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Observations of Stellar Chromospheres

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Observations of stellar chromospheres

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[Plate 10]

The term 'stellar chromospheres' is often used, but has never been defined. I understand by it phenomena analogous to the solar chromosphere in that the temperature increases outward in some parts of the lower atmosphere. From the observational point of view, of course, almost all stars would show a pinkish flash spectrum if we could eclipse them, but that phenomenon is of no special interest here; we are interested in temperature reversal, as well as flares and magnetic activity such as is associated with the sunspot cycle. We exclude shells.

Unfortunately, the number of stars in which the flash spectrum is observable is severely limited, and we must detect the presence of chromospheres in the integrated stellar spectrum. This limits us to observations of a few lines which satisfy two conditions: (1) they must have a reasonable optical depth in the chromosphere, and (2) they must show different behaviour in the chromosphere than in the photosphere. In the visual region only three lines satisfy these conditions frequently: the H and K lines of Ca II and the 1083 nm* line of metastable helium. The former appear as doubly reversed emission lines, and this emission must come uniquely from the chromosphere; the 1083 nm line does not have a great optical depth, but its excitation temperature is so high that it could only appear at temperatures higher than that of the photospheres of most late-type stars.

The Hα line is a more complicated case; it almost surely comes from the chromosphere, but the chromospheric effects are not so well-marked, except in M stars and other red stars where it may appear in emission. Chromospheric effects have also been observed on occasion in the D 3 line and, of course, in other hydrogen lines which also appear in emission.

It is important to bear in mind that we should never be able to detect chromospheric activity in stars like the Sun, except in the extreme ultraviolet. The extensive studies of K line and 1083 nm were only made possible by a level of activity far exceeding that in the Sun. Therefore, we must be cautious in our interpretation in terms of the Sun, although some characteristics of the phenomena in the stars agree surprisingly well with what we know of the Sun.

Observations of the H and K lines

K emission in the Sun is observed in all regions where the field exceeds 1 mT or so (the exact number is unknown because of the limited resolution of the magnetograms). This includes predominantly the edges of the cells of the chromospheric network and plages. There is also a sizeable contribution from bright points inside the chromospheric network cells. These points, which appear dark in Hα, have not been identified with any magnetic fields, and may not be connected with any. They appear predominantly on the blue wing, and appear to be due to rising granules.

In the integrated solar spectrum, the K line appears doubly reversed, with two peaks called

*1 nm = 10 Å.

K 2V and K 2R, and a central dip, K 3, which is broader near the limb. The line does not appear doubly reversed at individual points on the Sun, but usually bright on one side or the other, with absorption overlying. The emission peaks are relatively narrow (except in plages) while the absorption K 3 is broad. We interpret the emission as due to hotter elements with upward or downward velocities, and the self-absorption as due to overlying, hotter, less dense material of low excitation temperature. The broadness of the K 3 absorption is ascribed to the well-known increase in macroscopic velocities with height. Of course, there are other interpretations of this phenomenon and I am just giving my own.

The K line in stars has been studied for many years by Wilson and various co-workers. The line appears in various stages of reversal with great variation in intensity and width. Wilson has found, however, that these variations depend with great regularity on fundamental properties of the star; the intensity of the reversal depends on the age of the star for main sequence stars only, and the separation of the K 2 peaks is linearly dependent on the absolute visual magnitude. Furthermore, the line-width-absolute magnitude relation also holds for the sun. A. Skumanich (unpublished) has found no age-intensity correlation for giants. This may be the result of K 3 self-absorption in these stars.

Wilson (1964) also noticed an abnormally high level of H and K emission in close binary stars. Our work on the 1083 nm line confirms this.

The Wilson–Bappu (1957) relation between the K 2 separation and absolute visual magnitude M_V was based on analysis of high dispersion spectra of a large number of MK standards, and covered a wide range of stellar brightness. The results show that the line width (meaning the separation of the K 2 peaks) is linearly correlated with the MK absolute magnitudes over a range of 15 magnitudes. The relation also holds when trigonometric parallaxes are used, and is quite independent of the intensity of the K reversal. Further it holds over a fairly wide range of temperature from spectral classes G to M. Pagel (private communication) has found a scatter of about one magnitude in the Wilson–Bappu relation, but the general correlation over a range of 15 magnitudes may be considered good. Wilson (1968) also found evidence that the H and K lines are broadened primarily by the Doppler effect (the widths are the same and the intensities, nearly the same). Thus, the Wilson–Bappu relation tells us that the velocity fields in the stars increase with M_V. I would believe that this is connected with the decreasing surface gravity as M_V increases; if the scale height is increased, the corona–stellar wind is cooler, and more visible; rising currents are not decapitated by the corona, and we see a wider velocity range. It has been pointed out that M_V is not a fundamental stellar parameter, but it certainly is related to some, within the observed scatter of the Wilson–Bappu relation.

Kraft, Preston & Wolff (1964) studied the behaviour of Hα as an absolute magnitude discriminant. Such a relation would be particularly valuable because the K line is very weak in GO stars. They found a good relation between Hα width and M_V for G and K stars, but none for M stars. They do not remark on variations in the Hα central depth; but it must be borne in mind that chromospheric activity produces both brightening and darkening in the centre of Hα, and only in the wings is its effect unique.

We have not found any relation between 1083 nm widths and M_V because the line profiles are not good enough; but superficially the lines do appear broader in the supergiant stars.

As we have noted, the connexion of line-width with absolute visual magnitude can be considered reasonable (although I daresay never predicted) in terms of the lower surface gravity of the larger stars—whatever pressure inputs the photosphere makes can produce greater velocities,

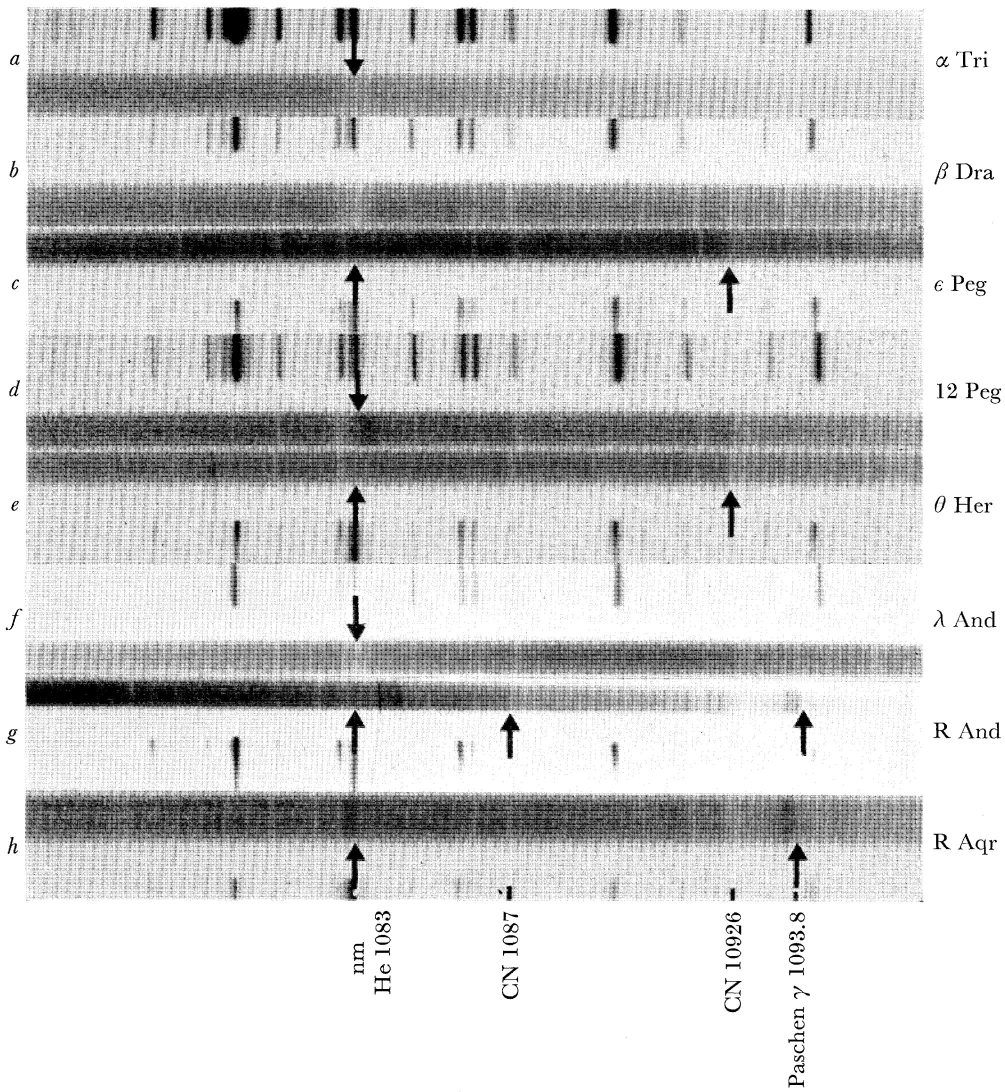

FIGURE 1. (*a*) α Tri, dF2, a close binary with strong 1083 nm absorption; the 1083 nm comparison line is indicated by an arrow drawn at its end. The range of the spectra is about 20 nm. The components of the He line are separated by 0.1 nm. (*b*) β Dra G2II with strong He absorption but no CN. (*c*) ε Peg K2Ib, with the 1092.6 nm edge of CN marked by an arrow. (*d*) 12 Peg K0Iab, showing P Cygni type 1083 nm emission. (*e*) θ Her, K1II, which was once in emission but now shows very little, CN bands still strong. (*f*) λ And G8III–IV, a star famous for strong chromospheric effects. (*g*) R And S6 with He and Pγ emission marked by arrows as well as the CN edge at 1087.0 nm. (*h*) R Aqr M8e, with strong He and Pγ emission marked.

(*Facing p.* 185)

and the deep atmospheres permit us to integrate over more velocities. But the relation between activity and age gives deeper evidence on the evolution of stellar atmospheres.

Wilson's (1964) first evidence for this connexion was based on several facts:

(1) H and K intensities in galactic clusters were much greater than in field stars. The effect is so well-marked it can be used to distinguish cluster members from field stars.

(2) The intensities are appreciably higher in young clusters like the Pleiades than in clusters such as the Hyades, and these in turn greater than in field stars.

(3) In binaries, which presumably have the same history, the K intensities are normally the same. The only exception (Wilson 1964) is where one member of the pair is a spectroscopic binary, and thus shows the enhancement characteristics of close binaries.

(4) There was no other characteristic correlated with H and K intensity. The availability of the Stromgren–Perry catalogue (Stromgren 1963), which allows a sorting out of field stars according to age, allowed Wilson and Skumanich (1964) to further establish the effect. A plot of the stars with intense K emission on the c_1 against $(b-y)$ diagram shows them concentrated near the lower edge, which consists of the young, unevolved stars. On the other hand, a plot on the m_1 against $(b-y)$ diagram, where m_1 measures metallic content, shows little systematic effect.

It is attractive to consider that each star begins its life with a relatively strong magnetic field condensed out of the interstellar medium, which it gradually dissipates in solar wind and the like. Alternatively, if the differential rotation is the source of solar magnetic fields, as in the models of Babcock (1961) and Leighton (1969), we might imagine (but with more difficulty) a storehouse of differential rotation which is gradually dissipated. In any event, our models of the sunspot cycle do not have to be completely self-renewing. However, we must bear in mind that the level of chromospheric activity is much lower in the sun, so we have no evidence at all on the age dependence of that low level of activity. Further, although the sunspot cycle is the source of most of the magnetic fields and chromospheric emission on the Sun, there is some generated by the supergranulation, and we cannot distinguish this in our H and K observation of stars. We can see how important it is to determine the solar analogue of the H and K emission in the stars.

The 1083 nm line

For some years, Arthur Vaughan and I have been studying the behaviour of the 1083 nm He line in a number of stars. Although the Mount Wilson 100-inch (254 cm) scanner has been used, the bulk of the data comes from the Palomar coude spectra, using a single stage image converter, with dispersions of 0.88 and 1.8 nm/mm. The image tube spectra have low modulations, and we are further hampered by a water vapour line at 1083.2 nm, but lines above 20 pm* can reliably be detected. Although more advanced image tubes exist, we have not yet been able to lay our hands on one; but the RCA tube we have is relatively very sensitive out to 1150 nm: it has been trouble free, and its speed has been enhanced by the use of two Canon *f*/0.95 camera lenses face to face for re-imaging. In 1 h, the spectrum of a star of magnitude $J = 4$ may be obtained with good seeing, and we now have several hundred such spectra. Because of the bright limiting magnitude, there are not many main sequence stars in the selection. Figure 1, plate 10, shows some examples.

The 1083 nm line is unique in that it cannot come from the photosphere of a cooler star but must be produced in a hotter layer above, at a temperature of around 20 000 K. It might also be

* 100 pm = 1 Å.

produced by a strong ultraviolet flux, but the existence of such a flux would, of course, also indicate a high temperature atmospheric layer.

Vaughan & Zirin (1968) reported on observations of 86 stars, of which about 25 showed He 1083 nm absorption and 6 showed emission. The sample was not a good one, for we observed primarily stars listed by Wilson & Bappu as having strong K emission. The He line was not very strong, only exceeding 25 pm in a dozen stars, so the observation is very difficult. The correlation between K emission and 1083 nm emission or absorption is ragged; K emission is a necessary but not sufficient condition for He to appear, and the K strength in supergiants is heavily affected by self-absorption. Almost no He absorption or emission was found in M stars. On the other hand, close binaries were found very likely to show He, consonant with Wilson's result. It is interesting that the properties of the K reversal in these binaries are different from most—the K 3 absorption is weak, and the reversal appears like a single strong line. The He absorption is likewise narrow in these stars.

Since these observations were made, I have obtained spectra of about 80 more stars with more or less the same results. In addition, a few more interesting facts turned up. I found He emission in the RV Tauri variable R Scuti and in the irregular R Aquarii. Up to this time, we have definite observations of He emission in 12 Peg, α Aql, ϵ Crv, R Sct, R And, θ Her, ϵ Gem, ρ Cas, R Hyd, η Per, ι Aur, and β Oph. The emission from ϵ Gem turned to absorption in 1968, and the absorption is currently very weak. In addition, strong He absorption appeared in α Aur, ϵ Leo, β Dra, β Sct, ϵ Eri, o CMa, σ Gem, ξ Cyg, ϵ Peg, δ Aur, θ Lyr, β Cam, ρ Mon, κ Cet, 58 Per, BL Ori, W Ori, α Crt, and β Cet. It would be important to search for X-rays from these stars. We have at least two plates of most of these stars. The chromospheric activity in these stars must be very strong; in the Sun 1083 nm absorption only appears in flares, and even in plages it is only a few tens of picometres in absorption.

The problem of the F stars is very interesting. F stars are not supposed to have convective envelopes, and hence are thought not to have chromospheres. The K line in these stars is very weak because of the high temperature, so K emission would be difficult to find anyway (but was observed in Procyon by Kraft & Edmonds 1959). There are not many F stars, and we have only observed a few. Possible He absorption appears in only one, Procyon, out of six in the Vaughan–Zirin list, and four out of six that I have observed since. But the two definite cases are γ Vir, which is peculiar anyhow, and the close binary, α Tri. Wilson (1966) found that K emission appeared abruptly after F 4, and was connected with the end of rotation; he believes the onset of activity brakes the surface layers. Unfortunately, the K line is weaker in the earlier stars and this may also play a role.

M stars

At the other end of the spectral sequence, the M stars present an anomalous picture. Although the K-line relation holds well, Kraft *et al.* (1964) found that there was no relation between Hα width and luminosity in these stars, and Vaughan & Zirin could not find any evidence of 1083 nm emission or absorption. Of course, in some of these stars 1083 nm might be masked by molecular bands, but in others the spectrum is sufficiently clear. It would appear that the chromospheres of M stars are too cool to permit excitation of 1083 nm, but hydrogen emission is a well-known phenomenon in these stars. I have also observed Paschen γ emission in a number of stars, and since this line is situated near the maximum of their spectra, it is clearly not a fluorescence effect. One can only guess that the hydrogen emission comes from a shell of some sort in which the chromospheric velocity fields do not play a role.

I have observed He 1083 nm emission and Pγ emission in very late and somewhat peculiar stars such as R Aqr, R And and R Hyd., but these can scarcely be typical cases. Still, the presence of emission lines of hydrogen and the K reversal in so many M stars points to important chromospheric effects.

Greenstein & Arp (1969) obtained a remarkable spectrum of a stellar flare in the dwarf Me star Wolf 359, which shows the typical strong hydrogen and neutral helium emission of solar flares. The phase of the flare is indeterminate, so we cannot say how representative this is. It appears just what we would expect from a hot hydrogen plasma. The solar physicist can fondly speculate on the possibilities of beautiful Hα cinematograms of such an event, but this is for later generations.

CN Bands

One of the most striking features of the 1.1 μm region is the set of strong CN bands beginning at 1087 nm.† I noticed that they were rather strong in ϵ Gem and θ Her, the stars with the strongest He emission in the V–Z list. Indeed, Redman & Griffin (1960) found these stars to have the strongest CN intensities of any star on their list. Since Redman & Griffin found the CN band strength to vary with something beside luminosity, and since Sheeley (1969) has found CN absorption to be distributed around the chromospheric network, this seemed an interesting possibility. We have thus measured the CN band intensity on many of our plates, but the correlation with He is unfortunately not definite. This is probably because He is hard to measure, CN is hard to distinguish from water vapour bands, and He is variable in many stars anyway. But I believe some definite effect exists.

Changes in time

All the investigators of chromospheric activity in stars have been eager to detect changes in the lines with time, by analogy with the solar cycle. On the other hand, variability is somewhat of a nuisance, as it makes it impossible to determine the level of activity in a star from one or two plates. We have found several of the stars with 1083 nm to show substantial variation; as noted, ϵ Gem was definitely in emission in 1966, the line changed to absorption in 1968, and now has almost disappeared. We have not established any CN variation in that star, for the early plates were not properly exposed for that part of the spectrum. A few other stars have shown less well-marked changes over intervals of 3 years or so, and because of the variations in plate quality and blending with the 1083.2 nm water vapour line, the results are inconclusive. A large number of stars appear not to have changed at all.

On the other hand, there is fairly good evidence for changes in the K line. A. J. Deutsch (unpublished) found rapid variations in the K line profile in Arcturus. O. C. Wilson (unpublished) has been following a number of stars with the scanner, and reports a number of changes, some short term. There is not yet any periodicity established for these changes except for one star.

† Spinrad & Wing (1969) discuss the identification of these bands.

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Discussion

Our observations of He show preferential occurrence of strong chromospheric effects in supergiants and close binaries (unfortunately, we can only observe a few main sequence stars, and indeed those with strong K emission, such as 61 Cyg and ϵ Eri have strong He absorption, but the lines are strongest in the classes mentioned) and lead us to speculate on the dependence of chromospheres on these factors. It is important to remember that the surface gravity is insufficient in the supergiants to retain a stellar corona—the material would simply escape. On the other hand, it is possible that all these stars have a low temperature stellar wind flowing out, some of the effects of which we see. The whole question of the behaviour of a chromosphere without a steep temperature rise overlying it is most intriguing. The boundary conditions must be such that the chromospheres in giant and supergiant stars are much deeper even than the scale heights would suggest. Further, the temperature of the 'corona' is limited, as Parker (1963) has pointed out, to 10000 K (i.e. the solar corona temperature divided by the ratio of scale heights). But we observe He lines which indicate a higher temperature, perhaps 20000 K, or else strong ultraviolet emission. It would be most interesting to carry out observations of these stars from above the atmosphere. The appearance of chromospheres in stars without hot coronas is quite important for solar physics in that it shows that back-conduction from the corona is not necessary for the production of a chromosphere.

The problem of close binaries is of less direct appeal to the solar astronomer, but of great astrophysical interest. The effect could either be produced by large mass loss, or by non-thermal tidal effects in the stars. The fact that there is little self-reversal in the binaries suggests the former. Hopefully, some theoreticians will get after this problem and sort out the intriguing possibilities.

I am grateful to Dr O. C. Wilson for many discussions of his pioneering work in this field and for reading the manuscript. This work was supported by the National Aeronautics and Space Administration and the National Science Foundation.

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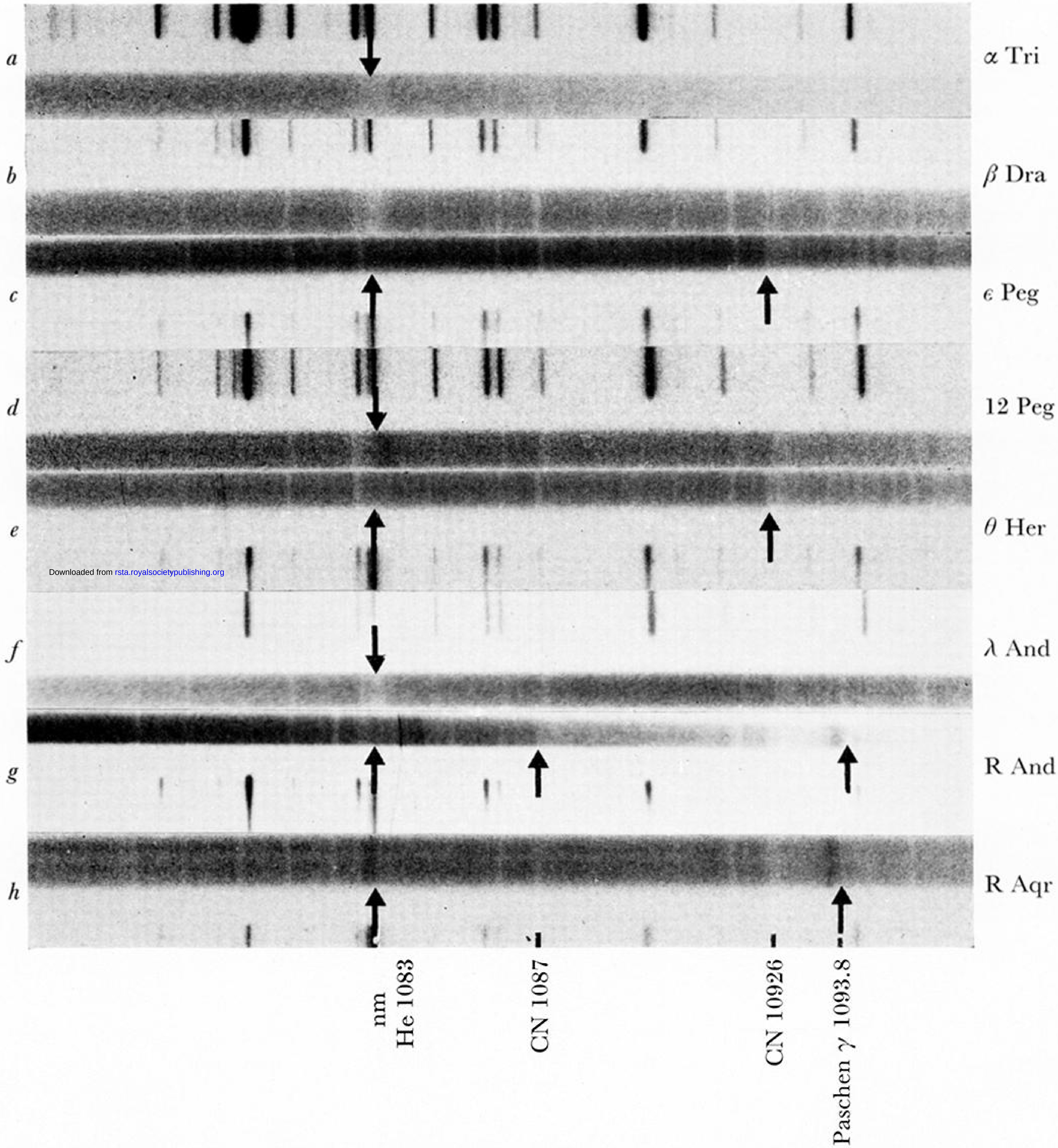

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