Mem. S.A.It. Vol. 84, 67

Memorie della

An intermediate-band photometric study of the "globular cluster" NGC 2419

A. Koch[1], M. Frank[1], S. Feltzing[2], D. Adén[2], N. Kacharov[1], and M. I. Wilkinson[3]

[1] Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany. e-mail: akoch@lsw.uni-heidelberg.de
[2] Lund Observatory, Box 43, SE-22100 Lund, Sweden
[3] Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH

Abstract. NGC 2419 is one of the remotest star clusters in the Milky Way halo and its exact nature is yet unclear. While it has traits reminiscent of a globular cluster, its large radius and suggestions of an abundance spread have fueled the discussion about its origin in an extragalactic environment, possibly the remnant of the accretion of a dwarf galaxy. Here, we present first results from deep intermediate-band photometry of NGC 2419, which enables us to search for chemical (light element) abundance variations, metallicity spreads, and thus multiple stellar populations through well calibrated Strömgren indices.

Key words. Globular clusters: general – Globular clusters: individual (NGC 2419) – Galaxy: halo – Galaxies: photometry

1. Introduction

1.1. NGC 2419

NGC 2419 is a stellar aggregate with a number of puzzling characteristics and its nature and origin are yet unclear. With a half-light radius r_h of 21.4 pc it is the fifth-most extended object listed in the 2010-version of the Harris (1996) catalogue, while it is also one of the most luminous globular clusters (GCs) in the Milky Way (MW; Fig. 1). At a Galactocentric distance of 90 kpc it resides in the outermost halo. All these traits have fueled discussions of whether it contains any dark matter or could be affected by non-Newtonian dynamics (Baumgardt et al. 2005; Conroy et al. 2011; Ibata et al. 2012). For instance, Ibata et al. (2012) argue that its kinematics is incompatible with a dark matter content in excess of some 6% of its total mass. Overall, these morphological and dynamical considerations beg the question to what extent NGC 2419 has evolved in isolation and whether it could be associated with a once-accreted, larger system like a dwarf (spheroidal) galaxy.

Also chemically, NGC 2419 has much to offer: Cohen & Kirby (2012) and Mucciarelli et al. (2012) identified a population of stars (ca. 30% by number) with remarkably low Mg- and high K-abundances, which could be the result of "extreme nucleosynthesis" (Ventura et al. 2012). The question of an abundance-spread has been addressed by several authors using high-resolution spectroscopy and low-

Send offprint requests to: A. Koch

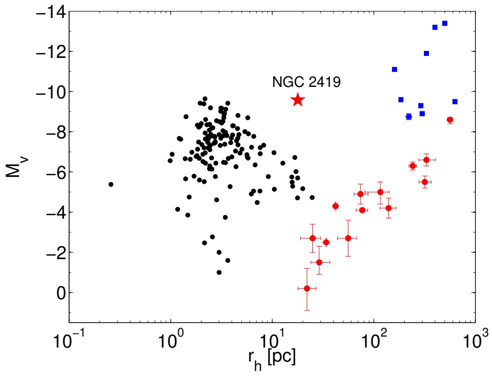

Fig. 1. Magnitude-half light radius plot for GCs (black dots), luminous dSphs (blue squares) and ultrafaint MW satellites (red circles). NGC 2419 is labeled – what is this object?

resolution measurements of the calcium triplet. However, the large abundance variation of the electron-donor Mg will upset the commonly used stellar model atmospheres so that any claimed spread in iron-, Ca-, and thus overall metallicity needs to be considered with caution. However, settling exactly this aspect is of prime importance, since any significant spread in heavy elements is a trademark signature of an object with a likely extragalactic origin (e.g., Fig. 1 in Koch et al. 2012).

The color-magnitude diagrams (CMDs) of Di Criscienzo et al. (2011) show a hint of a color-spread towards the subgiant branch and the presence of a hot, faint Horizontal Branch (HB), consistent with a second generation of stars with a strongly increased He-content. Thus, also NGC 2419 does appear to show signs of multiple stellar populations, in line with the majority of the MW GC system.

1.2. Strömgren photometry

While broad-band filter combinations have succeeded in unveiling multiple stellar populations in sufficiently deep data sets and more massive systems (e.g., Piotto et al. 2007), additional observations in intermediate-band Strömgren filters are desirable for a number of reasons:

i) The $c_1 = (u-v) - (v-b)$ index in combination with a color such as $v-y$ is a powerful *dwarf/giant separator* and can efficiently remove any foreground contamination (e.g., Faria et al. 2007). At $b = 25°$ this can be expected to be less of a problem in NGC 2419, but see, e.g., Adén et al. (2009) for an impressive demonstration of such a CMD cleaning. Our first assessment of the c_1-$(b-y)$ plane indicates that the foreground contamination is indeed minimal on the upper RGB (see also Fig. 2).

ii) The index $m_1 = (v-b) - (b-y)$ is a good proxy for stellar *metallicity* and calibrations have been devised by several authors (e.g., Hilker 2000; Calamida et al. 2007; Adén et al. 2009).

iii) *Multiple populations* in terms of split red giant branches (RGBs), multiple subgiant branches, and main sequence turnoffs are well separated in CMDs that use combinations of Strömgren filters, e.g., $\delta_4 = c_1 + m_1$ (Carretta et al. 2011), where optical CMDs based on broad-band filters still show unimodal, "simple stellar populations".

iv) This is immediately interlinked with the *chemical abundance variations* in the light chemical elements (e.g., Anthony-Twarog et al. 1995) that accompany the multiple populations, most prominently driven by N-variations. Accordingly, Yong et al. (2008) confirmed linear correlations of $c_y = c_1 - (b-y)$ with the [N/Fe] ratio.

2. Data and analysis

We obtained imaging in all relevant Strömgren filters (u,b,v,y) using the Wide Field Camera (WFC) at the 2.5-m Isaac Newton Telescope (INT) at La Palma, Spain. Its large field of view ($33' \times 33'$) allows us to trace the large extent of NGC 2419 out to several times its tidal radius ($r_t \sim 7.5'$).

Instrumental magnitudes were obtained via PSF-fitting using the Daophot/Allframe software packages (Stetson 1987). The instrumental magnitudes were transformed to the standard Strömgren system using ample observations of standard stars (Schuster & Nissen 1988). We set up transformation equations similar to those given by Grundahl, Stetson & Andersen (2002).

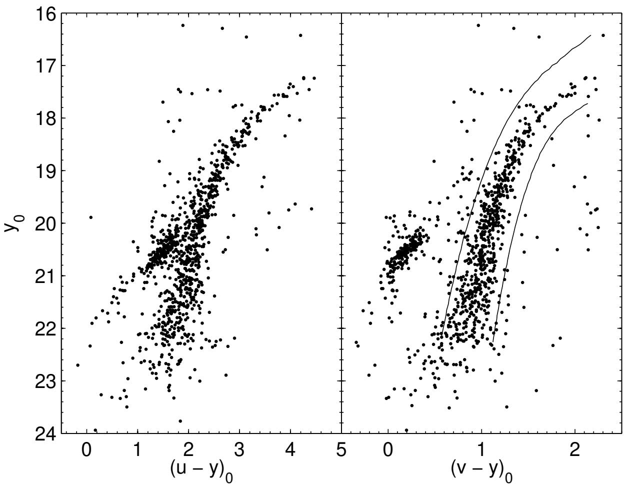

Fig. 2. CMDs of NGC 2419 for two possible Strömgren-filter combinations. Shown are stars between $r_h < r < 3\,r_h$; no other selection criteria have been applied. Stars falling within the lines shown right were used to construct the metallicity distribution in Fig. 3.

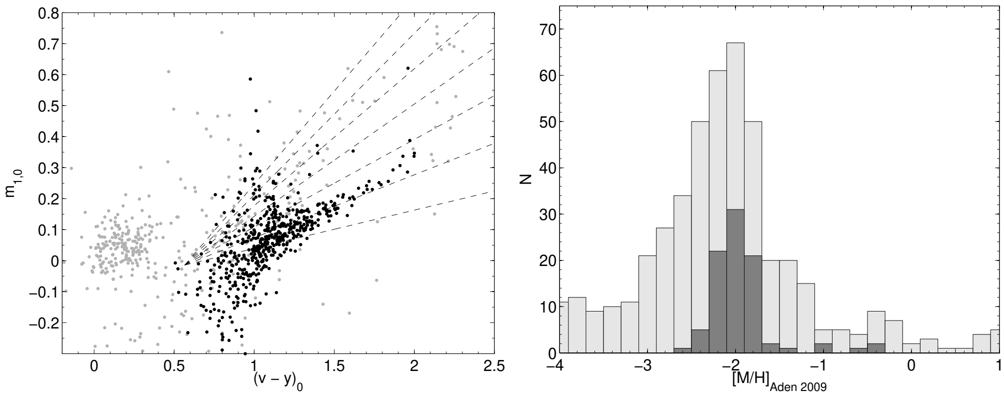

Fig. 3. Preliminary metallicity calibration in the m_1-vs-$(b-y)$ plane (left panel). Dashed lines indicate iso-metallicity curves based on the calibration of Adén et al. (2009) for [M/H] = −2.5 up to +0.5 dex in steps of 0.5 (bottom to top). Black dots are those within the RGB-ridge lines of Fig. 2, used to infer the MDF (light gray) in the right panel. The dark gray MDF in this plot uses a stricter RGB criterion of $(v-y)_0 > 1.4$.

3. Preliminary results: CMDs and [M/H]

Fig. 2 shows two CMDs of NGC 2419, where we restrict our analysis to the bona-fide region between 1 and 3 half-light radii to avoid potentially crowded, inner regions, yet minimizing the field star contamination of the outer parts. For the present analysis, we adopted a constant reddening of $E(B-V)= 0.061$ mag[1], and its respective transformations to the Strömgren system (Calamida et al. 2009).

While we do not resolve the main sequence turnoff, our photometry reaches about 1 mag below the HB at $y_{HB}\equiv V_{HB}\sim 20.5$ mag. All regions of the CMD are well reproduced, show-

[1] Obtained from `http://irsa.ipac.caltech.edu/applications/DUST`

ing a clear RGB, hints of an AGB and bright AGB (which stand out more clearly in other color indices; Frank et al. in prep.), and a prominent HB. Hess diagrams also highlight the presence of a clear RGB bump at $y_0 \sim 20.3$ mag. Moreover, the extreme, hotter HB stands out in the bluer u-band (left panel), confirming the presence of this He-rich, secondary population (Di Crisicienzo et al. 2011).

To obtain a first impression of the metallicity distribution function (MDF) of NGC 2419 (Fig. 3, right panel), we convert our Strömgren photometry to metallicities, [M/H], through the calibration by Adén et al. (2009). This was carried out for stars on the RGB (see ridge lines in Fig. 2, right panel, and Fig. 3, left). As a result, we find a mean [M/H] of −2 dex. This is in good agreement with the values listed in the Harris catalogue and the high-resolution data of Mucciarelli et al. (2012) and Cohen & Kirby (2012) of [Fe/H] = −2.15 dex.

The MDF also indicates the presence of a broad metallicity spread, where we find a nominal 1σ-spread of 0.5 dex, but this is probably still dominated by remaining foreground contaminants and photometric errors. While we cannot exclude the presence of an abundance spread in NGC 2419 from the present data, it is very likely much smaller than the one suggested by Fig. 3.

4. Discussion

Although our CMD does not allow us to clearly isolate any multiple stellar populations at this stage of our analysis, we nevertheless find strong reason to believe in their presence in NGC 2419, bolstered by recent optical images (Di Criscienzo et al. 2011). These authors detected a color spread at the base of the RGB and an extreme, hot HB, indicative of an increased He-abundance of a populous second stellar generation. This HB population is also visible in our intermediate-band CMDs.

Although our first analysis suggests a broad metallicity spread in NGC 2419, this is probably not significant and further CMD filtering is necessary. However, our derived mean metallicity is in line with the results from high-resolution spectroscopy, which indicates that our Strömgren photometry is well calibrated.

Acknowledgements. AK, MF, and NK gratefully acknowledge the Deutsche Forschungsgemeinschaft for funding from Emmy-Noether grant Ko 4161/1. This research has made use of the NASA/ IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

Adén, D., et al. 2009, A&A, 506, 1147
Anthony-Twarog, B. J., Twarog, B. A., & Craig, J. 1995, PASP, 107, 32
Baumgardt, H., et al. 2005, MNRAS, 359, L1
Calamida, A., et al. 2007, ApJ, 670, 400
Calamida, A., et al. 2009, ApJ, 706, 1277
Carretta, E., et al. 2011, A&A, 535, A121
Cohen, J. G., & Kirby, E. N. 2012, ApJ, 760, 86
Conroy, C., et al. 2011, ApJ, 741, 72
Di Criscienzo, M., et al. 2011, MNRAS, 414, 3381
Faria, D., et al. 2007, A&A, 465, 357
Grundahl, F., et al. 2002, A&A, 395, 481
Harris, W. E. 1996, AJ, 112, 1487
Hilker, M. 2000, A&A, 355, 994
Ibata, R., et al. 2012, MNRAS, 225
Koch, A., et al. 2012, European Physical Journal Web of Conferences, 19, 3002
Mucciarelli, A., et al. 2012, MNRAS, 426, 2889
Piotto, G., et al. 2007, ApJ, 661, L53
Schuster, W. J., & Nissen, P. E. 1988, A&AS, 73, 225
Stetson, P. B. 1987, PASP, 99, 191
Ventura, P., et al. 2012, ApJ, 761, L30
Yong, D., Grundahl, F., Johnson, J. A., & Asplund, M. 2008, ApJ, 684, 1159