The interpretation of the color magnitude diagram of Galactic star clouds

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Abstract : The color magnitude diagram of the stars in the Scutum cloud is considered. Proof is given that a conspicuous giant series is present. At the same time young stars are present. Internal motions must be present resulting in a mixture of stars of different ages. The stars in the Scutum cloud do not represent a homogeneous group but are a heterogeneous mixture.

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Özet : Scutum bulutundaki yıldızların renk parlaklıklari diyagramı nazarı itibare alınmıştır. Dev serilerin mevcudiyetine bir bakışla ispat verilmiştir. Aynı zamanda genç yıldızlarda vardır. İç hareketler, muhtelif çağdaki yıldızlar karmasında netice olarak verilmelidir. Scutum bulutundaki yıldızlar homojen bir gurup göstermezler fakat homojen olmayan bir karışım gösterirler.

§ 1. Introduction

Much of the observational evidence for the evolution of the stars comes from modern photo-electric studies of color magnitude diagrams of galactic star clusters and of globular clusters.

Sandage (6, 1958) has given a composite diagram in which he has summarized the observational data relevant to the evolutionary problem. The results obtained by various observers are summarized as follows :

" 1. evidence that in any one cluster the cosmic scatter of stars around the main sequence is very small or even zero;

2. the bright end of the main sequence terminates at different absolute magnitudes in different clusters ;

3. in clusters where yellow giants occur, the position of the giant sequence is systematically related to the turn-off point of the main sequence.„

Sandage next applies current ideas of star formation and subsequent evolution to his diagram and finds evidence for a considerable spread of ages among clusters. His ideas can be summarized in the following way. Current ideas are that the stars originate from interstellar medium, and fairly rapidly contract towards the main sequence. This period of rapid contraction, during which the central temperature rises, is known as the Helmholtz contraction period.

The star settles down to a stable state when the central temperature reaches a critical value and nuclear reactions begin. Its absolute magnitude depends upon the initial condensation. Due to the mass distribution function of these initial condensations at the time of stellar birth, stars are spread continuously along the main sequence.

The result of the nuclear reactions at first is to convert Hydrogen into Helium.

Using the theoretical results by *Schönberg* and *Chandrashekhar* (7, 1952), *Sandage* points out that the star remains close to the main sequence until a critical fraction, q_c, of its mass is exhausted.

Next the star rapidly expands and in the color magnitude diagram it moves towards the right. The stars of high luminosity are much more prodigous spenders of energy and will exhaust their critical fraction q_c in much shorter time than the fainter stars along the main sequence.

As a consequence in a cluster at a certain time T all stars, brighter than a certain absolute magnitude, have left the main sequence. *Sandage* identifies the point where the main sequence terminates with the stage when a star has exhausted the fraction q_c of its mass of Hydrogen. The older the cluster is, the lower will be this termination point.

If $\mathfrak{M}$ is the mass of a star, $X =$ the fractional abundance of Hydrogen, $\lambda_i = f(q_i)$ ergs/sec. = the rate at which the star releases energy which is a known function of q_i, L_T the luminosity of the main sequence termination point, $L_i = L_T\, h(q_i/q_c)$ ergs/sec. the rate of energy release written as a function of

L_T, q_i and q_c *Sandage* finds that the age of a cluster can be written as:

$$\tau = \frac{.007\mathfrak{M}c^2}{L_T} \int_{X q_i = 0}^{X q_i = X q_c} \frac{X\, dq_i}{h(q_i/q_c)} \qquad \cdots\cdots(1)$$

where c is the velocity of light.

Finally by inserting the *Schönberg-Chandrasekhar* solution in this equation *Sandage* obtains the simple relation:

$$\tau = 1.10 \times 10^{10} \frac{\mathfrak{M}}{L_T} \text{ years} \qquad \cdots\cdots(2)$$

where $\mathfrak{M}$ and L_T are in solar units. Applying this latter relation to different clusters, *Sandage* finds that their ages range from $\tau < 1 \times 10^{6}$ years to $\tau = 5 \times 10^{9}$ years. For further details the reader is referred to the original papers by Sandage.

§ 2. The color magnitude diagram in dense galactic star clouds.

In a far more crude way the results of Sandage may be described as follows. In a very young group of stars all points in the color magnitude diagram will fall along the main sequence and this main sequence can be traced far up to the upper left corner of the diagram e.g. up to the very bright O and B stars.

With the older groups of stars the points along the upper left part of the main sequence have disappeared but part at least of these have been moved over in such a way as to form a yellow giant series, while others can perhaps be traced in other parts of the color magnitude diagram. Which part of the main sequence has disappeared and the shape and position of the giant series depends on the age of the group of stars under consideration.

This is the way in which originally *Trümpler* (5, 1930) attempted to classify the galactic clusters according to their age.

In the following the question is considered to what extent these methods can be applied to the dense galactic star clouds.

It will be assumed that such a star cloud represents a group of stars all having approximately the same distance from the sun. If the star cloud has only recently originated, just as with the young galactic clusters, its color magnitude diagram simply represents the main sequence but shifted over an interval corresponding to distance modulus of the cloud. This distance modulus may be either taken equal to $m - M = 5 \log r - 5 + Ar$ or $m - M = 5 \log r - 5$ depending on whether or not the correction for interstellar absorption has been applied. In any case to the colors the necessary corrections for interstellar reddening must have been applied. When these conditions are fulfilled and the apparent magnitudes are on the fotographic scale, the color magnitude diagram will have the shape as indicated in figure 1, that is to say, the points representing the individual stars will be arranged along the thick drawn line in the figure having a relatively small scatter along this line. The horizontal line at the bottom of the figure of course represents the limiting magnitude of the observations. If next it is supposed that not all of the stars in the cloud are at one and the same distance, but have a scatter around a certain median distance, the stars in the cloud can be arranged in a number of parallel shells and we can select the surfaces in such a way that the ratio of the distances is such that $\log r_n/r_{n-1} = 0.2$.

The general distribution of the stars along the main sequence will be identical in all shells, but in each of the consecutive shells the situation of the main sequence has been shifted over an interval of one magnitude.

So if we draw a set of lines at intervals of one magnitude and parallel to the main sequence (as is done in figure 1), all the stars of which the representative points are within a given strip of the surface, are stars in one and the same shell. Also the surface density in the strip is related in a simple way to the space density in the shell. Owing to the way in which the surfaces of the shells were selected, when the space density is uniform the logarithmic ratio of the total numbers in the consecutive shells, and consequently also in the consecutive strips, will be equal to 0.6.

If the logarithmic ratio is > 0.6, the space density decreases, if it is < 0.6 the space density increases. All this is standard procedure. However, when we consider figure 1, it will be apparent, that when counting the numbers of representative points in the consecutive strips, we obtain quantities which cannot directly be compared. Proceeding from the bottom to the top the consecutive strips contain unequal intervals of the main sequence. The lower strips only contain a short interval, while the higher strips almost cover the complete sequence. Therefore if any comparison is made, only the numbers in equal intervals along the main sequence must be considered. This however,

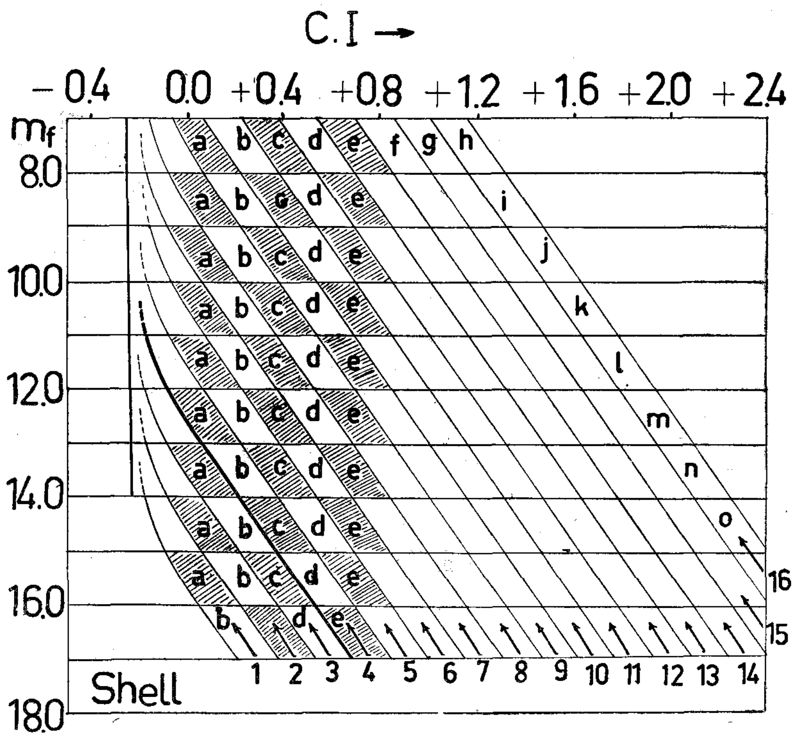

Fig. 1

leads to some difficulties. On the left hand side of the figure 1 the lines, representing the main sequence, have a steep slope and in the final stages the horizontal distances between the lines become exceedingly small. When the representative points are plotted in the diagram, both the observed colors and magnitudes are affected by the unavoidable errors of observation. While in this case the influence of the probable error in magnitude may not be serious, the probable error in color may entirely invalidat the results. Even small errors will cause the individual stars to be assigned to entirely wrong shells so that erroneous ratios will be obtained. Also it would appear from recent results (cumf. Johnson 1958) that even with young galactic clusters and star associations, the upper left part of the main sequence is no longer fully determined. It seems that in this part of the color magnitude diagram the stars already deviate from the main sequence at a very young age, thus causing a considerable horizontal scatter of the representative points. It seems better therefore to exclude the left part of the diagram. The bluest parts which could be used are those which at the lower end have a minimum color index 0,0 and which in figure 1 are indicated as the areas *a*.

Now especially, when we proceed towards the brighter stars the surface density in the areas *a* will be very small and no reliable values for the ratios can be derived. In order to obtain better results one will be forced as far as possible to combine the numbers in the areas *a* with those in *b*, *c*, *d*, etc.

Consequently if the numbers in the different areas are indicated by $N_{i,\alpha}$ the ratios will be equal to the numerical value of :

$$\frac{N_{2,a}}{N_{1,a}};\quad \frac{N_{3,a}+N_{3,b}}{N_{2,a}+N_{2,b}};\quad \frac{N_{4,a}+N_{4,b}+N_{4,c}}{N_{3,a}+N_{3,b}+N_{3,c}}\quad \cdots\cdots (3)$$

The stars contributing to the numbers $N_{4,a}$; $N_{4,b}$; $N_{4,c}$ etc. will all be situated in one and the same shell as are the stars contributing to $N_{3,a}$; $N_{3,b}$ etc.

It is obvious that while the numerical values of the first few terms of these series are determined by the relative numbers of the blue and white stars contained in the field, the numerical values of the higher terms will increasingly depend on the numbers of red stars. It should be noticed that the groups of stars which for instance determine the values $N_{4,c}$ are of a magnitude different from those which determine the value of $N_{4,b}$ and $N_{4,a}$ With each of the terms in the series (3) a different range of magnitudes is involved. As long as there are no systematic errors in the determination of the color index, no systematic error in the scale of apparent magnitudes, no large probable error in either the determination of the color or magnitude and as long as there is no large cosmic scatter of the individual representative points along the main sequence, this difference in the location of the intervals will not seriously impair the determination of the ratios 3. But it is obvious that the above mentioned conditions will not always be fulfilled.

For the present we will suppose all conditions are met and will consider what to expect. This depends on whether the shell corresponding to the numbers $N_{1,a}$, is on the farther or nearer side of the region of maximum space density in the star cloud. If this shell is on the farther side of the cloud, the space density in the nearer shells will at first increase and this means that:

$$\log \frac{N_{2,a}}{N_{1,a}} > -0{,}6 \; ; \qquad \log \frac{(N_{3,a} + N_{3,b})}{(N_{2,a} + N_{2,b})} > -0{,}6.$$

When the space density remains a constant, the logarithm of the ratio is equal to $-0{,}6$. If the space densities decrease the logarithmic ratio will be < -0.6. Therefore this also corresponds to standard procedures which have been applied many times. If the shell $N_{1,a}$ is on the nearer side of the cloud, the rapid decrease of the numbers will set in at once and all logarithmic ratios will be $< -0{,}6$.

Let us next suppose that the cloud is of non recent origin, so that in the upper left part of the color magnitude diagram the representative points have moved away from the main sequence and a giant series is present. Presumably the numerical values of the first few terms in the series (1) will remain unaffected.

The areas *a*, *b* and *c* involved in those terms, correspond to regions where the stars are in a state of rapid transition (the Hertzsprung gap) in which only occasional stars occur. But as we proceed to the higher terms of the series, the relative influence of the yellow and red stars increases.

If yellow and red giants are present, they will cause the numbers in the nearer shell to be overestimated. If the numbers of yellow and red giants are sufficiently large, this ought to show up in the following way. With the nearer shells the ratios $\sum_{\alpha} N_{i,\alpha} / \sum_{\alpha} N_{i-1,\alpha}$ will at first indicate a rapid decrease of the numbers of stars. As soon as the areas α contain a substantial number of giants projected on them, the rate of decrease will become less. Therefore if the slope of the curve $\sum_{\alpha} N_{i,\alpha} / \sum_{\alpha} N_{i-1,\alpha}$ is studied over a sufficient wide range, this should enable us to decide whether a giant series is present or not and to estimate at what point the giant series sets in.

§ 3. The stars in the Sçutum cloud.

We have tried to apply this reasoning to the stars in dense clouds of the Milky Way. The only cloud for which the colors and magnitudes have been determined up to sufficiently faint limiting magnitude seems to be the Scutum cloud. This cloud has been studied by *Kreiken* (2, 1922) and by *Krieger* (3, 1929). The color magnitude diagram found by Kreiken has also been reproduced by *Lundmark* in the «Handbuch der Astrophysik» (4, 1932).

Unfortunately both studies have been published fairly long ago and at a time when modern foto-electric methods were still unknown. The study by *Kreiken* is based on measurements of λ_{eff} and contains stars up to $m = 15{,}5$, but the statistical limit of completeness certainly is not fainter than $15^m.0$.

The reduction of λ_{eff} to color was carried out with the help of a number of standard stars outside the cloud. As a parameter for the spectral type the values λ_{eff} are known to be poor for the spectral types A and F.

Apart from a field in the center of the Scutum cloud *Kreiken* has also measured the stars in two adjacent dark fields with heavy obscurations. The three fields have equal surface areas and it appears that in the obscured fields hardly any stars with $m < 15.0$ occur.

So unless the clouds of heavy obscurations are at a much smaller distance than the rich Scutum cloud, in the color magnitude diagram of the Scutum cloud there is hardly any influence of foreground stars.

The colors determined by *Krieger* are derived from fotographic and fotovisual magnitudes. He used long exposures in a small field and shorter exposures in a larger field. His longer exposures contain stars up to $m_f = 18.0$, but statistically his material seems not to be complete beyond $m_f = 17.0$. His shorter exposures contain stars up to a magnitude slightly fainter than $m_f = 15.0$ but the statistical limit of completeness was taken to be $m_f = 14.0$. *Krieger* has also directly determined the spectral types of a number of the brighter stars in this field and this enables him to reduce his colors to the scale of the I.A.U.

Direct counts in the lists of stars given by the two authors give the numbers $N_{i,\alpha}$. The results appear in the tables I and II. The numbers in table I are based on the lists given by *Krieger*, those in table II on the lists given by *Kreiken*. The areas *a*, *b*, *c* and the shells 1, 2, 3,.... correspond to areas and shells indicated in figure 1. As stated before, for the bright stars *Krieger* has studied a larger surface area of the Scutum cloud than with the faint stars. Therefore with the faint stars the observed numbers had to be multiplied with a correction factor equal to the ratio of surface area. All numbers in table I which appear on the right side of the thick broken line in the table, have been multiplied with this correction factor. Obviously these are the numbers of stars corresponding to a magnitude $m_f > 14.0$. In the final two columns of the table the values $\Sigma N_{i,\alpha}$ have been inserted and the logarithm of the ratios

$$\sum_{\alpha} N_{i,\alpha} \,/\, \sum_{\alpha} N_{i-1,\alpha}$$

From the values in the final columns of the table it would appear that the shells 1, 2 and 3 are on the farther side of the region of maximum space density in the Scutum cloud.

This is even more evident if the values

$$\log \sum_{\alpha} N_{i,\alpha} \,/\, \sum_{\alpha} N_{i-1,\alpha}$$

are plotted against the corresponding values i. Figure 2 shows the results. The figure has been drawn in such a way, that for $i = 4$ the curve based on the numbers in table II coincides with that based on those in table I. The values based on table I are indicated by filled circles, those based on table II by crosses. The full drawn line in the figure indicates the curve

$$\log \sum_{\alpha} N_{i,\alpha} \,/\, N_{i-1,\alpha} = -\,0.6$$

and therefore corresponds to uniform space density.

TABLE I.

Numbers $N_{i,\alpha}$ as obtained from the list of stars given by *Krieger*. For the meaning of the symbols i and α compare figure 1. For further explanation see text § 3.

Shell Area	a	b	c	d	e	f	g	h	i	j	k	l	m	$\sum\limits_{\alpha} N_{i,\alpha}$	$\log \frac{N_{i,\alpha}}{N_{i-1,\alpha}}$
12	—	—	—	—	—	—	—	—	—	—	0	23	35	23 + 35	
11	—	—	—	—	—	—	—	1	2	2	17	29		22 + 29	+ 0.35
10	—	—	—	—	—	—	—	—	2	17	12			19 + 12	+ 0.15
9	—	—	—	—	—	—	—	7	6	12				13 + 12	+ 0.12
8	—	—	—	—	—	—	8	29	35					37 + 35	+ 0.74
7	—	—	—	1	—	3	35	47						39 + 47	+ 0.37
6	2	—	—	4	10	29	204							45 + 204	+ 0.80
5	—	4	8	29	29	82								70 + 82	+ 0.58
4	4	9	32	23	82									68 + 82	+ 0.33
3	3	23	6	29										32 + 29	− 0.05
2	7	6	17											13 + 17	− 0.03
1	6	6												12	− 0.04

TABLE II.

Numbers $N_{i,\alpha}$ as obtained from the list of stars given by *Kreiken*. For explanation see text section 3. Stars with $m > 14.0$ are indicated in the same way as before but no reduction factor is applied.

Shell Area	a	b	c	d	e	f	g	h	i	j	k	l	m	$\sum_{\alpha} N_{i,\alpha}$	$\log \frac{\sum N_{i,\alpha}}{\sum N_{i-1,\alpha}}$
13	—	—	—	—	—	—	—	1	1	5	9	1		16 + 1	
12	—	—	—	—	—	—	1	1	8	7	11			17 + 11	+ 0.24
11	—	—	—	—	—	1	1	9	20	22				31 + 22	+ 0.49
10	—	—	—	—	—	—	8	27	26					35 + 26	+ 0.29
9	—	—	2	1	1	4	34	32						42 + 32	+ 0.32
8	—	—	3	1	2	18	39							24 + 39	+ 0.18
7	—	4	7	5	12	58								28 + 58	+ 0.55
6	2	5	13	53	70									73 + 70	+ 0.71
5	7	4	120	87										131 + 87	+ 0.48
4	34	131	110											165 + 110	+ 0.32
3	57	74												131	— 0.10
2	—													—	—
1	—													—	—

If from the data in our figure we have to assign a "distance„ to the cloud, this "distance„ would roughly correspond to the shell $i = 4$. From the way in which the curves in figure 1 were drawn, it follows that the distance modulus of this shell is about $m - \mathrm{M} = 5 \log r - 5 + \mathrm{A}r = 12$ magnitudes.

Although this value of the distance modulus is a rough estimate, it is of the same order as the earlier determinations by *Kreiger* and *Kreiken* (2, 1929) which are mainly based on the

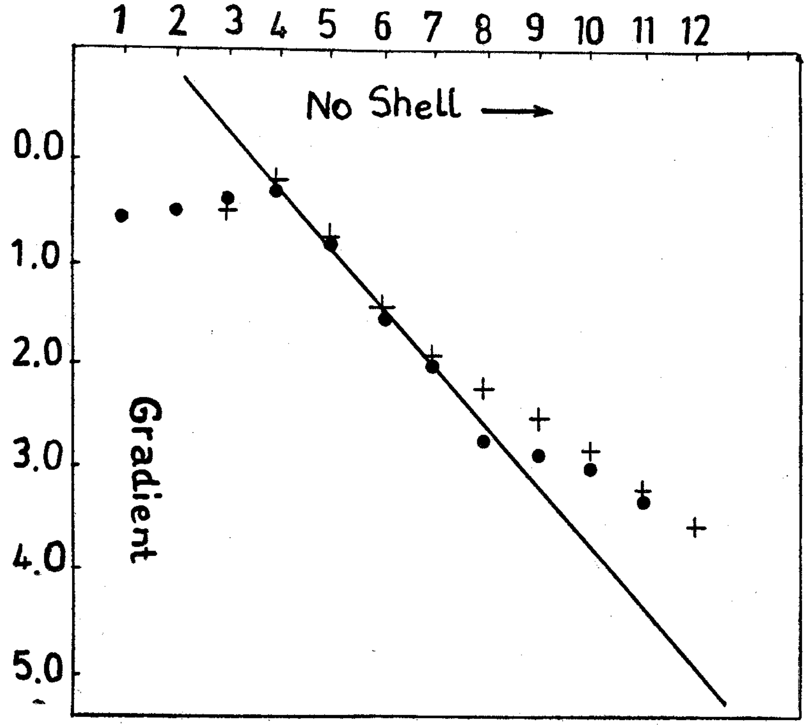

Fig. 2

stars of the earlier spectral types B and A, while in the present estimate these stars have largely been excluded. From figure 2 it would appear that in the shells with a distance larger than that of the shell 4, the space density rapidly decreases. But on the other hand while with the stars of early spectral types the region of maximum space density was fairly well determined, this is not the case in figure 2.

From $i = 4$ to $i = 7$ or 8 the space density seems almost to be a constant. With the shells for which $i > 8$ the space densities increasingly deviate from the curve of constant density. From a survey of the surrounding regions (see section 2) it would seem that the numbers of foreground stars are negligible. Consequently with the higher values of i we would expect the points indicating the space densities to fall below the curve of constant density. From figure 2 it appears that on the contrary all these points are above the curve of constant density.

With $i = 11$ the apparent space density is at least 20 times larger than could be expected. Therefore it is quite apparent that in the Scutum cloud the color magnitude diagram is not represented by a simple distribution of the representative points along the main sequence. In the cloud many stars must already have branched off the main sequence to form a giant series. It would seem that the influence of this giant series can be traced at least down to the shell $i = 7$. From the tables I and II it appears that the valuee $\sum_{\alpha} N_{i, \alpha}$ are mainly determined by the stars in the areas f, g and h with color indices from $+ 0.8$ to $+ 1.2$.

I do not think that our present material allows more than the general statement that a giant series is present.

In principle it would seem possible to derive to true relative numbers in the successive shells, by counting the numbers of stars of the earlier types and from these to derive a smoothed curve, from which the true ratios

$$\sum_{\alpha} N_{i, \alpha} \,/\, \sum_{\alpha} N_{i-1, \alpha}$$

can be read.

Next the numbers could be counted of the yellow and red stars in the faintest magnitude interval, that is to say, the interval one magnitude brighter than the statistical limit of completeness.

These numbers are substracted from the numbers in the nearer shells, but after having been multiplied with the appropriate reduction factor as read from the smoothed curve. The residuals would indicate the minimum numbers of giants. These would be scattered around certain mean magnitudes, the amount of scattering corresponding to the scatter of distances within the cloud. In that way a better determination of the giant series would be obtained and perhaps we could even hope to arrive at an estimate of the interval at which it branches off from the main sequence. Of this procedure a difficulty would be that with the very early types the main sequence is badly determined but perhaps we could avoid this difficulty by using only the later B and the A stars. The method seems simple and straightforward, but I do not think there is even a remote possibility to obtain any reliable results from our present material. The accuracy which can be obtained is insufficient. This is evident from even a superficial study of the numbers in the tables I and II. When the numbers $\sum_{\alpha} N_{i,\alpha}$ are computed for shorter ranges of α the result is that considerable fluctuations occur in the numerical values of $\log \sum_{\alpha} N_{i.\alpha} / \sum_{\alpha} N_{i-1,\alpha}$ given in the final column of the table. As far as can be judged from the present material these fluctuations are largely accidental. The magnitude of these fluctuations is such that it may be merely accidental that in figure 2 there is an excellent agreement between the two observed curves of which the one is based on the numbers in table I, the other on those in table II. It is readily seen that in the two tables the ranges of α in the numbers $N_{i,\alpha}$ are not identical. It will however be evident that when the procedure described was to be applied to the observed numbers the occurrence of condensations and deficiencies which are spurious will make it very difficult to trace the actual shape of the giant series. It could be argued that probably the fluctuations arise from accidental errors in the determination of colors and magnitudes, perhaps coupled with systematic errors in the determinations of colors and magnitudes, perhaps coupled with systematic errors in these determinations. But this makes it only more evident, that an attempt exactly to determine the shape and the location of the giant series in such condensation as the Scutum cloud, can better be postponed until modern foto-electric methods have been used to study a large range of magnitudes in the cloud.

§ 4. General Remarks and Conclusions.

The only definite result obtained in section 3 therefore is that the existence of a giant series among the stars in the Scutum cloud seems to be assured. Therefore many of the stars in the cloud must be of advanced age on the cosmic time scale. This does not imply that all stars in the cloud are of advanced age. Such would only be the case if the stars in the cloud could be considered as a group, perhaps a very extended cluster of stars, which were all born more or less simultaneously. However, in the lists published by *Krieger*, several bright B stars occur while in the color magnitude diagram published by *Kreiken* the main sequence can be traced up to at least the spectral type B_3. In these upper parts of the color magnitude diagram the main sequence is no longer very pronouced, but nevertheless it definitely is present. Obviously this implies that relatively young stars are also present in the Scutum cloud. This does not contradict our previous results but proves that even in such a conspicuous and dense Milky Way condensation as the Scutum cloud, the stars have not all condensed from interstellar material at one at the same time. The heavy obscurations by which the cloud is surrounded, indicate that even at present sufficiant material is available for new stars to be formed so that the occurrence of young stars is normal. The fact that these young stars occur even in the central parts of the cloud, indicates that even within a relatively short interval of time a thorough intermixture has taken place. This leads to the tentatively conclusion that considerable internal motions must be present. Apparently, therefore, the whole situation within the Scutum cloud is not so very much different from that prevailing in the immediate surroundings of our sun.

There is no reason why the mixture should be exactly the same in both cases and it would be interesting to know whether or not differences could be traced. As indicated above, in principle it should be possible to find an answer to this question but this must wait until modern observational techniques have been applied to this or other clouds.

We could summarize our results as follows :

a) The Scutum cloud seems to represent a knot in one of the spiral arms where originally large quantities of interstellar material were available.

b) At different times parts of this material have condensed into star. It may be presumed that in or near the cloud this formation of stars is still going on.

c) As a result of internal motions the older and younger stars have been intermixed.

d) Consequently among the stars in the Scutum cloud there both occur representatives of the young stars belonging to the upper end of the main sequence and of older stars in the stage of a giant series.

e) Therefore, the stars in the cloud cannot be considered as a homogeneous group, but as a heterogeneous mixture, more or less corresponding to that in surroundings of the sun.

f) As yet the observational material available does not permit any conclusions beyond these general statement, which partly at least were predictable.

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