SUMMARY

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I was asked to summarize this Conference. However I think that I can be more effective if I stay with those matters where I have some personal experience. Accordingly, I propose to restrict my talk to what I shall call solar-type chromospheres. I hope to review some of the things that are known, to point out what seem to me to be unsolved, or incompletely solved, problems, to comment on some issues raised during the meetings, and to bring you up-to-date on some of the current investigations. In this way, I hope to make some points of interest to the observers as well as to the theoreticians.

By solar-type chromospheres I mean two things: First that the H-K reversals satisfy the well-known width-luminosity relation; second that the morphology of the reversals is essentially of the common double peaked form which is familiar from the Sun. The cross-hatched region in the schematic H-R diagram shows where such chromospheres are found; on the main sequence from F5 down, and in the giants from GO to later types.

It is important to realize that a chromosphere is a completely negligible part of a star. Neither its mass nor its own radiation makes a significant contribution to those quantities for the star as a whole. Moreover, I know of no essential role that a chromosphere fills in the life of a star. For example, there are places on the main sequence where stars can be found which must have identical masses and energy productions, but whose chromospheres are very powerful in some, and absent, or almost completely so, in others. The stars in question function equally well with or without chromospheres. Hence an outsider might be pardoned for asking why this many people have spent four days here studying something which seems as nonessential and insignificant as chromospheres.

Actually, of course, the motivations for people to engage in this particular type of research are as varied as their own interests and specialties. In my own case, I have been attracted to chromospheres in the first place by pure curiosity and secondly by the fact that they turn out to be packed with information. By proper study of stellar chromospheres and, indeed, thus far involving only the H-K reversals, it is possible to derive very valuable knowledge about the absolute luminosities of late-type stars, about the ages of stars on the main sequence, and, more recently, about the occurrence of stellar analogs of the solar cycle. I have hoped that the theoreticians would be sufficiently intrigued by all this to provide believable explanations for the physical processes which underlie this wealth of information.

I shall return to some of the foregoing matters later. But first let us look at the schematic H-R diagram in Figure IV-11 and consider the boundaries contained therein. These are two in number: first, the one on the main sequence at spectral type approximately F5, and the other, which probably is essentially a vertical line through the giant and supergiant region, corresponding closely to spectral type GO. In the present context these boundaries separate those regions in which H-K emission can be seen readily at a dispersion of 10 A mm"^{1} from those in which H-K emission is invisible at this scale. Boundaries of this sort are likely to mark a place where some important physical change takes place and are therefore worthy of intensive study.

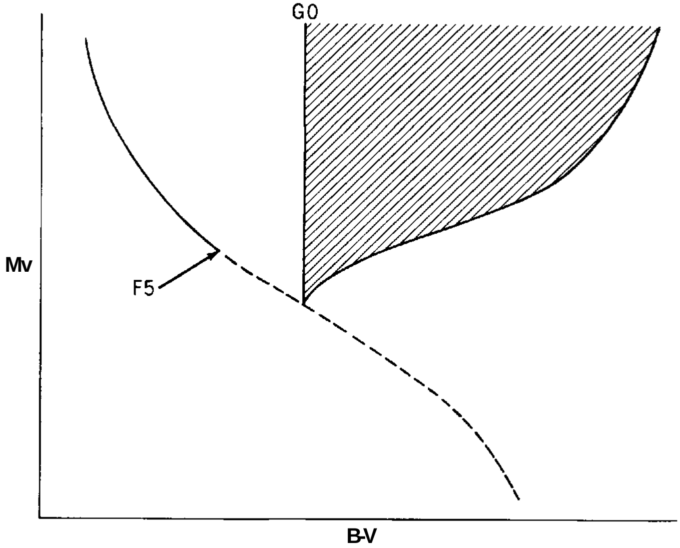

Figure IV-11 Schematic HR Diagram. Cross hatching shows regions of occurrence of solar-type chromospheres.

The main sequence boundary has been investigated much more thoroughly than the one in the giant region. The result is that the point on the main sequence where strong chromospheric emission terminates coincides, with great precision, with the point where the larger rotational velocities cease, as one proceeds down the main sequence from earlier spectral types. In fact, the mass range within which these two transitions occur can be only a very few percent at most. Since the deep hydrogen convection may also set in at approximately this same point, according to theoretical studies, it seems to me likely that both transitions, from weak to strong chromospheric activity, and from large to small rotational velocities, are due to the onset of deep convection. The one remaining necessary link in this argument, that braking of rotational Velocity is due to ejection of charged particles by chromospheric activity, and interaction of these particles with the magnetic field lines of the rotating star, has been supplied by Schatzman some years ago. Of course, even though this picture of what occurs at the transition zone on the main sequence appears to be both reasonable and consistent, it may not be correct, and one must be prepared to consider other interpretations.

The other boundary, in the giant region, requires further study. I have taken a few spectrograms of luminous stars of types F7-F9 and I have the distinct impression that, for these stars, the H and K lines become suddenly very much deeper than at GO, and the only emission, if present at all, appears merely as slight shoulders well down in the lines. This boundary should be investigated more completely than it has been to find the real nature of the chromospheric transition.

I should like now to comment on some recent developments, mostly unpublished as yet. The width-luminosity relationship was derived originally by making use of the MK standards of appropriate spectral types and the line widths were determined in the simplest fashion by setting the cross hair of an ordinary measuring engine first on one edge and then on the other edge of the emission lines. The result is a linear correlation between log W_o (W_o is the width in km s"^{1} after correction for instrumental width by subtraction of a constant) and the absolute visual magnitude, M_v; and this extends from stars of absolute magnitude -5 or more down to the faintest stars on the M.S. for which the dispersion of 10 A mm"^{1} is adequate, i.e., to +6 or +7. A recalibration using the Sun (high dispersion solar spectrograms in integrated light) and the yellow giants of the Hyades agreed very closely with the original one based on the MK standards. There is an admitted weakness in this calibration for the more luminous stars, since only £ Aurigae and some of the bright M-type supergiants in h and x Persei could be used as checks, although they too showed good agreement.

There have been various criticisms of this method of deriving absolute magnitudes, the most serious ones raising the question of a dependence upon the abundance ratio [Fe/H] I have recently been trying to shed some light on this matter, in collaboration with two colleagues at the Copenhagen Observatory, by observing certain physical pairs of stars. In these pairs, the primary is a G-K type giant and the secondary is a main sequence star of type A-F. Spectrograms of the primary yield its absolute magnitude on the basis of the Sun-Hyades calibration. The Copenhagen observers use the *uvby* system of Strömgren to derive the absolute magnitude of the secondary and the apparent magnitudes of both stars. Their photometry also yields values of [Fe/H] for both stars and the average difference in this quantity between the members of 18 of the pairs is only 0.09, which is very good agreement. Reduction of incomplete data for these 18 pairs shows that the Sun-Hyades calibration agrees with the Strömgren absolute magnitudes to an average difference of only 0.1 mag. The range of [Fe/H] encompassed is about 0.7, and over this range there is no definite evidence of dependence upon [Fe/H], but final completion of the project must be awaited before drawing more definite conclusions.

I refer now. briefly, to the question of ages of stars on the main sequence. All the evidence, and there is by now an impressive amount, indicates that the degree of chromospheric activity, as measured by the strength of the Ca II emission in a main sequence star, is indeed a decreasing function of its age. Thus, at the present time, it is quite possible to observe, say, all the K_o stars in the solar neighborhood in the proper way, and put them in the right order of age. This is, in itself, a valuable tool. But even more important is the work being done by Skumanich to calibrate the rate of chromospheric decay in absolute terms. I think it is possible now to look forward to the time when the actual ages of all main sequence stars from F5 down, within reach of the appropriate equipment, can be specified in years. The value of such data in, for example, the study of galactic stellar orbits as a function of age is obvious.

Calcium spectroheliograms have made it evident for a long time that the radiation in the chromospheric Ca II lines in the sunspot zones waxes and wanes in synchronism with the other indices of the solar cycle. If the stars behave in similar fashion, then, by monitoring the emission in these lines against the adjacent continuum, one should in principle be able to find and study stellar analogs of the solar cycle, and to determine the shapes, amplitudes, and periods of any cycles which occur. Since all theories of the solar cycle have, of necessity, been restricted to reproducing the features of the solar cycle itself, it may well be that they lack sufficient generality, and an extension to other stars should greatly improve this situation. To make this kind of observation it is essential to be able to isolate accurately narrow bands at the centers of the stellar H-K lines and to measure the flux in these bands with respect to the nearby continuum with precision.

The coude' scanner at the 100-inch telescope is an ideal instrument for this type of work, and, since 1966, I have been measuring the H-K fluxes in a number of main sequence stars from spectral type F5 to M_0. It is not feasible here to go into either the instrumental details or the results thus far obtained. Very briefly, it turns out that the earlier type main sequence stars, F5 to G5, have not so far shown variations that appear to be cyclical. Either they do not have them or their periods are too long compared to the time of observation. However, beginning at about type G8 there are perhaps a dozen stars whose variations could very well be cyclical in nature, though none have yet been followed through a complete period. Noteworthy also is the fact that not all stars of the same types show the same kind of behavior. A few more years of observation should settle some of these questions definitely

One item which has not been mentioned in this Conference, but which I think may well be of importance and which deserves further study, is the occurrence of He in emission in a number of stellar spectra. I first noticed this line in the spectrum of Arcturus in 1938, on a high dispersion plate. In this example, the He line has about the same width as the H-K emissions, but unlike them it has a smooth rounded top with no evidence for a central dip. It has seemed to me that these facts must contain important clues to chromospheric conditions, especially, perhaps, the approximate equivalence of line width for a ratio of atomic weights of 40:1.

Another topic which has been mentioned several times at this meeting is the well-known enhancement of chromospheric activity in the members of close binaries, a point which has been noted in the literature by several individuals. Here again is a field in which more systematic observation might succeed in shedding light on chromospheric mechanisms. I wish merely to call attention to what I consider a rather spectacular case which 1 came upon while looking for Li lines in binaries, and which I believe might repay further study. This is the bright member of the visual pair ADS 2644, and I published a brief note about it in *P.A.S.P.* 1964. This star is a spectroscopic binary, of spectral type G9 V. The H-K emissions are very strong and much wider, about 1 A, than is normal for a star of this type and luminosity. But at Ha the situation is even more abnormal; here the usual Ha absorption line is completely masked by a strong, broad emission band of width 5 to 10 A. Evidently the presence of the companion has induced very large velocities in the chromosphere of this star, and the velocity spread in the region of Ha formation appears to be several times larger than that where the Ca II lines are formed. It is not impossible that further study of this and similar systems might yield information useful in the understanding of normal, undisturbed chromospheres. In any case, the relationship of hydrogen and calcium line widths in this star is strikingly different than their relative widths in the presumably undisturbed chromosphere of Arcturus.

There has been mention of surface magnetic fields during this meeting, and of their role in chromospheric excitation. I think there is general agreement on the part of theoreticians that such fields are necessary in the transfer of mechanical energy from the hydrogen convection zone and in its deposition in the chromosphere and corona. However, there seems to be some disagreement as to the source of the fields. If we appeal to the observations, we have seen that on the M.S., below the boundary at spectral type F5, a star begins its main sequence life with strong chromospheric activity, but this activity gradually diminishes and may, in time, cease altogether. This can hardly be due to any change in the hydrogen convection zone whose existence depends only on the general parameters of the star, the great abundance of hydrogen, and the latter's high ionization potential. I cannot see what remains to explain the decrease in chromospheric activity except to suppose that the surface magnetic fields decrease with time, presumably because the magnetic energy is used up by transformation to energy of other kinds. This could happen if the magnetic energy in question is a residual left over from the star's extreme youth and not replenishable. But if it is produced by a dynamo within the star, then the dynamo must run down and effectively cease to operate. It is up to the theoreticians to decide which, if either, of these two views is the more acceptable.

There is, however, one more clue to be obtained from the observations. We see that when stars which have been sitting on the M.S. for a time long enough to reduce their chromospheric activities to very low values begin to evolve up the lower boundary of the giant region in the H-R plane, they need to go only a little way before their chromospheres reappear. Is this because some internal magnetic field has been allowed now to reach the surface, or has the internal dynamo been reactivated? I do not pretend to know the answer, but I feel that there are some fundamental and fascinating questions awaiting investigation.

The study of stellar chromospheres, either for themselves or to abstract the information they contain, is essentially a question of high, or at least medium, dispersion spectroscopy. I wish to call the attention of the observers to some recent instrumental developments which I believe portend gains in this field fully equivalent to those which resulted from the introduction of photography into astronomy a century ago. These developments, insofar as I am aware of them, are two in number. The first involves a silicon diode device which has not yet been applied to spectroscopy, but which appears very promising. The other has already produced very spectacular spectroscopic results. I refer you to a recent paper in the *Astrophysteal Journal* (J. L. Lowrance *et ah,* 171, 233, 1972). These authors succeeded in obtaining, in six hours, a spectrogram of dispersion of 9 A mm"^{1} of a QSO of magnitude 16.5.

The implications of this work for stellar spectroscopy are very impressive, especially since it is reasonable to anticipate improvements in the apparatus in the course of time. Let us consider only the application of the width -luminosity relationship to the determination of absolute magnitude as an example. It thus appears probable that in the relatively near future this method will become applicable to the red giants in a number of globular clusters, to the similar stars in many open clusters, and to vast numbers of non-cluster stars of special interest. Moreover, for stars which are now very difficult to handle at 10 A mm"^{1}, higher dispersion and increased accuracy should become easy. I cannot help feeling that coude stellar spectroscopy, including of course the study of chromospheres, is on the verge of a new era of accomplishment and vastly increased capability.

Finally I wish to address myself to the theoreticians. They have done much work, involving what might be called the standard theory, in attempting to explain the chromospheric emission lines. Their tools are non-L.T.E. theory, the equation of transfer, and source functions. I must confess that I have some misgivings about the applicability of their results to the real world. As an example, and I have seen others at various meetings, I refer to Dr. Avrett's worthy efforts to account for the width-luminosity relationship. By scaling up the quantities applicable to the Sun, he derives emission lines for a giant star, and they are indeed wider than the solar lines. But, unfortunately, they are quite different in shape from the lines one sees in nature. They have rather extensive wings, whereas the real lines have very well-defined edges which msut be very steep. Indeed, as a rough first approximation, the real lines must have edges which are nearly vertical; if this were not so the simple measurements which are employed in applying the width-luminosity relationship would not work, as they do, whether the lines are weak or strong. Incidentally, Avrett wishes to attribute the width-luminosity relationship to the effect of surface gravity, g and this carries the implication that *p* must be constant across horizontal lines in the H-R diagram, which is not the case.

I have the feeling therefore that the theoretical explanation of the chromospheric lines is presently incomplete. Perhaps some of the parameters involved can be modified so as to arrive at good agreement and still remain within the believable range. But I suspect that an essential ingredient may have been left out and that this ingredient may be the velocity distribution of the radiating elements. The problem may be one of hydrodynamics as well as of transfer theory In any case further work is urgently required. First, high dispersion stellar spectrograms should be processed with care in order to define accurately and quantitatively what the properties of the chromospheric lines really are. Then the theoreticians will have to reproduce these lines as best they can, even if it requires the introduction of additional parameters.

I have tried to give here a brief but fairly complete view of the current status of the study of stellar chromospheres. We have learned a few things, but I think the subject is still in its very early stages and is deserving of much more effort on the part of observers and of theoreticians. To me, one of its most attractive features is the curiously large number of contacts with other astronomical fields to which it is able to make contributions.

CONCLUDING REMARKS FOLLOWING THE SUMMARY

Thomas — Dr. Wilson was asked to summarize the conference, as it is customary to have someone with wide experience and breadth of knowledge in the field close such a symposium as this on a note of perspective. It is not necessary that he be an expert on all the matters covered; one hopes only to hear some sort of encompassing "impressions" of what we, the participants, have been exposed to, and how well it "registered" to one having a broad background. I, personally, regret that Dr. Wilson chose not to do this, because I think that we would all have benefited greatly to hear his impressions. But I think that someone should try to do it, both for the sake of those who have tried to present a digest of ideas and for those of us who have just listened and commented. Otherwise, one may be left with what I consider the mistaken impression that there is only one type of chromosphere really worth much attention, the solar type, and only one set of indicators of the universality of the chromosphere phenomenon, those relating to the H and K lines. So, let me attempt a rather general summary

First, I can say in an overall way that I disagree strongly with Dr. Wilson on his assessment of the general importance of chromospheres. If I follow the logic of Dr. Praderie, in her presentation, that the properties of a stellar atmosphere may be discussed in terms of two kinds of fluxes — electromagnetic radiation and mass — then *conceptually* the chromosphere is that part of the atmosphere directly dependent upon a non-zero mass flux generating a mechanical energy flux.

Also, in a wholly *observational* way, the chromosphere determines the properties of the cores of most strong lines in the solar (and most of the stellar) Fraunhofer spectrum: not what I would call an irrelevant thing.