Planetary Nebulae in the MW, LMC, SMC: results from FUSE and HST data

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ABSTRACT

We use FUSE and HST data to study Planetary Nebulae (PN) systems in the Milky Way, LMC and SMC. Theoretically, metallicity affects several aspects of the post-AGB evolution, including mass-loss and the yield of processed material, which are important factors in the chemical evolution of galaxies. Therefore, it is very important to study PNe in different environments. In Bianchi's FUSE programs, we observed CSPN in the Milky Way (Cycle 1), LMC (Cycle 2) and SMC (Cycle 3), representing a range of metallicities from solar to 1/10th solar. The far-UV range reveals the spectrum of the central star (CSPN), uniquely enabling a direct estimate of the ionizing source parameters. Combined with archive HST data, these spectra provide a measurement of T_{eff}, log g, L_{bol}, abundances, wind velocity and mass-loss rate for these post-AGB stars. Additionally, these spectra provide a measurement of the circumstellar H_2 and HI, which — added to the mass of the central star and of the ionized shell — allows us to test theoretical initial-final mass relations, and to put together a complete picture of the star's evolution.

1. Data and Reduction

The *Far Ultraviolet Spectroscopic Explorer* (FUSE) covers the wavelength range of 905—1187 Å at a spectral resolution of $R \approx 20,000$ (or 15 $\mathrm{km\,s^{-1}}$). The data were taken using FUSE's LWRS ($30'' \times 30''$) aperture, in "time-tag" mode, have been calibrated using the most recent FUSE data reduction pipeline, efficiency curves and wavelength solutions (CALFUSE v2.2.2). The FUSE spectra presented here were made by combining the data from different segments, weighted by detector sensitivity, were rebinned to a uniform dispersion of 0.05 Å. Bad areas of the detectors, and those regimes affected by an instrumental artifact known as "the worm" (FUSE Data Handbook v1.1), were excluded. The flux calibration accuracy of FUSE is $\lesssim 10$ % (Sahnow et al. 2000). Some of our LMC and SMC objects are among the dimmest stellar objects observed by FUSE, requiring long integration times, and their reduction required customized background subtraction (see Herald & Bianchi 2003 for details).

Archival data from the Hubble Space Telescope's *Faint Object Spectrograph* (FOS) and *Space Telescope Imaging Spectrograph* (STIS) instruments were also utilized for the LMC and SMC PN. The FOS archive data were taken in the $1''$ aperture, whose actual diameter following the COSTAR installation is $0.86''$. The angular sizes of the LMC PN are typically $\lesssim 1''$, so the FOS spectroscopy typically includes the entire nebula. For some objects, high-resolution STIS data was available, taken with the $52''$x$0.2''$aperture. The spectra are shown in Figs. 1-3.

2. Modeling

The modeling of these spectra generally consists of three parts: modeling the central star spectrum, the nebular continuum emission longwards of 1200 Å, and the sight-line Hydrogen (atomic and molecular)

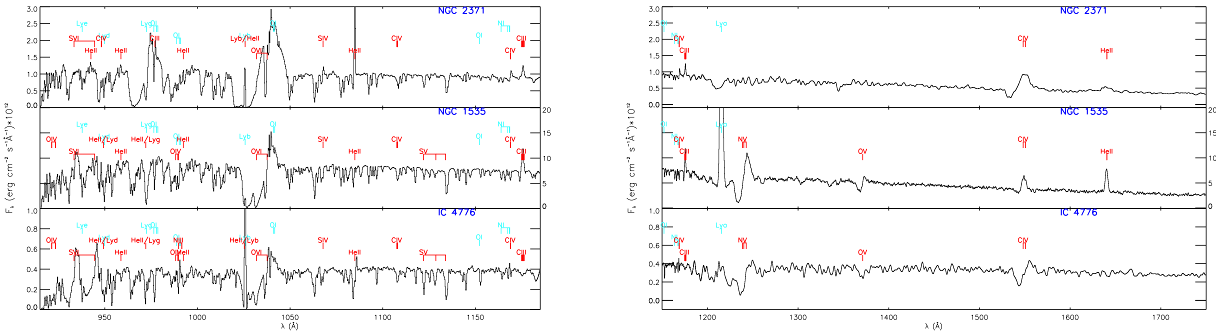

Fig. 1.— FUSE far-UV (**left**) and IUE/HST-STIS UV data (**right**) for two CSPN from our galactic program (IC 4776 and NGC 2371) and one archive CSPN (NGC 1535) are shown, along with line identifications (dark labels are stellar lines, faint are air glow). These objects show strong wind features, notably OVI $\lambda\lambda$ 1032,1038 and SVI $\lambda\lambda$ 933,944. They represent a phase of evolution between [WC] stars (CSPN with Wolf-Rayet spectra) and PG 1159 stars (hot stars with dwindling winds that are the entry point of the white dwarf cooling sequence). These "[WC]-PG 1159" objects thus cover a parameter range where their winds are in the process of "turning-off". In the UV, stellar features are sparse, owing to the high temperatures of these objects ($T_{eff} \gtrsim 90$ kK). Our modeling also indicates mass-loss rates of $10^{-8} - 10^{-7}$ $M_{\odot}$/yr. The terminal velocities of these winds are $\gtrsim 2300$ km/s. These mass-loss rates and terminal velocities are higher than those of the (lower metallicity) LMC sample (see Fig 2).

shortwards. Iterations between each are required to achieve a consistent solution. However, we discuss each in turn for clarity.

The Central Star: The hot CSPN require non-LTE models to derive stellar photospheric and wind parameters. We use the codes TLUSTY (Hubeny & Lanz 1995) and CMFGEN (Hillier & Miller 1998, 1999; Hillier et al. 2003). CMFGEN solves the radiative transfer equation in extended spherical atmospheres, and is necessary for those CSPN showing wind features (*e.g.* some of our Galactic objects and almost all of our LMC sample — see Figs. 1 and 2).

The Nebula: The LMC PN of our sample are compact, and so their optical and UV spectra are contaminated by the nebular continua and lines, which obscure and sometimes entirely mask the stellar spectrum. The nebular continuum emission models were computed accounting for two-photon, H and He recombination, and free-free emission processes using the nebular parameters (T_e, n_e, He/H, He^{2+}/He^{+}) found in the literature. The computed emissivity coefficient of the nebular gas is scaled as an initial approximation to the total flux at the Earth by deriving the emitting volume from the dereddened absolute $H\beta$ flux. In the cases where the observing aperture is smaller than the nebular size, the nebular flux was scaled by the corresponding geometrical factor. Because of this masking by the nebular continuum, FUSE provides the first and only direct measurement of stellar temperatures and luminosities for these objects.

Molecular Hydrogen (H_2): The FUV is home to numerous H_2 transitions, from the Lyman ($B^1\Sigma_u^+$–$X^1\Sigma_g^+$) and Werner ($C^1\Pi_u^{\pm}$–$X^1\Sigma_g^+$) series. For a "cool" molecular gas (*i.e.*, $\lesssim 100$ K) as found in the ISM, only the ground vibrational state is populated and the absorptions associated with its different rotational states show up as a series of discreet absorption "bands". However, we find that for many objects of our samples, a significant amount of *hot* (*i.e.*, 1000—5000 K) H_2 lies along their sight-lines, presumably associated with the nebula. At such temperatures, higher vibrational states become populated and the absorption pattern is much more complex, obscuring the entire FUV continuum spectrum. Thus the modeling of the star requires a working H_2 model.

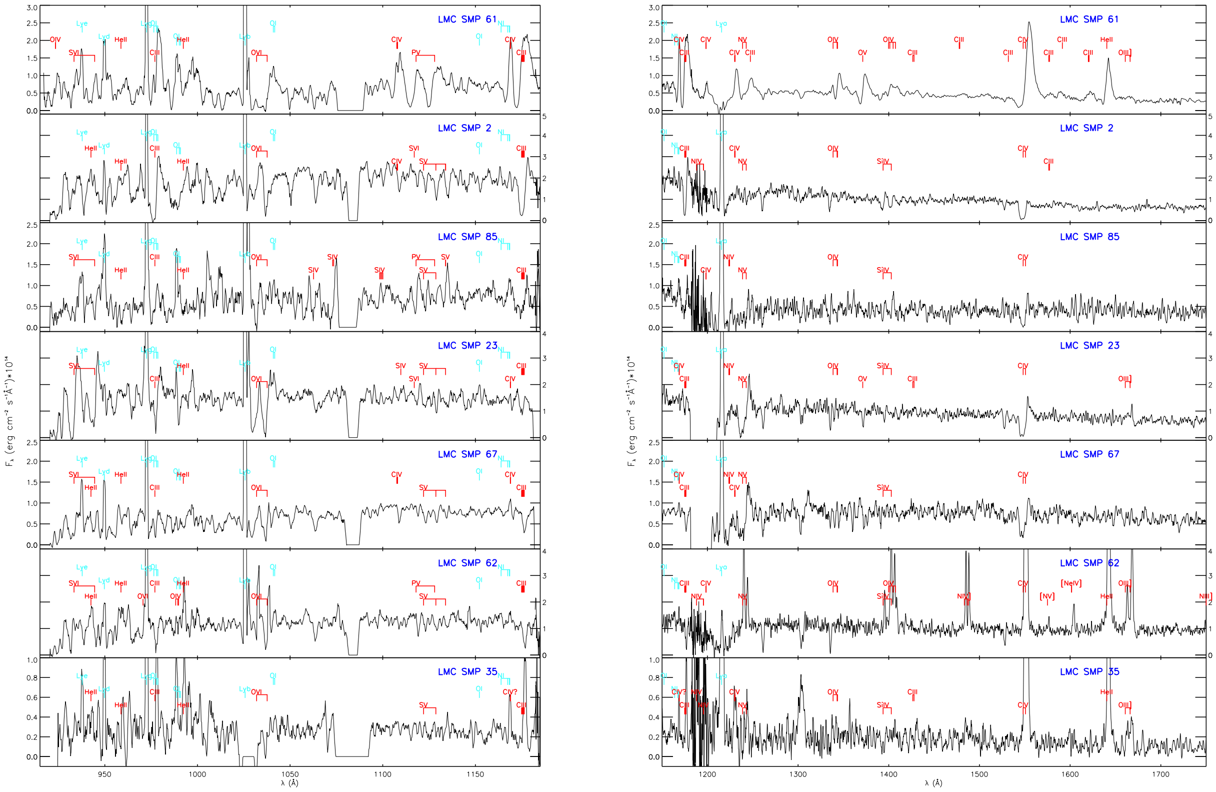

Fig. 2.— FUSE far-UV (**left**) and FOS/STIS HST UV data (**right**) of our LMC program stars. These PN are compact, and so are relatively young. Stars are arranged by spectral morphology, by decreasing strength of CIII λ1175, which is a strong (and non-saturated) mass-loss indicator in the parameter range of our program objects. Stellar and nebular lines are indicated by dark labels, airglow lines by faint labels. All objects show wind features (except perhaps LMC SMP 62). CIII features (either absorption or P-Cygni) are present in all objects, placing an upper bound on the effective temperature of the sample. LMC SMP 61 is a true [WC] star (a CSPN that has a Wolf-Rayet spectra) with mass-loss rate of $\sim 10^{-6}$ $M_\odot$/yr. The others have mass-loss rates ranging from $\sim 10^{-9}$ to $\sim 10^{-7}$ $M_\odot$/yr. All stars have terminal velocities between 750—1300 km/s, significantly lower than in the Galactic counterparts.

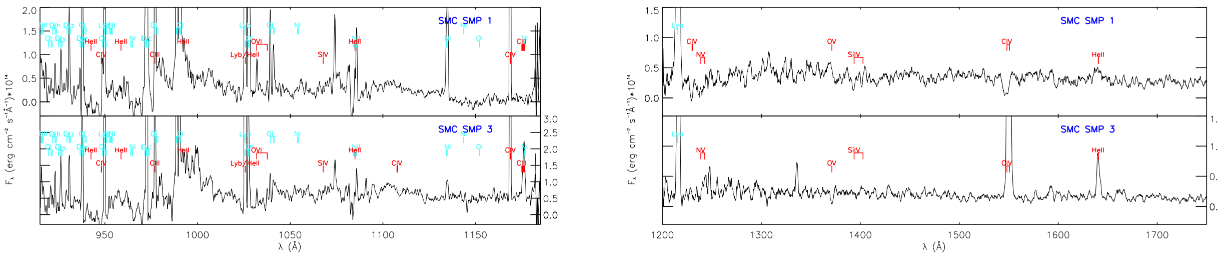

Fig. 3.— FUSE far-UV (**left**) and HST-FOS UV data (**right**) of two SMC CSPN from our FUSE program (4 objects total). The FUSE spectra are strongly affected by airglow lines (faint labels). Stellar and nebular lines are marked with dark labels. Both objects appear to have wind features, albeit weaker than those of the LMC sample.

3. Sample Results

One interesting phenomenon revealed by FUSE is that hot molecular hydrogen ($T \gtrsim 1000$ K) associated with PN is not uncommon. Fig. 4 shows a (non-windy) example of our modeling for Abell 35, a Galactic DAO white dwarf CSPN (*i.e.* a very evolved object). Our TLUSTY model ($T_{eff} = 80$ kK, $\log g = 7.7$, z=0.01$Z_\odot$) is shown, with our H_2 absorption models applied. We fit the H_2 features found in the FUSE spectrum using a two component model, and measured the HI column density [$\log N(HI)$=19.6] from STIS data. With these derived column densities, we assume typical gas/dust ratio for the ISM and make reasonable assumptions about the geometry of the circumstellar shell to derive the mass of the neutral circumstellar material to be $M_H \simeq 3.0\,M_\odot$ and the mass of the ionized mass to be 0.02 $M_\odot$. Combined with our derived a WD mass (0.5 $M_\odot$), we estimate the progenitor mass of A35 to be $\simeq$3.5 $M_\odot$, a result which can be compared with predictions of evolutionary codes. Details of this work can be found in Herald & Bianchi (2002).

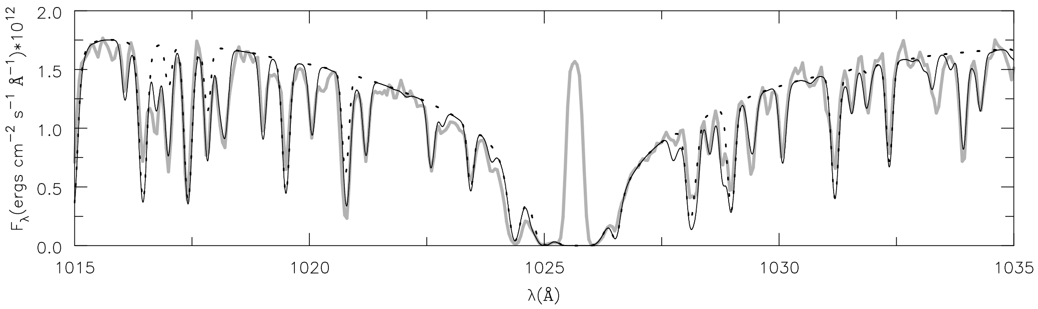

Fig. 4.— Fitting H_2 with a 2-component model: FUSE data (grey) and stellar model spectrum with H_2 absorption applied from "cool" component [$\log N(H_2, \mathrm{cool})$ = 19.6 cm^{-2}, T = 200 K] only (dashed), and from both "cool" and "hot" [$\log N(H_2, \mathrm{hot})$ = 17.4 cm^{-2}, T = 1250 K] components applied (solid). The cool component alone is not adequate for reproducing all the observed H_2 absorption features.

In Fig. 5 we show LMC SMP 23, an example of our LMC PN spectra. The nebular continuum emission is significant in the FOS spectrum, and so the star, nebula, and HI/H_2 must be modeled concurrently.

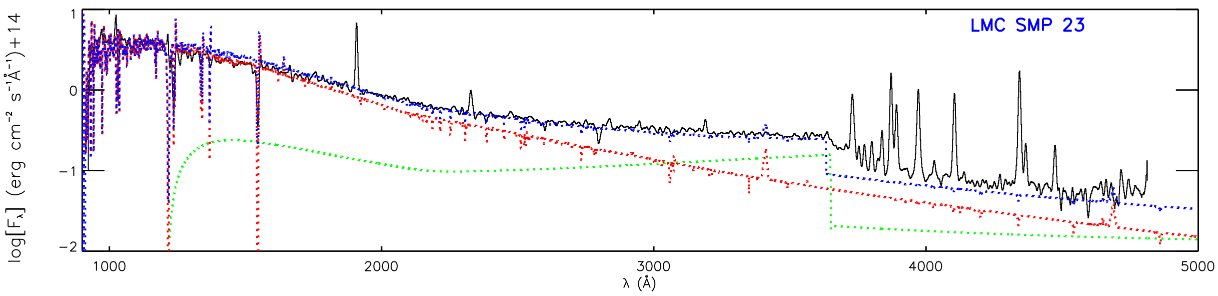

Fig. 5.— FUSE and FOS data for LMC SMP 23 are shown (solid). The best fit CMFGEN model ($T_{eff} \simeq 64$ kK, $\dot{M} \simeq 7.0 \times 10^{-8}$ $M_\odot$/yr, $R \simeq 0.65$ $R_\odot$, $L_{bol} \simeq 6500$ $L_\odot$) is also shown (medium dotted). We have applied Hydrogen absorption models, which include a hot molecular component ($\log N = 16.7$ cm^2, $T \sim 5000$ k). The computed nebular continuum is shown (light dotted), along with the sum of the stellar and nebular models (heavy dotted). The nebular continuum significantly contributes to the flux longwards of λ1200. Note the logarithmic flux scale.

This study is currently being extended to an additional LMC CSPN sample (spanning higher temperatures) during FUSE cycle 4. Preprints on the subject can be downloaded from **http://dolomiti.pha.jhu.edu** or requested from **bianchi@pha.jhu.edu**.

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