ON THE REMOTE GALACTIC GLOBULAR CLUSTER NGC 2419

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ABSTRACT

We present a new, deep (V ~ 26) study of the Galactic globular cluster NGC 2419 based on B, V, I time-series CCD photometry over about 10 years and extending beyond the cluster published tidal radius. We have identified 101 variable stars, of which 60 are new discoveries, doubling the known RR Lyrae stars and including 12 SX Phoenicis stars. The average period of the RR Lyrae stars (⟨P⟩ = 0.662 days and ⟨P⟩ = 0.366 days, for fundamental-mode—RRab—and first-overtone pulsators, respectively) and the position in the period-amplitude diagram both confirm that NGC 2419 is an Oosterhoff II cluster. The average apparent magnitude of the RR Lyrae stars is ⟨V⟩ = 20.31 ± 0.01 (σ = 0.06, 67 stars) and leads to the distance modulus μV = 19.60 ± 0.05. The color-magnitude diagram, reaching about 2.6 mag below the cluster turnoff, does not show clear evidence of multiple stellar populations. Cluster stars are found until r ~ 10.5′, and possibly as far as r ~ 15′, suggesting that the literature tidal radius might be underestimated. No extratidal structures are clearly detected in the data. NGC 2419 has many blue stragglers and a well-populated horizontal branch extending from the RR Lyrae stars down to an extremely blue tail ending with the “blue hook,” for the first time recognized in this cluster. The red giant branch is narrow, ruling out significant metallicity spreads. Our results seem to disfavor the interpretation of NGC 2419 as either having an extragalactic origin or being the relict of a dwarf galaxy tidally disrupted by the Milky Way.

Subject headings: Galaxy: halo — globular clusters: general — globular clusters: individual (NGC 2419) — stars: horizontal-branch — stars: variables: other — techniques: photometric

1. INTRODUCTION

NGC 2419 is one of the most distant and luminous globular clusters (GCs) in the Milky Way (MW). Although both the distance (RGC ~ 90 kpc; Harris et al. 1997) and the dynamical parameters (core radius r_c ~ 9 pc and half-mass radius r_h ~ 19 pc; Harris et al. 1997) put NGC 2419 among the outer halo Galactic globulars, the cluster has several unusual properties for an outer halo GC. It is much more luminous and metal-poor than the other outer halo clusters: with M_V ~ −9.5 mag (Harris 1996), NGC 2419 is among the five brightest clusters in the MW; and with [Fe/H] ~ −2.1 dex (Suntzeff et al. 1988), it belongs to the most metal-poor group of MW GCs, of which all, except AM-4, are located within R_GC ~ 20 kpc. The cluster horizontal branch (HB) also resembles that of much closer “canonical” metal-poor clusters like M15 or M68, and previous investigations show that NGC 2419 has the same age as M92, within 1 Gyr (Harris et al. 1997). However, NGC 2419 is not an inner halo cluster migrated out on an elliptical orbit, since its dynamical parameters and orbital properties (van den Bergh 1993, 1995, and references therein) are typical of an outer halo cluster. NGC 2419 is also anomalous in the half-light radius (R_h) versus M_V plane (see Fig. 11 of Mackey & van den Bergh 2005). Among the MW GCs, only ω Cen and M54 have similar properties in this plane, and they both are “peculiar,” since ω Cen hosts multiple stellar populations (see, e.g., Bedin et al. 2004; Rey et al. 2004; Sollima et al. 2005) and likely is the stripped core of a defunct dwarf galaxy (Villanova et al. 2007 and references therein); and M54 is thought to be the core of the Sagittarius (Sgr) dwarf spheroidal galaxy (dSph), which is currently merging with the MW (see, e.g., Layden & Sarajedini 2000). All these peculiarities and the similarity with ω Cen and M54 suggest that NGC 2419 could have an extragalactic origin and be the relict of a dwarf galaxy tidally disrupted by the MW (van den Bergh & Mackey 2004). Newberg et al. (2003) find that the cluster appears to lie within an overdensity of A-type stars connected to previously discovered tidal tails of the Sgr dSph and conclude that the cluster might once have been associated to Sgr. In addition, the cluster has a central velocity dispersion (σ_v) much lower than the dSph’s for which this quantity has been measured and, in the log σ_v versus M_V plane (Faber & Jackson 1976), lies 3 and 6 σ apart from the “fundamental plane” relations for GCs and elliptical galaxies, respectively (see de Grijs et al. 2005). For a comparison, in this plane ω Cen lies at the intersection of these two lines.

Color-magnitude diagrams (CMDs) of NGC 2419 published so far either do not go fainter than the main-sequence turnoff (TO) or cover small portions of the cluster (Christian & Heasley 1988; Harris et al. 1997; Stetson 1998, 2005; Saha et al. 2005; Sirianni et al. 2005). We also lack a modern study of the cluster variable stars based on accurate CCD photometry, the most recent variability survey being the photographic work by Pinto & Rosino (1977, hereafter PR), who detected 41 variables in the external regions of NGC 2419 and found the average period of the fundamental-mode RR Lyrae (RRab) stars to be consistent with NGC 2419 being an Oosterhoff II (OoII) cluster (Oosterhoff 1939).

In this Letter, we present a CMD reaching about 2.6 mag below the NGC 2419 TO and a new study of the variable stars...
Based on image subtraction techniques (Alard 2000), using $B$, $V$, $I$ time-series CCD photometry covering an area that extends well beyond the cluster published tidal radius ($r_t = 8.74\arcmin$, according to Trager et al. 1995). The new data are used to verify whether multiple stellar populations and tidal tails exist in the cluster and to check whether the properties of the RR Lyrae stars support an extragalactic origin for NGC 2419.

2. OBSERVATIONS AND DATA ANALYSIS

Time-series $B$, $V$ photometry of NGC 2419 (R.A. = 07$^\circ$38$'$24.0$^\prime$, decl. = 38$^\circ$54$'$00$^\prime$, J2000.0) was collected between 2003 September and 2004 February with DOLORES at the 3.5 m Telescopio Nazionale Galileo (TNG) telescope. The TNG data were complemented by Hubble Space Telescope (HST) Wide Field Planetary Camera 2 F555W and F814W archival photometry spanning 7 yr from 1994 to 2000 and by $V$, $I$ images of the cluster obtained with the Suprime-Cam of the Subaru 8.2 m telescope along four nights in 2002. The Subaru data set covers a total area of $50' \times 43$ arcmin$^2$ centered on NGC 2419 and includes both the TNG and HST fields. Results presented in this Letter refer to a region extending $\pm 10.5\arcmin$ in north-south and $\pm 18\arcmin$ in east-west from the cluster center. The total number of phase points of the combined data sets reaches 20, 205, and 48 in the $B$, $V$, and $I$ bands, respectively, with optimal sampling of the $V$ light curves of RR Lyrae stars, acceptable coverage in $B$, and rather poor sampling in $I$, since the $I$-band images were taken much more closely spaced in time.

Images were prereduced following standard techniques (bias subtraction and flat-field correction) with IRAF. We measured the star magnitudes by point-spread function photometry running the DAOPHOTII/ALLSTAR/ALLFRAME packages (Stetson 1987, 1994) on the TNG, HST, and Subaru data sets, separately. Typical internal errors of the $V$-band photometry for single phase points at the level of the HB are in the range from 0.01 to 0.02 mag. The absolute photometric calibration was obtained by using local standards in NGC 2419 from P.B. Stetson’s list. Zero-point uncertainties are of 0.022, 0.014, and 0.014 mag in $B$, $V$, and $I$, respectively. Further details on the data reductions can be found in M. Di Criscienzo et al. (2007, in preparation).

Candidate variable stars were identified using two independent methods: the optimal Image Subtraction Technique and the package ISIS 2.1 (Alard 2000), applied to the TNG $V$ time series; and an ad hoc procedure applied to the Subaru $V$ data that included calculation of the Fourier transform (in the Schwarzenberg-Czerny 1996 formulation) for each star with more than 25 epoch data and evaluation of the signal-to-noise ratio ($S/N$), followed with the analysis of the stars with $S/N > 6$ and magnitude $V < 23.7$ mag (excluding TO and subgiant branch stars). The two procedures returned a catalog of 101 confirmed variables. Periods (and type classification) were derived using GReTiS (Graphical Analyzer of Time Series), a custom software developed at the Bologna Observatory (see Di Fabrizio 1999; Clementini et al. 2000). Precision of the period determinations is of four to five decimal places (for variables with periods shorter than 2 days, 95 objects) and increases up to six digits for stars with the three data sets (TNG, HST, and Subaru) available. The good sampling of the $V$ light curves allowed a very accurate definition of the star’s visual mean magnitudes and amplitudes. Coverage of the $B$ and $I$ light curves is generally much poorer, and we often estimated average $B$ and $I$ magnitudes by scaling down in amplitude the star $V$ light curve to fit observations in the other bands (see M. Di Criscienzo et al. 2007, in preparation).

Figure 1 shows the $V$, $V-I$ CMDs (based on the Subaru data set) of objects in four annular regions at increasing distance from the cluster center: $50' < r < 4.5'$ (Fig. 1a: 36262 objects, 91 variable stars); $4.5' < r < 8.74'$ (Fig. 1b: 6116 objects, seven variables); $8.74' < r < 10.5'$ (Fig. 1c: 1592 objects, zero variables); and $16.5' < r < 18'$ (Fig. 1d: 594 objects, one variable, a field $\delta$ Scuti star), whose areas are in the ratio $1 : 3 : 2 : 1$. Only objects with $\chi < 1.2$, $a_r$, and $a_i < 0.2$ mag are displayed. Figure 1d shows the CMD of an external field devoid of cluster stars with same area as the cluster region in Figure 1a and thus provides an indication of the contamination by field stars in Figure 1a.

3. THE VARIABLE STAR POPULATION

PR identified 41 variable stars in their photographic study of NGC 2419: 25 $ab$- and seven $c$-type RR Lyrae stars, one Population II Cepheid, four red irregular-semiregular variables, and another four variables for which they did not provide period and classification. PR V39 was later recognized as double-mode RR Lyrae star (Clement & Nemec 1990). We recovered and derived reliable periods for all the previously known variable stars in NGC 2419 and detected 60 new variables that are mainly located in the cluster central regions. The new variables include: 11 $ab$- and 28 $c$-type RR Lyrae stars, 12 SX Phoenicis stars, three binaries, one long-period variable near the red giant tip, two field $\delta$ Scuti stars, and three variables of unknown type. Light curves for different types of variables are shown in Fig-

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5 See http://www.tng.iac.es/instruments/lrs.
6 See http://www.subarutelescope.org.
7 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.
8 Available at http://cadcwww.dao.nrc.ca/cadcbin/wdb/astrocat/stetson/query.
p overtone RR Lyrae stars, respectively, to compare with the location toward the cluster center. Addition of the new periods were missed by PR due to their small amplitude and were contamination by field stars; see M. Di Criscienzo et al. 2007, in preparation). Average periods are days (0.065 ± 0.010, is in perfect agreement with values of (dex; Suntzeff et al. 1988) and reddening, is used to estimate the cluster distance. Harris (1996) reports $E(B-V) = 0.11 ± 0.01$ mag (from the average of various sources), while a lower value, $E(B-V) = 0.065 ± 0.010$, is derived on the basis of the Schlegel et al. (1998) maps. We find $E(B-V) = 0.08 ± 0.01$ mag by matching the edges of the RR Lyrae instability strip of NGC 2419 to those of M68 [Walker 1994; ] and M5 [Reid 1996; $E(B-V)_{M68} = 0.07 ± 0.01$] and M5 [Reid 1996; $E(B-V)_{M5} = 0.020 ± 0.01$, mag], in good agreement with Schlegel et al. (1998). Assuming for the absolute luminosity of the RR Lyrae stars at [Fe/H] = −1.5, $M_1 = 0.59 ± 0.03$ (Cacciari & Clementini 2003), $\Delta M_{1}[Fe/H] = 0.214(±0.047)$ mag dex$^{-1}$ (Clementini et al. 2003) for the slope of the luminosity metallicity relation, $E(B-V) = 0.08$ mag, and [Fe/H] = −2.1 dex, the distance modulus of NGC 2419 derived from the mean luminosity of its RR Lyrae stars is $\mu_0 = 19.60 ± 0.05$ (D = 83.2 ± 1.9 kpc).

NGC 2419 hosts many blue straggler stars (BSSs). Among them, we detected one binary system and 12 pulsating variables with periods in the range from 0.041 to 0.140 days and several secondary periodicities. They are likely cluster SX Phoenicis stars (see M. Di Criscienzo et al. 2007, in preparation). One of them is located at $r = 15′$ from the cluster center.

4. THE COLOR-MAGNITUDE DIAGRAM

Figure 1 shows that the bulk of the NGC 2419 stars and variables is within $r ≤ 4.5′$ from the center (Fig. 1a). Cluster stars are found beyond the published tidal radius (8.74′; Trager et al. 1995) until $r ≈ 10.5′$ (see Fig. 1b) and possibly as far as $r = 15′$. The CMD appears to be dominated by field stars and contaminating galaxies for $r > 15′$. The main features of the NGC 2419 CMD include (Figs. 1a and 1b) a well-defined main sequence reaching about 2.6 mag below the cluster TO at $V$~23.4 mag, with no clear evidence of multiple substructures. The red giant branch (RGB) is narrow, ruling out significant differences in composition among cluster stars. The HB is well populated to the blue and has very few stars redder than the RR Lyrae stars. The most striking features are the well-defined BSS sequence outlined by many SX Phoenicis stars and the extremely prolonged HB blue tail, extending down to $V$~24.7 mag (i.e.,

![Image](image.png)

**Fig. 2.—** $V$ light curves of different types of variable stars in NGC 2419. From top to bottom, left: $ab$-type RR Lyrae star, $c$-type RR Lyrae star, Population II Cepheid; right: SX Phoenicis star, binary system, long-period variable. Filled and open circles are Subaru and TNG data, respectively.
et al. (2000) in their analysis of the RGB. First detected by Whitney et al. (1998) and D’Cruz et al. (2000) in their analysis of the ω Cen HB, blue-hook stars have been found so far only in very few GGCs (ω Cen, M54, NGC 2808, NGC 6388, and NGC 6273; see Rosenberg et al. 2004; Momany et al. 2007).

5. DISCUSSION AND CONCLUSIONS

The results presented in this Letter provide some constraints on the hypotheses put forward for the origin of NGC 2419. The finding that the cluster confirms to be of Oosterhoff type II is a key feature, as “normal” low-metallicity GGCs as M15 and M68, makes its extragalactic origin unlikely, since GCs in external galaxies generally have properties intermediate between Ool and OoII types (Catelan 2005). The lack of multiple populations or metallicity spreads does not corroborate the hypothesis that NGC 2419 might be the core of a defunct galaxy either. In addition, no cluster extratidal structures are clearly seen in our data beyond r ∼ 15′, to support the Newberg et al. (2003) suggestion of a past association with the Sgr dSph, a claim also disfavored by the Sgr field and cluster (M54) RR Lyrae stars having properties on the long-period tail of the OoI group and intermediate between Oosterhoff types, respectively (Cseresnjes 2001; Cacciari et al. 2002). From our data, NGC 2419 appears indeed to be a very normal, low-metallicity GGC, the only exception being the HB blue hook, a feature detected so far only in very few globulars and, most noteworthy, in those showing multiple main sequences and/or of likely extragalactic origin: NGC 2808 (Piotto et al. 2007), ω Cen (Villanova et al. 2007), and M54 (Layden & Sarajedini 2000). However, the only property these clusters seem to share is a large integrated luminosity (Rosenberg et al. 2004). On the other hand, NGC 2419’s peculiar position on the log σ0 versus Mv and Rv versus Mv planes remains unexplained. “Clearly there are still all kinds of mysteries that we do not yet understand at the intercept between dwarf spheroidal galaxies and globular clusters” (S. van den Bergh 2007, private communication).

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