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Formation and evolutionary properties of the galactic open cluster system

Paolo Battinelli[1] and Roberto Capuzzo-Dolcetta[2]

[1] *Osservatorio Astronomico di Roma, viale del Parco Mellini 84, I-00136, Roma, Italy*
[2] *Istituto Astronomico Università 'La Sapienza', via G.M. Lancisi 29, I-00161, Roma, Italy*

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SUMMARY

A set of 100 galactic open clusters in the solar neighbourhood was selected as a complete (in number) sample which we used to deduce some global properties of the system of galactic open clusters, with the future aim of a comparison with star clusters in other galaxies. As a source of data we adopted the fifth edition of the Lyngå's *Catalogue of Open Cluster Data*, which is the most up-to-date open-cluster database.

The age distribution of the sample was determined, discussed and compared with those available in the literature. Relevant information on the structure and evolution of the open-cluster system was derived by evaluating the formation rate of clusters and their evolutionary fading and destruction rates.

An outstanding fact, suggested by the short lifetimes obtained, is that a large fraction of clusters which are commonly referred as open clusters are probably gravitationally unbound systems. Possible scenarios of open-cluster formation compatible with the results presented in this paper are discussed. A comparison between the formation rate of open clusters and of molecular clouds provides an estimate of the efficiency of conversion of the total amount of gas available in molecular clouds into open-cluster stars.

1 INTRODUCTION

In recent years the increasing number of observations in the infrared (IR) and radio wavelengths of star formation in young embedded stellar clusters (see Lada 1990; Zinnecker 1990; Rieke, Ashok & Boyle 1989; Wilking, Lada & Young 1989; Leisawitz, Bash & Thaddeus 1989) has raised the interest of theoreticians in the problem of open-cluster formation (see Larson 1989, 1990, and references therein). It is in fact quite clear that young open clusters offer an almost unique opportunity to look at the process of ongoing star formation leading to an IMF. The utility of a statistically reliable knowledge of the main characteristic parameters of the galactic open clusters as a system is consequently ascertained. As an example, a suitable and reliable evaluation of the cluster formation rate in the solar neighbourhood can yield useful suggestions on the process of cluster formation from molecular clouds and quantitative estimates of the stellar formation rate in the galactic disc.

These considerations convinced us of the importance of the compilation of a data sample for open clusters, which can provide us with a general picture of their formation and evolution. As we will see in Section 3, an essential ingredient for obtaining the cluster formation rate and information on the disruption time-scales is the derivation of an 'unbiased' age distribution. Such an age distribution is that of the sample of 100 clusters discussed in Section 2. In Sections 3.1–3.3 results concerning formation, fading and disruption of open clusters are presented and discussed.

2 DETERMINATION OF A COMPLETE DATABASE

The 5th edition of the Lyngå's *Catalogue of Open Cluster Data* (1987) represents the most recent and richest collection of data for almost all the observed galactic open clusters. The problem of completeness of such a database has not been addressed by Lyngå, although it is relevant when reliable information on the open-cluster system as a whole is sought. For this reason we approached the problem of the determination of a sufficiently rich subsample of the Lyngå's Catalogue which is complete in number.

A possible source of incompleteness which we take into account is the well-known fact that the fainter a cluster is the harder it is to detect; that means that there are two parameters relevant to the probability of the detection of an open cluster: its absolute integrated magnitude and its distance. A further assumption is that the number of nearby open clusters within a projected (on to the galactic plane) distance d from the Sun increases with d^2, which corresponds to saying that the average number density over a circle of radius d is independent of d, i.e.

$$\bar{n}(d) \equiv \frac{\int_{-Z}^{Z} \int_{0}^{2\pi} \int_{0}^{d} n(R, l, z)\, R\, dR\, dl\, dz}{2\pi d^2 Z} = \text{constant},$$

where R, l and z are heliocentric cylindrical coordinates, and $2Z$ is the width of the disc in the solar neighbourhood. Hereafter $\bar{n}(d)$ will be referred to as 'average' density. These two hypotheses allow us to select a sample of objects which is complete in number. Note that the hypothesis of uniform 'average' density of open clusters around the Sun is not contradictory with the exponential profile of stellar density in the disc commonly suggested by galactic models (see the review by Gilmore, Wyse & Kuijken 1989). For instance, a density law in the usual form (in galactocentric cylindrical coordinates) $n(r, z) \propto e^{-\alpha r} e^{-\beta |z|}$ gives (with $\alpha^{-1} = 3.5$ kpc, $\beta^{-1} = 0.247$ kpc, see Bahcall & Soneira 1980) $\bar{n}(2\text{ kpc})/\bar{n}(\text{kpc}) = 1.04$, i.e. a departure of just 4 per cent from the uniform 'average' density.

In the present paper, to select a number-complete sample we follow the procedure outlined (and there applied to data of the 3rd edition of the Lyngå's Catalogue) in Battinelli & Capuzzo-Dolcetta (1989), which is briefly summarized below.

(i) The counts of open clusters with an available evaluation of the integrated magnitude are performed up to a limiting magnitude $M_{V,\text{lim}}$ as a function of d, so that $N(M_{V,\text{lim}}, d)$ is the number of open clusters brighter than $M_{V,\text{lim}}$ and having projected distance less than d.

(ii) At varying $M_{V,\text{lim}}$, the distance d_{lim} of departure of N from the d^2 proportionality is determined.

The set of clusters brighter than $M_{V,\text{lim}} = -4.5$ and inside the cylinder of radius $d_{\text{lim}} = 2$ kpc was chosen as the 'best' number-complete and magnitude-limited sample (see Fig. 1). This sample is the 'best' because of its richness (100 objects) and because the cut-off is at a magnitude ($M_V = -4.5$) which is faint enough to include almost all the very young clusters, whose consideration is crucial for the main aims of this paper.

The plot of log N against log d could appear linear if extra young clusters in spiral arms made up for incomplete listing of older clusters in the range $1 \le d/\text{kpc} \le 2$. Older clusters generally have absolute magnitudes closer to the limit $M_V = -4.5$ than young clusters and may be more difficult to detect. Anyway, in order to get the well-defined linearity between log N and log d shown in Fig. 1, it is necessary that there exists a quite unlikely balance between the excess of young clusters and the lack of older clusters. Thus we feel confident enough about the completeness of the discussed sample.

Note that the magnitude cut-off does not represent a limitation in a possible comparison with star clusters in nearby external galaxies. For instance, the van den Bergh (1981a) compilation of photometric characteristics of star clusters in the Large Magellanic Cloud (which is the nearest galaxy) contains only clusters brighter than $V \simeq 14$, corresponding to $M_V \le -4.5$.

Table 1 summarizes the main parameters of the 100 open clusters of the complete sample.

3 THE AGE DISTRIBUTION

The age distribution of open clusters in a given sample contains cumulative information on both formation and destruction processes, without allowing any quantitative distinction between the formative and evolutionary history of the sample. The open-cluster age distributions available in the literature (e.g. Wielen 1971; Pandey & Mahra 1986; hereafter referred to as W71 and PM) refer to samples whose number completeness is questionably addressed. Indeed, W71 and PM determine a complete sample by defining the maximum (projected) distance from the Sun inside which the age distribution of sub-samples in concentric circular shells is, statistically, the same. Thus they consider as complete the sample of all clusters within 1 kpc from the Sun. By its definition, this procedure does not allow any spatial variation of the age distribution, thus causing a bias in the conclusions inferred from the sample characteristics. This bias consists in taking as representative of the age distribution of the whole system of open clusters the sample relative to clusters with $d \le 1$ kpc, which are actually inter-arm clusters, i.e. older, in the average, than the outer $(1 < d/\text{kpc} \le 2)$ clusters which rather belong to a spiral arm population. The difference between our age frequency and those given by W71 and PM is shown in Fig. 2, where the age frequency $\tilde{\nu}(t) \equiv (1/n_{\text{tot}})\, dn(t)/dt$ is given in ordinate [$n(t)$ is the number of clusters with age t]. The main feature in Fig. 2 is the overabundance of old clusters ($\log t \ge 7.6$, hereafter t is in years) in the samples of W71 and PM with respect to ours. This is due to the above mentioned bias, as confirmed by Fig. 3, where the histograms of the age distribution of the clusters in our inner ($d \le 2$ kpc) and outer $(1 < d/\text{kpc} \le 2)$ shells, and in the total sample are shown. There is evidence of an age distribution shifted towards younger ages in the outer shell.

A deeper discussion on this subject can be found in Battinelli & Capuzzo-Dolcetta (1989, 1990).

3.1 The rate of formation of open clusters

A fundamental parameter to be determined when dealing with the formation and evolution of galactic open clusters is their rate of birth. The birth rate of open clusters can be obtained in the following way. The observed age distribution of a certain sample of clusters is essentially defined by three different processes: the formation, the fading below the

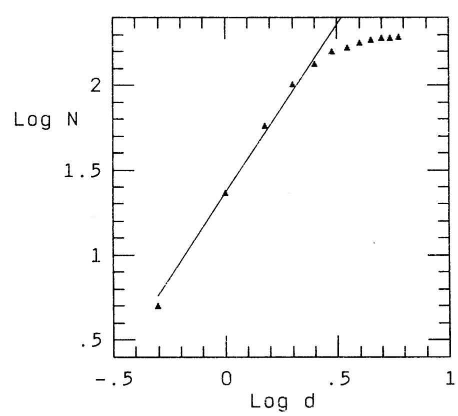

Figure 1. Count of open clusters brighter than $M_{V,\text{lim}} = -4.5$, as a function of the projected (on to the galactic plane) distance from the Sun (in Kpc). The straight line represents the expected count in the hypothesis of uniform 'average' number density of open clusters.

Table 1. Parameters of the 100 clusters in the complete sample. Col = Collinder, Pis = Pismis, Mar = Markarian, Fei = Feinstein, Tr = Trumpler, Hog = Hogg, Lyn = Lyngå, Rup = Ruprecht, Biu = Biurakan, Ber = Berkeley, Boc = Bochum; (l, b) are the galactic coordinates; M_V is the V absolute magnitude; d is the projected distance (in pc); N is the number of stars used to compute M_V; D is the angular diameter (in arcmin); $\log t$ is the logarithm of the age (in yr); $(B-V)_0$ is the dereddened integrated colour; $(B-V)_{TO}$ is the turn-off colour.

Name	l	b	M_V	d	N	D	$\log t$	$E(B-V)$	$(B-V)_0$	$(B-V)_{TO}$
NGC 129	120.25	-2.54	-6.32	1598	193	21.0	8.18	0.58	0.25	-0.19
NGC 654	129.09	-0.35	-7.50	1600	83	5.0	7.18	0.96	-0.12	-0.27
NGC 1027	135.78	1.48	-4.54	1000	152	20.0	8.54	0.40	0.18	-0.15
NGC 2099	177.65	3.09	-6.01	1348	1842	23.0	8.48	0.31	0.28	-0.05
NGC 1444	148.16	-1.29	-5.57	1000	57	4.0	7.40	0.70	-0.26	-0.20
NGC 1502	143.65	7.62	-5.38	942	63	7.0	7.30	0.77	-0.20	-0.30
NGC 1857	168.41	1.26	-5.57	1900	23	5.0		0.38	0.70	
NGC 1912	172.27	0.70	-4.95	1320	160	21.0	8.35	0.24	0.05	-0.08
Col 69	195.05	-12.00	-5.97	489	20	64.0		0.09	-0.09	
NGC 1960	174.52	1.04	-5.26	1270	50	12.0	7.40	0.24	-0.15	-0.20
IC 2157	186.45	1.25	-4.66	2000	56	6.0	8.00	0.50	0.01	-0.16
NGC 2169	195.63	-2.92	-4.80	1099	25	6.0	7.70	0.16	-0.07	-0.22
NGC 2168	186.58	2.18	-5.09	869	434	28.0	8.03	0.16	0.05	-0.10
NGC 2175	190.20	0.42	-6.60	1950	75	18.0	6.00	0.63	-0.43	-0.35
Col 89	188.21	3.70	-6.67	1297	15	35.0		0.58	-0.58	
NGC 2244	206.42	-2.02	-7.81	1699	46	23.0	6.48	0.47	-0.01	-0.31
Col 107	207.14	-0.91	-7.73	1700	204	35.0	7.00	0.54	-0.10	-0.30
NGC 2264	202.94	2.20	-5.46	749	222	20.0	7.30	0.06		-0.30
NGC 2287	231.10	-10.23	-4.88	728	69	38.0	8.00	0.01	0.38	-0.05
Col 121	235.39	-10.40	-7.83	1151	33	50.0	6.18	0.03	0.39	-0.20
NGC 2323	221.67	-1.24	-4.64	910	15	16.0	7.89	0.24	0.13	-0.15
NGC 2129	186.61	-0.13	-6.88	2000	73	6.0	7.21	0.67	-0.06	-0.20
NGC 2345	226.57	-2.30	-5.75	1799	59	12.0	7.90	0.70	0.18	-0.15
NGC 2354	238.42	-6.80	-5.27	1837	297	20.0	8.26	0.14	0.64	0.15
NGC 2362	238.18	-5.53	-7.49	1543	69	8.0	7.40	0.11		-0.30
NGC 2367	235.65	-3.84	-4.69	1996	15	3.5	6.00	0.35	-0.27	-0.30
NGC 2384	235.39	-2.41	-5.00	1998	15	2.5	6.00	0.29	-0.22	-0.30
NGC 2395	204.62	13.96	-4.63	1165	53	12.0	7.70	0.72	0.09	-0.20
NGC 2421	236.24	0.08	-4.55	1900	28	10.0	7.40	0.47	-0.08	-0.20
NGC 2439	226.42	-4.42	-5.22	1605	181	10.0	7.82	0.35	0.06	-0.19
NGC 2437	231.87	4.07	-5.08	1406	186	27.0	8.48	0.14	0.09	0.00
NGC 2477	253.58	-5.83	-5.61	1293	1911	27.0	8.85	0.27	0.57	0.23
NGC 2516	273.94	-15.88	-4.82	423	103	29.0	8.03	0.13	-0.09	-0.16
Col 173	261.72	-8.06	-7.27	327		370.0		0.09		
Pis 6	264.81	-2.87	-5.29	1598	53	1.5	7.50	0.41	-0.20	-0.25
IC 2395	266.57	-3.81	-5.39	848	50	7.0	7.20	0.11		-0.30
Col 197	261.56	0.88	-5.10	1000	21	17.0	6.80	0.58	-0.27	-0.25
Mar 18	269.21	-1.85	-5.61	1599	18	2.0	6.00	0.77	-0.27	-0.30
NGC 3114	283.34	-3.83	-5.76	898	171	35.0	8.03	0.06	0.21	-0.15
IC 2581	284.60	0.01	-8.07	1660	398	7.0	7.00	0.41	0.08	-0.25
Fei 1	290.04	0.38	-6.86	1159	27	25.0	6.00	0.40	-0.26	-0.30
NGC 3532	289.64	1.46	-5.62	500	677	55.0	8.54	0.04	0.24	-0.01
NGC 3590	291.21	-0.18	-4.71	1900	30	4.0	7.70	0.49	-0.19	-0.20
NGC 3766	294.11	-0.03	-6.44	1700	137	12.0	7.35	0.19	0.17	-0.24
NGC 4103	297.57	1.17	-4.94	1860	45	6.0	7.35	0.32		-0.20
NGC 4349	299.77	0.82	-4.78	1700	204	15.0	8.35	0.33	0.28	0.00
NGC 4463	300.65	-2.01	-4.52	1179	13	5.0	7.40	0.44	-0.02	-0.20
NGC 4609	301.90	-0.11	-5.11	1510	52	5.0	7.56	0.36	0.06	-0.20
NGC 5138	307.55	3.55	-4.51	1797	92	7.0	8.18	0.27	0.33	-0.15
NGC 5281	309.17	-0.70	-5.48	1300	18	5.0	7.71	0.26	-0.01	-0.20
NGC 5316	310.23	0.12	-4.80	1120	129	13.0	8.29	0.18	-0.10	-0.05
NGC 5606	314.84	0.99	-4.97	1700	15	3.0	7.10	0.49	-0.24	-0.24
NGC 5617	314.67	-0.10	-5.74	1200	292	10.0	7.66	0.53	0.17	-0.13
Tr 22	314.67	-0.59	-4.99	1700	68	6.0	8.04	0.56	0.02	-0.19
Hog 17	314.87	-0.90	-4.53	1700	41	6.0	8.26	0.54	0.03	-0.20
NGC 6025	324.54	-5.97	-5.02	835	139	12.0	8.03	0.16	0.00	-0.16
Lyn 6	330.37	0.34	-5.67	1600	60	5.0	7.60	1.34	-0.56	-0.21
NGC 6087	327.76	-5.40	-4.93	896	349	12.0	7.74	0.18	0.27	-0.16
NGC 6124	340.77	5.96	-4.76	487	46	29.0	7.71	0.68	0.22	-0.05
NGC 6169	339.38	2.51	-4.51	1099	40	6.0		0.29		
NGC 6167	335.32	-1.28	-6.45	1200	218	7.0	7.60	0.89	-0.01	-0.15
NGC 6193	336.70	-1.57	-6.88	1349	14	14.0	6.00	0.46	-0.32	-0.32
NGC 6231	343.47	1.22	-10.33	2000	93	14.0	6.50	0.46	-0.23	-0.30
NGC 6242	345.46	2.43	-5.20	1199	23	9.0	7.71	0.39	0.30	-0.17
NGC 6250	340.79	-1.83	-5.32	1019	37	7.0	7.15	0.38	-0.14	-0.23
NGC 6322	345.27	-3.07	-6.41	1198	38	10.0	7.00	0.65	-0.33	-0.35
NGC 6383	355.68	0.05	-6.25	1380	27	5.0	6.65	0.34	-0.28	-0.21
Tr 27	355.07	-0.70	-8.42	1650	82	6.0	7.00	1.30	0.24	-0.15
Tr 28	355.98	-0.26	-5.47	1500	85	7.0	8.30	0.74	-0.03	-0.05
Rup 127	325.89	-2.45	-5.27	1499	18	8.0	6.80	1.03	-0.03	-0.25
NGC 6396	354.02	-1.86	-5.08	1317	22	3.0	7.40	0.96	-0.05	-0.20
NGC 6405	356.50	-0.70	-5.16	600	331	14.0	7.71	0.15	0.13	-0.15
NGC 6416	356.94	-1.54	-4.84	800	304	18.0	8.50	0.33	0.29	0.00
Col 347	359.78	-0.32	-5.68	1500	20	4.0	6.80	1.16	-0.54	-0.25
NGC 6494	9.85	2.85	-4.78	659	131	27.0	8.35	0.38	0.15	-0.05
NGC 6514	6.99	-0.25	-5.62	1600	67	28.0		0.29	0.16	
NGC 6531	7.22	-0.44	-5.51	1300	63	13.0	6.66	0.27	-0.15	-0.20
NGC 6530	6.13	-1.36	-7.51	1600	113	14.0	6.30	0.35	-0.21	-0.31
NGC 6604	18.26	1.69	-7.58	1639	105	2.0	6.60	0.97	-0.41	-0.32

Table 1 – *continued*

Name	l	b	M_V	d	N	D	$\log t$	$E(B-V)$	$(B-V)_0$	$(B-V)_{TO}$
NGC 6613	14.15	-1.01	-4.95	1200	40	9.0	7.50	0.47	-0.13	-0.20
IC 4725	13.58	-4.48	-5.69	558	601	32.0	7.95	0.50	0.19	-0.20
NGC 6649	21.64	-0.78	-6.31	1630	477	5.0	7.70	1.34	0.11	-0.12
NGC 6664	23.95	-0.50	-4.74	1370	60	16.0	7.57	0.60	0.41	-0.10
Tr 35	28.29	-0.01	-5.52	1610	65	9.0	7.62	1.19	0.05	-0.15
NGC 6694	23.86	-2.92	-4.72	1548	120	14.0	7.95	0.57	0.30	-0.14
NGC 6705	23.31	-2.77	-6.68	1718	682	13.0	8.35	0.42	0.10	-0.05
NGC 6755	38.55	-1.70	-6.26	1499	157	14.0	7.55	0.93	0.17	-0.25
NGC 6830	60.14	-1.83	-4.67	1469	82	12.0	8.00	0.56	-0.05	-0.18
NGC 6871	72.64	2.08	-7.31	1649	66	20.0	7.00	0.46	-0.23	-0.25
Biu 2	72.76	1.35	-5.85	1500	78	12.0	6.00	0.41	-0.10	-0.30
IC 4996	75.36	1.31	-5.73	1620	56	5.0	7.00	0.64	-0.07	-0.40
Ber 86	76.66	1.26	-6.35	1720	11	7.0	6.78	0.99	-0.23	-0.20
NGC 6910	78.66	2.03	-6.94	1649	66	7.0	7.00	1.05	-0.32	-0.30
NGC 6913	76.92	0.60	-6.30	1250	81	6.0	7.00	0.78	-0.08	-0.28
IC 1396	99.29	3.73	-7.57	798	37	50.0	6.00	0.50	0.87	-0.35
NGC 7160	104.02	6.45	-4.60	894	61	7.0	7.00	0.30	-0.06	-0.20
NGC 7654	112.76	0.46	-5.70	1470	173	12.0	7.55	0.57	0.13	-0.06
NGC 7789	115.49	-5.36	-5.47	1892	583	15.0	9.20	0.25	0.73	0.30
Boc 14	351.19	1.37	-6.03	1150	11	2.0	6.00	1.62	-0.20	-0.35
Boc 13	6.37	-0.50	-6.68	1700	12	14.0	6.80	0.88	-0.24	-0.25

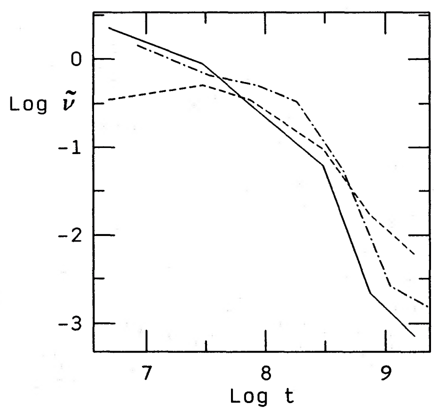

Figure 2. Comparison of the age frequency (in bi-logarithmic scale) from: this paper (solid line); Wielen (1971) (dot-dashed line); Pandey & Mahra (1986) (dashed line).

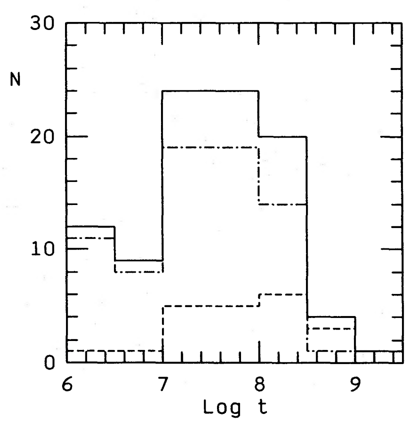

Figure 3. Age histograms for clusters in our sample. Solid line refers to all clusters in the sample; dashed and dot-dashed lines refer to the inner ($d \leq 1$ Kpc) and outer (1 Kpc $< d \leq 2$ Kpc) shells, respectively.

sample cut-off magnitude, and the destruction. They represent 'source' and 'sink' terms in the age distribution, which can be schematized with the formula

$$dn_{\rm obs} = F(t)\, D(t)\, \rho(t)\, dt, \qquad (1)$$

where $dn_{\rm obs}$ is the presently observed age distribution; $\rho(t)\,dt$ is the number of clusters formed between t and $t+dt$ years ago; $F(t)$ and $D(t)$ account for fading and destruction, respectively, in the sense that $1-F(t)\,D(t)$ is the fraction of clusters aged t faded below the cut-off magnitude or disrupted. An estimate of the present-day open-cluster formation rate $R \equiv \rho(0)$ can be given from equation (1), under the assumption that $D(t)=1$ for very young clusters and through an evaluation of $F(t)$ in the same age interval. The evaluation of $F(t)$ at any age t is possible through the knowledge of the luminosity function of the open-cluster system $\Phi(M_V, t)$, being (for the limiting magnitude of our sample):

$$F(t) = \frac{\int_{-\infty}^{-4.5} \Phi(M_V, t)\, dM_V}{\int_{-\infty}^{\infty} \Phi(M_V, t)\, dM_V}. \qquad (2)$$

Unfortunately, the observational data are insufficient to allow a suitable determination of the age-dependent luminosity function $\Phi(M_V, t)$; this lack makes, in addition, any theoretical assumption for Φ quite arbitrary. As a consequence, we prefer to express the fading function $F(t)$ in terms of a time-independent initial mass function $\Psi(m)$ and a mass–luminosity ratio which, of course, is a function of age. This way is more suitable because valid hints are available in the literature on both the form of the IMF and on the mass–luminosity ratio of open clusters. Indeed, a composite power-law IMF is supported by, e.g. Reddish (1978, p. 67–74) and Di Fazio & Capuzzo-Dolcetta (1987). In both these works evidence is given for a present-day mass function in the form of a steep rise to a maximum and a power-law high-mass tail. In this paper we actually chose a time-independent mass function (normalized to 1) in the simple form

$$\Psi(m) = \begin{cases} 0, & m \leq m_1; \\ k m_2^{-s}(m-m_1)/\Delta m, & m_1 \leq m \leq m_2; \\ k m^{-s}, & m_2 \leq m \leq m_3; \\ 0, & m > m_3. \end{cases} \qquad (3)$$

Here, $\Delta m = m_2 - m_1$ (hereafter masses are in solar units), and k is the normalization factor. The dependence of our results on the assumed values for the free parameters m_1,

Δm, m_3 and s is discussed later (see also Sections 3.2 and 3.3). The relation between $\Psi(m)$ and $\Phi(M_V, t)$ is

$$\Phi(M_V, t) = \Psi(m)\left|\frac{\partial M_V}{\partial m}\right|.$$

The time dependence in Φ is introduced by a time-dependent mass–luminosity relation. For all the 38 galactic open clusters for which homogeneous age, mass (from Schmidt 1963) and luminosity determinations are available, a bi-logarithmic least-squares fit of $A(t) \equiv m/L_V$ gives

$$\log A(t) = 0.39 \log t - 3.9. \qquad (4)$$

Fig. 4(b) shows the behaviour of the luminosity function obtained from the mass function (3), which is sketched in Fig. 4(a); the exponent s is the standard 2.35.

The fading function $F(t)$ given in equation (2) may be written in terms of $\Psi(m)$ as

$$F(t) = \int_{m_{\lim}(t)}^{\infty} \Psi(m)\, dm. \qquad (5)$$

The lower integration limit in equation (5) is the mass of the cluster having $M_V = -4.5$ at the age t. The time function $m_{\lim}(t)$ is given by

$$m_{\lim}(t) = 10^{-0.4(-4.5 - \mathcal{M}_V)} A(t). \qquad (6)$$

In order to give an evaluation of the present-day cluster formation rate R through equation (1), we need an estimate of both the disruption and fading factors for very young clusters. There are strong suggestions in the literature (e.g. Larson 1988; Leisawitz *et al.* 1989) that the assumption $D(t) = 1$ (i.e. no-destruction) is reliable only for ages t less than a few million years. For this reason we restrict the assumption $D(t) = 1$ to clusters younger than $\log t = 6.5$. The fading factor F is computed in this age interval varying the parameters defining the mass function $\Psi(m)$, in the ranges:

$$40 \le m_1 \le 120;\ 250 \le \Delta m \le 900;\ 10^4 \le m_3 \le 3 \times 10^4;\ 1.5 \le s \le 3.5. \qquad (7)$$

The variation of parameters in the specified intervals induces a ± 10 per cent variation in the R determination. We found $R = (45 \pm 4) \times 10^{-8}$ clusters kpc^{-2} yr^{-1}, which is about a factor of 2 larger than most other values in the literature (see Table 2). This difference is mainly due to the fact that the spatial extension of the samples used by the authors cited in Table 2 corresponds to our inner shell, where we proved there is a lack of very young clusters with respect to the outer shell, which is a site of more active star formation. Moreover, the neglect of fading and disruption in most of the papers cited in Table 2 also leads to a significant underestimate of the true R. For example, PM obtained their $R = 18$ from the number of open clusters or any magnitude with $d \le 1$ kpc and age $7 \le \log t \le 7.8$. This value of R may be incorrect because at these ages the neglect of fading and disruption is not allowed for (see Sections 3.2 and 3.3). Similarly, W71 assumed that only a minor fraction of clusters have lifetimes shorter than $\log t \simeq 7.7$. This is equivalent to assume $D = 1$ for $\log t \lesssim 7.7$. Finally, we note the agreement of our estimate of the cluster formation rate with the value given by van den Bergh (1981b); nevertheless he used a different procedure, i.e. a fit of the cumulative age distribution over all the interval of ages rather than our direct count of young clusters.

3.1.1 An estimate of the efficiency of formation of open clusters from molecular clouds

It is interesting to compare the present-day cluster formation rate with the analogous rate for molecular clouds. The latter can be roughly estimated by dividing the local number density of observed molecular clouds by a typical cloud lifetime (~20 Myr, see Larson 1981). Using the molecular cloud mass functions given by Elmegreen & Clemens (1985), we get $R_{MC} \simeq 4$ clouds kpc^{-2} Myr^{-1}, that is roughly 10 times the cluster formation rate, and an average molecular cloud mass $\langle m_{MC} \rangle = 10^4$. If we define a quantity $\varepsilon_c \equiv \dot{M}_* / \dot{M}_{MC}$, which gives the ratio between the mass going (in the unit time) into open-cluster stars and that going into newly formed molecular clouds, we have $\varepsilon_c = R\langle m_* \rangle / (R_{MC}\langle m_{MC} \rangle)$, where $\langle m_* \rangle$ indicates the average open-cluster mass. Assuming $\langle m_* \rangle = 500$, $\varepsilon_c = 5.5 \times 10^{-3}$ is obtained. Note that ε_c is an indicator of the efficiency of the process of conversion of mass from the molecular cloud gas phase to open-cluster star phase.

Under the reasonable hypothesis that only massive clouds form open clusters, we can determine the highest value of the left extremum, say m_l, of the mass spectrum of the molecular clouds able to form open clusters, compatible with the present-day cluster formation rate (in the sense that $R_{MC} \ge R$). By definition m_l satisfies the equation

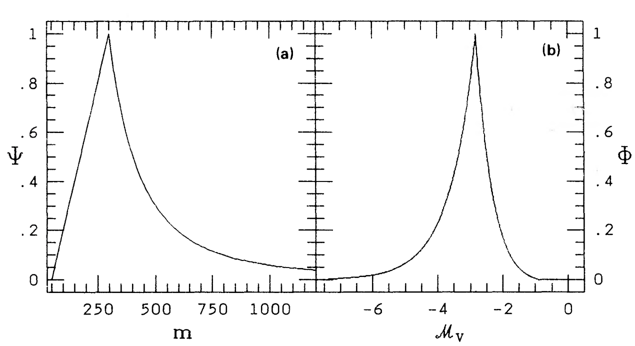

Figure 4. Panel (a) shows the mass function of the open cluster ensemble (equation 3) and panel (b) the corresponding luminosity function, taken at the age $t = 10^8$ yr.

Table 2. The present-day cluster formation rate R in units 10^{-8} clusters kpc^{-2} yr^{-1} as obtained by various authors using different catalogues and samples. d_{max} is the cut-off projected distance from the Sun (in kpc) of the sample.

Reference	R	Catalogue	d_{max}
Wielen (1971)	16	[1], [2]	1
van den Bergh (1981b)	50	[3]	0.75
Elmegreen and Clemens (1985)	25 ± 10	[1], [4]	1
Pandey and Mahra (1986)	18	[5]	1
Janes *et al.* (1988)	25	[6]	–
this paper	45 ± 4	[6]	2

The key to the references quoted in the catalogue column is: [1] Becker & Fenkart (1971); [2] Lindoff (1968); [3] Mermilliod (1980); [4] Lyngå (1981); [5] Lyngå (1983); [6] Lyngå (1987).

$$\frac{1}{t_{\rm MC}}\int_{m_l}^{m_{\max}} \Psi_{\rm MC}(m)\,dm = R, \tag{8}$$

where $t_{\rm MC}$ is the typical cloud lifetime, $\Psi_{\rm MC}(m)$ is the Elmegreen & Clemence's (1985) mass function, and $m_{\max}$ is the maximum molecular cloud mass. Equation (8), with $m_{\max} = 10^6$, leads to $m_l \simeq 6500\ M_\odot$. Unfortunately, this determination of m_l is quite sensitive to the assumption on $t_{\rm MC}$ (which is likely to be a sensitive function of the cloud mass in an unknown way) being $m_l \propto t_{\rm MC}^{-2}$. Of course, the equality of the two rates does not necessarily imply that clusters are not born from clouds lighter than $6500\ M_\odot$; anyway, the average mass of the cloud heavier than $6500\ M_\odot$ can be considered a typical cloud mass active in forming clusters. The Elmegreen & Clemence's (1985) mass function gives for this mass the value $\simeq 8 \times 10^4\ M_\odot$. As a consequence, the corresponding efficiency of the process of formation of an open cluster is $\varepsilon = \langle m_* \rangle/(8 \times 10^4) \simeq 6.3 \times 10^{-3}$, for $\langle m_* \rangle = 500$.

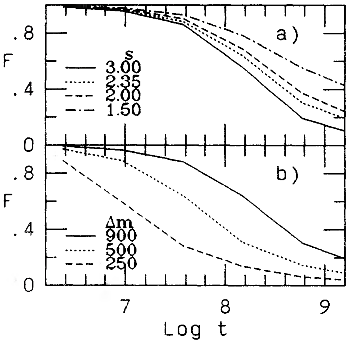

Figure 5. Time-dependence of F, at varying the exponent s [panel (a)] and Δm [panel (b)] in the mass function. The parameters m_1 and m_3 in the mass function are set to 50 and 2×10^4, respectively; in panel (a), $\Delta m = 900$; in panel (b), $s = 2.35$.

3.2 Luminosity fading of open clusters

Here we give an evaluation of the time evolution of the fraction of clusters having absolute V luminosity above an assumed cut-off limiting value. This fraction, $F(t)$, was defined in Section 3.1, equation (2), and computed using equation (5). The dependence of $F(t)$ on the mass function $\Psi(m)$ (see equation 3) is appreciable only through the parameters s and Δm, in the ranges given in (7).

In Fig. 5 we show the behaviour of F as a function of age for various s and Δm. The maximum variation of $F(t)$ (a factor of 3) is induced by the variation of a factor 3.6 in Δm at an age $\log t \simeq 7.6$. If we assume the classical Salpeter value 2.35 for the exponent in the mass function, Fig. 5 indicates that the luminosity evolution alone makes more than 80 per cent of clusters older than 1 Gyr too faint to be included in our magnitude-limited sample.

It is worth noting that the determination of R is based on the evaluation of F in the interval $\log t \lesssim 6.5$, where the indeterminacy of the fading function is not greater than ± 10 per cent (see Fig. 5).

3.3 The destruction function

In addition to the evolutionary fading, another important reason why some clusters are not detectable is that star clusters undergo several disruptive processes due to both external causes (e.g. close encounters with massive objects, tidal distortions, etc.) and internal causes (mass loss: stellar wind, stellar evaporation and sudden gas removal by supernova explosion). All these (and any other possible) phenomena are accounted for in equation (1) by the disruption function $D(t)$ defined as the fraction of the visible (i.e. brighter than the cut-off magnitude -4.5) clusters aged t, that have not been destroyed yet. Of course, this treatment cannot determine, among all the possible disruptive mechanisms, which ones are really working. Anyway, equation (1) is surely an improvement with respect to the equation used first by W71 (his equation 3) and later by PM, where the link between the observed age distribution and the true age distribution [note that their $\nu(0)$ has the same meaning of our R] was described by a single time function, which makes it impossible to distinguish disruption from disappearance due to luminosity fading.

To obtain $D(t)$ from equation (1) we need [in addition to the knowledge of $F(t)$] the time dependence of the rate of formation ρ. Because of the obvious difficulty of the determination of such a time dependence, we prefer to accept the widely used assumption of a constant cluster formation rate. The latter assumption is particularly suitable for open clusters, because for them what it is actually required is that ρ is unchanged during the last few billion years (~ age of the oldest open clusters).

Fig. 6 displays $D(t)$ for the same variation of the parameters defining the mass function as in Fig. 5. The dependence on s is negligible, while $D(t)$ is more sensitive to Δm at intermediate ages.

Fig. 7 shows how, in a bi-logarithmic plane, the D function is well-fitted by a straight line: this means that it behaves like a power law and not like the exponential laws suggested by van den Bergh (1981b) and Lyngå (1982). The difference in behaviour is likely to be due to the incompleteness of the age samples of these authors. Indeed they obtained an exponential law by comparing the observed age distribution with that corresponding to a constant cluster formation rate, neglecting the effect of fading incompleteness. The least-squares fit in Fig. 7 is $D = 1.41 \times 10^5 t^{-0.79}$. The fit was performed with the exclusion of the point at $\log t \simeq 9.4$, because the deficiency of very old clusters in our sample (only one has an age greater than 1 Gyr) makes that point not statistically significant.

The behaviour of $D(t)$ confirms that the often adopted hypothesis that young open clusters are only slightly affected by destructive processes (see Section 3.1) is acceptable only for the youngest clusters, $D(t)$ being a rapidly decreasing function of the age, in particular for ages less than 10^7 yr. This suggests that the expected open-cluster lifetimes might be significantly shorter than those commonly cited in the literature. To quantify this, we define a parameter $t_{1/2}$, related to the average lifetime as the age at which D is halved. By definition, 50 per cent of newly formed unfaded clusters ($M_V \lesssim -4.5$) are destroyed in $t_{1/2}$ yr. As deduced from Fig. 6, the range of variation of $t_{1/2}$ (at varying the mass function parameters) is $6.9 \lesssim \log t_{1/2} \lesssim 7.2$.

Janes & Adler (1982) give estimates of cluster's lifetimes for different richness classes. These lifetimes range in the logarithmic interval 7.28–9.60, with average value 2×10^8 yr,

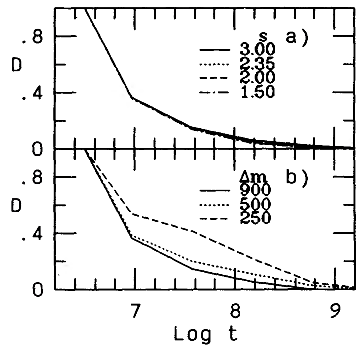

Figure 6. Time-dependence of D, at varying the exponent s [panel (a)] and Δm [panel (b)] in the mass function; other parameters as in Fig. 5.

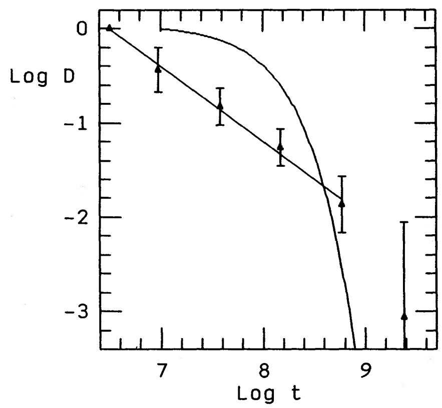

Figure 7. Time behaviour of our computed D (black triangles) in logarithmic coordinates. The bars refer to $1\,\sigma$ error. The straight line is the least-squares fit having slope -0.79; the other curve is the exponential law suggested by Lyngå (1982) (see text).

thus significantly larger than ours. Our 'lifetimes' are short (about one order of magnitude less) also when compared with those given by W71 and PM. This is mainly due to a bias towards older clusters in their adopted samples, either because they consist of nearby clusters (closer than 1 kpc), thus excluding the main region of present cluster formation (W71, PM), or because young clusters are *a priori* excluded in order to try to separate actual open clusters from stellar associations (PM; Lyngå 1982). We preferred to keep all clusters in our sample without performing any sharing between bound and unbound systems, because this separation is necessarily done on quite arbitrary basis (as it is the crude exclusion of the youngest systems) thus leading to the loss of both associations and true open clusters, with the consequence of increasing the deduced lifetimes. Indeed, according to the commonly adopted definition of a stellar association as an unbound stellar system, the only suitable way to distinguish young open clusters from associations would be the evaluation of the internal energy of the system. This requires the proper motions, radial velocities and masses of the member stars together with an evaluation of the gas content in the system, which could be a relevant quantity as indicated, for example, by the observational results of Leisawitz *et al.* (1989) and Pandey, Mahra & Sagar (1990). This difficult task, as yet, has not been extensively approached. It would be, however, a work of fundamental importance because, in our opinion, many of the newly formed clusters are 'intrinsically' unstable systems. Indeed, the 'lifetimes' we have found (of the order of 10 Myr) are significantly shorter than the time-scales of efficiency of external disruptive mechanisms (tidal interaction with the general field, collisions with giant molecular clouds), or of collisional evaporation of stars. Actually, the tidal interaction with galactic field causes cluster instability (see Bok 1934) on a time-scale probably larger than the rotation time ~200 Myr, while the gravitational encounters with GMCs are disruptive on a time around 300 Myr for a typical open cluster with mass 250 $M_{\odot}$ and core radius 1 pc (Wielen 1985). Terlevich (1987) has performed several N-body computations of the evolution of open clusters with a power-law mass spectrum, in a smooth linearized galactic tidal field and undergoing transient shocks caused by encounters with extended interstellar clouds. Her results show that the time $T_{1/2}$ needed to reduce the number of stars to 50 per cent, which is an indicator of the efficiency of evaporation as a dispersing mechanism, ranges from 174 to 770 Myr, for $250 \leq N \leq 1000$ and average stellar mass 0.5 $M_{\odot}$. As a conclusion, a considerable fraction of very young clusters should be 'intrinsically' unstable – in the sense that they have positive initial mechanical energy – or they may dissolve due to energy injection by massive stars (see Margulis, Lada & Dearborn 1985; Verschueren & David 1989) and/or due to gas ionization caused by OB stars in early cluster stages, when a large fraction of the total mass is still gaseous (von Hoerner 1968; Whitworth 1979; Larson 1988). Consequently, a realistic scenario for the formation of the open clusters is that of a massive gas cloud which starts collapsing due to some instability and begins to form stars; at this point the efficiency and rapidity of star formation plays a crucial role in the fate of the cluster. Whitworth (1979) showed that a formation efficiency of just 4 per cent is sufficient for the formed stars to blow away the remaining gas. Indeed, as soon as the first massive stars are formed and evolve, the remaining gas, whose mass depends on the efficiency of star formation, is heated and tends to be swept away together with a quantity of binding energy which may or may not be sufficient to make the stellar system unstable. One or the other case happens depending on the quantity of gas blown out, and on the shallowness of the potential well of the region of star formation. This scenario of cluster formation is supported by the observations by Leisawitz *et al.* (1989) who found, for a sample of 34 open star clusters, that: (i) all the surveyed clusters younger than ~5 Myr have associated with them at least one molecular cloud more massive than 10^4 $M_{\odot}$; (ii) clusters older than ~10 Myr do not have associated molecular clouds more massive than a few times 10^3 $M_{\odot}$; (iii) molecular clouds are receding from young clusters at ~10 km s^{-1}. Somewhat different conclusions are deduced by Pandey *et al.* (1990) from their evaluation of the gas content in some open clusters through their differential reddenings. Pandey *et al.* infer that the average gas removal time should be larger than 10^8 yr.

It is worth noting that the Leisawitz *et al.* data seem to indicate that the process of gas removal is already active also in very young clusters (age $\lesssim 5$ Myr). Since 5 Myr is roughly the pre-supernova lifetime of a 40 $M_{\odot}$ star of solar composition (Brunish & Truran 1982; Maeder 1987), Larson (1988) pointed out that the only destruction mechanism efficient in such a short time-scale is the ionization due to hot stars. On the other hand, de Geus (1988) showed that the energy released to the surrounding gas via stellar wind from an O-type star along its pre-supernova evolution is in the range 10^{48}–10^{50} erg, i.e. enough to contribute significantly to the gas depletion.

We note that ~ 30 per cent of clusters in our sample have ages $\leq 10^7$ yr, which can be considered (from the Leisawitz *et al.* data) to be a rough time-scale of gas removal from open clusters. This means that one cluster out of three in our sample is expected to be fully embedded in a gas cloud.

4 CONCLUSIONS

An updated 'statistically complete' sample of open clusters in our Galaxy has been obtained from the last edition of the Lyngå's *Catalogue of Open Cluster Data* (1987).

The age distribution of the clusters in the sample allowed us to obtain relevant information on some structural average characteristics of the system of open clusters as a whole. As an important result, we derived an estimate of the present-day cluster formation rate from a sample of clusters up to 2 kpc projected distance from the Sun, far enough to include regions of actual cluster formation. The value we obtained for the cluster formation rate, 0.45 clusters $\mathrm{kpc}^{-2}\ \mathrm{Myr}^{-1}$, is nearly twice that commonly cited in the literature. This is mainly due to the fact that the latter determinations of the formation rates are based on samples of clusters restricted to 1 kpc from the Sun. Under some hypotheses, our estimate of cluster formation rate leads to 6.3×10^{-3} as a typical value of the star formation efficiency in open clusters.

The substantial improvement introduced by this paper, relating to the methodology of the analysis of the age distribution of galactic clusters, is the ability to separate the contribution of the luminosity fading and disruptive mechanisms to the observed age distribution. This allowed us to study the cluster destruction mechanisms through the evaluation of a properly defined destruction function D. In this way, we obtained results suggesting short average cluster lifetimes (about 10 Myr). These lifetimes cannot be explained in terms of both collisional and tidal disruption and stellar evaporation due to internal relaxation, thus requiring the likely hypothesis that a large fraction of very young clusters are born as unstable systems. Finally, the $D(t)$ function shows a power-law time behaviour rather than the exponential law suggested by van den Bergh (1981b) and Lyngå (1982).

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REFERENCES

Bahcall, J. N. & Soneira, R. M., 1980. *Astrophys. J. Suppl.*, **44**, 73.
Battinelli, P. & Capuzzo-Dolcetta, R., 1989. In: *Evolutionary Phenomena in Galaxies*, eds Beckman, J. E. & Pagel, B. E. J., *Astrophys. Space Sci.*, **157**, 75.
Battinelli, P. & Capuzzo-Dolcetta, R., 1990. In: *Physical Processes in Fragmentation and Star Formation*, p. 441, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.
Becker, W. & Fenkart, R., 1971. *Astr. Astrophys. Suppl.*, **4**, 241.
Bok, B. J., 1934. *Harvard Obs. Circulars*, Vol. 8, No. 384.
Brunish, W. M. & Truran, J. W., 1982. *Astrophys. J.*, **256**, 247.
de Geus, E., 1988. *PhD thesis*, University of Leiden.
Di Fazio, A. & Capuzzo-Dolcetta, R., 1987. *Astr. Astrophys.*, **184**, 263.
Elmegreen, B. G. & Clemens, C., 1985. *Astrophys. J.*, **294**, 523.
Gilmore, G., Wyse, R. F. G. & Kuijken, K., 1989. *Ann. Rev. Astr. Astrophys.*, **27**, 555.
Janes, K. A. & Adler, D., 1982. *Astrophys. J. Suppl.*, **49**, 425.
Janes, K. A., Tilley, C. & Lyngå, G., 1988. *Astr. J.*, **95**, 771.
Lada, E. A., 1990. In: *Physical Processes in Fragmentation and Star Formation*, p. 193, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.
Larson, R. B., 1981. *Mon. Not. R. astr. Soc.*, **194**, 809.
Larson, R. B., 1988. In: *Galactic and Extragalactic Star Formation*, p. 459, eds Pudritz, R. E. & Fich, M., Kluwer, Dordrecht.
Larson, R. B., 1989. In: *Structure and Dynamics of the Interstellar Medium, IAU Coll. No. 120*, p. 44, eds Moles, M., Tenorio-Tagle, G. & Melnick, J., Springer-Verlag, Berlin.
Larson, R. B., 1990. In: *Physical Processes in Fragmentation and Star Formation*, p. 389, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.
Leisawitz, D., Bash, F. N. & Thaddeus, P., 1989. *Astrophys. J. Suppl.*, **70**, 731.
Lindoff, U., 1968. *Ark. Astr.*, **5**, 1.
Lyngå, G., 1981. *Catalogue of Open Clusters*, Stellar Data Center, Observatoire de Strasbourg.
Lyngå, G., 1982. *Astr. Astrophys.*, **109**, 213.
Lyngå, G., 1983. *Catalogue of Open Cluster Data*, 3rd edn, Stellar Data Center, Observatoire de Strasbourg.
Lyngå, G., 1987. *Catalogue of Open Cluster Data*, 5th edn, Stellar Data Center, Observatoire de Strasbourg.
Maeder, A., 1987. *Astr. Astrophys.*, **173**, 247.
Margulis, M., Lada, C. J. & Dearborn, D., 1985. In: *Dynamics of Star Clusters, IAU Symp. No. 113*, p. 463, eds Goodman, J. & Hut, P., Reidel, Dordrecht.
Mermilliod, J. C., 1980. In: *Star Clusters, IAU Symp. No. 85*, p. 129, ed. Hesser, J. E., Reidel, Dordrecht.
Pandey, A. K. & Mahra, H. S., 1986. *Astrophys. Space Sci.*, **126**, 167.
Pandey, A. K., Mahra, H. S. & Sagar, R., 1990. *Astr. J.*, **99**, 617.
Reddish, V. C., 1978. *Stellar Formation*, Pergamon Press, Oxford.
Rieke, G. H., Ashok, N. M. & Boyle, R. P., 1989. *Astrophys. J.*, **339**, L71.
Schmidt, K.-H., 1963. *Astr. Nach.*, **287**, 41.
Terlevich, E., 1987. *Mon. Not. R. astr. Soc.*, **224**, 193.
van den Bergh, S., 1981a. *Astr. Astrophys. Suppl.*, **46**, 79.
van den Bergh, S., 1981b. *Publs astr. Soc. Pacific*, **93**, 712,
Verschueren, W. & David, M., 1989. *Astr. Astrophys.*, **219**, 105.
von Hoerner, S., 1968. In: *Interstellar Ionized Hydrogen*, p. 101, ed. Terzian, V., Benjamin, New York.
Whitworth, A., 1979. *Mon. Not. R. astr. Soc.*, **186**, 59.
Wielen, R., 1971. *Astr. Astrophys.*, **13**, 309.
Wielen, R., 1985. In: *Dynamics of Star Clusters, IAU Symp. No. 113*, p. 449, eds Goodman, J. & Hut, P., Reidel, Dordrecht.
Wilking, B. A., Lada, C. J. & Young, E. T., 1989. *Astrophys. J.*, **340**, 823.
Zinnecker, H., 1990. In: *Physical Processes in Fragmentation and Star Formation*, p. 201, eds Capuzzo-Dolcetta, R., Chiosi, C. & Di Fazio, A., Kluwer, Dordrecht.