*RevMexAA (Serie de Conferencias)*, **18**, 133–135 (2003)



# UV OBSERVATIONS OF NEUTRON CAPTURE ELEMENTS IN PLANETARY NEBULAE

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RESUMEN

Se presentan resultados de una búsqueda entre los datos existentes del *Far Ultraviolet Spectroscopic Explorer (FUSE)* y del *HST*, de especies formandas por captura de neutrones en nebulosas planetarias (NP), que se pueden enriquecer por captura lenta de neutrones (proceso-$s$) en las estrellas progenitoras. La medición de tales enriquecimientos arroja luz sobre el proceso-$s$ en estrellas AGB y el enriquecimiento de elementos pesados en el medio interestelar. Derivamos abundancias de Ge ($Z$=32) relativas a S ó Fe de observaciones de Ge III $\lambda$1088.46 para cinco NP; cuatro de éstas tienen abundancias de Ge un factor >3–10 por arriba de la solar, dependiendo de las suposiciones sobre la pérdida en el polvo. En contraste, encontramos abundancia aproximadamente solar para el Ge en IC 4776, y también en el medio interestelar hacia Abell 36 según se deriva de Ge II $\lambda$1237.06. Otro elemento formado por captura de neutrones, Ga ($Z = 31$), probablemente se ha detectado en SwSt 1 por medio de Ga III $\lambda$1495.05, con una intensidad que indica una gran abundancia de Ga. La evidencia mas fuerte de enriquecimiento de Ge se observa en NP con estrellas centrales Wolf-Rayet (WR) deficientes en H y ricas en C. Aunque el camino evolutivo que produce las estrellas centrales WR no se conoce bien, es probable que estos objetos han experimentado mezcla profunda y dragado de material procesado nuclearmente.

ABSTRACT

We present results from a search through existing *Far Ultraviolet Spectroscopic Explorer (FUSE)* and *HST* data for neutron capture species in planetary nebulae (PNe), which can be enriched by slow neutron capture (the $s$-process) in the progenitor stars. Measurements of such enrichments shed light on the $s$-process in AGB stars and the heavy element enrichment of the interstellar medium. We derive Ge ($Z$=32) abundances relative to S or Fe from observations of Ge III $\lambda$1088.46 for five PNe; four of these exhibit Ge abundances elevated by a factor of >3–10 above solar, depending on assumptions about depletion into dust. In contrast, we find an approximately solar abundance for Ge in IC 4776, and also in the ISM towards Abell 36 as derived from Ge II $\lambda$1237.06. Another neutron-capture element, Ga ($Z = 31$), is probably detected in SwSt 1 via Ga III $\lambda$1495.05, with a strength indicating a greatly enhanced Ga abundance. The strongest evidence for enrichment of Ge is seen for PNe with H-deficient, C-rich Wolf-Rayet central stars. While the evolutionary path producing a [WR] central star is not well understood at present, these objects are likely to have experienced extensive mixing and dredge-up of nuclear-processed material.

*Key Words:* **LINE: IDENTIFICATION—NUCLEAR REACTIONS, NUCLEOSYNTHESIS, ABUNDANCES — PLANETARY NEBULAE: GENERAL — STARS: AGB AND POST-AGB**

## 1. INTRODUCTION

In asymptotic giant branch (AGB) stars, iron-peak elements capture neutrons released primarily by the $^{13}C(\alpha,n)^{16}O$ reaction. In this slow neutron-capture, or $s$-process, the seed nuclei undergo a series of neutron captures and $\beta$-decays as they are processed into heavier elements. The resulting trans-iron nuclei can be transported to the surface of the star by convective mixing during the third dredge-up, and thereby enrich the surface abundances of these elements (Busso et al. 1999). When the star evolves off the AGB and ejects its envelope to form a planetary nebula (PN), the ejecta may therefore be enriched in $s$-process elements. Although the $s$-process enhancement is most pronounced near elements $Z$ = 40 and 56 (the "light-$s$" and "heavy-$s$" peaks, respectively), the elements from $Z$ = 30–36 are more abundant in the Solar System. While these less massive neutron capture elements are believed to be created primarily in massive stars, they are also produced in AGB stars, albeit to a lesser degree. Due to the low initial abundances of these nuclei, even a modest addition of processed material can significantly increase their overall abundances.

Evidence for such enrichments has been pre-

The eighth Mexico-Texas Conference on Astrophysics: Energetics of Cosmic Plasmas (Mexico City, Mexico, 31 October - November 2, 2002)
Editors: Mauricio Reyes-Ruiz & Enrique Vazquez-Semadeni

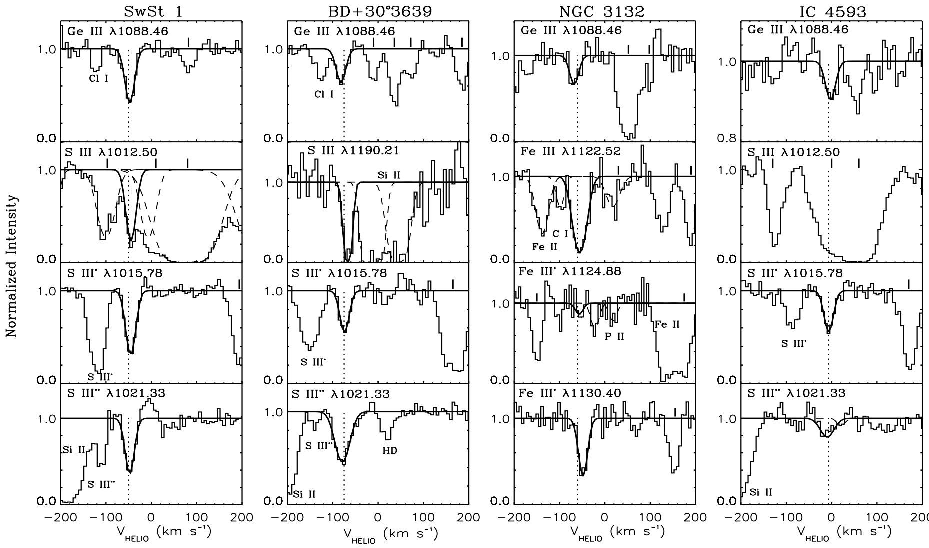


Fig. 1. Continuum-normalized column density profiles are plotted against the heliocentric velocity for the *FUSE* spectrum of IC 4776 and the STIS spectrum of SwSt 1.

sented by Péquignot & Baluteau (1994) based on optical spectra, and by Dinerstein (2001; 2003) based on infrared emission line measurements. Several neutron capture elements that cannot be observed in the optical or infrared can be detected via resonance absorption lines in the UV, but their detectability depends on the line of sight column of ionized gas toward the central star, as well as the excitation of the nebula. Despite such intrinsic limitations, Sterling et al. (2002; hereafter SDB) discovered germanium in four PNe via the strong ($f = 1.84$) resonance line Ge III $\lambda$1088.46. All four nebulae appeared to have strongly enhanced Ge abundances (>3–10 times), leading us to follow up this discovery with a broader search for signs of other *s*-processed species in *HST* and newly accessible *FUSE* data, for which we report the results to date in this paper.

## 2. SPECTRAL ANALYSIS

Ge has been detected in six PNe with *FUSE*, including the objects from SDB. We calculated the abundance of Ge in five of the six PNe by using S or Fe as a reference element and assuming that $\mathrm{Ge/S} \approx \mathrm{Ge^{++}/(S^{+} + S^{++})}$ or $\mathrm{Ge/Fe} \approx \mathrm{Ge^{++}/Fe^{++}}$, respectively (see Table 1). Sulfur is the preferred reference element since it is not depleted onto dust or produced or destroyed in the progenitor star. A detailed account of the abundance determinations is given in SDB and will not be repeated here.

We searched the medium and high-resolution spectra of 24 PNe observed by STIS or GHRS on *HST*, and detected only one case in which nebular *s*-process lines are likely seen (SwSt 1). (Note, however, that the small wavelength coverage of the GHRS for ten of these objects did not allow an exhaustive search from 1150-1750 Å.) We have tentatively identified features at $\lambda\lambda$1495.05 and 1534.46 in the STIS spectrum of SwSt 1 as transitions from the ground state of Ga III. If correct, this marks the first time any ion of Ga ($Z = 31$) has been found in a planetary nebula. We determined the abundance of Ga by using S III as the reference ion and assuming $\mathrm{Ga/S} \approx \mathrm{Ga^{++}/S^{++}}$. Furthermore, we have possibly identified a weak feature at 1234.87 Å as Se IV. This identification is uncertain due to the unknown oscillator strength of this transition, as well as its small observed equivalent width. The continuum normalized profiles for IC 4776 and SwSt 1 are shown in Figure 1 as examples of the component fitting.

We also detected interstellar Ge along the line of sight to Abell 36, from the resonance line ($f = 1.23$) Ge II $\lambda$1237.06. The lines P II $\lambda$1532.53 and Mn II $\lambda$1201.12 are used to calculate the elemental abundance ratios Ge/P and Ge/Mn, respectively. We find that the interstellar Ge abundance in this sight line is slightly below solar, indicating only a mild degree of depletion.

TABLE 1

ABUNDANCES

| Object | Abundance Measured | $N$(X)/$N$(R$^{+i}$)[a] CNM[b] | $N$(X)/$N$(R$^{+i}$)[a] WIM[b] | [X/R][a] CNM[b] | [X/R][a] WIM[b] |
|---|---|---|---|---|---|
| SwSt 1.... | Ge/S | 6.87±2.18 (−3) | 1.65±0.52 (−3) | 1.65±0.15 | 0.86±0.15 |
| BD+30°3639..... | Ge/S | 3.55±1.35 (−3) | 8.55±3.14 (−4) | 1.18±0.17 | 0.57±0.17 |
| NGC 3132...... | Ge/S | 1.62±0.41 (−4) | 4.07±1.02 (−4) | 0.09±0.12 | 0.49±0.12 |
| IC 4593..... | Ge/S | 3.55±2.17 (−3) | 8.51±3.50 (−4) | 1.20±0.19 | 0.57±0.19 |
| IC 4776 .... | Ge/S | 7.19±1.12 (−4) | 1.73±0.27 (−4) | 0.50±0.07 | −0.12±0.07 |
| NGC 5315[c] | ... | ... | ... | ... | ... |
| SwSt 1 .... | Ga/S | 4.39±1.39 (−2) | 3.17±1.01 (−3) | 2.78±0.14 | 1.64±0.14 |
| Abell 36 (ISM).... | Ge/P | 1.02±0.40 (−2) | 4.57±1.79 (−3) | −0.05±0.18 | −0.38±0.18 |
| Abell 36 (ISM).... | Ge/Mn | 7.09±2.61 (−3) | 6.03±2.22 | −0.25±0.18 | −0.32±0.18 |

[a]The column density ratios of $N$(X)/$N$(R$^{+i}$) where X is the $s$-process element and R$^{+i}$ is the reference ion(s) are given for each object, as well as the relative abundances [X/R] = log(X/R)−log(X/R)$_\odot$. Cited errors are 1 $\sigma$ estimates. Reference solar abundances derived from meteoritic data are taken from Grevesse & Noels (1993).

[b]CNM: The column densities of Ge III, Fe III, Ga III, P II, and Mn II are adjusted to account for the amount of depletion as seen in the cold diffuse cloud toward $\zeta$ Ophiuchi measured by the GHRS (Savage et al. 1992); sulfur is assumed to be undepleted. WIM: $N$(Fe III) is adjusted for the amount of depletion in the warm cloud toward $\zeta$ Oph, while all other elements are assumed to be undepleted.

[c]Continuum is too low near the reference lines to determine the Ge abundance.

## 3. ABUNDANCES AND DISCUSSION

The Ge abundances of SwSt 1, BD+30°3639, NGC 3132, and IC 4593 are enhanced with respect to solar by factors of ∼3–30, depending upon the amount of depletion assumed (the range of depletion is from 0 to −0.62 dex; see footnotes in Table 1). Ge is nearly solar in IC 4776, which provides evidence that abundances derived from Ge III $\lambda$1088.46 are not unrealistically large due to errors in the atomic data or another systematic effect. The value we found for [Ga/S] in SwSt 1 seems quite large in light of the derived [Ge/S] value in this object. In fact, Arlandini et al. (1999) predict that Ge should be enriched to a greater degree in AGB stars than the odd-numbered element Ga. It is not clear at this stage whether the theoretically determined $f$-value for Ga III (Curtis & Theodosiou 1989) listed in Morton (1991) is incorrect, or whether the line identification is in error.

As noted in SDB, PNe with Wolf-Rayet ([W-R]) type central stars exhibit the strongest Ge III absorption features detected. This is not entirely surprising, since most mechanisms invoked to explain these H-deficient central stars involve deep mixing, which enriches the surface of the star with highly processed material. Non-detections of Ge III in other [W-R] PNe such as NGC 6905 and NGC 2371 are probably due to ionization effects, and therefore are inconclusive since higher ions of Ge do not have transitions in the *FUSE* spectral range. Further searches for Ge and other $s$-process elements, in the UV and in other wavelength regions, are underway to determine whether there is in fact a correlation between neutron-capture enrichments and [W-R] central stars.

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