Ultraviolet imaging of planetary nebulae with *GALEX*

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Abstract Over four hundred Galactic Planetary Nebulae (PNe) have been imaged by *GALEX* in two ultraviolet (UV) bands, far-UV (FUV, 1344–1786 Å, $\lambda_{eff} = 1528$ Å) and near-NUV (NUV, 1771–2831 Å, $\lambda_{eff} = 2271$ Å). We present examples of extended PNe, for which UV spectroscopy is also available, to illustrate the variety in UV morphology and color, which reflects ionization conditions. The depth of the *GALEX* imaging varies from flux $\approx 0.4/5 \times 10^{-18}$ ergs cm⁻² s⁻¹ Å⁻¹ □''⁻¹ (*FUV/NUV*) for exposures of the order of ~ 100 seconds, typical of the survey with the largest area coverage, to $\sim 0.3/8.3 \times 10^{-19}$ ergs cm⁻² s⁻¹ Å⁻¹ □''⁻¹ (*FUV/NUV*) for ~ 1500 sec exposures, typical of the second largest survey (see Bianchi in *Astrophys. Space Sci.* 320:11, 2009; Bianchi et al. in *Adv. Space Res.* 53:900, 2014). *GALEX* broad-band FUV and NUV fluxes include nebular emission lines and in some cases nebular continuum emission. The sensitivity of the *GALEX* instrument and the low sky background, especially in FUV, enable detection and mapping of very faint ionization regions and fronts, including outermost wisps and bow shocks. The *FUV-NUV* color of the central star provides a good indication of its T_{eff} , because the *GALEX* FUV-NUV color is almost reddening-free for Milky Way type dust (Bianchi et al. in *Astrophys. J. Suppl. Ser.* 230:24, 2017; Bianchi in *Astrophys. Space Sci.* 335:51, 2011, Bianchi in *Astrophys. Space Sci.* 354:103, 2014) and it is more sensitive to hot temperatures than optical colors.

Keywords Astronomical data bases: surveys · Stars: white dwarfs · ISM: planetary nebulae: general · ISM: planetary nebulae: individual

1 Introduction

Planetary Nebulae (PN) are the evolved descendants of intermediate mass stars, the major providers of important chemical elements such as carbon and nitrogen. The expanding layers of gas, shed in the previous Red Giant phases and then ionized by the hot central star (CSPN), offer clues about the progenitor's evolution, in particular about the chemical elements produced by nucleosynthesis and brought up to outer layers, about the temperature and luminosity of the stellar remnant, through their ionization, and about mass-loss and wind momentum in subsequent phases, through their complex expansion kinematics and density structure. Studies of both the nebula and the central star benefit by observations in the Ultraviolet (UV), where crucial diagnostic transitions of important chemical elements, and trace elements, abound (e.g., Bianchi 2016, 2012). CSPNe, the hottest stars known, emit most of their light at UV wavelengths or shortwards. *IUE* and *HST* spectrographs have collected UV spectra of a few hundred PNe, mostly of their central stars. FUSE has provided high resolution spectra at shorter UV wavelengths (905–1187 Å) for several objects. The FUSE observations, although difficult to obtain and limited to the brightest sources, have enabled major discoveries, such as highly ionized neon in the wind of CSPNe (Herald et al. 2005; Herald and Bianchi 2009, 2011; Keller et al. 2011, among others), whose lines are a crucial diagnostics for the hottest ($T_{eff} > 85000$ K) CSPN; the brightest PNe in the Magellanic Clouds were also observed by FUSE (Her-

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Fig. 1 The “Helix” PN (NGC 7293, PK036-57.1) observed with *GALEX*. The color-composite image shows FUV in blue, NUV in yellow. Note that field stars, which are mostly of low temperature, appear yellow. At a distance of 219 pc (Harris et al. 2007), the *GALEX* $\sim 5''$ resolution corresponds to 0.005 pc. The lower panel shows a zoomed-

in portion of the image, and a plot of archival *IUE* spectra taken in the bright part of the nebula, with the *GALEX* transmission bands overplotted, suggesting that the FUV flux mostly originates from HeII emission in the inner regions

ald and Bianchi 2004, 2007). For a review of the role of UV observations in the understanding of CSPNe see Bianchi (2012).

A completely different, new type of information has become available thanks to the deep sensitivity and wide field of view of the *GALEX* instrument. In this work we show examples of UV images of Planetary Nebulae, which

uniquely complement ground-based and *HST* imaging in optical emission lines, and spectroscopic information.

2 The data: UV imaging

Figures 1 to 3 show FUV and NUV imaging data of selected PN obtained with *GALEX*. The instrument was first

Fig. 2 Examples of PNe observed with *GALEX*, for which *IUE* spectra exist. The right-hand panels show radial profiles of the background-subtracted FUV flux (solid line) and NUV flux (dotted line), and 1σ error on the FUV flux profile (diamonds). In most cases the central star is saturated, so the flux value at radius ~ 0 is not meaningful. Images

have different size (in arcsec), to optimally display the PN: the extent of each object in UV can be estimated from the X-axis scale of the flux profiles. Archival *IUE* spectra are shown with the *GALEX* FUV, NUV transmission curves overlapped

described by Martin et al. (2005), and its performance by Morrissey et al. (2007). The characteristics of the data and the sky surveys are described by Bianchi (2009), Bianchi et al. (2011a, 2011b, 2014); in depth discussion of data quality and an updated version of science-enhanced catalogs of UV sources are presented in Bianchi et al. (2017, 2018).

GALEX imaged the field in two bands simultaneously: FUV (1344–1786 Å, $\lambda_{eff} = 1528$ Å) and NUV (1771–2831 Å, $\lambda_{eff} = 2271$ Å), with a field of view of 1.28/1.24° [FUV/NUV] diameter, and resolution of $\approx 4.2/5.3''$ [FUV/NUV]. The images, reconstructed from photon counting detector recordings, are sampled with virtual pixels of $1.5''$ size. *GALEX* sky coverage is fairly complete except for the Galactic plane, due to brightness safety limits (see Bianchi et al. 2017, 2014) which explains why the known PNe samples, mostly concentrated near the Galactic plane, are not entirely included in the UV surveys.

Of the over 1000 known Galactic Planetary Nebulae, about 400 are included in the *GALEX* UV imaging surveys, out of the 1312 objects list of Kerber et al. (2003) with an additional ~ 20 objects from the list of 111 new PN candidates of Acker (2016, Vizier online Table 1). Most are observed in the All-sky Imaging Survey (AIS), which has by far the largest sky coverage (see Bianchi et al. 2014, 2017), with a typical minimum exposure of ~ 100 seconds (5σ flux limit $\sim 0.4/5 \times 10^{-18}$ ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$ □ $''^{-1}$ in FUV/NUV). Some objects have exposures up to several thousand seconds.

3 Discussion

Figures 1, 2 and 3 show seven PNe observed by *GALEX*, for which *IUE* archival spectra exist. The spectra are use-

Fig. 3 Examples of PNe observed with *GALEX*, for which *IUE* spectra exist (continued from previous figure). For these objects we show *IUE* spectra both of the central star and of PN regions excluding the central star

Fig. 4 Nebular continuum emission computed for a typical range of physical conditions electron temperature (T_e), electron density (N_e), and He abundance (see *legenda*). The transmission curves of *GALEX* FUV, NUV imaging filters are overplotted

Fig. 5 Distribution of *GALEX* magnitudes (left) and *FUV-NUV* color (right) for the PNe in the *GALEX* UV surveys. About 400 PNe have NUV measurements (thin-line, large histogram in the left panel), but only about 100 of them were observed with both FUV and NUV detectors on (thick-lines, smaller histograms on the left panel). The magnitudes correspond to the best-fit of each source shape as determined

by the pipeline; more details for extended objects resolved by *GALEX* will be provided in a forthcoming paper, where measurements of the central star will be isolated, and curve-of-growth provided for the nebula (Gómez-Muñoz et al. 2018). The vertical lines mark the flux limit above which non-linearity sets in (10% roll-off limit), for FUV and NUV (blue-dashed and red-dotted lines respectively)

ful to interpret the nature of the UV emission in the broad-band images of the nebula. There is little overlap between the *GALEX* sample and the PNe observed spectroscopically by *IUE* or *HST*, because the objects observed spectroscopically were mostly too bright for *GALEX*; on the other hand, interesting features such as faint outer shells, wisps and sharp cusps at the edges of the outer shells, seen clearly in some *GALEX* images, are beyond the reach of past spectroscopic capabilities, and mostly inaccessible also to current and forthcoming UV spectrographs. *GALEX* FUV and NUV images present a unique advantage, as they reveal outer features which are critical e.g., to interpret the dynamical co-evolution of the nebular shell within the surrounding medium (e.g., Villaver et al. 2018) as well as a challenge, because the broad-band filters may include several emission lines (Figs. 2 and 3) as well as stellar (in the PN center) and nebular continuum (Fig. 4). To help the interpretation of the *GALEX* broad-band fluxes, the scant *IUE* spectroscopic data and *GALEX* grism data (e.g., Bianchi et al. 2012) will be complemented by a grid of ionization models (Gómez-Muñoz et al. 2018); consistency with corollary data further helps the interpretation of the UV images.

Figures 2 and 3 show for each PN the *GALEX* combined FUV and NUV image, and radially averaged flux profiles.

For the objects with archival UV spectroscopy, some central stars exceed the brightness limit for *GALEX* non-linearity or saturation, therefore the flux profile is not meaningful at radius ~ 0 , and measurements of *FUV* and *NUV* magnitudes for such CSPNe are not reliable. For PNe with marked asymmetries a radially averaged flux profile is a simplified representation, nonetheless it gives a compact and homogeneous indication of the overall flux level and *FUV-NUV* color distribution, with good significance because of the integration over annuli areas.

The sample in Figs. 2 and 3 shows a wide variety in morphology and ionization structure, illustrating the rich information contained in the UV wavelength range. The radial profiles in this bright sample show that almost everywhere in the nebula the *FUV* flux is higher than the *NUV* flux, in spite of the *NUV* filter having a much wider wavelength window. In some cases the *FUV* and *NUV* profiles are similar, which may also indicate nebular continuum emission significantly contributing to the flux. Figure 4 shows that the nebular continuum is rather flat across the *GALEX* wavelength range, for a range of typical nebular conditions. It is computed adding the contributions of H and He recombination and two-photon continuum. In some cases (e.g., NGC 40) the *FUV* and *NUV* profiles are significantly dis-

crepant, suggesting a complex ionization structure across the nebula.

Figure 5 gives an overview of the distribution in magnitude and FUV-NUV color of the known objects included in the *GALEX* surveys. Because the FUV detector failed before the mission was completed, and most of the regions towards the Galactic plane were observed late in the mission (Bianchi et al. 2014, 2017), about 400 objects have at least NUV measurements, and about 100 of them were observed with both NUV and FUV detectors on. Some PNe are included in more than one observation, amounting to a total of over 600 measurements of ~ 400 objects. The magnitudes used for Fig. 5 are the best fit to the source shape performed by the *GALEX* pipeline, thus they may have a different meaning for extended (resolved) or compact objects, the relative contribution of the central star and nebular flux varying across the sample. A forthcoming work will extricate measurements of the central star and curves of growth for the PN flux for objects extended enough to be resolved by *GALEX* (Gómez-Muñoz et al. 2018).

More information on *GALEX* data, science catalogs and projects can be found at the author's *UVSKY* web site <http://dolomiti.pha.jhu.edu/uvsky>.

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