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METALS REMOVED BY OUTFLOWS FROM MILKY WAY DWARF SPHEROIDAL GALAXIES*

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ABSTRACT

The stars in the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way are significantly more metal-poor than would be expected from a closed box model of chemical evolution. Gas outflows likely carried away most of the metals produced by the dSphs. Based on previous Keck/DEIMOS observations and models, we calculate the mass in Mg, Si, Ca, and Fe expelled from each of eight dSphs. Essentially, these masses are the differences between the observed amount of metals present in the dSphs' stars today and the inferred amount of metals produced by supernovae. We conclude that the dSphs lost 96% to > 99% of the metals their stars manufactured. We apply the observed mass function of Milky Way dSphs to the ejected mass function to determine that a single large dSph, like Fornax, lost more metals over 10 Gyr than all smaller dSphs combined. Therefore, small galaxies like dSphs are not significant contributors to the metal content of the intergalactic medium. Finally, we compare our ejected mass function to previous X-ray measurements of the metal content of the winds from the post-starburst dwarf irregular galaxy NGC 1569. Remarkably, the most recent starburst in that galaxy falls exactly on the ejected mass-stellar mass relation defined by the Milky Way dSphs.

Subject headings: galaxies: dwarf — galaxies: abundances — galaxies: evolution — intergalactic medium — Local Group

1. INTRODUCTION

In a closed box model of chemical evolution (van den Bergh 1962; Schmidt 1963), the peak of the stellar metallicity distribution lies at the nucleosynthetic yield. For most supernovae (SNe), the nucleosynthetic yield is about solar metallicity or higher (Woosley & Weaver 1995; Limongi & Chieffi 2003; Nomoto et al. 2006). However, the peaks of the stellar metallicity distributions of all known dwarf spheroidal galaxies (dSphs) are less than solar (e.g., Aaronson & Mould 1985; Buonanno et al. 1985). The dSphs likely lost metals during star formation, which reduced their effective nucleosynthetic yields (Hartwick 1976; Yoshii & Arimoto 1987). Almost no dSph with 250 kpc of the Milky Way (MW) contains any detectable gas at present (e.g., Blitz & Robishaw 2000; Grcevich & Putman 2009). Therefore, the missing metals are not hiding in the galaxies' interstellar medium. The metals have been lost.

Supernova winds drive gas out of galaxies, particularly small ones (Larson 1974; Dekel & Silk 1986). It is possible to detect this gas flowing out of galaxies, but it is very difficult to measure the metallicity or even the mass of galactic winds. Absorption line studies of distant galaxies, including galaxies at cosmological redshift, can measure column densities and outflow velocities (Martin 2005; Rupke et al. 2005; Weiner et al. 2009; Steidel et al.

2010; Rubin et al. 2010) but not mass or composition. Smaller galaxies may be even more prone to gas outflows due to their shallow gravitational potential wells. Martin (1999) showed that the observed hot gas around gas-rich dwarf irregular galaxies (dIrrs) in the nearby universe must be escaping from those galaxies in the form of outflows. Just a few such galaxies are suitable for X-ray spectroscopy to measure the composition of the escaping gas (e.g., NGC 1569 Martin et al. 2002),

Dwarf galaxies, which are numerous and have shallow gravitational potential wells, may be important contributors to the metal content of the the intergalactic medium (Oppenheimer & Davé 2008; Martin et al. 2010) or to their host galaxies. However, most nearby dwarf galaxies, especially dSphs, have not experienced appreciable star formation for several Gyr. As a result, it is even more difficult to observe gas expelled from Local Group dwarfs because it must have happened so long ago.

Kirby et al. (2010, 2011b) recently measured the stellar metal content of dSphs. The amount of metals produced over cosmic time for an individual dSph may be estimated from its stellar mass, an assumed stellar initial mass function (IMF), and theoretical SN yields and explosion rates. The difference between the inferred metal production by SNe and the current stellar metal content gives the amount of metals the galaxy has lost. This letter presents that calculation and discusses the role of dSphs in enriching the intergalactic medium (IGM) and their host galaxies.

2. CALCULATIONS OF METALS EXPELLED

Kirby et al. (2011a, hereafter K11a) constructed a basic chemical evolution model in order to explain the metallicity and $[\alpha/\text{Fe}]$ distributions of eight MW dSphs: Fornax, Leo I, Leo II, Sculptor, Sextans, Draco, Canes Venatici I, and Ursa Minor. The model assumes that each galaxy begins its life with a certain amount of gas ($M_g(0)$) but no stars. Primordial, metal-free gas flows

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into the galaxy at a prescribed inflow rate ($dM_g/dt = A_{\text{in}} t e^{-t/\tau_{\text{in}}}$). Stars form according to a star formation rate law ($dM_*/dt = A_* M_*^\alpha$). Type II SNe explode from massive (10–100 M_\odot) stars, and Type Ia SNe explode according to an empirical delay time distribution (Maoz et al. 2010). Most importantly for this letter, the galaxy loses a fixed amount of gas (A_{out}) during each SN explosion. K11a varied the parameters $M_g(0)$, A_{in} , A_* , A_{out} , τ_{in} , and α until the modeled metallicity and $[\alpha/\text{Fe}]$ distributions matched the observed distributions.

This model provides good matches to the abundance distributions of the less luminous dSphs. The inferred star formation histories also were qualitatively consistent with histories measured from color-magnitude diagrams. Essentially, nearly all stars in the less luminous dSphs are ancient, and they formed in 2 Gyr or less. However, the models for the most luminous dSphs (Fornax, Leo I, and to some extent, Leo II) have chemically measured star formation durations of only ~ 1 Gyr. The color-magnitude diagrams for these galaxies rule out such short star formation lifetimes, and they also rule out single bursts of star formation. These dSphs experienced several epochs of an increase in star formation rate (SFR) followed by a decrease. The K11a models permit only one episode of star formation (a single rise and fall of SFR). Therefore, the models are imperfect descriptions of Fornax, Leo I, and possibly Leo II.

On the other hand, for an old enough population, such as the MW dSphs, most of the SNe that will ever explode have already exploded. Therefore, the star formation history (SFR as a function of time) has a small effect on the total metal production integrated over cosmic time. Because SN yields are metallicity-dependent, the star formation history does matter to a small degree.

As a supplement to the work of K11a, we compute the mass in a number of metals, M_{ejected} , that the dSphs lost to SN winds. The K11a chemical evolution model tracks the amount and composition of expelled gas with each 1 Myr time step. The model was terminated when the dSphs were exhausted of gas. Although dSphs lose a small fraction of stars to tidal interactions with the MW (Majewski et al. 2000), we neglect this deduction from the final stellar mass. The existence of the luminosity-metallicity relation (Mateo 1998; Kirby et al. 2011b) limits the severity of tidal stripping of luminous matter (also see Peñarrubia et al. 2008) because tidally stripped versions of massive satellites would be just as metal-rich as other massive satellites, but small, metal-rich satellites do not exist.

In order to mitigate the uncertainties imposed on M_{ejected} from uncertain star formation histories, we advance the chemical evolution model for each dSph to an age of 10 Gyr. We compute the amount of ejecta—mostly in Fe—from Type Ia SNe over 10 Gyr, even though star formation ends in the models long before then. Like K11a, we use Nomoto et al.’s (2006) nucleosynthetic yields for Type II SNe, Iwamoto et al.’s (1999) yields for Type Ia SNe, and Maoz et al.’s (2010) delay time distribution for Type Ia SNe. The first Type Ia SN explodes 100 Myr after the birth of its progenitor, and the Type Ia SN rate declines as $t^{-1.1}$. Based on the theoretical yields and IMF (Kroupa et al. 1993) we have adopted, Type Ia SNe produce 94% of the iron over

10 Gyr. Asymptotic giant branch stars are included in the chemical evolution model, but at these low metallicities, they are responsible for only a few percent of the total production of Mg, Si, Ca, and Fe (Karakas 2010).

Table 1 gives M_{ejected} for Mg, Si, Ca, and Fe for the eight MW dSphs in our sample. We do not attempt to estimate errors on M_{ejected} because the dominant source of uncertainty is the SN yields. Differences between different yield models (e.g., Woosley & Weaver 1995; Nomoto et al. 2006) can be a factor of several for some elements.

If Type Ia SNe have a prompt component (Scannapieco & Bildsten 2005), then the Type Ia SNe at early times could feed the same wind as the Type II SNe. However, the delayed Type Ia SNe at late times explode at a low rate. Without continuous explosions, it may not be possible to drive a wind. Nonetheless, nearly all dSphs are free of gas. Therefore, the “missing metals”—the difference between the current metal content of the dSph and the amount of metals estimated to have been produced by all of the dSph’s SNe—have left the dSphs, whether in coherent winds or otherwise.

K11a assumed that the composition of the gas lost to SN winds was the same as the gas within the galaxy at the time of loss. However, outflows could be metal-enhanced, especially because the SNe that expel gas from the galaxy are the same events that enrich the galaxy with metals (Vader 1986; Mac Low & Ferrara 1999). The mass of the outflow is related inversely to its unknown metallicity, and K11a showed that increasing the outflowing metallicity decreased the total amount of galactic mass loss required by as much as a factor of 40. Given this uncertainty, we estimate only the mass in ejected metals and not the total mass of ejected material. The uncertainty in the metallicity of the outflows does not extend to the independent estimate of the ejected metal mass.

3. RELATIONS WITH STELLAR MASS

3.1. Total Metal Output

Figure 1 shows the mass in each of several metals lost to SN winds summed over 10 Gyr. Not surprisingly, the dSphs with larger stellar masses eject more metals than the dSphs with smaller stellar masses. The $M_{\text{ejected}} - M_*$ relation is linear, which is the result expected if the dSphs lost all of their metals. The intercepts of the best-fit lines indicate that dSphs lost a constant 0.5% of their final stellar masses in the form of Fe, 0.2% as Si, 0.1% as Mg, and 0.01% as Ca.

Of course, the dSphs could not have truly lost all of their metals because the stars are not metal-free. However, the amount of metals retained (M_{retained} , the filled points in Figure 1) in stars is tiny compared to the amount of metals produced. Kirby et al. (2011b) measured the average metallicity of Fornax to be $\langle [\text{Fe}/\text{H}] \rangle = -1.0$.⁵ Given its stellar mass of $1.9 \times 10^7 M_\odot$, Fornax’s stars contain $4 \times 10^3 M_\odot$ of Fe. Even though Fornax retained the highest fraction of Fe of all eight dSphs considered here, the galaxy presently has only 4% of the Fe

⁵ We adopt the solar abundance of Fe as $12 + \log(n(\text{Fe})/n(\text{H})) = 7.52$ (Snedden et al. 1992). We adopt 7.58, 7.55, and 6.36 for Mg, Si, and Ca, respectively (Anders & Grevesse 1989).

TABLE 1
INFERRED EJECTED MASSES OVER 10 GYR

DSph	$L (L_{\odot})$	$M_{*} (M_{\odot})$	$M_{\text{Mg}} (M_{\odot})$	$M_{\text{Si}} (M_{\odot})$	$M_{\text{Ca}} (M_{\odot})$	$M_{\text{Fe}} (M_{\odot})$
Fornax	$(1.8 \pm 0.5) \times 10^7$	$(1.9 \pm 0.5) \times 10^7$	1.2×10^4	2.9×10^4	1.9×10^3	8.3×10^4
Leo I	$(5.6 \pm 1.7) \times 10^6$	$(4.6 \pm 1.4) \times 10^6$	3.7×10^3	7.9×10^3	4.9×10^2	2.1×10^4
Sculptor	$(2.3 \pm 1.1) \times 10^6$	$(1.2 \pm 0.6) \times 10^6$	9.9×10^2	2.1×10^3	1.3×10^2	5.5×10^3
Leo II	$(6.6 \pm 1.9) \times 10^5$	$(1.4 \pm 0.4) \times 10^6$	1.2×10^3	2.7×10^3	1.7×10^2	7.1×10^3
Sextans	$(4.1 \pm 1.2) \times 10^5$	$(8.5 \pm 2.4) \times 10^5$	6.6×10^2	1.5×10^3	9.2×10^1	3.8×10^3
Draco	$(2.7 \pm 0.4) \times 10^5$	$(9.1 \pm 1.4) \times 10^5$	7.0×10^2	1.6×10^3	9.7×10^1	4.0×10^3
Can. Ven. I	$(2.3 \pm 0.4) \times 10^5$	$(6.3 \pm 1.1) \times 10^5$	4.9×10^2	1.1×10^3	6.8×10^1	2.8×10^3
Ursa Minor	$(2.2 \pm 0.7) \times 10^5$	$(5.6 \pm 1.7) \times 10^5$	3.9×10^2	9.1×10^2	5.5×10^1	2.3×10^3

REFERENCES. — L (luminosity): Martin et al. (2008) for Canes Venatici I; Irwin & Hatzidimitriou (1995) otherwise. M_{*} (stellar mass): Woo et al. (2008), except that we assumed that Canes Venatici I the same M_{*}/L as Ursa Minor.

that it produced. In Ursa Minor, that fraction is only 0.2%.

The bottom panel of Figure 1 expresses metal retention in another way. The black circles show the stellar mass-iron metallicity relation for MW dSphs (Kirby et al. 2011b). The other points show the mass-metallicity relations for other elements. The smaller dSphs retain a larger fraction of α elements relative to iron than the larger dSphs. The dependence on stellar mass indicates that the larger dSphs formed stars for longer and therefore experienced a higher ratio of Type Ia to Type II SNe.

3.2. Relative Metal Output

The mass-metallicity relation indicates that the more massive dSphs retained more of their metals in stars rather than losing them to galactic winds. Therefore, the less massive dSphs contribute a larger fraction of their metal mass to the IGM or to their host galaxies. To further explore the importance of small dSphs, we convolve the ejected mass function with the stellar mass function for MW dSphs. Koposov et al. (2008) calculated the luminosity function of MW dSphs by correcting the observed Sloan Digital Sky Survey luminosity function for sky coverage and bias against low surface brightness dSphs. The result was $dN/dM_V = 10 \times 10^{0.1(M_V+5)}$. Assuming the stellar mass-to-light ratio for an old population, $M_{*}/L = 2$, the relation becomes $dN/d \log M_{*} = 284 M_{*}^{-0.25}$ where M_{*} is measured in M_{\odot} .

Figure 2 shows the product of this dSph mass function and the ejected mass function from Figure 1. Even though the small dSphs are more numerous, they are not significant contributors to IGM metals. Even if the relation for the smaller dSphs is extrapolated to zero mass, then all dSphs the size of Leo I or smaller contributed just $7.5 \times 10^4 M_{\odot}$ of Fe to the IGM over 10 Gyr. Fornax alone provided more Fe, and even more massive galaxies likely make Fornax’s contribution negligible. The same argument applies to the other metals as well.

3.3. $[\alpha/\text{Fe}]$

Averaged over a long enough time, the ratio of the numbers of Type II to Type Ia SNe asymptotes to the same value in all dSphs as long as the IMF is the same. As a result, the $[\alpha/\text{Fe}]$ ratios of ejecta from dSphs integrated over 10 Gyr are not functions of stellar mass. Expressed relative to the solar ratios, the 10 Gyr ra-

tios for our adopted SN yields and our adopted IMF are $[\text{Mg}/\text{Fe}] = -0.45$, $[\text{Si}/\text{Fe}] = -0.15$, and $[\text{Ca}/\text{Fe}] = -0.30$.

4. COMPARISON TO NGC 1569

Mayer et al. (2006) theorized that gas-rich dIrrs can be converted into gas-free dSphs by interaction with their host galaxies. Tidal stirring can turn disks into spheroids, and ram pressure stripping—in addition to supernova-driven outflow—can remove all of the gas. With this relationship between dIrrs and dSphs in mind, we compare our inferences for the metals ejected from dSphs to the observed metal content of the wind presently flowing out the post-starburst dIrr NGC 1569 ($M_{*} = 1.8 \times 10^8 M_{\odot}$, Israel 1988).

Martin et al. (2002) estimated that the most recent starburst in that galaxy ejected $M_{\text{O}} \approx 3.4 \times 10^4 M_{\odot}$ of oxygen. They based this estimate on an X-ray spectral fit to several α elements, including O and Mg. In order to compare to our own ejected metal estimates, we note that M_{O} is related to M_{Mg} by a multiplicative factor (about 15, which is also the solar ratio) because both elements are formed in similar nucleosynthetic processes in massive stars. Therefore, the starburst must have ejected $M_{\text{Mg}} \approx 2.3 \times 10^3 M_{\odot}$ of magnesium. The mass of stars formed in the burst was $M_{*} \approx 3.4 \times 10^6 M_{\odot}$ over 10–20 Myr.

NGC 1569 is more massive than any of the dSphs we consider, and the SFR in the burst was much higher than the average rates in the dSphs. Nonetheless, the outflowing magnesium mass from the recent burst in NGC 1569 agrees remarkably well with the relation between M_{Mg} and M_{*} defined by MW dSphs. Figure 1 shows that the NGC 1569 outflow falls exactly in line between Leo I and Leo II. Of course, we must keep in mind that we are considering only the very recent starburst and not the entire galaxy, which is 50 times more massive. However, only the ejecta of the current starburst is directly measurable, and the measurement is uncertain by a factor of at least 2.

Martin et al. (2002) also measured the $[\alpha/\text{Fe}]$ ratio to be 0.3–0.6 (2–4 times solar). This value is larger than what we infer for the MW dSphs. However, the winds flowing out of NGC 1569 came from a very short burst—likely short enough that Type Ia SN ejecta is not present in the winds. Therefore, the $[\alpha/\text{Fe}]$ ratios merely reflect the fact that the star formation was intense in the recent burst in NGC 1569 but not in the dSphs.

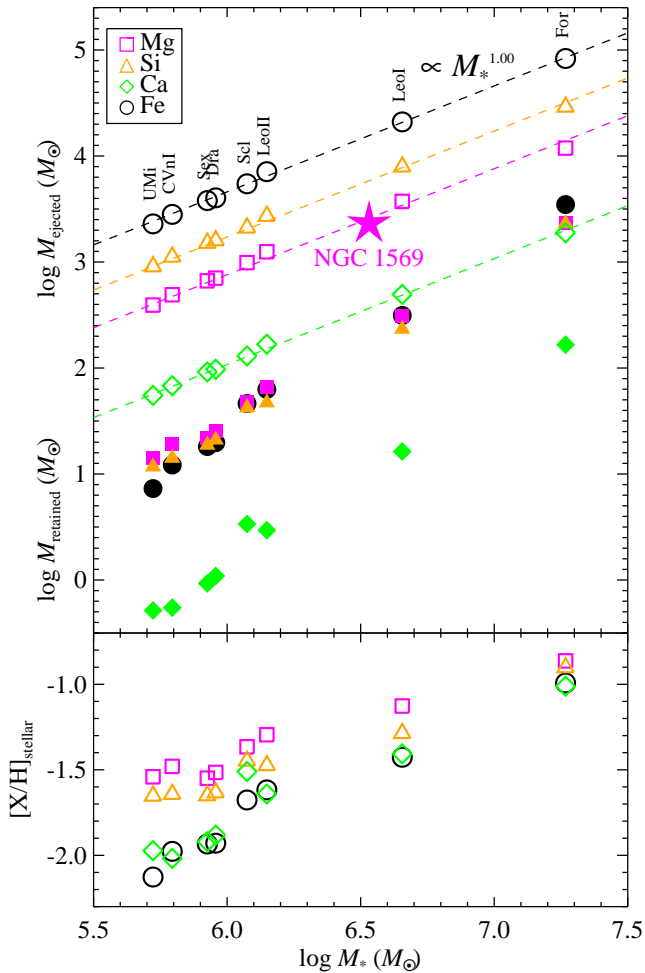


FIG. 1.— Top: The mass in four different metals inferred to have been lost from (hollow points) or retained in (filled points) MW dSphs as a function of their present stellar mass. The hollow points show the “missing metals,” which should have been produced by the SNe in these dSphs but are not present in the stars. The masses of ejected metals include the ejecta of Type Ia SNe that exploded up to 10 Gyr after the cessation of star formation. The dashed lines illustrate slopes of $M_*^{1.00}$, which is the expected relation if dSphs lost all of the metals they produced. The large star shows the Mg mass in the current outflow from NGC 1569 versus the stellar mass of the most recent starburst (Martin et al. 2002). Bottom: The stellar mass-metallicity relation for the stars in dSphs (Kirby et al. 2011b). Metallicity is given separately as [Fe/H], [Mg/H], [Si/H], and [Ca/H].

Martin et al.’s completely independent method for measuring the metal content of galactic winds has placed a different, though possibly related, type of dwarf galaxy on the same $M_{\text{ejected}}-M_*$ relation as the one defined by MW dSphs. This result has several implications. First, NGC 1569 retained almost none of the metals produced in its recent starburst, a result that Martin et al. found from their own chemical evolution model. Second, the theoretical SN yields are accurate enough to place the observed magnesium mass ejected from NGC 1569 on the same relation as the masses ejected from dSphs, which were calculated from the theoretical yields. Finally, even a galaxy as massive as NGC 1569 ($\sigma_v = 21 \text{ km s}^{-1}$, Stil & Israel 2002, compared to 10 km s^{-1} for a typical dSph) loses nearly all of the metals it produces.

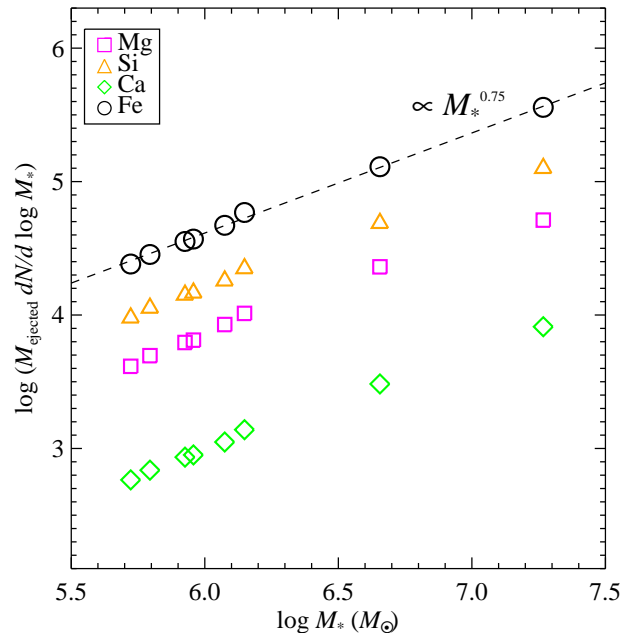


FIG. 2.— The metals ejected from dSphs convolved with the luminosity function for MW dSphs ($dN/d \log M_* \propto M_*^{-0.25}$, Koposov et al. 2008). The dashed line shows $M_*^{0.75}$. The axes are logarithmic, and the metal output from small dSphs is negligible compared to large dSphs.

5. DISCUSSION

The possibility that the majority of metals that currently reside in the IGM were originally ejected by low-mass systems (Oppenheimer & Davé 2008; Martin et al. 2010) emphasizes the need for constraints on models for galactic outflows. Galaxy evolution models (e.g., Somerville et al. 2001; Oppenheimer & Davé 2006) generally assume that star-forming galaxies drive outflows whose metallicity tracks the interstellar medium, and whose outflowing mass is proportional to M_*/σ^α . Here, σ is the velocity dispersion that scales with the halo mass ($\sigma \propto M_h^{1/3}$), and α is a scaling parameter. Setting $\alpha = 1$ yields a momentum-driven scaling, and $\alpha = 2$ yields an energy-driven scaling. Some models (e.g., Bower et al. 2006) invoke a stronger scaling ($\alpha = 3$) in order to match the faint end of the luminosity function. Let us assume that the metallicity of outflowing gas Z_W tracks the stellar metallicity Z_* , which in turn scales with stellar mass as $M_*^{0.31}$ (Kirby et al. 2011b). Let us further assume the stellar mass–halo mass scaling that is observed at low masses ($M_* \propto M_h^{2.17}$, Leauthaud et al. 2011). The mass in ejected metals is the outflow mass multiplied by the wind metallicity. Therefore, the model assumptions correspond to the assumption that $M_{\text{ejected}} \propto (M_*/\sigma^\alpha)Z_W = M_*^{1.31}/M_h^{\alpha/3} = M_*^{1.31-\alpha/6.51}$, or $M_*^{1.16}$ and $M_*^{1.00}$ for momentum-driven and energy-driven scalings, respectively. Taken at face value, our observation of the ejected mass relation, $M_{\text{ejected}} \propto M_*^{1.00}$, favors an energy-driven scaling.

We emphasize that these inferences depend strongly on the assumed stellar mass–halo mass relation as well as the metallicities within the outflows. They also neglect many physical processes, such as tidal stripping, that could preferentially affect low-mass systems. Furthermore, much of the metals from Type Ia SNe are

lost well after the cessation of star formation and well after the galaxies are devoid of interstellar gas. That makes the distinction between energy- and momentum-driven winds poorly defined. These uncertainties emphasize the need for improved observational constraints on the kinematics of low-mass systems as well as the mass-loading and metal mass fractions of outflows from low-mass galaxies.

The biggest limitation of our approach at measuring M_{ejected} is that we have measured the mass only in metals. We provide no constraints on the total outflowing mass, including hydrogen. Therefore, we also provide no constraints on the metal fraction of the outflows. One way to constrain the metallicity is to fix the total mass participating in gas flows and star formation. For instance, we could assume that the baryonic mass associated with a dSph obeys the cosmic baryon-to-dark matter ratio. Unfortunately, the disconnect between stellar and dark matter mass (Mateo 1998; Strigari et al. 2008) and the tidal interactions (Peñarrubia et al. 2008) of MW dSphs make it impossible to estimate their total, original dark matter masses.

Semi-analytic models (e.g., Cooper et al. 2010) may provide a path forward. By treating a variety of pro-

cesses that likely affected dSph growth, such as tidal stripping, pre-enriched inflows, and returning outflows, they provide a flexible but complete account of how outflows impact metallicities. A model galaxy whose chemical abundances match observed abundance distributions (Kirby et al. 2011a,b) and our inferred ejected metal masses might inform us about these processes. We encourage interested modelers to interrogate their existing semi-analytic models for unique constraints that our observations place on the way in which low-mass galaxies process their gas into outflows, stars, and evolving gas reservoirs.

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Facility: Keck:II (DEIMOS)

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