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LETTER

Letter to the Editor

A deep optical luminosity function of NGC 6712 with the VLT: Evidence for severe tidal disruption*

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Abstract. The VLT on Cerro Paranal was used to observe four fields located at $\sim 2\farcm3$ from the center of the Galactic globular cluster NGC 6712 in the V and R bands. The resulting color-magnitude diagram shows a well defined main sequence reaching down to the $5\,\sigma$ detection limit at $V \simeq 25$, $R \simeq 23.5$ or approximately 4 magnitudes below the main sequence turn-off, the deepest obtained so far on this cluster. This yields a main sequence luminosity function that peaks at $M_R \simeq 4.5$ and drops down to the 50% completeness limit at $M_R \simeq 8.5$. Transformation to a mass function via the latest mass-luminosity relation appropriate to this object indicates that the peak of the luminosity function corresponds to $\sim 0.75\,M_\odot$, a value significantly higher than the $\sim 0.25\,M_\odot$, measured for most other clusters observed so far. Since this object, in its Galactic orbit, penetrates very deeply into the Galactic bulge with perigalactic distance of ~ 0.3 kpc, this result is the first strong evidence that tidal forces have stripped this cluster of a substantial portion of its lower mass star population all the way down to its half-light radius and possibly beyond.

Key words: stars: luminosity function, mass function – stars: low-mass, brown dwarfs – stars: Population II – Galaxy: globular clusters: general – Galaxy: globular clusters: individual: NGC 6712

1. Introduction

NGC 6712 is a small (tidal radius $\simeq 8'$) and relatively loose ($c = 0.9$) and faint ($m - M = 15.6$; Djorgovski 1993) Galactic globular cluster (GC) that has not yet received much observational attention. Its main claim to fame so far is due to the presence in its core of the high luminosity X-ray burster X1850–086 whose optical counterpart may be a faint UV-excess object (Anderson et al. 1993). This fact presents somewhat of a puzzle since one would expect such an X-ray source to be located in a highly concentrated cluster where the stellar density favors its formation via tidal capture of a neutron star (Hertz & Grindlay 1985). Most other sources of this type have indeed been found in high density core collapse clusters suggesting that, perhaps, NGC 6712 has already undergone such an event in the past and is now in a state of re-expansion (Grindlay et al. 1988).

This unusual situation may also be connected in some way to its Galactic orbit as computed recently by Dauphole et al.(1996) that is fairly well restricted to the vicinity of the disk and penetrates very deeply in the Galactic bulge. This certainly means that one would expect this cluster to have undergone severe tidal shocking during the numerous encounters with both the disk and the bulge during its lifetime and the consequences on the dynamical status of the cluster to be significant and observable. A simple single-mass approximation of these effects was computed by Gnedin & Ostriker (1997) for both disk and bulge shocks under differing assumptions on the Galactic model with a resultant time to destruction as small as $0.03\,H_o$. According to these calculations, then, the cluster should have evaporated long ago and at the very least may have lost a very substantial portion of its original mass during its lifetime.

Clearly, this catastrophe should be well impressed on its present day distribution of stars on the main sequence (MS) with its lowest mass members beyond the half-mass radius particularly vulnerable to escape. This effect may well have been detected already in M 4, another cluster at significant risk of tidal disruption (Kanatas et al. 1994; Pulone et al. 1998a), but until this cluster's structural parameters are pinned down more accurately this remains still speculative. There is, therefore, much interest today in determining accurately the present day mass function (PDMF) of NGC 6712 to look for the signature of such powerful effects. Currently available observations of the color–magnitude diagram (CMD) of this cluster, however, only reach to just above the MS turn-off (Cudworth 1988; Anderson et al. 1993) and are, therefore, of limited use for this task. In order to push the observations well into the relevant part of the MS below the turn-off (TO), the VLT was used to probe deeply into this cluster with its unprecedented sensitivity and resolution. This paper describes the first results of these observations that

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* Based on observations collected at the European Southern Observatory, Paranal, Chile (VLT-UT1 Science Verification Program)

Table 1. VLT–SV observations of NGC 6712

Field	RA	DEC	r	t_V	t_R
F 1	18:53:09.1	–8:41:17	145″	900 s	1800 s
F 2	18:53:02.0	–8:41:02	105″		1800 s
F 3	18:53:10.0	–8:43:04	130″	2700 s	2467 s
F 4	18:52:59.5	–8:43:25	135″	900 s	900 s

give clear evidence that there is indeed a distortion of the MF of NGC 6712 with respect to that of other dynamically much less disturbed clusters.

2. Observations and data analysis

The observational data used in this paper were collected during the Science Verification (SV; Giacconi et al. 1999) phase of the first 8 m-diameter Very Large Telescope (VLT) at ESO, using the VLT Test Camera (VLT-TC). Readers interested in the VLT and its instruments should consult ESO's world-wide web at `http://www.eso.org/paranal`, while the scope of the VLT Science Verification is described in Leibundgut, De Marchi, & Renzini (1998). Images of the globular cluster NGC 6712 were taken with the VLT-TC in the V and R bands. With a $2,080 \times 2,048$ square pixel detector and a plate scale of $0\farcs045$ pixel^{-1}, the VLT-TC offers a field of view of $\sim 90'' \times 90''$. SV observations, however, were obtained with an electronically enforced 2×2 binning of the CCD, so that the actual size of each pixel in these images is of $0\farcs091$ on a side. Observations of four regions of the cluster are available, located between one and two times the half-light radius ($r_{\rm hl} \simeq 78''$; Djorgovski 1993). The coordinates (J2000) of the center of each field are given in Table 1 along with the total exposure time in each band. Fields F 1 and F 2 were observed during the night of 1998 Aug 23, and F 3 and F 4 on 1998 Aug 27.

In our investigation we have used the standard SV combined datasets corresponding to Field 1, 3, and 4 which are shown in Fig. 1 (Field 2 was not used as V-band observations are not available). The quality of these images is excellent, with seeing full width at half maximum (FWHM) always of order $\sim 0\farcs6$. As can be seen in Fig. 1, however, the stellar density increases considerably towards the cluster center, thus making it progressively more difficult to accurately measure the magnitude of faint stars. Since the robustness of the luminosity function (LF) that one could determine from such images is inversely correlated with the level of crowding, we have restricted our analysis to the quadrants farthest away from the center (see Fig. 1), where the star density and the number of bright objects is smaller. The distance between the center of each quadrant and the nominal cluster center is given in Table 1.

The IRAF automated star detection routine *apphot.daofind* was applied to the data, by setting the detection threshold at $5\,\sigma$ above the local background level. We then carefully examined by eye each individual object detected by daofind and discarded heavily saturated stars and a few extended objects whose FWHM exceeds by a factor of two or more that typical of stel-

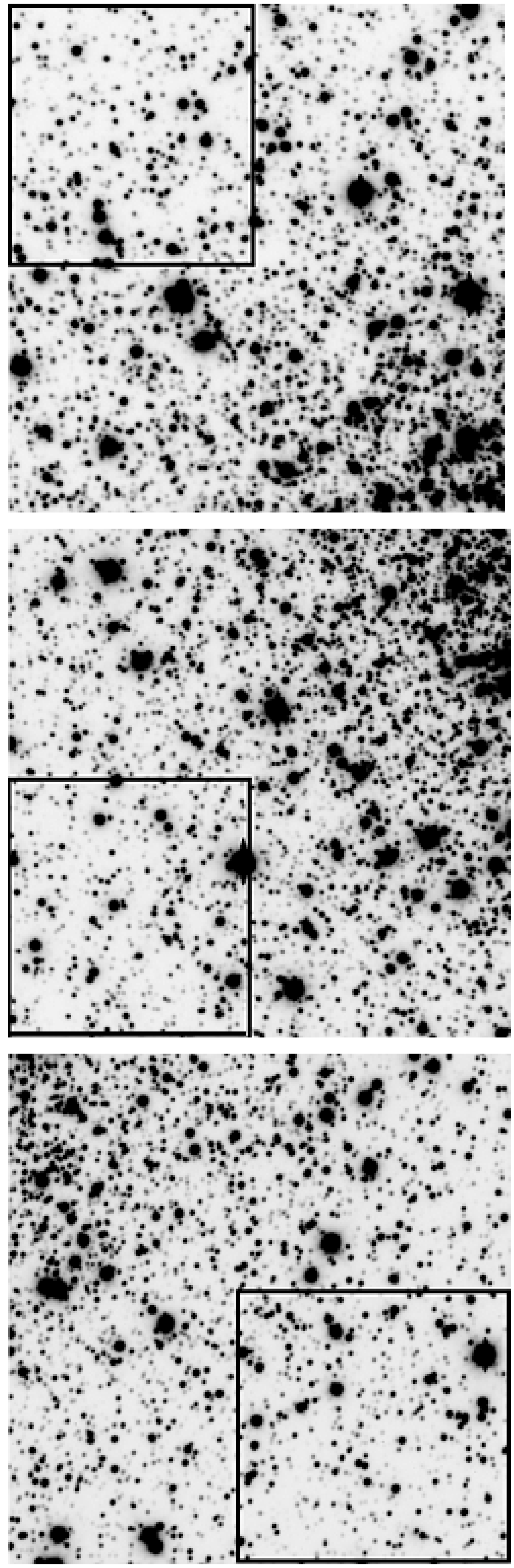

Fig. 1. Negative R-band image of fields F 1, F 3, and F 4 (*top* to *bottom*). North is up and East points to the left. Only stars falling within the boxes are studied in this paper

Table 2. Photometric coefficients

Night	Band	c_1	c_2	c_3
23 Aug	V	–26.764	0.057	0.187
23 Aug	R	–26.916	0.054	0.122
27 Aug	V	–26.798	0.064	0.210
27 Aug	R	–26.980	0.059	0.168

lar sources in our frames (FWHM $\simeq 0\farcs6$). We identified in this way 328, 500, and 568 well defined stellar objects in both bands respectively in the outer quadrants of Field 1, 3, and 4, and measured their fluxes using the standard IRAF *apphot.phot* aperture photometry routine, by setting the object radius to $r = 0\farcs46$ and the background annulus from $0\farcs46$ to $0\farcs73$. We have estimated that this choice of aperture and background annulus samples a fraction of the total stellar flux (defined as that falling within an aperture of $6''$) which, on average, corresponds to $\varepsilon_R \simeq 0.48$ and $\varepsilon_R \simeq 0.45$ respectively in the V and R bands. Instrumental magnitudes were converted into the standard Johnson system using the calibration provided by ESO as part of the SV data release, namely:

$$\mathrm{mag} = -2.5 \log{(c\,\varepsilon/t)} - c_1 - c_2\,\mathrm{colorterm} - c_3\,\mathrm{airmass} \quad (1)$$

where c is the number of counts measured within the selected aperture, ε is the corresponding encircled energy, and t is the exposure time. The coefficients c_1, c_2, and c_3 are given in Table 2.

The resulting CMD is shown in Fig. 2, where the data from Field 1, 3, and 4 are marked with boxes, triangles, and crosses, respectively. Stars brighter than $R \simeq 17$ are heavily saturated and are not plotted. Objects brighter than $R \simeq 18$ are likely to be affected by some degree of non linearity in the detector response and, as such, their magnitudes are not reliable, while stars fainter than $R \simeq 18.5$ are comfortably within the linear regime of the camera.

We have compared the V and R magnitudes of several stars in Field 1 and 3 with those measured on a set of short WFPC 2 exposures in F555W and F675W extracted from the HST archive. We find that the zero point of our photometry agrees with that of the HST (VEGAMAG system) to within ~ 0.1 and ~ 0.2 magnitudes respectively in the V (F555W) and R (F675W) bands. The still preliminary calibration of the VLT-TC coupled with the uncertainty in our aperture corrections because of crowding prevent us from determining the zero point of our photometry with greater accuracy. Nevertheless, because the VEGAMAG system does not reflect exactly the Johnson system (particularly F675W), we consider this agreement very good. We should also point out that the results of the investigation presented in this paper are insensitive to errors of a few tenths of a magnitude in the zero point (see Sect. 4 below).

The MS of NGC 6712 is rather well defined from the turn-off (TO) at $R \simeq 19$ down to $R \simeq 23$, where it broadens due to the increasing photometric errors. In fact, the accuracy of our measurements varies from less than ~ 0.05 mag at $R \simeq 18.5$

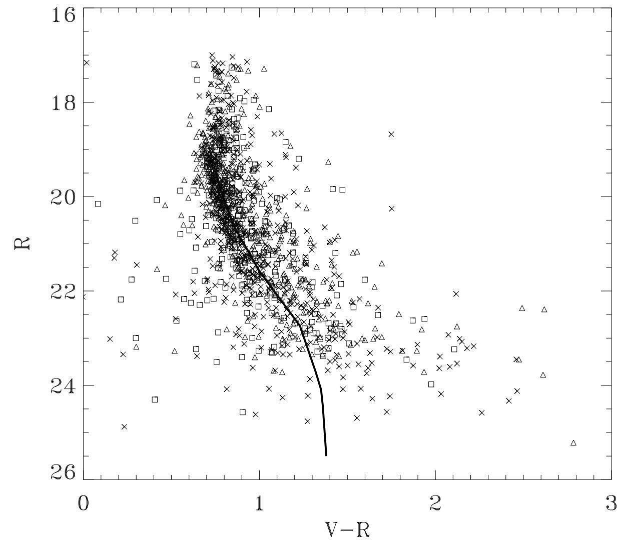

Fig. 2. Color–magnitude diagram of the stars detected in Fields F 1 (boxes), F 3 (triangles), and F 4 (crosses). The solid line shows the location of the MS as predicted using the models of Baraffe et al. (see text)

to ~ 0.35 mag at $R \simeq 23$. The solid line plotted over the CMD in Fig. 2 corresponds to the expected location of the MS as predicted using the theoretical models of Baraffe et al. (1997) for the metallicity, distance, and reddening appropriate to NGC 6712 ([Fe/H]$= -1.0$, from Zinn & West 1984; $(m - M)_o = 14.16$ and $E(B-V) = 0.46$, from Djorgovski 1993). The good agreement between our data and the models suggests that the latter are reliable, and that the use of the corresponding M-L relations when converting a MF into a LF (see Sect. 4) should give accurate results. The CMD in Fig. 2 also reveals a few objects on both sides of the MS which are likely contaminating field stars due to the low galactic latitude of the cluster ($b_{II} \simeq -4.3$ at ~ 500 pc below the Galactic plane).

3. The luminosity function

From the CMD of Fig. 2, we have measured the LF of MS stars in each field by counting the number of objects in 0.5 mag bins along the R axis. In our exercise, we have not accounted for the contamination due to field stars and, as a result, our LFs are probably an overestimate of the true distribution. This effect, however, becomes significant only below $R \simeq 21$, where photometric incompleteness increases considerably and is likely to represent the largest source of uncertainty in our measurements. In fact, the artificial star tests that we have carried out to estimate the level of completeness as a function of magnitude (see Table 3) show that at $R \simeq 22$ we only sample two thirds of the total population, and that this fraction drops to 50% at $R \simeq 23.5$.

The LFs measured in this way and corrected for photometric incompleteness are shown in Fig. 3 as a function of the R-band magnitude. The LFs have been registered through a vertical shift in the logarithmic plane by imposing a least square fit in the range $19 < R < 23$. The error bars associated with each point reflect the poisson statistics of the counting process (and

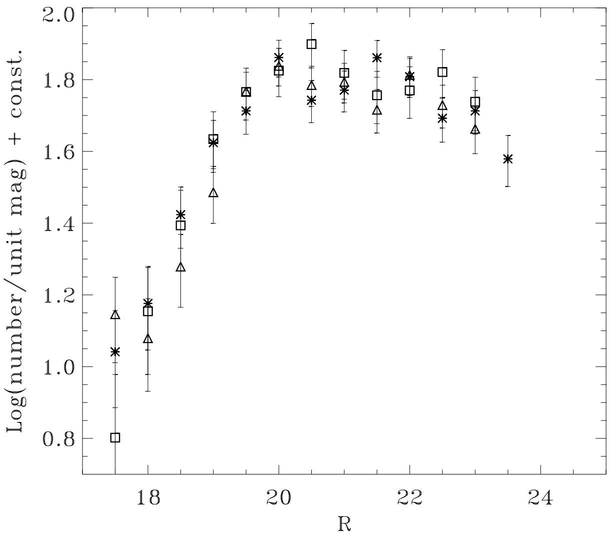

Fig. 3. Luminosity functions of MS stars measured in Fields F 1 (boxes), F 3 (triangles), and F 4 (crosses), after correction for photometric incompleteness

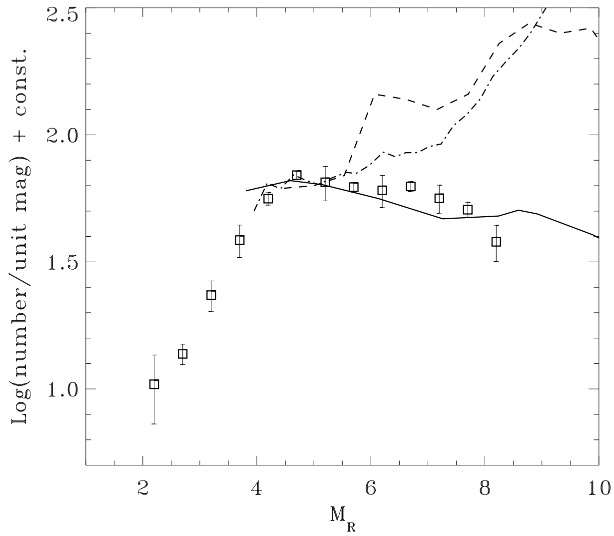

Fig. 4. Boxes: average of the three LFs shown in Fig. 3, converted to absolute magnitude (M_R); dashed and dot-dashed lines: LFs of NGC 6397 and 47 Tuc translated to the R band and normalized to ours at the TO ($M_R \simeq 4$); solid line: best fitting power-law MF ($dN/dm \propto m^{1.5}$)

Table 3. Photometric completeness as a function of magnitude

R mag =	18.0	19.0	20.0	21.0	22.0	23.0	23.5
F 1	1.00	0.92	0.83	0.77	0.70	0.55	0.48
F 3	1.00	0.98	0.90	0.82	0.60	0.50	0.40
F 4	1.00	0.95	0.88	0.78	0.70	0.62	0.58

include the correction for incompleteness). These LFs can be directly compared to one another as they have all been measured at the same radial distance from the center ($r \simeq 2\farcm3$ or ~ 1.7 times the half-light radius $r_{\rm hl}$). They show the same overall trend, i.e. an increase with decreasing luminosity up to a peak at $R \simeq 20$ (close to the TO luminosity), and from there they all flatten out and possibly drop with decreasing luminosity even after the incompleteness of our photometry has been accounted for. And indeed, to ensure that our LFs are robust, we have not included in Fig. 3 any datapoints whose associated photometric completeness is worse than 50%.

4. Discussion and conclusions

Stars brighter than $R \simeq 19$ have already evolved off the MS and, therefore, their LF provides no information on the underlying MF without uncertain corrections for evolution (Scalo 1998). Moreover, because of saturation at the bright end of our CMDs, the brightest portion of our LFs is uncertain. For cluster stars which are still on their MS, however, the LFs in Fig. 3 directly reflect the PDMF of the local population and immediately indicate a relative deficiency of low mass objects with respect to the stars with the TO mass ($\sim 0.8\,{\rm M}_\odot$,), as we discuss below.

Indeed, the most important conclusion that one can draw from Fig. 3 is that the shape of the LFs completely deviates from that of any other GC for which relatively deep photometric data are available near the half-mass radius. Observations carried out with the WFPC 2 on board the HST over the past few years (Paresce, De Marchi & Romaniello 1995; Cool, Piotto, & King 1996; Elson et al. 1995; De Marchi & Paresce 1995a, 1995b, 1996a, 1997; Piotto, Cool, & King 1997; Pulone et al. 1998a; King et al. 1998; De Marchi 1998) have consistently revealed LFs that, near the cluster half-mass radius, increase with decreasing luminosity from the TO magnitude all the way down to about $M_V \simeq 11$ ($\simeq 0.25\,{\rm M}_\odot$,) where they flatten out and drop at fainter luminosities. Inverted LFs such as those shown in Fig. 3 have been observed right in the core of high density GCs (47 Tuc, NGC 6397, M 15) but in those cases a simple isothermal model of a cluster in equilibrium can easily explain this effect as being due to mass segregation (Paresce, De Marchi, & Jedrzejewski 1995; King, Sosin, & Cool 1995; De Marchi & Paresce 1996b). More complete multi-mass King–Michie models show, however, that thermal relaxation is much less efficient (if at all) at depleting low-mass stars near the half-mass radius (see Pulone, De Marchi, & Paresce 1998b), and we cannot therefore trace the origin of the LFs that we observe back to the effects of mass segregation alone.

To make it easier to compare the LF of NGC 6712 with that of other clusters, we display it in Fig. 4 as a function of the absolute R-band magnitude, assuming $(m-M)_o = 14.16$ and $E(B-V) = 0.46$ or $A_R = 1.15$ (Djorgovski 1993). Rather than showing the three individual LFs, we have combined them together into one single function by averaging their values in each magnitude bin, and have taken the standard deviation as a measure of the associated uncertainty (error bars). The dashed line shown in Fig. 4 corresponds to the LF of the low-metallicity cluster NGC 6397 as measured by King et al. (1998), while the dot-dashed line reproduces the LF of the metal rich cluster

47 Tuc from Hesser et al. (1987). Both LFs have been translated into the R-band by using the M–L relationship of Baraffe et al. (1997) for the appropriate metallicity, i.e. the magnitude corresponding to each observed point in the LF has been converted into a mass which has then been used to read the corresponding magnitude in the R band from the appropriate M-L relation. The size of each magnitude bin has also been rescaled to reflect the difference in the slopes of the M-L relationships for different bands. We have selected NGC 6397 and 47 Tuc as they both have accurate LF measurements at and below the TO luminosity, where we have normalized them to our observations, and because the metal content of these clusters nicely brackets that of NGC 6712 ([Fe/H]$= -1.0$; Zinn & West 1984). It should, nevertheless, be clear that, due the uncertainties in the theoretical M-L relations and in the observed LFs, our comparison will only provide an indication of the true differences.

The difference between these two LFs and that of NGC 6712 is striking. While the LFs of NGC 6397, measured at $1.6\, r_{\rm hl}$, shows a steep increase starting from the TO, the LF of NGC 6712 sampled at $\sim 1.7\, r_{\rm hl}$ slowly drops from the TO all the way to the detection limit at $M_R \simeq 8.5$. We would like to point out that the discrepancy is so large that to bring the two LFs into agreement would require us to have underestimated the photometric incompleteness by a factor of ~ 10. The same reasoning holds true for the LF of 47 Tuc, which has been measured at $\sim 5\, r_{\rm hl}$. This difference must thus be physical and reflect the properties of the local stellar population.

Under the simple assumption that the MF should be represented by an exponential distribution in the mass range $0.4 - 0.8\,{\rm M}_\odot$, (a reasonable hypothesis given the narrow mass range), we have used the M–L relationship of Baraffe et al. (1997) appropriate for the metallicity of NGC 6712 to reproduce the observed LF. We obtain a fairly reasonable fit to the observations with a power-law distribution of the type $dN/dm \propto m^{1.5}$ (Salpeter's IMF would be $dN/dm \propto m^{-2.35}$), in which the number of objects decreases with mass (solid line in Fig. 4).

Richer et al. (1991) and, more recently, De Marchi & Paresce (1997), Vesperini & Heggie (1997), and Pulone et al. (1998b) have convincingly shown that near the cluster half-mass radius the LF should closely reflect the IMF, as dynamical modifications should leave these regions almost untouched. In fact, the internal relaxation mechanism governed by energy equipartition through two- and three-body encounters mostly affects the region within a few core radii, while the interaction with the Galactic tidal field is expected to simply speed up the evaporation of light stars near the tidal boundary, but none of these processes should, in principle, significantly alter the properties of stars located close to the much safer half-mass radius area.

If this were true for NGC 6712 as well, one should conclude that this cluster is the only one so far to feature an inverse IMF (increasing with mass) that has not been observed in any other environment. While this hypothesis cannot be safely ruled out, there are far better reasons to believe that NGC 6712 might have experienced a much stronger interaction with the Galaxy than any other of the clusters studied so far. And indeed, with a perigalactic distance smaller than 300 pc this cluster ventures so frequently and so deeply into the Galactic bulge (Dauphole et al. 1996) that it is likely to have undergone severe tidal shocking during the numerous encounters with both the disk and the bulge during its lifetime. The latest Galactic plane crossing could have happened as recently as $4\,10^6$ year ago (Cudworth 1988) which is much smaller than its half-mass relaxation time ($5\,10^8$ yr). Such an event might have imparted strong modifications on the mass distribution not only of the stars in the cluster periphery but also well into its innermost regions, perhaps even reaching the core where it could have triggered a premature collapse because of tidally induced relaxation (see Kundić & Ostriker 1997 and Gnedin & Ostriker 1997 for a detailed description of this mechanism).

As a result of such a catastrophe, it would be surprising if the present-day MF were still to bear any memory of its parent IMF anywhere in the cluster, including the half-mass radius region. Vesperini & Heggie (1997) have estimated that these effects would substantially decrease the slope of a simple power law MF, much in the same way as we are observing here. We, therefore, conclude that the VLT has revealed the consequences of the strong tidal stripping that the Galaxy (and particularly its bulge) exerts on GCs orbiting close to the center, and which might have contributed to the destruction of an initially much more numerous population of GCs (Aguilar, Hut, & Ostriker 1988; Vesperini 1997). Although Kanatas et al. (1994) and Piotto et al. (1997) had speculated that similar events could have happened respectively in M 4 and NGC 6397, the result that we show here is the first, clear, unambiguous detection of this mechanism. To characterize the strength and extent of these phenomena more accurately would require the investigation of the MS population outside the half-mass radius in many more clusters, and possibly at larger distance from the Galactic center, so as to probe the intensity of the stripping process as a function of the depth of the Galactic potential well. If the Z component of the space velocity of NGC 6712 is indeed appropriate for a halo cluster, as suggested by Cudworth (1988), then this violent stripping process might not be restricted only to objects orbiting the innermost Galactic regions.

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