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The Chemical Evolution of Milky Way Satellite Galaxies from Keck Spectroscopy

Evan N. Kirby†

Department of Physics, University of California, 4129 Reines Hall, Irvine, CA 92697, USA
email: ekirby@uci.edu

Abstract. The primary data product of a recent Keck/DEIMOS spectroscopic campaign of eight Milky Way dwarf spheroidal (dSph) satellite galaxies is a catalog of nearly 3000 red giants with spectral synthesis-based abundance measurements of Fe and the α elements Mg, Si, Ca, and Ti. The dSph metallicity distributions show that the histories of the less luminous dSphs were marked by massive amounts of metal loss. The [α/Fe] distributions reveal that the early star formation histories (at a lookback time of > 12 Gyr) of most dSphs were very similar and that Type Ia supernova ejecta contributed to the abundances of all but the most metal-poor ([Fe/H] < -2.5) stars. This large data set allows inferences of past outflows from the dSphs in order to determine their contribution to the metal content of the intergalactic medium.

Keywords. galaxies: dwarf, galaxies: abundances, galaxies: evolution, galaxies: stellar content, intergalactic medium, stars: abundances

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The Milky Way dSphs are attractive targets for resolved stellar spectroscopy because their stellar populations are at uniform distances in small patches of the sky. Spectroscopically derived chemical abundances can reveal their early star formation histories, where color-magnitude diagrams have limited sensitivity to relative ages. Kirby, Guhathakurta, Simon, *et al.* (2010) observed about 3000 red giants in eight dSphs. Using spectral synthesis, they measured metallicities ([Fe/H]) for each of these stars. When possible, they also measured the abundances of four individual α elements: Mg, Si, Ca, and Ti.

The average metallicities of dSphs range from one tenth to one hundredth of the solar metallicity. The lack of metals indicates that the galaxies suffered a great deal of metal loss. Although the missing metals cannot be observed directly, the degree of loss can be inferred from the stellar mass and current metallicity. The stellar mass—combined with an assumed initial mass function and theoretical supernova yields—dictates the total amount of metals that the stellar population produced. The amount of metals lost, shown in Figure 1, is the difference between the amount produced and the present metal content. The dSphs lost the vast majority of their metals. However, they were not significant contributors to the intergalactic medium (IGM). Fornax alone injected more Fe into the IGM than all smaller dSphs combined. More massive galaxies presumably enriched the IGM even more. For more information, see Kirby, Martin, & Finlator (2011).

Despite the near inability of the dSphs to retain any metals, they did experience chemical evolution. Figure 2 shows that all of the [α/Fe] ratios decline with increasing [Fe/H]. This pattern indicates that Type Ia supernovae exploded during the star formation lifetimes of all of the dSphs. Therefore, the dSphs must have formed stars over at least the delay time of a Type Ia supernova, which is at least 100 Myr. Kirby, Cohen, Smith, *et al.* (2011) developed a chemical evolution model that suggests that even Ursa Minor, the dSph with the shortest star formation lifetime, actually lasted for at least 500 Myr.

† Center for Galaxy Evolution Fellow

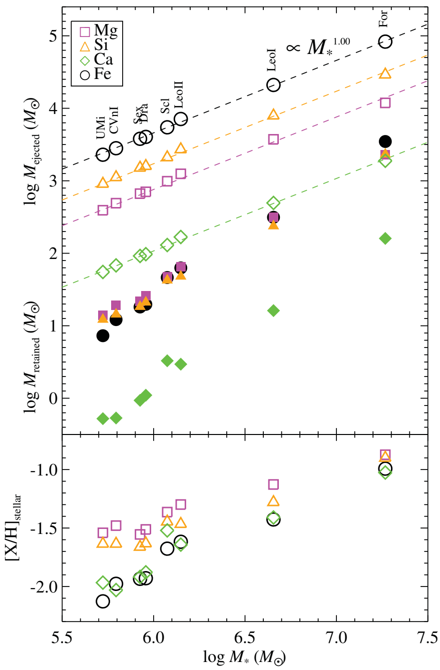

Figure 1. *Top:* Metals presently in dSphs (*filled symbols*) and inferred to have been lost (*open symbols*) versus stellar masses. *Bottom:* The dSph mass-metallicity relation that Kirby, Lanfranchi, Simon, *et al.* (2011) measured from Keck/DEIMOS spectroscopy.

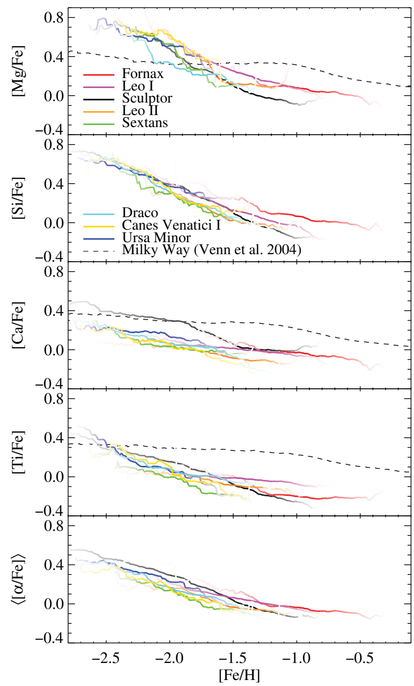

Figure 2. The moving averages of [α/Fe] ratios versus metallicity compared to the Milky Way halo. The bottom panel shows the averages from the top four panels. Different dSphs are indicated by color or shade.

The [α/Fe] paths in Figure 2 show no plateau in the metallicity range $-2.5 <$ [Fe/H] < -1.0. The only exception is [Ca/Fe] in Sculptor. This pattern shows that the ejecta from Type Ia supernovae polluted the dSphs even when the metallicity was only [Fe/H] $= -2.5$. There are two possibilities: (1) Type Ia supernovae can be extremely prompt, or (2) the star formation rates were so low in dSphs that over 100 Myr (the minimum delay time for a Type Ia supernova) elapsed before the metallicity of the dSphs reached [Fe/H] $= -2.5$.

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