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Luminosity Distribution and Shape of the Hyades Cluster

J. H. Oort

Sterrewacht-Huygens Laboratorium, P. O. Box 9513, Leiden, The Netherlands

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Summary. The distribution of stellar luminosities has been determined for the entire Hyades cluster. Members of the cluster have been identified from proper motions and radial velocities in a survey by van Bueren (1952) down to $B \sim 10.5$, from proper motions by Pels (1975) between $B \sim 10.5$ and ~ 13.0, and for selected regions down to $B \sim 16.0$; for the stars fainter than 10.5 the membership criteria have included photometric data obtained by Johnson et al. (1962) and by Upgren and Weis (1977). There appears to be a shortage of members fainter than $M_B = 9$ compared to the luminosity function of the general field in our vicinity.

A new map of Hyades brighter than 13.0 is presented. The outer regions show evidence of a flattening of the cluster parallel to the galactic plane, with an axial ratio of the order of 2.0; the cause of the flattening is not clear. The cluster may be slightly elongated in the direction of the galactic centre.

Key words: Hyades – clusters – luminosity distribution

1. Luminosity Distribution

A preliminary luminosity distribution of the Hyades was derived a few years ago by Pels et al. (1975, hereafter called Paper I) using the Hyades found in an extensive proper motion survey made by Pels between 1949 and 1962. The survey comprised all stars of the Astrographic Catalogue in the region α 3^h0^m to 5^h30^m; δ +1°0 to +30°0, except the zone +4°5 to +10°5 (which was being observed in Toulouse), and was intended to obtain a complete picture of the density distribution of the fainter Hyades. The data were practically complete to $B = 13.0$. In addition, in 16 fields of the Paris Carte du Ciel zone (the "deep fields") measurements were made to a fainter limit, around $B = 16.0$. The Carte du Ciel co-ordinates of the deep-field centres of interest for the present investigation are listed in Table 1. Each field covers an area of roughly 2°×2°.

It has turned out that the accuracy of the motions, though from two to three times better than that of other surveys for faint members, was insufficient for picking out unambiguously Hyades farther than about 4 pc, or 6°, from the centre (the cluster extends to 10 or 12 pc). In these outer regions faint Hyades can at present only be found by combining proper motion data with photometric observations. At the time of writing Paper I adequate photometry made especially for this purpose by Johnson et al. (1962) was available for about two thirds of the 99 stars found from the Astrographic Catalogue, but for none of the 20 faint stars in the

Table 1. Field centres for deep plates

δ	α				
+24°	3^h52^m	–		4^h24^m	4^h32^m
+22	–	4^h8^m	4^h16^m	4 24	4 32
+20	–	–	4 16	4 24	4 32
+18	–	–	4 16	4 24	4 32

Table 2. The Hyades between $B = 10$ and 13

Leiden no.	BD or Luyten no.	α (1950)	δ	B
2	+12°479	$3^h25^m54^s$	+13° 0.'0	10.65
3	+19 547	3 27 37	+19 55.7	12.18
6	+23 571	3 48 4	+23 45.3	11.39
7		3 49 40	+25 39.4	12.45
8	+12 530	3 52 15	+12 20.4	11.19
10	+17 679	4 2 47	+17 48.2	10.19
11	+19 650	4 0 45	+19 19.1	11.20
12		4 2 31	+19 18.4	12.76
14		4 5 40	+12 3.6	12.59
15	+14 653	4 4 11	+15 12.1	11.67
16	+16 558	4 4 52	+16 23.2	10.93
18	+23 622	4 5 36	+23 38.2	10.34
20	+23 635	4 8 56	+23 30.5	10.47
23	LP 474-197	4 12 4	+12 55.8	11.94
24	LP 474-205	4 12 21	+14 16.5	12.94
25		4 13 18	+18 45.7	13.35
26	+18 614	4 14 30	+18 54.5	12.06
27		4 12 11	+22 59.5	12.05
28	+22 666	4 14 8	+22 33.1	11.00
30	+17 704	4 15 29	+17 18.1	11.10
33	+10 568	4 19 39	+11 11.4	11.00
34		4 21 5	+13 56.2	12.18
35	+15 616	4 20 34	+15 38.9	11.74
36	+16 593	4 22 8	+16 52.3	11.31
37		4 22 31	+17 48.2	12.43
38	LP 358-202	4 21 9	+22 0.3	12.22

Table 2 (continued)

Leiden no.	BD or Luyten no.	α (1950)	δ	B
39	+17 715	4 21 23	+17 53.3	11.02
48		4 23 55	+12 34.5	11.88
49	LP 475-75	4 24 1	+13 1.6	11.62
50	+13 685	4 25 15	+13 45.5	9.86
51	+13 684	4 24 36	+14 9.0	11.50
52	+14 699	4 24 57	+14 18.5	10.41
53		4 25 19	+16 21.7	12.46
54		4 25 59	+16 10.8	12.03
55	+15 634	4 26 39	+16 8.2	11.47
56	+16 609	4 27 5	+16 33.9	9.93
57	+18 639	4 25 4	+18 23.4	11.24
58	LP 415-856	4 23 50	+21 7.4	12.60
59	+10 576	4 24 2	+10 45.6	10.49
60		4 29 37	+13 0.5	12.24
61	+15 638	4 27 44	+15 37.6	9.79
62		4 29 1	+15 23.6	12.38
63	+17 744	4 28 43	+17 36.2	10.52
64	+18 647	4 29 45	+19 0.5	11.61
65	LP 415-200	4 30 46	+18 54.6	11.92
66	+20 774	4 30 39	+21 2.8	11.92
75		4 30 57	+12 36.4	14.15
76	+16 630	4 33 8	+16 26.4	12.09
77	LP 415-1399	4 31 53	+20 17.5	12.42
79		4 31 24	+11 27.3	13.15
80	+12 623	4 37 3	+12 37.9	11.12
81	LP 475-254	4 38 41	+13 7.6	12.69
82	+16 640	4 37 33	+16 25.1	10.56
83		4 35 31	+17 26.6	11.31
85	LP 358-493	4 36 56	+23 2.5	12.78
90	+16 646	4 40 22	+16 58.6	10.85
91		4 44 44	+14 48.1	12.89
92	+17 782	4 43 55	+17 39.6	10.55
93	LP 359-220	4 44 25	+22 57.8	11.79
94	+10 618	4 40 45	+11 4.5	11.45
95	LP 416-43	4 45 8	+16 58.1	12.62
96	+16 655	4 47 8	+16 19.6	11.77
98	+18 746	4 49 28	+18 54.9	11.36
101	+13 741	4 54 11	+13 50.1	12.11
104		4 58 46	+13 51.7	12.76
107	+13 783	5 0 18	+13 39.6	9.78
118		4 35 19	+ 4 34.2	12.87
119		4 43 41	+ 3 32.8	12.19

"deep fields". It was therefore impossible to derive the luminosity distribution for the faint stars.

Upgren and Weis (1977) have recently completed an accurate photometry for most of the 119 stars listed in Table 2B of Paper I. This enables us to obtain at least a rough determination down to $B \simeq 15$.

Table 3. Hyades between $B \sim 13.0$ and 16.0 in thirteen $2° \times 2°$ fields

Leiden no.	Luyten no.	α 1950	δ	B
40	LP 415-794	$4^h22^m20^s$	$+18°51'.6$	14.30
41	LP 415-27	19 46	+18 9.1	14.52
42	LP 415-65	22 19	+17 8.9	14.75
44		16 32	+21 38.1	15.55
68		25 35	+17 35.2	13.64
69		28 35	+17 36.8	13.38
70		29 30	+17 38.8	14.30
71	LP 415-121	26 6	+18 33.9	14.61
72	LP 415-109	25 4	+18 39.0	15.80
73	LP 358-351	26 39	+21 33.6	15.76
74		30 22	+23 53.2	14.14
86	LP 415-1582	33 9	+18 47.3	15.02
87	LP 415-1619	33 44	+18 31.0	14.77

A practically complete list of Hyades brighter than $B = 13.00$ up to 15° from the centre of the cluster may be obtained by combining Table 2A of Paper I with Table 2 below. The former contains essentially the Hyades of Van Bueren's 1952 catalogue (Bull. Astr. Inst. Neth, *11*, 385) with some rejections explained in the remarks following Table 2A of Paper I. The total number remaining is 148; they are mostly brighter than $B = 10.5$. Table 2 gives the fainter members, down to $B \simeq 13.0$, found by Pels in his comprehensive search over the entire region covered by Van Bueren's catalogue. Details on these stars are given in Table 2B of Paper I. A number of the stars suggested as members on the basis of their proper motions had to be rejected on the evidence of photometric data by Johnson et al., and were marked as such in Table 2B. Upgren and Weis' subsequent photometry has indicated which additional stars, not observed by Johnson et al., had to be rejected for the same reason. The remaining list of 68 Hyades between roughly $B \simeq 10.5$ and $B \simeq 13.0$ is given in Table 2. The list should be nearly complete, except for the zone between $+4°.5$ and $+10°.5$ declination which was not observed by Pels.

Thirteen additional members found in the fields searched to a fainter limit are collected in Table 3.

In each table the first column contains the Leiden no. which is required to identify the stars in Table 2B of Paper I which contains the proper-motion evidence for this membership. The second column gives the *BD* No.; in case the star is not in the *BD* but does occur in Luyten's catalogue of about 4600 proper motions in the region of the Hyades (Luyten, 1971) the Luyten No. is given. Most of the latter and about half of the *BD* stars had been marked by Luyten as possible Hyades. He marked 543 stars as such, but remarked that probably only a small fraction would be genuine members. A few stars in Tables 2 and 3 had previously been assigned to the Hyades by other investigators, viz., Nos. 34, 53, 54, and 62 by van Rhijn and Raimond (1934), Nos. 37 and 83 by Osvalds (1952), No. 70 by Humason and

Table 4. Luminosity distribution

B	M_{pg}	Table 2A	Table 2 corr.	"Carte" corr.	n (total cluster)	log n	m.e.
3.00– 3.99	0.5	1			1	0	
4.00– 4.99	1.5	14			14	1.15	± 0.13
5.00– 5.99	2.5	15			15	1.18	± 0.13
6.00– 6.99	3.5	20			20	1.30	± 0.10
7.00– 7.99	4.5	29			29	1.46	± 0.08
8.00– 8.99	5.5	25			25	1.40	± 0.09
9.00– 9.99	6.5	30	4		34	1.53	± 0.08
10.00–10.99	7.5	12	11		24	1.38	± 0.09
11.00–11.99	8.5	1	26		30	1.47	± 0.09
12.00–12.99	9.5		24		26	1.42	± 0.09
13.00–13.99	10.5		2	3	19	1.30	± 0.25
14.00–14.99	11.5			7	44	1.66	± 0.17
15.00–15.99	12.5			4	25:	1.40:	± 0.24

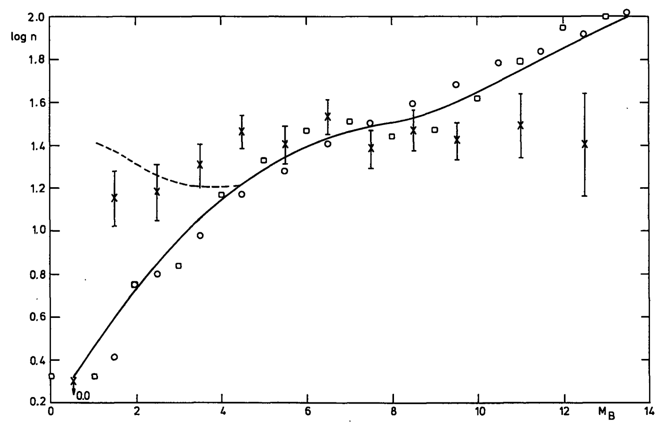

Fig. 1. Luminosity distribution. Crosses: Logarithms of numbers of Hyades in the entire cluster. Mean errors are indicated by vertical bars. Full drawn curve and circles and squares: general luminosity distribution according to Luyten and van Rhijn, respectively. Dashed curve: Salpeter's "initial luminosity curve". All adjusted so as to co-incide with the numbers of Hyades between M_B+5 and $+9$

Zwicky (1947), and Nos. 68 and 69 by Van Altena (1969). I am indebted to Luyten for these references.

Among the stars for which the photometric data have confirmed their membership only two show a difference of more than 0".019 between the observed value of μ_δ and that expected for a member of the Hyades. They are No. 79, with $\Delta\mu_\delta = -0''.020$, and No. 94, with $\Delta\mu_\delta = +0''.028$. The membership of No. 79 has been confirmed by a radial-velocity measurement (Griffin, private communication).

In Figs. 1 and 2 of Upgren and Weis a considerable number of points lie considerably above the main sequence. Practically all of these refer to stars that are considered to be members of the cluster. Upgren and Weis ascribe their deviations to duplicity. On this basis they consider that among the 81 genuine Hyades in Table 2B of our Paper I there are 17 unresolved binaries. In 4 of these the binary character is supported by data on radial velocities which were obtained by Griffin and Gunn in a comprehensive programme of velocity measurements in the Hyades. For the others no sufficient velocity data are yet available. I am indebted to Dr Griffin for this information. It may be mentioned that the deviations from the main sequence are often quite large: in 7 cases it exceeds $1^m.0$ in either or both of the diagrams.

The data for the stars whose membership is confirmed by photometry are summarized in Table 4. The third column gives the Hyades in the list compiled by van Bueren (1952) and contained in Table 2A of Paper I. The fourth column, marked Table 2 corr., refers to the photometrically confirmed Hyades in Table 2B of Paper I as collected in the above Table 2. These are almost complete to $B=13.0$, except that the Toulouse zone of the Astrographic Catalogue was not surveyed. A factor of 1.10 has been applied to the numbers in column "Table 2" to correct for this incompleteness. The column "Carte" corr. contains those Hyades found on the deep plates whose membership was confirmed by Upgren and Weis. The total surface surveyed in the relevant deep fields is 48 square degrees, situated at distances between 0.5 and 6 pc from the centre. In order to find the numbers of faint stars in the entire cluster I assumed that the density distribution of the faint stars is the same as that for the bona fide Hyades of Table 2B of Paper I. Of these latter 12 are situated in the fields of the deep plates, while the total for the whole cluster is 64. The numbers in the column "Carte" should therefore be multiplied by 64/12 to obtain the total for the cluster. The factor actually applied was 6.2, which takes into account the lacking Toulouse zone.

The total numbers thus obtained are shown under *n* (total) and under log *n*.

The second column gives the mean photographic absolute magnitude for an assumed distance of 40 pc, for which $m-M=3.0$. The results are shown graphically by crosses in Fig. 1. Vertical bars indicate the statistical mean square errors.

Circles and squares indicate the luminosity distribution for the vicinity of the Sun, as derived by Luyten (1968) and van Rhijn (1936) respectively (cf. van Rhijn, 1965), the ordinates of both were adjusted so as to coincide with the numbers of Hyades between $M_B=+5$ and $+9$. The curve indicates the smoothed average of Minneapolis and Groningen.

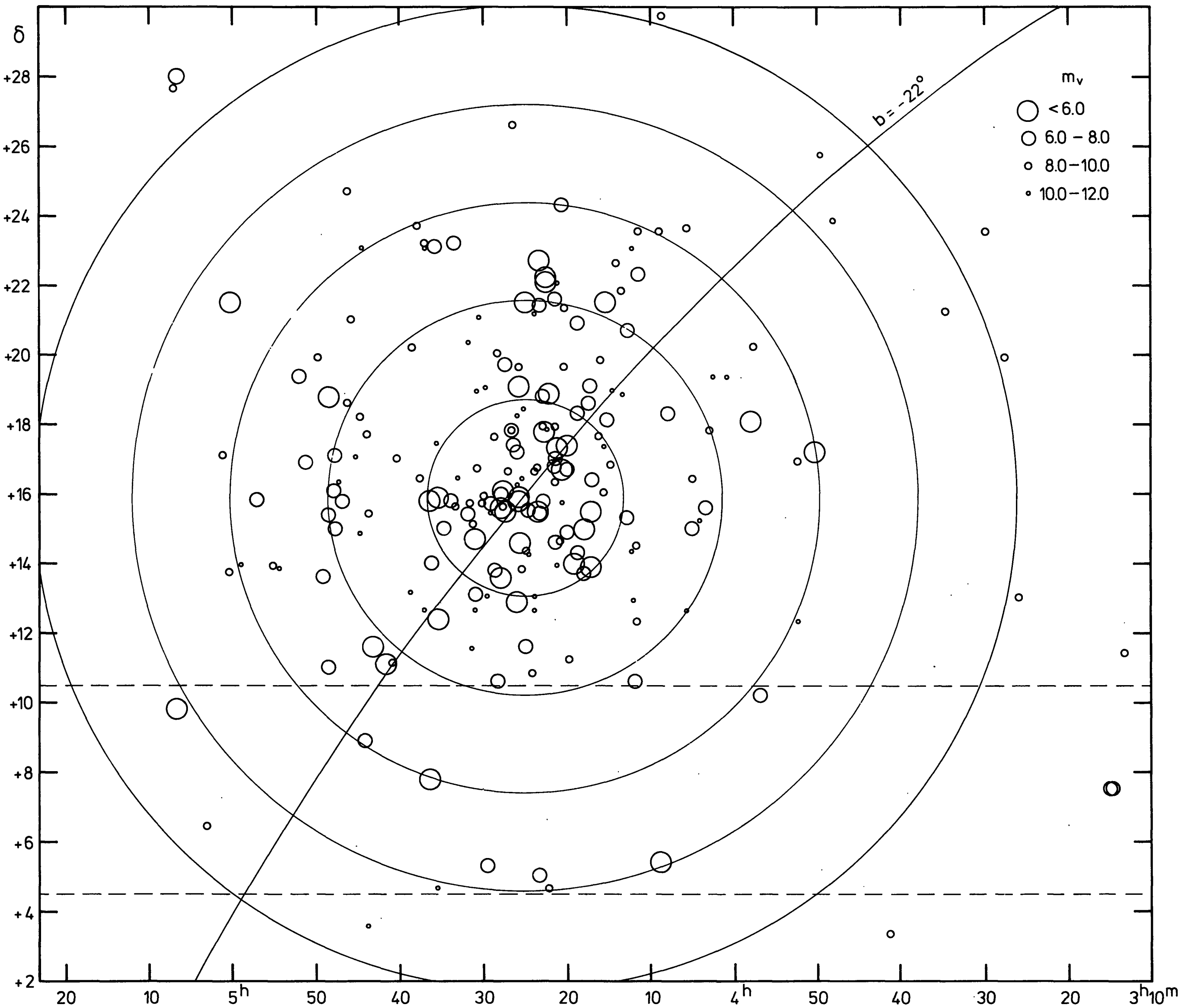

Fig. 2. Distribution of Hyades brighter than $V=12.0$. The lines at $\delta=+4.5$ and $+10.5$ indicate the limits of the Toulouse zone of the Carte du Ciel where the stars fainter than $V\simeq 9.5$ have not been observed. The circles have radii of 2, 4, 6, 8, and 10 pc

For M_B between $+1$ and $+5$ the Hyades are between 2 and 3 times more numerous than the values shown by the curve. The difference may be ascribed to the shortage of bright stars in the general luminosity curve caused by the shorter lives of these stars. In fact, Salpeter's "initial luminosity curve" (Salpeter, 1955) indicated by the dashed curve in Fig. 1 agrees reasonably well with the Hyades up to $M_B \sim +2$. The still brighter stars have disappeared in the Hyades as a consequence of its evolution[1].

At the faint end the Hyades seem to be relatively less numerous than what would be expected from the luminosity curve. At first sight one is naturally inclined to ascribe the relative shortage of faint stars to an increased rate of escape for stars of small mass. Numerical simulations have indicated, however, that except for a relatively small number of heavy stars that become concentrated near the centre the escape rate is almost independent of the mass (cf. Aarseth, 1973, pp. 25 and 36; Wielen, 1975, p. 119; Aarseth and Woolf, 1972). It may be noted that the Hyades themselves provide some relevant observational evidence, in that, outside the central region, the distribution of bright and faint stars is practically identical (Paper I, Figs. 2 and 3). Although this conclusion may not be final, the evidence suggests that the observed shortage of faint stars may reflect a difference in the birth function of stars of different mass between the Hyades and the stars at large.

Extensive surveys for faint members have been made by several astronomers, in particular Osvalds (1952), Luyten (1971 and references therein), and van Altena (1969). Luyten surveyed a considerable area and indicated 543 fainter stars as possible members. By inadvertence in Paper I no mention of his investigation was made, for which we wish to apologize. We had orig-

1 Among the stars in the interval B 4.00–4.99 (M_B 1.0–2.0) there are 4 K_0 giants. For a comparison with Salpeter's "initial luminosity curve", which refers to main-sequence stars, these should be removed. This would lower the point at $M_B=+1.5$ in Fig. 1 by 0.15

Table 5. Flattening of the cluster (numbers in different quadrants)

r (pc)	NW + SE	NE + SW
<4	67	58
4–12	47	29

Table 6. Search for elongation in radial direction

b	Δb	n	$[\mu/\mu_H]$	r/r_H
−32° to −25°	−10° to to − 3°	10	1.078	1.074
−19° to −16°	+ 3° to + 6°	17	0.993	0.948
−16° to −12°	+ 6° to +10°	11	0.965	0.930

inally intended to include a comparison with his data for the determination of our mean errors, but finally left it out because it did not provide new information on these errors. However, the reference to his work remained in the list of References. Van Altena investigated an area of 40.5 square degrees around the centre, extending to $r=2$ pc. He indicated 90 as probable main sequence members.

In the cases of Luyten and van Altena the mean errors are so large (Luyten, 1971, estimates them at $\pm 0''.020$) that many of the stars indicated as "probable" or "possible" members must be spurious. In fact, Luyten states that probably only a small fraction of his 543 stars would be genuine Hyades. For the present they are therefore of no use for investigating the luminosity distribution. Van Altena's material is likely to contain less spurious members because he studied an area near the centre, where the percentage admixture of field stars must evidently be less. Nevertheless the comparison with our data (given in Sect. 9 of Paper I) showed that about 20% of the stars designated by him as Hyades were spurious. This was for stars between m_B 10 and 13. For the fainter stars, where the relative number of background stars increases considerably it may have seriously affected van Altena's luminosity distribution, which was indicated by filled circles in Fig. 6 of Paper I. This shows a very slight rise between $M_B=+4$ and $+14$. His region contains roughly one third of the total number of Hyades.

2. The Density Distribution

Figure 2 shows the distribution of the Hyades brighter than $V=12.0$ identified by the combination of Pels's proper motion data and the photometric data of Johnson, Mitchell and Iriarte, and of Upgren and Weis. Presumably the map is practically complete over the entire region outlined, except that the Toulouse zone of the Carte du Ciel (between $\delta=+4^\circ.5$ and $+10^\circ.5$, indicated by dashed lines) was not included in Pels's survey and stars fainter than $V\simeq 9.5$ are therefore lacking in this zone. A comparison with Fig. 1(a) in Pels, Oort and Kluyver (1975) shows that a considerable number of faint stars beyond 8 pc from the centre have been excluded on the basis of the new photometric data. The asymmetry in the distribution of these stars in the former figure has thereby disappeared.

The space density distribution was checked by including the information yielded by the new photometry. No significant difference from the densities obtained in Paper I was found. This is not surprising, as the systematic effect of spurious members had previously been determined from the stars for which photometric data were available at the time of writing Paper I, and a correction for this effect was applied to the stars without photometric data.

There is no change in the section of Paper I dealing with the escaping stars. The outlying members discussed in that section are all bright stars, for which complete information on photometry, spectral type and radial velocity was available at the time of writing Paper I.

Aarseth's discussion of the role played by heavy binaries in the evolution of clusters, and his suggestion that the triple star 80 Tauri in the Hyades nucleus (No. 80 in Table 2A of our Paper I) may have absorbed a large fraction of the initial energy of the cluster, has now been published (Aarseth, 1977). It should be noted that the concentration of massive stars in which 80 Tauri is situated lies slightly off the geometric centre of the cluster, viz. $0^\circ.5$, or 0.3 pc, East of it.

One aspect needs, however, to be rediscussed, viz., the flattening parallel to the galactic plane. In Paper I (p. 439, column 1) Pels et al. commented on the absence of clear signs of such a flattening, and noted an apparent discordance in this respect with computer simulations of cluster evolution made by Aarseth (1973), which gave axial ratios of about 2:1 for the outer third of a similar cluster. Aarseth has informed me that other computed models gave much the same general flattening in the z-direction.

The statement on the absence of flattening of the cluster must be revised. There is now a fairly clear indication of such a flattening in the outer region. This may be seen in Table 5, which gives a comparison of the members in the North-West and South-East quadrants (which are roughly parallel to the galactic equator) with those in the North-East and South-East quadrants for two ranges of distance r from the centre. For $r>4$ pc the ratio between the number in the NW+SE quadrants to that in the NE+SW quadrants is $1.62^{+0.46}_{-0.31}$ m. e.

Because the cluster lies at a latitude of 22° the flattening as seen from the Sun will be less than the actual flattening. A spheroid of axial ratio 2 :1 observed under an angle of 22° with its equatorial plane will show an apparent axial ratio of only 1.65, and the corresponding ratio of the counts in the outer parts of the quadrants would be 1.45, in approximate agreement with the numbers in Table 5.

The significance of this agreement is uncertain. Wielen has reminded me of the fact that the equipotential surfaces of a cluster in the gravitational field of the Galaxy are elongated in the direction towards the galactic centre, the ratios of the radial, transverse and z-axes being as 2.0 :1.4 :1.0 for the outermost potential surfaces. As the Hyades lie at 180° longitude it is the latter ratio which we should observe; at the latitude of 22° this would be reduced to 1.26; the corresponding ratio of the counts in the two pairs of quadrants is then at most 1.11. This seems at variance with what is observed and with the results of the simulations mentioned above.

If the cluster's outer contours would be mainly determined by the regular galactic field and be strongly elongated in the radial direction the part below −22° latitude should be nearer than that above −22°. In looking for such an effect I have taken the brighter Hyades (those in Table 2A of Paper I) in a longitude interval of 12° around the Hyades centre and compared their proper motions to the motions μ_H which they would have if situated at the average distance of the Hyades. Table 6 gives the average values of μ/μ_H in three interval of b. The last column gives the distance ratio expected if the Hyades would be elongated like the potential surfaces; n is the number of stars.

The data are evidently too meagre for a definite conclusion. The most one can say is that they do not contradict the existence of such an elongation.

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