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Comparing Chemical Abundances of the Damped Lyα Systems and Metal-Poor Stars

Jason X. Prochaska

UCO/Lick Observatory, UC Santa Cruz, Santa Cruz, CA, 95064

Abstract. I briefly draw comparisons between the fields of damped Lyα and metal-poor stellar abundances. In particular, I examine their complementary age-metallicity relations and comparisons between the damped Lyα and dwarf galaxy abundance patterns. Regarding the latter, I describe a series of problems concerning associating high z damped Lyα systems with present-day dwarfs.

1. Introduction

I wish to first acknowledge the wisdom of the organizers for bringing the damped Lyα and metal-poor stellar abundance communities together in a Joint Discussion aimed at heightening communication and collaboration between the two fields. While previous conferences on chemical abundances have included members of each group, talks were generally organized such that we have talked to one another instead of with one another. From the perspective of a DLA researcher, the preceding 50 years of stellar abundance research is invaluable for drawing interpretations on nucleosynthesis from DLA observations. I suspect that as DLA abundance studies become a mature field, the stellar community will similarly gain from observations of these young, metal-poor galaxies.

The organizers charged me with reviewing the fields to open the JD. In Sydney, I briefly compared the observations, techniques of analysis, and major systematic uncertainties in each field. I then described a few areas of research where the fields clearly intersect and where a joint analysis impacts on theories of chemical evolution, nucleosynthesis, and galaxy formation. In this proceeding I present an even more brief summary.

2. Observations and Analysis

Presently, the data for damped Lyα and metal-poor stellar abundance research is acquired with the same telescopes on the same instruments and with comparable spectral resolution. Ionic transitions are analyzed in a similar fashion: integrated equivalent widths or column densities are derived from isolated, 'clean' lines while spectral synthesis or line-profile fitting techniques are applied to blended and crowded regions. The derivation of elemental abundances from the ionic measurements, however, follows different paths. For stellar abundances, one introduces a stellar atmosphere derived from the spectroscopic and/or photometric observations of the star. The atmosphere is typically parameterized by three parameters – temperature, gravity, and microturbulence – and one solves the radiative transfer equations to predict equivalent widths and/or spectral profiles. The uncertainties attributed to this modeling (e.g. non-LTE corrections; see M. Asplund's contribution) generally dominate the statistical errors associated with the observations.

With the DLA systems, one must consider ionization corrections to convert the measured ionic column densities into elemental abundances. In practice, the corrections are generally assumed to be small. This assumption is supported by theory and observation, although with exception (see Vladilo et al. 2001; Prochaska et al. 2002). The most important systematic error in the DLA analysis is dust depletion; the DLA observations provide gas-phase abundances which may significantly underestimate the true abundances of refractory elements like Fe, Cr, and Ni which deplete from the gas-phase onto dust grains (e.g. Jenkins 1987). This effect dominates the uncertainty of DLA abundance studies and plays a central role in nearly all interpretations drawn from the observations.

3. Age-Metallicity Relation (AMR)

One research area where the two fields nicely complement each other is in describing an age-metallicity relation (AMR). Stellar research has focused primarily on Galactic disk stars and therefore probes the chemical enrichment history of a single galaxy over the past $\approx$ 10 Gyr. Because of the uncertainties of isochrone fitting, it is difficult to determine absolute ages with meaningful precision for ages $>$ 10 Gyr. In contrast, the DLA observations reveal the AMR of the population of high z galaxies which dominate the H I content of the universe. Therefore, the DLA trace the 'cosmic' mean metallicity in neutral gas (e.g. Prochaska et al. 2003). The ages of the DLA systems are precisely calculated by combining their cosmological redshift with the 'concordance cosmology' (e.g. Spergel et al. 2003). The challenge with DLA studies is pursuing the AMR to $z < 1.7$ because space-bourne UV observations are required to observe the Lyα profile. Therefore, the DLA and stellar abundance measurements complement one another both temporally (spanning nearly the entire history of the universe) and spatially (examining a single galaxy to a population of galaxies).

For very different reasons, the AMR's measured from Galactic stars and the DLA systems have had controversial histories. Indeed, my own studies have contributed to the controversy surrounding the AMR derived for the DLA systems (see also Kulkarni, 2003). In this case, the analysis has been limited by uncertainty relating to small sample size; even with 50 DLA systems there was no statistically significant evolution in the cosmic metallicity. Similarly, the AMR of the Galactic disk remains a point of great debate with competing groups arguing for and against any trend of metallicity with age (Edvardsson et al. 1993; Rocha-Pinto et al. 2000; Feltzing, Holmberg, & Hurley 2001; Ibukiyama & Arimoto 2002). It remains unclear to me whether the debate revolves around sample bias or age determinations.

These uncertainties aside, it is illustrative to compare AMR's taken from the two fields of research. In Figure 1, I present a census of DLA age-metallicity observations overplotted with one estimate of the Galactic AMR (Rocha-Pinto et al. 2000) and rough estimates for the age and metallicity of the Galactic bulge, thick disk, and halo stellar components. Clearly, the DLA systems at

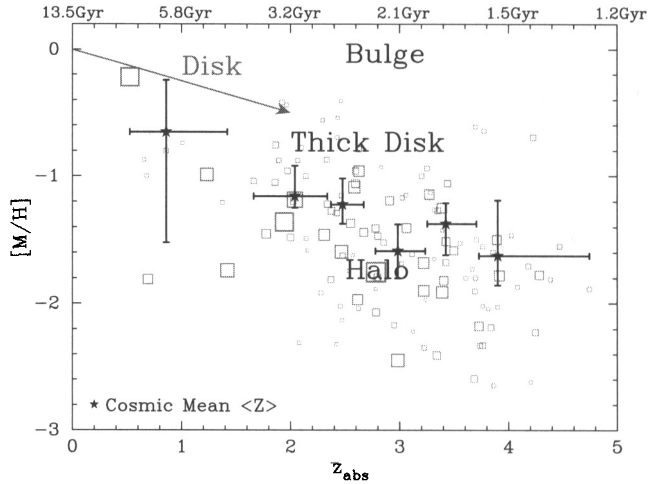

Figure 1. Age-metallicity relations for the DLA systems (summarized by the individual and binned data points) and the Galactic disk (solid arrow). The rough locations for the Galactic thick disk, halo, and bulge are also shown in the figure.

$z > 2$ are distinct in both metallicity and age from the Galactic disk AMR. As first noted by Pettini et al. (1997), the majority of DLA metallicities lie between the peaks of the distributions for the thick disk and halo populations. This indicates the majority of gas associated with the DLA systems at $z > 2$ may feed the formation of the thick disk and halo populations but has insufficient metallicity at these epochs to produce the majority of disk stars.

As the AMR's are refined and extended to include additional stellar populations and local galaxies as well DLA systems at $z < 1$, one will gain further insight into the nature of the DLA systems and their connection to modern galaxies. Future surveys will reveal whether a sample of metal-rich DLA exist at $z \sim 1.5$ which can be identified as the gas reservoirs of spiral disk formation. The identification of this gas is an important aspect of tracing the history of disk formation. In addition, age-metallicity measurements for high z galaxies (e.g. LBG, ERO's) will allow comparisons with the DLA and stellar populations, illuminating the processes of galaxy enrichment during the early universe.

4. DLA systems, Dwarf Galaxies, and the Galactic Halo

One of the most exciting aspects of connecting the fields of DLA and stellar abundance research is to draw comparisons between abundance patterns of local stellar populations and those observed in the early universe. Indeed, this was the focus of several talks and posters of this JD (e.g. Tolstoy, Bonifacio, Dessauges-Zavadsky). A principal challenge to drawing such comparisons is uncertainty in the DLA abundance patterns related to differential depletion. This point is well illustrated by Figure 2 where I present gas-phase Si/Fe ratios against metallicity for a sample of 56 DLA systems with echelle observations. As noted by Prochaska & Wolfe (2002), the metal-poor DLA systems exhibit

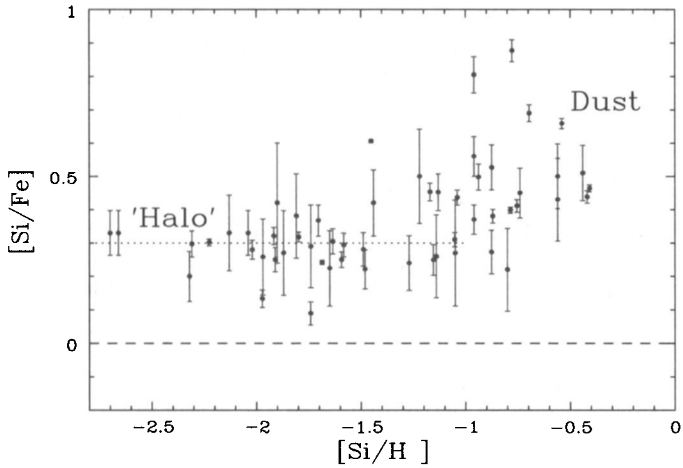

Figure 2. Gas-phase Si/Fe measurements for 56 DLA systems observed with echelle spectroscopy. At low metallicity, the Si/Fe values exhibit a 'plateau' at [Si/Fe] $\approx +0.3$ dex which matches the nominal value for the Galactic halo (dashed line; McWilliam et al. 1995). At higher metallicity, however, the Si/Fe values increase because of the effects of differential depletion (Fe is more readily depleted from the gas-phase onto dust grains).

[Si/Fe] values comparable to the Galactic halo with remarkably small scatter (particularly given that each data point represents a unique galaxy with its own specific chemical enrichment history). This Si/Fe plateau suggests the metal-poor DLA systems have been predominantly enriched by Type II supernovae, perhaps in the same manner as the Galactic halo. At higher metallicity, however, the Si/Fe ratios *increase*, in contradiction with any empirical or theoretical trends of chemical evolution. The rise in Si/Fe is explained by differential depletion; higher metallicity DLA systems have significant dust-to-gas ratios and a substantial fraction of their Fe is locked into dust grains. If one explains the rising Si/Fe ratios in terms of differential depletion, it raises the possibility that the enhancement of Si/Fe at all metallicity is dominated by differential depletion. Presumably, this interpretation would require an uncomfortable degree of fine-tuning to reproduce a [Si/Fe] plateau at [Si/H] < -1 which matches the nucleosynthetic enhancement of Si/Fe observed for the Galactic halo, yet more peculiar coincidences exist.

Presently, the majority of both communities favor imposing significant depletion corrections to the observed DLA abundances (e.g. Vladilo 2002). To estimate the corrections, one must assume the intrinsic value for the relative abundance of a refractory and non-refractory element and also assume a differential depletion pattern. Standard practice is to adopt an empirical depletion pattern based on ISM observations (e.g. Savage & Sembach 1996) and to assume [Zn/Fe] ≈ 0 intrinsically (i.e. attribute any departures from solar as depletion). Under this assumption, one finds that the majority of the DLA systems show nearly solar relative abundances at nearly all metallicity and redshift where Zn is observed. This leads to the conclusion that the relative abundances of the metal-poor DLA do not match Galactic metal-poor stars, specifically the enhanced α/Fe ratios observed for these stars (note the contradiction with my interpretation of Figure 2). Instead, these researches argue the DLA abundance patterns more closely resemble recent results for dSph and dIrr galaxies (e.g. Shetrone et al. 2001; Venn et al. 2003; Tolstoy et al. 2003).

At first glance, the correspondence between the DLA systems and dwarf galaxies is a comforting picture. In hierarchical cosmology, galaxies at $z \sim 2$ are actively merging to build-up our present-day galaxies. The DLA systems are identified with 'protogalactic clumps' within dark matter halos (Haehnelt et al. 1998; Maller et al. 2001) whose masses might be comparable to modern dSph and dIrr galaxies. For the following reasons, however, I contend that connecting the DLA systems to modern dwarf galaxies is premature and potentially in great conflict with hierarchical cosmology. Consider:

• In hierarchical cosmology, the majority of DLA systems will not evolve into present-day dwarf galaxies.

In order to explain the kinematic characteristics observed for the DLA systems (Prochaska & Wolfe 1997) within the paradigm of hierarchical cosmology, the 'protogalactic clumps' identified as DLA systems must arise predominantly in galaxies with $v_c > 125$ km/s (e.g. Maller et al. 2001). Furthermore, these clumps are actively merging with one another to build up the central galaxy of the dark matter halo. In this scenario, only a small fraction of the DLA population (presumably the low mass tail) could serve as the progenitors of present-day dwarfs; the majority will be merged into larger galaxies by $z \sim 1$. Therefore, any correspondence between the abundance patterns of the $z \sim 2$ DLA systems and present-day dwarfs may have to be considered a coincidence.

• Where is the gas enriched by Type II SN?

An important challenge raised by observers studying the elemental abundances of dSph in the Local Group is that these stars exhibit abundances which are very different from those measured for the Galactic halo (specifically, the Galactic halo within a few kpc of the Sun). This apparently contradicts the favored scenario for the formation of the Galactic halo in hierarchical cosmology, i.e., it formed from the accretion of dwarf satellites during the first few Gyr of the universe. One possible (and fashionable) resolution of this problem is that the dwarf galaxies which exist today (i.e. those which have not yet merged with the Milky Way) have had different chemical enrichment histories from those which merged to form the Galactic halo. As noted above, however, in CDM cosmology it is the DLA systems which correspond to the merging dwarfs. This identification leads to a more significant conflict regarding the origin of Galactic metal-poor stars. If we interpret the DLA abundance patterns as matching present-day dwarf galaxies, one is left with the problem: "Where is the gas enriched by Type II SN in the early universe which fueled the formation of the metal-poor stars of the Milky Way?"

• Ages, SFR, Zn, etc.

There are a number of other issues which may contradict or at least complicate the dwarf/DLA connection: (1) the ages of the DLA galaxies are too young to be consistent with the slow, steady SFH generally associated with dIrr galaxies; (2) SFR's derived for the DLA systems from the C II* absorption are typical of those expected for spiral disk galaxies (Wolfe, this proceedings); (3)

the DLA galaxies are gas-rich whereas the dSph galaxies are gas-poor. To link the two populations, one may require that the duty cycle for star formation in the dSph galaxies was significantly longer than the starburst behavior suggested by their stellar populations; and (4) the reported agreement between DLA and dwarf abundance patterns hinges on the assumption that [Zn/Fe]=0 intrinsically. If [Zn/Fe] is even +0.2 dex, then the DLA observations would be in good agreement with the Galactic halo abundance patterns. I note that several new issues related to the [Zn/Fe]=0 presumption were raised at the JD by Nissen, Asplund, and Israelian.

These issues aside, comparisons of the DLA and metal-poor stellar abundance patterns offer a powerful and insightful means of studying nucleosynthesis and galaxy formation. I am confident that ongoing studies of stellar populations in the Milky Way and Local Group as well as more comprehensive analysis of the DLA systems (e.g. Prochaska, Howk, & Wolfe 2003; Dessauges-Zavadsky et al., 2003) will lead to new puzzles and discoveries over the next years.

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