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, \( \lambda_{\text{eff}} = 1528 \) Å) and near-NUV (NUV, 1771–2831 Å, \( \lambda_{\text{eff}} = 2271 \) 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 \( \approx 0.4/5 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ arcsec}^{-1} \) (FUV/NUV) for exposures of the order of \(~ 100 \) seconds, typical of the survey with the largest area coverage, to \(~ 0.3/8.3 \times 10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ arcsec}^{-1} \) (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 \( T_{\text{eff}} \), 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, 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 \( (T_{\text{eff}} > 85000 \text{ K}) \) CSPN; the brightest PNe in the Magellanic Clouds were also observed by FUSE (Her...
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 ∼ 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.

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
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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 $\sim 0$ 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 overplotted 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. 2014, 2017), with a typical minimum exposure of $\sim 100$ 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.
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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 legend). 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).

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-

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 $\sim 0$, 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.
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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