RevMexAA (Serie de Conferencias), **42**, 38–40 (2013)

STELLAR ARCHAEOLOGY IN THE M31 HALO

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RESUMEN

Presentamos los resultados de un estudio sobre las estrellas variables y las poblaciones estelares de la galaxia esferoidal enana, compañera de la Galaxia M31, Andrómeda IX (And IX). Este estudio está basado sobre series temporales de imágenes adquiridas en el marco del nuestro programa ESO de larga duración en el Gran Telescopio Canarias (GTC; PI G. Clementini). En And IX se han descubierto más de veinte estrellas del tipo RR Lyrae y se han obtenido curvas de luz con un buen muestreo temporal de su periodo. Se ha obtenido una precisión en la medidas individuales mejor de 0.1 magnitudes, aún cerca el mínimo de las curvas de luz de las estrellas RR Lyrae que cae alrededor de $g' \sim 25.5$ mag. El diagrama color-magnitud (CDM) de And IX obtenido como resultado de una reducción con ALLFRAMES de las imágenes de una sola época llegan a una magnitud límite de $g' \sim 26.3-26.4$ mag. Promediando todas las 26 parejas de imágenes g' y r' disponibles para esta galaxia hemos conseguido una magnitud límite de $g' \sim 27.3$ mag. Esto nos permite llegar 2 magnitudes más debiles de los diagramas color-magnitud publicados hasta la fecha. El diagrama color-magnitud de And IX presenta una rama de las gigantes rojas (RGB) prominente. La rama horizontal se ve con claridad y tiene una magnitud de $g' \sim 25.3$ mag, pero está bastante contaminada por las medidas de las estrellas que no pertenecen a And IX. La línea promedio del diagrama color-magnitud de un cúmulo globular de baja metalicidad, como NGC 2419 ([Fe/H] = −2.2 en la escala de metalicidad de Carretta et al. 2009), ajusta bien el diagrama color-magnitud de esta galaxia.

ABSTRACT

We present results on the study of the variable stars and stellar populations of the Andromeda IX (And IX) dwarf spheroidal companion of M31, based on g', r' time-series photometry we obtained as part of our ESO Large Program 186.D-2013 at the Gran Telescopio Canarias (GTC; PI G. Clementini). More than twenty RR Lyrae stars were discovered in And IX and well sampled light curves were obtained, with an accuracy of the individual data points to better than 0.1 mag even at the RR Lyrae minimum light, which is around $g' \sim 25.5$ mag. The color magnitude diagram (CMD) of And IX obtained by reduction of the single epoch data reaches $g' \sim 26.3$-26.4 mag, while by stacking the 26 pairs of g', r' exposures available for the galaxy we were able to reach $g' \sim 27.3$ mag. This is 2 mag fainter than presently found in the literature. And IX shows a prominent red giant branch (RGB). The horizontal branch (HB) is clearly visible at $g' \sim 25.3$ mag, although it is rather contaminated by field stars. The galaxy CMD is well fitted by the mean ridge lines of a metal poor globular cluster such as NGC 2419 ([Fe/H]= −2.2 on the Carretta et al. 2009 metallicity scale).

Key Words: galaxies: dwarf — galaxies: individual (Andromeda IX) — galaxies: stellar content — stars: variables: RR Lyrae

1. GENERAL

The number of dwarf spheroidals (dSphs) surrounding the Andromeda galaxy (M31) has increased in the last 5–6 years from the 6 systems known until 2004 up to 25, as a result of the wide-field photometric surveys carried out at the Isaac Newton and the Canada-France-Hawaii telescopes (Richardson et al. 2011, and references therein) and the analysis of the Sloan Digital Sky Survey data (Slater et la. 2011; Bell et al. 2011). The new dSphs are generally fainter than previously known M31 companions. In the absolute magnitude versus half-light radius

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diagram they are found at the faintest hand of the distribution of the M31 "classic" dSphs and on the extension to brighter luminosities of the Milky Way "ultra-faint" dwarfs (UFDs). We are studying the stellar populations and the variable stars of a number of the M31 new companions using both space- (the *Hubble Space Telescope*) and ground-based facilities (the GTC; the Large Binocular Telescope, LBT; the Telescopio Nazionale Galileo, TNG) as they can provide insight to reconstruct the star formation history and the merging episodes that led to the assembling of the M31 halo. Here we present results for And IX (Zucker et al. 2004), that was observed with the GTC as part of our ESO Large Program 186.D-2013.

2. OBSERVATIONS AND DATA REDUCTION

The time-series photometry of the And IX dSph was obtained with the OSIRIS camera of the GTC during nine nights in October–November 2010. The observations were organized into 26 elementary observing blocks (OBs) of about 1 hr, each corresponding to one pair of [g',r'] exposures of 26.7 min per filter. To avoid sky saturation each 27.6 min exposure was split into 8 sub-exposures of 200 sec. All OBs were executed under seeing better than 1.0 arcsec, and using a 2×2 binning giving an actual scale of 0.25 arcsec/pixel. For each night of observation were available bias observations as well as five sky flats in the g'-band, and 15 in the r'-band. For each band and CCD we thus combined the sky flats through a median. In CCD1 the flat field homogeneity is better than 2% in each filters over the fully unvignetted field, while for CCD2 this value is around 4% in both filters. Vignetting of the 2 CCD mosaic of the OSIRIS camera is significant in the first 500 pixels of CCD1 and in the first 500 bottom pixels of both CCDs. This vignetting defines a maximum un-vignetted field of 721×1017 pixels ($3.0'\times4.2'$) for CCD1 and 713×1617 pixels ($3.0'\times6.7'$) for CCD2.

We performed a point spread function (PSF) photometry of the pre-reduced images with the DAOPHOTIV-ALLSTAR-ALLFRAME packages (Stetson et al. 1987, 1994). All the 200 sec sub-exposures were analyzed separately in order to use a most adequate PSF profile. We then averaged the catalogues of the 8 sub-images that form each individual epoch to produce the 26 epoch data (in both g' and r') used to study the variable stars in And IX. For the photometric calibration of the data we used as local standards 100 stars observed in the field of And IX by the SDSS with photometric accuracy $\sigma'_r < 0.1$ mag. These stars are distributed quite evenly on both CCDs. The calibration equations obtained with this procedure have an r.m.s. of ∼0.04 mag.

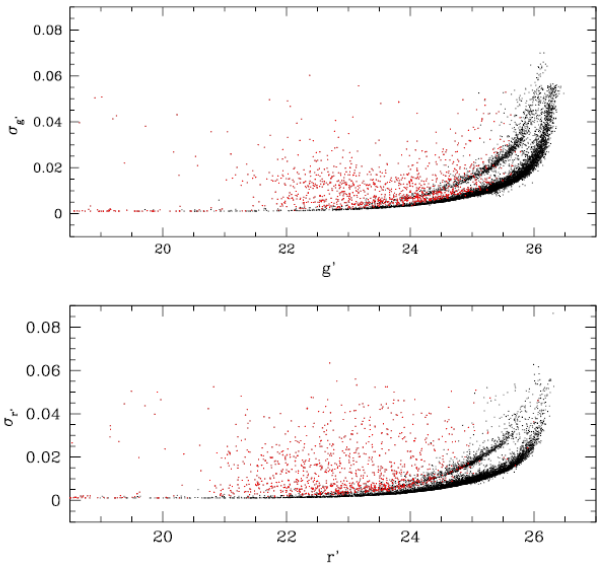

Fig. 1. Internal errors of the g' and r' photometry of And IX. We have marked in red stars with $\chi > 1.2$, these stars were not plotted in the galaxy CMD (see below). The upper sequence is due to stars that were measured on a smaller number of frames because of the large dithering that was erroneously applied during the observations of the galaxy.

The internal photometric errors of our photometry of And IX are shown in Figure 1.

3. VARIABLE STARS

We have detected and obtained well sampled light curves for more than twenty variables in And IX. They are mainly RR Lyrae stars. As an example of the quality of the data, in Figure 2 we show the g'-band light curves of a fundamental mode (RRab) and of a first overtone (RRc) RR Lyrae of And IX. The two variable stars have periods of 0.65 and 0.30 days, respectively. The error-bars are representative of the uncertainty of the single epoch data. This uncertainty is below 0.1 mag even for the RR Lyrae minimum light, which is around $g' \sim 25.5$ mag.

4. COLOR-MAGNITUDE DIAGRAM

The 26 epoch data of And IX were further averaged to obtain a deep CMD for the galaxy. The left panel of Figure 3 shows the resulting CMD for stars within 2.50 arcmin from the And IX center and with Stetsons' χ parameter lower than 1.2. The right panel of the figure shows the CMD of foreground/background field stars in a more external annular region between 2.50 and 3.53 arcmin from the

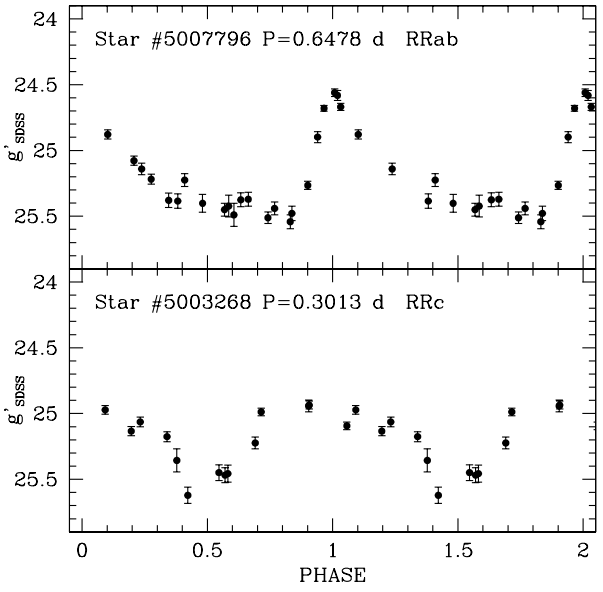

Fig. 2. g'-band light curves of an ab- (top) and a c-type (bottom) RR Lyrae star in the And IX dSph. Period and type are labeled.

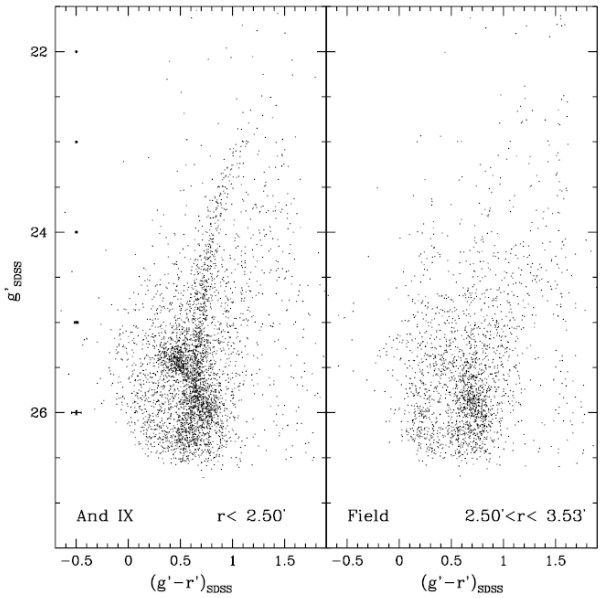

Fig. 3. CMD of the And IX galaxy, based on the average PSF photometry of the single-epoch data. Left panel: CMD of stars within 2.50 arcsec from the galaxy center; right panel: CMD of the foreground/background field stars. The sky area covered by the two panels is the same. Only stars with Stetsons' χ parameter lower than 1.2 are displayed.

galaxy center. The error-bars display the internal precision of the photometry at different magnitude levels. And IX has an half light radius of 1.43 arcmin. The CMD in the left panel corresponds to an area of about two times the galaxy half light radius and shows a very complex structure. The CMD of And IX obtained by the reduction of the single epoch data reaches $g' \sim 26.3 - 26.4$ mag, while by stacking the 26 pairs of g', r' exposures available for the galaxy we were able to reach $g' \sim 27.3$ mag, this is 2 mag fainter than presently available in the literature (see e.g. Collins et al. 2010). The CMD of And IX resembles that of a metal poor Galactic globular cluster and can be well fitted by the mean ridge lines of NGC 2419 ([Fe/H] $= -2.2$ dex, on the Carretta et al. 2009 metallicity scale). The CMD is characterized by a very prominent RGB. A residual of this RGB can still be seen in the right panel of Figure 3, thus suggesting that And IX extends beyond $r' = 3.5$ arcmin. The horizontal branch is clearly visible at $g' \sim 25.3$ mag, although it is rather contaminated by field stars. And IX is close to the M31 disk and in a region crossed by several streams. This explains the rather complex structure of the CMDs shown in Figure 3.

5. SUMMARY

We were awarded 126 hours GTC time as part of the ESO Large Program 186.D-2013 (*Stellar Archaeology in the M31 halo: variable stars and stellar populations in the And IX, And X, And XXIV, and And XV dwarf spheroidal galaxies*, P.I. G. Clementini), to obtain time series photometry of 5 of the M31 dwarf spheroidal satellites. Observations have already been completed for all the five targets. The PSF photometry with DAOPHOT/ALLSTAR/ALLFRAME of the And V, And IX and And X datasets has been completed, while it is in progress for And XV and And XXIV. The CMD of And IX obtained by stacking the 26 pairs of g', r' images available for the galaxy reaches $g' \sim 27.3$ mag. We have identified more than 20 RR Lyrae stars in this galaxy. A detailed study of the light curves is in progress.

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