Absorption-Line Spectroscopy of Planetary Nebulae with \textit{FUSE}: Probing the Molecular, Atomic, and Ionized Gas

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Abstract.

The central stars of planetary nebulae (PNe) are natural targets for \textit{FUSE} due to their UV brightness. The \textit{FUSE} spectra of many PNe show absorption features due to circumstellar material in species ranging from H$_2$ and neutrals in the photodissociation region (PDR) to ions resident in the H II region. We report results from a program designed to search for nebular components in the H$_2$ Lyman and Werner resonance lines that are responsible for the fluorescent excitation of H$_2$ in strong FUV radiation fields. Our failure to detect H$_2$ in absorption in several PNe with strong near-infrared H$_2$ emission indicates that the molecular material has an asymmetrical or clumpy distribution. We also detect enrichments in the s-process product Ge, find that Fe is not depleted into dust along at least one line of sight through a PN, and show that starlight fluorescence can affect the populations of the excited fine-structure levels of O I.

1. Introduction

The strong FUV continua of planetary nebula central stars provide excellent backdrops for observing absorption lines produced by circumstellar material as well as foreground interstellar (IS) clouds. The \textit{FUSE} band contains a uniquely broad suite of spectral features from different phases of material that may be present in the circumstellar environment, providing information on physical conditions along a path that traverses the entire multi-phase nebular envelope.

An important consideration is the need to resolve circumstellar from IS features, for species that may be present in both components. We preferentially selected targets with favorable velocities, such as BD+30$^\circ$3639, in which nebular Na I absorption is seen at $v_{\text{helio}} \sim$–70 km s$^{-1}$, blueshifted by \sim 55 km s$^{-1}$ with respect to the IS components (Dinerstein, Sneden, & Uglum 1995).

2. Search for Circumstellar H$_2$

The primary motivation for our program was to search for the Lyman and Werner resonance lines that initiate the fluorescent excitation of H$_2$. This process is one of two chief mechanisms for exciting the near-infrared (NIR) H$_2$ quadrupole emission lines seen in many PNe, the other being collisional excitation in shock-heated gas (e.g. Black & van Dishoeck 1987). Although initially
the NIR emission in PNe was attributed to shocks, it has become clear that fluorescence plays an important role as well (Dinerstein et al. 1988; Hora, Latter, & Deutsch 1999). \textit{FUSE} directly samples the pump lines from the \( v = 0 \) levels of the ground state (e.g. McCandliss 2003). Furthermore, because of their large oscillator strengths, the FUV lines are sensitive to much smaller column densities of \( \text{H}_2 \) than can be detected through NIR emission.

Table 1. Results of \textit{FUSE} \( \text{H}_2 \) Search

| Object          | IR \( \text{H}_2 \) Emission | FUV \( \text{H}_2 \) Absorption |
|-----------------|-------------------------------|-------------------------------|
| BD+30\(^{\circ}\)3639 | yes                           | yes                           |
| NGC 40          | yes                           | no                            |
| NGC 5882        | unknown                       | no                            |
| NGC 6210        | no                            | no                            |
| NGC 6720        | yes                           | no                            |
| NGC 7662        | no                            | no                            |
| SwSt 1          | yes                           | no                            |

Table 1 summarizes the results for our program. Although four of the targets are known sources of NIR \( \text{H}_2 \) emission, only one – BD+30\(^{\circ}\)3639 – shows nebular \( \text{H}_2 \) absorption. This object also shows excited \( \text{H}_2 \) in its \textit{HST}-STIS UV spectrum, which contains hundreds of lines from \( v \geq 2 \) in the ground electronic state (Dinerstein & Bowers 2004; Dinerstein et al, in preparation). The \textit{FUSE} spectrum of BD+30\(^{\circ}\)3639 resembles that of M27, the Dumbbell Nebula, which is rife with nebular \( \text{H}_2 \) (McCandliss et al. 2000). On the other hand, no nebular \( \text{H}_2 \) is seen toward the central star of NGC 6720, the Ring Nebula, where the NIR \( \text{H}_2 \) emission is clumpy and concentrated near the bright ring (Speck et al. 2003). The \textit{FUSE} results are consistent with the \( \text{H}_2 \) residing in an equatorial torus, since the Ring is seen pole-on, whereas the Dumbbell is nearly equator-on.

From the \textit{FUSE} data, we set upper limits of \( N_J(\text{H}_2) \leq 5 \times 10^{13} \text{ cm}^{-2} \) for \( J = 2 - 5 \) on the circumstellar components for three PNe with NIR \( \text{H}_2 \) emission: NGC 40, NGC 6720, and SwSt 1. These values are \( \sim 50 \) times lower than the actual column densities in BD+30\(^{\circ}\)3639, and also than the beam-averaged values of \( N_J(\text{H}_2) \) from the NIR emission in the same PNe. We conclude that the \( \text{H}_2 \) in these PNe has a very non-uniform distribution, being either globally asymmetrical (e.g. in a torus) or concentrated in dense clumps. Only in a few cases does the line of sight to the central star intercept circumstellar \( \text{H}_2 \).

3. Excitation of O I

The \(^3P\) ground term of O I has two excited fine-structure levels that give rise to forbidden transitions at 63 \( \mu \text{m} \) and 145 \( \mu \text{m} \). For \( n \geq 10^3 \text{ cm}^{-3} \), [O I] 63 \( \mu \text{m} \) is the strongest cooling line from PDRs, the transition regions between ionized and molecular material. Ratios of the [O I] lines and [C II] 158 \( \mu \text{m} \) are diagnostics of physical conditions and PDR parameters (Kaufman et al. 1999).

The populations of the O I fine-structure levels can also be measured via UV absorption lines. The 1302–1306 Å triplet (observable with \textit{HST}) is often saturated, and the line from the first excited level, 1304 Å, is blended with Si II.
The FUSE band includes other, weaker transitions which can be used to derive the level populations. For example, the O I triplet near 1040 Å in SwSt 1 yields a value of $N(O I^{**})/N(O I^*)$ which is twice the ratio of statistical weights. This is possible only if a non-collisional process dominates the excitation. Based on the reported strengths of the optical O I lines (De Marco et al. 2001), we identify this mechanism as fluorescent excitation by stellar continuum photons (Sterling et al., in preparation). In SwSt 1 the effect is obvious; elsewhere, it could be more insidious, elevating the population of the $^3P_0$ level and strengthening [O I] 145 µm, thereby leading to an overestimate of the gas temperature.

4. Conditions and Abundances in the Ionized Gas

The UV spectral region also contains resonance lines from ions in the H II region. These can provide diagnostics of physical conditions and values for gas-phase abundances. We used FUSE observations of UV lines from the ground and several excited fine-structure levels of Fe III, Fe II, and S III to derive the gas-phase Fe/S ratio in SwSt 1, for which we find an essentially solar value (Sterling et al., in preparation). This result suggests that Fe is not depleted into dust along this particular path through the nebula, in marked contrast to the results found from the optical and NIR emission lines, which indicate depletion factors of $\geq 15$. The implied inhomogeneity in the dust-to-gas ratio echoes the inhomogeneity seen in the H$_2$ in this PN (see §2).

FUSE also offers access to some species that cannot be observed in other spectral regions. For example, the neutron-capture element Ge ($Z = 32$) can be observed via the Ge III resonance line at 1088 Å (Sterling, Dinerstein, & Bowers 2002). The Ge abundance in PNe can be enhanced by the dredge-up of s-processed material during the AGB phase. We find that Ge/S is enriched by factors of three or more in a few PNe observed by FUSE.

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