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 $\sim 2.3$ 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 5σ detection limit at $V \approx 25$, $R \approx 23.5$ 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 $M_R \approx 4.5$ and drops down to the 50% completeness limit at $M_R \approx 8.5$. 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 $\sim 0.3$ 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: globular clusters: general – globular clusters: individual: NGC 6712 – stars: luminosity function, mass function – stars: low-mass, brown dwarfs – stars: Population II

1. Introduction

NGC 6712 is a small (tidal radius $\approx 8'$) 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 Gyr. 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 M4, another cluster at significant risk of tidal disruption (Kanatas et al. 1994; Pulone et al. 1998), 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 1985; 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

\* Based on observations collected at the European Southern Observatory, Paranal, Chile (VLT-UT1 Science Verification Program)
was used to probe deeply into this cluster with its unprece-
dented sensitivity and resolution. This paper describes the
first results of these observations that give clear evidence
that there is indeed a distortion of the MF of NGC 6712
with respect to that of other dynamically much less dis-
turbed clusters.

2. Observations and Data Analysis

The observational data used in this paper were col-
lected during the Science Verification (SV; Leibundgut
& Renzini 1998) phase of the first 8m-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 clus-
ter NGC 6712 were taken with the VLT-TC in the V and
R bands. With a 2,080 × 2,048 square pixel detector and
a plate scale of 0′′.045 pixel−1, the VLT-TC offers a field of
view of ∼ 90′′ × 90′′. SV observations, however, were ob-
tained with an electronically enforced 2 × 2 binning of the
CCD, so that the actual size of each pixel in these images
is of 0′′.091 on a side. Observations of four regions of the
cluster are available, located between one and two times
the half-light radius (rhl ≃ 78′′; Djorgovski 1993). The co-
ordinates (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.

| Field | RA (J2000) | DEC | r (arcsec) | tV (s) | tR (s) |
|-------|------------|-----|------------|-------|-------|
| 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  |

In our investigation we have used the standard SV
combined datasets corresponding to Field 1, 3, and 4 which
are shown in Figure 1 (Field 2 was not used as V-band
observations are not available). The quality of these im-
ages is excellent, with seeing full width at half maximum
(FWHM) always of order ∼ 0′′.6. As can be seen in Fig-
ure 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 cor-
related with the level of crowding, we have restricted our
analysis to the quadrants farthest away from the center
(see Figure 1), where the star density and the number of
bright objects is smaller. The distance between the center

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.
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 5σ 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 stellar sources in our frames (FWHM ≃ 0′06). 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′.46 and the background annulus from 0′.46 to 0′.73. 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 εR ≃ 0.48 and εR ≃ 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:

\[
mag = -2.5 \log(c \varepsilon/t) - c_1 - c_2 \text{colorterm} - c_3 \text{airmass}(1)
\]

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 c₁, c₂, and c₃ are given in Table 2.

**Table 2. Photometric coefficients**

| Night | Band | c₁ | c₂ | c₃ |
|-------|------|----|----|----|
| 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 |

The resulting CMD is shown in Figure 2, where the data from Field 1, 3, and 4 are marked with boxes, triangles, and crosses, respectively. Stars brighter than R ≃ 17 are heavily saturated and are not plotted. Objects brighter than R ≃ 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 ≃ 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 Section 4 below).

The MS of NGC 6712 is rather well defined from the turn-off (TO) at R ≃ 19 down to R ≃ 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 ≃ 18.5 to ~ 0.35 mag at R ≃ 23. The solid line plotted over the CMD in Figure 2 corresponds to the expected location of the MS as predicted using the 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)₀ = 14.16 and (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 Section 4) should give accurate results. The CMD in Figure 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 (b₈₁ ≃ −4.3 at ~ 500 pc below the Galactic plane).
3. The Luminosity Function

From the CMD of Figure 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 \( R \approx 21 \), 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 \( R \approx 22 \) we only sample two thirds of the total population, and that this fraction drops to 50% at \( R \approx 23.5 \).

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 |

The LFs measured in this way and corrected for photometric incompleteness are shown in Figure 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 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 (\( r \approx 2'3/3 \) or \( \sim 1.7 \) times the half-light radius \( r_{hl} \)). They show the same overall trend, i.e. an increase with decreasing luminosity up to a peak at \( R \approx 20 \) (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 Figure 3 any datapoints whose associated photometric completeness is worse than 50%.

4. Discussion and Conclusions

Stars brighter than \( R \approx 19 \) 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 Figure 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 (\( \sim 0.8 M_\odot \)), as we discuss below.

Indeed, the most important conclusion that one can draw from Figure 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 1993; Cool, Piotto, & King 1996; Elson et al. 1993; 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 \( M_V \approx 11 \) (\( \sim 0.25 M_\odot \)), where they flatten out and drop at fainter luminosities. Inverted LFs such as those shown in Figure 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 1993; King, Sosin, & Cool 1997; 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 Figure 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 Figure 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) appropriate for the metallicity 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 \(r_{hl}\), shows a steep increase starting from the TO, the LF of NGC 6712 sampled at \(1.7 r_{hl}\) slowly drops from the TO all the way to the detection limit at \(M_R \sim 8.5\). 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 \(\sim 10\). The same reasoning holds true for the LF of 47 Tuc, which has been measured at \(\sim 5 r_{hl}\). 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 \(0.4 - 0.8 M_{\odot}\), (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 Figure 4).

Richer et al. (1997) and, more recently, De Marchi & Paresce (1997), Vesperini & Heggie (1997), and Pulone et al. (1998) 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 (Dauphorne 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 last Galactic plane crossing could have happened as recently as \((10^8 \text{ yr})\) (Cudworth 1988) which is much smaller than its half-mass relaxation time (\(5 \times 10^8 \text{ yr}\)). 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. (1995) and Piotto et al. (1997) had speculated that similar events could have happened respectively in M4 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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