 etc. give the profile designation along the slit (Bappu and Sivaraman, 1971).

(iv) Another parameter which is of interest is the K_2-line width where the line width is defined as the peak to peak separation as shown in fig. 3.6. This line width shows some kind of a variation which is synchronized with the variation in intensity. If a movie is taken depicting the evolution of this feature at any particular

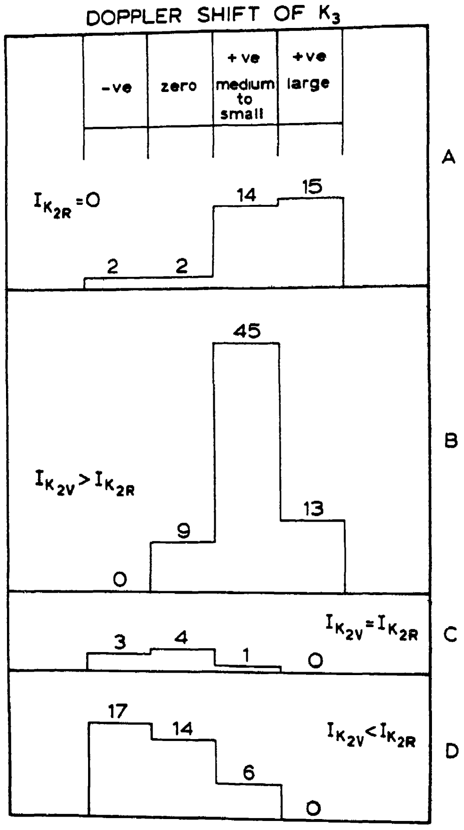


Fig. 3.5 Relation between Doppler shifts of K_3 and the four intensity categories of $I_{K_{2R}}$ and $I_{K_{2V}}$. Numbers in the diagram represent the number of instances in each category. Note that when $I_{K_{2R}}=0$ the Doppler shifts of K_3 are predominantly redward while for $I_{K_{2V}} < I_{K_{2R}}$ the K_3 shifts are primarily negative (Bappu and Sivaraman, 1971).

location on the solar surface, then one would find that the intensity first picks up right at the bottom of the K-line and the peaks become brighter and then slowly the peaks fade in brightness and then the emission feature vanishes. In other words, one finds a feature very much like what one would expect if there is a piston pushing up the matter right from the photospheric levels below.

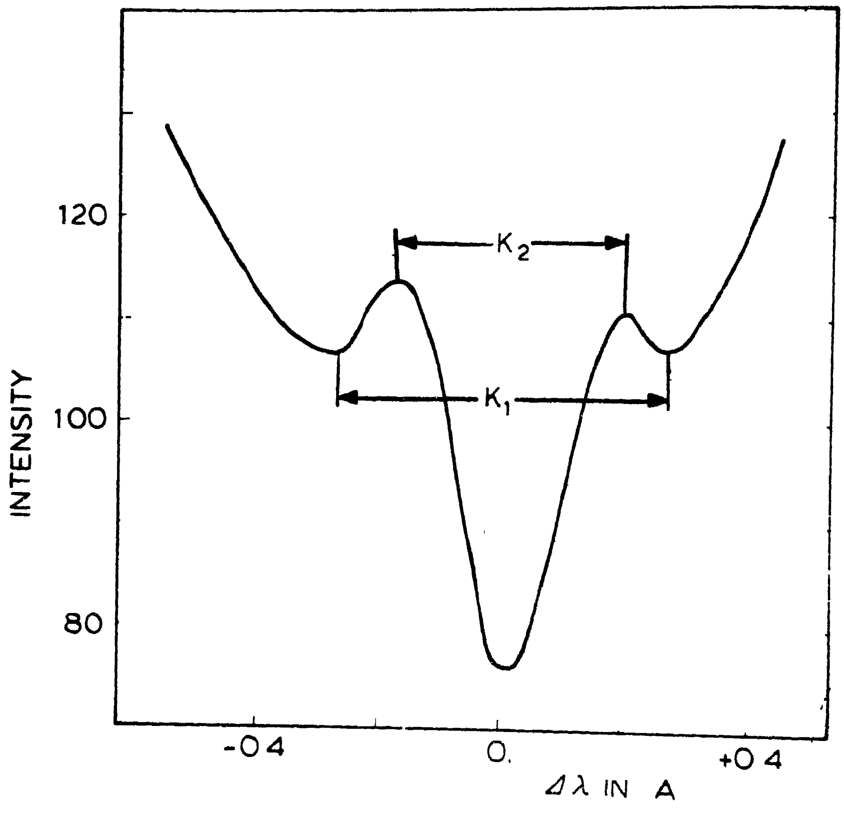


Fig. 3. 6 K-line emission profile showing definitions of K_2 and K_1-line widths (Bappu and Sivaraman, 1971).

Now, though in the integrated spectrum the width of the lines is more or less constant for a particular star, the line widths measured in pictures taken for very short durations show very small variations of the order of 3 to 4 kilometers per second. In case of the Sun, the average width at any particular location is of the order of 36 kilometers per second and since the integrated spectrum is an average of the entire feature, an error of 3 to 4 kilometers per second is not very significant.

What then are these bright points which, as we have seen now, seem to be the cause of all these features? Let us see.

Fig. 3.7(b) shows a picture of a magnetogram which has a very high resolution and shows regions of very small magnetic fields (one to two Gauss) - a very difficult picture which represents the limit of the technological capability at the present moment. Fig. 3.7(a) is a spectroheliogram obtained simultaneously; the similarities between the two pictures is very striking.

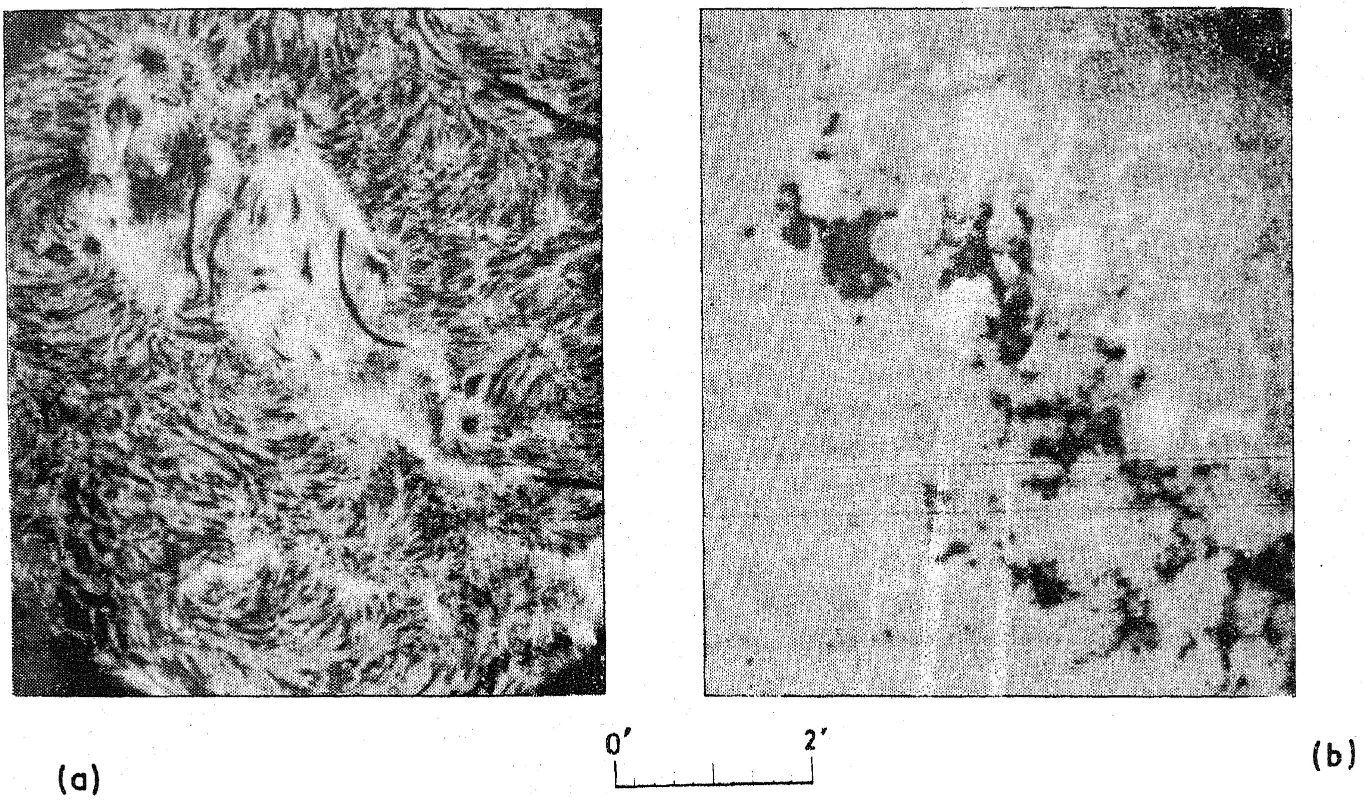


Fig. 3.7 Correlation between longitudinal magnetic field and bright H-alpha emission. (a) large active region and its surroundings photographed at the centre of H-alpha with a Zeiss 1/4 Å filter; (b) simultaneous magnetogram obtained by D. Vravec in 6103 Å of Ca I (Bray and Loughhead, 1974).

One of the very interesting features that one notices is that the bright points seen in the spectroheliogram are always found in localised regions of enhanced magnetic field whereas, the regions of high magnetic field do not always have bright points. This indicates that the magnetic fields favour the formation of the bright points as a result of which we find that the bright points always come from regions of enhanced magnetic field.

However, what exactly these bright points are, we are still not sure. The possibility that these might be spicules cannot be excluded because it is very difficult to see spicules projected on the disk. It is also difficult to pick out spicules by tuning an H-alpha filter and going to off-band characteristics because H-alpha emission has a different nature of excitation in the chromosphere than the calcium line; the former is a case of photoionisation whereas the latter is collisionally dominated. But we know that spicules are formed in and around the magnetic knots and therefore, we are now in a quandary as to whether these bright points are spicules or whether spicules are formed in the same locales as those of the bright points.

However, a word of caution would be appropriate here. For getting the magnetogram, the magnetic field is generally picked up by the displacement of the line caused by the Zeeman effect. So, one of the things that is done in getting a magnetogram is to average out the Doppler effect and for this purpose, there is generally a Doppler compensator in the instrument.

Hence, if a Doppler signal is incorrectly cancelled - and it is very difficult to exactly know and correctly cancel a Doppler signal - you can have similar black and white appearances as seen in fig. 3.7(a), giving incorrect informations about the magnetic fields. So while drawing a conclusion from such pictures one has to be careful and at the present moment such experiments need to be repeated with more care and attention to establish this connection.

Canopus Puzzle: Apparant Violation of the Width-Magnitude Relationship

Now let us move on to the stars and carry out our analysis in a similar vein as we did for the Sun. We saw that the bright points are tied up with the acoustic waves (due to convection) and magnetic fields. Also we saw that, K_2-line width - absolute magnitude relationship comes mainly because of the K_2 emissions from the bright points.

Now we consider the case of Canopus, which is a supergiant of spectral type FOIb. A Ca II-K line profile for Canopus, with its characteristic emission bumps, was obtained by a group in South Africa in 1965. It was interesting to see that the absolute magnitude of Canopus calculated in accordance with the width-magnitude relationship using the K_2-line width of the above mentioned profile, was totally inconsistent with the actual value. This led people to think that here was an example which demonstrated the violation of the width - magnitude relationship in a nice manner. And this should indeed violate our previous explanation because in a FOIb star one would not expect such bright points and hence such emissions found in this star should violate our previous explanation. But we must remember that in a star of spectral type FOIb like Canopus, there can be some kind of plage activity on the stellar surface which can give rise to the calcium emission. The intense magnetic field in the plage areas will tend to narrow down the K_2-line width as a result of which the line width would be much smaller than what the luminosity of the star calls for and hence you would have what you have in Canopus.

That this is actually the case with Canopus is supported by the fact that right from 1975 onwards we have looked in vain for a repetition of this phenomenon and have not been able to detect any emission even though we have used three times the dispersion that had been used to get the picture of 1965.

This indicates that Canopus has a 'patchy' surface and sometimes the 'patchiness' is more and it was at such an opportune occasion that the spectrum of Canopus in 1965 was obtained. This, however, gives us enough hint to look for features by means of which we could detect cycles in other stars equivalent to the solar cycles and this we shall see now.

3.1.2. Cycle Characteristics of Calcium-emission: a Potential Means of Detecting Star Cycles

Now we come to some properties of the integrated Sun which are characteristics of the solar cycle and may be useful in detecting similar cycles in other stars.

Fig. 3.8(a) shows the spectrum near the Ca II-K line taken for the integrated Sun near sunspot maximum (1979) and sunspot minimum (1976) where we find that the intensity of the spectrum at the sunspot maximum has an enhancement compared to that taken at the sunspot minimum. As explained below this enhancement can come about by virtue of three components: (i) the bright points, (ii) the network and (iii) the plages.

As it is seen in fig. 3.8(b), since we find calcium in emission in the plages, the contribution of the plages is to enhance the intensity level of the calcium emission. Now, we know that the plages are first born and then they evolve and die and when they die, they intensify the network in the neighbourhood. Hence the network contribution also goes up. Also,

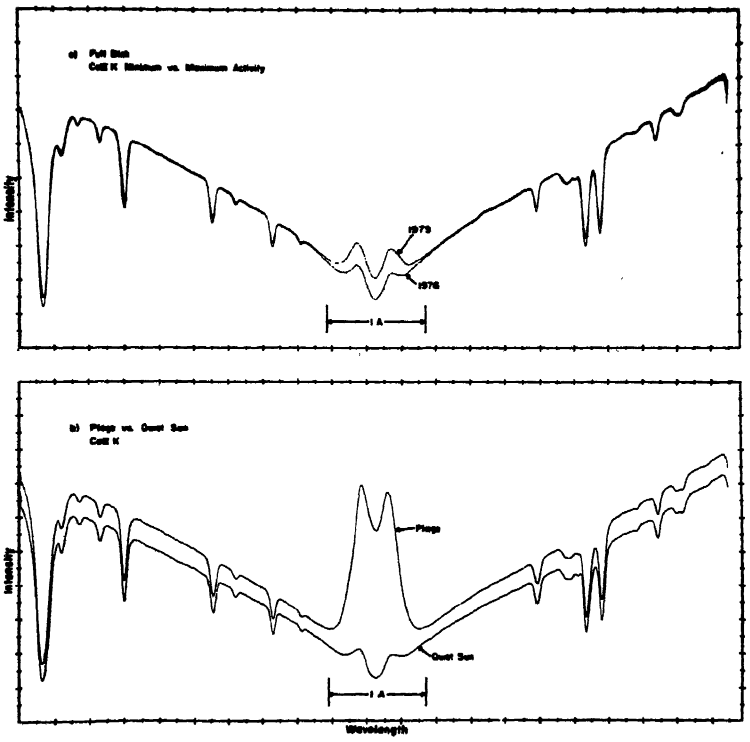


Fig. 3.8 The variability of Ca II-K line profiles (a) Full disk K line profiles at sunspot minimum and sunspot maximum, and (b) average profiles for an active region and a nearly quiet region at the same distance from the center of the solar disc (White and Livingston, 1981).

since we have high magnetic fields in these regions, there is a possibility that the brightness of the bright points, which may be correlated with the magnetic field intensity, would also increase. Apart from this, there may be a modulation of the intensity which one would expect by virtue of the rotation of the Sun.

Another interesting feature is shown in fig. 3.9 where we find that at sunspot minimum the violet component was brighter and it gradually

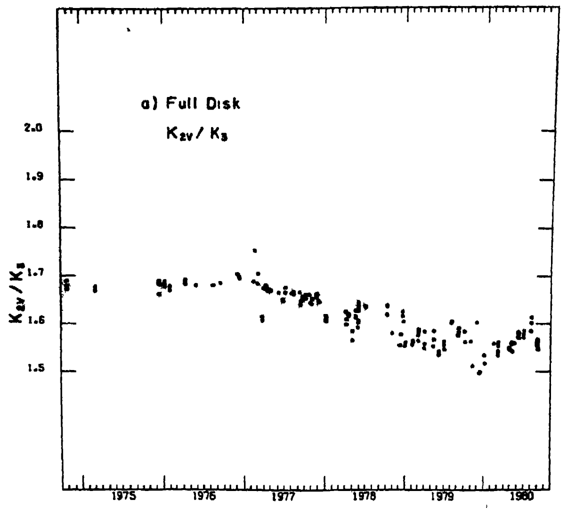


Fig. 3.9 The cycle variation of the K_{2v}/K_3 intensity ratio as determined from full disk measurements (White and Livingston, 1981).

decreased in intensity towards sunspot maximum meaning thereby that there is a shift of the K_3 feature towards violet as you go from sunspot minimum to sunspot maximum. This is a very good confirmation of the fact that it is the location and subtle variation of K_3 that causes some of the asymmetries in the ratio of the violet to redward component of the K line (K V/R) shown in fig. 3.10.

These features show that the cycle characteristics of calcium emission can be used for detecting cycles similar to stellar cycles and this, alongwith our previous finding of Canopus, leads us to think that, these stars that provide K-line widths larger than what is consistent with

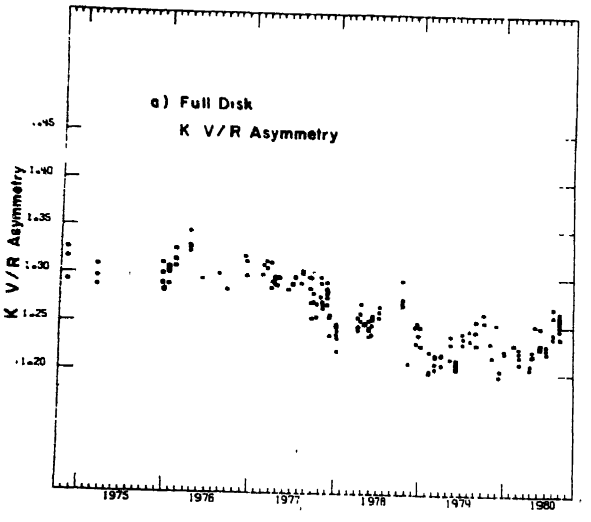


Fig. 3.10 The cycle variation of the V/R asymmetry parameter as determined from full disk measurements (White and Livingston, 1981).

their visual magnitude inferred otherwise may prove more suitable for detection of star cycles, than would be the case if only enhanced intensity of K emission were the criterion of selection.

3.2 AGE CHARACTERISTICS OF CALCIUM EMISSION

3.2.1. In the Main Sequence:

Let us look into some family characteristics of this emission. We consider some families which are formed at different times, stars of each family being of the same age. Then we find that the members of a particular family have more or less similar degree of emission intensity which differs from that of other families. The younger the family, the brighter is the emission intensity. This leads to the possibility of emission intensity being an index of the age of the star.

Lithium abundance is also a very efficient age indicator. It appears that lithium depletion has a similar behaviour as that of calcium-II emission intensity with the age until times of the order of Hyades age (about 6×10^{8} years).

A study of this has shown that after the correction for spectral type effects, the calcium-II emission intensity varies roughly as inverse square root of the age. Also it has been found that the onset of calcium emission has a correlation with the rapid decay of the rotational velocity. Then the rotational velocity also seems to be inversely proportional to the square root of the age.

Also, we know that the calcium-II emission intensity has a linear relationship with the magnetic field strength. The above findings go to show that the average surface (dynamo) field is proportional to rotational velocity which has an inverse correlation with the age of the star in the main sequence.

3.2.2. Beyond the Main Sequence:

Now the questions which arise are : Are only the main sequence stars privileged with these characteristics? What can we expect to see, as the star in its evolution moves away from the main sequence?

We know that as one goes to an earlier spectral type the emission intensity tends to decrease. But at the same time, as can be seen from fig. 3.11 we find that in NGC 188 which is a very old cluster, the calcium intensity is quite striking and we find a similar feature in M67 which too is a very old cluster.

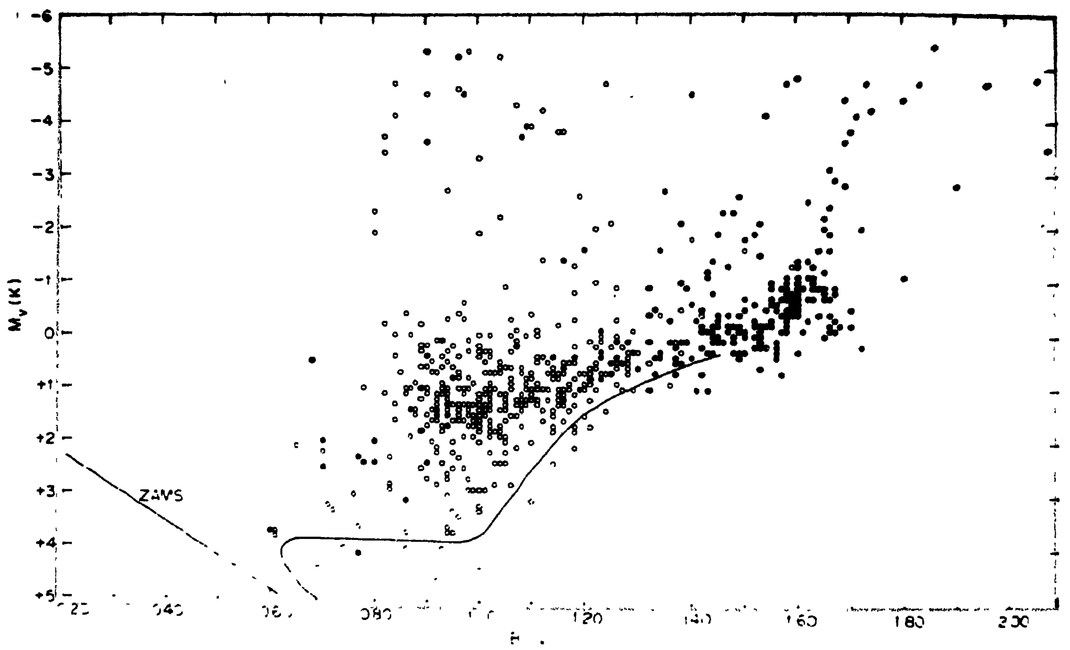


Fig. 3.11 Colour-magnitude diagram constructed from the M_V (K). Open circles indicate stars with weak Ca II emission and filled circles with strong emission (Wilson, 1976).

An interesting conclusion which stems from this is that, if the dependance of age on calcium intensity is an established parameter for the main sequence, then the stars that had calcium emission at an earlier phase would loose all this emission at a later phase and at the giant phase again, by some process of rejuvenation, the calcium intensity becomes higher. Also this indicates that there is a replenishment of the magnetic fields as the star evolves to the red giant phase.

However, the above picture is not a very correct representation of the fact, in the sense that if there is a lower intensity of calcium emission in an F-star background, it would be higher if the same energy were at the bottom of the line emission in a K-star. So a different and a more correct approach would be to consider the emission intensity normalised to the total intensity of the star. The disadvantage of this approach is that one gets fewer number of points and there is more scatter in the diagram. However, one obtains the following hint which is of considerable importance.

It is found that the supergiants are at the top of such a diagram which indicates that it is possible to draw a locus of emission intensity at the top and then make the following assumption. This locus of intensity represents the upper limit of the intensity that a star can have either at a very early stage when there is high chromospheric activity or at a subsequent time at the giant phase when it again builds up its chromospheric activity. The deviation from this locus becomes symbolic of the age and the Sun being rather old is far away from this locus which agrees with our picture.

So we found that in trying to draw a more correct picture, even though we followed a different approach, it is consistent with our earlier conclusion.

The magnesium emission also shares the same properties with calcium.

3.2.3. Why Does the Calcium-Intensity Increase as the Star Gets off the Main Sequence

Now, how do we interpret this replenishment of calcium intensity as the star becomes older and gets off the main sequence? Uchida and myself (1982) have a mechanism for this in terms of stellar evolution which is as follows.

After the star burns out its core hydrogen and reaches the Chandrasekhar-Schönberg limit, sooner or later the star gets off the main sequence and reaches the giant phase and at this stage the star has the following configuration:

(i) a contracting core which we assume as rotating and

(ii) an outer envelope which is expanding to the red giant stage.

As the core keeps contracting, it spins faster and faster to conserve the angular momentum and the outer envelope keeps expanding. Now, there is a narrow transition region which is standstill in between the contracting core and the expanding envelope. We assume that the fields at the surface are already exhausted or relatively insignificant and so there is no more calcium emission coming from the surface.

In the expanding shell, as the surface cools down by means of radiation, a convection starts at the top and this convection slowly trickles down and down, and then we have all the ideal conditions for the start of a new dynamo action and an enhanced magnetic field. And slowly, as the convection layer comes down, it picks up the magnetic field and transports it to the surface and enhances the fields available at the surface. Once there is an enhanced magnetic field at the surface, there is enhanced calcium emission.

This is the picture that we have in mind which explains why there is a rejuvenation of the magnetic field and hence the calcium intensity, as the star evolves from the main sequence to the red giant phase.

The above picture of ours is consistent with Iben's calculations on stellar evolution which also tells about the time scales involved in this process. Iben's calculations show that the time taken for the convection to work its way down from the surface to the region where it can pick up the magnetic field and come to the top is large. Since it is a slow process and takes time to build up, we find that there is no calcium emission just before the turn off point from the main sequence, intensity is low at the subsequent phase and the intensity slowly picks up as it goes towards the peak of the giant phase. In this picture, after the sudden contraction of the core, at the bottom of the rising branch of the giant phase, the convection comes deepest and then onwards one should find calcium intensity in plenty. However, this is still at the level of an interesting speculation because this has not been fully confirmed.

If this mechanism really works then one should see this mechanism in action in objects like M67 or NGC 188 where one should find enhanced calcium emission in those particular locations in the colour-magnitude array as dictated by the above theory. But even in M67, the brighter of the two, the stars vary in brightness from tenth to about thirteenth magnitude and the H and K technique is rather demanding for photons here, and it is difficult to make a verification by this technique. So we have asked for time in International Ultraviolet Explorer where we hope to examine the magnesium intensity in very low dispersion (since the low brightness does not allow for high dispersion work), and the fact that magnesium lines are a little more sensitive may enable us to get this feature even at low dispersion and hence a confirmation of the above speculation.

3.3 THE SOLAR-STELLAR CONNECTIONS (CONTD.)

3.3.1. Coronae: Detection in Stars of almost All Spectral Types

Fig. 3.12 shows an X-ray picture of the Sun with a coronal hole. Fig. 3.13 is a set of pictures which are taken in different lines which show different levels from chromosphere to corona around a coronal hole. In Lyman-alpha (1216 Å) the corona is hardly noticeable but as one goes to higher and higher excitations one begins to have a suggestion of the corona. In magnesium X (625 Å), which comes from the transition region having a temperature of 50,000 to 100,000 K, the coronal hole is clearly visible.

The difficulty with using ground based techniques is that the emission lines like H-alpha, Ca-K etc., which one uses for chromospheric studies, are not capable of detecting the corona. The best indicator for ground based observations, therefore, would be the Helium-I line at 10,830Å and even with this indicator, the possibility of detecting the corona is just marginal due to the fact that there is only a slight enhancement in intensity as one goes from the interior to the corona of the Sun. So the only way to study the corona until radio astronomy came along was to observe the corona during total solar eclipses and at a later time to simulate an artificial eclips by means of a coronagraph. Even during eclipses we could observe the corona only at the limb but radio astronomy changed that picture to some extent. Now, by means of the space observatory we are able to study corona features without eclipses and thus we have also an idea of the high temperatur transition region.

From a typical spectrum thus obtained from an object like Capella we find coronal features similar to what the Sun would show at

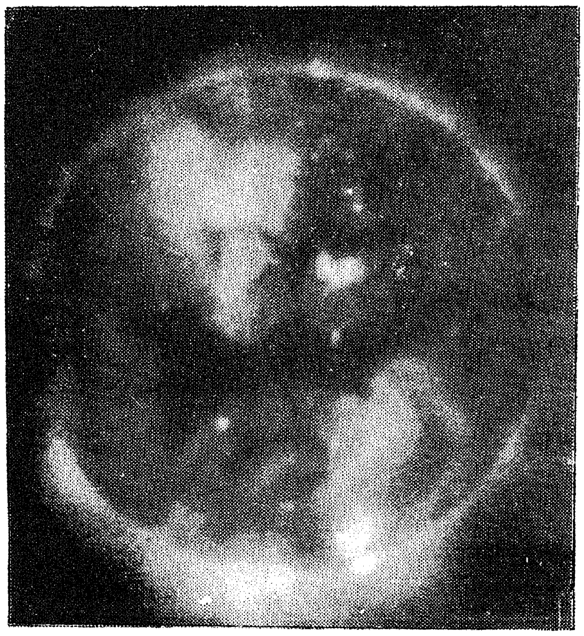
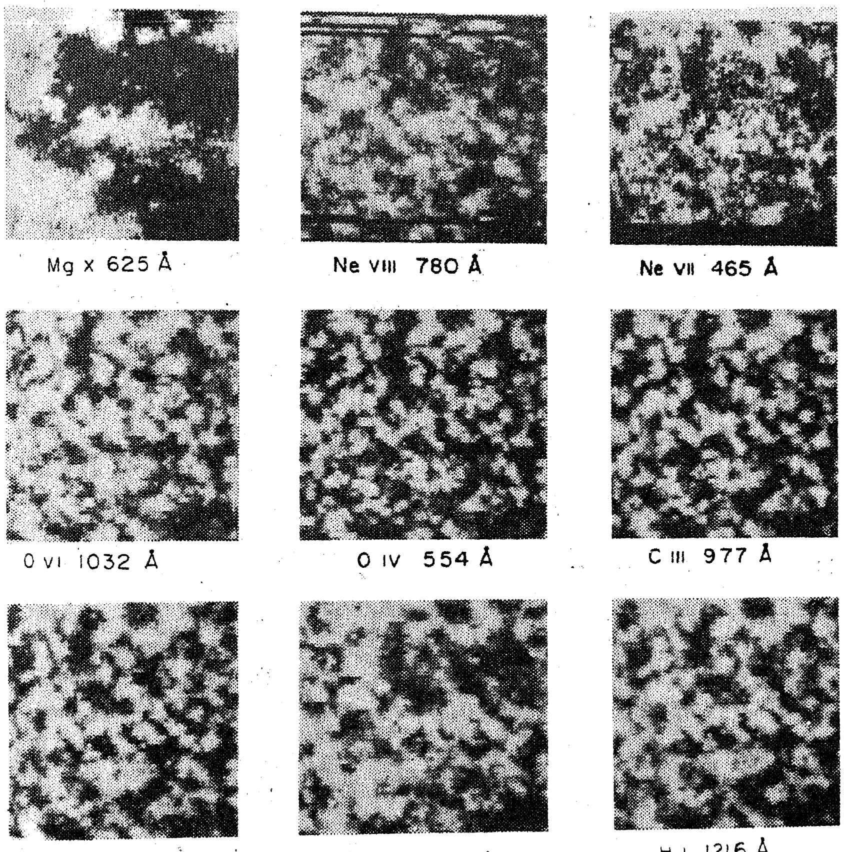


Fig. 3.12 A photograph of the X-ray corona taken from Skylab; bandpass includes 2 to 32 Å. Note the coronal loops, the coronal hole and bright active regions.



Mg x 625 Å

Ne viii 780 Å

Ne vii 465 Å

O vi 1032 Å

O iv 554 Å

C iii 977 Å

336 Å

He i 584 A

H i 1216 Å

Fig. 3.13 The coarse network, taken in different spectrum lines showing different levels from chromosphere to corona as recorded from Skylab.

a distance of one parsec. Coronal high excitation lines like NV or CIV are quite low in intensity in the Sun as compared to RSCVn objects like alpha-Aur which go to show that coronae in those objects are much more striking than that of the Sun.

Again, from observations from the space observatory we know that there are two different kinds of objects so far as coronal features are concerned. In the first kind we find objects which have large number of high excitation lines like NV, CIV, HeII etc. and in the second kind we find objects which do not show such an abundance of high excitation lines.

The above findings are of considerable interest to us because they show that there may be some kind of threshold in the Hertzsprung-Russel diagram to the left of which we find objects like the Sun and the dwarfs and some of the giants which show up coronae and to the right of which we find objects like alpha-Orionis, alpha-Bootis and other super giants which do not show the high temperature characteristics of the corona.

It is found that the objects which lack coronal features show circumstellar absorption features and these circumstellar absorption features indicate tremendous winds that are responsible for a large amount of mass outflow. Here, the mass outflow is quite large - so large that the solar wind is a mild breeze compared to the magnitude of the phenomena operating here! The mass loss here would be of the order of 10^{-7} $M_{\odot}$/year in contrast with a mass loss of 10^{-13} $M_{\odot}$/year for the Sun; and for the Wolf-Rayet stars the mass outflow is still larger being of the order of 10^{-4} $M_{\odot}$/year. It is obvious that, if there is a large mass outflow, the temperature does not get a chance to build up at the region where there would have otherwise been a corona and so the corona is available only when there is no such large outflow of matter.

After seeing that stars having a very large outflow of matter do not show coronal features, let us reexamine the question as to which stars in the HR diagram have coronae. Are coronae available only for stars where there is a convection zone and which show chromospheric features? Or are coronae available only for stars which belong to early spectral classes like O and B which have very high temperatures? Or are they associated only with peculiar stars like RS CVn stars? The Einstein observatory provided an answer to these questions and fig. 3.14 is a kind of HR diagram of Hyades cluster drawn with the help of the observations from the Einstein observatory.

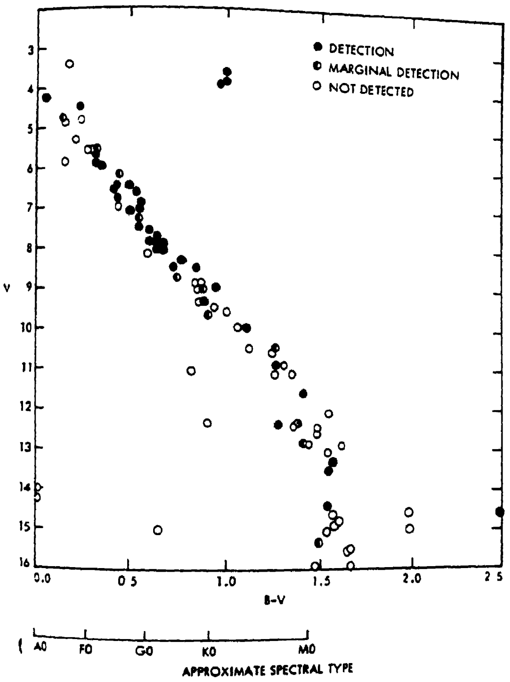


Fig. 3. 14 HR diagram of Hyades in survey fields, indicating those for which coronal soft X-ray characteristics (0. 2-4. 0 KeV) are detected (Stern et al. 1981).

Though there are large variations in the X-ray characteristics of different kinds of objects, we notice that the main sequence stars of almost all spectral types as well as the giants, sub giants, dwarfs etc. show coronal features of one kind or the other.

3.4 SUMMARY

We started this sequence of examinations on the Sun and the stars with the idea of looking for features in the stars which, we know, exist on the solar surface. Then, reversing the argument and using our knowledge of certain features which we observe in the stars, we tried to reflect them back on the solar behaviour.

In this connection several things have become obvious. We saw that it is essentially because of the newer and finer techniques that we have been able to see solar-like granulations in other stars and we explored the possibility of finding supergranulations in other stars which needs still finer techniques. We applied a different approach in our search for spots in other stars and saw that several other stars certainly do show spots similar to sunspots which are so very striking on the solar surface. Then we looked for short period oscillations in other stars like the five minute oscillations which have been so well studied, both theoretically and observationally in case of the Sun and then, as a feed back to the solar physics, we looked for long period oscillations - the type we come across so often in our studies of stellar variability - on the solar surface; and definitely succeeded in detecting one such mode, namely the one sixty minute oscillations. Then after having a glance at the solar and stellar atmospheres in general, and different mechanisms operating in the solar chromosphere in particular, we looked at a sequence of chromospheric phenomena which we had learnt from the stars and came back to the Sun as a reference source for interpretation. Then we went back to the stars and saw how the evolution characteristics can modify some of these features and we were in a position to postulate a model which could explain this.

Then, as we are always interested in looking at some features which we find in the Sun and would like to see in the stars, we carried out a search to find out whether stellar coronae exist or not. In this respect, the life was found to have been considerably changed by tremendous technological advancements made in the last one decade.

3.5 FUTURE PROSPECTS

There are many other aspects that can be studied and need to be studied in our examinations on the Sun and the stars and to name just one such aspect, it would be extremely interesting to look at the magnetic fields in the corona. Of course, it is a difficult task because the coronal magnetic fields are of the order of a few Gauss, and we have some very difficult techniques whereby we choose certain lines, measure the linear polarisations of these lines, and by some complicated theory make an evaluation of the magnetic field. Then we can extend our search to pick out magnetic fields in the normal stars (not in stars like A-peculiar or white dwarfs where we find the magnetic fields tremendously large) by using a technique where one can look for a differential widening for certain magnetically selected lines as compared to certain lines which are insensitive to magnetic fields.

Thus, in general, there is a tremendous opportunity for newer techniques to be introduced for a better understanding of the solar and stellar phenomena; there is a tremendous opportunity for understanding the stars by means of a further detailed study of the Sun and there is a tremendous opportunity for newer results in our observations of the Sun in studying several phenomena that, we know, take place in other stars.

---

* The K-line width - absolute magnitude relation, more commonly known as Wilson-Bappu effect (named after the discoverers (Wilson and Bappu, 1957))is given by

$$\frac{d\,M_v}{d\,(\log W_2)} = \text{Constant}$$

where W_2 is the K_2 - line width and M_v is the absolute visual magnitude of the star.

Fig. 3.1 illustrates the above relation where the points in the figure represent the stars whose trigonometric parallaxes, and hence absolute magnitudes are known. Wilson-Bappu effect provides a powerful means of determining the distances of the stars since the intrinsic luminosity is found by a mere inspection of the spectrum. This also serves as a useful cross-check in our other methods of determining the distances of the stars.

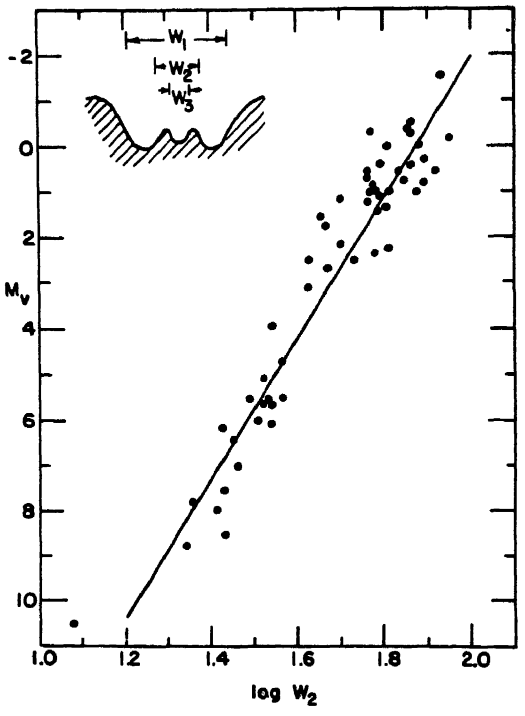


Fig. 3.1 Plot of W_2, the K_2-line width ot ionized calcium (Ca II) against absolute magnitude derived from trigonometric parallaxes. The insert at the left hand top of the figure explains the line widths W_1, W_2 and W_3. This illustrates how Wilson-Bappu effect allows us to determine absolute magnitudes of late type stars by merely measuring W_2 (Wilson and Bappu, 1957).

REFERENCES

Adam M. G., Ibbetson P.A. and Petford A. D., 1976, MNRAS, 177, 687.

Adam M. G., 1959, MNRAS, 119, 460.

Bappu M. K. V., Grigorjev V. M. and Stepanov V. E., 1968, Sol. Phys., 4, 409.

Bappu M. K. V. and Sivaraman K.R., 1971, Sol. Phys., 17, 316.

Blamont J.E., 1961, Phys. Rev. Lett., 7, 437.

Blamont J.E., 1977, Modern Aeronomy, Vikram Sarabhai Memorial Lectures, PRL Publications.

Bray R. J. and Loughhead R. E., 1974, The Solar Chromosphere, Chapman and Hall.

Chandrasekhar S., 1960, Radiative Transfer, Dover Publications (New York).

Claverie A., Isaak G. R., McLeod C. P., van den Raay H. B., Pall P. L. & Roa Cortes T., 1982, Nature, 299, 704.

Dicke R. H., 1983, Nature, 303, 293.

Dravins D., Lindegren L., Nordlund A., 1981, Astron. Astrop., 96, 345.

Dravins D., 1982, Ann. Rev. Astron. Astrophys., 20, 61

Duvall T. L. Jr. & Jones H. P., 1983, Nature, 304, 517.

Gibson E. G., 1973, The Quiet Sun, NASA SP-303.

Hart A. B., 1954, MNRAS, 114, 17.

Hart A. B., 1956, Ibid 116, 38.

Huber M. C. E., Foukal P. V., Noyes R. W., Reeves E. M. Schmahl E. J., Timothy J.G., Vernazza J. E. and Withbroe G. L., 1974, Ap. J. Lett., 194, L115.

Jordan S. (Ed.), 1981, the Sun as a Star, NASA SP-450.

Leighton R. B., Noyes R. W. and Simon G. W. 1962, Ap. J., 135, 474.

Linsky J.L. and Avrett E.H., 1970, PASP, 82, 169.

Skumanich A., 1972, Ap. J., 171, 565.

Stern R.A., Zolcinski M.C., Antiochos S.K. and Underwood J.H., 1981, Ap. J., 249, 647.

Uchida Y. and Bappu M.K.V., 1982, J. Astrophys. Astron., 3, 277.

White O.R. and Livingston W.C., 1981, Ap. J., 249, 798.

Wilson O.C. and Bappu M.K.V., 1957, Ap. J., 125, 661.

Wilson O.C., 1976, Ap. J., 205, 823.

Prepared by Physical Research Laboratory, Ahmedabad-380009, India and
Printed at the National Institute of Printing Technology for the Deaf,
New Delhi, India.