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THE STELLAR POPULATION OF NGC 5634. A GLOBULAR CLUSTER IN THE SAGITTARIUS DSPH STREAM? [1]

MICHELE BELLAZZINI, FRANCESCO R. FERRARO
INAF - Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127, Bologna, ITALY
bellazzini@bo.astro.it, ferraro@apache.bo.astro.it
RODRIGO IBATA
Observatoire de Strasbourg, 67000 Strasbourg, France
ibata@newb6.u-strasbg.fr
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ABSTRACT

We present the first $(V, V-I)$ Color − Magnitude Diagram (CMD) for the poorly studied globular cluster NGC 5634. The CMD shows a steep Red Giant Branch (RGB) and a predominantly blue Horizontal Branch (HB): both these characteristics suggest a low metal content for this cluster. From the position of the RGB in the CMD we estimate $[Fe/H] = -1.94 \pm 0.10$ and $E(B-V) = 0.06 \pm 0.01$. The CMD presented here reaches $V \simeq 23$, allowing us to obtain the first measure of the Main Sequence Turn-Off (TO) $V_{TO} = 21.22 \pm 0.15$ for this cluster. By combining this figure with the apparent luminosity of the *Zero Age HB* (ZAHB), $V_{ZAHB} = 17.90 \pm 0.10$ we obtain $\Delta V_{TO}^{HB} = 3.32 \pm 0.16$, a value which is fully compatible with that derived for the bulk of Galactic globulars. We also derive a true distance modulus of $(m-M)_0 = 17.17 \pm 0.12$ corresponding to a distance of ~ 27.2 kpc. Most interestingly, the cluster is shown to have position and radial velocity fully compatible with the orbit of the Sgr dwarf spheroidal (dSph) galaxy. The similarity between the stellar populations of the cluster and the Sgr globular Ter 8 and the metal poor population of the Sgr dSph, also suggest that NGC 5634 was a former member of this disrupting galaxy, torn off by the Galactic tidal field and now lost in the Sgr stream.

Subject headings: clusters: globular clusters: individual (NGC 5634) - galaxies: individual (Sagittarius dwarf spheroidal)

1. INTRODUCTION

NGC 5634 is a high-latitude globular cluster (l^{II} = 342.21, b^{II} = +49.26) in the northern hemisphere. Its luminosity ($M_V = -7.66$, according to Djorgovski 1993, hereafter D93) and concentration ($c = log(r_t/r_c) = 1.60$, where r_t and r_c are the tidal radius and the core radius, respectively; see D93 and references therein) are typical figures for a Galactic Globular Cluster (GGC).

Despite its brightness, the cluster was really poorly studied in the past, since no Color - Magnitude Diagram (CMD) has been published so far. A possible cause of this, could be the presence of a very bright foreground star located at only 1.7 arcmin to the East of the center of the cluster. This observational drawback may have turned the attention of observers toward less problematic alternative clusters.

In the Peterson (1986) compilation of GGC CMDs only three items are quoted for this cluster: (1) the search for variable stars by Baade (1945), in which seven RR Lyrae variable stars were identified; (2) the follow-up study by Liller & Sawyer Hogg (1976), who assessed the light curves and periods of six of the seven variables found by Baade; and (3) an unpublished CMD by Racine, quoted also by Liller & Sawyer Hogg (1976). All the above works were based on photographic plates.

The ADS database (as well as other databases) does not report any further study to date. NGC 5634 is included in the *HST Snapshot Survey of globular clusters* (GO-7470, see Zoccali et al. 1999, for details and references) collecting HST-WFPC2 shallow photometry for a large sample of Galactic globulars. However, up to now, only a few parameters (such as the HB level and the RGB-bump) have been derived from the HST data-set and published by this team (Zoccali et al. 1999; Bono et al 2001); while, the CMD of the cluster and its overall characteristics have not been discussed in any paper, yet.

Globular clusters are crucial tracers of the early history of the Galaxy, in particular the rare Outer Halo clusters that are found at Galactocentric distances $R_{GC} > 10$ kpc. Since NGC 5634 belongs to this latter group, it is certainly worth of studying.

In this paper we present the *first CMD of NGC 5634*. New estimates of reddening, metallicity and distance are obtained and the Horizontal Branch (HB) morphology is discussed. A differential age estimate is also obtained by comparison with well studied clusters of similar metal content. The possible connection with the huge stellar stream left by the disrupting Sagittarius dwarf spheroidal galaxy along its orbital path (Sgr Stream, see Newberg et al. 2002, and references therein) is also discussed.

The plan of the paper is as follows. We present the observations and the data analysis in Section 2, the overall properties of the main branches of the CMD (RGB, HB) are presented in Section 3. Section 4 is devoted to the determination of the distance and the age of the cluster. Finally Section 5 is dedicated to discuss the possible connection between NGC5634 and the Sgr galaxy.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Observations*

The data were obtained at the 3.52 m Italian telescope *Telescopio Nazionale Galileo* (TNG, Roque de los

Muchachos, La Palma, Canary Islands, Spain), using the LSR-Dolores Camera equipped with a 2048 × 2048 pixels thinned and back-illuminated Loral CCD array (gain= $0.97e^{-}/ADU$, read-out noise 9.0 ADU rms). The pixel scale is 0.275 arcsec/px, thus the total field of view of the camera is $9.4 \times 9.4\ arcmin^2$. Two fields have been observed in the region of the cluster: (1) a field roughly centered on the cluster center (Central Field; hereafter CF) and (2) a second one centered at ~ 6 arcmin NE with respect to the cluster center (Field NE). The observations were carried out during one photometric night (March 19, 2001), under not excellent seeing conditions ($FWHM \simeq 1.2 - 1.4$ arcsec) as a backup program while the main targets were not visible.

The data consists of two V and two I 30 s exposures for the FC and only one long exposure (600 s) in each band for the outer Field NE.

The observational strategy was similar to that described in Bellazzini et al. (2001): the short exposures in the central part samples the majority of the cluster Red Giants and HB stars, conversely, with the long exposures in the outer region the Main Sequence (MS) stars are observed in a field less plagued by the stellar crowding. The two fields (FC and Field NE) have an overlapping region $\sim 3 \times 3$ arcmin wide, which is used (see Section 2.2) to derive robust coordinate and magnitude transformations between the two fields.

2.2. *Data Analysis*

The raw images were corrected for bias and flat field, and the overscan region was trimmed using standard IRAF[2] procedures. Each couple of $t_{exp} = 30\ s$ images, in each band, has been averaged, so that the final analysis was performed on each averaged V and I image.

The PSF-fitting procedure was performed independently on each V and I average images, using a version of DoPhot (Schechter, Mateo, & Saha 1993) modified at the Bologna Observatory (by P. Montegriffo) to read images in double precision format. A final catalogue listing the instrumental V,I magnitudes for all the stars in each field has been obtained by cross-correlating the V and I catalogues. Only the sources classified as stars by the code have been retained. The spurious sources erroneously fitted by DoPhot (as cosmic rays, bright background galaxies etc.) have been removed by hand from the catalogues. In order to obtain a CMD as clean as possible, all the sources with photometric errors (in V or in I) larger than two times the mean error at their magnitude were removed from the catalogue, as well as all the sources with photometric error larger than 0.2 mag in at least one passband.

The two catalogs were then matched together: stars in the overlapping area were used to transform the magnitudes and coordinates of each field to a common system. In particular both the V and I instrumental magnitudes and coordinates for stars in the NE Field catalog were reported to the FC system. In the homogeneous coordinate system the cluster center is at $(X_{px}, Y_{px}) \simeq (860, 920)$.

Finally, to minimize the effects of crowding on the definition of the main branches of the CMD we include in the final catalogue: (a) all the stars from the FC catalogue with $V < 19.5$ and, (b) all the stars from the Field NE catalogue more distant than 280 px ($r > 1'.28$) from the cluster center.

The absolute calibration has been obtained from repeated observations of Landolt (1992) standard fields, including all the stars listed in the extended catalogue of calibrators provided by Stetson (2000). The details of the process as well as the (successful) tests on the accuracy of the calibration will be described in a forthcoming paper devoted to describe the results of the main observational program whose the observing nights were assigned (Bellazzini et al. 2002b). The derived color equations:

$$V = v - 0.097(v - i) + 26.196$$

$$I = i + 0.048(v - i) + 25.849$$

(where V,I are calibrated magnitudes and v,i are instrumental magnitudes reported to 1 s of exposure time and to infinite aperture) provides a zero-point accuracy of ± 0.02 mag and no detectable residual color effect.

The final calibrated catalogue is presented in Table 1 where, for each star, the following information is listed: the identification number (column 1), the V magnitude and error (columns 2 and 3), the I magnitude and error (columns 4 and 5), and the X and Y coordinates in pixels (columns 6 and 7). Column 8 reports a flag indicating the RR Lyrae variables identified in the catalogue of Baade (1945), according to his nomenclature. The stars with identification number $ID < 10,000$ are from the FC sample, those with $ID \geq 10,000$ are from the Field NE catalog.

3. THE PROPERTIES OF NGC 5634

3.1. *The overall CMD morphology*

The final $(V, V - I)$ CMD of NGC 5634 is presented in Fig. 1. Stars with $V < 19.5$ (lying above the dotted line in Fig. 1) are from the FC catalogue, while those with $V > 19.5$ are from the Field NE catalogue. The main characteristics of the CMD are the following:

(1) The RGB is well defined also in the upper part and it is quite steep suggesting a low metal content for the cluster stars. The brightest star in the region of the giant tip is at $V \sim 14.5$ and $(V - I) \sim 1.6$), which is about 3.4 mag. above the *Zero Age Horizontal Branch* (ZAHB) level (see §3.2). A few Asymptotic Giant Branch (AGB) stars are also visible on the blue side of the RGB, from $V \simeq 16.0$ to $V \simeq 17.0$.

(2) The HB is populated essentially on the blue side of the instability strip, at $(V - I) \leq 0.3$. However the cluster is known to contain also a few RR Lyrae variables (Baade 1945).

(3) Despite the not excellent quality of the photometry for $V > 20.5$ the Sub Giant Branch (SGB) and the Turn Off (TO) region are sufficiently defined and the TO point can be reliably located at $V_{TO} \simeq 21.2$.

(4) The (modest) effects of foreground contamination by field stars are mostly evident around $V - I \simeq 0.4$, for $V > 19.5$, and for $V - I \geq 1.2$ at faint magnitudes.

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

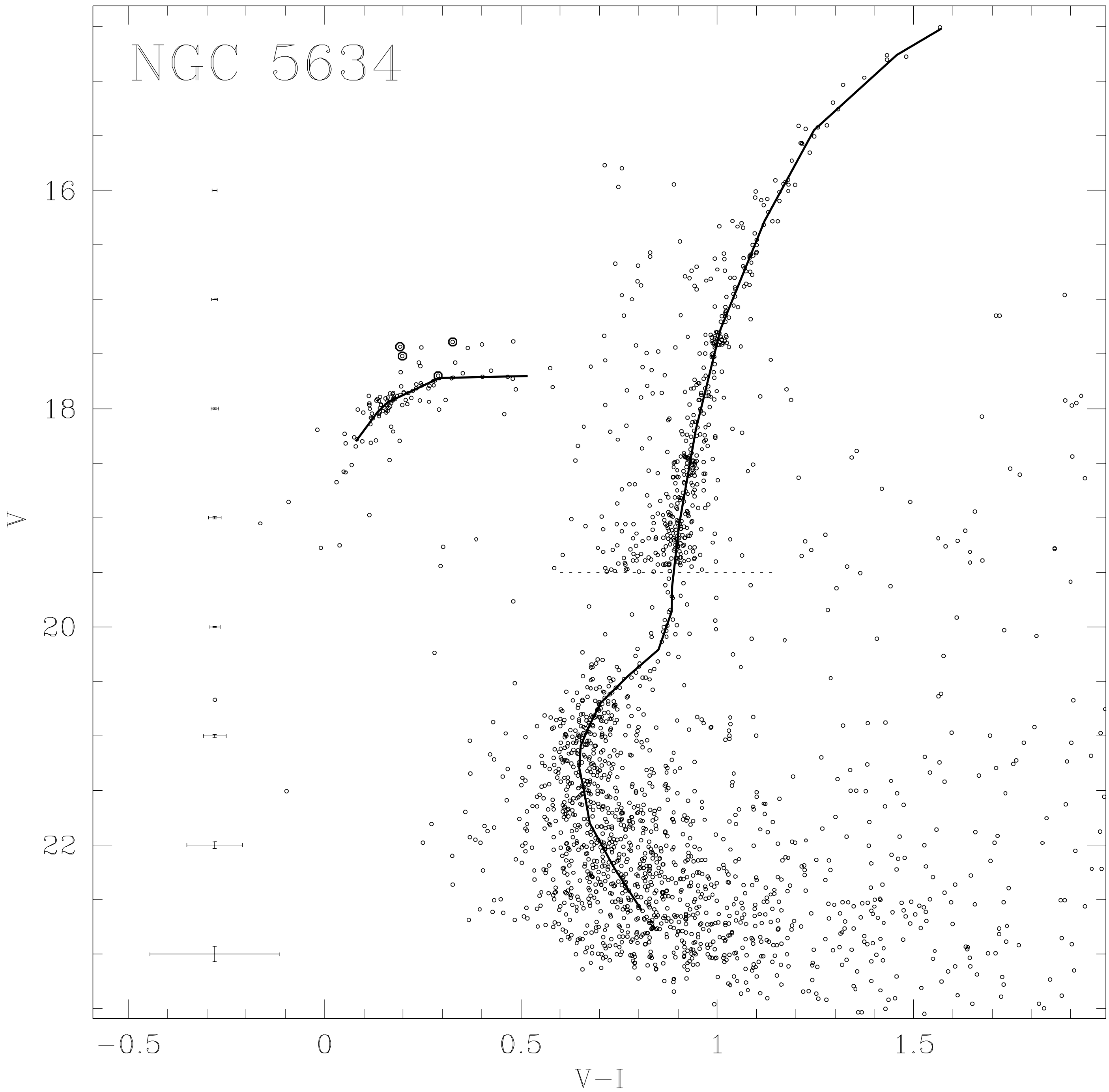

Fig. 1.— The final CMD of NGC 5634, including 2065 selected stars. The four RR Lyrae variables identified in Plate 1 of Baade (1945) and included in our catalog are marked with large open circles. The dashed horizontal line $V = 19.5$ separates the two observed samples (FC and Field NE - see text). Note that only stars measured in the Field NE are considered for $V > 19.5$. The mean ridge line of the main branches are over-plotted on the CMD. The photometric errors at different magnitude levels are marked on the left of the diagram.

We have identified and included in the final catalog four of the seven RR Lyrae stars discovered by Baade (1945), i.e. variable n. 1, 2, 4 and 6 (hereafter V1, V2, etc.), that are marked in Fig. 1 with large empty circles. The identification of V1, V4 and V6 is safe, while some uncertainty remains for the cross-identification of variable V2. V3 was identified but it has been excluded from our catalogue because of very uncertain photometry due to blending with other sources. Variable V7 is blended in a group of stars that was too crowded to be resolved in our images; V5 was probably observed at a phase near the minimum, since it appears to be very faint in our 30 s exposures with respect to the other RR Lyrae, and was not included in the final catalogue because it did not pass the severe selection criteria adopted. It may be interesting to recall that V1 and V2 are classified as *ab* type and V4 and V6 as *c* type RR Lyrae, according to Liller & Sawyer Hogg (1976). According to their results Liller & Sawyer Hogg (1976) classified the cluster as Oosterhoff II type, typical of very metal deficient globular cluster.

The mean ridge lines of the main branches in the CMD for NGC5634 have been obtained by dividing each sequence in appropriate magnitude (for the MS and the RGB) or color (for the HB) bins and applying a $2-\sigma$ clipping algorithm to each bin, accordingly to the procedure adopted in Bellazzini et al. (2001). The adopted ridge lines are listed in Table 2 and plotted (as a heavy solid line) in Fig. 1.

3.2. *HB level*

The determination of the HB level in clusters that have a blue HB morphology is a difficult task. Moreover, as emphasized in (Ferraro et al. 1999, hereafter F99), some confusion in the definition of the HB level does exist in the literature since some papers refer to mean level of the HB or the mean magnitude of the RR Lyrae ($<V_{RR}>$), other to the ZAHB level (V_{ZAHB}). We recall that the V_{ZAHB} is the only value which can be directly compared with the theoretical predictions.

In the following we apply two procedures in order to independently determine the $<V_{RR}>$ and the V_{ZAHB} for NGC5634.

3.2.1. *The $<V_{RR}>$ level*

We adopt here the same procedure followed by Montegriffo et al. (1998, hereafter Mo98) for Ter 8, another cluster with a similar blue HB (see, also the case of NGC 288 in Bellazzini et al. 2001, and discussion therein). Following this approach, the $<V_{RR}>$ level in a cluster with a blue HB morphology is obtained by the comparison with the HB of a cluster with a well studied population of RR Lyrae variables, used as a template. As in the case of Ter 8 we choose M68 (Walker 1994) as the reference cluster. In panel (a) of Fig. 2 the HB stars of M 68 (open dots) are shifted ($\Delta V=+2.04\pm0.06$ and $\Delta V-I=+0.04$) to match the HB stars of NGC 5634 (full dots). The thick dashed line marks the mean level of the RR Lyrae variables in M 68 ($V_{RR}=15.64\pm0.01$ Walker 1994) once shifted by the same amount, thus giving $V_{RR}^{NGC5634}=17.68\pm0.06$. This value is used in Section 3.3 to determine a set of RGB parameters which depend on the metal content and the reddening of the cluster.

In *panel (b)* of Fig. 2, the result of a further consistency check is shown: the HB of Ter 8 (open squares) has been shifted (by $\Delta V=-0.28\pm0.08$ and $\Delta V-I=-0.06$) to match the HB of NGC5634 (full dots). As can be seen, the match is very good: by appling the shift in magnitude obtained above ($\Delta V=-0.28$) to the mean RR Lyrae level of NGC5634 ($V_{RR}^{NGC5634}=17.68\pm0.06$) we obtain, for Ter 8, $V_{RR}^{Ter8}=17.96\pm0.06$, a figure which is fully consistent with the value found by Mo98 ($V_{RR}^{Ter8}=17.95\pm0.05$). This test demonstrates the good degree of repeatability of the whole "HB matching" technique adopted here.

3.2.2. *The $<V_{ZAHB}>$ level*

We also determine the level of the Zero Age Horizontal Branch (ZAHB) at $LogT_e=3.85$, following the the semi-empirical approach adopted by F99. The method is based on the comparison of synthetic and observed HB. The observed HB morphology is reproduced by means of synthetic HB diagrams (see F99 for more details). Once the observed HB distribution is properly reproduced, the synthetic HB is shifted in order to match the observed one and the ZAHB level at $LogT_e=3.85$ is read from the shifted sythethic HB. The procedure applied to NGC 5634 yelds $V_{ZAHB}=17.90\pm0.10$.

As above, an additional consistence check can be done with the cluster Ter8. In fact, by coupling the value of the ZAHB obtained above for NGC5634 and the value listed in Table 2 by F99 for Ter8 ($V_{ZAHB}^{Ter8}=18.15\pm0.10$) we obtain $\Delta V_{ZAHB}(NGC5634-Ter8)=-0.25\pm0.10$, in excellent agreement with the difference in $<V_{RR}>$ found above.

The difference between V_{ZAHB} and $<V_{RR}>$ levels for NGC5634 is $\delta V(ZAHB-RR)\sim0.22$ mag, confirming that a significant difference between the two levels does indeed exist in blue-HB morphology clusters (see F99). Note also that $\delta V(ZAHB-RR)$ is larger that what is expected by using relation (2) in F99. This evidence confirms once more that such relations should be used to have only a first-guess estimate, since the actual difference between the two levels strictly depends on the HB morphology, and it is particularly large for clusters with essentially blue HB morphology.

The derived V_{ZAHB} also suggests that the reddest part ($V-I>0.3$) of the BHB, and possibly the bluest part of the instability strip, may be populated by evolved stars significantly brighter than the ZAHB, similar to the case of NGC 288 (see Catelan et al. 2001; VandenBerg 2000; Grundahl 1999, for discussion and references).

3.3. *Metallicity and reddening*

From integrated colors (in particular from the reddening-free parameter Q39) Zinn (1980) derived a reddening $E(B-V)=0.04\pm0.03$ while Reed, Hesser & Shawl (1988) report $E(B-V)=0.06\pm0.03$. With the same parameter Zinn & West (1984) estimated $[Fe/H]_{Q39}=-1.87$, while a slightly higher value is reported from ΔS measures by Smith & Perkins (1982), (see also Pilachowski 1984). The final average value reported by Zinn & West (1984) is $[Fe/H]=-1.82\pm0.13$, which takes also into account the fact that the scale adopted by Smith & Perkins (1982) gives metallicity values sistematically higher by ~0.2 dex with respect to those by Zinn & West (1984).

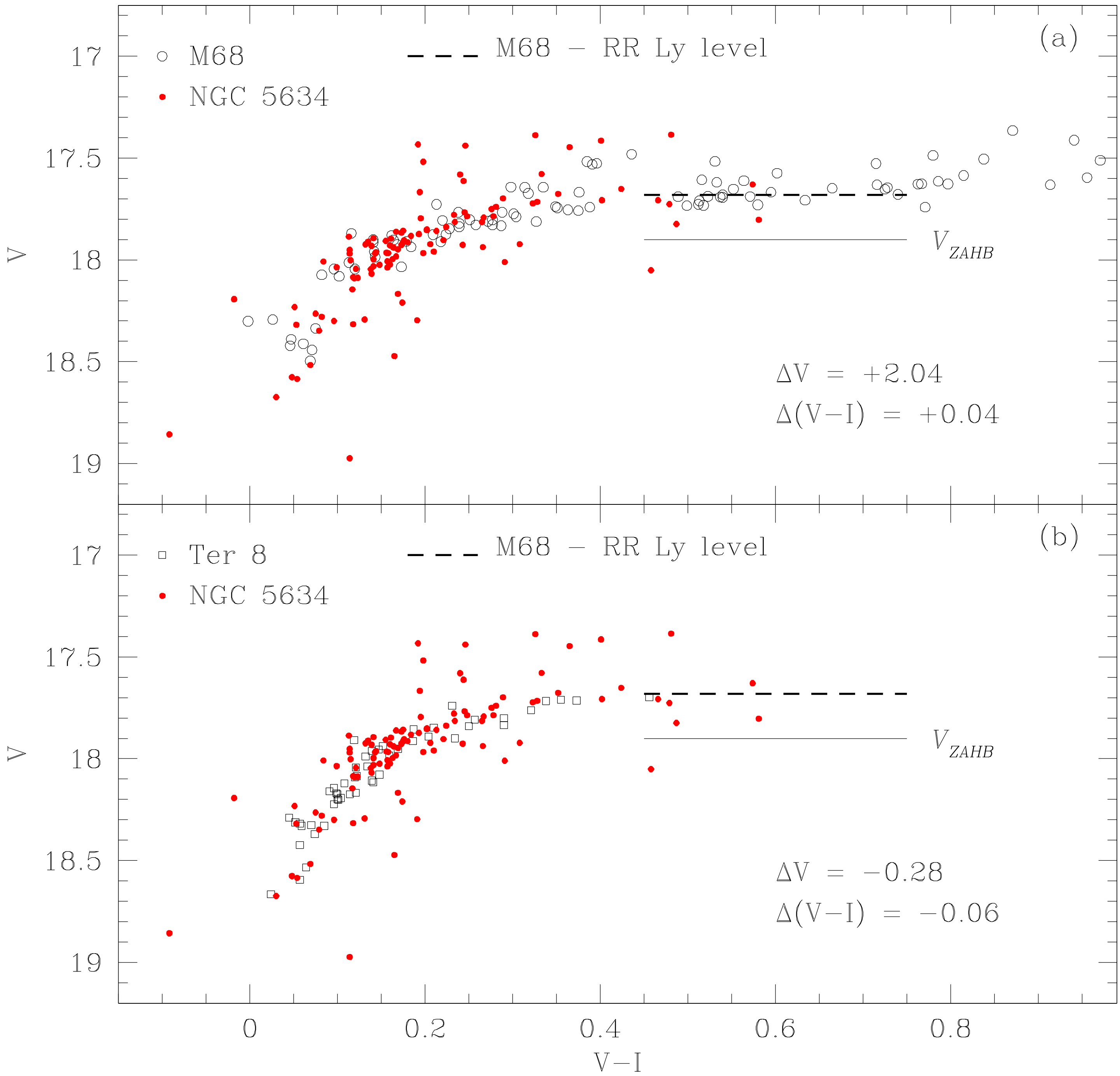

FIG. 2.— The HB level in NGC5634. *Panel (a)*: HB stars of M 68 (open circles; data from Walker 1994) have been shifted to match the HB of NGC 5634 (solid circles). The shift in magnitude and colors are indicated. The dashed line is the mean RR Lyare level of M 68 (estimated by Walker (1994)) after the magnitude shift has been applied. The solid line is the ZAHB level obtained following the method described in F99. *Panel (b)*: The same for Ter 8 (open squares). The two levels ($< V_{RR} >, V_{ZAHB}$) are reported as in *panel (a)*.

The original $[Fe/H]_{Q39} = -1.87$ is probably the most consistent figure to compare with.

We use the photometry presented here in order to derive an independent photometric estimate of the cluster metallicity from the position and the morphology of the giant branch. In the following we adopt E(V-I)=1.34E(B-V), according to Dean, Warren & Cousins (1978).

Sarajedini (1994) introduced a method (SMR method) to derive simultaneously the metallicity and reddening of a globular cluster by using a set of relations tieing $[Fe/H]$ with two observables: the color $[(V-I)_{0,g}]$ and the slope $[\Delta V_{1.2}]$ of the RGB. Since $(V-I)_{0,g}$ depends on reddening while $\Delta V_{1.2}$ does not, the procedure provides also the value of the reddening for which the consistency between the two independent relations is reached. The SMR method has also been recently calibrated in the (Carretta & Gratton 1997, hereafter CG97) metallicity scale by Carretta & Bragaglia (1998).

A clear and robust solution is found here for both the calibrations, giving $[Fe/H]_{ZW84} = -1.98 \pm 0.10$, and $E(B-V) = 0.060 \pm 0.010$ for the Sarajedini (1994) calibration, and $[Fe/H]_{CG97} = -1.94 \pm 0.10$, and $E(B-V) = 0.063 \pm 0.010$ for the Carretta & Bragaglia (1998) one. The reddening estimate is in good agreement with the values reported in the literature as well as with the estimate obtained from the IRAS-COBE maps (Schlegel, Finkbeiner & Davis 1998, $E(B-V) = 0.056 \pm 0.005$). In the following we adopt $E(B-V) = 0.06 \pm 0.01$. The derived metallicity in the ZW84 scale is slightly lower than what reported by ZW84, but still compatible within the errors.

In order to be fully consistent with the assumptions and scales adopted in F99, we also determine the global metallicity ([M/H]) (as defined by eq 1 in F99). By assuming $[Fe/H] = [Fe/H]_{CG97} = -1.94$, the global metallicity turns out to be $[M/H] = -1.74$.

3.4. *The RGB bump*

The RGB-Bump is an evolutionary feature occurring along the RGB which flags the point where the H-burning shell crosses the chemical discontinuity left by the maximum penetration of the convective envelope. From the observational point of view it was only recently identified in a significant number of clusters (Fusi Pecci et al. 1990; Zoccali et al. 1999, F99).

The change in the slope of the cumulative luminosity function (LF) and the excess of star counts in the differential LF of the RGB are the main tools to identify the RGB-Bump. In particular Fusi Pecci et al. (1990) suggest that the change in the slope of the cumulative LF is the safest indicator of the RGB-Bump.

In Fig. 3 the RGB LF for NGC5634 in the bump region is shown. The change in the slope of the cumulative LF is shown in *panel (b)*. As can be seen it corresponds to the obvious peak in the differential LF shown in *panel (a)*. Thus, the RGB-Bump is clearly identified at $V_{RGB}^{bump} = 17.38 \pm 0.05$. A clear clump of RGB stars at that magnitude is clearly visible also in the CMD shown in Fig. 1.

Our determination of the RGB-Bump magnitude is significantly different from the value listed by Zoccali et al. (1999), who presented the RGB-Bump magnitudes for 28 GGCs, from the HST *snapshot survey*. For NGC5634 they listed $V_{RGB}^{bump} = 17.77 \pm 0.03$. The large discrepancy ($\Delta V \sim 0.4$ mag) suggests a serious problem in the zero-point in one of the two photometries. However, since our calibration was carefully checked against other well-calibrated fields observed during the same night (see §2.3), we regard our measure as the most reliable one. Moreover a new re-calibration of the HST data-set seems to suggest a RGB-Bump magnitude for NGC 5634 significantly brighter than that published in Zoccali et al. (1999) (Piotto 2002 - private communication).

The magnitude of the RGB-bump with respect to the HB level (ΔV_{HB}^{bump}) has been used by Fusi Pecci et al. (1990) (and later by F99 and Zoccali et al. (1999)) to compare the observations with the theoretical predictions. The ΔV_{HB}^{bump} parameter is mainly a function of the metallicity and it has only a mild dependence on age (see Fusi Pecci et al. 1990, F99). Adopting the ZAHB level obtained in Section 3.2, $V_{ZAHB} = 17.90 \pm 0.10$ we obtain for NGC 5634 $\Delta V_{HB}^{bump} = -0.52 \pm 0.08$. Fig. 4 shows the comparison of the value obtained for NGC 5634 with 47 GGCs from the data-base by F99, in the $[Fe/H]$ vs. ΔV_{HB}^{bump} plane. The position of NGC 5634 in this plot is in excellent agreement with the mean locus defined by the other Galactic globulars, independently of the assumed metallicity scale (see panels a and b of Fig. 4).

4. DISTANCE AND AGE

In deriving the distance to NGC 5634 we use (following F99) the ZAHB level as primary standard candle: by using the F99 calibrating relation (their Eq. 5, $M_V^{ZAHB} = 0.23[M/H] + 0.94$) and the global metallicity obtained in §3.3 we derive $M_V^{ZAHB} = 0.54$. Coupling this value with the observed ZAHB level ($V_{ZAHB} = 17.90 \pm 0.1$, see §3.2) and the reddening ($E(B-V) = 0.06 \pm 0.01$, see §3.3), we obtain for NGC 5634 a *true* distance modulus $(m-M)_0 = 17.17 \pm 0.12$.

We can check this result using the RGB bump as a standard candle, with the empirically-calibrated relations between M_V^{bump} and metallicity presented by F99 (their Eq. 6.7 and 6.8). In both cases we obtain $(m-M)_0 = 17.22 \pm 0.34$, in excellent agreement with the above estimate.

Finally, we determined the distance modulus differentially with respect to M 68. By adopting the shift found in §3.1, the distance modulus and reddening of M 68 given by F99, we obtain $(m-M)_0 = 17.09 \pm 0.12$, also in agreement (within the uncertainties) with our final estimate.

4.1. *The Relative Age of NGC 5634*

A number of observational evidences (such as the low metal content, the blue HB morphology and the position of the RGB bump) suggest that NGC 5634 is an old cluster. However a quantitative estimate can be obtained only from the direct measure of the key age-diagnostic of stellar populations: the MS Turn Off (TO) point.

As is well known two main methods are currently used to determine relative ages for GGCs: the *vertical method*, based on the measure of the parameter ΔV_{TO}^{HB} (Buonanno, Corsi & Fusi Pecci 1989), which measure the luminosity of the TO point with respect to the HB level; and the *horizontal method* based on the difference in color between the

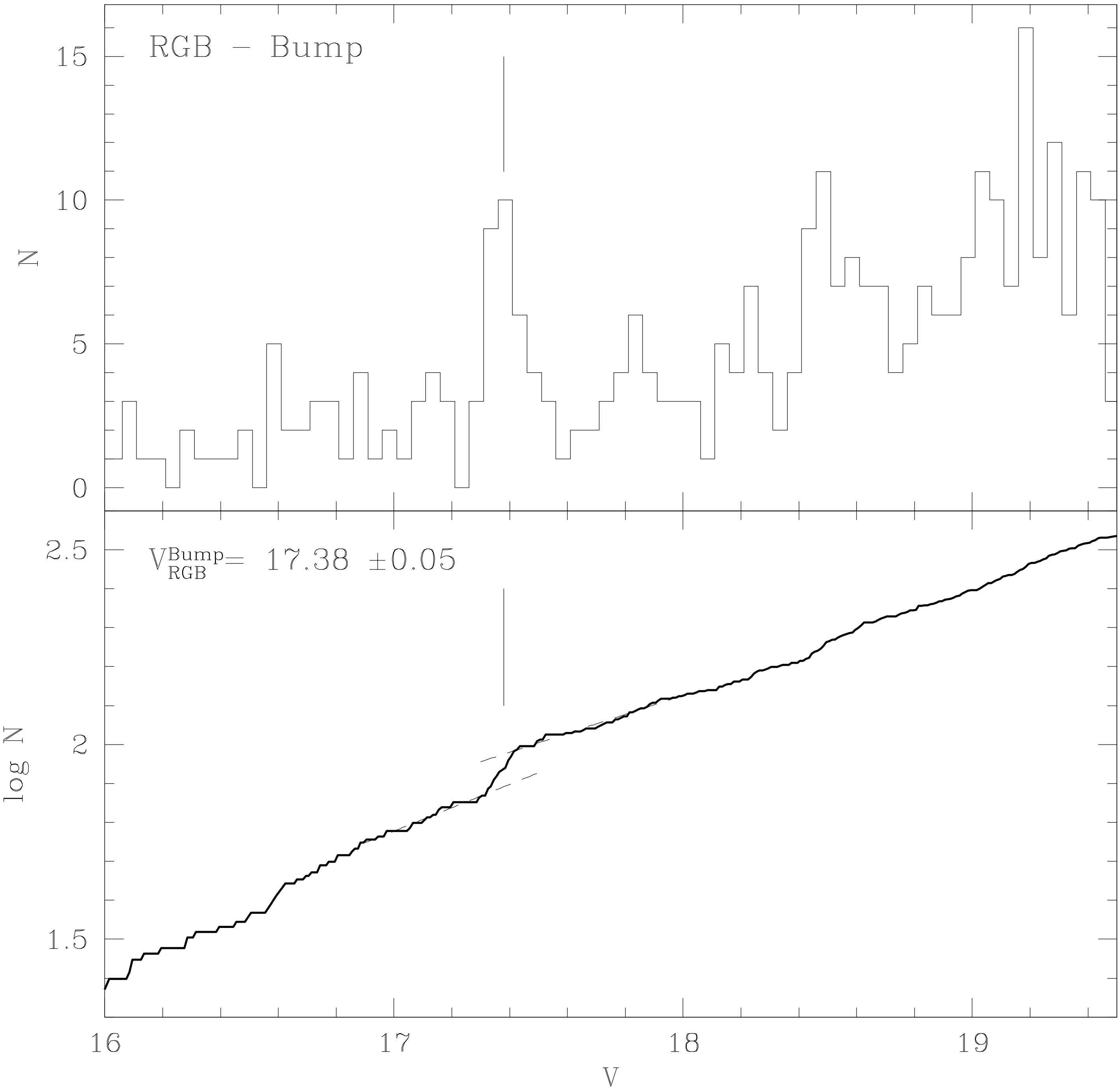

FIG. 3.— Panel (a): the differential luminosity function of the RGB of NGC 5634. The peak indicated by the vertical line corresponds to the RGB bump. The same feature is identified in Panel (b) by the sudden change in slope of the logarithmic cumulative luminosity function.

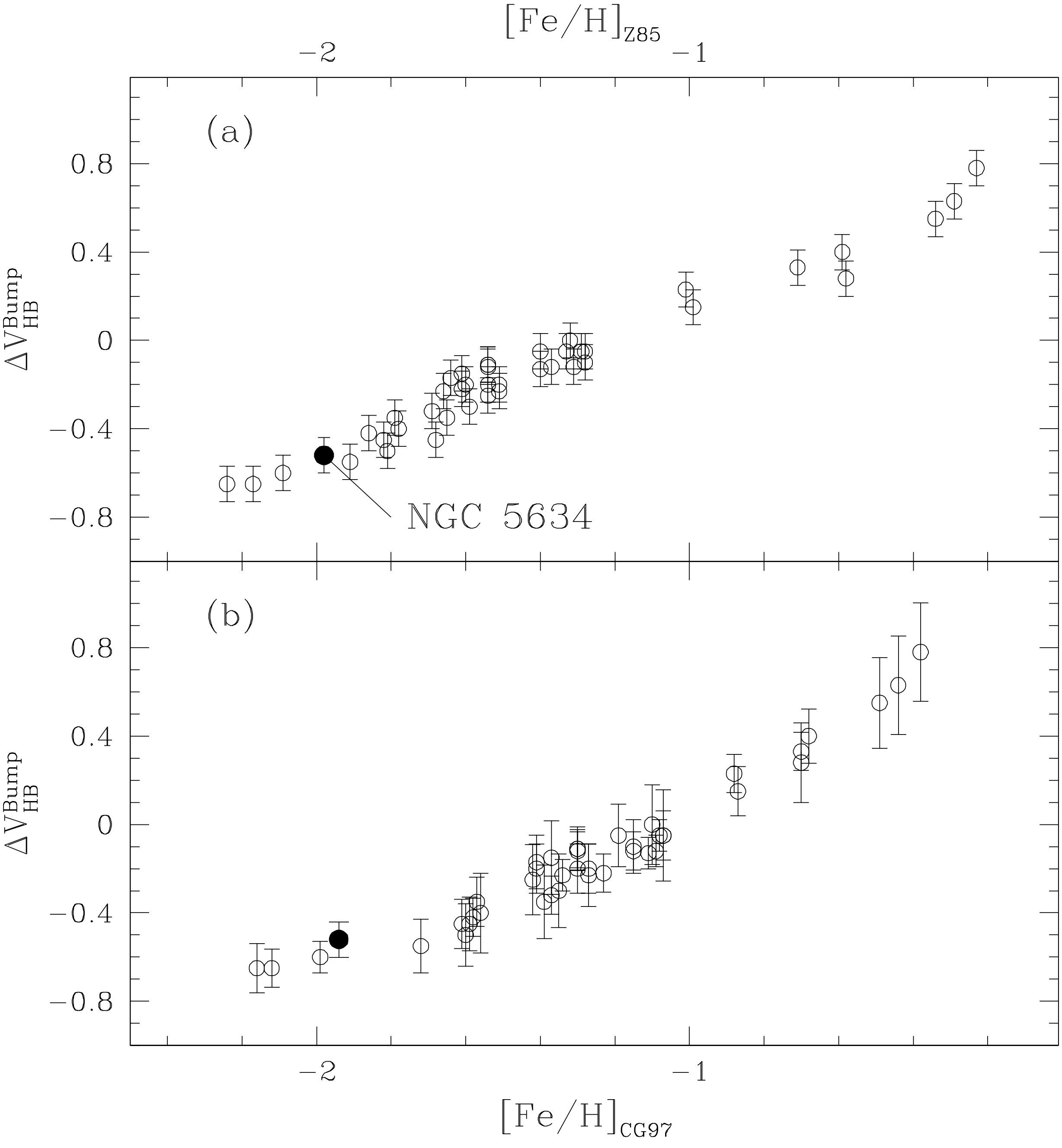

FIG. 4.— The difference in magnitude between the RGB-Bump and the ZAHB level (ΔV_{HB}^{Bump}), as a function of the metallicity in the Zinn scale ($[Fe/H]_{Z85}$) and in the CG97 scale, *Panel (a)* and *(b)*, respectively. The filled circle is NGC5634, the empty circles are the clusters from Table 5 of F99.

TO and a point along the RGB 2.5 mag brigther than the TO point (Stetson, VandenBerg, & Bolte 1996).

As has already been emphasized elsewhere, the horizontal method is particularly sensitive to color uncertanties: even small ($\simeq 0.02$ mag) errors generate large (~ 2 Gyr) differences in the derived relative ages. Since our photometry is not sufficiently accurate for $V > 20.5$, to derive a precise measure of the TO color, in the following we rely only on the vertical method to estimate the relative age of NGC5634 and we will use the TO color only as a consistency check.

From the ridge line listed in Tab. 2 we obtain $V_{TO} = 21.22 \pm 0.15$ and $(V-I)_{TO} = 0.647 \pm 0.03$. Adopting the value of the ZAHB level (V_{ZAHB}) derived above, we get ($\Delta V_{TO}^{HB} = 3.32 \pm 0.16$). This value is in good agreement with the bulk of the other old and metal poor Galactic globulars, as homogeneously measured by Rosenberg et al. (1999) [3]. The *horizontal* age parameter turns out to be $\delta(V-I)_{@2.5} = 0.272 \pm 0.04$, a value which is also in agreement - within the errors - with other old and metal poor Galactic globulars.

Rosenberg et al. (1999), for example, report for M68 $\Delta V_{TO}^{HB} = 3.30 \pm 0.12$ and $\delta(V-I)_{@2.5} = 0.306 \pm 0.010$. These values are also consistent with what found in Ter 8. In fact, using the results by Mo98 and F99, we obtain $\Delta V_{TO}^{HB} = 3.40 \pm 0.14$ and $\delta(V-I)_{@2.5} = 0.301 \pm 0.04$ for Ter 8. These values are very similar to those derived for NGC 5634, suggesting that the cluster is as old as M 68 and Ter 8 (within the observational uncertainties of $\sim \pm 2 Gyr$).

5. NGC 5634: A CLUSTER IN THE SGR STREAM

Since its discovery (Ibata et al. 1994) the Sgr dSph has been suspected to be the damaged relic of a fomerly larger stellar system that was harrassed by the tidal field of our Galaxy. This view has now received many observational confirmations (see, for example Newberg et al. 2002, and references therein). The stars lost by a disrupting satellite are expected to be distributed along its orbital path, in a sort of stellar *stream* more or less spread around the orbit depending on the degree of flattening of the Galactic dark halo and on the effect of the gravitational potential of the disc (see, for instance, Johnston, Hernquist & Bolte 1996; Johnston et al. 1999; Ibata & Lewis 1998). In the last few years, many different teams have found clumps and/or density structures in the Galactic halo that are probably associated with the stream of the Sgr galaxy (Vivas et al. 2001; Dohm-Palmer et al. 2001; Yanni et al. 2000; Ivezic et al. 2000; Ibata et al. 2001a,b; Majewski et al. 1999; Mateo et al. 1996; Alard 1996) and in two cases a clear and direct association has been obtained (Martínez-Delgado et al. 2001; Newberg et al. 2002) by comparing the stellar population of the stream with that of the Sgr galaxy. From these studies it seems that the stars lost by the Sgr galaxy are distributed in a giant halo substructure, a low density band probably encircling the whole sky, approximately following the past orbital path of Sgr (Ibata et al. 2001b; Newberg et al. 2002).

Since the main body of the Sgr dSph still encloses four globular clusters (M 54, Ter 8, Arp 2, and Ter 7) that ultimately will be incorporated into the globular cluster system of the Milky Way, it may be presumed that also some previous Sgr globular may have been lost along the Sgr stream. A strong case for this occurrence has already been made for Pal 12 on the basis of its present position and three-dimensional velocity (Dinescu et al. 2000). Here we show that the galactocentric position and the radial velocity of NGC 5634 are compatible with the hypothesis that also this cluster is associated with the Sgr stream and it was a former member of the Sgr galaxy.

In Fig. 5 the Galactic globular clusters of the outer halo (i.e., those with $R_{GC} \geq 10$ kpc) are reported as open circles in the planes R_{GC} vs. V_r (panel a), X vs. Z, X vs. Y and Y vs. Z (panels b, c, and d, respectively), where V_r is the radial velocity in km/s and X,Y,Z are galactocentric coordinates in kpc.

The filled circles are the Sgr globulars and the filled square is Pal 12. The large encircled dot is NGC 5634. In the same planes we have also reported the orbital path followed by the Sgr dSph in the last Gyr (from 1 Gyr ago to the present), according to the orbit computed by Ibata & Lewis (1998), based on the proper motion measured by Ibata et al. (1997, 2001a). The small arrow at one end of the orbital path marks the position (and velocity) of the Sgr galaxy 1 Gyr ago.

NGC 5634, as well as Pal 12, lie near the predicted orbit in all the planes displayed in Figure 5. This means that *its position and radial velocity are fully compatible with the hypothesis that the cluster is following the same orbit of the Sgr dSph*, i.e. it belongs to the Sgr Stream [4]. Note that in all the considered planes NGC 5634 and Pal 12 have a distance from the orbit that is lower than the spread of confirmed Sgr clusters around the orbit itself.

While an ultimate confirmation - at least for NGC 5634 - can be achieved only with accurate proper motion and a more secure assessment of the Sgr orbit[5], the evidence is very suggestive and the idea deserves serious consideration. It would mean that NGC 5634 was a former member of the globular cluster system of the Sgr dSph and that it formed in that stellar system. In the following we will take this association as a working hypothesis and we will shortly discuss some interesting clues:

- We remark the already noted similarity of NGC 5634 with the Sgr globular Ter 8. Considering the stellar content, the two clusters appear as "identical twins". They share the same metal content, the same HB morphology and the same age.

- The stellar population of NGC 5634 appears more similar to the population found in the Sgr Stream (Newberg et al. 2002) than that observed in main body of the Sgr galaxy. Newberg et al. (2002) found

[3] To preserve the homogeneity with the age scale of Rosenberg et al. (1999), the vertical parameter are computed with respect to the ZAHB level.

[4] We have found evidence that other clusters share these properties in the (X,Y,Z,V_r) space. The case is discussed in detail in a dedicated paper, (Bellazzini, Ferraro & Ibata 2002a).

[5] Another possible observational test would be the search for Sgr stream stars in a wide field around the cluster, lying at the same distance from us as the cluster itself (see, e.g. Martínez-Delgado et al. 2002).

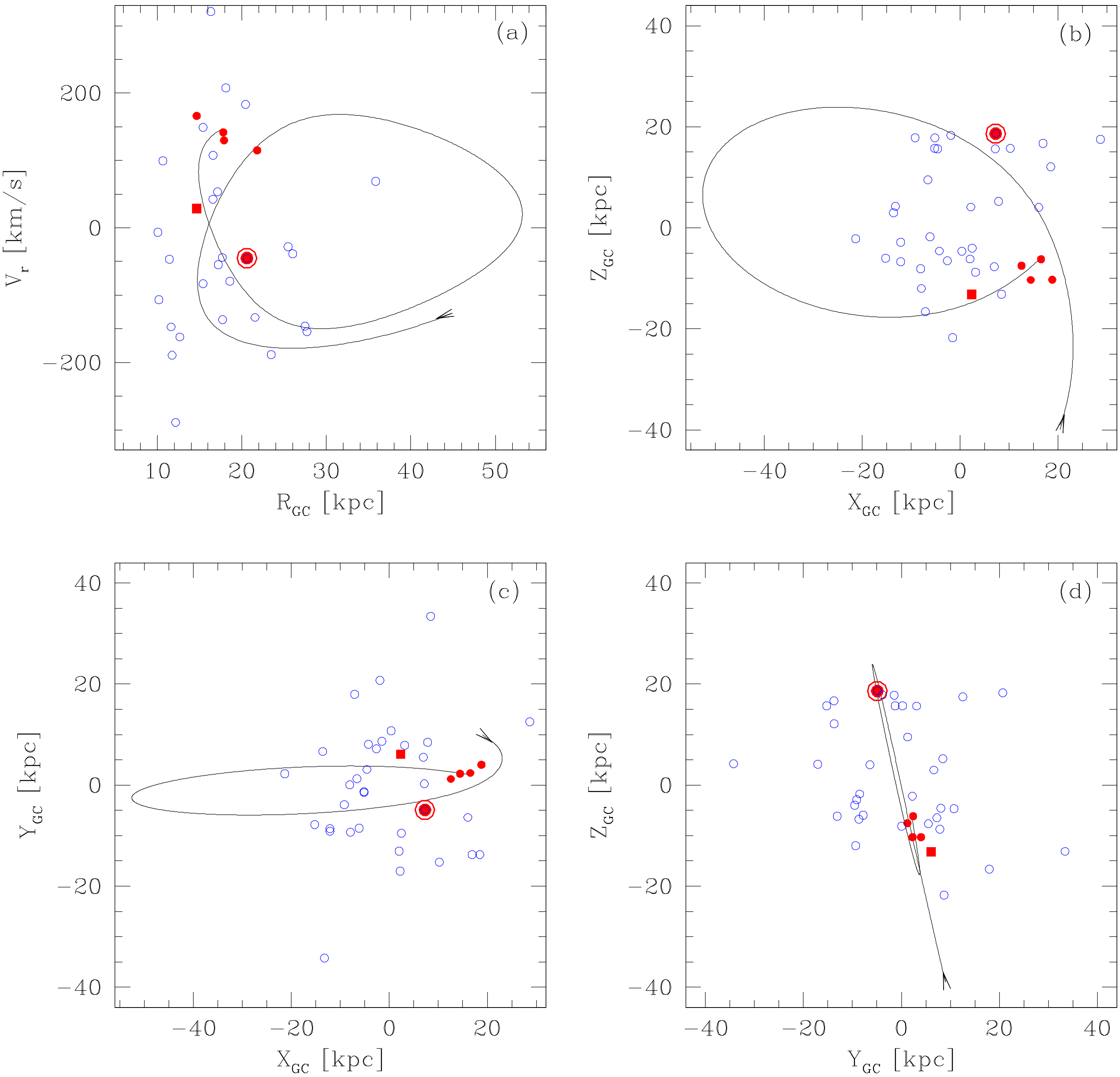

FIG. 5.— The outer Galactic globular clusters (with $R_{GC} \geq 10$ kpc) are plotted (open circles) in the R_{GC} vs. V_r plane (*panel (a)*) and in three different projections in the space of galactocentric coordinates (X vs. Z, X vs. Y and Y vs. Z in *panels (b), (c)*, and *(d)*, respectively). All the globular cluster data are from the Harris (1996) catalogue. The globular clusters presently associated with the main body of the Sgr dSph, i.e. M 54, Ter 8, Arp 2 and Ter 7 are plotted as small filled circles. The position of NGC 5634 is marked as a large filled circle. The full square is the globular cluster Pal 12 that has been indicated as a former member of the Sgr galaxy by Dinescu et al. (2000). The continuous line is the orbital path followed by the Sgr dSph during the last Gyr, according to the orbit computed by Ibata & Lewis (1998). The arrow marks the point corresponding (in the simulation) to 1 Gyr ago, while the other end of the path corresponds to the present.

that the stars in the Sgr stream show a BHB population (similar to that of Ter 8 and NGC 5634) much more pronounced than what is found in the central regions of the galaxy.

- Bellazzini, Ferraro & Buonanno (1999a) found evidences of the presence of an old and very metal poor population (similar to that of Ter 8) in the Sgr dSph. The existence of this population has been confirmed by Cseresnjes (2001) and Cacciari, Bellazzini & Colucci (2001). Furthermore, many independent studies (Sarajedini & Layden 1995; Bellazzini, Ferraro & Buonanno 1999a,b; Layden & Sarajedini 2000; Alard 2001; Cacciari, Bellazzini & Colucci 2001) have found evidence of a metallicity (and population) gradient in the Sgr dSph, with the most metal poor stars being more abundant in the outer regions of the galaxy.

All the above evidence is consistent with a scenario in which the more external stars of the Sgr dwarf are preferentially stripped from the galaxy and thus, the Sgr stream is populated by a stellar mix in which the metal poor stars are more abundant, because of the metallicity gradient. NGC 5634 should have the same origin as the metal poor population of the Sgr galaxy, so it is not surprizing that it shared the same "dynamical destiny" as most of the metal poor halo of the Sgr dSph, and it is now lost in the Sgr stream.

If this interpretation of the heritage of NGC 5634 is correct, it has interesting consequences for our understanding of the Sgr stream. One important difference between NGC 5634, and the previously identified clusters (and former clusters) of the Sgr system, is that it lags the main body of the dwarf galaxy by an exceedingly large distance. Taking the IL98 orbit, we find that the lag along the orbital trajectory is 151 kpc. To separate tidal debris from the main body of the dwarf galaxy by such a large distance requires a considerable time. The internal velocity dispersion within the bound core of the Sgr dwarf is $11.4 \pm 0.7\,\mathrm{km\,s^{-1}}$ (Ibata et al. 1997), so if the material that becomes unbound acquires a similar velocity dispersion, it would take ~ 13 Gyr to spread out over 151 kpc. A better estimate of this separation time can be made from numerical experiments. In Figure 6 we show the end-point structure of the best-fit simulation in Ibata et al. (2001a), where we have plotted only those points which were bound 4 Gyr ago (right panel). The downstream tail nearly reaches the position of NGC 5634 (marked with an asterisk). Since particles that were bound to the dwarf galaxy model less than 4 Gyr ago are unable to disperse along the orbit to the position of the globular cluster, this simulation suggests that NGC 5634 became unbound more than 4 Gyr ago. (A significantly longer time, ~ 6 Gyr, is required for more than 10% of the stream to drift beyond the distance of the star cluster). This sets a useful limit on the disruption history of the dwarf galaxy. It would suggest that no significant deflection of the orbit of Sgr occurred during this time, contary to what is required by the scenario envisaged by Zhao (1998), who proposed that Sgr was shot into its present orbit, where it suffers vigorous disruption from the Galactic tides, following a close encounter with the LMC 2–3 Gyr ago. It also places a strong constraint on the proposal by Cseresnjes (2001), that Sgr is a structure that was torn off from the LMC, since the time of that incident has to have happened before the time when NGC 5634 became unbound from the Sgr galaxy.

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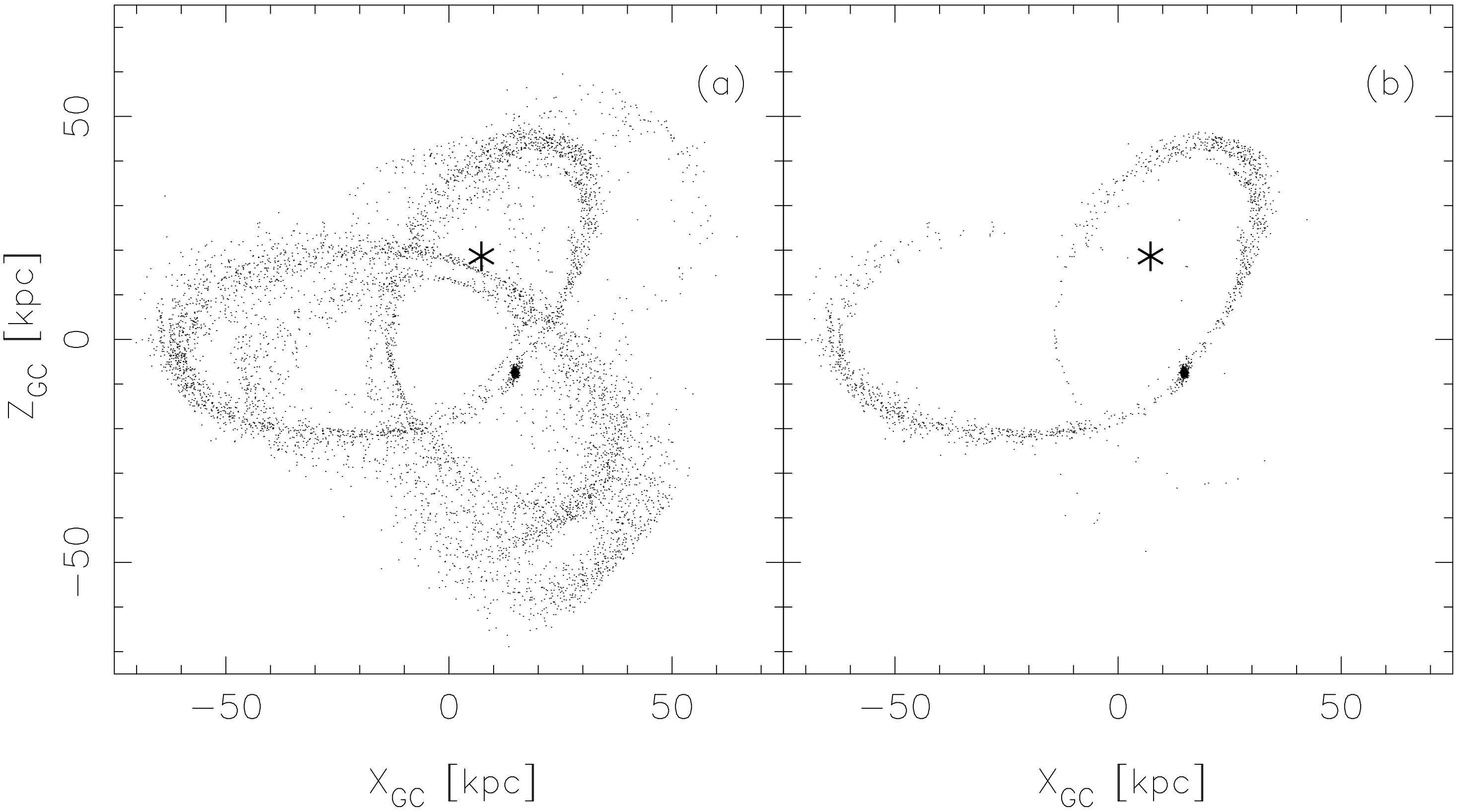

FIG. 6.— The structure of the tidal stream of the Sgr dwarf galaxy in the Galactic X-Z plane (with the Sun located at $X_{GC} = -8$ kpc), according to the best-fit simulation of Ibata et al. (2001a) which retains a bound center at the present day. The simulation corresponds to the Ibata et al. (2001a) dwarf galaxy model is "D1", and halo model "H2", in a Galactic potential with circular velocity $v_c = 200\,\mathrm{km\,s^{-1}}$ at 50 kpc. The left-hand panel displays all particles, whereas in the right-hand panel only those particles that were gravitationally bound to Sgr 4 Gyr ago are plotted. Particles that became unbound more recently do not reach the position of NGC 5634 (indicated by an asterisk), from which we deduce that if NGC 5634 was previously a member of the Sgr system, it must have parted company with that galaxy more than 4 Gyr ago.

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Table 1
Photometry of NGC 5634

ID	V	ϵ_V	I	ϵ_I	$X_{[px]}$	$Y_{[px]}$	Var. n.
1	14.505	0.002	12.938	0.007	1207.79	703.35	0
2	14.776	0.003	13.295	0.008	497.33	913.35	0
3	14.761	0.002	13.329	0.005	1060.98	1242.67	0
4	14.802	0.003	13.369	0.006	911.93	1165.44	0
5	14.967	0.002	13.593	0.010	684.00	535.87	0
6	15.032	0.003	13.711	0.011	879.92	945.47	0
7	15.196	0.003	13.901	0.006	863.80	863.90	0
8	15.258	0.003	13.950	0.005	887.75	917.10	0
9	15.404	0.003	14.125	0.005	987.92	859.35	0
...	...	...	...	...	...	...	...

Note. — A sample of the photometric catalog. The complete catalog is available in ASCII format in the electronic edition of the paper. The variable stars are numbered after the nomencalture by Baade (1945)

Table 2
Ridge lines of the RGB,MS and HB.

RGB+MS		HB	
V	V-I	V-I	V
14.52	1.570	0.080	18.30
14.76	1.457	0.135	18.03
15.45	1.247	0.160	17.94
16.28	1.121	0.292	17.72
17.27	1.008	0.517	17.70
18.19	0.946	...	...
19.06	0.902	...	...
19.63	0.885	...	...
19.86	0.884	...	...
20.21	0.850	...	...
20.45	0.773	...	...
20.70	0.702	...	...
20.90	0.675	...	...
21.09	0.652	...	...
21.29	0.648	...	...
21.49	0.659	...	...
21.80	0.676	...	...
22.21	0.737	...	...
22.60	0.808	...	...