2. BASIC FACTS OF STELLAR EVOLUTION

By Walter Baade

Our present knowledge about stellar evolution is still so limited that, in presenting the basic facts, I wish to restrict myself to a discussion of a very simple but fundamental question.

The question is this. Are we today in a position to point out two groups of stars, one which in terms of the cosmical time scale is young, the other which is old? The two groups of stars which I want to discuss are the O- and B-type stars of high luminosity as an example of young stars and the stars in globular clusters as an example of old stars.

I. Young stars

Let us turn to the O- and B-stars of high luminosity first. When it became clear some fifteen years ago that the conversion of hydrogen into helium through thermonuclear processes in the interiors represents the main energy source of the stars it was pointed out at once that the O- and B-stars of very high luminosity must be quite young stars because with their rate of energy production they will exhaust their hydrogen in 10^7 to 10^8 years. According to a recent computation by B. Strömgren, the lifetime of a main sequence star of absolute magnitude -5^M, of a mass equal to 15 solar masses, and with an original hydrogen content amounting to 80% of its mass, is about 6.10^7 years. For the most luminous stars which we observe in nearby galaxies—stars of absolute magnitude $-7^M{\cdot}5$—the lifetimes must be still shorter and 10^7 years should represent the right order.

We obtain figures of the same order if we consider with Ambartsumian the lifetimes of the O-associations of our galaxy. These spatial concentrations of O, B, P Cygni and Wolf-Rayet stars are dynamically unstable because their mean mass densities are much smaller than the density of the galactic field in which they are imbedded. Hence they will disperse. The average velocity with which such a group disperses can be inferred from quite general kinematical considerations. It has to be larger than 1 km./sec. because otherwise galactic rotation would flatten out the associations and such an effect is not observed. On the other hand it has to be smaller than 10 km./sec. because otherwise it would show up in the radial velocities of the members and that is not the case.

Adopting the mean of these two limiting values, i.e. 5 km./sec., for the velocity of expansion in O-associations, Ambartsumian obtains for the age of the well-known group of high-luminosity stars around h and χ Persei $1{\cdot}7.10^7$ years, corresponding to the present diameter of 170 parsecs for the group.

But the most striking and convincing example of this kind is the ζ Persei group of stars which Dr Blaauw of the Leiden Observatory has recently investigated. This group, at a distance of 300 parsecs, consists of about a dozen and a half O- and B-stars which range in absolute magnitude from $-6^M{\cdot}0$ to $-1^M{\cdot}6$, and which are contained within a sphere of 30 parsecs diameter. Since accurate proper motions and radial velocities of the members are known, a thorough investigation of the kinematics of the group becomes possible and Blaauw has been able to show beyond any doubt that the group expands. The mean linear velocity of expansion turns out to be ± 12 km./sec. which, combined with the present diameter (30 parsecs), leads to an age of the group of $1{\cdot}3.10^6$ years. This age may appear, as Blaauw himself remarks, surprisingly short: however, the reality of the expansion appears so well established that it is difficult to see how one could obtain a higher age.

Obviously we are dealing with a very young group of stars. Altogether we have convincing evidence that the O- and B-stars of high luminosities (stars brighter than -5^M) are young stars with lifetimes well below 10^8 years. Their formation in our own Galaxy and others, where we observe them, must therefore be going on at the present time. Together with them stars of lower masses and luminosities are being formed, as the example of the ζ Persei group shows, or the combination of high luminosity O's and B's with main-sequence dwarfs in some well-known galactic clusters.

We have also convincing evidence that these stars are formed in the big dust clouds of galaxies because galaxies which are free of dust do not contain this sort of stars which I have called the population I. The close relation between dust and population I is particularly striking in the spiral nebulae. On several occasions during the past few years I have pointed out that the available facts force us to conclude that the spiral structure in galaxies is primarily a feature of the dust and gas and that the emergence of the population I, that is star formation, is a secondary phenomenon.

One of the most striking illustrations of this fact is one of the inner spiral arms of the Andromeda nebula. Farther away from the nucleus it is densely studded with the supergiants of the population I, but as the arm spirals inward, the pearl string of stars stops rather abruptly while the spiral arm continues as a dust lane into the centre region of the nebula. It is typical of the inner arms of the Andromeda nebula that the population I appears mostly along the borders of the dust lanes and is only rarely seen within the lanes themselves. This is undoubtedly caused by the heavy absorptions in the arms which must be nearly opaque. As a result we see only the outer fringes of the population I. As we go farther away from the centre the role of the dust becomes less prominent in the spiral arms and the stars of the population I, with dust clouds interspersed between them, now dominate the spiral structure.

All these facts fit perfectly into the picture that star formation is still going on in the Andromeda nebula and similar galaxies and that the stars are formed in the large cloud complexes which are the basic feature of the spiral structure.

One may ask, of course, whether we know of any cloud complex in our galaxy or rather in our solar neighbourhood in which star formation is still going on so that we might study it in more detail.

As things stand, we can guess only, but it is probably a good guess that in the large cloud complex of which the Orion nebula forms a part, star formation is going on at the present time. The dark part of this cloud is quite opaque and we are unable to observe what is going on inside. However, in the part excited by the Trapezium stars, the luminous Orion nebula, increased transparency permits us to look deeper into the nebula, especially in infra-red light. What we observe is a huge cluster of stars, centred on the Trapezium. It is still an open question whether the falling off in star numbers with increasing distance from the Trapezium is real or simply a result of decreasing transparency with increasing distance from exciting stars. However, it seems quite certain that the star density in the nebula is much higher than that in a corresponding volume in front of it. Observations carried on since 1947, at the 100-inch telescope, leave no doubt that practically all stars of this huge 'cluster' are variable and that they belong to the T Tauri class. Moreover, Haro has recently shown that a considerable percentage of these stars, practically all dwarfs, show Hα emission, either permanently or temporarily. Obviously we are dealing with an outstanding example of what the Russian astronomers have called a T-association.

There is every reason to suspect that these stars are not restricted to the excited region of the dust cloud, but pervade the whole cloud. The association of the Trapezium stars which cannot be very old with the strong concentration of T Tauri stars in the Orion cloud certainly is most suggestive.

II. Old stars

Let us now turn to the stars in globular clusters. During the past two years we have tried at the Mount Wilson and Palomar Observatories to extend the colour-magnitude diagrams of a few of the nearest globular clusters in high galactic latitude to absolute magnitude $+5^{M}$ or $+6^{M}$. The clusters in question are M3, M13, and M92. Since the work has not yet been finished I can present only some of the first results.

I would like to make first, however, a few remarks on how we have proceeded in obtaining these diagrams. It is well known that scale transfers by photographic intercomparisons are always somewhat hazardous, especially with instruments of long focal length, if one wants to avoid systematic errors in the final magnitudes. Such systematic errors are especially bothersome if the essential correctness of two scales—the photographic and the photovisual—has to be guaranteed as in the case of a colour-magnitude diagram.

To avoid all these difficulties we have made the necessary transfers photo-electrically. That means, in each cluster an extended sequence of photographic and photovisual magnitude has been established by direct photo-electric intercomparisons either with the polar sequence or with one of our new primary Selected Areas which have been rigidly interconnected with the pole. We are therefore certain that our sequences are on the International System, or as close to it as this system is defined. The photographic plate then merely serves to interpolate a large number of cluster stars into the standard sequence. Let me add that even so the transfer of the scales turned out to be a slow, painstaking task and that another observing season will be required to check the very faintest standards which we have used so far, comparison stars between the twenty-first and twenty-second magnitude.

The first diagram is that of M 92 (Fig. 1). All the work on this cluster was entirely carried out at the 60-inch and 100-inch reflectors at Mount Wilson, in fact the work on M 92 was planned as a training programme for our young observers Arp, Baum and Sandage, with Baum providing the photo-electric sequences.

You see, in the upper half of Fig. 1, the well-known features of the colour-magnitude diagram of globular clusters: the red-giant branch which begins at $M_{pv} = -3$ and splits into two branches at about $M_{pv} = -1$. To the left it continues as the so-called horizontal branch with a number of cluster-type variables marked as crosses. For these variables their mean magnitudes and mean colour indices, each integrated over a whole light cycle, are plotted. You will note that in M 92 there are on the horizontal branch many more stars to the left of the cluster-type variables than to the right and that these stars are quite blue, running in colour index from $0^m \cdot 0$ to nearly $-0^m \cdot 4$. Note also that far below the horizontal branch, at absolute magnitude $+4^M$, there are two blue stars, stars which fall into the region of known ex-novae, such as Nova Aquilae 1918 and Nova Persei 1901.

Let us consider now the second branch. It runs nearly vertically through the region of the subgiants for about three magnitudes, then suddenly veers off towards the left and joins what appears to be the beginning of the ordinary main sequence at about $+3^M \cdot 3$. That we are indeed dealing with the beginning of the ordinary main sequence is shown by the colour-magnitude diagram of M 3 (Fig. 2).

This diagram, based on plates taken at the 100-inch and 200-inch telescopes, is the work of Dr A. Sandage and shows what we are really driving at. You will note again the splitting of the giant branch. The sharp gap in the horizontal branch is the region of the cluster-type variables. It stands out in the present diagram so clearly because all variable stars were left out in the measuring process. In contrast to M 92 the stars of the horizontal branch are about equally distributed in numbers to the left and to the right of cluster-type variables and I may mention in passing that in M 13, on which Dr Savedoff is working, practically all stars of the horizontal branch are lying to the left of the cluster-type variables. You will also notice some exceedingly blue stars in M 3 at the end of the horizontal branch.

As in M 92 the second branch runs nearly vertically through the subgiant region and then rather abruptly turns toward the ordinary main branch which it reaches at a point defined by $M_{pv} = +3 \cdot 6$, c.i. $= +0^m \cdot 34$, or spectral type F 7. There are two reasons which make it quite certain that we are dealing with the well-known main sequence of the Hertzsprung-Russell diagram.

First, within the present errors of measurement the slope of this branch, between colour index $0^m \cdot 0$ and $+0^m \cdot 6$, is the same as that derived photo-electrically by Dr Harold Johnson of the Yerkes Observatory from nearby stars of well-determined trigonometric parallaxes. To prevent misunderstandings it should be pointed out that the diagrams, given in Figs. 1 and 2, do not correctly represent the numbers of giants and dwarfs in the two clusters since the measures for the fainter cluster members refer to smaller areas in each cluster.

Second, the best fit between Johnson's main branch, based on nearby stars of well-determined trigonometric parallaxes, and the branch observed in M 3 leads to an absolute magnitude of the cluster-type variables which is in close agreement with the accepted value. Moreover, the question of reddening and absorption does not enter into these arguments since M 3 is a high galactic latitude object and the nearby stars of Johnson are too close to show any such effects. We conclude therefore that we are dealing with the main sequence of the Hertzsprung-Russell diagram and that this sequence is represented in globular clusters only by stars of $M_{pv} = +3{\cdot}5$ and fainter.

How do we have then to interpret the colour-magnitude diagram of the globular clusters? We know today that the position of a star in the Hertzsprung-Russell diagram is determined by its mass, original chemical composition, age, and rotation. We also know that for stars of small mass—dwarfs much fainter than the Sun—evolutionary changes resulting from a change in chemical composition are quite negligible, even if these stars were formed some $3 . 10^9$ years ago. But for stars of the main sequence brighter than the Sun the situation is quite different. On account of their higher hydrogen consumption their chemical position and hence their position in the Hertzsprung-Russell diagram changes markedly in $3 . 10^9$ years, the more so, the higher the initial luminosity. It is well known that the evolutionary track which such a star follows when its chemical composition changes as a result of the conversion of hydrogen into helium depends very much upon one circumstance: whether the matter in its interior is well mixed or not. Since rotation is the most powerful agent in producing mixing, stars with large equatorial velocities are considered as well mixed, those with small equatorial velocities as unmixed.

In M 3 the main sequence is represented by stars of spectral type F 7 and later. According to O. Struve main-sequence stars of spectral type F 7 are mostly slowly rotating stars, with perhaps a slight sprinkling of stars of higher equatorial velocities. We consider therefore the evolutionary tracks for both cases. For well-mixed stars they were computed several years ago by Strömgren with the following result: with decreasing hydrogen content the stars move upward and slightly to the left from their initial position in the H–R diagram, but unless their hydrogen content becomes very small they never deviate much from the main sequence. Perhaps the sprinkling of stars in M 3 earlier than F 7 and close to the main sequences represents such well-mixed stars which moved upward from $M_{pv} = +3{\cdot}6$, C.I. $= +0^{m}{\cdot}34$.

The evolutionary tracks for main-sequence F stars, in which no mixing between the core and the outer envelope takes place, have recently been computed by Schwarzschild and Sandage. In this case an isothermal core develops, as the hydrogen is being used up in the centre of the star. During the first phases of this process the star only brightens somewhat but still remains close to the main sequence. However, it begins to move quite abruptly from the main sequence to the right when the growing isothermal core contains about 10% of the mass. There seems to be hardly any doubt that we have to identify this abrupt turning off from the main sequence with the observed knee in the diagram of M 3. Since we know precisely the interior conditions of a star passing this point, it is possible to compute how much time the star required to burn 10% of its hydrogen, that is, its age. The answer according to Schwarzschild and Sandage is $3{\cdot}4 . 10^9$ years, if one uses for the bolometric magnitude of the turning off point the value $+3^{M}{\cdot}65$, as indicated by the diagram of M 3. The stars in globular clusters are therefore old stars.

Why the evolutionary tracks of unmixed stars, after moving from the main sequence to the right, suddenly turn upward, we do not know yet. Perhaps new energy sources in the interiors come into play at this point. It must be left to further investigations not only to provide the answer to this question but also to explain the whole further run of the diagram. Even so the interpretation of the colour-magnitude diagram of globular clusters, suggested by the work of Schwarzschild and Sandage, throws new light on the occurrence of giants in these systems. These giants cannot have formed in recent times because there is no dust and gas in globular clusters.

On the other hand their luminosities are so high that it is difficult to see how they could have survived for $3{\cdot}4 . 10^9$ years. It is obvious now that they are stars of relatively small mass, somewhere between 1 and 2 solar masses, which have spent most of their time as F

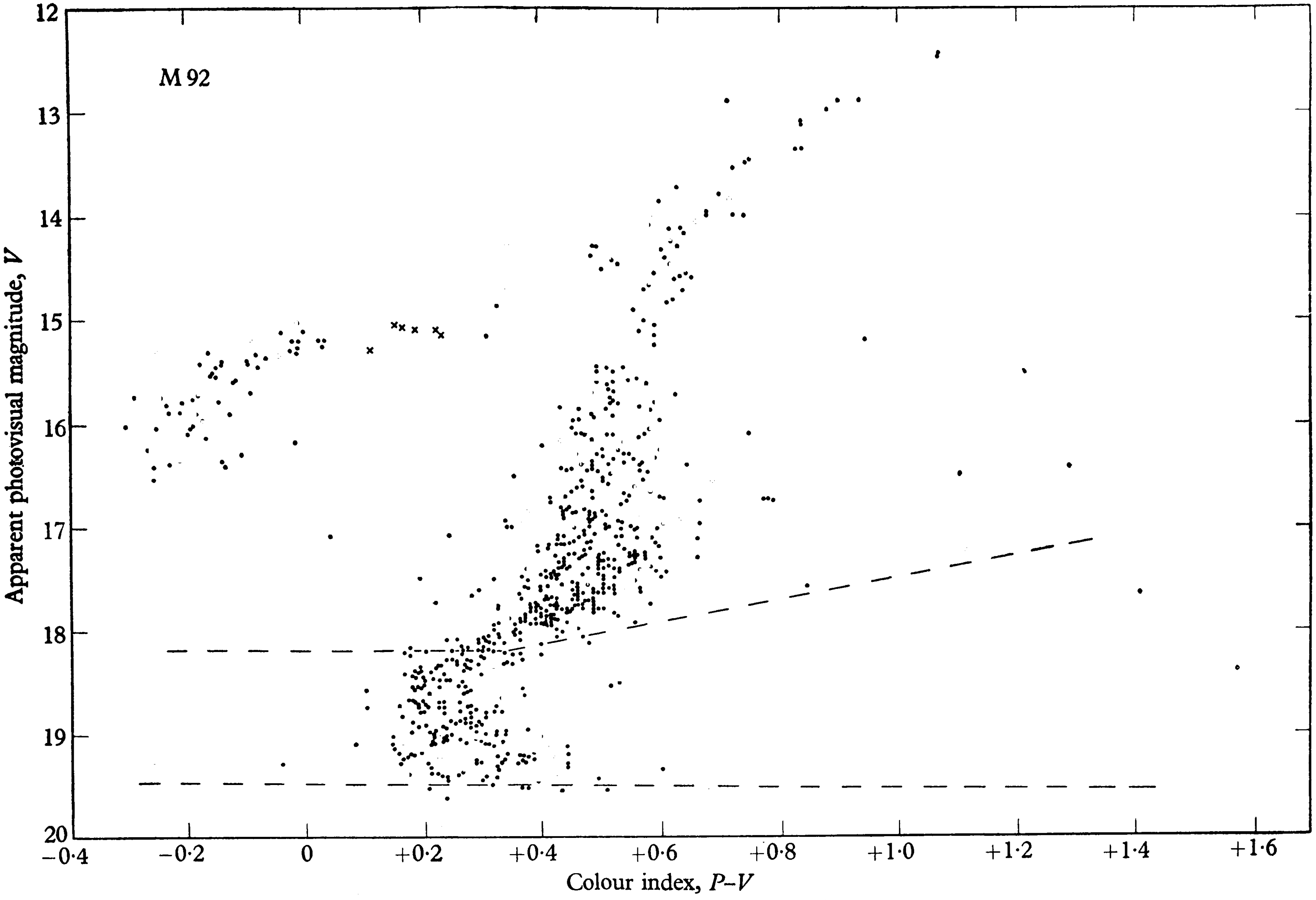

Fig. 1. Colour-magnitude diagram of Messier 92.

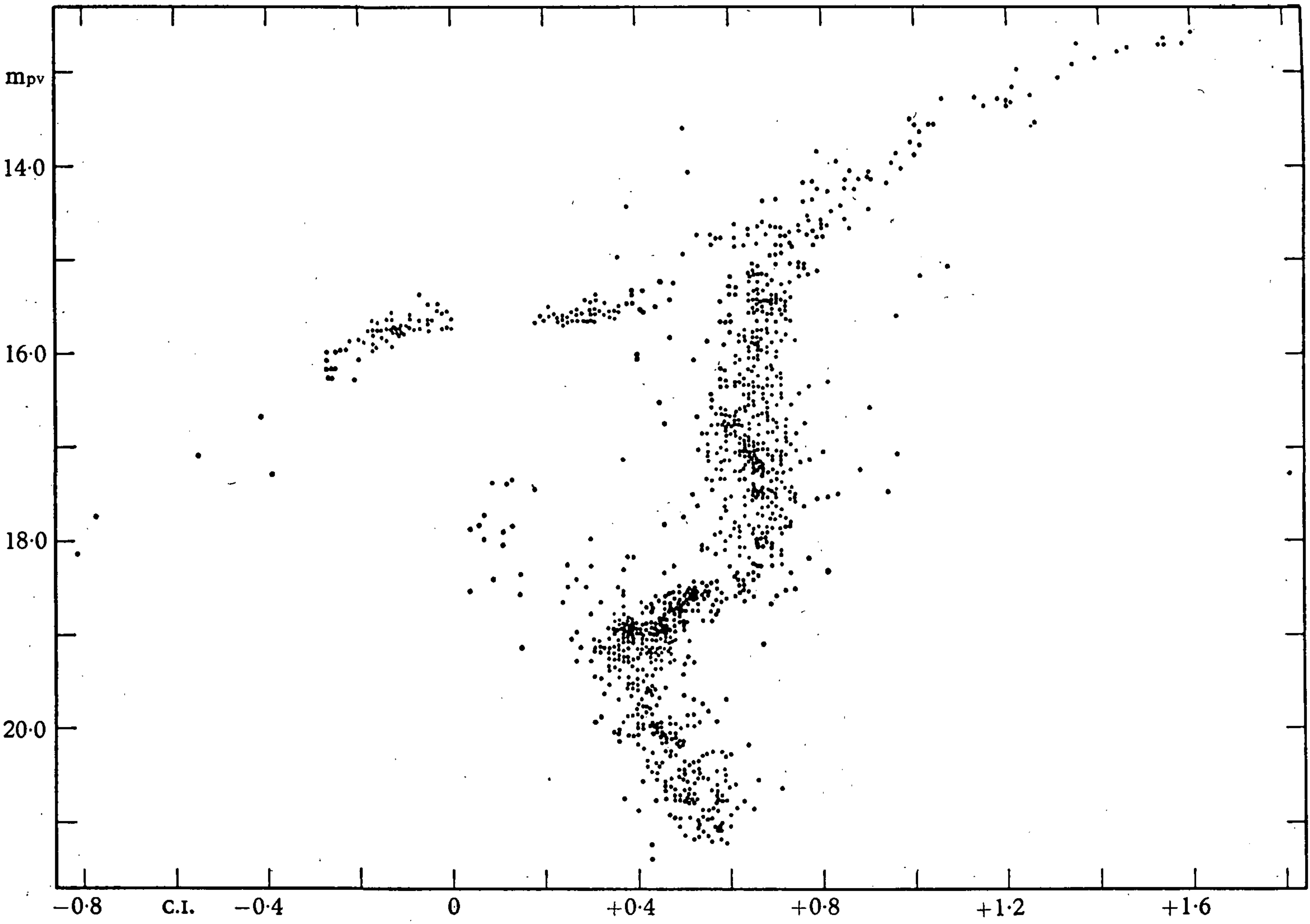

Fig. 2. Colour-magnitude diagram of Messier 3.

dwarfs on the main sequence and have brightened up only recently after leaving the main sequence with an exhausted isothermal core.

That the giants in globular clusters are a breed entirely different from the ordinary giants of the population I became obvious this spring when O. C. Wilson obtained the first spectra of the brighter members of M 3 and M 92 at the coudé focus of the 200-inch telescope with a dispersion of 38 A./mm. From their well-determined colour indices we expected them to be early K types, perhaps K 3 to K 5. To our great surprise they turned out to be F or G types, depending on the criteria which were used. As an illustration one of the stars in M 92 may serve which has the absolute magnitude $M_{pv} = -3{\cdot}08$ and the colour index c.i. $= +1^{m}{\cdot}22$. For normal giants this colour would correspond to the spectral type K 3.

Actually the following spectral types were established:

F3 (from the strength of the metals, especially Fe).
F3 (from the strength of the G band (CH)).
G2 (from the strength of the hydrogen lines).
G3 (from the intensity ratios of Fe and Cr lines).

Obviously these giants in globular clusters are so different from ordinary giants, that we have to establish an entirely new system of spectral classification for them.

Altogether we seem to have convincing arguments now that, in dealing with highly luminous O- and B-stars—the typical representatives of the population I—on the one hand and the stars in globular clusters—the prototypes of the population II—on the other, we are dealing with two different age groups of stars: recently formed stars and old stars, formed more than 3.10^9 years ago.

Discussion sur l'article de Baade

Ambartsumian voudrait savoir quelle est la magnitude absolue des étoiles bleues figurant dans le diagramme de Russell dernièrement présenté.

Baade donne la valeur $0^{M}{\cdot}0$ et plus faible.

Kukarkin exprime sa satisfaction de la communication de Baade, dans la mesure où elle est basée sur les faits d'observation. Mais il émet des doutes sur l'interprétation. Kukarkin pense qu'au fur et à mesure que nous obtiendrons, pour d'autres systèmes, des diagrammes analogues au diagramme présenté pour M 3, on verra apparaître une forme différente pour chacun d'entre eux. Pour Kukarkin, nous ne pouvons nous limiter à deux types d'étoiles seulement. En effet, le processus de formation des étoiles a pris beaucoup de temps et est encore en cours.

Kukarkin dit qu'à son avis, la distinction des étoiles suivant leur appartenance à un système plat, sphérique ou intermédiaire est meilleure, et conduit à de meilleurs résultats. En effet, les propriétés physiques des étoiles changent moins vite que leurs propriétés dans l'espace des phases; leurs propriétés cinématiques sont les plus importantes. Il est possible d'attribuer à toutes les étoiles d'un système plat ou sphérique la même filiation génétique.

Kukarkin estime que la différence entre étoiles jeunes et vieilles est trop grossière. Par exemple, on trouve dans les systèmes sphériques des étoiles variables de courte période ayant de grandes vitesses, donc pouvant échapper à la galaxie. Leur présence même est une preuve qu'elles sont jeunes. Elles ne peuvent venir du dehors.

Dans sa réponse, Baade insiste sur les raisons de sa distinction des étoiles en populations I et II, d'après les propriétés des nébuleuses extragalactiques, certains systèmes étant population II pure, les autres systèmes étant mélangés, population I plus population II. Baade pense que Kukarkin mélange la question de l'évolution des étoiles et celle de la constitution dynamique de la galaxie.

Autour de notre galaxie existe une couronne de population II. Dans notre galaxie elle-même, les populations sont mélangées. Cette situation reflète l'évolution et plaide en faveur de l'existence de vieilles étoiles et d'étoiles jeunes encore en formation.

Kukarkin rappelle le traitement qu'il a donné de ces questions dans son livre.

Gratton fait remarquer que le grand nuage de Magellan, jusqu'ici considéré comme de pure population I, est en réalité un mélange de population I et population II, ainsi qu'il a été établi par la découverte de variables d'amas.

Kourganoff demande s'il est exact que Baade pense qu'il y a eu formation massive d'étoiles à différentes époques.

Baade exprime l'opinion que les étoiles dans les nébuleuses elliptiques ont dû se former il y a longtemps, parce que la poussière dans ces systèmes est épuisée, et qu'il y a eu formation continue d'étoiles, jusqu'à présent, dans les nébuleuses spirales.

Shapley fait remarquer que les vérifications qui ont été faites des périodes des étoiles variables dans le grand nuage de Magellan ne permettent pas de conclure à la présence de variables d'amas.

Compléments au rapport de Baade:

'Faits principaux liés à l'évolution stellaire', par P P Parenago (lu par Kharadze).

Baade, dans un article bien connu, montra la différence de population stellaire entre le centre et la périphérie des nébuleuses spirales. Cependant, la division de la population des galaxies en deux types (I et II) qui fait partie intégrante d'un grand nombre de travaux publiés les dernières années, semble quelque peu primitive.

Les recherches de B. V Kukarkin sur la distribution dans l'espace des étoiles variables, commencées avant la guerre et rassemblées dans une Monographie sur 'la structure et le développement des galaxies d'après les recherches sur les étoiles variables', ainsi que des articles de Parenago sur les mouvements stellaires et le diagramme de Hertzsprung-Russell, publiés depuis 1944, montrent clairement que la structure réelle de la galaxie est beaucoup plus complexe que d'après le simple schéma de Baade. Sans aucun doute, la galaxie consiste en un certain nombre de sous-systèmes qui s'interpénètrent, caractérisés par des degrés divers d'aplatissement et par différentes dispersions des vitesses. D'après Kukarkin, il est commode de classer les sous-systèmes en système plat, intermédiaire et sphérique, aux deux premiers types correspond le type I de Baade, au troisième, le type II de Baade. En étudiant un sous-système, il est parfois difficile de savoir auquel des deux types voisins il doit être relié. L'idée de l'existence de différents sous-systèmes galactiques est largement utilisée en U.R.S.S.

La distribution des différentes caractéristiques spectrales sur le diagramme spectre-luminosité correspond aux différents sous-systèmes. Ce diagramme, comme il a été montré au cours de travaux menés depuis 10 ans en U.R.S.S., est plus compliqué qu'il n'avait été supposé jusqu'à présent par la plupart des astronomes. A côté des séquences connues, séquence des sous-naines, séquence bleue-blanche, P P Parenago a montré que la séquence principale n'est pas un groupe stellaire uniforme et doit consister en deux parties dont la frontière est voisine du type solaire. Une telle division de la séquence principale fut découverte tout d'abord en analysant la répartition des étoiles dans l'espace des vitesses et confirmée par le travail de A. G. Masevich et P P Parenago, dans un article sur la relation masse, rayon, luminosité. D'autres confirmations furent trouvées, y compris sur le diagramme lui-même, sur la base des mesures d'indice de couleur d'Eggen.*

Il semble à l'auteur que les recherches portant sur l'analyse de la structure de la galaxie en un certain nombre de sous-systèmes, l'analyse de la structure complexe du diagramme de HR, et l'hétérogénéité de la séquence principale, ont une grande importance pour l'étude de l'évolution des étoiles. On notera que la division de la séquence principale en deux parties est en bon accord avec les idées de V A. Ambartsumian sur les deux types d'associations stellaires O et T

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* Un résumé de tous les arguments en faveur de la division de la séquence principale en deux parties peut être trouvé dans le volume 1 de *Questions de cosmogonie* et dans la publication des textes de la conférence qui s'est tenue en U.R.S.S. sur les problèmes de cosmogonie stellaire sous les auspices de l'Académie des Sciences, en Mai 1952.