THE AGES OF STARS IN THE NEIGHBOURHOOD OF THE SUN

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1. Introduction

This introductory paper is divided into two sections.

In the first section a short summary is given of the IAU Colloquium No. 17 on Stellar Ages held in Paris-Meudon Observatory in September 1972. The summary will concern particularly those subjects relevant to this Joint Discussion.

In the second part the ages of nearby stars located in the subgiant region of the ($\log T_{\text{eff}}$, M_{bol}) diagram are discussed.

2. IAU Colloquium No. 17: Stellar Ages

In planning the Colloquium we divided the stellar ages contributions into four arbitrary groups. Stellar ages as understood:

(a) from an evolutionary point of view,
(b) from kinematic criteria,
(c) from nucleosynthesis aspects,
(d) from spectrophotometric criteria.

We shall now report briefly on these four points.

2.1. Age from the HR diagram

The main method of determining stellar ages is still to comput a grid of isochrones in the ($\log T_{\text{eff}}$, M_{bol}) plane from a set of evolutionary tracks. Two isochrone grids have been presented by Hearnshaw (1972; see Figures 2 and 3, paper XLI, IAU Colloq. No. 17). They are the two sets of isochrones interpolated by Sandage and Eggen (1969) from the evolutionary tracks of both, Iben (1967) and Aizenman *et al.* (1969).

Other isochrone sets have been presented by Hejlesen *et al.* (1972; Figure 2, paper XVII, IAU Colloq. No. 17) and Hejlesen (1972; Figures 3 and 4, paper XVIII), and have been calculated by the Danish school.

Despite of all the uncertainties remaining in the physics of stellar structure these sets of isochrones agree with each other within 25% in age, and are suitable for fixing the proper stellar chronology with a possible error in the total age of the Galaxy.

In the practical use of isochrones very important limitations do occur:

(1) The theoretical Zero Age Main Sequence (thereafter ZAMS) is not accurate enough to fit without corrections to the empirical ZAMS.

(2) In some parts of the HR diagram three different isochrones cross at a given

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point and therefore there is no unique solution to the age of a star of given effective temperature and luminosity. Fortunately, when that happens one solution corresponds to a very fast stage of evolution (phase of gravitational contraction of an exhausted convective core) and has a nearly zero probability of being observed, and the ages of the isochrones corresponding to the other two solutions do not differ by more than 20 to 30% (see Figure 3, paper XVII, IAU Colloq. No. 17).

(3) In some parts of the HR diagram the isochrones are so close to each other that observational errors result in very large uncertainty in stellar ages determinations. The accuracy of the age determinations are largely dependent on the accuracy of the effective temperatures and the parallaxes. Great uncertainties occur in particular in the vicinity of the main sequence and along the yellow red giant branch, close to the Hayashi limit. In practice one is left, for accurate dating, with subgiant stars and with early-type stars which cannot be old anyway.

(4) Strictly speaking, in the determination of the age of a star its helium content and its metal content should be taken into account, as well as its rotation.

The metal content is usually known from a metallicity index or a spectral analysis. The helium content is usually unknown, but for stars like the subgiants which have not yet undergone the mixing process, recent works favor a rather uniform value of the helium/hydrogene ratio (Demarque, 1972).

About the rotation of a star, it has been shown that rotation does not affect the life time on the main sequence by more than 5% (Maeder, 1972).

2.2. Age and Kinematical Properties

As stellar ages were not readily available most former works use spectral class groups instead of age groups. That has of course the inconvenience that if early spectral

TABLE I

Mean motion and velocity dispersion of nearby dwarfs

	Mean motion			Dispersion		
Sp	$\langle U \rangle$	$\langle V \rangle$	$\langle W \rangle$	σ_U	σ_V	σ_W
B0	+10	−15	−7	10	9	6
A0	+ 7	−14	−7	15	9	9
F0	+ 9	−10	−7	3	3	13
G0	+15	−21	−6	26	18	20
K0	+11	−15	−7	28	16	11
M0	+ 6	−15	−7	32	21	19

types are really a selection of young stars, more advanced types are older in average but contain a mixture of old and young objects. It was found very early that the dispersion of the velocities increases steadily from the early types to the late types. This can be seen in Table I (Delhaye, 1965), in which the first column contains six spectral groups of nearby dwarfs, the next three columns the mean space motions for each spectral group, and the last three columns their velocity dispersions. Table I shows that the young early-type stars have a much smaller velocity dispersion than the more advanced spectral types which are a mixture of stars of different ages.

It was also found that stars of intermediate age, of the order of one galactic year ($\sim$200 m. y.) have a very asymmetrical velocity distribution with respect to the galactic coordinates. It is now believed that this phenomenon, known as the asymmetric drift, has something to do with the spiral structure of the Galaxy and we shall hear more on this subject later on in this Joint Discussion.

The lion's share in the study of 'kinematical properties vs age' comes from Sir Richard Woolley and his Herstmonceux school (Woolley, 1970).

If one defines a pseudo-eccentricity for the galactic orbit of each star in the solar neighbourhood, there is a strong correlation between each class of eccentricity and the age of the group. Figure 1 shows this correlation: three M_v vs $B-V$ diagrams are reproduced from a paper by Woolley (1971). The first diagram shows the position

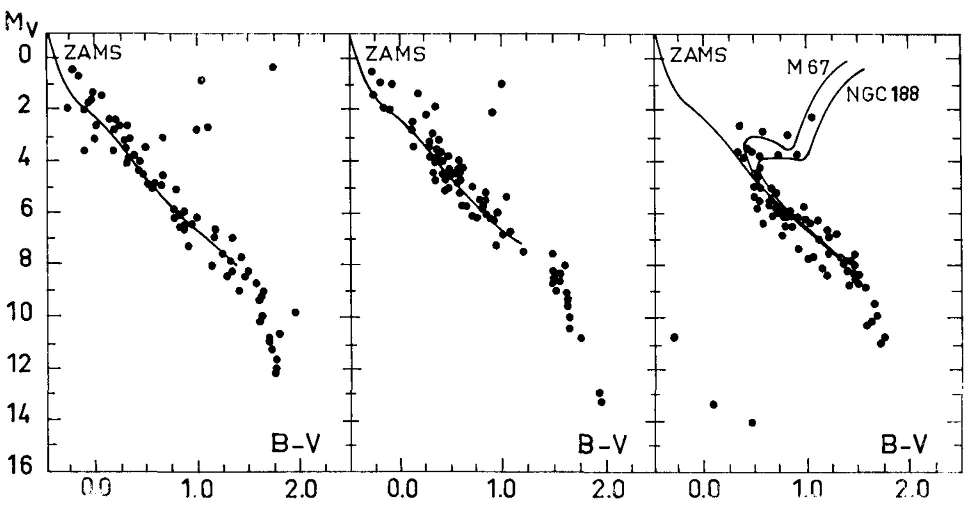

Fig. 1. Empirical HR diagrams after Woolley (1972) for three samples of nearby stars having different eccentricities ($e \leqq 0.05$, $0.075 \leqq e \leqq 0.100$, $0.150 \leqq e \leqq 0.200$) and the same box angle ($i \leqq 0.05$).

of nearby stars having an eccentricity of their galactic orbit smaller than 0.05: $e \leqq 0.05$ and $i < 0.05$, i being the box angle of the orbit of a star, defined as the maximum elongation from the galactic plane, with the center of the Galaxy as origin. The second and the third diagrams show the position of nearby stars having an eccentricity within: $0.075 \leqq e \leqq 0.100$ and $0.150 \leqq e \leqq 0.200$ respectively and with the same condition on i. On the two first diagrams the upper main sequence is well populated, whereas on the third one there is a turn-off point corresponding to an age of the old galactic clusters: M 67 and NGC 188. Woolley also found that the perigalactic distance is well correlated with the ages of the stars.

2.3. Age from nucleosynthesis aspects

Reeves (1972) discussed the chronology of the chemical elements resulting from nuclear interactions taking place at various times and in various locations of the Galaxy.

Furthermore Reeves spoke about the relative abundance of long-lived radioisotopes. The abundance of such isotopes, observed directly through their fossil remnants in the Earth and in the meteorites can give us some information on various events and their epoch of occurence during the lifetime of the Galaxy.

Lithium as a stellar age indicator has been discussed by Vauclair (1972). The lithium abundance is correlated with age in F and G dwarfs.

2.4. Age from spectrophotometric criteria

2.4.1. *Age from Emission Lines*

Wilson and Skumanich (1964) and Skumanich (1965, 1972) have derived an empirical relationship between the intensity of the emission in H and K lines in dwarf stars and the age of the star. They have found that:

$$\tfrac{1}{2}(F_{\mathrm{H}} + F_{\mathrm{K}}) \sim (\mathrm{age})^{-1/2}.$$

Kuhi (1972) discussed this relation which is not expected to be valid without an important dispersion but is nevertheless useful for F, G, and K dwarfs for which no evolutionary age is available.

It is interesting to note that as early as 1953 Delhaye (1953) found that M dwarf stars with strong emission lines have a velocity distribution resembling the velocity distribution of relatively young stars and not the velocity distribution of ordinary non-emission late dwarfs.

2.4.2. *Age from Chemical Composition*

The systematic enhancement of heavy elements with time in the Galaxy was supposed fifteen years ago to be a main clue to the time of birth of a star.

Recent works of Powell (1972) and Clegg and Bell (1973) suggest that a slight enrichment does occur, but is unfortunately of the order of magnitude of the scatter at any time in the history of the Galaxy. In particular Janes and McClure (1972) find that CN stars, which are believed to be young stars, include some significant old population.

The only safe statement is that strongly metal deficient stars, by more than an order of half a magnitude in respect to normal solar composition, are all belonging to the halo population and are therefore as old as the Galaxy. The reciprocal is not true: one can find some old stars having normal chemical composition.

3. Ages of Nearby Subgiants

I shall present now some results that I have just obtained concerning the nearby subgiants contained in the catalogues of Gliese (1969) and Woolley (1970).

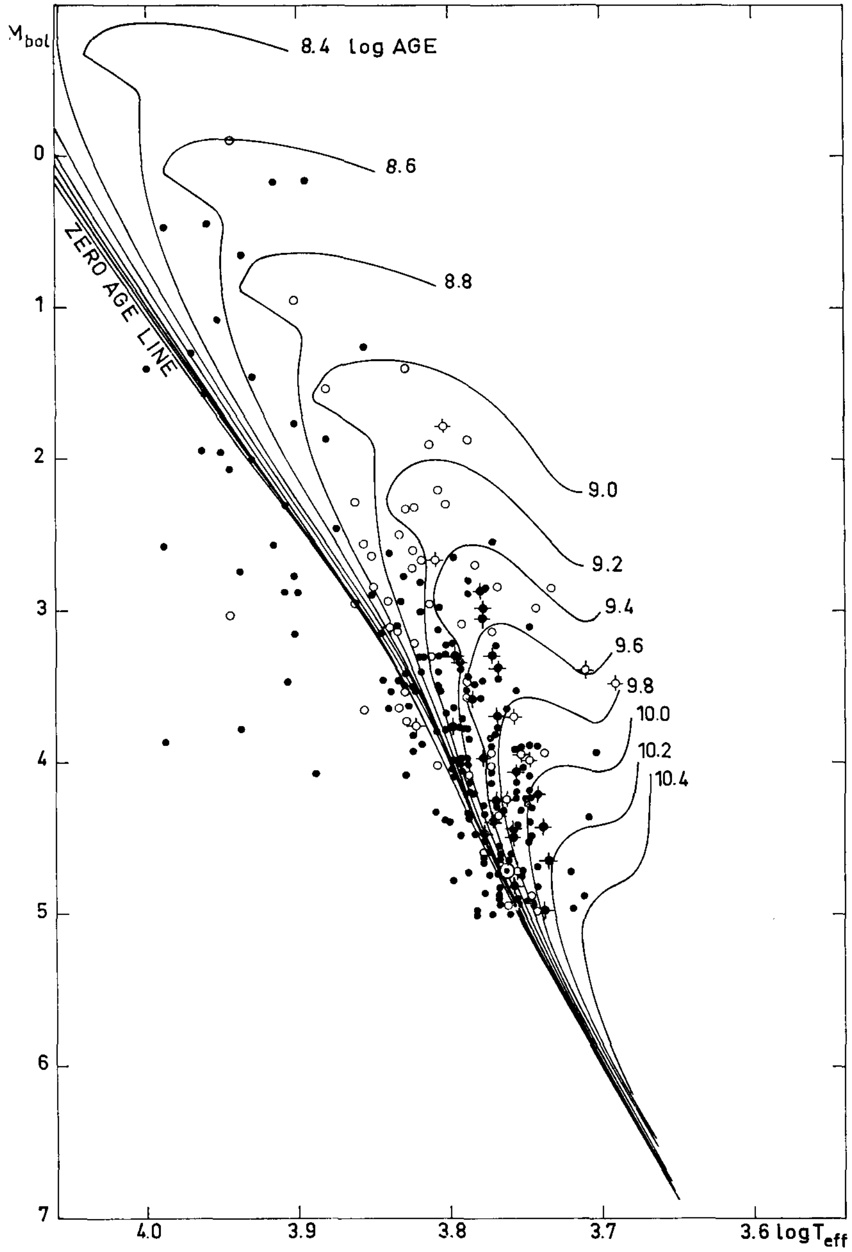

Fig. 2. Grid of isochrones in the HR diagram derived for $(X, Z) = 0.7, 0.03$. The full circles in the diagram are the loci occupied by stars classified in Woolley's Catalogue as dwarfs, the open circles are stars classified as subgiants; full circles with crosses and open circles with crosses are stars for which a detailed analysis is available in the literature.

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For this sample of nearby stars I preferred to study, as Hearnshaw (1972) has already done for a sample of 19 southern late subgiants, the kinematical characteristics in function of age rather than the contrary, because the kinematical characteristics are of statistical nature and therefore any attempt to select stars with given kinematical characteristics necessarily includes the tail distribution of other kinematical groups.

To do so, it is necessary to group the nearby stars by ages and to plot their velocity distribution by age groups.

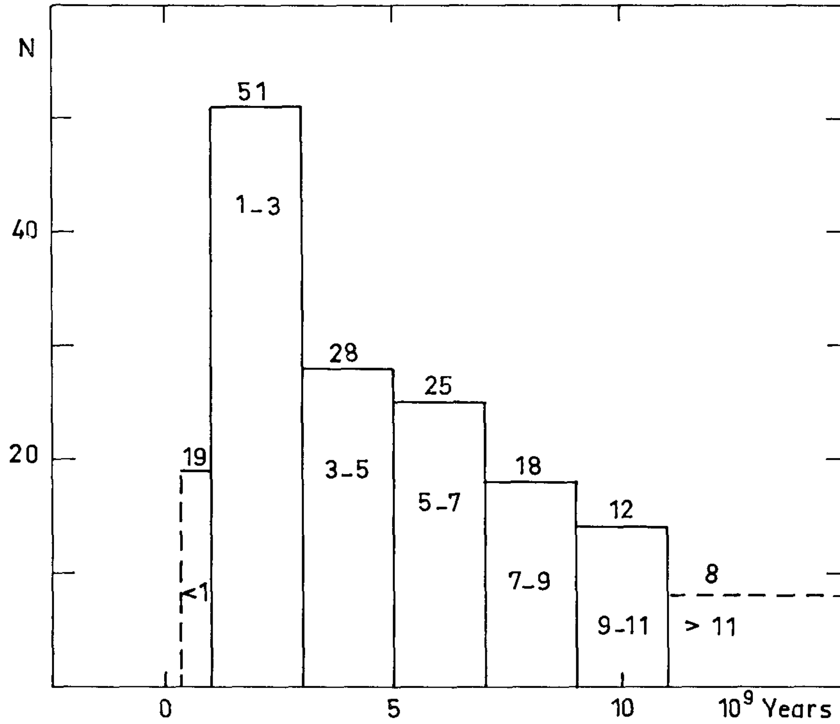

Fig. 3. Histogram of the age of 161 nearby subgiants falling in the ($\log T_{eff}$, M_{bol}) diagram region within the limits $\log T_{eff} = 3.68$ and 4.0 and M_{bol} within 0 and 5. The numbers above the top of each lane are the number of stars with an age in billions of years in the range given below the top.

The difficulty is that out of 1566 stars in Woolley's catalogue with trigonometric parallaxes larger than 0.″040, only 10% show enough evolution to be dated according theoretical evolutionary tracks. The 90% of the remaining stars are so close to the main sequence that only an upper limit to their age can be found.*

In Figure 2 nearby dwarfs and subgiants are plotted on the isochrone set computed by Hejlesen *et al.* (1972). These isochrones are the most complete set computed up to date. The isochrones have been derived for $(X, Z) = 0.7, 0.03$. Hejlesen *et al.* attempted to make the models of internal structure as realistic as possible within the limitations

* Dr Gliese advised me during the Joint Discussion to use only absolute magnitudes derived from trigonometric parallaxes; therefore I worked chiefly with Woolley's catalogue.

imposed by present uncertainties in the theory of convective flux and available opacity tables.

On the isochrones of Figure 2 only stars with effective temperatures between 4000 K and 10000 K and bolometric magnitudes between 0 and 5 have been plotted. The inclusion of stars cooler or fainter does not allow to date any other object with some accuracy in view of the closeness of the isochrones in such a region.

The full circles in the diagram are stars classified as dwarfs, the open circles stars classified as subgiants; full circles with crosses and open circles with crosses are stars for which a detailed analysis is available in the literature. The Sun is represented as an open dotted circle.

To get the bolometric magnitude of the stars we have used Johnson (1966) bolometric correction, corrected by 0.07 to have the standard definition of M_{bol}. The effective temperature of the stars has been mainly derived from $(R-I)$ colour indices and from high dispersion analysis.

Figure 2 shows that stars classified as dwarfs are already evolved and that stars classified as subgiants are not yet evolved.

In total 161 evolved stars have been dated. Figure 3 shows a histogram of the age of these stars. This histogram is not representative of an unbiassed sample of the nearby stars because of the selection procedure. Nevertheless it suggests that the rate of star formation one or two billion years ago was very substantial, compared to the average rate of star formation during the lifetime of the Galaxy. This conclusion can be drawn because the lifetime in the subgiant stage of the stars falling in the one to three billion lane is shorter than the lifetime of older subgiants.

We grouped the stars by age and we plotted the groups on a Böttlinger diagram.

Figure 4 shows this diagram. Filled dots stand for stars younger than 3×10^9 yr, open circles for stars with an age between 3×10^9 and 7×10^9 yr, and crosses for stars older than 7×10^9 yr. The 'kidney-like-lines' are iso-eccentricity lines in the U' and V' plane, in which the direction of U is taken opposite to the galactic center, and V in the direction of the galactic rotation.

The Böttlinger diagram of nearby subgiants shows that the youngest stars have

TABLE II

Mean motion and velocity dispersion of nearby subgiants

		Mean motion			Dispersion			e
N	Age	$\langle U\rangle$	$\langle V\rangle$	$\langle W\rangle$	σ_U	σ_V	σ_W	
19	$<10^9$	+9.1	−7.2	−8.1	23.0	10.1	9.7	0.09
51	$1\text{–}3 \times 10^9$	+12.5	−16.4	−10.3	30.3	16.7	12.9	0.12
28	$3\text{–}5 \times 10^9$	+9.4	−12.8	−13.1	30.6	24.2	22.6	0.15
25	$5\text{–}7 \times 10^9$	+17.2	−22.0	−3.8	39.5	24.6	18.1	0.18
18	$7\text{–}9 \times 10^9$	+20.4	−36.3	−7.7	54.6	20.9	28.9	0.20
12	$9\text{–}11 \times 10^9$	+15.2	−22.3	−4.7	33.9	22.4	19.0	0.14
8	$>11.10^9$	+27.1	−31.9	+9.5	61.1	32.4	31.5	0.23

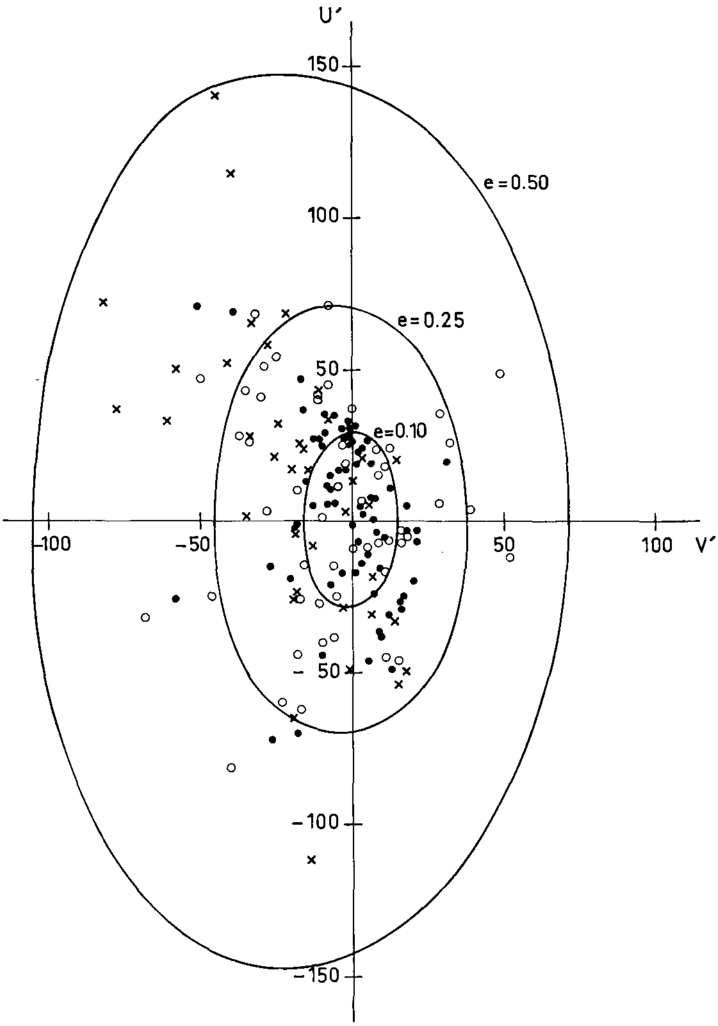

Fig. 4. Böttlinger diagram of the sample stars. Filled dots stand for stars younger than 3×10^9 yr, open circles for stars with an age between 3×10^9 and 7×10^9 yr, crosses for stars older than 7×10^9 yr.

the more circular orbits and they show a significant asymmetric drift; stars between three and seven billion years show a larger dispersion and stars older than 7 b.y. have a significant drag with respect to the galactic rotation. On the diagram we can see that old stars do not avoid small eccentricity orbits.

Table II shows the mean space motions and the velocity dispersions for seven groups of ages.

The velocity dispersions increase from younger to older groups. The mean space motion in the direction of galactic rotation $\langle V' \rangle$ is significantly higher than for the average mean motion of G and K dwarfs in Table I. Here the drag in the galactic rotation is visible.

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4. Conclusion

In the first section of this paper we learned something about the actual tools which permit a star to be dated.

In the second section we applied one of the dating techniques to a sample of nearby stars. Some of the results of this exercise are:

(a) The delimitation between class V and class IV luminosities from spectral classification is poorly representative of actual luminosities.

(b) The peak we found on the histogram of Figure 3 suggesting a substantial rate of star formation two billion years ago is in agreement with a statement of Woolley (1970, p. 139). Nevertheless Clegg and Bell (1973) who have recently studied the abundance and age distribution of 500 F stars in the solar neighbourhood have not found this peak. In view of difficulties involved by selection effects in our sample we are not going to discuss this point further.

(c) The fact that the velocity dispersion increases with age (Table II) is of course not a new result. But it is satisfactory to find that this result can be obtained directly starting from stars which have been grouped according to their physical age.

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DISCUSSION

Gliese: I would warn against using the resulting parallaxes instead of the trigonometric data in the 'Catalogue of Nearby Stars'. Resulting parallaxes include spectroscopic and/or photometric parallax data. The latter have been derived by setting the stars exactly on a mean sequence.

Further, the collection of parallax data in this catalogue, naturally, has preferred objects with positive errors in trigonometric parallax measurements. Therefore, on an average, the mean distance of the star groups will be too small. In the F star region this effect causes a systematic error in the mean absolute magnitudes of about 0.15, even if we restrict ourselves to parallaxes with small accidental errors (p.e. smaller than 10%).

Cayrel de Strobel: I used trigonometric parallaxes of subgiants wherever they were available and resulting parallaxes in all other cases.

Gliese: If you would have taken only stars with trigonometric parallaxes your sample of subgiants would have been smaller.

Cayrel de Strobel: Yes, therefore I took also the resulting parallaxes but that did not matter because the probable error of the resulting absolute visual magnitudes does not exceed 0.2. And with this error in magnitude the conclusion on the ages of the F and G subgiants can still be true.

Iwanowska: To summarize what we know about the lifetimes of stars located in different parts of the HR diagram from the evolutionary isochrones we show Figure 5.

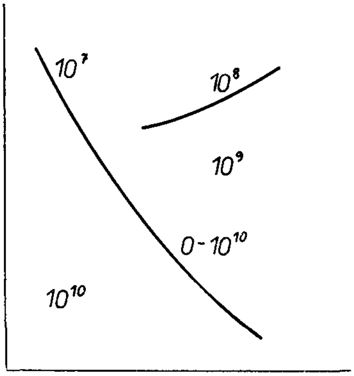

Fig. 5.

Further, from our investigations on stellar motions in connection with stellar populations we are led to believe that the velocity dispersion as well as eccentricities and inclinations of stellar galactic orbits depend not only on the lifetimes but also on the masses of stars. The arguments to this we see in the fact that e.g. kinematical parameters for very old white dwarfs are not greater in the mean than those of younger late-type dwarfs. Also, young dMe stars show these characteristics larger than young stars of large mass. I do not claim that our Galaxy is in a state of equipartition of energy but it seems to have made some steps in this direction.

Cayrel de Strobel: I certainly agree with you if you want to compare ages and velocity distributions of MeV and AV stars. I have not considered mass groups for the results presented in my table. Anyway the mass spectrum of F and G subgiants is very limited.

Cayrel: I just wish to point out a recent work now submitted to *The Astrophysical Journal* by Ann Merchant Boesgaard and Wendy Hagen on the age of our neighbour α Cen A. From high dispersion spectra taken at Mauna Kea with 1.7 and 3.4 Å mm^{-1}, the authors have derived an age for α Cen A using the three criteria: Li 6707 line strength, rotation of the star, and the H and K emission and the decay curves published by Skumanich in 1972. Li strength gives 3.4×10^9 yr, rotation 3.6×10^9 yr, and H and K emission gives only a lower limit of 2×10^9 yr. The authors conclude that the star is 3.5×10^9 yr old, i.e., 10^9 yr younger than the Sun. The fact that Proxima Centauri, a member of a triple system, is a flare star, is interesting because the age of flare stars is generally assumed to be 10^9 yr at the most.

Buscombe: As a practising spectroscopist, what criteria do you think should be used for classifying late-type subgiants, which might yield absolute magnitudes more closely fitting the isochrones?

Cayrel de Strobel: (1) Trigonometric parallaxes up to 0.″035, (2) High dispersion detailed analyses, knowing in advance the temperature of the star from a colour index, e.g. $(R-I)$, (3) Some good line ratios.