Abundances of Iron-Group Elements in Planetary Nebulae and Consequences for Chemical Enrichment

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Abstract. We have developed a method for determining elemental Fe-group abundances in planetary nebulae using an infrared emission line of Zn, the least refractory Fe-group species. Many planetary nebulae, particularly those of the Milky Way's thick disk and bulge, display subsolar [Fe/H] (as inferred from Zn) although their abundances of α elements such as O, S, and Ar are nearly solar. We discuss the implications for determining enhancements of species synthesized by the progenitor star during the AGB (e.g., s-process products), and for galactic chemical evolution in view of the metallicity dependence of AGB nucleosynthetic yields.

Keywords. planetary nebulae: general, stars: AGB and post-AGB, nuclear reactions, nucleosynthesis, abundances

1. Introduction

The primary index of metallicity in stars has historically been the Fe abundance expressed as [Fe/H], the base 10 logarithmic difference between Fe/H in the star and the Sun. Recent spectroscopic surveys include more elements but continue to use Fe as a reference for normalizing the abundances of other elements X; the values of [X/Fe] specify abundance patterns in 'chemical tagging' (e.g., Freeman & Bland-Hawthorn 2002).

Meanwhile, the element that is most accurately and easily measured in ionized nebulae is O. If O and Fe always varied together during galactic chemical evolution things would be simple, but this is not the case since they have different primary sites of origin. It has long been recognized that enrichment of α species such as O, Ne, S, and Ar proceeds rapidly after a stellar generation forms, since the massive-star supernovae that disperse them occur promptly, while the enrichment of Fe-group elements by Type Ia supernovae is necessarily time-delayed since it requires the pre-existence of white dwarfs (Tinsley 1979). Indeed, [α/Fe] ratios are widely used to set constraints on star formation histories of stellar ensembles, with high values indicating 'bursty' pasts and low ones reflecting a more continuous, quiescent history of star formation.

Multiwavelength spectroscopic observations of planetary nebulae (PNe), especially in the UV and infrared, have recently expanded the palette of elements for which abundances can be determined. They include species affected by nuclear processing in the progenitor star as well as elements that retain their initial abundances and thus provide information on the star's parent population. For example, advances in measuring self-enrichments

of trans-iron nuclei synthesized by slow neutron-capture reactions (the '*s*-process') have been largely propelled by infrared spectroscopy, which has enabled determinations of abundances for several elements with atomic numbers in the 30s and above: Ge, Se, Kr, Rb, & Cd (Dinerstein 2001, Sterling & Dinerstein 2008, Sterling et al. 2015, Sterling et al. 2016; also see the review by Sterling, this volume).

A crucial missing ingredient in our picture of the composition of PNe has been the abundance of Fe. This is not due to a lack of spectral features from multiple Fe ions. In fact, Fe^{++} alone is observable from the far-UV (in absorption, e.g., Sterling et al. 2005) to the infrared (e.g., Likkel et al. 2006), as well as in optical emission lines. However, these trace only the gas phase component, whereas most Fe atoms are in the dust (Delgado-Inglada & Rodríguez 2014). To be an effective proxy for Fe, a non-depleted species is required. Unfortunately, most of the other members of the Fe-group of elements are also highly refractory, Zn being the only exception (e.g., Welty et al. 1999). Consequently, the discovery of an infrared emission line of its dominant ion, Zn^{+3}, was immediately recognized by Dinerstein & Geballe (2001) as having unique potential for determining the first truly elemental abundances for the Fe group in PNe.

2. Results: Fe Abundances from Zn

At 3.625 μm, the [Zn IV] line lies in the thermal infrared, where ground-based measurements are challenging. Our first targeted observations of [Zn IV], made at Gemini South, included one PN each in the Large Magellanic Cloud (SMP LMC 62) and Sgr dSph (Hen 2-436) as well as a few Milky Way PNe to serve as control objects (Wood et al. 2007, Dinerstein et al. 2007). As additional Galactic disk PNe were observed with UKIRT and IRTF over the next few years, it quickly became apparent that a substantial fraction of them showed Zn deficiencies, with a typical value of [Zn/H] ≈ -0.6. Most of these are Type III objects in the classification system of Peimbert (1978), which are distinguished by having high radial velocities and belong to the population now called the thick disk. Type II PNe, which have radial velocities consistent with the thin disk population, show a range of [Zn/H] values but are more concentrated towards the solar abundance. Our sorting of PNe into these two categories is imperfect since there is limited information on their space motions. At present only the radial velocities are known, hence some thick disk PNe may be misclassified as thin disk objects due to unfavorable directions of motion (this situation should be partly remedied by GAIA). More recently, Zn measurements were acquired for several PNe in the Galactic bulge (Smith 2014, Smith et al. 2014), which display a wide range of [Zn/H] values.

A second major finding is that most PNe with low [Zn/H], hence by inference [Fe/H], have elevated [α/Zn]. This is particularly true for O, although other α species, for example Ar, are also enhanced albeit to a lesser degree. As described above, elevated [α/Fe] values are characteristic of some stellar populations in the Milky Way and are a natural consequence of rapid modes of star formation. This creates ambiguity for studies of PNe in which the only observed elements with abundances unchanged from their original values are α species. To be specific, the α abundances of an Fe-deficient PN with enhanced [α/Fe] may be the same as those of an object of solar composition. Unless [α/Fe] is known, abundances of the α elements alone may be unreliable or even misleading indicators of metallicity (Dinerstein et al. 2011, Dinerstein et al. 2014, Dinerstein et al. 2015).

Figure 1 presents a comparison of our results for PNe with abundances for stars of the same Galactic populations, in the [O/Fe] vs [Fe/H] diagnostic plane (right and top axis labels). We use Zn as a proxy for Fe in the PNe (left and bottom axes). The stellar data are from Bensby et al. (2014, and earlier works referenced therein). Their O abundances were
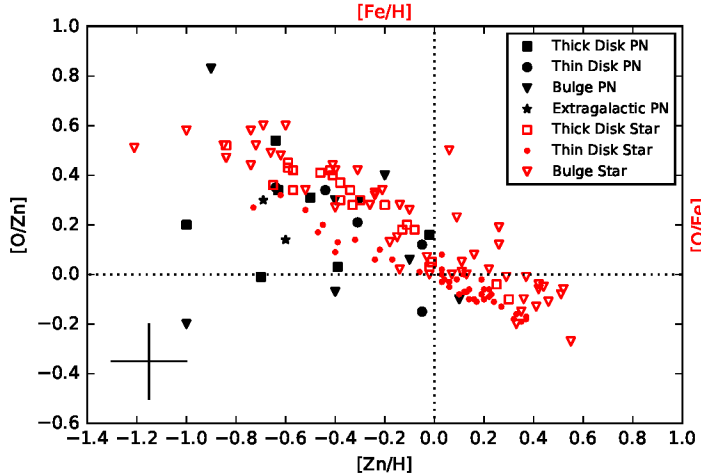
Figure 1. Abundance ratios [O/Zn] vs. [Zn/H] for the observed PNe (filled symbols, larger dots) overplotted on [O/Fe] vs. [Fe/H] for stars of several Milky Way populations (open symbols, small dots). Most PNe follow the same trend as the stellar data, which are from Bensby et al. (2014, and references therein). The asterisks are SMP LMC 62 and Hen 2-436.

derived using the most reliable method, based on forbidden [O I] lines, and the bulge values are for gravitationally-lensed dwarf stars. It can be seen that the PNe occupy similar regions of the diagram as the corresponding stars, although there are fairly large uncertainties for individual nebulae. While this diagram seems to indicate that a larger fraction of PNe than stars have solar [O/Fe] at low [Fe/H], low [α/Fe] disk stars do exist although they are not represented in this particular plot. The general agreement between the PNe and the (unevolved) stars argues that the enhancements in [O/Zn] are primarily a population effect rather than due to self-enrichment in O, which can occur at low metallicities (Karakas & Lattanzio 2014).

3. Conclusions and Consequences

We have demonstrated the utility of an infrared line of Zn as a tracer of the abundances of Fe-group elements in gaseous media. Zn is lightly depleted out of the gas phase, in contrast to all other Fe-group species, especially in warm and ionized ISM phases (by ≈ -0.1 to -0.2 dex, Welty et al. 1999). Any small residual depletions of Zn are likely to be offset by other minor systematic effects (to be discussed more fully in Dinerstein et al., in preparation). At present, and likely permanently, Zn offers the best available opportunity for determining initial [Fe/H] values for PN progenitor stars.

Many PNe are found to be moderately subsolar in [Zn/H], and since Zn is a surrogate for Fe, this means they are [Fe/H]-deficient. As is the case for many metal-poor stars, this Fe deficiency is often accompanied by elevated values of [O/Fe] and other [α/Fe] ratios. As a result, the fact that a PN is descended from an Fe-poor star may be masked by an α enhancement, leading to incorrect inferences about the properties of the progenitor star. The larger scatter exhibited by PNe (compared to stars) in the [O/(Fe,Zn)] vs. [(Fe,Zn)/H] diagram is probably mainly due to measurement uncertainties, but the general consistency between stars and PNe of the same stellar population is clear.

Knowing the initial [Fe/H] of a PN is critical for obtaining an accurate assessment of the nucleosynthesis that occurred within the star during its overall lifetime, especially

during the AGB phase, when some of the most dramatic alterations in composition occur (Karakas & Lattanzio 2014). In order to derive quantitative enrichments for an element, for example an s-process product, we must adopt an initial abundance. This is usually assumed to be the solar value, but that is unlikely to hold for metal-poor stars. Sterling et al. (2015) attempted to take this into consideration in interpreting Se enrichments in thick vs. thin disk stars, but were limited to a statistically-based assessment. To address this for individual PNe would require measurements of many additional Zn abundances.

The above consideration affects the empirically-based yields for elements made within the star. Fe abundances are particularly relevant when making comparisons of observations and theory for neutron-capture species because Fe is the main seed that initiates the neutron-capture reactions. Consequently, the amounts of trans-iron elements and ratios among different nuclides synthesized in AGB stars are sensitive to the star's initial [Fe/H] (Karakas & Lattanzio 2014). Fixing the value of [Fe/H] enables other properties, such as initial stellar mass and the efficiency of s-processing, convective mixing, and dredge-up, to be constrained by observational results. Furthermore, accurate yields of nucleosynthetic products per star must be known in order to calculate the cumulative contributions of stars of the mass range that gives rise to PNe to the ISM of galaxies, which are essential inputs for models of galactic chemical evolution.

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