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A long history of star formation in a low mass stellar system, Leo T

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Abstract. Nearby star-forming dwarf galaxies with small masses and low metallicity offer insights into the cosmic history of galaxy assembly. In this framework, we present results from the first combined study of variable stars and star formation history of the Milky Way (MW) "Ultra-Faint" dwarf (UFD) galaxy Leo T, based on F606W and F814W multi-epoch archive observations obtained with the Wide Field Planetary Camera 2 on board the Hubble Space Telescope. We have detected 14 variable stars in the galaxy, including one fundamental-mode RR Lyrae star and 10 Anomalous Cepheids with periods shorter than 1 day, thus suggesting the occurrence of multiple star formation episodes in this UFD, one of which about 10 Gyr ago produced the RR Lyrae star. A quantitative analysis of the star formation history, based on the comparison of the observed color-magnitude diagram (CMD) with a library of artificially generated CMDs, confirms that Leo T has experienced a complex star formation history dominated by two enhanced periods about 1.5 and 8 Gyr ago, respectively.

Key words. galaxies: dwarf – galaxies: stellar content – galaxies: individual (Leo T) – Stars: variables: RR Lyrae – Stars: variables: Anomalous Cepheids

1. Introduction

The recent discovery of "ultra-faint" (surface brightness around 28 mag/arcsec^2 or less) dwarf galaxies (UFDs) in the outskirts of the MW and M31 spirals, mainly thanks to the Sloan Digital Sky Survey (SDSS) data (see e.g. Belokurov et al. 2007), has opened a novel route for testing the Λ-cold-dark-matter paradigm of hierarchical structure formation (e.g. Bullock & Johnston 2005). In terms of age ($> 10 Gyr$) and metallicity (very low), these new satellites resemble Galactic globular clusters (GC) like M92, M15 and M68 (see e.g. Moretti et al. 2009; Brown et al. 2012), except for the half-light radius which is much larger.

Are the UFD galaxies the relics of the primeval "building blocks"? To address this question, a good starting point is to study those UFDs which present peculiarities, suggesting that they may be in an intermediate stage between primordial and present UFDs. At the bright end of the MW UFD distribution in the

$M_V - \log r_h$ plane, Leo T (Irwin et al. 2007) is the only known UFD exhibiting at least two distinct populations, an intermediate-age one, with an isochronal metallicity of [Fe/H] ~ -1.6 dex, and a young one composed by blue stars of age $\sim$ 200 Myr (Irwin et al. 2007). Indeed, deeper ($g \lesssim 26.5$ mag) Large Binocular Telescope observations (de Jong et al. 2008) confirmed the presence of very young stars with ages between $\sim$ 200 Myr and 1 Gyr, as well as a population older than 5 Gyr. Moreover, Ryan-Weber et al. (2008) found that Leo T is embedded into an HI cloud, thus making Leo T the only UFD found to contain a significant amount of neutral gas.

Despite all of these differences, the similarities with classical UFDs are also clear. First of all, Leo T is metal poor like the majority of UFDs. From Ca triplet absorption lines of 19 red giants Simon & Geha (2007) estimated a mean metal abundance of [Fe/H]=-2.29 ± 0.10 with a dispersion of $\sigma_{\rm [Fe/H]}$=0.35 dex. Kirby et al. (2008) have re-analyzed Simon & Geha (2007) spectroscopic material for Leo T by applying an automated spectral synthesis technique. They derived metallicities in the range of [Fe/H]=-0.12 to -3.22 dex, with an average value of $\langle$[Fe/H]$\rangle$ = -2.02 ± 0.05 dex and dispersion $\sigma_{\rm [Fe/H]}$=0.54 dex. This value was later revised to $\langle$[Fe/H]$\rangle$ = -1.99 ± 0.05 dex, $\sigma_{\rm [Fe/H]}$=0.52 dex, by Kirby et al. (2011). The spectroscopic mean metallicities are lower than the values found by Irwin et al. (2007) and de Jong et al. (2008). Finally, Leo T is typically"dark". Simon & Geha (2007) measured a mean stellar velocity of 38.1 ± 2.0 km s^{-1} with a dispersion of 7.5 ± 1.6 km s^{-1}, in excellent agreement with the HI velocity and gas velocity dispersion of 6.9 km s^{-1} measured by Ryan-Weber et al. (2008). From the velocity dispersion Simon & Geha (2007) infer a dark halo mass of $(8.2 \pm 3.6) \times 10^6 M_\odot$ and a mass-to-light ratio of $138 \pm 71 M_\odot/L_{\odot,V}$ for Leo T, while from the HI observations, Ryan-Weber et al. (2008) infer a lower limit for the total dynamical mass of $\sim 3 \times 10^6 M_\odot$ and a mass-to-light ratio of $\gtrsim 56 M_\odot/L_{\odot,V}$.

As part of a wide project aimed at understanding the evolution of the UFDs, we present our analysis of Leo T through archival Hubble Space Telescope WFPC2 observations (GO program 11084, PI. D. Zucker) in F606W and F814W. Pulsating stars and normal stars are used to constraint the galaxy distance and star formation history (SFH).

2. Variable stars

The identification of the variable stars was carried out using the F606W and F814W time-series data separately and a variety of search methods that produced a list of about a hundred candidates, of which 14 were eventually confirmed. This sample includes one fundamental-mode RR Lyrae star with period P=0.6027 day, and 13 variables about one magnitude brighter than the HB with periods shorter than 1 day. No candidate variables fainter than the galaxy HB could be reliably confirmed, nor was any variable star detected among the few blue loop objects in the galaxy's CMD, hence no Classical Cepheids seem to be present in Leo T, indicating a negligible SF rate in the last half Gyr.

The period of the RR Lyrae star suggests an Oosterhoff-Intermediate classification, providing a further difference with other UFDs (except CVn I) which are all Oosterhoff type II. Moreover, using for the RR Lyrae star the mean metal abundance of the galaxy RGB stars measured spectroscopically $\langle$[Fe/H]$\rangle$=-1.99 ± 0.05, $\sigma_{\rm [Fe/H]}$=0.52 dex (Kirby et al. 2008, 2011), a reddening value of $E(B-V)$=0.031 ± 0.026 mag (Schlegel et al. 1998), and a distance modulus for the LMC of 18.52 ± 0.09 mag (Clementini et al. 2003), we find a distance modulus of 23.06 ± 0.15 mag (409^{+29}_{-27} kpc).

The 13 variables brighter than the RR Lyrae star are located in a region of the CMD roughly corresponding to the classical instability strip of bright pulsating stars. Moreover, although their periods and luminosities do not allow a clear distinction between short period Classical Cepheids (SPCs) or Anomalous Cepheids (ACs; the blue extent of the red-clump, partially electron-degenerate central helium-burning stars), the comparison with theoretical isochrones seems to corroborate the second hypothesis (Clementini et al. 2012).

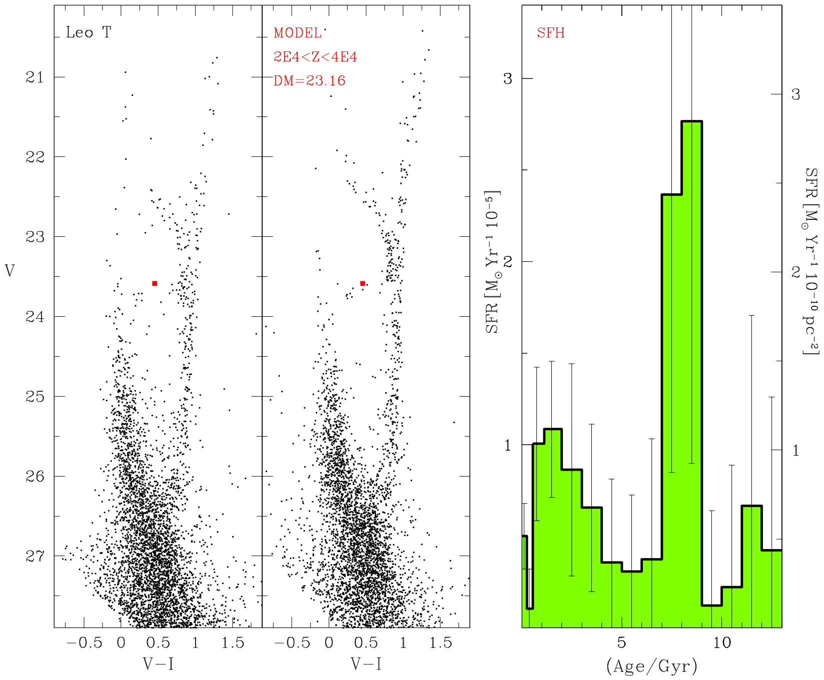

Fig. 1. Left panel: observational CMD. The RR Lyrae star is marked by a (red) filled circle. Middle panel: best synthetic CMD. Right panel: best recovered SFH.

3. SFH

To recover the SFH we used a population synthesis method applied to the CMD (see Cignoni & Tosi 2010, Cignoni et al. 2011 and Cignoni et al. 2012). The adopted stellar evolution tracks are taken from the Pisa Evolutionary Library (Cariulo et al. 2004). To limit the number of free parameters, the following properties are kept fixed in all simulations: 1) a Salpeter initial mass function (IMF); 2) a binary fraction of 30%; 3) a foreground reddening of $E(B-V) = 0.03$ mag, according to Schlegel's maps; 4) a random metallicity between $Z = 0.0002$ and $Z = 0.0004$, motivated by the spectroscopical information and by the observed magnitude difference between ACs and the RR-Lyrae stars (see Clementini et al. 2012). Beside the star formation, also the distance modulus and the differential reddening $E(B-V)$ were varied in the ranges of 23.00 – 23.2 mag and 0.0 – 0.05 mag, respectively. The right panel of Figure 1 shows the best reconstructed SFH. The large error bars are partly due to the sample size and partly due to the photometric errors. Overall, Leo T has produced stars continuously since the earliest epochs with a gasping regime. Approximately 36% of the stars were formed in the last 6 Gyr. The most relevant features are:

– Two broad peaks of SF around 1.5 Gyr and 9 Gyr ago; the relatively old age of the former peak provides further support that the 10 variable stars above the RR-Lyare star are ACs and not young SPCs;

- Three significant gaps in the age range of 0.25 to 0.5 Gyr, 4 Gyr to 6 Gyr, and 9 Gyr to 13 Gyr ago;
- A low intensity SF activity started less than 250 Myr ago.

The best-fit distance modulus is $(m - M)_0 =$ 23.16 mag, in good agreement with the RR-Lyrae inferred distance.

Our results (for a detailed description see Clementini et al. 2012) confirm those of de Jong et al. (2008) and Weisz et al. (2012), who used similar CMD analyses to recover the SFH. We all agree that a large amount of SF took place in the earliest ages, followed by a relative decrease at intermediate ages and then a renewed activity in the last few Gyr which decreases towards the present time. Interestingly, our study also revealed a previously overlooked feature, an initial activity between 10 and 13 Gyr ago significantly lower than at later epochs.

4. Conclusions

We have studied the variable stars of the Leo T UFD and performed a quantitative analysis of its SFH. We have detected 14 variables in Leo T, they include 1 fundamental-mode RR Lyrae star, 10 likely ACs, and two putative binaries. The average period of the RR Lyrae star (P=0.6027 d) suggests an Oosterhoff-Intermediate classification for Leo T, similarly only to CVn I, among the UFD galaxies. The magnitude difference between ACs and the RR Lyrae star suggests a metallicity lower than Z=0.0004, and more likely around 0.0002 ([Fe/H]=−2.0 dex) for the intermediate-age and the oldest stellar components in Leo T. In spite of the low mass, Leo T underwent a complex SFH, with two major star forming episodes, about 7-9 Gyr ago and 1-2 Gyr ago, overimposed on a continuous star formation activity.

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