OBSERVATIONAL EVIDENCE FOR ATMOSPHERIC PHYSICAL CHARACTERISTICS RELEVANT TO STELLAR EVOLUTION

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1. Introduction

As a star burns its nuclear fuel, its radius R and its luminosity L are modified. Its mass may as well be affected if the mass loss rate has a time scale comparable to the nuclear time scale ; this is likely to occur for stars of very high luminosity. Currently, the change in radius R and luminosity L of an evolving star is described in the so-called theoretical Herzsprung-Russel diagramme with in abscissa the logarithm of the effective temperature defined by :

$$\sigma T^4_{eff} = \frac{L}{4\pi R^2} \qquad (1)$$

(σ Stephan's constant, π usual meaning) and in ordinate Log L.

The path described by the star in this reference frame is known as the "evolutionary track" of the star. If we want to restrict our attention to the stellar atmosphere itself, it must be noted that a stellar atmosphere of given chemical composition is determined not by effective temperature and luminosity, but effective temperature and gravity. Unfortunately, both in the language and in practice, the concepts of luminosity and gravity are often mixed up. For example, the "luminosity classes" in MK classification are in fact gravity classes, and gravity criteria in many classification systems are most of the time calibrated in terms of absolute magnitudes. If mass loss does not occur during stellar evolution this confusion between luminosity and gravity is not too great of a problem, because there is a one-to-one relationship between luminosity and gravity along each evolutionary track :

$$g = \frac{G\,M}{R^2} = \frac{G\,M}{L}\quad 4\pi\sigma T^4_{eff} \qquad (2)$$

But, if mass loss does occur at the same stage of evolution, a low gravity (for example) may either be the result of a large radius or of a low mass, and the confusion does matter. This is not all an academic

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part II, 105-114.

https://doi.org/10.1017/S1539299600003208 Published online by Cambridge University Press

question, as we shall see later in the case of our neighbour Arcturus.

2. Evolution of the main sequence from photospheric data

2.1 Theory

By far the most significant evidence of stellar evolution displayed by the atmosphere of a star is the decrease in gravity caused by the increase of radius undergone as the star moves off the main sequence towards the giant branch. This effect is shown in Figs. 1 and 2.

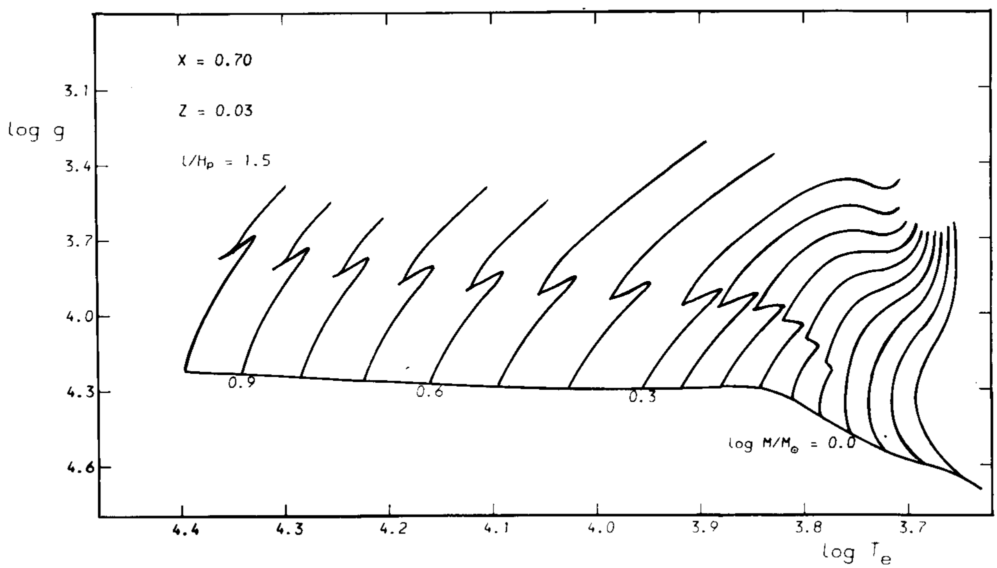

Fig.1 : Evolutionary tracks in the (log T_{eff}, log g) plane according to Hejlesen (courtesy I.A.U. Colloquium no.17).

Figure 1 shows the evolution of stars following the fate of individual objects of various masses (evolutionary tracks) ; whereas Fig.2 shows where stars of all masses fall in the diagram (log T_{eff}, log g) after prescribed times (Isochrones). Figure 3 shows the same type of diagramme computed taking into account overshooting from the convective core (Maeder, 1976). The locus of stars at zero age, referred to as the zero age main sequence (ZAMS), is of particular interest, as it defines the starting point of the evolution. The location of the ZAMS on the (log T_{eff}, log g) phase depends upon the initial chemical composition of the star, namely upon the fraction by mass Y of helium, and the fraction by mass Z of elements heavier than hydrogen and helium, lumped together. As usual we designate by X the fractional image of hydrogen. One has obviously :

$$X + Y + Z = 1 \quad (3).$$

Before anything can be derived from the knowledge of (log T_{eff}, log g) for a given object of its evolutionary status, Y and Z must be known.

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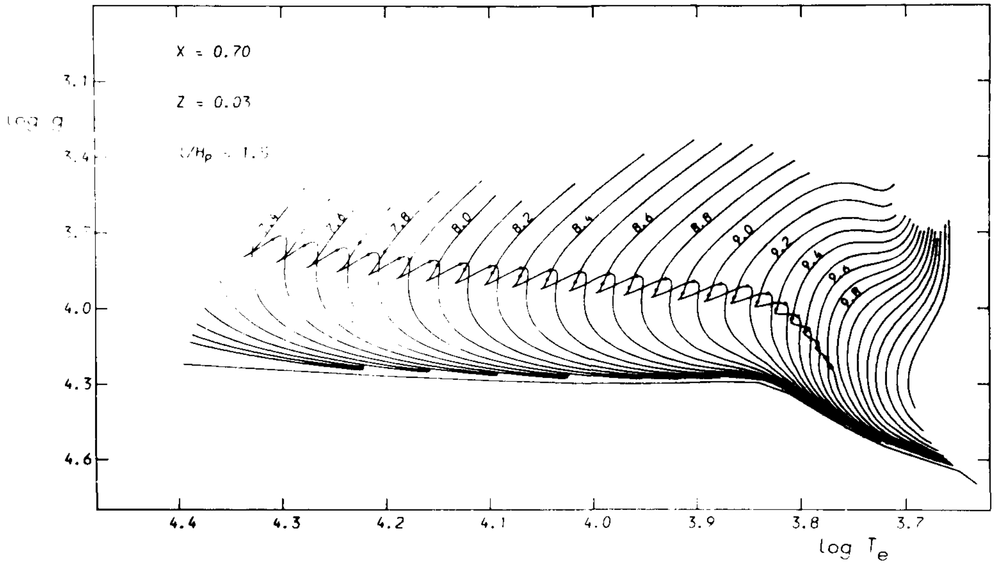

Fig. 2 : Isochrones in the (log T_{eff}, log g) plane according to Hejlesen (courtesy I.A.U. colloquium no.17).

Figure 4 shows the sensitivity of the ZAMS to the value of Z. It must be noted that the effect of a change in Z is not only an upwards or downwards translation of the ZAMS but also that a star of given mass moves in effective temperature when Z changes. It is interesting to note that a star of one solar mass (big dots on Fig. 4) has its ZAMS effective temperature moved from 5600° to 6900°K when Z varies from 0.03 to 0.04 respectively, its gravity remaining practically constant at log g = 4.5. If the star is such that the diffusion processes discussed in Michaud's and Vauclair's papers do not occur thanks to efficient stirring mechanisms, it is possible to infer from a detailed spectroscopic study of the atmosphere of the star and therefore to account properly for this Z effect from purely atmospheric observations. More troublesome is the effect of a change in Y as shown on Fig.5. The ZAMS seem little affected by a change in Y (or X = 1 - Y - Z, fraction of hydrogen by mass) as long as the mass of the star is ignored. However, a star of one solar mass, with Z = 0.02, has its ZAMS effective temperature moved from 5200°K to 6750°K when Y varies from 0.18 to 0.38, respectively. The difficulty here is that Y is generally unknown by lack of helium lines in the photospheric spectrum of stars later than the spectral type B0. If there is still the theoretical possibility of deriving a helium abundance from chromospheric lines one must admit that this is not yet a very practical nor reliable procedure. Therefore we stress the point that before any " spectroscopic" mass can be claimed (even on the ZAMS), a reliable determination of Z and Y must be available.

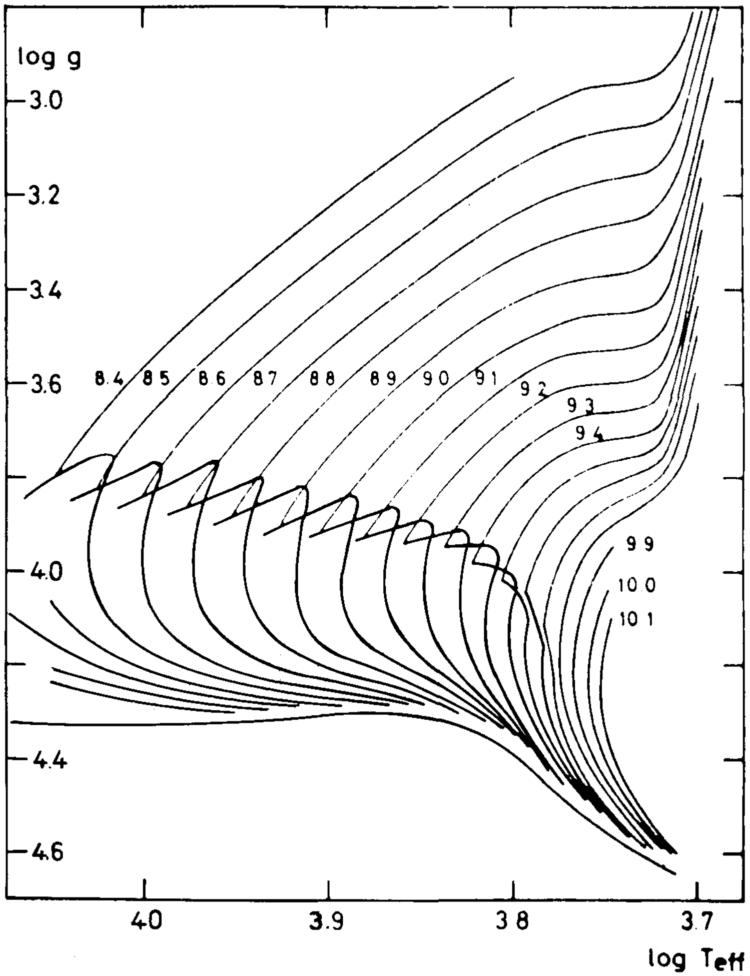

Fig. 3 : Isochrones in the (log T_{eff}, log g) plane according to Maeder, with convective overshooting in the core (courtesy Astron. & Astrophys.)

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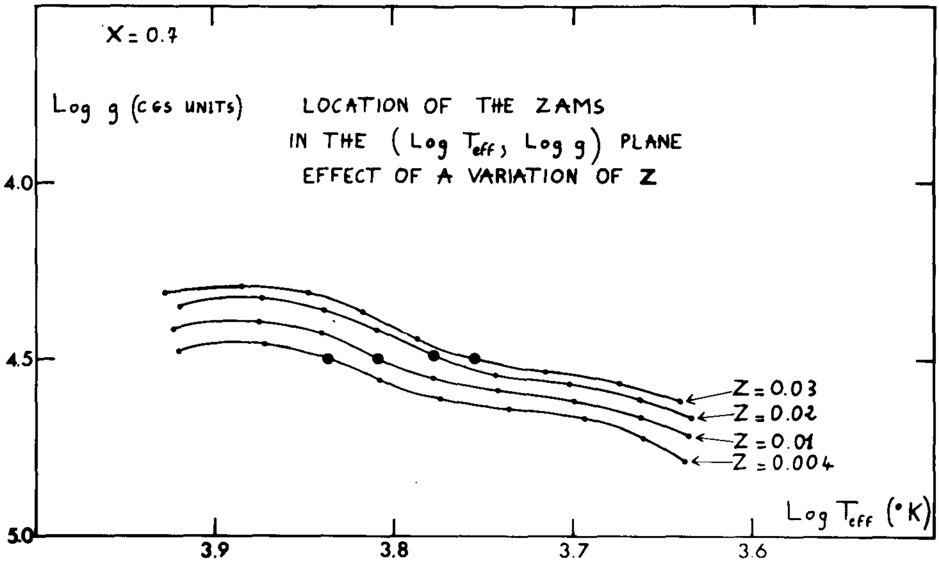

Fig. 4 : Variation of the ZAMS in the (log T_{eff}, log g) plane in function of the heavy elements content.

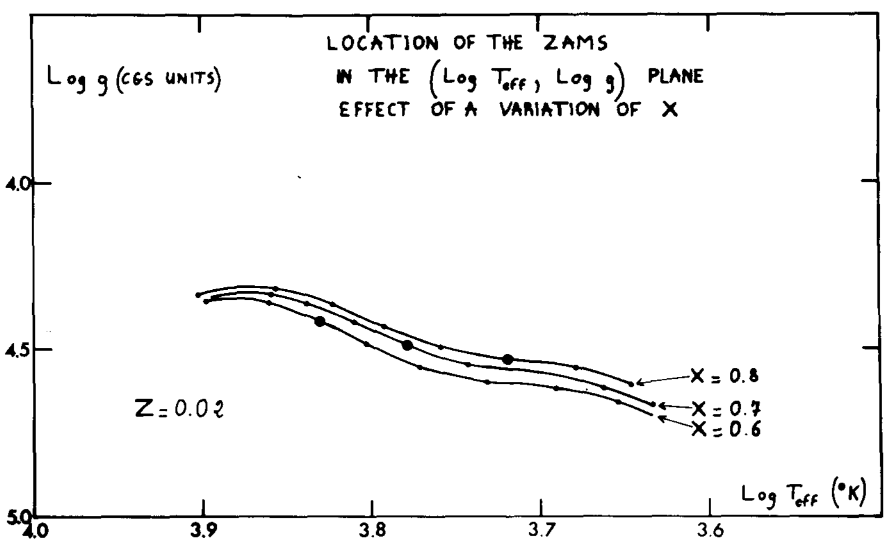

Fig. 5 : Variation of the ZAMS in the (log T_{eff}, log g) plane in function of the helium content.

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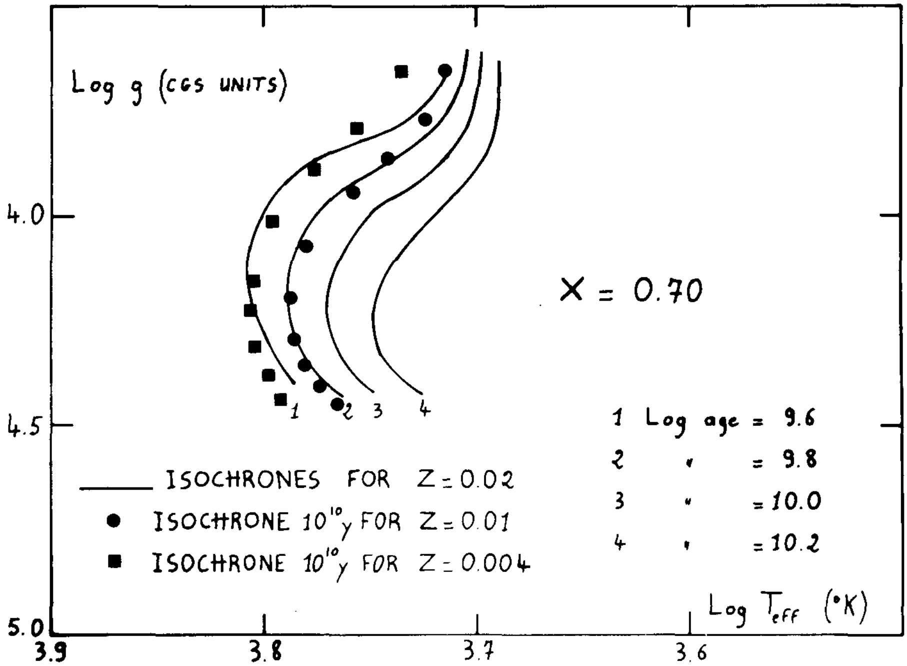

Fig. 6 :Dependence of isochrones upon the content Z in heavy elements. (Evolutionary tracks according to Hejlesen).

Equally interesting is the effect of Y and Z on the age of an evolved star. Figure 6 shows the isochrones for various ages corresponding to Z = 0.02. The open dots represent the isochrone 10^{10} years for Z = 0.01. One notes that this isochrone practically coincides with the isochrone (Z = 0.02, 6.3 x 10^9 years at log age = 9.8). This demonstrates the sensitivity of age determination upon actual value of Z. An error by a factor of 2 on Z produces for a sub-giant an error of 0.2 dex on its age. The more metal deficient is the object, the older it is for a given position in the(logT_{eff}, log g) plane.

A similar effect exists for the content in helium. Figure 7 illustrates this effect.

One notes that the more helium poor is the object, the younger it is for a given location in the (log T_{eff}, log g) plane. Figures 4 to 7 are all based on Hejlesen evolutionary tracks (Perrin et al.1977).

2.2 Observations

It is possible to locate a given star in the (log g , T_{eff}, log g) by using detailed analyses of stellar atmospheres. This has been done recently by M.N. Perrin (Thesis, Dec. 1975, Univ. Paris VII, and M.N. Perrin et al., 1977). Much more frequently the observations are done

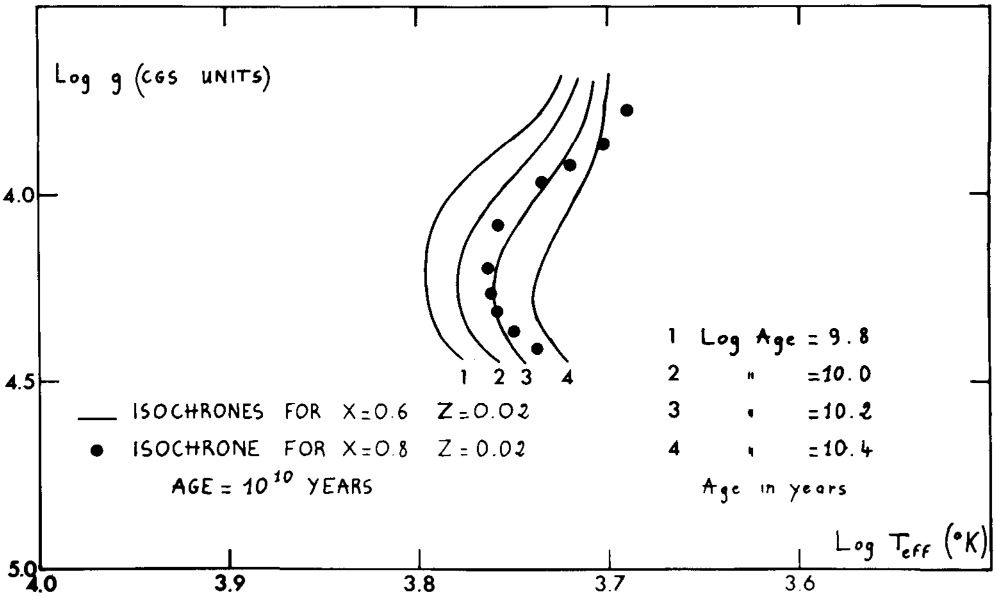

Fig. 7 : Dependence of isochrones upon the content Y in helium. (Evolutionary tracks according to Hejlesen).

on a classification system, (for example the Stromgren Crawford uvby β system, the Barbier-Chalonge-Divan (φ_b, D, λ_1) system, the DDO photometric system, the Cambridge system, the Gêneva 7-color photometric system, the Danish system ,etc...).

The internal accuracy of such systems may be very high but the main problem is their calibration. A recent and very good review of this question may be found in the proceedings of the conference "Multicolor photometry and the theoretical H R diagram " cited in the reference list.

Of particular interest in the cited reference are those papers on the calibrations of the uvby β system respectively by Crawford, by Breger and by Philip and Matlock ; the calibration of the DDO system by Janes and McLure, and a paper on empirical effective temperatures, bolometric corrections and fundamental stellar properties by Code. The calibration of the Cambridge system can be found on a series of papers by Williams (1975) and in a paper by Bell (1970). The danish system has been calibrated by Hansen and Kjaergaard (1971) and the consistency of their calibration has been investigated by Olsen (1971). On the average it is difficult to obtain $\log/T_{eff}$ with an accuracy greater than 0.01 to 0.02 dex and log g better determined than 0.1 dex and often worse. The internal accuracy of some photometric systems is of course much greater. For example the uvby β system has a discrimination power almost one order of a magnitude larger for spectral types

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near F0 IV-V .

It is nevertheless discouraging to see that in the case of Arcturus, for which top quality spectrophotometric data are available, a controversy on the actual log g value is still going on, with extreme values of 0.9 ± 0.35 (Mäckle et al., 1975) to 1.7 ± 0.2 (Ayres and Johnson (1976) and log g = 1.8 (Martin Mullor, 1977) letting an uncertainty of over an order of magnitude on the mass of Arcturus.

The pattern of isochrones in the (log T_{eff}, log g) plane makes that the errors on age and mass determination corresponding to a given error on log T_{eff} and log g vary very much according to the location in the plane. The funelling effect of evolutionary tracks along the Hayashi limit makes age and mass determinations extremely unaccurate for K giants. The most favourable region is the one of stars evolved by one or two magnitude above the ZAMS, i.e. stars with log g between 4.5 and 3.6 and an effective temperature not less than 5500OC.

2.3 Interplay between internal structure, stellar atmospheres and basic stellar data.

So far we have seen that taking for granted the validity of internal structure computation it is possible to determine from stellar atmosphere characteristics alone , the evolutionary stage (or age) and mass of a star, provided :

i) some assumption is made on the helium content of the object ,

ii) the Z value found in the atmosphere is representative of the whole star ,

iii) mass loss has been insignificant during evolution.

If the star is member of a multiple system the mass of the star may be available from astrometric observations and assumption (i) can be relaxed.

But it must be stressed that having M, g and T_{eff} does not allow us yet to check observationally the validity of internal structure computations.

If the distance of the star is known then the luminosity of the star is known. Unfortunately that does not give any further way of checking the internal structure as the radius or the luminosity can be derived from g , m, and T_{eff} already. If an apparent diameter of the star is known R can be derived directly without using the effective temperature determined via the stellar atmosphere. If one is tempted to completely by-pass the data derived from the stellar atmosphere one needs to determine L from the absolute magnitude, R from apparent diameter plus distance, and from the orbital motion (companion star or planet is needed). There are only 4 stars with such data left : the sun, Procyon, Sirius and Spica (cf Code in Philip and Matlock ref.)

In conclusion, it is not possible to check the validity of internal structure computations by observing unrelated individual stars, as the number of parameters which can be determined is always smaller than (or equal to) the total numbers of parameters from which the star depends on (M, Y, Z, age).

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It is possible to check internal structure computation only when one has a cluster of stars, because then the assumption that all stars in the cluster have the same age and the same chemical composition decreases the number of free parameters for all stars, except one of them.

3. Evolution from chromospheric lines

3.1 Evolution from chromospheric width.

In 1957, Wilson and Bappu made the amazing discovery that the width of the ca II K_2 chromospheric emission lines was merely in a one-to-one relationship with the absolute visual magnitude of the star. A discussion of this question is given in another paper of this joint discussion (by B.E.J. Pagel). I shall then just mention here the fact, as a way of telling from a chromospheric line if the star is near zero age or how much evolved it is, from its departure in luminosity from the ZAMS. A recent paper by O.C. Wilson (1976) updates this remarkable discovery. Preston has shown that a similar effect exists with the shape of the core of H .

3.2 Evolution from chromospheric intensity of Ca II K_2 line

On the main sequence and at a given effective temperature the intensity of Ca II K_2 emission line has a wide spread. Wilson (1963) has shown that this spread might be due to a time variation of the emission, the emission being stronger in young stars then in older stars. Wilson and Wooley (1970) have been able to confirm this hypothesis using kinematical data and Wilson and Skumanich (1966) using a correlation with the c index of Strömgren classification. Skumanich (1972) has also claimed a correlation with the Li resonance line strength and rotation and has suggested an inverse square root time variation of the emission.

4. Evolution from turbulence in the atmosphere

The subject is dealt with in the next paper by R. Foy and will not be approached here.

5. Conclusion

Atmospheric physical parameters supply ample evidence for stellar evolution, mainly through the decrease of the surface gravity as the star evolves off the main sequence.
When one attempts to use this criterion quantitatively one is faced with several problems. The main one is the fact that the helium content is not known by direct spectroscopic determination for most star locations on the HR diagram. A second one is the difficulty on obtaining a proper calibration of spectroscopic gravity criteria in terms of actual values of effective temperature under gravity. Finally there are very few stars for which all fundamental parameters mass, radius, luminosity and chemical composition (including helium) are known with satisfactory accuracy.

We shall conclude by saying that atmospheric physical parameters are an essential tool in connecting observations with internal structure computations as they supply three of the fundamental parameters, (Z, T_{eff}, g). The ultimate goal is of course to combine these three parameters with other independent data (mass or absolute magnitude) in order to interpret or to check the theory of stellar evolution.

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