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Stellar Chromospheres

Besides being of intrinsic interest, these outer stellar envelopes provide very useful astrophysical tools.

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The chromospheres of normal, nonvariable stars are of interest because observation has revealed some general and unexpected properties of the outer layers of many stars, and because these properties can be usefully exploited in the solution of various problems. While considerable progress has been made in the field in the past decade, there are still many gaps in our knowledge, both observational and theoretical, and this article should be considered as a progress report on the exploratory aspects of the subject.

When the sun undergoes total eclipse, a colorful display of bright, red features is frequently seen here and there around the obscured disk of the sun. These are solar prominences which owe their color to the strong emission of the red Hα line of hydrogen. The name "chromosphere" was applied in the 19th century to that part of the solar atmosphere in which the prominences arise, and is still in general use.

Since the sun is the only star whose surface features and activity can be studied in detail, it is clear that precise knowledge of chromospheric mechanisms and processes must be derived from solar observation and that the sun must serve as the principal proving ground for chromospheric theories. Thus, it is appropriate to begin with a brief discussion of a few selected topics relating to the solar chromosphere.

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Practically all the observable radiation from the sun, together with the thousands of molecular, atomic, and ionic absorption lines in its spectrum, originates in a layer only a few hundred kilometers in thickness which forms the visible surface. This thin layer is known as the photosphere. Just above it, though not separated by any distinct boundary, is the chromosphere, and still higher, fading out gradually for several solar radii, is the corona. The thickness of the chromosphere cannot be defined precisely, but is of the order of a few thousand kilometers, and there is no sharp boundary between it and the corona.

The sun is near enough that surface detail down to a scale of 1 second of arc, or even less on occasion, can be observed, and the phenomena of the solar atmosphere have been studied for many years (*1*). As a result, much is now known about the processes which take place in the solar chromosphere, and quantitative data are steadily accumulating. The chromosphere is clearly a region of great activity and equally great complexity. No comprehensive theoretical account of the geometric, kinematic, and thermodynamic structure of the solar chromosphere is yet possible, although bits and pieces of the final solution seem to be emerging. Even these are still subject to much disagreement of interpretation. The reader is referred to a recent paper by Athay (*2*) for an account of the current state of chromospheric physics.

Despite the difficulties of explaining the details of chromospheric structure and activity, there is fairly general agreement among theoretical investigators concerning several aspects of the problem. In the first place, hydrostatic equilibrium predicts at the solar surface a scale height (the height at which the density decreases by $1/e$) of only about 100 kilometers, and the solar atmosphere would, under these circumstances, dwindle away to inappreciable density in only a few hundred kilometers. One concludes, therefore, that hydrostatic equilibrium is not present. Further, since there is much vertical motion in the chromosphere (for example, the spicules), it is concluded that the chromosphere and corona consist of material impelled upward from below and that they are dynamic rather than static structures.

The only known source of the mechanical energy necessary to maintain the chromosphere and corona is to be found in the hydrogen convection zone. In the sun this zone extends from just below the visible surface to a depth of the order of 10^5 kilometers, through the region where hydrogen, which comprises the bulk of the solar material, is partially ionized. In this region an appreciable fraction, perhaps of the order of half, of the energy flux is carried by the turbulent mass motions of convection (*3*). (The inexactness of these statements is a consequence of the lack of precise theories of the relevant phenomena.) Thus it would be expected that all stars with surface temperatures lower than that of the sun possess hydrogen convection zones. Proceeding toward higher surface temperatures, one must expect the region of partial hydrogen ionization to become thinner and finally disappear. It appears likely that the hydrogen convection zone ceases to be very effective for stars of early F type that have surface temperatures of the order of

1000° higher than that of the sun. This brief and inadequate description of the hydrogen convection zone, whose existence was first established by A. Unsöld many years ago (*4*), is perhaps sufficient to indicate its importance for the understanding of the phenomena in the outer layers of the solar and stellar atmospheres. In general, as will be seen, chromospheres of the kind familiar to us from the sun are found in just those stars where effective hydrogen convection zones are expected.

Theoretical investigators agree also as to the general means by which energy is transported from the hydrogen convection zone into the chromosphere and corona. The turbulent elements in the upper part of the convection zone are believed to generate acoustic waves which propagate through the photosphere into the more rarefied regions above, carrying energy. As the density encountered decreases, the waves become more magnetohydrodynamic in character and finally build up to shocks whose dissipation releases energy in the chromosphere. These ideas were originated independently by Biermann (*5*) and Schwarzschild (*6*) and have been extended by several individuals. A good recent exposition of the subject has been given by Osterbrock (*7*).

The role of magnetic fields in feeding energy into the chromosphere is not entirely clear. However, that there is an intimate association between magnetic fields and chromospheric heating is shown by detailed studies of magnetic fields on the solar surface. In those areas where spectroheliograms indicate enhanced chromospheric emission [see Fig. 4 of Athay's article (*2*), for example], measurable longitudinal components of magnetic field are always found, and these fields are absent in the darker, unexcited areas (*8*). In plages, where the chromosphere radiates still more strongly, the fields are correspondingly greater. Thus there is a correlation—although the exact relationship does not seem to have been derived as yet—between the degree of chromospheric heating at any point on the sun and the magnetic field strength at the same point.

The sun is the only star whose surface we can investigate in detail and in whose outer layers the processes that occur can be observed from point to point and can be compared with the predictions of theory. For all other stars the light that enters a spectrograph comes from the entire hemisphere turned toward the observer, and the resulting spectrogram represents an integration over the stellar disk of all the activity taking place during the observation. Spectrograms of the integrated light of the sun (easily obtained by observing the sunlit sky) show very little effect of the chromosphere, and none at all of the corona. This result is to be expected since estimates of the total emission of the chromosphere plus corona indicate that it amounts to only about 10^{-4} of the entire solar energy flux (*7*). In the shorter-wavelength regions of the spectrum, observable only from high-altitude rockets or from satellites, both the chromosphere and corona provide a wealth of emission lines, but these will not be considered here, since this article is concerned with the study of chromospheres from ground-based facilities.

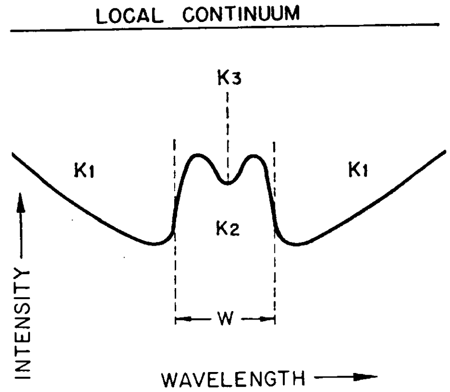


Fig. 1. Schematic representation of a typical K line as seen in the integrated solar spectrum or in a stellar spectrum. The deep, broad absorption, K_1, is formed in the photosphere; the emission, K_2, is produced in the chromosphere. (For explanation of *W*, see text.)

When the integrated solar spectrum is obtained with sufficient dispersion (2 or 3 Å/mm, or more), very weak emission features are seen at the centers of the two broad, deep, absorption lines due to ionized calcium and known as the H and K lines. These emission features have a characteristic double-peaked appearance, with the peaks separated by a central depression or absorption. It is customary to denote the broad, strong, absorption lines that are formed in the photosphere as H_1 and K_1, the emissions as H_2 and K_2, and the central depressions as H_3 and K_3 (Fig. 1). From detailed spectroscopic investigation over the solar surface, it is clear that these weak emissions originate in the chromosphere (Fig. 2). High-dispersion spectrograms of the

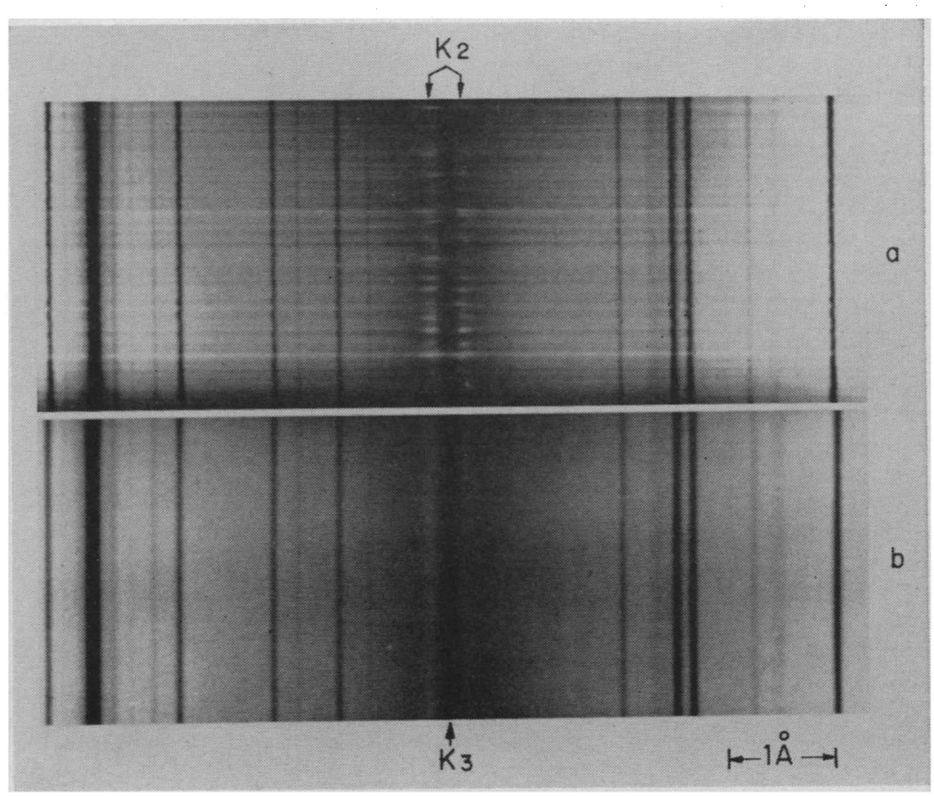


Fig. 2. (*a*) The K line as seen on a portion of the solar surface at very high dispersion under good observing conditions. Note that the emission in K_2 is discontinuous along the slit direction; note also the velocity fluctuations (wiggles) in the absorption lines. (*b*) The K line in integrated light from the entire disk of the sun, analogous to the observations of stars. [Photo courtesy of Dr. O. C. Mohler, McMath-Hulbert Observatory]

solar surface show certain irregularities within the central cores of some of the strong absorption lines. These irregularities are believed to represent velocity fluctuations in the upper portions of the photosphere or within the chromosphere, and hence the cores of these lines as seen in the integrated spectrum may arise in the chromosphere, at least in part; observations of stellar spectra have supported this view (9). Finally, observation of the HeI absorption line at 10830 angstroms in late-type stars will be of great interest, since this line, which is formed in the chromosphere, occurs frequently in the solar spectrum over excited regions of the sun's surface.

These three items represent the only known contributions of chromospheres to stellar spectra. Until it becomes possible to observe the ultraviolet spectra of numerous stars from above the earth's atmosphere, knowledge of stellar chromospheres must depend chiefly upon the study of the H_2, K_2 emissions in stellar spectra.

The importance of investigating stellar chromospheres lies in two factors. First, students of the solar chromosphere are automatically restricted to a star with a fixed set of physical characteristics such as mass, radius, luminosity, surface temperature, chemical composition, age, magnetic state, and the like, and theory has provided no guidance as to what correlations, if any, might be anticipated between these parameters and observable chromospheric properties. That some such correlations exist is demonstrated by observation, and these correlations, therefore, provide both additional clues to, and boundary conditions that must be satisfied by, any comprehensive chromospheric theory. Second, the correlations mentioned are sharply enough defined to constitute valuable tools with which other astronomical problems—in themselves having no intrinsic connection with chromospheric matters—can be successfully attacked.

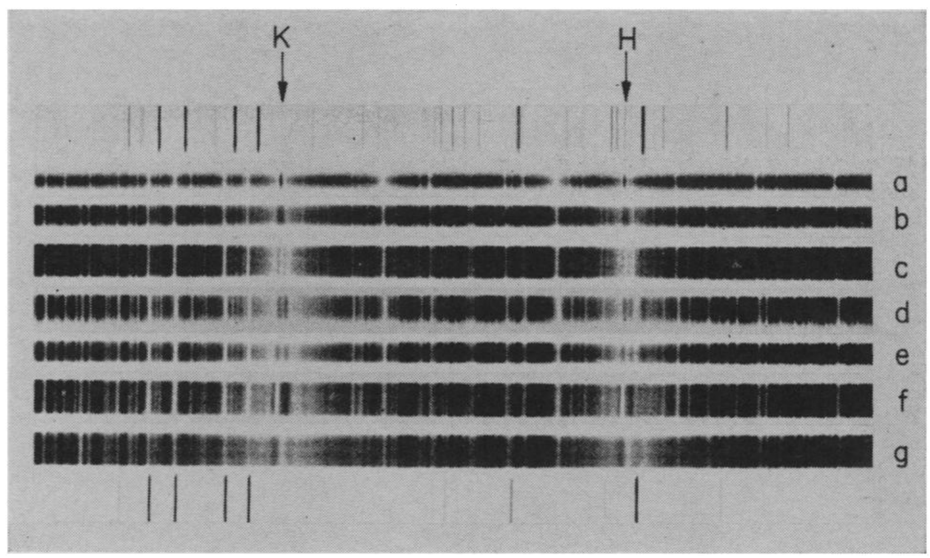


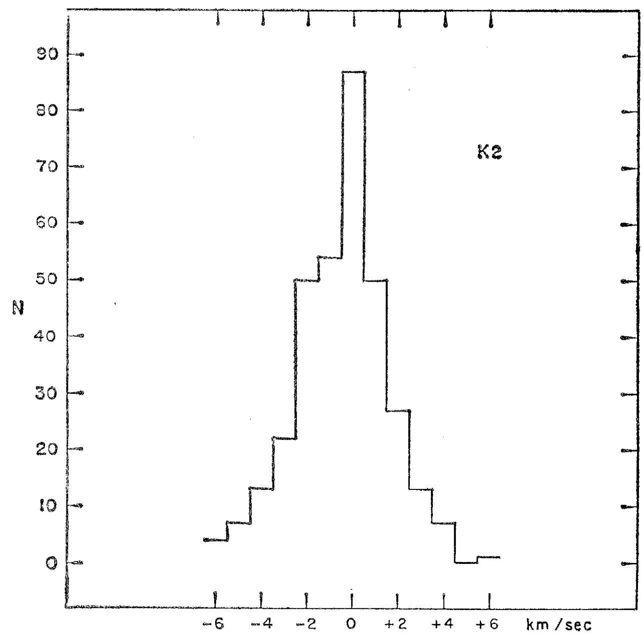
Fig. 3. A series of stellar spectra showing the general form of the chromospheric H and K emissions and the increase of H_2, K_2 width with intrinsic luminosity. The absolute visual magnitudes of stars *a* and *g* are approximately +10 and −6, respectively. In stars *d* and *e*, note the emission due to the hydrogen line H_ϵ just to the right of the H line. In star *f*, sharp absorption components displaced toward shorter wavelengths are visible in the H and K emissions.

H and K Emissions in Stellar Spectra

Emission components at the centers of H and K, observable even with rather small dispersion, have been known in the spectra of some bright stars since 1913 (*10*). Since at these dispersions the solar H_2 and K_2 lines are far below the level of observability, the presumption is that some stars can, and do, possess much more active chromospheres than does the sun. As will be seen, this presumption—that H and K emission in a stellar spectrum originates in a chromosphere—is rendered virtually certain by further observations. Since 1913 H and K emission has been found in the spectra of many stars, and catalogs of these stars have been published (*11*). Most of these discoveries have been accidental, and only in the past decade have stellar chromospheres been systematically investigated. A large part of the delay in undertaking this task was due to the necessity of awaiting the development and construction of suitable spectrographic equipment. Furthermore, since it has been necessary to observe many stars in order to define the problems involved, some of the recent work has been based on rather rough semiquantitative procedures, and these will have to be replaced in some areas by more precise methods in the future.

When the spectra of the stars are examined systematically with adequate dispersion (10 Å/mm has been used for the most part, and at this dispersion the solar H_2, K_2 are invisible), it is found that H-K emissions are almost universally present among the giants and supergiants of spectral types G, K, and M, although there is a considerable intensity range within each spectral type. These are the intrinsically luminous stars with surface temperatures similar to and below that of the sun. On the main sequence, H-K emissions are found among the same spectral types, and even in stars of type F5, which have surface temperatures about 1000° higher than that of the sun. Near type F5, emissions strong enough to be seen at 10 Å/mm are quite rare, and their frequency increases steadily as one proceeds down the main sequence, although a large range of intensity is apparent within all spectral types, including the M-type dwarfs, whose surface temperatures are about 2500° below that of the sun. Among the giants and supergiants the significance of the intensity of H_2, K_2 is as yet unknown. On the main sequence, however, the meaning of these intensities within groups of stars of substantially equal surface temperature is becoming clear, as is discussed below. In general, the average H_2, K_2 intensity increases as one proceeds toward cooler stars, because these lines are seen against the neighboring continuous background, which diminishes rapidly with decreasing surface temperature over the relevant temperature range. One notes also that chromospheres occur among the stars in which hydrogen convection zones are expected.

Where the spectrographic resolution is sufficient—that is, among the subgiants, giants, and supergiants—the H_2, K_2 emissions nearly always have a double-peaked structure, as in the sun (Fig. 3). For stars on the lower main sequence, where the whole emission pattern of H_2, K_2 becomes much narrower, the dispersion used has been inadequate



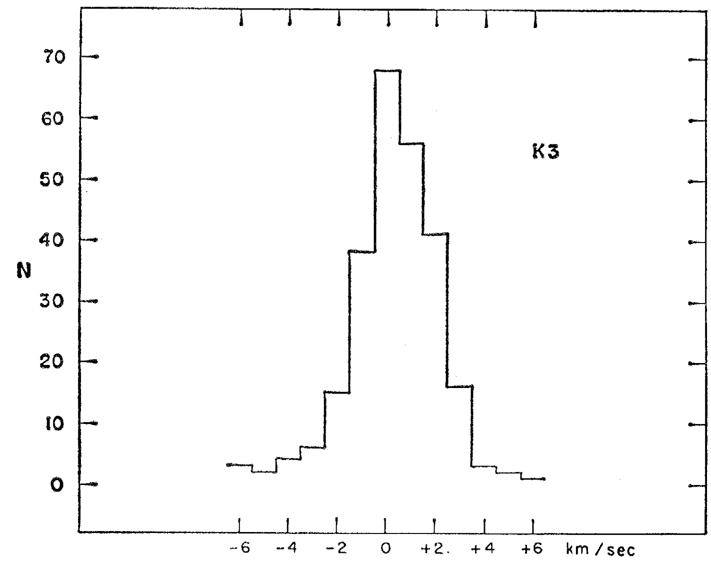


Fig. 4. Histograms of frequencies of (left) displacements of K_2 and (right) displacements of K_3 in a sample of normal giant stars. Ordinate is number of stars, *N*.

to reveal the inner structure of the lines. Presumably, by analogy with the sun, the emission-line structure in these stars also conforms to the standard pattern. In any event, the fact that in a great many stars the H_2, K_2 structure is similar to that of the solar lines provides strong presumptive evidence of chromospheric origin for all.

It is interesting to note that a similar structure has also been found in the Mg II lines and the Lyman α and Lyman β lines of hydrogen in the ultraviolet solar spectrum (*12*). All these lines, like H and K, are resonance lines of the respective atoms and ions; that is, they correspond to transitions between the ground state—or lowest energy level—and a higher one. On the other hand, the hydrogen line $H\epsilon$ occurs rather frequently in emission in stars showing H and K emission (*13*) and presumably also arises in the stellar chromospheres (Fig. 3). $H\epsilon$ is a subordinate line corresponding to a transition between two energy levels, neither of which is the ground state, and is always smooth and rounded at the top, lacking the central depression analogous to H_3, K_3. A typical example is provided by the star Arcturus (*14*). These differences in line structure may be due to differences in optical thickness of the various lines in the layers producing them. A resonance line would be expected to have much larger optical thickness than a subordinate line of the same atom because the population in the ground state would normally greatly exceed that in a considerably higher energy level.

Among the supergiants of spectral types K and M, the appearance of H_2, K_2 is sometimes confused by the presence of a sharp absorption component, occasionally more than one, displaced toward shorter wavelengths (Fig. 3). These sharp absorptions arise in huge low-density envelopes of matter ejected by the stars and moving outward with relatively low velocities (*15*). The mechanism of the ejection process is not yet completely understood, although it may well be similar to that responsible for the solar wind. In any event, the underlying H_2, K_2 emissions in these stars appear to be more or less of the standard double-peaked form.

The question of variability of H_2, K_2 in stars is one of very great interest. In the integrated solar spectrum one would expect to find two maxima of intensity of H_2, K_2 within the 22-year cycle of magnetic polarity reversal, since all types of chromospheric activity are more pronounced at times of sunspot maximum. I have been unable to find this information in the literature, although with present observational techniques it would not be difficult to acquire. No investigation of this kind has yet been made for stars, although it is extremely important since, in principle, it could shed much light on the existence and characteristics of stellar analogs of the solar sunspot cycle. What is needed for such work is an accurate and rapid procedure that would permit the monitoring of the strength of H_2, K_2 (with respect to the nearby continuous background) in a considerable number of stars of various luminosities and spectral types over a period of some years. Photographic methods are relatively slow, and several spectrograms of each star would be required at each epoch of observation to insure sufficient precision. A suitable photoelectric technique is clearly much to be preferred.

The only clear-cut case of variability in H_2, K_2 in normal, nonvariable stars has recently been found by Griffin (*16*) in the spectrum of Arcturus. In this star the relative intensities of the red and violet peaks change from time to time in quite unmistakable fashion, without any corresponding variation in line width or, as far as is known, in total strength. Whether there is any periodicity to these changes, whether they occur also in other stars, and what they signify are all quite unknown at present. It is clear, however, that these are important questions for further study.

Quantitative Measures of Line Structure

Some features of the stellar H_2, K_2 lines are measurable with rather surprisingly high accuracy on an ordinary measuring engine. The outer sides of these lines are steep, and thus their positions can be measured without much error even over a considerable range of plate density. The positions of the central depressions, H_3, K_3, can also be determined quite accurately in many instances. Measures to define the locations of the red and violet peaks are considerably less successful, since in many stars these features are rather broad and not well defined.

When, at the same time, a number of absorption lines produced in the photosphere are included in the measures, it is possible to look for systematic motions of chromospheric material with respect to the main body of the star. Naturally, conclusions must be based on measures of a considerable number of stars in order to reduce the effects of errors of measurement. Results for K_2 and K_3 in a number of ordinary giant stars are shown in the histograms of Fig. 4. It is evident that the emissions (K_2) are displaced toward the violet by 1 to 2 kilometers per second on the average, and that the central depressions (K_3) are displaced toward the red by a similar amount. It is curious that these displacements, in direction and amount, are very similar to those found for the sun by St. John many years ago (*17*), especially since they refer to stars some 4 to 5 magnitudes brighter. St. John attributed his results to a slow average upward motion of the chromospheric material producing K_2, and a similar slow fall of a higher, cooler layer within which he believed K_3 to be formed by absorption. In view of the complexity now known to prevail in the chromosphere, it is perhaps doubtful if St. John's simple explanation is correct. Nevertheless, the stellar displacements seem to be quite real and must eventually be accounted for.

The widths of H_2, K_2 are simply the differences between the readings on the outer edges of the lines, expressed in any convenient units. Because velocities in kilometers per second are very familiar to all stellar spectroscopists, this was the unit chosen in the original work, although this may not have been the best possible choice. After a simple slit-width correction, the same for all stars observed with given equipment, has been subtracted from all measured line widths, it is found that the logarithms of the H_2, K_2 widths are linearly correlated with the absolute visual magnitudes of the stars over a luminosity range of some 12 to 15 magnitudes (*18*) (see Fig. 3). Moreover, this correlation appears not to be affected by the intensities of the emission lines or by the spectral types—that is, by the surface temperatures of the stars. It reflects, therefore, a phenomenon of the stellar chromospheres that is quite insensitive to the immediately local gravity and temperature and that provides a measure of the total energy generation deep within the stellar interiors. This result, entirely unanticipated by theory, immediately and obviously broadens the base of chromospheric investigation provided by the solar chromosphere, since the widths of the H_2, K_2 lines of the integrated solar spectrum accurately fit the correlation given by the stellar observations.

Table 1. H-K emission intensity in field stars (see text).

Spectral type	Intensity grouping		
	0–1	2–3	4–5
G0–G4	27	0	3
G5–G9	27	7	0
K0–K2	26	8	6
	80	15	9

In fact, the procedure has been inverted and the H_2, K_2 lines of the sun, together with those of the four K-type giants in the Hyades, have been used to calibrate the method as a means of deriving absolute visual magnitudes of stars (*19*). The Hyades are a moving cluster which has been studied for many years, and the point on the celestial sphere upon which all the cluster members appear to be converging is known, as are also the proper motions and radial velocities of the stars. These data suffice for the accurate calculation of the distances, and hence of the intrinsic luminosites, of the Hyades giants, which are therefore eminently suitable for calibration purposes. Tests of the method—using stars with the most reliable trigonometric parallaxes—indicate that it is capable of a precision of 0.2 magnitude, which is sufficient to render it highly useful. If L_V represents the intrinsic visual luminosity of a star, and W_0 the corrected width of H_2, K_2, the calibration shows that, to a close approximation, $L_V \propto W_0{}^6$. Applications of this procedure and its physical basis are briefly discussed in a later section.

Intensities of H_2, K_2 Lines

We turn now to the question of the strength of the H and K emission components in main-sequence stars. As previously noted, the significance of this datum for giants is as yet unknown. Relevant observations have all been made by the semiquantitative procedure of careful eye estimates of line intensity—a method quite capable of uncovering the major relationships involved but which, for some purposes at least, must eventually be supplanted by photometric measurements. Also, the strength of H_2, K_2 lines is estimated essentially in terms of the nearby continuous background of the stellar spectrum.

Anyone having occasion to examine spectrograms of numerous main-sequence stars of spectral type F5 and later types cannot fail to notice the very great range of intensity of the H-K emissions among objects whose spectra are otherwise quite indistinguishable. This strange situation must have annoyed stellar spectroscopists for a long time, yet it is only in the last few years that clues leading to an explanation have been forthcoming. In large part this is because it is also only within recent years that the development of the theory of stellar evolution and the assiduous collection of the necessary photometric observations have led to the determination of the ages of a number of star clusters. The spectroscopic observations have been guided by the simple assumption that knowledge might be gained by comparing the chromospheric properties of genetically related groups of stars with those of genetically unrelated groups. In this context a "genetically related group" refers to the members of a star cluster, or to the members of a smaller, gravitationally bound association such as a binary or triple star, and the "unrelated" stars are those found in the general field. The latter must be a mixed lot whose ages and other properties cover a wide range. A basic premise is, of course, that the members of any genetic group are of virtually the same age and started with the same chemical composition.

A study of 104 field stars with spectral types from G0 to K2, inclusive, results in the statistical distribution of H_2, K_2 intensities given in Table 1 (*20*). The three intensity groupings (0–1, 2–3, 4–5) may properly be thought of as weak, medium, and strong, respectively. About 10 percent of these stars have strong emissions, and the majority have weak emission components at H and K.

When these observations are extended to small groups, visual binaries and triples, the results are quite informative. In the first place, the overall distribution of H_2, K_2 intensities is similar to that found for single field stars; but, more important, within each small group these intensities are about the same when the spectral types of the members do not differ greatly, where-as, when the spectral types differ significantly, the intensities are generally greater in the member of later type—that is of lower surface temperature. In other words, there is a very strong tendency toward equality of emission in H and K within these small genetic groups. Since it is reasonable to assume that the members of a group are coeval, it must be concluded that the amount of chromospheric activity currently present in these stars is dependent either upon their ages or, in some fashion, upon the circumstances of their formation. In any event, it is difficult to avoid the conclusion that the chromospheric activity of a main-sequence star is a function of its past history (*20*).

Extension of the investigation to main-sequence stars in several clusters greatly strengthens the foregoing conclusion. In these large groups, photometric measures by a number of individuals, combined with the results of theoretical computation of the properties of stellar models, permit an approximate determination of the ages of the groups. This is accomplished, in effect, through comparison of the distribution found by plotting the colors against the magnitudes of the stars (the color-magnitude diagram) with the results of computation.

Spectroscopic examination of numerous main-sequence stars in the Hyades, Praesepe, Pleiades, and Coma clusters has shown that, in contrast to the local field stars, strong H_2, K_2 emissions for the spectral type range under consideration are the rule rather than the exception. Furthermore, the intensities are greater in the Pleiades stars than in the corresponding members of the other clusters. A brief summary illustrative of these results is given in Table 2, where Coma has been omitted because only six stars were observed in this cluster (*20*).

Table 2. Distribution of H_2, K_2 intensities (percent) in various star groups.

Object	No. of stars	Intensity: Weak	Medium	Strong
G0–G4				
Field stars	30	90	0	10
Hyades	8	38	62	0
Praesepe	9	33	67	0
Pleiades	24	8	71	21
G5–G9				
Field stars	34	80	20	0
Hyades	20	10	85	5
Praesepe	17	0	94	6
Pleiades	19	0	42	58
K0–K2				
Field stars	40	65	20	15
Hyades	18	0	17	83
Praesepe	4	0	25	75
Pleiades	8	0	0	100

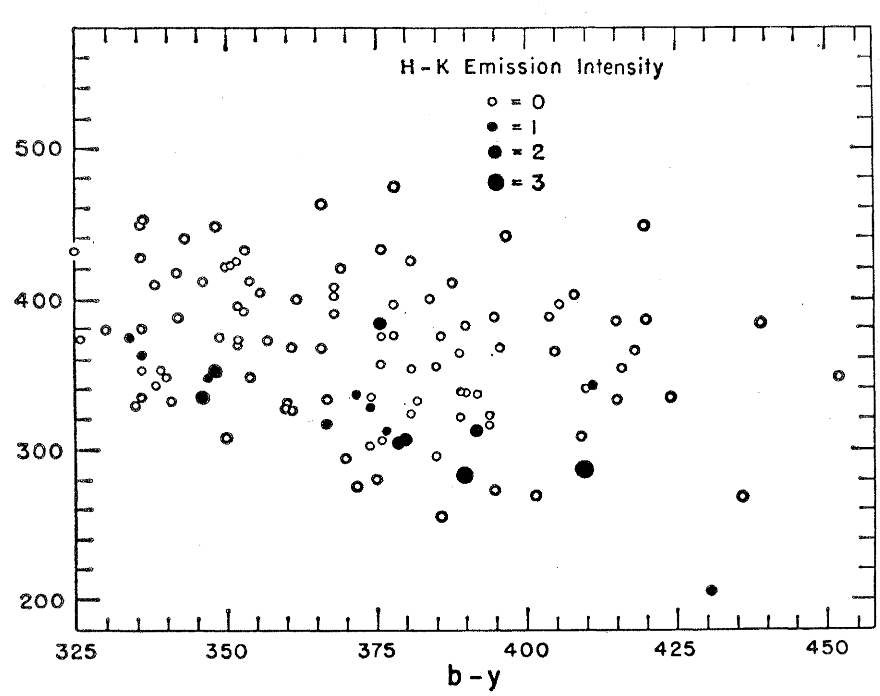


Fig. 5. A $c_1 - (b - y)$ diagram (see text). The stars with H-K emission (solid circles) are concentrated close to the lower edge of the distribution and are therefore among the youngest stars represented. Stellar temperature decreases toward the right; luminosity increases upward. Spectral type F8 corresponds to $b - y = 0.35$.

In the integrated spectrum of the sun (spectral type G2), which we regard here as a field star, H_2, K_2 emissions are far below the limit of visibility with the equipment used to observe the stellar spectra (dispersion, 38 Å/mm for the cluster stars). In round numbers, the age of the sun is about 5×10^9 years, and the approximate ages of the clusters are: Hyades-Praesepe, 5×10^8 years; Pleiades, 5×10^7 years (*21*). It thus appears very likely that age is the major factor in determining the strength of H_2, K_2 in main-sequence stars. Nevertheless, since this conclusion is based on a comparison of the members of large clusters with a field star, and since stars formed in such clusters might have special characteristics of some kind, one would feel more secure if the age dependence of H_2, K_2 intensity could be demonstrated for a group composed only of field stars.

Fortunately this can be accomplished, thanks to recent work by Strömgren and Perry, who have observed numerous main-sequence field stars with specialized photometric techniques (*22*). Two of their observed parameters, c_1 and $(b - y)$, are such that, when the stars are plotted on a $c_1 - (b - y)$ diagram, the main sequence appears as a band of points whose lower edge is composed of the youngest, essentially unevolved, stars, and the remainder of the plotted points represent older stars that have evolved away from the zero-age edge. Some 114 of the stars in Strömgren and Perry's catalog have been observed spectroscopically, and 17 of them are found to have H and K emission components (*23*). In Fig. 5 it is seen that nearly all the stars with H, K emission lie on, or near, the lower edge of the distribution, which means that they are among the youngest of the field stars represented in the plot. This evidence, together with that from the clusters and the sun, points very strongly to an age dependence of chromospheric activity for main-sequence stars. It is therefore highly probable that all main-sequence stars with strong hydrogen convection zones possess active chromospheres upon arrival on the main sequence, and that thereafter such activity gradually declines as the stars age. In particular, since the sun is a typical star of this kind, it may reasonably be assumed that some 3 to 5 billion years ago the solar chromosphere and corona were much more potent than they are at present. It would follow that in these earlier epochs in the history of the solar system the planets must have been subjected to a much larger flux of energetic particles and of ultraviolet and x-radiation than they are today, and it is an interesting question whether these may have played an important role in the prebiological or even early biological developments on and near the earth's surface.

It would be most premature to claim that the cause of a decay of chromospheric activity with time in main-sequence stars is understood. The best that can be done at the moment is to reason by analogy. Nevertheless, we know that on the sun there is a point-to-point correlation between chromospheric activity and magnetic-field strength. If an ideal experiment were possible in which all the surface magnetic-field intensities on the sun could be suddenly increased by some factor, the result would probably be a corresponding increase in the radiation from the chromosphere. Hence one can only suggest that chromospheres decay in activity because the stellar magnetic fields decrease with time. This would be physically reasonable if magnetic energy is gradually transformed to other kinds which are radiated away and if there are no means by which it is replaced.

Applications of Stellar Chromospheres

Once calibrated, correlations between observable properties of stellar chromospheres and other stellar parameters can be used as tools for the investigation of other problems, even though the physics underlying the correlations may be quite unknown. A good example of such an empirically based relationship in astronomy is the period-luminosity law for cepheid variables, which served as a very valuable distance indicator for a long time before its physical significance was uncovered.

Of such correlations, the one between the absolute visual luminosity and the H_2, K_2 width is the more firmly established in that it is calibrated and its accuracy is known fairly well from comparison with luminosities derived from trigonometric parallaxes. There is even some evidence from the star Groombridge 1830 that the method is not sensitive to the metal-to-hydrogen ratio. This star is a nearby subdwarf in which the metal-to-hydrogen ratio is about 30 times less than in the sun (*24*). The star has a large trigonometric parallax, in excess of 0.1 second of arc, and the widths of the H_2, K_2 lines in its spectrum yield a luminosity equal, within the limits of measurement, to that given by the parallax. Thus it would seem that chromospheric properties can be used with confidence in deriving stellar luminosities. Naturally, the method is restricted to stars that have chromospheres, and, among these, to objects bright enough for spectroscopic observation with sufficient dispersion. These are fairly severe limitations, but a good deal can be accomplished with the procedure nonetheless.

The members of a star cluster are all at approximately the same distance from the sun. Hence the color-magnitude diagram for a cluster is relatively easy to obtain, except for corrections due to interstellar reddening and obscuration, which are sometimes troublesome. It is much more difficult in principle to acquire the same information for field stars in the solar vicinity because these objects lie at different distances, all of which must be known

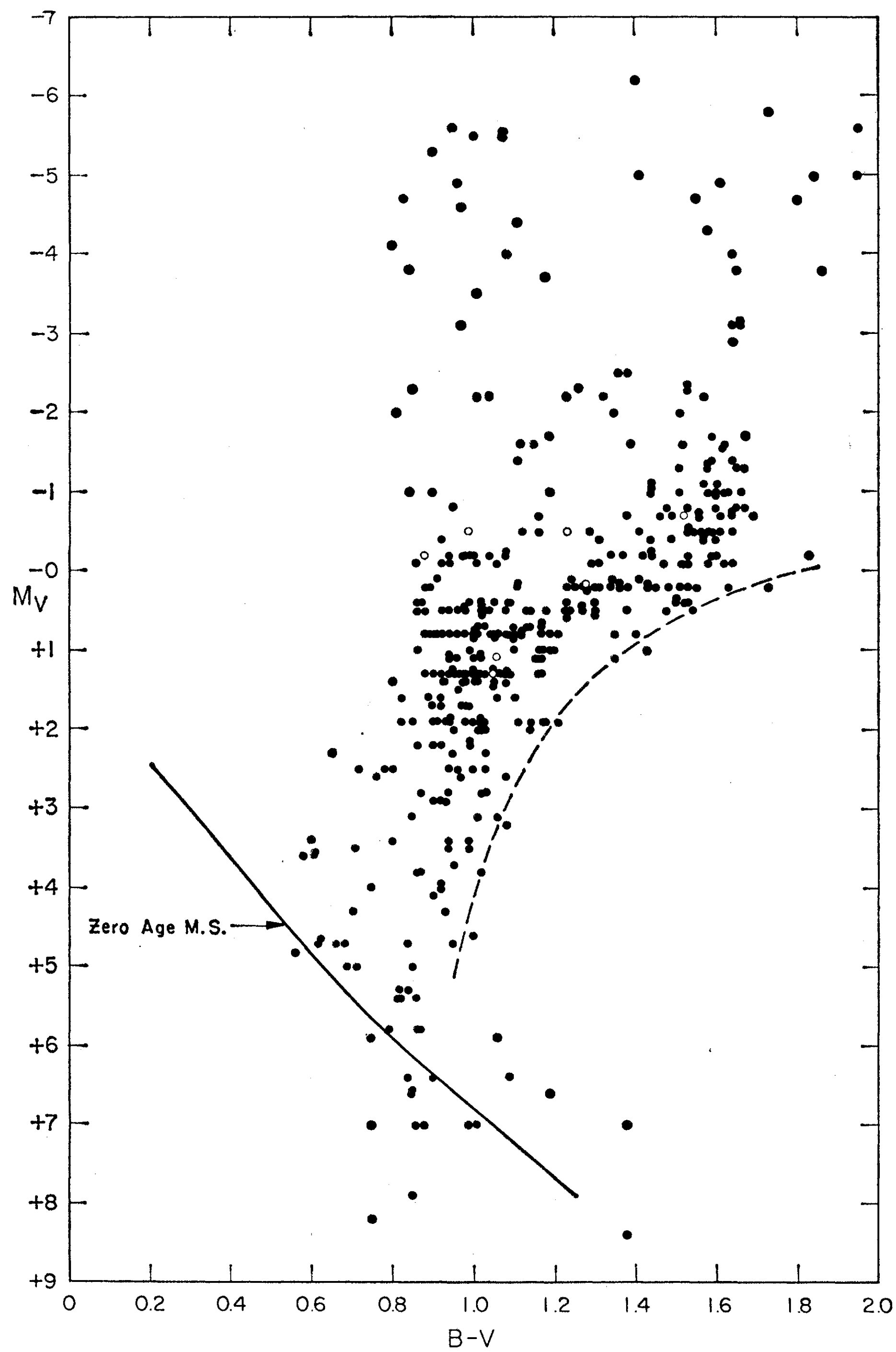


Fig. 6. A color-magnitude diagram for several hundred field stars. The colors, $B - V$, are photoelectric measures from several sources; the absolute visual magnitudes have been derived from the correlation between H_2, K_2 widths and luminosity. Temperature decreases toward the right; luminosity increases upward.

if the colors and absolute magnitudes are to be assembled in the proper relationships, and the accuracy of trigonometric parallaxes is inadequate for this purpose. A color-magnitude diagram for several hundred field stars whose absolute visual magnitudes have been determined from the widths of H_2, K_2 is shown in Fig. 6. The lower boundary of the region occupied by the giants and subgiants is quite sharply defined. It has been drawn 0.2 magnitude above the lowest observed points in order to allow approximately for observational scatter. Figure 7 is a composite color-magnitude diagram for several star clusters, compiled by Sandage (*25*), in which the lower boundary from Fig. 6 has been included. From this plot it is apparent that the age defined by the lower boundary in the color-magnitude diagram for field stars is approximately 1.5×10^{10} years, which, if the sample used is representative of the galaxy as a whole, is also the age of the galaxy. A closer estimate is not feasible as yet, both because there may be some unrecognized error in the luminosity determinations and because the calculations of stellar models have probably not yet reached their final form.

Another area in which chromospherically determined luminosites have been very useful is in the measurement of the masses of evolved stars. There is considerable information on the masses of main-sequence stars, but practically none on those of stars that have evolved away from the main sequence and are now in the giant region of the color-magnitude diagram (*26*). This is because all individual stellar masses must be found from the gravitational interaction of stars in binary systems, and among such pairs in the giant region either the periods are so long that the orbital parameters cannot yet be determined accurately or the trigonometric parallaxes are too small and unreliable. The formula that gives the mass (M) of a binary system is

$$M = a^3/P^2 \pi^3,$$

in which a is the semimajor axis in seconds of arc, P is the period in years, and π is the parallax, also in seconds of arc. Since π enters to the third power, it is evident that only systems with accurately known parallaxes can be used. The literature provides data on several visual binaries, with fairly well-known orbital parameters, which are within the spectral-type and brightness ranges to which the H-K procedure is applicable. These stars have been observed frequently enough to reduce the measuring errors in the determinations of absolute magnitude to less than 0.2 magnitude, and their masses have been found from the above equation (*27*). The results are shown graphically in Fig. 8, a color-magnitude diagram in which the present locations of the stars have been connected by dotted lines with the points on the zero-age main sequence where the same masses are found. Hence, if there has been no appreciable mass loss during evolution, the dotted lines of Fig. 8 represent mean evolutionary trajectories. They seem to be in quite good accord with the predictions of the theory of stellar evolution.

The correlation between age and H_2, K_2 intensity for main-sequence stars is not yet known accurately enough to provide an age in years simply from measurements of the emission intensity, but the correlation can be used to establish relative ages, including equality, or lack of it, between groups of stars.

One such obvious application is that of confirming the membership of stars in clusters or in moving groups. In the Hyades, for instance, it is found that every main-sequence star later than spectral type about F5 has bright H and K lines, and that these increase gradually in strength as the spectral type becomes later. Hence, among the fainter candidates for membership, where the usual criteria of proper motion and radial velocity become less reliable or may be lacking altogether, the presence of H_2, K_2 of the correct strength provides an additional membership criterion of considerable weight. This procedure is of value in any cluster young enough for its main-sequence stars to have moderately strong H_2, K_2.

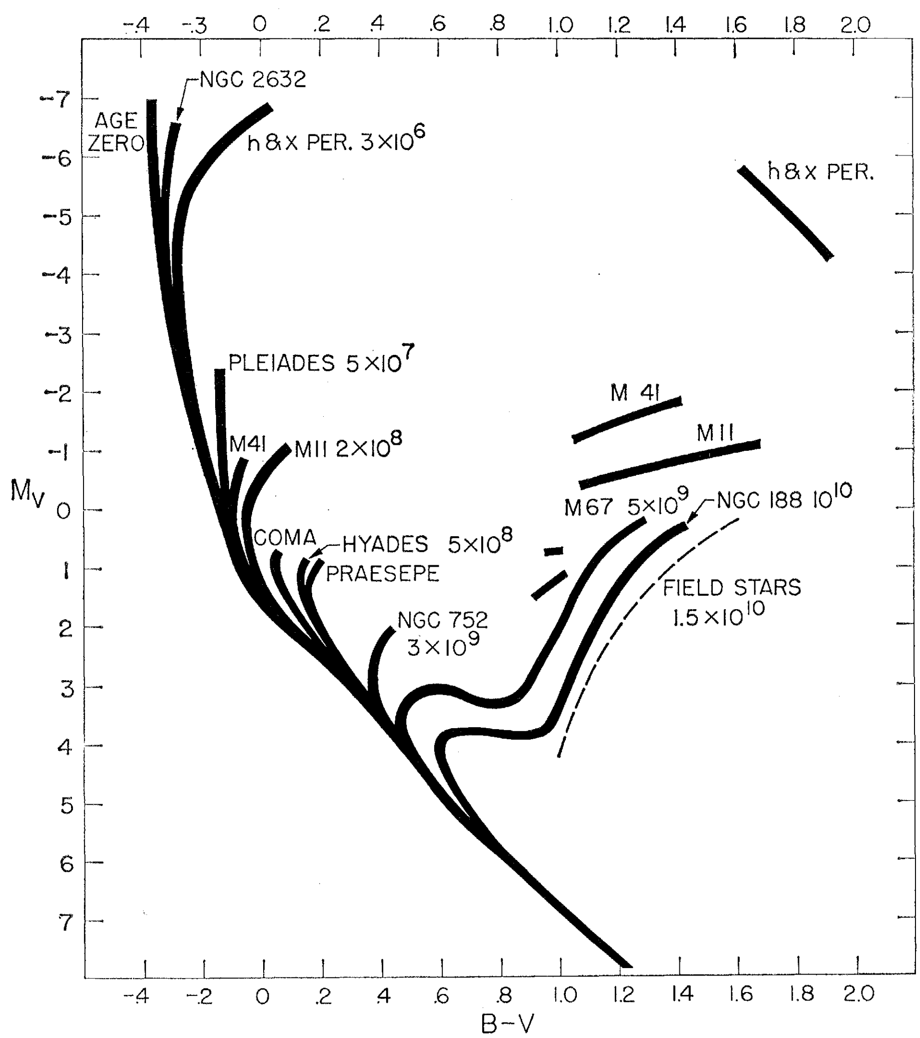


Fig. 7. A composite color-magnitude diagram for several star clusters, compiled by A. R. Sandage, who also supplied the age estimates. The lower boundary of the giant-subgiant region from Fig. 6 is included to illustrate how measures of stellar chromospheric line widths can contribute to the solution of the problem of the age of the galaxy.

In very old clusters the method would be much less useful, since one would then have to look for the absence or weakness of emission, and, as this is a characteristic of the field stars (Table 1), the chance of confusion with background objects would be much enhanced.

It has been suggested (*28*) that the Hyades form a much more extended system than the cluster itself and that there are stars scattered over much of the sky that are members of a so-called Hyades group and have a common space motion with the cluster. If such a group existed, its members would be expected to be coeval with the cluster stars and, for main-sequence objects, to have closely similar H_2, K_2 intensities for corresponding spectral types. Spectroscopic examination of a number of these stars has shown that this expectation is not fulfilled. Thus, from 29 "group" members lying within the same spectral range as the field stars of Table 1, the distribution of H_2, K_2 strength is that shown in Table 3. This distribution resembles much more closely that for the field stars in Table 2 than that for the Hyades. Moreover, from direct comparison of the "group" members with stars of similar spectral types in the cluster, only eight out of the 29 have approximately the correct H_2, K_2 intensities to qualify as members. Although these results are preliminary and should be extended, they illustrate one application of the H_2, K_2 intensities and indicate that the existence of the Hyades group is rather doubtful.

Table 3. H_2, K_2 intensities (percent) in the Hyades group.

No. of stars	Intensity		
	Weak	Medium	Strong
29	59	28	14

A question of considerable interest relating to the origins of stars is whether all stars are formed in clusters, and stellar chromospheres should be able to provide, if not an answer, at least some useful information. Thus it has been found that observable chromospheres among the main-sequence field stars extend to a value of $b - y = 0.30$ (*29*), and this is also where chromospheres are encountered in the Hyades. Therefore, one may conclude that field stars exist that are no older than the Hyades, whose age is approximately 5×10^8 years. Such objects must, therefore, have been born in much smaller groups which have been gravitationally unstable over periods of a few hundred million years. Whether still younger field stars can be found is as yet unknown. They will be rare, and a large sample will have to be examined to uncover them if they exist. If objects as young as the Pleiades (5×10^7 years) are found among the field stars, then the possibility of the formation in the interstellar medium of

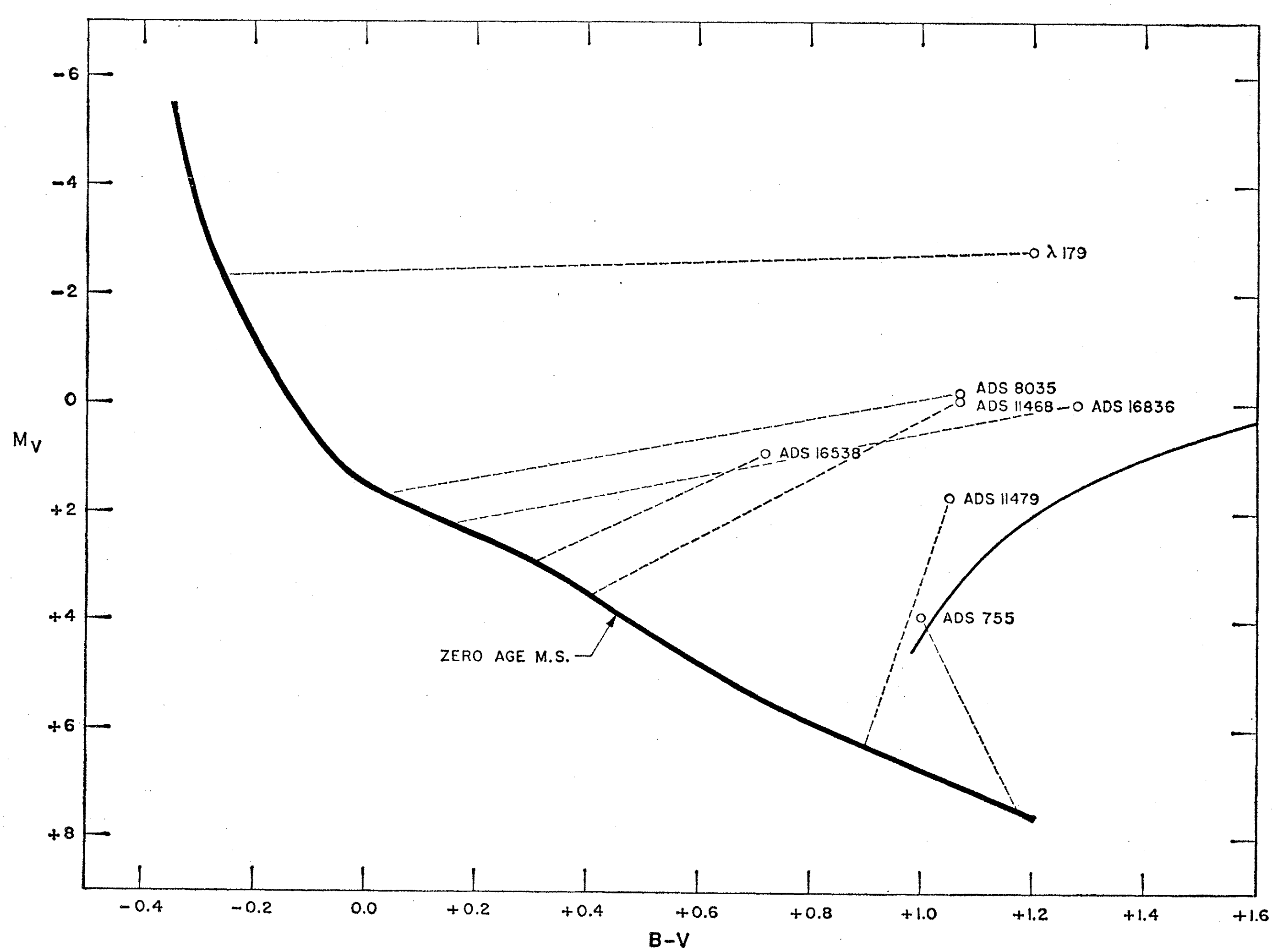


Fig. 8. The masses of the stars in this color-magnitude diagram have been determined with the aid of the correlation between luminosity and H_2, K_2 width. The dotted lines connect the present locations of the stars with the points on the zero-age main sequence where the same masses occur. If there has been no significant mass loss, the dotted lines represent mean evolutionary trajectories in the $M_v - (B - V)$ plane.

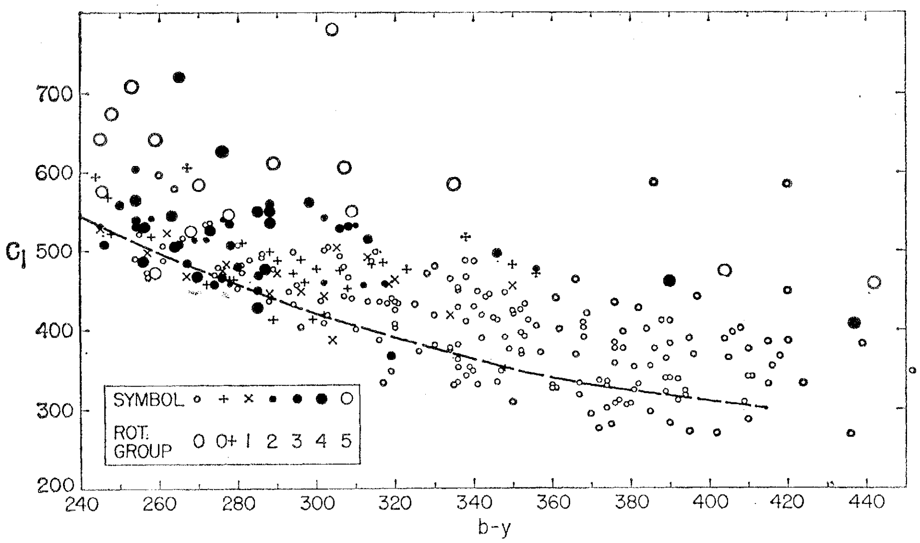


Fig. 9. Distribution of axial rotational velocities of field stars from observations with dispersion of 10 Å/mm. Rotational groups 0 and 5 correspond to $V \sin i \leq 10$ km/sec and > 55 km/sec, respectively. The dashed curve is the zero-age main sequence. Note sudden onset of larger rotations on the zero-age main sequence at $b - y = 0.285$. Although not shown in this plot, chromospheric H-K emissions on the zero-age main sequence have been observed as far toward the left as $b - y = 0.30$.

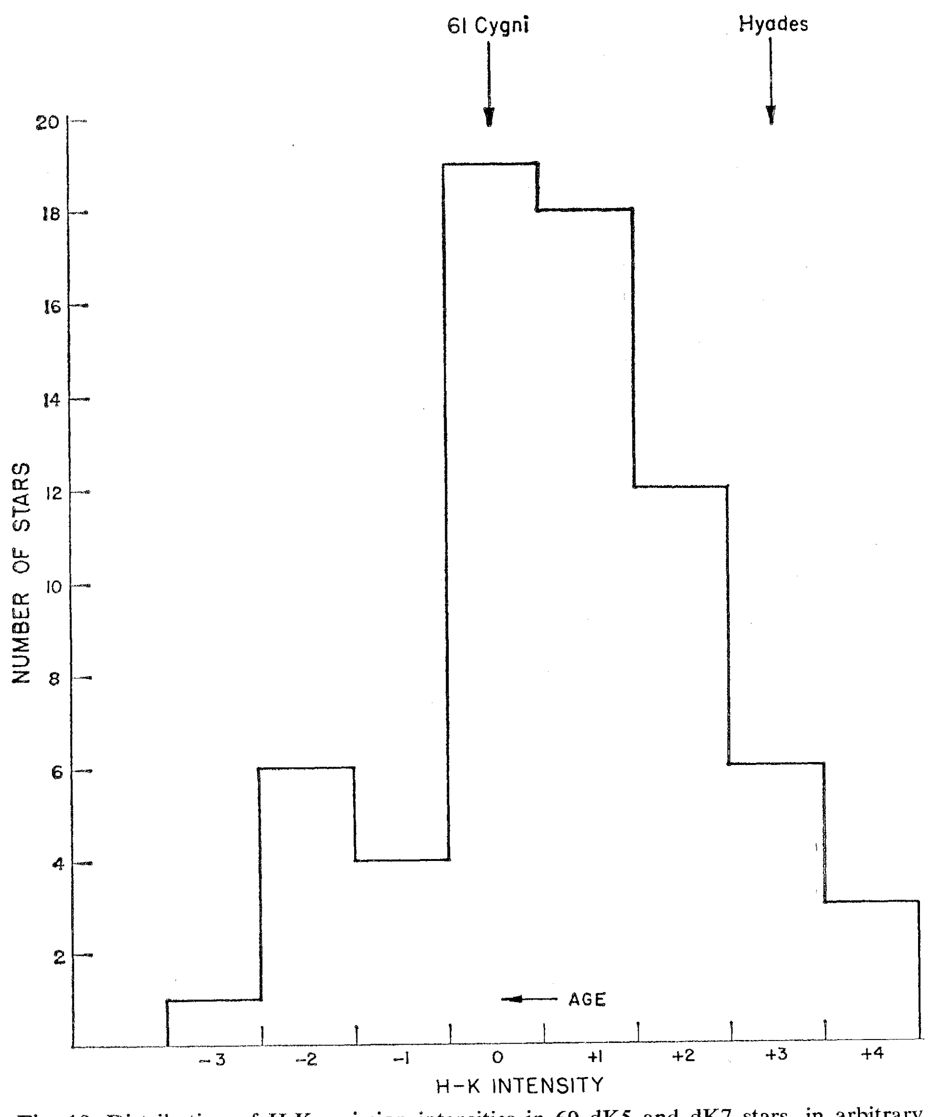


Fig. 10. Distribution of H-K emission intensities in 69 dK5 and dK7 stars, in arbitrary intensity units. Presumably this plot is also a representation of the relative rates of star formation as a function of time. Line intensities increase from left to right, and age, therefore, increases in the opposite sense, although it is not yet possible to supply a scale for this quantity.

single, isolated stars must be seriously considered. At any rate, this application of the H_2, K_2 age correlation appears worthy of further investigation.

Figure 9 contains information about another topic of much interest in astrophysics—namely, stellar rotation. On the right-hand side of the diagram are several stars which have relatively large rotational velocities and which lie slightly above the main body of main-sequence stars, none of which show evidence of rotation at the dispersion used. The question as to where on the zero-age main sequence these rapidly rotating stars originated has been answered by extending the observations on the left-hand side of the plot to $b - y = 0.24$ (*29*). It is evident that rapid rotation among the youngest stars sets in very abruptly at $b - y = 0.285$—that is, for spectral type F4. Since chromospheres are observed at spectral type F5 ($b - y = 0.30$), and since the presence of a chromosphere almost certainly requires a strong hydrogen convection zone, the gap between the onset of rotation and the appearance of the earliest-type stars known to have convection zones is quite small. I believe these observations imply that the presence of a strong hydrogen convection zone is in some way responsible for removing angular momentum from stars. This idea has been expressed before and, in fact, Schatzman (*30*) has presented a mechanism to account for the required braking action. The point here is that the observations appear to support the basic theoretical ideas.

Probably one of the most important aspects of the H_2, K_2 age correlation is that it provides a means of measuring the rate of star formation throughout a long period in the history of the galaxy. For this purpose it is necessary to work with stars which cannot have evolved very far from their initial positions on the main sequence, and in which the fading H_2, K_2 lines remain observable, even if the star is very old. Both conditions are met by main-sequence stars of spectral types later than about K4. Furthermore, the sample of stars must not have been selected on the basis of kinematic properties, since these properties depend, statistically, on age. Fortunately a fairly large sample of such stars, selected solely from their spectra, is available, thanks to Vyssotsky and his colleagues (*31*). In principle, it is necessary only to find the frequency distribution of H_2, K_2 strengths, after making appropriate adjustments so that stars of various spectral types can be represented on a single diagram. An extensive investigation of this kind is now in progress. A preliminary study of 69 field stars of spectral types K5 and K7 gives the distribution shown in Fig. 10. These results were obtained by making eye estimates of the intensities of H_2, K_2 against those of the standard stars of these types, 61 Cygni A and B, respectively. Several Hyades stars were included, and they appear among the younger stars, as they should. Further, it appears that star formation began gradually, built up to a maximum about the time of formation of 61 Cygni, and has since declined. The provision of an actual time scale on such diagrams is likely to be difficult, though perhaps not impossible. Figure 11 shows the H-K emissions in a sequence of dK5 stars.

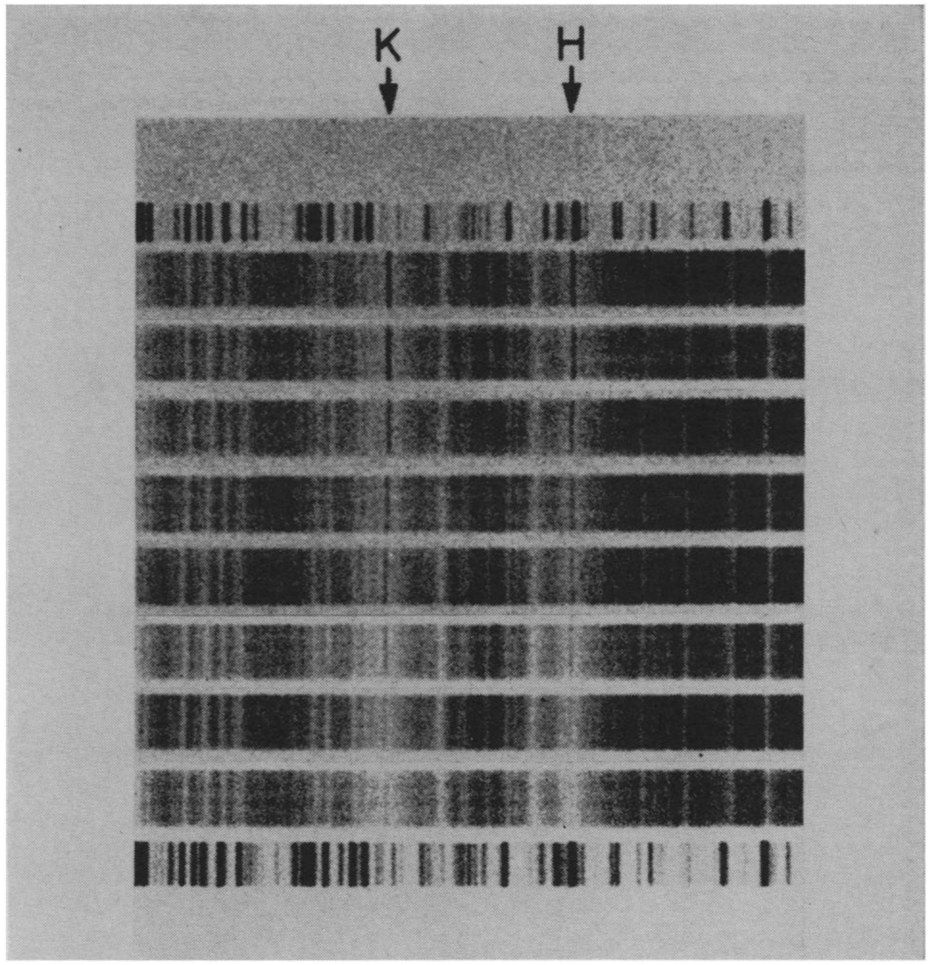


Fig. 11. A sequence of dK5 stars from the sample used to derive the results of Fig. 10. The standard dK5 star, 61 Cygni A, is fifth from the top, and is therefore of intermediate age among the stars shown. The H and K lines are separated by 35 angstroms, and a comparison with the scale of Fig. 2 illustrates the enormous difference in dispersion between spectrograms used in the study of the solar chromosphere and those which must be employed in some of the stellar work.

Conclusion

We have seen that properties of stellar chromospheres, which are measurable at modest, or even rather small, dispersions, can contribute to the solution of such problems as the age of the galaxy, the masses of evolved stars, the rate of star formation, and others. It would be highly satisfying to be able to end this article with a brief and correct account of the physics which underlie these capabilities, but unfortunately this is not possible. Although the H and K reversals have been known in the solar spectrum for about a century and in stellar spectra for half as long, it is an exasperating fact that their formation is still not properly understood. There have been a number of theoretical papers on this subject in recent years, but they are all incomplete in one respect or another and are in various ways and degrees unconvincing. The best that can be done under the circumstances is to indicate the requirements of a comprehensive theory and to point out some of the highlights of the theoretical discussions.

The width-luminosity correlation really requires the solution of two problems: first, the identification of the physical factors responsible for the line widths and the establishment of a mechanism by which the line widths are produced; second, an explanation of how the mechanism operates to provide the observed variation with the visual luminosity.

Miyamoto (*32*) has suggested that the chromosphere is optically thick (*33*) in H and K and that the photons, produced largely by collisional processes, become trapped and escape through the line wings after thermal modification of their frequencies. In this way he is able to account approximately for the shapes and intensities of the H_2 and K_2 reversals in the sun. It is not clear how this scheme could explain the stellar observations.

In a general way, a good deal of the discussion of the H_2, K_2 features revolves about the question of optical thickness. If the gas is optically thin at the centers of H and K, the peak intensity of K should exceed that of H (in the limit $K/H = 2$), and the half-widths of the lines at half intensity should be the same and should be equal to $0.883\ \Delta\lambda D$, where $\Delta\lambda D$ is the Doppler width. If the gas is optically thick and the line widths are determined by radiation damping, then the central intensities of H and K should be the same, but their widths should be in the ratio $K/H = 2^{\frac{1}{2}}$. A third alternative, pointed out by Goldberg (*34*), is that in which, although the lines are optically thick, their widths are determined again by Doppler effect. In this instance, the peak intensities of H and K as well as their widths would be equal, but the velocities necessary to produce given line widths are much less than when the lines are optically thin.

The available evidence seems to favor the optically thin picture. In a study of the Ca II reversals over the solar surface, Smith (*35*) finds that the peak intensities of K exceed those of H by about 40 percent, on the average, and that the widths agree to within 10 percent. Suemoto (*36*) measured the intensity ratio K/H in a number of stars and found that the ratio lies within the range 1.2 to 2.0. Moreover, the stellar line widths do not show any systematic difference between H and K (*18*).

These results seem to indicate that the gas masses involved are optically thin in H and K, and that the line widths are determined by a velocity spread among the Ca II ions which ranges up to values close to 200 kilometers per second in the supergiants. If this is correct, the problem of the width-luminosity correlation becomes one of accounting for the variation of these velocities with absolute visual magnitude in accordance with the stellar observations.

Jefferies and Thomas (*37*) have attempted to analyze the H-K reversals by examining in detail the source function for these lines through the chromosphere. This commendable effort is both difficult and complicated and has not yet been carried to the point where real comparison with the stellar observations is possible. In general, these authors are able to reproduce the K_2-K_3 structure by proper choice of parameters, especially the temperature gradient. However, it is not clear to what extent the idea that the line widths are determined by the velocity field will require modification.

Papers attempting to explain the width-luminosity correlation, all of which implicitly assume that the lines are optically thin, have been published by de Jager (*38*), Schatzman (*39*), Kraft (*40*), and Hoyle and Wilson (*41*). The first two are rather brief and incomplete. The latter two papers are basically similar, the work of Hoyle and Wilson being somewhat more comprehensive. These latter authors derive a velocity, within the convection zone, which is found to vary with the visual luminosity. The fact that this leads to the observed correlation between the emission line widths and the visual, rather than the bolometric, luminosity is an important and encouraging point. However, the theory also predicts a strong dependence of line width on metal abundance, and this is apparently contradicted by the results on Groombridge 1830, although the matter requires further investigation.

Finally, it is not impossible that the spicules, observable only on the sun but presumably an essential component of all chromospheres, may play a fundamental role. On the basis of careful measures of the structure of emission lines from spicules made during a recent solar eclipse (*42*), Suemoto has suggested the following rather attractive picture, which is supported quantitatively by his results. He postulates two kinds of area on the solar disk, one associated with spicules, the other not. Where there are spicules, they emit an emission line whose width is determined by the velocity distribution among the individual spicules. Between the spicules is only the bare photosphere, which emits a continuous spectrum containing absorption lines, and at the centers of H and K are sharp central cores. The usual spectrogram of a portion of the solar disk, or the integrated spectrum of a star, is an algebraic sum of such spectra, which would indeed resemble the H_2, K_2 structure as observed. From this viewpoint the central depression, K_3, is merely the central core of the photospherically produced absorption line, and the width-luminosity correlation would have to be explained by a relationship between the visual luminosity and the spicule velocities. These ideas could be confirmed in various ways, and it will be interesting to see how well they are supported by further observation. Definitely against this picture is the fact that the solar Lyman lines of hydrogen also show central reversals. However, the optical thickness in the Lyman lines must be many orders of magnitude greater than in H and K, and scattering processes may well be of importance which are ineffective when the optical thickness is small.

As to the chromospheric activity-age correlation for main-sequence stars, there has as yet been very little theoretical development. Unsöld (*43*) has pointed out that the decay times indicated by the stellar observations are consistent as to order of magnitude with the results of approximate computations of the decay times of magnetic fields in convection zones of solar-type stars. To this extent, the suggestion that the correlation is the result of a secular decay of magnetic fields receives modest support.

In conclusion, it is evident that theoretical understanding of the physics which must underlie the observed chromospheric correlations is fragmentary and unsatisfactory, and that, for the time being, the uses to which these correlations are put must be based chiefly on empirical calibration. In addition, it might be remembered that the amount of stellar spectrum available for study from the earth's surface comprises about 7000 angstroms, of which the H-K reversals occupy something like 1 to 4 angstroms, depending on the stellar luminosity. It would seem not entirely inappropriate, therefore, to paraphrase a certain well-known historical statement: Seldom has so much been learned from so little.

References and Notes

1. One second of arc on the sun is approximately 770 kilometers.
2. R. G. Athay, *Science* **143**, 1129 (1964).
3. E. Vitense, *Z. Astrophys.* **32**, 135 (1953).
4. A. Unsöld, *ibid.* **1**, 138 (1930).
5. L. Biermann, *ibid.* **25**, 161 (1948).
6. M. Schwarzschild, *Astrophys. J.* **107**, 1 (1948).
7. D. E. Osterbrock, *ibid.* **134**, 347 (1961).
8. G. W. Simon, thesis, California Institute of Technology (1963).
9. R. P. Kraft, G. W. Preston, S. C. Wolff, *Astrophys. J.* **140**, 235 (1964).
10. K. Schwarzschild and G. Eberhard, *ibid.* **38**, 292 (1913).
11. A. H. Joy and R. E. Wilson, *ibid.* **109**, 231 (1949); W. P. Bidelman, *Astrophys. J. Suppl.* **1**, 175 (1954).
12. F. S. Johnson, J. D. Purcell, R. Tousey, N. Wilson, *Astrophys. J.* **117**, 238 (1953); R. Tousey, *Quart. J. Roy. Astron. Soc.* **5**, 123 (1964).
13. O. C. Wilson, *Astrophys. J.* **126**, 46 (1957).
14. ———, *Publ. Astron. Soc. Pacific* **50**, 245 (1938).
15. A. J. Deutsch, *Astrophys. J.* **123**, 210 (1956).
16. R. F. Griffin, *Observatory* **83**, 255 (1963).
17. C. E. St. John, *Astrophys. J.* **32**, 36 (1910).
18. O. C. Wilson and M. K. V. Bappu, *ibid.* **125**, 661 (1957).
19. O. C. Wilson, *ibid.* **130**, 499 (1959).
20. ———, *ibid.* **138**, 832 (1963).
21. A. R. Sandage, *ibid.* **125**, 435 (1957); L. G. Henyey, R. Le Levier, R. D. Levee, *ibid.* **129**, 2 (1959).
22. B. Strömgren and C. Perry, "Photoelectric *uvby* photometry for 1217 stars brighter than $V = 6^m.5$" (Institute for Advanced Study, Princeton, N.J., 1962).
23. O. C. Wilson and A. Skumanich, *Astrophys. J.* **140**, 1401 (1964).
24. J. Jugaku, *Carnegie Inst. Wash. Yearbook* **59**, 6 (1960).
25. A. R. Sandage, private communication. The age estimates have been revised in some instances from earlier values.
26. D. L. Harris, III, K. Aa. Strand, C. E. Worley, *Basic Astronomical Data*, K. Aa. Strand, Ed. (Univ. of Chicago Press, Chicago, 1963).
27. O. C. Wilson, *Modern Astrophysics: A Memorial to Otto Struve*, M. Hack, Ed. (Gauthier-Villers, Paris, in press).
28. O. J. Eggen, *Monthly Notices Roy. Astron. Soc.* **118**, 65 (1958); *ibid.* **120**, 540 (1960).
29. O. C. Wilson, *Astrophys. J.*, in press.
30. E. Schatzman, *Ann. Astrophys.* **25**, 18 (1962).
31. A. N. Vyssotsky, *Astron. J.* **61**, 201 (1956). This is the last in a series of papers on this subject and contains references to the earlier ones.
32. S. Miyamoto, *Z. Astrophys.* **31**, 282 (1953).
33. "Optical thickness," as used here, is the opacity in the line center integrated through the gas mass in question. It is usually designated by τ. Roughly speaking, optically thin means $\tau \leq 1$; optically thick, $\tau >> 1$.
34. L. Goldberg, *Astrophys. J.* **126**, 318 (1957).
35. E. van P. Smith, *ibid.* **132**, 202 (1960).
36. Z. Suemoto, private communication.
37. J. T. Jefferies and R. N. Thomas, *Astrophys. J.* **131**, 695 (1960).
38. C. de Jager, "Étoile à raies d'emission," *Proc. Liège Colloquium, 8th* (1958), p. 172.
39. E. Schatzman, *ibid.*, p. 370.
40. R. P. Kraft, *Ann. Astrophys.* **22**, 164 (1959).
41. F. Hoyle and O. C. Wilson, *Astrophys. J.* **128**, 604 (1958).
42. Z. Suemoto, *Proc. Japan Acad.* **39**, 463 (1963); *Publ. Astron. Soc. Japan* **15**, 531 (1963).
43. A. Unsöld, *Observatory* **84**, 152 (1964).