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# Abundances of *s*-process elements in planetary nebulae: Br, Kr & Xe

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**Abstract.** We identify emission lines of post-iron peak elements in very high signal-to-noise spectra of a sample of planetary nebulae. Analysis of lines from ions of Kr and Xe reveals enhancements in most of the PNe, in agreement with theories of *s*-process in AGB stars. Surprisingly, we did not detect lines from Br even though *s*-process calculations indicate that it should be produced with Kr at detectable levels.

**Keywords.** ISM: abundances, planetary nebulae: general, nucleosynthesis

## 1. Introduction

As remnants of AGB stars, planetary nebulae (PNe) represent material that has undergone nuclear processing in their precursors via the *s*-process. The analysis of nebular emission provides essential information for stellar models. However, the detection of emission lines from *s*-elements has been hampered by their weakness and by uncertainties in the atomic data. A pioneering attack on the problem was made by Pequignot & Baluteau (1994), who identified a number of post-Fe emission lines in NGC 7027. Dinerstein and collaborators studied *s*-process elements in PNe by searching for their IR emission (Dinerstein 2001; Sterling & Dinerstein 2004, and this volume) and far-UV absorption (Sterling *et al.* 2002, 2003). As part of an on-going program to detect weak lines in PNe, we have obtained a number of high resolution spectra of very high S/N.

## 2. Observations and Analysis

Our current sample of objects consists of four PNe (IC 2501, IC 4191, NGC 2440, and NGC 7027). The spectra were obtained with the KPNO 4m using the Cassegrain echelle spectrograph and the LCO 6.5m with the MIKE echelle spectrograph at a resolving power of about 25,000. Fig. 1 shows the quality of our spectra. The deep spectra enable us to detect extremely faint lines with a flux of $\sim 10^{-6}$ the intensity of H$\beta$. For comparison, we also searched for Kr and Xe in two H II regions, the Orion Nebula (Baldwin *et al.* 2000) and NGC 3576 (García-Rojas *et al.* 2004).

We have detected krypton and xenon emission lines, [Kr III] $\lambda$6827, [Kr IV] $\lambda\lambda$5868, 5346, [Kr V] $\lambda$6256, [Xe III] $\lambda$5846, [Xe IV] $\lambda\lambda$5709, 7535, and [Xe V] $\lambda$7077. However, we failed to detect Br lines, [Br III] $\lambda$6133 and [Br IV] $\lambda$7368, even though the current *s*-process calculations indicate that Br should be produced along with Kr at detectable levels. The reason remains unknown.

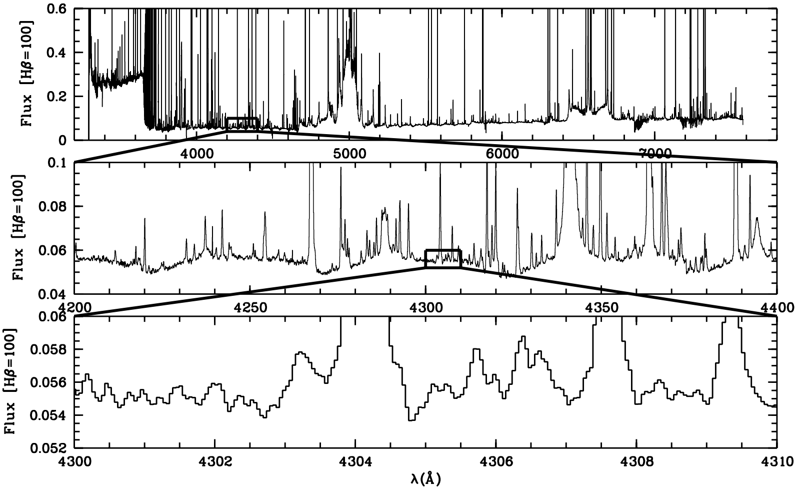


**Figure 1.** Spectrum of IC 2501 illustrating the quality of our spectra.

**Table 1.** Abundances of Br, Kr, and Xe.

| | PNe | | | | | H II regions | |
|---|---|---|---|---|---|---|---|
| Abundance | IC 418 | IC 2501 | IC 4191 | NGC 2440 | NGC 7027 | Orion | NGC 3576 |
| [Br/Ar] | $< -0.8$ | $< -1.2$ | $< -0.5$ | $< -1.0$ | $< 0.3$ | ... | ... |
| [Kr/Ar] | 0.76 | 0.04 | 0.38 | 0.15 | 1.04 | $-0.08$ | $< -0.69$ |
| [Xe/Ar] | 0.91 | 0.01 | 0.51 | 0.33 | 0.87 | $< 0.58$ | ... |

Using the current available atomic data, we have determined Kr and Xe abundances. We converted ionic ratios to elemental values by making use of the similarity in ionization potentials of the noble gases, from which it follows that $(\mathrm{Kr}, \mathrm{Xe})/\mathrm{Ar} = [(\mathrm{Kr}^{+2}, \mathrm{Xe}^{+2}) + (\mathrm{Kr}^{+3}, \mathrm{Xe}^{+3})]/(\mathrm{Ar}^{+2} + \mathrm{Ar}^{+3})$ and $[(\mathrm{Kr}^{+2}, \mathrm{Xe}^{+2}) + (\mathrm{Kr}^{+3}, \mathrm{Xe}^{+3}) + (\mathrm{Kr}^{+4}, \mathrm{Xe}^{+4})]/(\mathrm{Ar}^{+2} + \mathrm{Ar}^{+3} + \mathrm{Ar}^{+4})$ for low- and high-excitation PNe, respectively. The upper limits for the Br abundances were estimated. These results, relative to the solar values, are given in Table 1. It is evident that Kr and Xe are both enhanced by similar factors of up to 10 in the five PNe, but not in the two H II regions which represent unprocessed ISM gas.

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