DETECTION OF FLUORINE IN THE HALO PLANETARY NEBULA BoBn 1: EVIDENCE FOR A BINARY PROGENITOR STAR

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ABSTRACT

We have found the fluorine lines [F iv] λ3996.92, 4059.90 in the extremely metal-poor ([Ar/H] = −2.10 ± 0.21) halo planetary nebula (PN) BoBn 1 in high-dispersion spectra from the 8.2 m VLT UVES archive. Chemical abundance analysis shows that the fluorine abundance is [F/H] = +1.06 ± 0.08, making BoBn 1 the most fluorine-enhanced and metal-poor PN among fluorine-detected PNe and providing new evidence that fluorine is enhanced by nucleosynthesis in low-mass metal-poor stars. A comparison with the abundances of carbon-enhanced metal-poor (CEMP) stars suggests that BoBn 1 shares their origin and evolution with CEMP- s stars.

Subject headings: ISM: abundances — planetary nebulae: individual (BoBn 1)

1. INTRODUCTION

Currently, over 1000 objects are regarded as planetary nebulae (PNe) in the Galaxy (Acker et al. 1992), while 14 of them have been identified as halo members from their location and kinematics since the discovery of K648 (Ps 1) in M15. All halo PNe are metal-poor objects ([S/H]) = −1.3; Pereira & Miranda 2007) and are suspected of being descendants of stars formed in the early history of the Galaxy. Halo PNe should convey important information for the study of the evolution of metal-poor stars as well as the early physical and chemical conditions of the Galaxy. Their origins are, however, not well understood yet.

BoBn 1 (PN G108.4−76.1) is a halo PN that is located in the direction of the south Galactic pole. The heliocentric distance to this object is estimated to be between 16.5 kpc (Henry et al. 2004) and 29 kpc (Kingsburgh & Barlow 1992) and the heliocentric radial velocity is +191.9 ± 0.8 km s−1 (Otsuka 2007). Zijlstra et al. (2006) have associated BoBn 1 with the leading tail of the Sagittarius dwarf spheroidal galaxy, which traces several halo globular clusters. BoBn 1 is an extremely metal-poor ([Ar/H]) = −2.10 ± 0.21; Otsuka 2007) and C- and N-rich halo PN ([C/O] = +1.50 ± 0.27, [N/O] = +1.02 ± 0.13, [O/H] = −0.96 ± 0.05, according to Otsuka 2007; [C/O] = +1.32, [N/O] = +1.07, [O/H] = −1.07, according to Howard et al. 1997), which composes a class of PN together with K648 and H4-1.

These C- and N-rich halo PNe have some unresolved issues on their origin. For example, halo PNe can become N-rich, but not C-rich, if the initial mass of the progenitor is ~0.8 M⊙, which is the turnoff star mass of M15, according to the theoretical models of single metal-poor stars (e.g., Fujimoto et al. 2000). To become C-rich PNe, the third dredge-up (TDU) must take place in the late asymptotic giant branch (AGB) phase. But, the TDU takes place in stars with initial masses ≥1.2–1.5 M⊙ (e.g., Straniero et al. 2006). Also, current stellar evolutionary models predict that the post-AGB evolution of stars with initial masses ~0.8 M⊙ proceeds too slowly for a visible PN to be formed. These issues must be resolved before one proceeds to discuss the evolution of metal-poor stars and the early chemical evolution of the Galaxy through the observation of halo PNe.

Chemical abundance analysis of PNe is a key tool for investigating these issues. Comparing the observed abundances with those from theoretical evolution and nucleosynthesis models for metal-poor stars will shed light on the origin and evolution of C- and N-rich halo PNe. In this Letter, we present the first estimation of the fluorine (F) abundance of BoBn 1. The abundances of F and heavy elements via the slow neutron capture process (the s-process), which are synthesized in the He-rich intershell of AGB stars and are brought to the surface by the TDU, would be an effective tool to examine how BoBn 1 became C- and N-rich, when combined with the C abundance. We discuss the origin and evolution of BoBn 1 by comparing the F and other elemental abundances with the abundances of carbon-enhanced metal-poor (CEMP) stars.

2. DATA AND REDUCTION

High-dispersion spectra of BoBn 1 in the range 3260 to 6680 Å are available from the European Southern Observatory (ESO) archive. The observations were performed by Perinotti & Gilmozzi (proposal ID: 69.D-0413A) on 2002 August 4, using the Ultraviolet Visual Echelle Spectrograph (UVES; Dekker et al. 2000) at the Nasmyth B focus of Kueyen, the second of four 8.2 m telescopes of the ESO Very Large Telescope (VLT) at Paranal, Chile. The entrance slit size was 11.0″ in length and 1.5″ in width, giving a spectral resolution of ~36,000. The sampling pitch along the wavelength dispersion was ~0.02 Å pixel−1. The data were taken as a series of 2700 s exposures and the total exposure time was 10,800 s. The seeing was between 1″ and 1.5″ during the exposure. The standard star HR 9087 was observed for flux calibration. Data reduction was performed mostly by the Image Reduction and Analysis Facility (IRAF) software package distributed by the National Optical Astronomy Observatory (NOAO).
3. RESULTS

We have found candidates of the fluorine forbidden lines [F iv] $\lambda 3996.92$ (transition: $3D_{3/2} - P_{3/2}$) and [F iv] $\lambda 4059.90$ ($3D_{3/2} - 3P_{1/2}$). We show the line profiles of [F iv] in Figure 1. The abscissa and ordinate axes indicate the heliocentric wavelength and the flux density normalized to the total Hβ flux $F(H\beta)$. We have fitted the line profiles of these [F iv] with a single Gaussian. The resulting fittings are summarized in Table 1. The second and third columns are the position of the center of the Gaussian and the normalized line intensity (interstellar reddening corrected using $c(H\beta) = 0.21 \pm 0.02$; Otsuka 2007), respectively. We confirmed that BoBn 1 has no high-density components exceeding a critical density of $3 \times 10^8$ cm$^{-3}$ at the level of $D_4$, using the intensity ratios of Balmer lines [Hn; n (principal quantum number) = 3–25] to Hβ (H4), which are sensitive to high electron density ($>10^8$ cm$^{-3}$). Therefore, the effect of collisional de-excitation is negligibly small, so that the intensity ratio of [F iv] $I(\lambda 4059.90)/I(\lambda 3996.92) = 2.82$, which is in good agreement with our measurement ($3.01 \pm 0.40$). Hence, these two emission lines can be identified as the fluorine forbidden lines [F iv] $\lambda 3996.92$ and [F iv] $\lambda 4059.90$.

The triply ionized fluorine abundance $F^{++}/H^+$ has been estimated from each detected [F iv] line by solving the statistical equilibrium equations for the lowest five energy levels ($^3P_{0,1,2}, ^1D_2, ^3S_1$). The collision strength and transition probabilities of [F iv] lines are given by Lennon & Burke (1994) and Garstang (1951), respectively. To estimate $F^{++}/H^+$, we use an electron temperature of $T_e = 13430 \pm 170$ K, derived from the ratio of $[O iii] I(\lambda 4959 + \lambda 5007)/I(\lambda 4363) = 80.05 \pm 2.67$, and a density of $n_e = 4550 \pm 1270$ cm$^{-3}$ from the ratio of [Ar iv] $I(\lambda 4711)/I(\lambda 4740) = 1.01 \pm 0.08$ (Otsuka 2007). The resulting $F^{++}/H^+$ are presented in the fourth column of Table 1, which include the errors of the line intensity, $T_e$, $n_e$, and $c(H\beta)$. Finally, we adopted a value of $F^{++}/H^+$ from the intensity of the weighted mean, presented in the fourth column, last row of Table 1.

To estimate the elemental fluorine abundance $F/H$ using only $F^{++}/H^+$, we must correct for unobserved fluorine ion abun-

Table 1: Fluorine Ionic and Elemental Abundance of BoBn 1

| $\lambda^{\alpha}$ | $\lambda^{\beta}$ | $I(\lambda^{\alpha})$ | $I(\lambda^{\beta})$ | $F^{++}/H^+$ | $Ic(F)$ |
|-------------------|-------------------|---------------------|---------------------|--------------|--------|
| 3996.92           | 3996.76           | 1.03 ± 0.03         | 5.08 ± 0.21         | ...          | ...    |
| 4059.90           | 4062.73           | 3.09 ± 0.04         | 5.40 ± 0.18         | ...          | ...    |

Adopted

$Ic(F) = (Ne/H) \times (Ne^{++}/H^+)^{-1}$,

where $Ne/H$ and $Ne^{++}/H^+$ are the elemental and triply ionized neon abundances, respectively. We assume that $Ne/H$ of BoBn 1 is the sum of $Ne^{++}/H^+$, $Ne^{++}/H^+$, and $Ne^{++}/H^+$.

In Table 2, we present the $F/H$ abundance of 11 disk PNe and a halo PN NGC 4361 from Zhang & Liu (2005) and of NGC 7662 from Hyung & Aller (1997), together with [C/H], [N/H], [Ne/H], [Ar/H], and [F/Ar] abundances. All the abundances of PNe in this table originate from the nebula material. For PNe, Ar is used as a metallicity indicator instead of Fe, because Ar is not depleted by dust. To our knowledge, BoBn 1 is the most metal-poor and F-rich PN among detected PNe. We also present the abundances of the CEMP star HE 1305+0132 (HE 1305 hereafter), estimated by Schuler et al. (2007). It should be noted that its C and F overabundances are comparable to those of BoBn 1. Since the extremely enhanced

Table 2: Fluorine Abundances of PNe and HE 1305+0132

| Object | $[F/H]$ | $[C/H]$ | $[N/H]$ | $[Ne/H]$ | $[Ar/H]$ | $[F/Ar]$ | Ref. |
|--------|---------|---------|---------|----------|----------|----------|------|
| IC 418 | +0.41   | +0.40   | +0.09   | -0.09    | -0.27    | +0.68    | 1, 2 |
| IC 2003| +0.20   | +0.02   | -0.13   | -0.13    | -0.60    | +0.80    | 3    |
| IC 2501| -0.14   | -0.40   | +0.33   | +0.26    | -0.31    | +0.17    | 4, 5 |
| NGC 40 | +1.02   | +0.45   | +0.10   | +0.14    | -0.61    | +1.63    | 6    |
| NGC 2022| +0.09  | -0.07   | -0.37   | -0.03    | -0.43    | +0.52    | 7    |
| NGC 2440| -0.72  | -0.02   | +1.17   | +0.09    | -0.23    | -0.49    | 7, 8 |
| NGC 3242| -0.29  | -0.26   | -0.30   | +0.02    | -0.56    | +0.27    | 7    |
| NGC 3918| -0.37  | +0.25   | +0.19   | +0.10    | -0.31    | -0.06    | 7    |
| NGC 5315| +0.60  | -0.06   | +0.69   | +0.43    | +0.01    | +0.59    | 7    |
| NGC 6302| -0.26  | -0.51   | +0.69   | +0.01    | -0.21    | -0.05    | 7    |
| NGC 7027| +0.22  | +0.70   | +0.31   | +0.20    | -0.25    | +0.47    | 7    |
| NGC 4361| +0.19  | -0.27   | -0.42   | -0.30    | -0.75    | +0.94    | 10   |
| NGC 7662| +0.37  | +0.28   | +0.36   | +0.09    | -0.44    | +1.01    | 6, 11|
| BoBn 1 | +1.06  | +0.54   | +0.06   | +0.06    | -2.10    | +3.17    | 12   |
| HE 1305 | +0.50  | +0.18   | -0.90   | -0.25    | -3.50    | +3.10    | 13   |

Notes.—The elemental abundances in PNe except for C in IC 2501 are estimated from forbidden lines. C in IC 2501 is estimated from recombination lines. For the CEMP star HE 1305+0132 (HE 1305), Fe is used as a metallicity indicator. The solar abundances are referred to Lodders (2003).

References.—For second column see text. For remaining columns, (1) Pottasch et al. 2004; (2) Hyung et al. 1994; (3) Wesson et al. 2005; (4) Henry et al. 2004; (5) Sharpe et al. 2007; (6) Liu et al. 2004; (7) Tsamis et al. 2005; (8) Hyung & Aller 1998; (9) Zhang et al. 2005; (10) Torres-Peimbert et al. 1990; (11) Hyung & Aller 1997; (12) this work + Otsuka 2007; (13) Schuler et al. 2007.
F abundances in these objects cannot be explained by primordial pollution of material from rapidly rotating massive stars (Palacios et al. 2005), we assume that F in BoBn 1 and HE 1305 is mostly produced by nucleosynthesis in the progenitor single star or a possible binary companion.

4. DISCUSSION AND CONCLUSIONS

In low-mass AGB stars (initial mass of 1–4 M$_\odot$; Herwig 2005) suffering the TDU and not hot bottom burning, the F abundance at the stellar surface is efficiently enhanced. Its only stable isotope, $^{19}$F, is synthesized via the $^1$H($\alpha$, $\gamma$)$^4$He($\alpha$, $\gamma$)$^8$Be($\alpha$, $\gamma$)$^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction chain during He-shell burning inside thermal pulses (TPs). Fluorine is further carried to the surface of the star by the TDU, together with other products of He burning: mostly $^{12}$C to the stellar envelope, which is then converted into $^{13}$C and $^{14}$Na due to the partial mixing and subsequent dredge-up. Such a star, however, would not have survived in the Galactic halo up to now.

To circumvent this issue, BoBn 1 might have evolved from a binary and experienced binary mass transfer from a massive companion. The abundances of BoBn 1 are compatible with the final [F/H] predicted by the AGB single-star models of Karakas & Lattanzio (2007) and Lugaro et al. (2004) for initial masses of 1–4 M$_\odot$ stars with $Z = 10^{-4}$ ([Fe/H] $\approx -2.3$). The single metal-poor star models of Fujimoto et al. (2000) and Suda et al. (2004) predict that stars with [Fe/H] $\leq -2.5$ and initial masses of 1.2–3.5 M$_\odot$ will become C, N, and S-process elements enriched by the partial mixing and subsequent dredge-up. Such a star, however, would not have survived in the Galactic halo up to now.

In Figure 2a, we show the diagram of [C/Ar] versus [F/Ar] for PNe, MS/S stars, and HE 1305. It clearly shows that [F/Ar] increases with [C/Ar]. Figure 2b shows a correlation between [Ne/Ar] and [F/Ar], which again is to be expected if $^{22}$Ne is also carried to the surface by the TDU. Figure 2c further shows a strong correlation between [Ar/H] and [F/Ar]. This is predicted by the models because of the primary contribution to the F production due to the effect of the TDU, as discussed above.

The [F/H] abundance of BoBn 1 is comparable to NGC 40, which has a WR-type central star ([WC8]; De Marco & Barlow 2001). The strong stellar wind from WR stars may also be important for the F injection. In BoBn 1, strong and narrow C iii, C iv, and N iii lines have been detected (Otsuka 2007), suggesting that the central star is a WELS (weak emission-line star) known as a class of H-deficient stars. The central star might have suffered a very late thermal pulse (VLTP) and become H-deficient. Zijlstra et al. (2006) noted that the Ne enhancement of BoBn 1 could be caused by VLTP. The strong stellar wind and VLTP might contribute to the enhancements of F, C, and Ne in the nebula.

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et al. (2007) concluded that HE 1305 might have experienced mass transfer and predicted that s-process elements should be enhanced in this object. Considering the model of Karakas & Lattanzio (2007), Lugaro et al. (2008) concluded that HE 1305 consists of ~2 $M_\odot$ (primary) and ~0.8 $M_\odot$ (secondary) stars with $Z = 10^{-4}$ and the enhanced C and F are explained by binary mass transfer from the primary star via Roche lobe overflow and/or wind accretion. BoBn 1 might also have evolved from a binary consisting of ~2 and ~0.8 $M_\odot$ stars, since its C and F abundances and metallicity are comparable to HE 1305. The enhanced C and F of BoBn 1 can be explained by the model of Lugaro et al. (2008) including the extra $^{13}$C and $^{14}$N, or the upper limit of the $^{18}$F($\alpha$, p)$^{21}$Ne reaction. The chemical similarities between BoBn 1 and CEMP-s stars suggest that this PN shares a similar origin and evolutionary history, although we have not detected any s-process elements in this object. The contradiction on the evolutionary timescale of this object can be avoided if BoBn 1 has indeed evolved from a CEMP-s star such as HE 1305.

Abundances of s-process elements and F should be enhanced in K648, H4-1, and BoBn 1, if they have evolved from CEMP-s stars. For K648 and H4-1, there have been no reports on the detection of F and s-process elements. High-sensitivity spectroscopic observations are necessary in the optical and near-infrared to investigate those elements. We would be able to settle the origin and evolution of halo PNe, if we find enhanced abundances for those elements.

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