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Light Neutron-Capture Elements in Planetary Nebulae

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Abstract

Intermediate-mass stars synthesize many trans-iron nuclei during the Asymptotic Giant Branch (AGB) phase, via slow neutron capture reactions during the evolutionary stage marked by periodic He-shell burning episodes called "thermal pulses." When the stellar envelope is expelled and ionized, comprising an observable planetary nebula (PN), it retains the compositional imprint of the thermal pulses and subsequent convective dredge-up processes. I present results from ultraviolet, optical, and infrared spectroscopy of PNe that demonstrate the presence of enhanced abundances of several of the lightest n-capture elements, created by the first few n-captures on the seed nuclei, in particular, Ge (Z = 32), Se (Z = 34), and Kr (Z = 36). In contrast, Zn (Z = 30) is not found to be enriched. These results constrain models of this poorly understood phase of stellar evolution, and clarify the role of PN-producing stars in the chemical enrichment of the Galaxy.

1.1 Introduction: s-process Products in Planetary Nebulae

One of the major sites of slow neutron-capture nucleosynthesis in the universe is the interiors of moderate-mass stars during the late red giant stages of their life cycles. During the double-shell burning or "thermally-pulsing" Asymptotic Giant Branch (TP-AGB) stage, runaway episodes of vigorous triple-α burning in a thin shell in the stellar interior alternate with interpulse periods when convective zones, activated by the deposition of energy generated by the fusion reactions, dip down into layers rich in freshly synthesized nuclei and carry them to the surface. This so-called "third dredge-up" phase actually consists of multiple events which incrementally build up the concentrations of nucleosynthetic products in the upper and surface layers of the star (e.g. Arlandini et al. 1999; Lugaro et al. 2003). Subsequent mass outflows, which include both stellar winds and the eventual expulsion of the bulk of the envelope during the creation of a planetary nebula (PN), convey this enriched material into the ISM (Busso, Gallino, & Wasserburg 1999).

Uncertainties remain regarding some of the details, including some important nuclear reaction rates, and what factors control the amount of the intermediate product ^{13}C synthesized; this is crucial because it provides the neutron source for the "main" s-process, which is believed to be driven by the reaction $^{13}C(\alpha, n)^{16}O$ (e.g. Käppeler, Beer, & Wisshak 1989). However, there is no doubt that this process does operate, since the results – in the form of dramatically enhanced surface abundances of many s-process products – are widely observed in various classes of C-rich AGB stars (e.g. Smith 1997; Busso et al. 2001).

Since PNe are constituted of material which was previously at or near the surface of the precursor star, they should bear the imprint of all nucleosynthetic reactions, dredge-ups, and dilutions that occurred while on the AGB. Furthermore, since they represent the end-point of the TP-AGB phase, in principle PNe can tell us how many shell flashes occurred up to the point when a particular star left the AGB, as well as defining the "yields" of specific nuclei in this last, most concentrated injection of stellar nuclear products into the ISM.

Such considerations led Péquignot & Baluteau (1994; hereafter PB94) to search for emission lines of *n*-capture elements in a long-exposure optical spectrum of NGC 7027. They reported possible detections of up to a dozen heavy elements ranging from Se (Z = 34) to Ba (Z = 56) to Pb (Z = 82), with varying degrees of confidence in the line identifications. Since collision strengths were not available for the observed lines, ionic abundances could be estimated only approximately; abundances $\sim$ 20–50 $\times$ solar system values were found for several elements, including some (e.g. Xe) that are dominated by *r*-process isotopes. The fact that the latter species are unlikely to be self-enriched in PNe raises the concern that some of the lines might not be correctly identified. PB94 point out that, because the spectral resolution of their data was only R$\sim$10,000, many of the reported features have alternate possible identifications as lines of more abundant species (e.g. He, C, N, etc.). The possibility of confusion is aggravated by the fact that the energy levels (and line wavelengths) are not known to high precision for many heavy ions. An additional effect is that excitation cross-sections tend to increase with increasing atomic number (Schöning & Butler 1998), which could lower the enrichment factors derived by PB94 by up to an order of magnitude.

1.2 Infrared Spectroscopy of *n*-Capture Elements

1.2.1 Identification of the K-band Lines of Kr and Se

Péquignot & Baluteau's pioneering paper only considered lines within the spectral range of their data, approximately 4000 Å $\leq \lambda \leq$ 1.1 μm. Hence, most of the transitions they considered connect ground and excited terms of ground configurations – e.g. ^{3}P–^{1}D for $n\ p^2$ or $n\ p^4$ ions. These configurations also give rise to transitions among fine-structure levels of the ground term, e.g. $^3P_1$–$^3P_0$, etc. Some such fine-structure transitions which fell within their spectral range were considered by PB94 (see their Tables 8 and 14). Others, however, lie in the infrared. These include the lowest-lying, hence most populated, excited levels, and are generally likely to be the strongest emission lines from their respective ions.

For over a quarter century, two conspicuous *K*-band emission lines in PNe, at 2.199 and 2.287 μm respectively, remained unidentified. These lines were discovered during the early detections of near-infrared quadrupole lines of H_2 in PNe (Treffers et al. 1976; Smith, Larson, & Fink 1981). Due to their fortuitous near-coincidences with transitions of vibrationally-excited H_2 – 2.199 μm with H_2 v = 3–2 $S(3)$, and 2.287 μm with the H_2 v = 3–2 $S(2)$ line – they were often confused with H_2, but Geballe, Burton, & Isaacman (1991) recognized that they were distinct from H_2 and probably arose from an ionized species.

In Dinerstein (2001; hereafter D01), I identified the 2.199 μm line as the lowest fine-structure transition ($^2P_1$–$^2P_2$) of [Kr III], for which PB94 had reported detecting the $^1D_2$–$^2P_2$ line at 6828 Å (see Fig. 1.1). Since Schöning (1997), prompted by PB94's reported detections of these lines, had calculated the relevant collision strengths, D01 was able to estimate the ionic ratio $n(Kr^{++})/n(H+)$ and show that the elemental abundance ratio n(Kr)/n(H) was several times solar. Krypton, atomic number 36, was considered by PB94 to be one of their

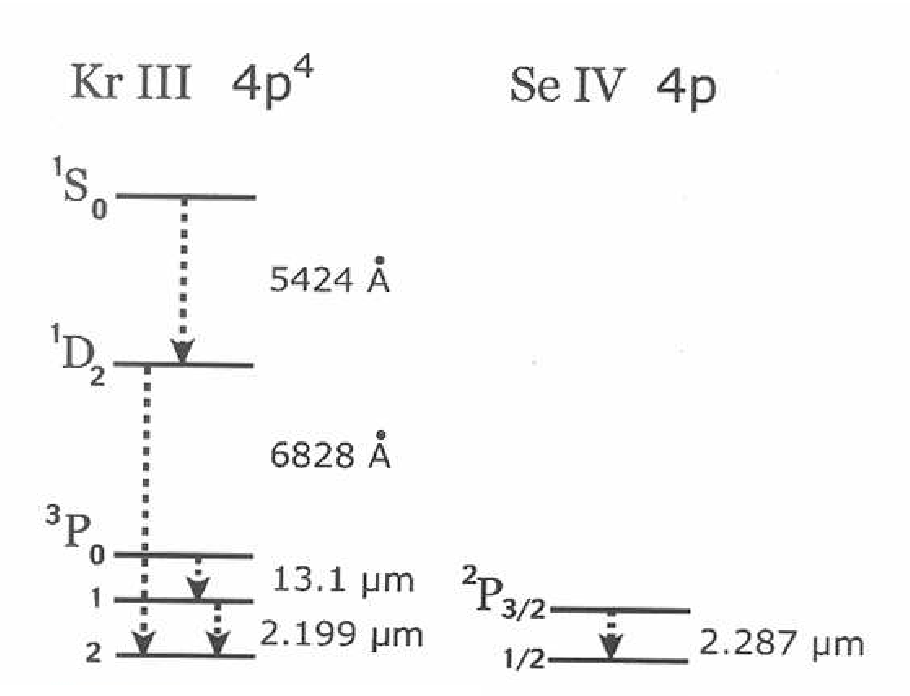

Fig. 1.1. Energy level diagrams of Kr III and Se IV, from Dinerstein (2001).

best examples of a detected *n*-capture element. From there, it was natural to associate the 2.287 μm line with a similar species: I quickly found a good match of the line wavelength with [Se IV] $^2P_{3/2}$–$^2P_{1/2}$ (D01). The latter ion has a 2-level (4*p*) ground configuration, so there are no other ground-state lines. Unfortunately, there is no published collision strength for [Se IV], so a direct determination of the abundance cannot be performed at present.

1.2.2 General Considerations for Observable Infrared Lines

The relative ease with which these fine-structure lines of light *n*-capture elements were detected (2.287 μm can be up to 8-10% the strength of Br γ) led me to investigate the possibility that other unrecognized or undetected fine-structure lines of trans-iron elements might be observabe in the infrared. Such lines are complementary in several ways to the more frequently observed optical lines, offering access to ions with no optical/UV transitions, enabling studies of regions with large extinctions, and revealing the presence of cool and/or neutral material (see review of Dinerstein 1995).

Optical spectroscopic studies of ionized nebulae focus mainly on the interpretation of collisionally excited lines from ions with p^2, p^3, or p^4 ground configurations. For example, intensity ratios of lines arising from different upper terms of p^2 or p^4 configurations (i.e. ^{1}S–^{1}D/^{1}D–^{3}P) are good indicators of electron temperature T_e, due to the strong (and differential) exponential dependences of the level populations. The most widely used index of this kind is 2p^2 [O III] 4363/(4959, 5007) Å. The p^3 configurations have no low-lying excited levels, and therefore generally do not produce observable transitions between fine-structure levels

Table 1.1. *Utility of Various Configurations.*

Configuration	Optical View	Infrared View
$p^{1,5}$	unobservable	favorable
$p^{2,4}$	T_e indicator	sensitive to n_e
p^3	n_e indicator	not useful

of a single term. On the other hand, p^3 ions often provide useful density (n_e) indicators, for example $^2D_{5/2,3/2}$–$^4S_{3/2}$ transitions such as [O II] 3726/3729 Å or [S II] 6716/6731 Å. Configurations with only two fine-structure levels, mostly familiarly $n\ p$ and $n\ p^5$, but also (for heavier ions) $n\ d$ and $n\ d^9$, are optimal for infrared spectroscopy. In this case, all of the ions are in one of the two levels, maximizing the strength of the single infrared transition and eliminating the need to correct for populations in other levels. Table 1.1. summarizes the pros and cons of various ground-state configurations.

There are four general criteria to be taken into account when considering which infrared lines are most likely to be observable:

(1) Sufficiently high abundance of the originating element.

- A solar system abundance (which can be considered a "baseline" value) of $\geq$ 2.5–3.0 on the scale of [X/H] = $log\ [n(X)/n(H)] + 12$.
- One or more isotopes produced copiously by the *s*-process.
- Not heavily depleted into dust in the ISM.

(2) A favorable ionization range, such that it is a major or dominant ionic stage in PNe.

- The "bounding" ionization potentials should lie in the range 13.6 eV – 75 eV; preferably between $\sim$ 25–40 eV.
- This constraint favors X^{++} (X III) and especially X^{+3} (X IV) ions.

(3) A favorable energy level structure in the ground configuration (those with a small number of low-lying energy levels favor fewer, stronger lines).

- "Two-level" ions are best; e.g. $3d^9$, $4p$, $4p^5$, $4d$, etc.
- Ions with a ground-term triplet (^{3}P) are next best; e.g. $4p^2$, $4p^4$.
- For ions with a larger number of levels, e.g. $d^{5,6,7}$, higher element abundances can compensate for a less favorable energy structure; e.g., [Fe II], [Ni II].

(4) Lines with convenient wavelengths.

- Ideally, accessible from ground-based telescopes; next best, from airborne platforms such as *SOFIA*.
- Minimal crowding or confusion with spectral features of other, more abundant, species (e.g. ions, also abundant molecules such as H_2).

By applying these criteria to the elements in atomic number range $26 \leq Z \leq 40$, I was able to identify infrared fine-structure lines that were likely to be strong in PNe. These elements have solar system abundances which are relatively high for trans-iron elements (Grevesse & Sauval 1998), and cover the first few *n*-captures in the nucleosynthesis chain (Käppeler, Beer, & Wisshak 1989), extending from the iron peak to the "light" *s*-process peak. The

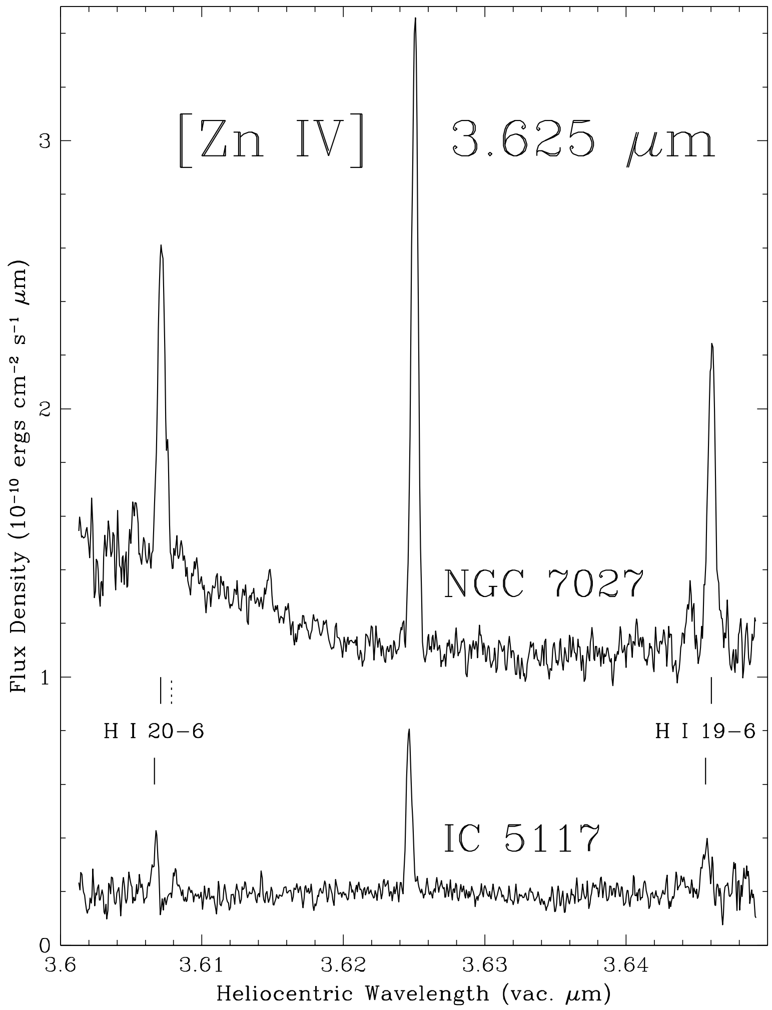

Fig. 1.2. The [Zn IV] line and adjacent H I transitions (Dinerstein & Geballe 2001).

latter is represented primarily by Sr (Z = 38) and Zr (40) in studies of AGB stars, although recent work has also targeted the odd-numbered elements Rb (37) and Y (39) (e.g. Lambert et al. 1995; Abia et al. 2001). Some of the "light-*s*" elements, in particular Se and Kr, are not observable in stars; even their solar system values are derived from meteoritic samples rather than from the solar photosphere (Grevesse & Sauval 1998).

The "best bets" for infrared lines are transitions from even-numbered elements with two or three low-lying energy levels, most of which fall in the wavelength range, $\sim$ 1-12 μm; generally, elements with higher nuclear charge lie at at shorter wavelengths. Some of these had already been detected, for example [Ni II] $^2D_{3/2}$–$^2D_{5/2}$ 6.64 μm, discovered in NGC 7027 from the Kuiper Airborne Observatory by Bregman et al. (1983), and [Se IV] $^2P_{3/2}$–$^2P_{1/2}$ 2.287 μm. The next step was to search for lines which had not yet been reported.

1.2.3 Prediction and Confirmation of [Zn IV] 3.625 μm

One of the most favorable candidate lines was the analog to [Ni II] 6.64 μm for a nearby heavier even-numbered element: [Zn IV] $^2D_{3/2}$–$^2D_{5/2}$. Firstly, Zn^{+3} should be a major ion in high-excitation PNe, since the ionization potential (*IP*) to create it is 39.7 eV, while it is destroyed (ionized) at 59.4 eV. Secondly, Zn is $\sim$ 20 $\times$ more abundant than Se and Kr in the solar system. Finally, Zn is relatively undepleted into dust in the ISM (Savage & Sembach 1996). Although some Zn is synthesized in the *s*-process (Arlandini et al. 1999; Goriely & Mowlavi 2000), most of the solar system Zn is thought to come from massive stars: from iron-peak element production in supernovae, with a contribution from the *r*-process (Burris et al. 2000; Truran et al. 2003). Any additional contribution of Zn from the *s*-process, while large compared to other *s*-process nuclides, will lead to at most a modest increase in the *total* element abundance, and therefore be less noticeable than the proportionately larger self-enrichment factors for rarer elements such as Kr, etc.

As was true for the *K*-band lines, it turned out that [Zn IV] 3.625 μm had been previously seen, but assigned to a different species. In one case, it was identified as a transition of H_2, the v = 0–0 S(15) line (Sandford 1991); in an *ISO* study, it was attributed to a blend of two H I recombination lines (Bernard Salas et al. 2001). Dinerstein & Geballe (2001) presented higher-resolution spectra of two PNe, NGC 7027 and IC 5117 (Fig. 1.2), and demonstrated that the feature at 3.625 μm is [Zn IV], based on both a more accurate line wavelength and the observed spatial distribution. While no collision strength is currently available, for a nominal value of Υ = 1, the inferred ionic abundance is about $\frac{1}{3}$ solar, which suggests that the elemental abundance of Zn is not significantly enriched.

The fact that Zn is minimally affected by depletion has made (Zn/H) a popular surrogate for (Fe/H) in the ISM of high-redshift QSO absorbing systems (e.g. Pettini et al. 1997). By the same token, once the collision strength is known, the 3.625 μm line will offer the possibility of measuring iron-peak element abundances in ionized nebulae, enabling comparison of nebular and stellar abundances within a given stellar population.

1.2.4 Search for [Zr IV] 7.99 μm

Of the other favorable infrared fine-structure lines, several fall in spectral regions which can only be observed from airborne or space-based platforms. A possible exception is the $^2D_{5/2}$–$^2D_{3/2}$ transition of the 4*d* ion [Zr IV] at 1250.7 cm^{-1}. The caveat "possible" is given because the energy levels and hence transition frequencies of heavy ions are often known only to $\pm$ 0.3–1 cm^{-1} (DG02, from Y. Joshi, private communication). Shifts of this order can easily move a spectral feature into or out of telluric absorption features, even at high-altitude observatories such as Mauna Kea. Zirconium, Z = 40, shows substantial self-enrichment in AGB stars, where the TiO bands that dominate O-rich giants give way to ZrO bands in the moderately C-rich S stars (e.g. Vanture & Wallerstein 2002).

A search for the [Zr IV] line was conducted with the high-spectral resolution mid-infrared

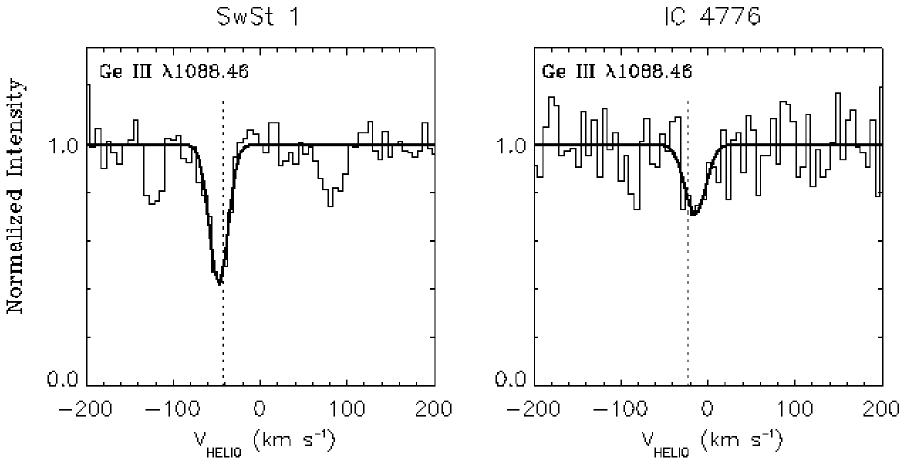

Fig. 1.3. Ge III 1088 Å detections from *FUSE* spectra; Ge/S in SwSt 1 (*left*) is $\sim 7\times$ solar, whereas in IC 4776 (*right*), Ge/S $\sim$ solar (SDB02; SD03).

spectrometer *TEXES* (Lacy et al. 2002) on NASA's IRTF in fall 2002. Several PNe were observed, but no [Zr IV] lines were detected. As with [Se IV] and [Zn IV], there is no published collision strength for [Zr IV] 7.99 μm. However, if we assume $\Upsilon \sim 5$, a value typical of the fine-structure transitions of Kr, Xe, and Ba (Schöning 1997; Schöning & Butler 1998), we can set a rough upper bound on the ionic abundance. For SwSt 1 (PK001.5-06.7), a preliminary analysis yields $n(Zr^{+3})/n(H) \leq 8 \times 10^{-9}$ and an enrichment factor of ≤ 20, if no correction is made for other ionic stages or depletion into dust. Since we find enrichments of ≤ 5–7 for Ge and Kr, this is not a strong limit, but we hope to improve on this result with further observations and analysis. A more complete report on our search for Zr will be given in Dinerstein et al. (2003, in preparation).

1.3 UV Absorption-Line Spectroscopy of *n*-Capture Elements

An alternate method for searching for the spectroscopic signature of *n*-capture elements is to use resonance absorption lines in the far ultraviolet (FUV), seen against the continuum of the UV-bright central star. This method has been used to detect several trans-iron elements in the diffuse ISM, for example Ge, Kr, and Sn (e.g. Savage & Sembach 1996; Welty et al. 1999). However, in those cases the detected ions are generally neutrals and singly-ionized species, which are prevalent in the ISM and translucent clouds. In the case of PNe, there is also the possibility of detecting higher ionization species (which require energies > 13.6 eV to create) in the H^+ region. Such searches are made efficient by the availability of extensive compendia of resonance absorption lines by Morton (1991; 2000).

1.3.1 Discovery of Ge III with FUSE

The Far Ultraviolet Spectroscopic Explorer, *FUSE*, has observed several dozen PNe, for a variety of science programs ranging from studies of the central stars, to searches for the Lyman-Werner bands of H_2. Sterling, Dinerstein, & Bowers (2002; hereafter SDB02), while looking for H_2 as part of a General Investigator project, discovered the strong resonance line Ge III 1088.46 Å in the *FUSE* spectra of four PNe. Subsequently, Sterling & Dinerstein (2003; SD03) detected Ge III in two additional PNe, and also measured Ge II in the foreground ISM along the line of sight to still another PN. Germanium, $Z = 32$, lies between Zn and Se, at the leading edge of the "light-*s*" peak. The production of Ge in the solar system is attributed about 50% each to the *r*- and *s*-processes (e.g. Burris et al. 2000).

The doubly-ionized state, Ge III, occupies an ionization potential range similar to that of S II and S III taken together, enabling one to derive the gas-phase abundance of Ge using S as a reference element. Since S is one of the least-depleted elements in the diffuse ISM, this provides a strong lower limit to the element ratio; and since S is not made in the progenitor star, this also indicates the degree of self-enrichment in Ge. The Ge depletion has been measured along only a handful of ISM sight lines. In cold clouds towards ζ Oph the depletion is ~ -0.6 dex, while it is less severe in warm ionized gas (Savage & Sembach 1996; Welty et al. 1999). Since the depletions of other elements (e.g. Fe) in PNe resemble those in the warm ionized medium, we made the conservative (lower limit) assumption that neither Ge nor S are significantly depleted. This yields enrichment factors of 3–7 for Ge in the four PNe in our initial sample (SDB02), while IC 4776 was found to be essentially consistent with the solar system value. Fig. 1.3 shows the regions of the Ge III line for IC 4776 and for SwSt 1; the latter has the largest Ge enrichment found so far. The fact that IC 4776 is found to have the solar value eliminates at least some possible sources of systematic error, e.g. an incorrect oscillator strength.

1.3.2 Search for Other Elements in the Satellite UV

In Section 1.2.2 and Table 1.1, I discussed the advantages and disadvantages of various ionic configurations as they apply to infrared and optical emission lines. Some of the considerations for searches using UV absorption lines are different from both of these. As before, it is advantageous to observe lines that arise from elements with large "baseline" (solar system) abundances, are relatively unaffected by depletion, into dust, and that originate from ions which are abundant if not dominant in PNe. For UV lines, however, the ideal species are ones with no fine-structure levels in the ground configuration, such as closed-shell configurations, whereas for emission lines, closed-shell configurations are essentially unobservable. Next best are ions with relatively few fine-structure levels likely to contain significant populations, and for which one can to observe transitions from all the important levels. An example is the reference ion S III, for which there are two excited levels in addition to the ground level (SDB02). On the other hand, Fe III has several fine-structure levels which may contain significant populations in gas near 10,000 K, one of several reasons why it is not ideal as a reference species.

Other factors determining the utility of a particular UV line include the intrinsic line strength as indicated by the *f*-value, which should be in a regime such that the line is detectable but not saturated; and whether the line wavelength happens to lie near transitions of other species. For example, some potentially interesting lines fall inside spectral features that are heavily saturated, such as H I Lyman lines or H_2 bands. Other lines fall in spectral regions where the source continuum is weak or the instrument is less sensitive (e.g. $\lambda \leq$ 1000 Å, for *FUSE*). Longward of $\lambda \sim 1180$ Å, the relevant instruments for absorption-line searches are STIS and its precursor, GHRS, on the Hubble Space Telescope (*HST*). Archival data from these instruments are available for a number of PNe from NASA's Multimission Archive (MAST) at the Space Telescope Science Institute, and were surveyed by SD03 in

Table 1.2. *Lines Observed to Date*

Atomic No.	Ion	λ	Method	Abundance
30	[Zn IV]	3.625 μm	IR emission	$\sim$ solar?
32	Ge III	1088 Å	UV absorption	$\sim$ 3-7 $\times$ solar
34	[Se IV]	2.287 μm	IR emission	unknown
36	[Kr III]	2.199 μm	IR emission	$\sim$ 1-5 $\times$ solar
40	[Zr IV]	8.99 μm	IR emission	$<$ 20 $\times$ solar

an attempt to find additional lines of *n*-capture elements. Apart from Ge III 1088 Å, the only other possible detection to date is Ga III 1495.05 Å (Ga, Z = 31, is the element between Zn and Ge). We reported this line as being marginally present in SwSt 1 (SD03), but it is near the limit of detectability and the nominal equivalent width indicates a substantially larger enrichment in Ga than in Ge. Confirmation from other data or a detection in another source would be necessary in order to consider this a clear detection.

1.4 Optical Emission Lines Revisited

The initial report of spectral features from *n*-capture elements in a PN, PB94, was based on an optical spectrum. The natural follow-up to this work is optical spectroscopy at higher spectral resolution, in order to verify the presence of particular features and determine the identity of lines that might be confused with other species. We have been using a set of spectra of $\sim$ 45 northern hemisphere PNe obtained with the McDonald Observatory 2.7 m Harlan J. Smith reflector and a coudé spectrograph providing a resolving power of R $\sim$ 60,000 (Tull et al. 1995). These spectra, originally obtained in order to study Na I and other neutral species in absorption (French, Dinerstein, & Sneden 2000), also provide information on many weak emission features in the spectral range 3800 Å $\leq \lambda \leq$ 9600 Å.

This data set provides both the advantage of higher resolving power, and the ability to confirm lines in more than one object. We find, for example, that some of the Ba and Xe lines reported by PB94 do not appear in the spectrum of NGC 7027 at the levels they suggest (note: some of these were listed as "possible" or "probable" features by PB94). On the other hand, we confirm and measure the fluxes of lines from several ions of Kr, for which collision strengths were computed by Schöning (1997). By summing ionic abundances derived from [Kr III] 6826 Å (see D01), [Kr IV] 5436 Å, and [Kr V] 6256 Å, we find that Kr/H is elevated above the solar value by approximately a factor of 5 in NGC 7027 and IC 5117. In these relatively high-excitation PNe, the correction for unobserved ionic stages is likely to be small, and Kr, a noble gas, should not be depleted into dust, so this should approximate the elemental ratio. A complete report on Kr abundances for these objects and others in the sample, will be given in a future paper (Dinerstein et al., in preparation).

1.5 Summary

This brief review has demonstrated that it is feasible to observe signatures of *n*-capture elements in the spectra of PNe and to determine the amount of self-enrichment that occurred in the AGB progenitor star, in particular the enrichments in *s*-process products.

Such studies are just beginning, but in the future, especially when critical atomic data become available (e.g. collision strengths and oscillator strengths), they can be used to obtain new insights into the late stages of stellar evolution and the details of the *s*-process in AGB stars, as well as to constrain the parameters of galactic chemical enrichment.

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