FUSE studies of Galactic and LMC CSPN

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Abstract

We present the first results from a comprehensive spectral analysis of FUSE, IUE, HST and ground-based data of Galactic Central Stars of Planetary Nebulae (CSPN). The FUSE data enable us to determine the parameters of the central star through stellar modeling, and in some cases derive characteristics of the circumstellar envelope. This provides unprecedented details of each object's evolutionary history. By extending such work to include CSPN in the LMC (FUSE cycle 2) and the SMC (FUSE cycle 3), we will be able to compare CSPN evolution in environments of differing metallicity.

As an example, we discuss in detail our work on the binary CSPN Abell 35 (A35). We have determined the hot central star to be a DAO white dwarf (WD) of T_{eff}=80 kK, $\log g$=7.7. We have also determined the mass of the neutral material contained in the circumstellar envelope to be $\simeq 3.0$ M$_\odot$, and infer a progenitor mass of $\simeq 3.5$ M$_\odot$. This is consistent with the progenitor's mass as inferred by comparison of the current WD parameters with evolutionary calculations, and may be the first time such an accurate accounting of the progenitor mass has been done.

Introduction

Central Stars of Planetary Nebulae (CSPN) offer great opportunities for understanding the evolutionary history of low/intermediate mass stars. The nebular chemical composition reflect that of the star's when the nebula was ejected, giving clues to its evolutionary phase at the time. The velocity and size of the nebula indicate how far in the past the ejection occurred. The mass contained in the circumstellar shell (ionized material, H I and H_2) show what the star has lost in its history. Combining this information with the star's current parameters (determined through spectral modeling) gives a fairly complete empirical picture of the star's life.

Although the nebula can be studied in the optical, the high temperature CSPN emit the majority of their radiated energy in the ultraviolet. Until recently, an important part of the CSPN picture — the parameters of the central star — were not well known. Typically, black-body extrapolations were made off the Rayleigh-Jeans tail available to the HST/IUE instruments. The *Far Ultraviolet Spectroscopic Explorer* (FUSE) can observe from 1187 Å down to the Lyman-limit (916 Å) - giving coverage of the critical FUV energy distribution of the central star.

Bianchi's CSPN FUSE program is a comprehensive study of Galactic (P133), LMC (B001), and SMC (C056) CSPN in environments of differing metallicities. We use the FUSE data in conjunction with IUE/HST/optical data to study the central stars and their circumstellar material. Hot star spectra are modeled with non-LTE codes such as CMFGEN (for stars with extended atmospheres such as the [WC] objects — Hillier & Miller 1998, 1999) and TLUSTY (for plane parallel atmospheres such as white dwarfs — Hubeny & Lanz 1992, 1995). Using these, stellar parameters such as T_{eff}, $\log g$, and chemical abundances are determined. Furthermore, we use FUSE to study the circumstellar H_2 by analyzing the H_2 features which occur in the FUV.

Here we give a summary of our work on the Galactic CSPN, using Abell 35 (A35) as a detailed example.

Galactic CSPN

The Galactic CSPN of our study are listed below, along with their classification and the code used in their spectral analysis. The FUSE data along with preliminary models are shown in Figure 1.

Name	Obs. Name	Classification	Code
A35	P13301	DAO WD + G8IV	TLUSTY
NGC2371	P13303	[WC3]	CMFGEN
NGC3132	P13304	hot star + A0V	Black body
IC 4776	P13305	[WC6](?)	CMFGEN
K1-26	P13306	O(H)	TLUSTY

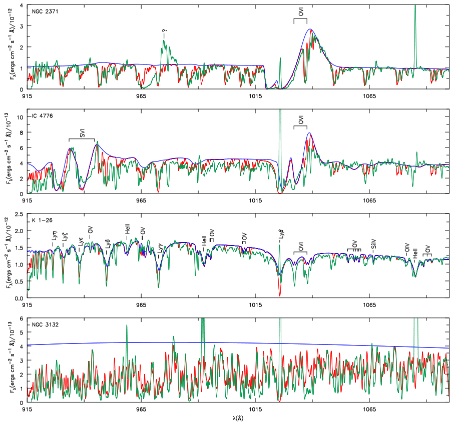

Figure 1. The FUSE data for our Galactic CSPN are shown in green. Our stellar models, with and without the absorption effects of intervening H I and H_2, are shown in red and blue, respectively. All spectra have been convolved to 0.5 Å for clarity, and the main stellar features are labeled. Our fit of A35 is shown at the bottom of the poster.

Abell 35 (A35)

A35 is a rare example of a CSPN with a binary nucleus. Such objects are important tests of binary interaction theories. Longward of 2800 Å, A35's spectrum is dominated by its G8IV star, thus UV-FUV observations are needed to study its hot central star (see Figure 2).

The hot component of A35 is a DAO white dwarf (as speculated by Grewing & Bianchi 1988 and confirmed here). We modeled its FUV/UV spectrum using the plane-parallel, NLTE code TLUSTY. The derived parameters are shown below. We use a Kurucz model (Kurucz 1991) of T_{eff}=5 kK, $\log g$=3.5 for the G8IV star. A comparison of the model fits with the UV data are shown in Figure 2, and a close-up of the FUSE region is shown in Figure 3. The FUSE data have been reduced using the CALFUSE v2.0.4 pipeline.

Parameter	Value	Parameter	Value
T_{eff} (kK)	80±10	X_{He} ($X_\odot$)	0.3–0.5
$\log g$ (cm s^{-2})	$7.7^{+0.3}_{-0.7}$	X_C ($X_\odot$)	$5\,x10^{-3}$–10^{-2}
R_* (R$_\odot$ x10^{-2})	$1.65^{+1.0}_{-0.60}$	X_N ($X_\odot$)	$< 10^{-3}$
$\log L_*/L_\odot$	$1.0^{+0.6}_{-0.7}$	X_O ($X_\odot$)	$5\,x10^{-3}$–10^{-2}
M_{WD} (M$_\odot$)	$0.5^{+0.5}_{-0.4}$	X_{Si} ($X_\odot$)	$< 10^{-2}$
E_{B-V} (mag)	0.04±0.01	X_{Fe} ($X_\odot$)	0.1–0.5

The FUSE observations reveal a hot ($T \sim 2000$ K) circumstellar shell of H_2 around A35. Because the resulting absorption is so severe, the star and the H_2 gas had to be modeled concurrently. We have modeled the H_2 using a two component model, consisting of a hot [T = 2000 K, $\log N_i(H_2)$=17.4] and a cool [T = 200 K, $\log N_i(H_2)$=19.6] components. We also determine the H I column density to be $\log N_i$(H I)=20.9 by fitting the H Lyα feature (1216 Å). Our stellar model with our H_2 absorption model applied can be seen in Figure 3.

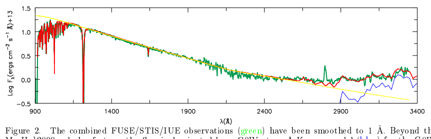

Figure 2. The combined FUSE/STIS/IUE observations (green) have been smoothed to 1 Å. Beyond the Mg II λ2800 nebular feature, the flux is dominated by a G8IV star. A Kurucz model (blue) for the G8IV star (T_{eff}=5 kK, $\log g$=3.5) scaled to the observed m_v=9.6, is shown. Our TLUSTY model (T_{eff}=80 kK, $\log g$=7.7), summed with the Kurucz model, is shown in red (also smoothed to 1 Å). Prior to FUSE, blackbody approximations (T_{eff}=120 kK) were made (yellow) to determine stellar parameters and fluxes. This illustrates the importance of the FUSE observations in determining the parameters of the hot central star. Note we have used a log flux scale for clarity. The FUSE range is shown on expanded scale in Figure 3, below.

A35 — Conclusions

Using a recent Hipparcos parallactic distance of D=163 pc (Gatti et al. 1998), reasonable assumptions about the geometry of the circumstellar shell and our measured H I and H_2 column densities, we derive the mass of the neutral circumstellar material to be $M_H \simeq 3.0$ M$_\odot$. The mass of the ionized gas, using $n_{ion} = 4.7$ cm^{-3} and a nebular radius of 7.5′ (Hollis et al. 1996), is 0.02 M$_\odot$. Combining these with our derived mass for the WD of 0.5 M$_\odot$, we estimate the progenitor mass of the hot central star of A35 to be $\simeq$3.5 M$_\odot$. Comparison of our derived T_{eff}, L_* with the post-asymptotic giant-branch (AGB) tracks of Blöcker (1995) or Vassiliadis & Wood (1994) and the calculations of Marigo (2001) indicate a current mass of ~ 0.6 M$_\odot$, an evolutionary age of $\gtrsim$300,000 yr, and a progenitor mass of $3 \lesssim M_{ZAMS} < 4$ M$_\odot$, consistent with our findings. This represents — to our knowledge — the first such empirical account of the total object (progenitor) mass, and thus a direct comparison to evolutionary calculations.

Our findings also indicate the evolution of the WD has not been impacted significantly by the presence of its cooler G8IV companion, further evidence that A35 is a wide binary system which did not undergo a common envelope phase as suggested by Gatti et al. (1998).

The FUV data flux is very sensitive to extinction, thus allowing us to precisely constrain E_{B-V}=0.04±0.01 towards this object. Using the typical ratio of N_i(H I)/ E_{B-V} for the ISM (Bohlin et al. 1978), this value corresponds to N_i(H I) $\simeq 1.9\,x10^{20}$, much smaller than our measured value of $7.9\,x10^{20}$. This result implies that there is little or no dust associated with the circumstellar neutral hydrogen.

Our work on A35 is an example of the usefulness of a comprehensive, multi-wavelength analysis to the study of CSPN evolution. We are currently performing similar analyses on the other Galactic and LMC CSPN.

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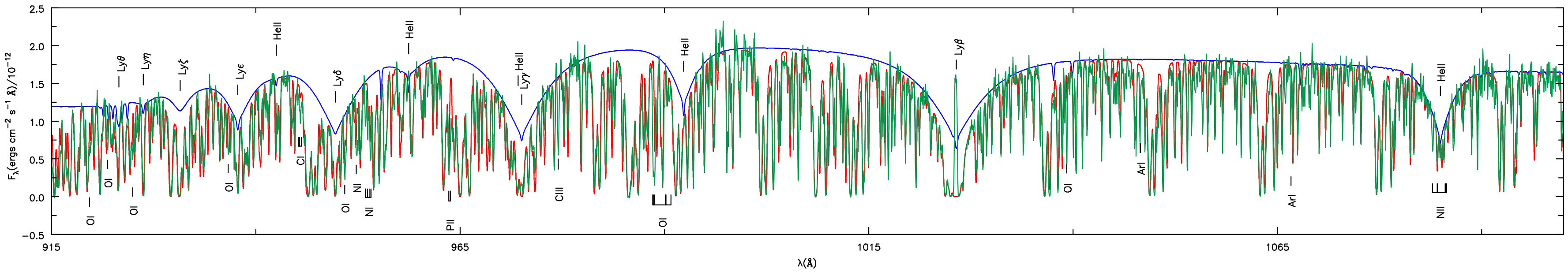

Figure 3. The FUSE data of the DAO white dwarf of A35 (green) shown at full resolution (0.05 Å bins). Our TLUSTY model (T_{eff}=80 kK, $\log g$=7.7, z=0.01 Z$_\odot$) is shown, both with (red) and without (blue) our HI/H_2 absorption models applied. A reddening of E_{B-V}=0.04 has been applied to the stellar model, and the prominent stellar and interstellar features are indicated.