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LETTER

Letter to the Editor

Searching for open cluster remnants

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Abstract. The likely observational properties of the final stages of the evolution of open clusters are investigated by numerical calculations. It is found that they depend upon the membership of the cluster, the abundance of primordial binaries and the initial mass function. Remnants of poorly populated clusters are relatively easy to identify because of the presence of early-type stars. Remnants of rich open clusters are difficult to detect and might exist in large numbers. Detection of rich open clusters remnants (OCRs) is a big challenge for the largest available telescopes. The existence of a large number of OCRs may be relevant for dark matter in the Galactic disk.

Key words: galaxy: kinematics and dynamics – open clusters and associations: general – dark matter

1. Introduction

Open clusters are known to disintegrate on a time scale which depends both on their membership and galactocentric distance. The final residue of an open cluster evolution is often called an open cluster remnant (hereafter OCR). The number of disrupted open clusters in our Galaxy is probably very large (Lodén & Rickman 1974).

Ambartsumian (1938) and Spitzer (1940) showed, from a theoretical point of view, that it is impossible for a star cluster to evaporate totally; furthermore, Spitzer pointed out two possible final destinies for a star cluster: evaporation provokes physical collisions between stars, or evaporation proceeds until a stable binary or higher multiplicity system is generated. For rich clusters new theoretical scenarios were found (see e.g. Heggie 1985 for a review) in which the gravitational collapse, predicted by Antonov (1962) and Lynden-Bell and Wood (1968), is arrested by some energetic mechanism: a central black hole, central binary systems or central mass loss. As regards numerical simulations, for systems with some 25 to 250 stars, von Hoerner (1960, 1963), Aarseth (1968) and van Albada (1968) suggested that the final outcome of cluster evolution is one or more tightly bound binaries (or even a hierarchical triple system). Van Albada pointed out several observational candidates (σ Ori, ADS 12696, ρ Oph, 1 Cas, 8 Lac and 67 Oph) as being OCRs and Wielen (1975) indicated another one, the Ursa Major cluster (Collinder 285). Very recently (de la Fuente Marcos 1997b, and references therein), some attention has been paid to the final stages of the evolution of open clusters; this new numerical work suggests that OCRs are regions in the sky where the concentration of binaries (and multiples) is significantly greater than the mean for field stars.

The purpose of this Letter is to shed new light on this topic, by presenting and discussing recent results from simulations for the expected main features of the OCRs. On the basis of detailed analysis of numerical integrations, these computational results are of interest in order to plan future surveys and evaluate the usefulness of the known data on loose clusters.

2. Properties of the residual component

The observational data provided by the database for stars in open clusters (BDA, `http://obswww.unige.ch/bda/`) have been used in this study. This database has been developed since 1987 at the Institute of Astronomy (University of Lausanne) by Mermilliod (Mermilliod 1996, and references therein). For the present purpose, several data are required, namely distance and angular diameter in order to compute the real diameter, age, and earliest spectral type observed. Only 418 clusters with both distances and angular diameters known have been found. The vast majority of the diameters have been taken from Lyngå's catalogue (Lyngå 1987) and correspond more or less to the central part of the cluster. The distribution of the clusters used in this work as a function of the cluster radius is shown in Fig. (1a). This sample is strongly biased; Fig. (1b) shows that only young clusters with massive and bright stars are observed at large distances.

These observational data will be compared with results from a large set of simulations performed with the standard N-body code NBODY5 (Aarseth 1985) in the last five years (de la Fuente Marcos 1997b) for clusters situated in the solar neighbourhood. These computations include the effects of stellar evolution, the galactic tidal field and realistic initial mass functions. The change in the distribution of cluster properties (number of

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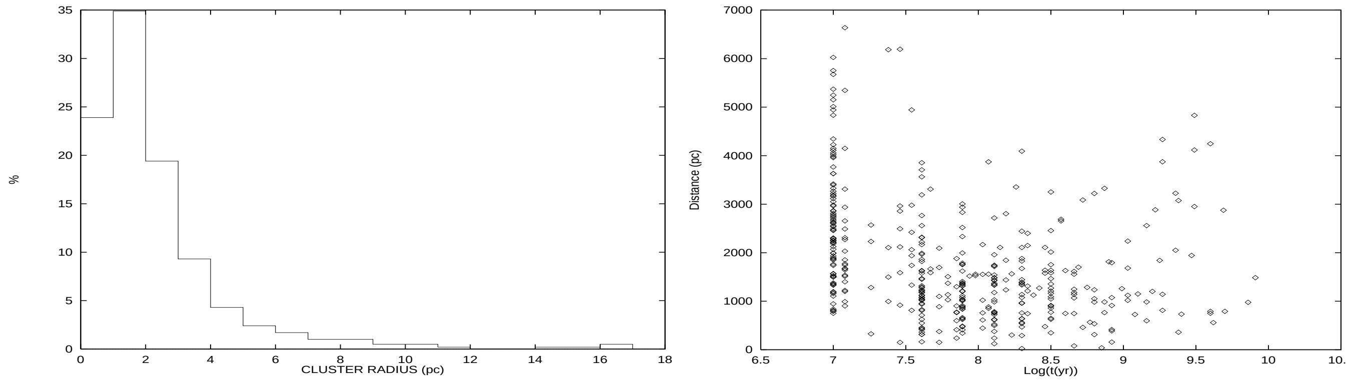

Fig. 1. a *(Left panel)* Apparent distribution of open clusters as a function of cluster radius. All clusters with radius greater than 7 pc have ages smaller than 0.1 Gyr. Almost 90% of clusters in the sample have radius smaller than 4 pc. **b** *(Right panel)* Dependence of cluster distance with age. For large distances only young clusters are found because of the high luminosity of massive stars. This shows that the sample utilized has a selection effect, so the possible existence of a large number of old and faint clusters at large distances (> 4 kpc) should be considered.

stars, half-mass radius, fraction of binaries) with time for the computed models is analyzed in de la Fuente Marcos (1997a) and references therein.

2.1. Stellar density and remnant radius

Detecting OCRs requires a certain contrast of the candidate object against the stellar background. In order to be observed, a cluster must have a stellar density larger than the local Galactic value. When considering the solar neighbourhood, the stellar density of the system should be greater than 0.044 $M_\odot$ pc^{-3}. Moreover, the density of a star cluster in the solar neighbourhood must be greater than about 0.08 $M_\odot$ pc^{-3} in order to be stable against tidal disruption. On the other hand, the smallest mean mass density for detected open clusters is about 0.5 $M_\odot$ pc^{-3} (Lohmann 1977, and references therein) so probably a loose cluster should be about ten times denser than the surrounding star field in order to be detected. Although extended stellar associations have typical values of 0.1 $M_\odot$ pc^{-3}, they have very bright and massive stars which facilitate their observation. Fig. (2) shows superimposed the evolution of the cluster (half-mass and core) radius for three selected models with a fraction of primordial binaries (hereafter PBs) in the sample of clusters considered. For N = 100, the model reaches a stellar density approximately equal to that of the solar neighbourhood when its half-mass radius is about 4.6 pc, and for N = 750 this value is reached for a half-mass radius of about 5.5 pc. It is clear from the figure that only a very small fraction of the observed clusters seems to match the properties of such an OCR. However, for N = 10, 500 the OCR has a stellar density larger than the solar neighbourhood (about 12 $M_\odot$ pc^{-3}) even when the population is as low as 30. It is possible that some of the oldest known open clusters are in fact remnants of densely populated ($N \approx 40,000$) clusters. Table (1) shows the half-mass radius, population and age for a selected group of models with binary fractions equal to 0 and 1/3 respectively. These values are for the instant at which the half-mass stellar density (density inside the half-mass radius) is about the reference value. OCRs from rich clusters with a certain binary fraction have higher populations than similar models with no PBs. OCRs from poor clusters ($N \leq 100$) should contain about 40% of their initial population in order to have a stellar density larger than the field. For N in the range 750-1,000, it should keep about 7% of its initial population. OCRs from clusters in the range 200-500 have 10-20% of their initial members. Densely populated clusters (N = 10, 000) generate OCRs containing about 0.1% of the initial population, but with stellar densities in the range 0.3-15 $M_\odot$ pc^{-3}.

Table 1. Main properties of the OCRs*

	f = 0			f = 1/3		
N_0^{a}	$< R >^{\mathrm{b}}$	N^{c}	T^{d}	$< R >$	N	T
100	4.60	42	111	4.60	40	169
250	3.97	42	359	3.20	14	494
500	2.90	15	601	5.33	45	537
750	3.35	15	807	5.45	54	454

[a] Initial population.
[b] Half-mass radius of the OCR in pc.
[c] Remnant population.
[d] Remnant age in Myr.
[*] All the models have the Miller-Scalo (1979) initial mass function and the initial half-mass stellar density is about 6 $M_\odot$ pc^{-3}.

2.2. Differential stellar content

Since the initial membership of a star cluster is the main parameter as regards cluster life-time for a given galactocentric distance, it is expected that there is some kind of differential behaviour depending on N. Neglecting the possible effect of binary stellar evolution, it should be easy to distinguish between OCRs from poor and rich clusters considering their stellar content. OCRs from poorly populated clusters should have massive stars because they reach the local mass density before dominant mass loss, and those from densely populated clusters should not have massive stars at all. Moreover, the characteristics of the remnant depend on the initial binary fraction of the model.

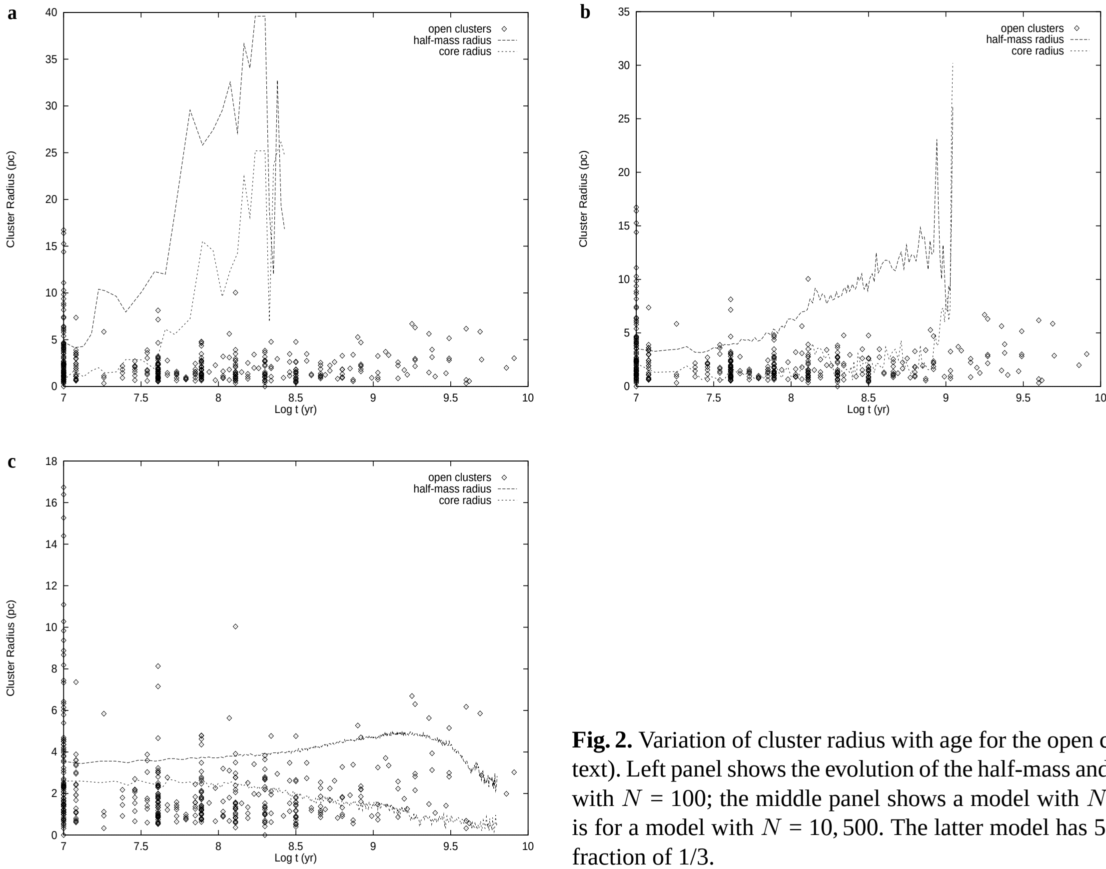

Fig. 2. Variation of cluster radius with age for the open cluster sample used (see the text). Left panel shows the evolution of the half-mass and the core radius for a model with N = 100; the middle panel shows a model with N = 750; and the right panel is for a model with $N = 10,500$. The latter model has 500 PBs, the others a binary fraction of 1/3.

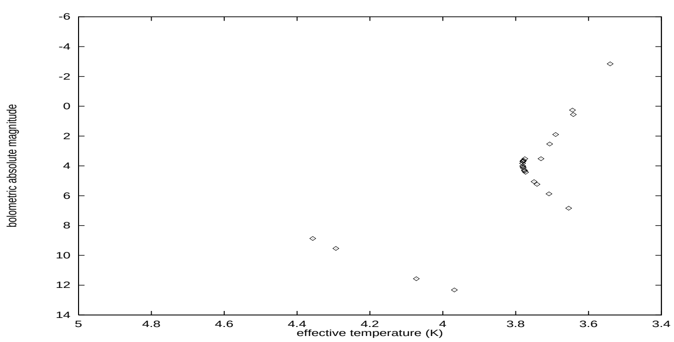

Fig. 3. H-R diagram for a simulated OCR with an age of 5.387 Gyr. It contains 32 stars with several white dwarfs. The core radius is 0.77 pc, the half-mass radius is 1.95 pc and the tidal radius is 4.48 pc. The initial population of the model was 10,010 stars with 10 PBs. There is only one binary in the OCR. The half-mass stellar density is about 0.44 $M_\odot$ pc^{-3}.

The percentage of binaries in OCRs for models without PBs is about 20% and up to 80% for models with PBs. The exact stellar composition of an OCR depends also on the initial mass function. For models with PBs and a few hundred stars, the cluster disintegration occurs before intermediate mass stars have left the main sequence, so most of the binaries have not yet been destroyed due to mass loss. Binaries in an OCR have the same probability of being massive because most of the former have not been disrupted or ejected from the cluster. If the initial population of the cluster increases, then the disintegration time scale is similar to that needed for stars with masses greater than 4 $M_\odot$ to leave the main sequence. For clusters with $N \geq 500$, it is sometimes possible to find a white dwarf in the OCR as a primary or even a secondary. Neutron stars are ejected from the cluster due to a large velocity kick after the supernova. For clusters with about 1,000 stars most binaries in the OCR have masses of about 1.2 $M_\odot$ which corresponds to both components typically in the range K5-M5, although sometimes a sub-giant or even a giant is observed. For densely populated clusters, the probability of finding white dwarfs increases significantly. Fig. (3) shows the synthetic Hertzsprung-Russell diagram for one of these objects. For models without PBs, the OCR usually contains one binary but a differential behaviour as regards the stellar content is also observed, depending on the initial cluster richness. In any case, it is clear that simulations can help to study the original properties of an observed cluster remnant. For example, our calculations suggest that some of the oldest open clusters known could be remnants of very rich open clusters. However, we see young clusters today, which do not necessarily contain 10^4 stars so this fact could point to different physical conditions at early stages of the formation of the galactic disk. A single, but striking, example of this possibility are the Magellanic Clouds which show very populous and young star clusters.

3. Discussion

An immediate implication of the present results is that OCRs from poorly populated clusters are relatively easy to detect even using low resolution techniques (e.g. objective-prism plates) because of the presence of early-type, luminous stars. On the contrary, OCRs from rich clusters should be formed preferentially by low-mass, faint stars. In any case, an overabundance of binaries and hierarchical systems should be observed. Unfortunately, there have only been a few observational attempts to study OCRs. Using objective-prism plates, Lodén (1987, 1988, 1993, and references therein) has investigated the frequency of clusters in the Milky Way under the hypothesis that the stars should have similar luminosities and spectral types. He has found that about 30% of the objects in his sample could be catalogued as a possible type of cluster remnant. The membership for these objects is $N \leq 15$. The typical age of these systems is about 150 Myr with a range from 50 to 200 Myr. They show an increased density of binaries and a considerable probability for optical binaries. The stars of these OCRs have a tendency to be massive and hence early-type (A-F) stars although this observational method includes a noticeable selection effect (Lodén 1996) because bright early-type spectra are easier to detect than fainter and later ones. In fact, almost no stars with spectral type later than F appear among his objects. On the other hand, these results are not fully conclusive because there are known regions in the sky with many stars of the same spectral type but in which it is difficult to find two stars with the same velocity. A striking example of this fact is Upgren 1; initially, it was suggested that this small group of seven F stars was the remnant of an old cluster (Upgren & Rubin 1965) but later, Gatewood et al. (1988) concluded that Upgren 1 is only a chance alignement of F stars resulting from the close passage of members of two dynamically different sets of stars. Very recently, Stefanik et al. (1997) have shown that one of the sets is formed by 5 stars including a long-period binary and an unusual triple system. The properties of this unbound set match very well when those found in numerical models with an initial population of about 1,000 stars.

If the luminosity of the cluster stars is very low, the surface brightness of the object can be extremely small. OCRs from rich clusters would consist mainly of early K stars, which are extremely difficult to detect at a distance. As regards poor clusters, it is very probable that many of the loose clusters found by Lodén are poor OCRs (progenitor with $N \leq 500$ stars) in which the low-mass stars have not yet been detected because of the low resolution technique utilized. On the other hand, if most of stars were born in small open clusters the probability of finding these OCRs is higher; this point can help to explain Lodén's results. The properties of OCRs make them very suitable for the new generation of detectors, the STJ (Superconducting Tunnel Junction) devices (Peacock et al. 1996). The possible existence of a large number of OCRs in the Galactic disk may have some implications for dark matter. If stars form mainly in open clusters, the number of these systems had to be very large in the past in order to explain the stellar population of the disk. Considering a mean population of 300 stars for a typical open cluster and about 10^{11} stars in the disk, the number of possible remnants could be about 3×10^8. If the typical mass of such an object is about 30 $M_{\odot}$, it is possible that the mass in OCRs could be as large as $10^{10} M_{\odot}$, roughly a sixth of the Galactic disk mass. This hypothesis could be tested by using the capabilities of the proposed global astrometry mission GAIA.

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References

Aarseth S.J., 1968, Bull. Astron., Ser. 3, 3, 105
Aarseth S.J., 1985, in: Multiple Time Scales, eds. J.U. Brackbill, B.I. Cohen, (New York: Academic Press) p. 377
van Albada T.S., 1968, Bull. Astron. Inst. Neth. 19, 479
Ambartsumian V.A., 1938, Ann. Len. State Univ., # 22, 4, 19 (English translation in: Dynamics of Star Clusters, eds. J. Goodman, P. Hut, (Dordrecht: Reidel) p. 521)
Antonov Y.A., 1962, Bull. Univ. Leningrad 7, 135 (English translation in: Dynamics of Star Clusters, eds. J. Goodman, P. Hut, (Dordrecht: Reidel) p. 525)
de la Fuente Marcos R., 1997a, A&A 322, 764
de la Fuente Marcos R., 1997b, Ph.D. thesis, Universidad Complutense de Madrid
Gatewood G., De Jonge J.K., Castelaz M., et al, 1988, ApJ 332, 917
Heggie D.C., 1985, in: Dynamics of Star Clusters, eds. J. Goodman, P. Hut, (Dordrecht: Reidel) p. 139
von Hoerner S., 1960, Z. Astrophys. 50, 184
von Hoerner S., 1963, Z. Astrophys. 57, 47
Lodén L.O., 1987, Ir. Astron. J. 18, 95
Lodén L.O., 1988, A&SS 142, 177
Lodén L.O., 1993, A&SS 199, 165
Lodén L.O., 1996, private communication
Lodén L.O., Rickman H., 1974, in: The Stability of the Solar System and of Small Stellar Systems, ed. Y. Kozai, (Dordrecht: Reidel) p. 231
Lohmann W., 1977, A&SS 51, 173
Lynden-Bell D., Wood R., 1968, MNRAS 138, 495
Lyngå G., 1987, Fifth Catalogue of Open Cluster Data (CDS)
Mermilliod J.-C., 1996, in: The Origins, Evolutions, and Destinies of Binary Stars in Clusters, eds. E.F. Milone, J.-C. Mermilliod, ASP Conference Series, vol. 90, p. 475
Miller G.E., Scalo J.M., 1979, ApJS 41, 513
Peacock A., Verhoeve P., Rando N., et al., 1996, Nat 381, 135
Spitzer L., 1940, MNRAS 100, 397
Stefanik R.P., Caruso J.R., Torres G., Jha S., Latham D.W., 1997, Baltic Astronomy 6, 137
Upgren A.R., Rubin V.C., 1965, PASP 77, 355
Wielen R., 1975, in: Dynamics of Stellar Systems, ed. A. Hayli, (Dordrecht: Reidel) p. 97