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Stellar Populations of the Leo I and Leo II dSph Galaxies: Chemical Abundances and Ages

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Abstract

Our goal is to map the chemical abundance distribution and the age–metallicity relationship of the stellar populations of the Leo I and Leo II dwarf spheroidal (dSph) galaxies to constrain the physical processes that regulate their evolution. We are measuring chemical abundances from spectroscopy of individual red giant branch (RGB) stars using the Ca II absorption lines in the near–infrared ($\lambda\lambda$ 8498, 8542, and 8662 Å) observed with the Low Resolution Imaging Spectrometer (LRIS) on the Keck I 10–meter Telescope†. We obtained spectra of 41 stars in each dSph from which abundances with random errors of 0.08 dex and total errors of 0.17 have been derived. The median metallicities are [Fe/H] = −1.35 and [Fe/H] = −1.57 for Leo I and Leo II, respectively. Both dSphs have a significant dispersion in metallicity of $\approx$ 1 dex. Using Padova isochrones, we derive ages for the RGB stars using broad–band photometry and the abundances that we derived from spectroscopy. Leo I stars have ages between 2 and 15 Gyrs with many stars being younger than 5 Gyrs. Most Leo II stars have ages between 5 and 15 Gyrs, and few stars are younger than 5 Gyrs.

1.1 Introduction

The color–magnitude–diagrams (CMDs) of Leo I and Leo II dSphs show that their star formation histories (SFHs) are much more complicated than theory would predict for such low mass, low luminosity, low surface-brightness galaxies. Leo I seems to have had a large burst of star formation $\approx$ 1 to 7 Gyrs ago when $\approx$ 87% of its stars were formed, while $\approx$ 13% of star formation occurred between 7 and 15 Gyrs ago (Gallart, et al. 1999; Dolphin, 2002). In contrast, Leo II has hardly any stars younger than $\approx$ 7 Gyrs, which means that star formation stopped after the first $\approx$ 7 Gyrs of Leo II's evolution (Mighell & Rich 1996). Each dSph should exhibit a range in metallicity if the ejecta from supernovae were retained by the galaxies and recycled into new stars. We use the strengths of the near–infrared Ca II triplet absorption lines to derive metallicities for 41 RGB stars in both galaxies. We derive age–metallicity relationships for the Leo I and Leo II dSphs using Padova isochrones, broad–band photometry and the spectroscopic metallicities of the stars.

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1.2 Observations and Data Reduction

Our observations were made with the Keck I 10–meter telescope at the W. M. Keck Observatory on February 8, 2002 with the LRIS (Oke, et al, 1995), a multislit spectrograph, to obtain spectra of $20-35$ stars per exposure. We had a wavelength coverage of approximately 7800 – 9445 Å and a resolution of 1.55 Å. An integration time of 1 hour for each of the Leo fields led to an median signal–to–noise ratio of 27 per pixel.

We obtained spectra for 41 stars in both Leo I and Leo II. Reductions were made using standard IRAF packages and our own IDL routines. We measured the equivalent widths of the Ca II triplet lines ($\lambda\lambda$ 8498, 8542 and 8662 Å) and errors using an IRAF-based FORTRAN code, EW (G. Da Costa 1999, private comm) that fits a Gaussian shaped profile to the absorption lines.

Our abundances were derived using the calibration of Rutledge, et al. (1997) and Rutledge, Hesser & Stetson (1997) (hereafter, Rut97a and Rut97b), which relates the equivalent widths of the Ca II absorption lines to [Fe/H]. We have followed the Rut97a convention of

$$\begin{aligned} \mathbf{\sum W} &= \mathbf{0.5\ W_{8498Å} + W_{8542Å} + 0.6\ W_{8662Å}}, \\ \mathbf{W'} &= \mathbf{\sum W + 0.64\,(V - V_{HB})}, \end{aligned}$$

where V_{HB} is the horizontal branch magnitude of the cluster or galaxy. Note that lower weights are given to the weaker lines in order to yield higher precision. The "reduced equivalent width", W', scales linearly with [Fe/H] and removes the gravity sensitivity of the Ca II strengths to first order. Metallicities were derived from the Rut97b calibration of W' to [Fe/H] for the metallicity scale of Caretta & Gratton (1997; hereafter CG97). Rut97b found

$$\mathbf{[Fe/H] = -2.66 + 0.42\,W'}$$

for the 19 Galactic globular clusters from CG97, where [Fe/H] was determined from the equivalent widths of Fe I lines measured from high dispersion spectra of cluster stars.

We observed 8 to 9 stars in each of the globular clusters NGC 4590, NGC 1904 and M3 to tie our equivalent width measurements to the Rut97a W' scale. Padova isochrones (Girardi, et al. 2000) were then used to derive ages for the RGB stars from the derived metallicities and broad–band photometry (Stetson, P. B. 2002, unpublished).

Memberships were determined from the velocities of our stars. All stars have heliocentric velocities within 5σ of the average, and therefore we consider all observed stars to be members.

1.3 Results

1.3.1 Leo I

For Leo I, we assume $V_{HB} = 22.6$ based on the RR Lyrae work of Held, et al. (2001). We find a median metallicity of $[Fe/H] = -1.35$ and a range in metallicity of $-1.98 \leq [Fe/H] \leq -0.76$. Our mean random error is 0.08 dex and mean total error is 0.16 dex per star (See Fig. 1.1A & Fig. 1.2B), where the random errors are derived from the uncertainties in the measurements of W', and the total errors are the random uncertainties plus the uncertainties from the calibration, excluding possible differences in the Leo I [Ca/Fe] versus [Fe/H] relationship compared to the Galactic relationship. Remember that the calibration assumes a [Ca/Fe] versus [Fe/H] relationship of Galactic globular clusters, but note that Galactic globular clusters show a trend of decreasing [Ca/Fe] with increasing [Fe/H]. However, abundance

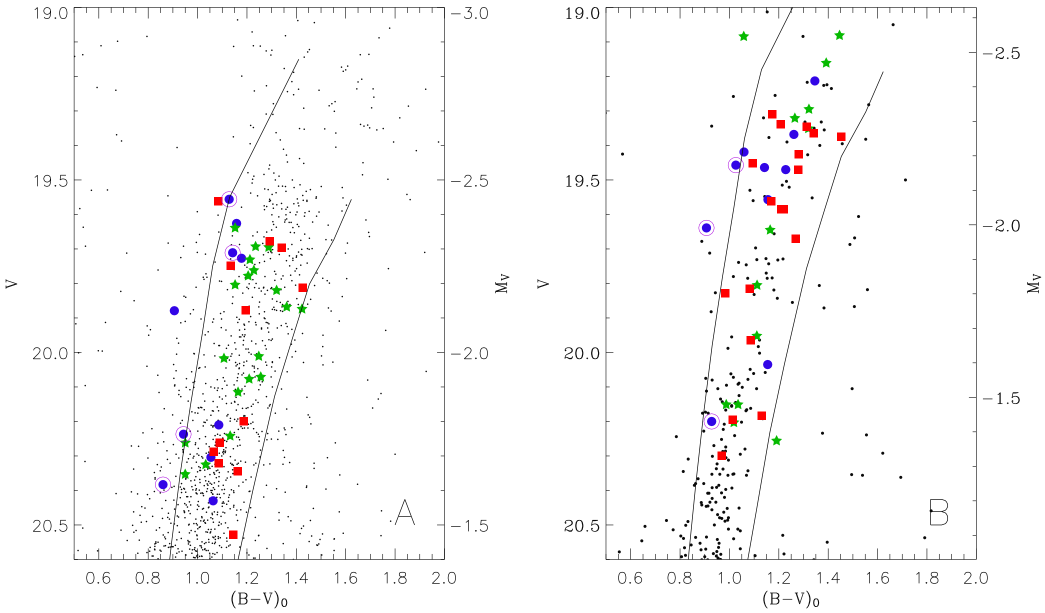

Fig. 1.1. RGBs: A: The RGB for Leo I with observed stars color–coded based on their [Fe/H] values: red boxes for [Fe/H] ≥ -1.2; green stars for $-1.2 >$ [Fe/H] ≥ -1.61; blue circle for [Fe/H] < -1.61. B: RGB for Leo II: red boxes for [Fe/H] ≥ -1.55; green stars for $-1.55 >$ [Fe/H] ≥ -1.80; blue circles for [Fe/H] < -1.8. Fiducial RGBs for two clusters are also shown: M68 ([Fe/H]=-1.92; Sandquist, et al. 1996) & M5 ([Fe/H] $= -1.17$; McClure, et al. 1987). Interesting stars are circled (see text for details and figures 1.2B & 1.2D).

ratios measured for two stars in Leo I (Shetrone, et al. 2003) follow the same relationship as Galactic globular clusters; one star has [Fe/H] $= -1.52$ and [Ca/Fe] $= +0.15$, and the other has [Fe/H] $= -1.06$ and [Ca/Fe] $= +0.02$. Therefore, there may be no systematic calibration problems caused by large differences in [Ca/Fe] ratios.

The metallicity distribution of Leo I is Gaussian–shaped with a slight excess metal–poor tail. The large spread in [Fe/H] has not been applied to previous analysis of the Leo I CMD which either assumed a constant [Fe/H] (Gallart et al. 1999) or a much narrower range in [Fe/H] (Dolphin 2002). There is a significant discrepancy of ≈0.4 dex between the average abundance inferred from CMD modeling (Dolphin 2002) and those derived spectroscopically, which cannot be attributed to plausible differences in [Ca/Fe] ratios. The observed discrepancy could be explained if [Ca/Fe] ≈ –0.5 for Leo I, but this is lower, by a factor of two, than *any* observed [Ca/Fe] for stars in the Galaxy or dSphs. Thus, calibration problems due to large variations in [Ca/Fe] is an unlikely explanation for the differences between the spectroscopic metallicity distribution and that inferred from modeling the CMD.

We derived ages for 29 of our stars using the Padova isochrones (assuming solar–scaled abundance ratios), our derived [Fe/H] values and V and I magnitudes. The rest of the stars did not fit on the isochrone grids, so the ages could not be determined. We find a range in age of 1 – 14 Gyrs (See Fig. 1.2B). The age–metallicity relationship is flat for ages > 5 Gyrs,

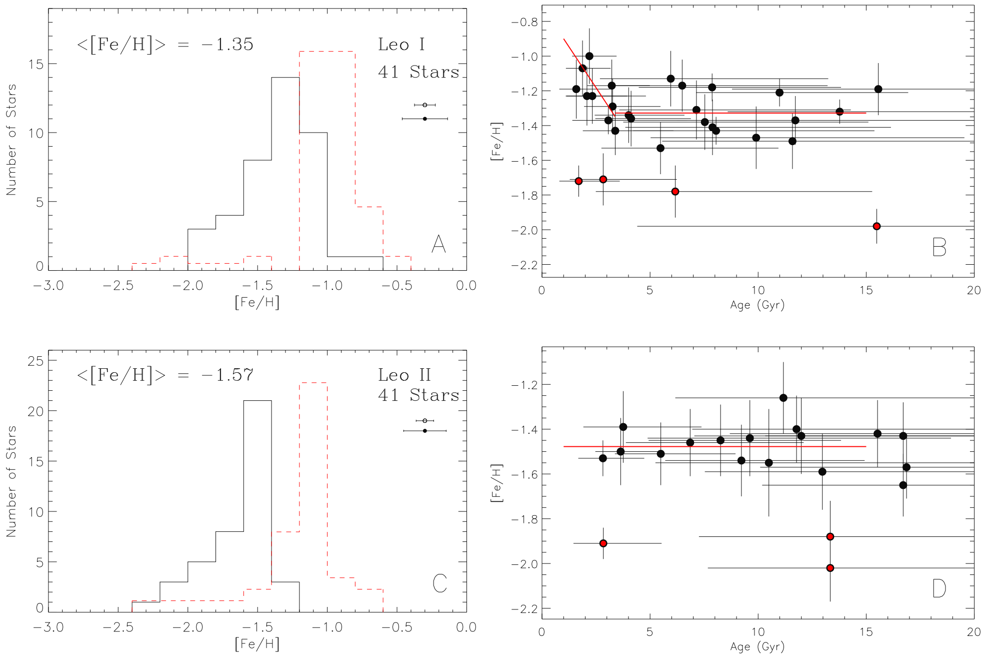

Fig. 1.2. A & C: The metallicity distributions in Leo I and Leo II are shown in the black histogram. (Typical 1 σ random and total errors are shown in the upper right with open and filled circles, respectively). Overplotted in the red histogram is the metallicity distribution derived from modeling the HST CMD (Dolphin 2002). Models have been scaled to the same total number of stars. B & D: The age–metallicity relationships for Leo I and Leo II RGB stars, respectively. In Leo I, notice the change at $\approx$ 4 Gyrs. Outliers for Leo I and Leo II are plotted in red and circled on the RGBs in figures 1.1A & 1.1B.

while metallicity increases for ages $<$ 5 Gyrs. We find three low metallicity stars with young ages, 2 to 6 Gyrs, which may indicate that Leo I experienced late time infall of metal–poor gas. Such infall is expected in hierarchical galaxy formation models (Bullock, Kravtsov, & Weinberg 2000) and may have fueled new star formation, which could account for the large size of Leo I's young population.

1.3.2 Leo II

For Leo II, we assumed V_{HB} = 22.17 based on the RR Lyrae work of Siegel & Majewski (2000). We find a median metallicity of $[Fe/H] = -1.57$ and a range in metallicity of $-2.32 \leq [Fe/H] \leq -1.26$. Our mean random error is 0.07 dex and mean total error is 0.15 dex per star (See Fig. 1.1B & Fig. 1.2C). The metallicity distribution has a sharp cutoff at the metal–rich end at $[Fe/H] \approx -1.5$. Our results are in very good agreement with Mighell & Rich (1996) who inferred average metallicity of $[Fe/H] = -1.60 \pm 0.25$ using V and I band photometry of RGB stars and the shape of the RGB. They also found a metallicity spread of 0.9 dex, which is similar to our results.

There is a dramatic cutoff in the metallicity distribution for $[Fe/H] \geq -1.5$ possibly indicative of a sudden stop in star formation. The average metallicity from our observations and the average metallicity inferred from CMD modeling (Dolphin 2002) is lower by ≈ 0.4 dex. As in the case of Leo I, the discrepancy between the observed distribution and that inferred from modeling the CMD cannot be explained by abundance variations.

We find a range in age of 2 – 13 Gyrs for 20 of our stars using Padova isochrones (See Fig. 1.2D). The age–metallicity relationship for all 20 stars is flat with the exception of three low metallicity outliers. One of the problems with determining ages for the rest of the Leo II stars may be attributed to the fact that we needed to use B–V colors instead of V–I, and the isochrones used may not be as reliable for B magnitudes and B–V colors, which are highly metallicity dependent and may be less accurate.

1.4 Conclusions and Future Work

We have obtained low dispersion spectra of 41 red giant stars in both Leo I and Leo II dSph galaxies based on the strengths of the near infrared Ca II triplet lines. We find Leo I has an internal metallicity spread of 1.2 dex with a median metallicity of $[Fe/H] = -1.35$, and Leo II has a metallicity spread of 1.1 dex but is more metal–poor with a median metallicity of $[Fe/H] = -1.57$. The fact that the metallicity distribution of Leo II cuts off more dramatically than Leo I may be due to greater mass loss in the less massive Leo II galaxy. The ages derived for the Leo I and Leo II stars show that Leo II has very few young stars (ages < 5 Gyrs) and a constant age–metallicity relationship while Leo I has a significant number of young stars with a few young, metal–poor stars indicative of inflow of metal–poor gas.

Our goal is to map the chemical abundances of both Leo I and Leo II dSphs using $\approx$ 100 red giant stars in each galaxy. We obtained spectra for the rest of our sample in March, 2003. In addition, we will reinterpret the Ca II line strengths for Leo I and Leo II stars using our new calibration of W' to [Ca/H], and extension of the calibration to younger ages (Bosler, Smecker-Hane, & McWilliam 2002). The calibration to [Ca/H] will be independent of star formation history unlike the current calibration, which assumes a Galactic [Ca/Fe] vs. [Fe/H] relationship. We will also select several of the Leo I and Leo II stars for further investigation using high signal–to–noise, high dispersion spectroscopy to derive abundance ratios.

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