THE GAP IN THE H-R DIAGRAM OF OPEN CLUSTERS WITH SPECIAL REFERENCE TO NGC 2169, NGC 1778 AND Tr 1

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(Received October 8, 1977 ; revised March 28, 1978)

Abstract

The colour-magnitude diagrams of the open clusters NGC 1778 and Tr 1 indicate the presence of gaps on the rising branches of the evolving main sequences. The positions of these gaps are compared with those found in other clusters and the effect of evolution on the position of the gap is discussed. The initial luminosity functions of these clusters as also for NGC 2169, closely fit the respective cluster luminosity functions.

INTRODUCTION

In the H-R diagrams of open clusters, a gap on the rising branch of the evolving main sequence has been noticed for several clusters, e.g., NGC 2477 (Eggen and Stoy 1961), NGC 752 (Eggen 1963), M67 (Eggen and Sandage 1964), NGC 188 (Eggen 1969), the Hyades (Eggen 1970). This gap is an indicator of the presence and size of the convective core and the evolution of the respective cluster. In this communication, a study of this gap has been carried out with special reference to the open clusters NGC 2169, NGC 1778 and Tr 1.

The luminosity functions for clusters NGC 2169, NGC 1778 and Tr 1 have also been studied.

EVOLUTIONARY EFFECT ON THE POSITION OF THE GAP

A gap in the evolving part of the main sequence can be explained in terms of the rapid contraction of the core (on a gravitational contraction time scale), following hydrogen exhaustion, in stars that have an overshoot mixing of the convective core that precedes the hydrogen burning in the shell (Aizenman *et al.* 1969; Maeder 1974b; Prather and Demarque 1974).

Table 1 lists the gap parameters and the turnoff colours for 16 open clusters in which the gap is clearly visible in their colour-magnitude diagrams. The relations between M_V^b and M_V^f, respectively the luminosities at the brighter and fainter ends of the gap, and the intrinsic turnoff colour, $(B-V)_0^t$, are shown in Figs. 1a and 1b respectively. From these figures, considering that the turnoff colour of a cluster gets redder with its age (Gray 1963), one infers that, for clusters older than 2.6 $\times 10^7$ years, the luminosities of the brighter and the fainter ends of the gap (and hence the position of the gap itself) generally move towards the fainter side as the age of clusters increases. The corresponding linear regression lines are :-

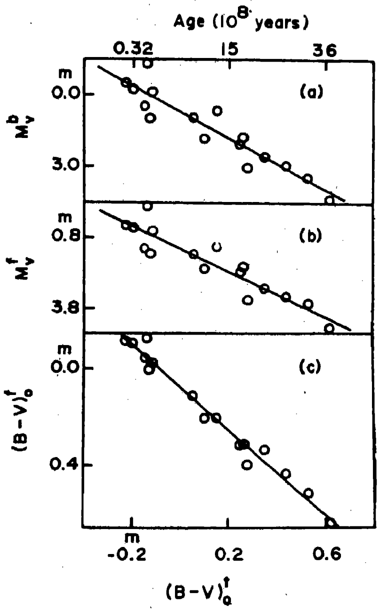

Fig. 1 : Dependence of gap parameters on age. (a) Plot of M_V^b vs $(B-V)_0^t$; (b) Plot of M_V^f vs $(B-V)_0^t$; (c) Plot of $(B-V)_0^f$ vs $(B-V)_0^t$.

TABLE 1

Gap parameters for open clusters

Open Cluster	Gap width ($\triangle$V)	Limit of Fainter end of the gap M_V^f	Limit of Brighter end of the gap M_V^b	(B-V)o at the fainter end of the gap $(B\text{-}V)_0^f$	Turn-off colour $(B\text{-}V)_0^t$	References
	m	m	m	m	m	
NGC 188	0.20	4.53	4.33	0.63	0.62	Eggen and Sandage (1969)
NGC 752	0.35	2.93	2.58	0.33	0.35	Eggen (1963)
NGC 1778	0.60	0.45	–0.15	–0.03	–0.12	Joshi *et al.* (1975)
NGC 2360	0.25	1.97	1.72	0.31	0.26	Eggen (1968)
NGC 2477	0.38	3.39	3.01	0.39	0.28	Eggen (1963), Eggen and Stoy (1961)
NGC2632(praesepe)	0.48	1.12	0.64	0.20	0.15	Johnson (1952)
NGC 2682 (M67)	0.20	3.62	3.42	0.51	0.53	Eggen and Sandage (1964)
NGC 3680	0.30	3.24	2.94	0.43	0.44	Eggen (1969)
NGC 6087	0.77	1.22	0.45	–0.05	–0.15	Fernie (1961)
NGC 6939	0.02	2.2	2.00	0.31	0.25	Cannon and Lloyd (1969)
Coma	0.56	1.48	0.92	0.11	0.05	Johnson and Knuckles (1955)
Hyades	0.24	2.04	1.80	0.20	0.10	Johnson and Knuckles (1955)
Pleiades	0.78	–0.56	–1.34	–0.13	–0.14	Johnson and Mitchell (1958)
Tr 1	0.70	0.20	–0.50	–0.12	–0.23	Joshi and Sagar (1977)
Tr 2	0.47	1.45	0.98	0.00	–0.13	Pandey (1978)
α Per	0.56	0.32	–0.24	–0.11	–0.20	Mitchell (1960)

$$M_V^b = 0.72 + 5.40\,(B\text{-}V)_0^t;\ \sigma M_V^b = 0^m58; \quad (1)$$

$$M_V^f = 1.24 + 4.77\,(B\text{-}V)_0^t;\ \sigma M_V^f = 0^m54. \quad (2)$$

Likewise, the relation between the colour $(B\text{-}V)_0^f$ at the fainter end of the gap and $(B\text{-}V)_0^t$ is linear (Fig. 1c) and is given by

$$(B\text{-}V)_0^f = 0.07 + 0.87\,(B\text{-}V)_0^t;\ \sigma(B\text{-}V)_0^f = 0^m04 \quad (3)$$

Following Maeder (1974a), we have also plotted in Fig. 2, the observed values $\triangle V\ (= M_V^f - M_V^b)$ of the gap as a function of the colour at the fainter end of the gap, $(B\text{-}V)_0^f$. However, contrary to the inference by Maeder (1974a), we find that none of the models given by Iben (1967) or by Hijlesen *et al.* (1972) (HJPR) explain the variation of $\triangle V$ with $(B\text{-}V)_0^f$. In fact, the data seem to indicate a nearly linear relationship between these two parameters given by the least square regression equation

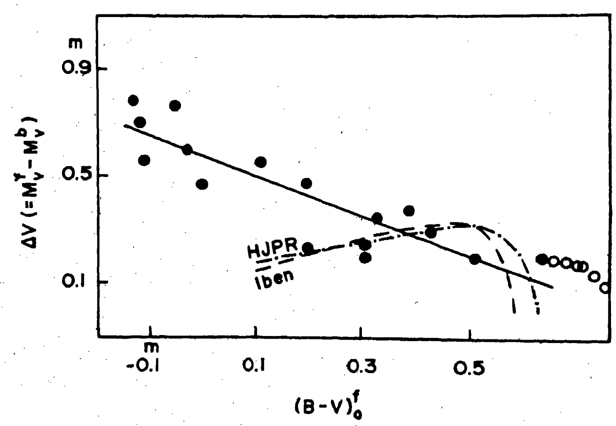

Fig. 2: $\triangle V$ as a function of $(B\text{-}V)_0^f$. Solid line represents the regression line, dashed line represents the values based on Iben's model and the dashes & dots represent the values based on Hijlesen's model. Filled circles represent the observed points and open circles represent the points based on the model by Prather and Demarque.

$$\triangle V = 0.58 - 0.74\ (B-V)_o^f;\quad \sigma_{\triangle V} = 0^m.10, \qquad (4)$$
$$-0^m.15 < (B-V)_o^f < 0^m.65.$$

The conclusions by Maeder were perhaps based on too meagre data.

Since $(B-V)_o^f$ is related to the age of the cluster through an intermediate parameter $(B-V)_o^t$, (vide Fig.1c), one can infer that within the limits included in our discussion, the gap width generally diminishes with cluster age.

We have also plotted in Fig. 2 the gap width calculated on the model by Prather and Demarque (1974), where they have taken into account the effect of the overshoot mixing of the convective core. Although these values are somewhat higher than those obtained by the relation (4) but in better agreement than the values obtained on the models by Iben and HJPR. The value of the gap width based on the model by Prather and Demarque (1974) decreases as the cluster age increases from 4×10^9 years to 10×10^9 years but what happens to the gap width if the cluster is younger than 4×10^9 years and older than 2.6×10^7 years is not known.

Relations (1), (2), (3) and (4) can be used to obtain the approximate estimates of reddening and of apparent distance modulus for clusters whose colour-magnitude diagrams show the above type of gaps, since the extent of the gap is independent of reddening.

THE CLUSTERS NGC 2169, NGC 1778 AND TR 1

The results of the UBV photoelectric photometry of the open clusters NGC 2169, NGC 1778 and Tr 1, carried out at the Uttar Pradesh State Observatory have been reported earlier (Sagar 1976; Joshi *et al.* 1975; Joshi and Sagar 1977) and are summarised in Table 2. For each of these clusters, its apparent distance modulus and colour excess E(B-V) have been used to convert the apparent visual magnitude and the observed (B-V) colour of each of its member stars into the absolute V-magnitude M_V, and the intrinsic colour $(B-V)_O$, respectively. These in turn have been used for the construction of the composite colour-magnitude diagram (CMD) for the clusters. The reality of the observed gaps in the CMD is tested by the chi-square criterion (Hawarden 1971). The probability that the gap is an accidental result is about 2 per cent for NGC 1778 and 3.4 per cent for Tr 1.

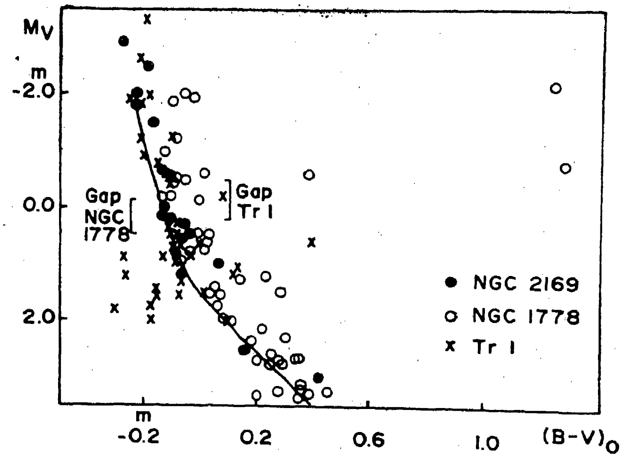

Fig. 3 : Composite colour-magnitude diagram for three open clusters. The gaps in the CMD'S of NGC 1778 and Tr 1 are marked.

The observed luminosity function for each cluster has been obtained by counting the stars, excluding giants, lying within one magnitude intervals. The general luminosity function $\phi(M_V)$ and the initial luminosity function $\psi(M_V)$ (Sandage 1957), for each of the clusters, have been normalised for the number of stars observed in the respective cluster, and then compared to the observed luminosity function of the cluster.

COLOUR-MAGNITUDE DIAGRAM

A composite CMD of the open clusters NGC 2169' NGC 1778 and Tr 1 is plotted in Fig. 3. The solid line represents the zero age main sequence (ZAMS).

A. NGC 2169

The CMD for NGC 2169 extends from $M_V = -2^m.9$ to $+3^m.0$ and no evolutionary effect is apparent. The cluster is star deficient and no definite gap is found. Nine out of the seventeen cluster stars populate the ob-

TABLE 2

Data of the clusters

Cluster	Apparent distance modulus	Distance(Kpc)	Colour Excess E(B-V)	Age (10^7 years)	Reference
NGC 2169	$10^m.63$	0.83	$0^m.18$	0.9	Sagar (1976)
NGC 1778	12.20	1.26	0.34	16	Joshi *et al.* (1975)
Tr 1	13.30	3.3	0.52	2.6	Joshi and Sagar (1977)

served main sequence of the CMD in the magnitude interval $-0^{m}\!.1 < M_V < 1^{m}\!.2$, with only two stars populating the fainter end of the observed main sequence.

B. NGC 1778

The CMD for this cluster extends from $M_V = -2^{m}\!.2$ to $+ 3^{m}\!.3$ (Fig. 3). The brighter end of the observed main sequence terminates near $M_V = -2^{m}\!.0$, $(B-V)_0 = -0^{m}\!.05$. The stars brighter than $M_V = 0^{m}\!.0$ appear to evolve off the ZAMS and two such stars have moved off the ZAMS to the giant phase. In the rising branch of the evolving main sequence, their is a gap in the magnitude interval $-0^{m}\!.15 < M_V < 0^{m}\!.45$.

C. Tr 1

The CMD extends from $M_V = -3^{m}\!.3$ to $+ 2^{m}\!.0$ (Fig. 3). The brighter end of the observed main sequence terminates near $M_V = -3^{m}\!.3$, $(B-V)_0 = -0^{m}\!.20$. Any evolutionary effect is barely visible, but no giant branch appears. The stars brighter than $M_V = -2^{m}\!.0$ appear to be evolving off the ZAMS. In the rising branch of the evolving main sequence, a gap appears in the magnitude interval $-0^{m}\!.50 < M_V < 0^{m}\!.20$. Most of the stars populate the main sequence of the CMD in the magnitude interval $0^{m}\!.10 < M_V < 1^{m}\!.10$. A group of stars situated in the region $M_V > 0^{m}\!.30$ and $(B-V)_0 < -0^{m}\!.15$ is well below the ZAMS.

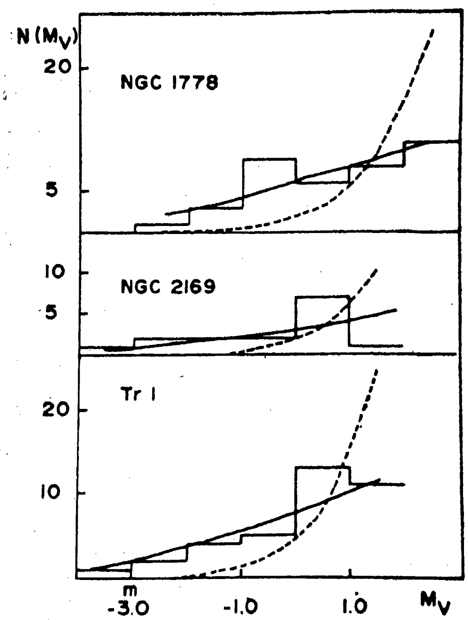

Fig. 4: The luminosity functions for NGC 2169, NGC 1778 and Tr 1. The histograms are the observed luminosity functions of the clusters. Dotted lines represent the respective general luminosity function and the continous lines the respective initial luminosity function.

The composite CMD (Fig. 3) shows that NGC 2169 ,Tr 1 and NGC 1778 are in increasing order of age, which is in agreement with the results of Table 2. The gaps in the rising branch of the evolving main sequence of NGC 1778 and Tr 1 are similar to those found in

TABLE 3

Luminosity functions of the three open clusters

Magnitude interval	NGC 2169			NGC 1778			Tr 1		
	Numbers observed (n)	$\phi(M_V)$	$\psi(M_V)$	Numbers observed (n)	$\phi(M_V)$	$\psi(M_V)$	Numbers observed (n)	$\phi(M_V)$	$\psi(M_V)$
—4 to —3	1	0.0	0.7	—	—	—	1	0.0	1.7
—3 to —2	2	0.1	1.3	1	0.1	2.3	2	0.2	3.0
—2 to —1	2	0.2	1.9	3	0.2	3.6	4	0.6	4.6
—1 to 0	2	1.0	2.7	9	0.9	5.2	5	2.3	6.6
0 to +1	7	3.3	3.7	6	3.9	7.0	13	8.0	8.8
+1 to +2	1	10.4	4.7	8	9.4	8.9	11	24.9	11.3
+2 to +3	2	—	—	11	24.4	11.0	1	—	—
+3 to +4	—	—	—	7	—	—	—	—	—
Total	17	15	15	45	38	38	37	36	36

other open clusters. The gap in Tr 1 is situated towards brighter side as compared to that of NGC 1778, which again indicates that Tr 1 should be younger than NGC 1778.

From the earlier discussion it can be inferred that :-

(i) NGC 2169 is so young that its stars have not yet reached the hydrogen exhaustion phase (HEP), which is also supported by its age.

(ii) The stars, brighter than $M_V = -0^m.15$ in NGC 1778 and those brighter than $M_V = -0^m.50$ in Tr 1 have passed the HEP.

LUMINOSITY FUNCTION

In Table 3, we compare the luminosity function of each of the clusters with its normalised general luminosity function, $\phi(M_V)$, and the initial luminosity function, $\psi(M_V)$. The luminosity functions for the three clusters are also shown in Fig. 4. Inspection of these figures shows that $\psi(M_V)$ is a considerably better approximation to the cluster luminosity function than $\phi(M_V)$. The close fit of $\psi(M_V)$ to the cluster luminosity function provides an observational test of the theory of stellar evolution (Sandage 1957). The poor fit of the general luminosity function with cluster luminosity function at the brighter end shows that the cluster stars are much younger than the general field stars while the poor fit at the fainter end shows that faint field stars have been well segregated from the cluster stars. The apparent dip in the observed luminosity function for NGC 1778 (Fig. 4) around $M_V = +0^m.50$ is caused by the gap in the colour-magnitude diagram of that cluster. A sudden increase in the observed luminosity function for NGC 2169 (Fig. 4) and Tr 1 (Fig. 4) around $M_V = 0^m.50$ is due to the fact that most of the stars populate this region of the observed main sequence in the colour-magnitude diagram of these clusters. After Sandage (1957), the number of original main sequence stars which have disappeared from the main sequence by exhaustion of their energy sources has also been calculated with the help of the initial luminosity function for each of these clusters. These predicted numbers are : one for NGC 1778 and zero for NGC 2169 and Tr 1, which look reasonable considering the present evolutionary stage of the individual clusters.

ACKNOWLEDGEMENT

The authors are thankful to Dr. S. D. Sinvhal for guidance and helpful discussions and also to the referee for his useful suggestions.

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