Very Large Telescope Observations of the peculiar globular cluster NGC 6712. Discovery of a UV, Hα excess star in the core[1]

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ABSTRACT

We present results from multi-band observations in the central region of the cluster NGC 6712 with the ESO *Very Large Telescope*. Using high resolution images we have identified three UV-excess stars. In particular two of them are within the cluster core, a few arcsec apart: the first object is star "S" which previous studies identified as the best candidate to the optical counterpart to the luminous X-ray source detected in this cluster. The other UV object shows clearcut $H\alpha$ emission and, for this reason, is an additional promising interacting binary candidate (a quiescent LMXB or a CV). The presence of two unrelated interacting binary systems a few arcsec apart in the core of this low-density cluster is somewhat surprising and supports the hypothesis that the (internal) dynamical history of the cluster and/or the (external) interaction with the Galaxy might play a fundamental role in the formation of these peculiar objects.

Subject headings: globular clusters: individual (NGC 6712) — stars: evolution – binaries: close

1. Introduction

Two main classes of X-ray sources have been found to exist in Galactic globular clusters (GGCs): *(i)* high luminosity X-ray sources (with $L_X > 10^{34.5} \, \mathrm{erg \, sec^{-1}}$), the so-called Low Mass X-ray Binaries, LMXB; *(ii)* low luminosity X-ray sources (hereafter LLGCXs) with $L_X < 10^{34.5} \, \mathrm{erg \, sec^{-1}}$). Although the true nature of these objects is still a matter of debate, both these categories of objects are thought to be associated with interacting binary systems. In particular, LMXBs, because of their X-ray bursts, might be binary systems with an accrete neutron star, while LLGCXs (or at least the faintest LLGCXs with $L_X < 10^{32} \, \mathrm{erg \, sec^{-1}}$) are supposed to be binary systems in which a white dwarf (instead of a neutron star) is accreting material from a late type dwarf (main sequence or sub-giant branch star; see Verbunt et al. 1994), and, for this reason, they might be possibly connected to cataclysmic variables (CVs).

In dense environments such as the cores of GGCs one can expect interacting binaries to result from the evolution of various kinds of binary systems, with a variety of origins and nature. For example, binaries in dense clusters could have been created by dynamical processes (Hut & Verbunt 1983; Bailyn 1995), while in low-density clusters they might result from the evolution of primordial systems (Verbunt & Meylan 1988).

In this scenario, the case of NGC 6712 is quite interesting. Although it is a relatively loose, intermediate density GGC ($c = 0.9$, $Log\rho_0 \sim 3$;, Djorgovski & Meylan 1993), it is one of the 12 (out of 150) GGCs harbouring in its core a LMXB burster ($1RXSJ185304.8 - 084217$; see Voges et al. 1999). Indeed, NGC 6712 is the lowest density cluster in the Galaxy containing a LMXB: its central density is significantly lower than the mean density of GGCs containing LMXBs ($< Log\rho_0^{LMXB} >= 4.9 \pm 0.3$, Bellazzini et al. 1995).

The optical counterpart to the X-ray burster in NGC 6712 has long been searched (see Cudworth 1988, Bailyn et al. 1988, Nieto et al. 1990). Finally, it has been identified by ground based observations as a faint UV-excess star (star S) by Bailyn et al. (1991) and Auriere & Koch-Miramond (1992) and afterwards confirmed from HST observations by Anderson et al.

(1993).

Moreover, NGC 6712 shows another peculiar characteristic: its orbit, as computed by Dauphole et al. (1996), suggests that this cluster has experienced a severe interaction with the Galaxy during its numerous passages through the disk and bulge. Preliminary VLT observations (De Marchi et al., 1999), now confirmed by Andreuzzi et al. (2000), fully support this picture, since the main sequence (MS) luminosity function (LF) shows that the mass fuction of the cluster has been severely depleted of lower mass stars, probably stripped by the tidal force of the Galaxy.

As part of a long term project specifically devoted to the study of the global stellar population in a sample of GGCs, we imaged the core of NGC 6712, exploiting the exceptional performances of the ESO *Very Large Telescope*. The complete data set, together with other specific aspects connected to the unevolved (MS) and evolved (red giant branch, horizontal branch, etc.) stars, are discussed separately in a series of companion papers (Andreuzzi et al. 2000, Paltrinieri et al. 2000, in preparation). In this letter, we briefly discuss the properties of a few UV-excess stars, in particular we report on the discovery of an object with strong UV and Hα excess, located in the very central region of NGC 6712, a few arcsec away from the optical counterpart to the LMXB source.

2. Observations and results

The data have been obtained on 1999 June 16 at the *ANTU* Unit Telescope 1 (UT1) of the Very Large Telescope (VLT) at ESO on Cerro Paranal (Chile) using FORS1. A large set of frames were secured in the central region of NGC 6712, using different levels of resolutions. Here we discuss only the results obtained from short multiband exposures using the High Resolution (HR) mode of FORS1. In this configuration the plate-scale is $0''1/pixel$ and the FORS1 2048×2048 pixel^2 array has a global field of view of $3'4 \times 3'4$. The data consist of five 10 s B-, V-, R-band exposures, five 120 s U-band exposures and one 700 s $H\alpha$ exposure, roughly centered on the cluster center. All the observations were performed in service mode under good seeing conditions
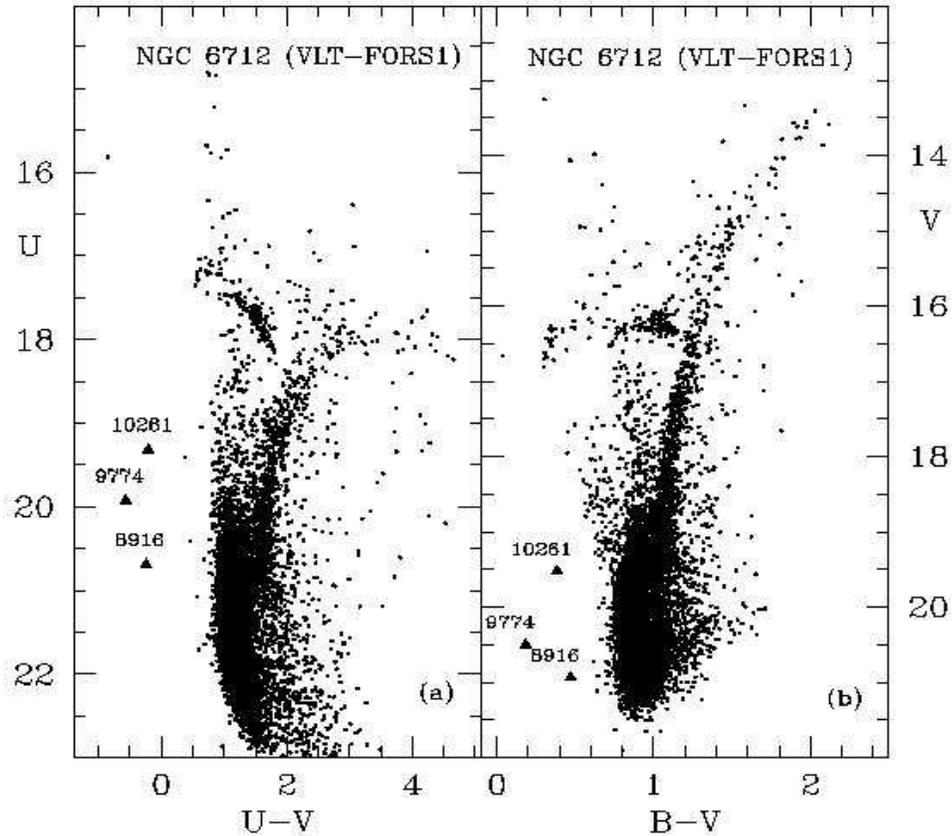
Fig. 1.— *Panel (a):* $(U, U - V)$ color–magnitude diagramme (CMD) for NGC 6712. All stars detected in the FORS1-HR field of view have been plotted. *Panel (b):* $(V, B - V)$ CMD for NGC 6712 from FORS1-HR images. The three UV-excess stars have been plotted as large filled triangles and marked with their identification number in our catalogue.

(FWHM= $0{.}''4 - 0{.}''5$).

A more detailed description of the observations and reductions of the data-set discussed in this Letter will be given elsewhere (Paltrinieri et al. 2000). In short, all the reductions have been carried out using ROMAFOT (Buonanno et al. 1983), a package specifically developed to perform accurate photometry in crowded fields. Independent searches have been performed in the best blue (U, B) and in the best red (V, R) images, in order to properly optimize the search for blue and red objects. The *blue* and the *red* masks with the star positions have been then adapted to each individual stellar image and the PSF-fitting procedure performed. The *blue* and the *red* data-set

were then matched together and a final catalogue with the average instrumental magnitude in each filter and coordinates has been compiled for all the stars identified in the FORS1 field of view.

Photometric calibration of the instrumental magnitude was then performed using ten photometric standard stars in selected areas PG1528, PG2213, PG2331 (Landolt 1992). $H\alpha$ magnitudes were treated and calibrated like R-band images, except that an offset of ~ 4 mag was applied in
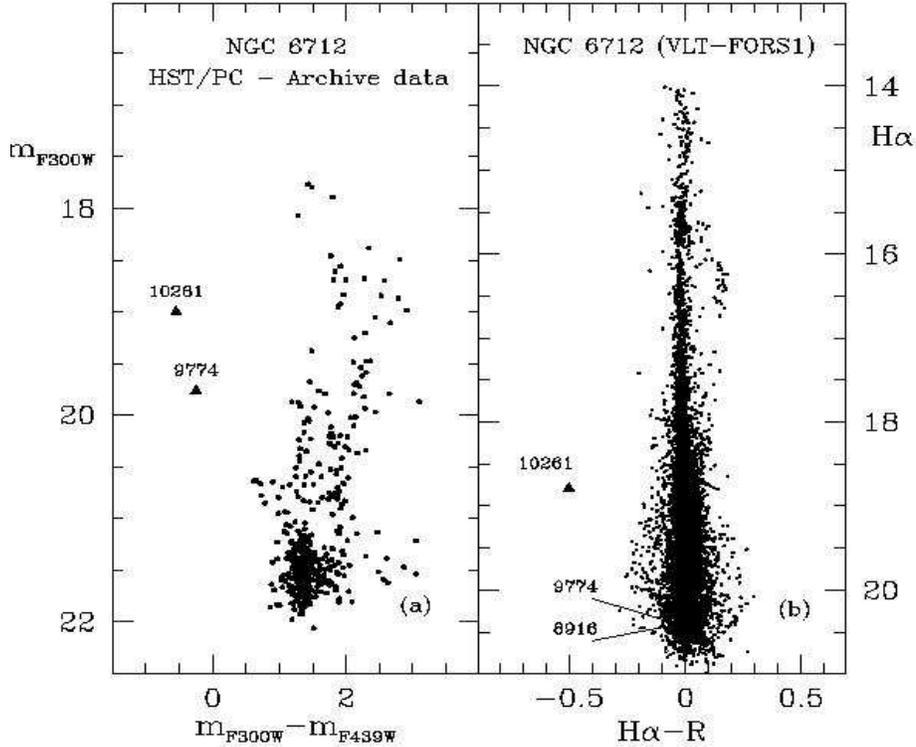

Fig. 2.— *Panel (a):* $(m_{F300W}, m_{F300W} - m_{F439W})$- CMD from HST-WFPC2 archive data. Only stars lying in the Planetary Camera are plotted. *Panel (b):* $(H\alpha, H\alpha - R)$ CMD for NGC 6712 from FORS1-HR images. Only star #10261 (*large filled triangle*) shows a significant $H\alpha$ excess. In both panels the UV-excess stars have been plotted as large filled triangles and marked with their identification number in our catalogue.

Figure 1 shows the $U, U - V$ CMD for more than 10,000 stars measured in the FORS1-HR field of view. As can be seen, apart from one bright blue object at $U \sim 15.8, U - V \sim 0.8$ (a cooling

post-AGB star?), which will be discussed elsewhere (Paltrinieri et al. 2000, in preparation), only three relatively faint ($U > 18$) UV-excess stars ($U - V < 0$) have been found to significantly lie outside the main loci defined by the cluster stars. These stars (#10261, #9774 and #8916) are marked as large filled triangles in Figure 1. The peculiar blue colour of these stars is confirmed by the $V, B - V$ CMD (Figure 1 b): where the three stars also clearly lie outside the sequences defined by cluster stars.

In order to further confirm the anomalous blue colours of the three stars plotted in Figure 1, we retrieved public WFPC2-HST data from the archive. Four 300 sec exposures through the F330W filter and one 160 sec exposure in F439W, have been analysed. The standard procedure described in Ferraro et al. (1997a) was used to reduce these HST-images. The $(m_{F330W} - m_{F439W}, m_{F330W})$ CMD is plotted in Figure 2(a), where only stars in the *Planetary Camera* (PC) have been plotted. As can be seen, both star #10261 and #9774 are confirmed to be UV-excess object, while star #8916 is well outside the field of view of the PC.

A further test of the nature of these UV-excess stars can be made by checking whether they exhibit $H\alpha$-emission. Figure 2 b shows the $(H\alpha - R, H\alpha)$ CMD. Only unsaturated stars in the long $H\alpha$ exposure have been plotted. The CMD reveals that only star #10261 (among 10,000 stars measured) shows a significant excess of $H\alpha$ emission. The other two UV-excess stars have *normal* colour (($H\alpha - R) > -0.1$), and thus they are fully compatible, within the errors, with the $(H\alpha - R)$ colour of *normal* cluster MS stars.

3.   Properties of the UV-excess stars

The absolute magnitudes and colours of the three UV-excess stars have been computed adopting a distance modulus of $(m - M)_0 = 14.56$ and $E(B - V) = 0.33$ (see the discussion in Paltrinieri et al. 2000). Both distance modulus and reddening estimates have been obtained applying the method described in Ferraro et al. (1999a).

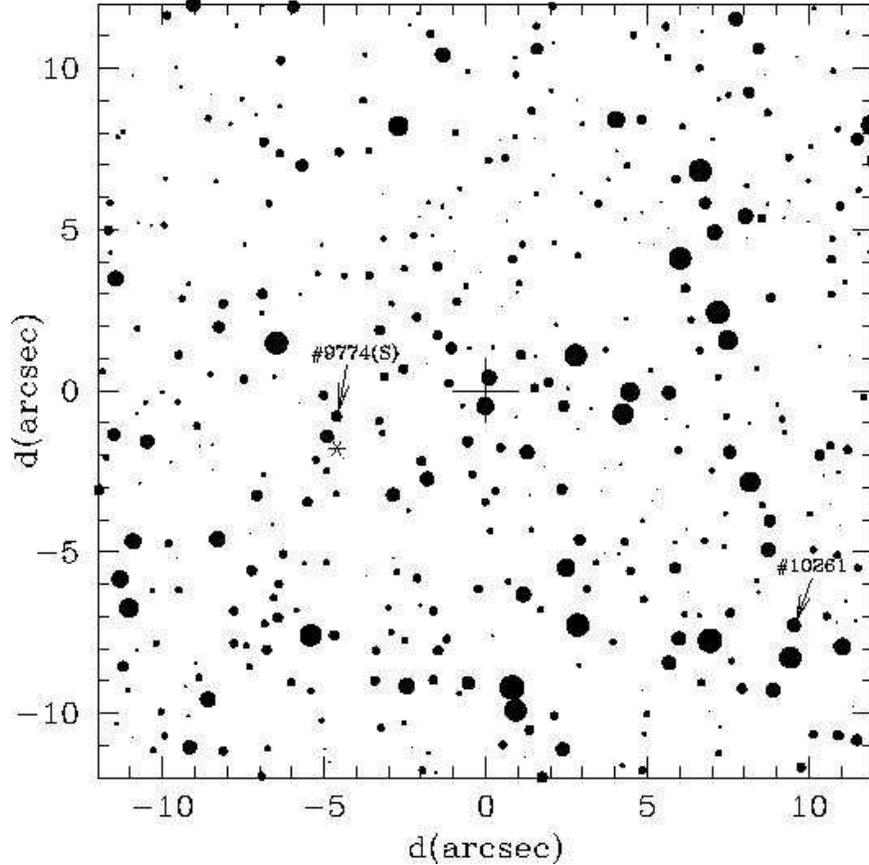In order to properly locate the three UV-excess stars with respect to the cluster centre, we

Fig. 3.— U map of the inner ($\sim 24'' \times 24''$) region of the cluster. The X and Y scales are in arcsec with respect to the center of gravity (C_{grav} indicated by a cross in the figure). The location of the two UV-excess stars in the core is also marked. The nominal position of the of the X-ray source is indicated by a an asterisk. North is up and East on the left.

have determined the gravity centre (C_{grav}) of the cluster following the procedure already adopted in other papers (Ferraro et al. 1999b): we averaged the X and Y pixel coordinates of all stars with $V < 20$ and lying within 1000 pixel ($\sim 100''$) of the cluster centre, at first extimated by eye. C_{grav} turns out to be located at $\alpha_{J2000} = 18^h\,53^m\,04\overset{s}{.}6, \delta_{J2000} = -08° \, 42' \, 18\overset{''}{.}50$ which is $\sim 6''$ NE of the luminosity centre reported in the Djorgovski (1993) compilation.

Grindlay et al. (1984) provide an accurate position (within a few arcsec) of the LMXB derived from Einstein HRI at $\alpha_{J2000} = 18^h\,53^m\,04\overset{s}{.}91, \delta_{J2000} = -08° \, 42' \, 20\overset{''}{.}15$. More recently, Lehto et

al. (1990) detected a radio emission from the X-ray source in NGC 6712 and their accurate Very Large Array position suggests that the global uncertainty on the position of the X-ray source can be hardly larger than a few arcsec.

Absolute positions, relative distances with respect to the C_{grav} and to the X-ray source, and the absolute magnitudes of the three UV-excess stars marked in Figure 1 and 2 are listed in Table 1. With the exception of star #8916, which is located $\sim 84''$ away from the cluster center, well outside the cluster core ($r_c = 56''$ Harris 1996), the other two objects (namely #9774 and #10261) are very close to each other and within a few arcsec of the cluster centre and of the nominal position of the X-ray source (see Figure 3).

Star #9774 is star S identified by Anderson et al. (1993) as the optical counterpart to the LMXB. Its positions (see Table 1) turns to be only $\sim 1''$ away from the X-ray source (in agreement with Anderson et al. (1993)). Our observations confirm that it is the bluest object within $\sim 15''$ of the X-ray source's nominal position, and for this reason it remains the best candidate to be the optical counterpar to the LMXB. Following this assumption, we can use the B magnitude obtained from our photometry to derive the parameter $\zeta = B_0 + 2.5 Lg F_X(\mu J)$. This parameter has been used by Van Paradjis & McClintock (1995) to characterize the ratio of X-ray to optical flux for LMXB in the field, and recently used by Deutsch et al. (1998) to derive the mean characteristics of LMXBs in GGCs. Assuming for the reddening the figure quoted above, we obtain $B_0 = 19.33$, and with the X-ray flux listed in van Paradjis (1995), we obtain $\zeta = 21.44$, a value fully compatible with the mean value obtained by van Paradjis & McClintock (1995) for LMXBs in the field $< \zeta >= 21.8 \pm 1.0$.

4.   Discussion

Star #10261 is the brightest object among the three faint UV-sources marked as large triangles in Figure 1 and Figure 2. Moreover it is the only object showing a clearcut $H\alpha$ excess. Star #10261 is, however, located $\sim 17''$ away from the X-ray source: this distance seems to be too

Table 1: Position of the UV-excess stars in NGC 6712

Name	M_U	M_B	M_V	M_R	α_{2000}	δ_{2000}	$d(center)$	$d(X-raysource)$
$X1850-086$	–	–	–	–	$18^{\rm h}\,53^{\rm m}\,04\overset{\rm s}{.}91$	$-08°\,42'\,20\overset{''}{.}15$	$6''$	$--$
#9774(S)	3.7	4.7	4.9	5.1	$18^{\rm h}\,53^{\rm m}\,04\overset{\rm s}{.}91$	$-08°\,42'\,19\overset{''}{.}35$	$4\overset{''}{.}7$	$1''$
#10261	3.1	4.0	3.9	4.0	$18^{\rm h}\,53^{\rm m}\,03\overset{\rm s}{.}96$	$-08°\,42'\,25\overset{''}{.}84$	$12''$	$15''$
#8916	4.5	5.5	5.3	5.2	$18^{\rm h}\,53^{\rm m}\,03\overset{\rm s}{.}44$	$-08°\,40'\,57\overset{''}{.}70$	$83''$	$85''$

large to suggest a physical connection between this object and the X-ray source.

$H\alpha$ emission and UV-excess detected for star #10261, however, suggest that this object might be a binary system in which a compact object (neutron star or white dwarf) is accreting material from a secondary star via an accretion disc (the accretion disc being the primary source of the UV emission and of the $H\alpha$ emission lines; see Robinson 1976).

Thus star #10261 is an additional excellent candidate LMXB in quiescence (since quiescent LMXBs show strong $H\alpha$ emission - Grindlay 1994) or a CV. Although its colours are fully compatible with the typical values obtained for CVs in the field: ($V-R = 0.5$, Echevarria & Jones 1984, $U-B = -1.0$), its absolute magnitude (see Table 1) is somewhat bright for a CV in quiescence. It is still compatible with the magnitude of the accretion disc of a dwarf nova at maximum of outburst ($M_V = 3-6$, Warner 1987). On the other hand, the fact that bright CVs in outburst are expected not to show strong $H\alpha$ emission lines (Grindlay, 1994) works against this scenario.

X-ray to optical flux ratio is an important clue in disentangling CVs and quiescent LMXBs (Grindlay 1984). Thus, to shed some light on the true nature of this object, we searched for possible X-ray emission in this area. The images retrieved from the ROSAT archive, however, do not show any secondary X-ray emission at the location of star #10261. Yet, this object is so close to star S (see Figure 3), that high resolution, high sensitivity X-ray observations are needed

to reveal possible X-ray emission from this object, since the expected X-ray flux from a CV or a quiescent LMXB is significantly lower (up to 4 orders of magnitude) than that of an X-ray buster: if a dim X-ray source were connected to #10261, it would be totally overwhelmed by the X-ray emission from the burster.

LMXBs have been found to be very overabundant (by a factor of ~ 100) in GGCs with respect to the field, where they are expected to form by the evolution of primordial binaries. This finding is generally interpreted as evidence that the high stellar density has led to many capture binaries. On the other hand NGC 6712, has a probability to form LMXB via two body encounters which is $\sim 10^5 - 10^6$ times smaller that high-density clusters (Bellazzini et al. 1995). Thus the discovery of another by-product of the evolution of a binary system in this low density cluster increases the mystery about the formation of these objects.

Another possible by-product of binary systems evolution has been recently serendipitously discovered (Deutsch et al. 1999) a few arcsec away from the brightest X-ray source ever observed in a GGC, in the core of NGC6624. We note here, however, that the discovery of multiple binary systems in the vicinity of the very small core ($r_c \sim 4''$) of the high-density ($Log\rho_0 \sim 5.6$), post-core collapsed NGC6624 is much less surprising than what we have found in the central regions of NGC 6712, since the internal dynamical evolution of the cluster surely plays a fundamental rule in the formation of these objects. In fact, there is now a growing consensus that dynamical evolution of the cluster can produce, via collisions, several classes of peculiar objects (see, for example the exceptionally large population of collisional blue stragglers recently discovered in the core of the high-density GGC M80 - Ferraro et al. 1999a).

On the other hand, NGC 6712 is not the only low-density GGCs in which candidate interacting binary systems have been found: for example, two faint UV-excess stars, probably connected to low luminous X-ray emission have been recently discovered (Ferraro et al. 1997b) through HST observation in the core of M 13, a GGC with central density $Log\rho_0 \sim 3.4$, comparable to that of NGC 6712. These observations suggest that interacting binaries (LMXBs and CVs) are also present in low-density GGCs, where they might originate from the normal evolution of primordial

binaries (see Davies 1997).

Furthermore, evidence is now mounting that the dynamical history of NGC 6712 is much more complex than that of other normal GGCs. The orbit computed by Dauphole et al. (1996) for this cluster suggests that it is experiencing a strong interaction with the disc and the bulge of the Galaxy. This interaction might have deeply modified the structure of this cluster, over the last 10 Gyr. The inverted mass function found by De Marchi et al. (1999) and recently confirmed by Andreuzzi et al. (2000), is a clear signature of strong tidal stripping. Moreover, Takahashi & Portegies Zwart (2000), from extensive N-body simulations, have recently found that such a signature is very rare and only appears in clusters which have lost $\geq 99\%$ of their initial mass. These facts suggest that NGC 6712 was much more massive and, probably, much more concentrated in the past than it is today (Grindlay 1985 suggested it is a post collapsed core in re-expansion phase), since its dynamical evolution is driving it towards dissolution. If this scenario finds further support in the observations, then we could conclude that what we are observing now is only the *fossil remnant* core of one of the most massive cluster in the Galaxy, may be even more massive than ω Cen. Stellar interactions among its stars, could have produced, at some earlier epoch, a variety of exotic objects such as interacting binaries. Due to mass segregation, some of these high-mass by-products are still confined in the most inner region of the dissolving core (Takahashi & Portegies Zwart 2000) and might reveal their existence in the form of the peculiar objects that we have discussed in this Letter.

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