THE BORN-AGAIN PLANETARY NEBULA A78: AN X-RAY TWIN OF A30

J.A. TOALÁ¹, M.A. GUERRERO¹, H. TODT², W.-R. HAMANN², Y.-H. CHU^{3,†}, R.A. GRUENDL³, D. SCHÖNBERNER⁴, L.M. OSKINOVA², R.A. MARQUEZ-LUGO¹, X. FANG¹, AND G. RAMOS-LARIOS⁵

¹Instituto de Astrofísica de Andalucía IAA-CSIC, Glorieta de la Astronomía s/n, 18008 Granada, Spain; toala@iaa.es

²Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Str. 24/25, D-14476 Potsdam, Germany

³Department of Astronomy, University of Illinois, 1002 West Green Street, Urbana, IL 61801, USA

⁴Leibniz-Institut Für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany and

⁵Instituto de Astronomía y Meteorología, Av. Vallarta No. 2602, Col. Arcos Vallarta, 44130 Guadalajara, Mexico

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ABSTRACT

We present the XMM-Newton discovery of X-ray emission from the planetary nebula (PN) A78, the second born-again PN detected in X-rays apart from A30. These two PNe share similar spectral and morphological characteristics: They harbor diffuse soft X-ray emission associated with the interaction between the H-poor ejecta and the current fast stellar wind, and a point-like source at the position of the central star (CSPN). We present the spectral analysis of the CSPN, using for the first time a NLTE code for expanding atmospheres which takes line blanketing into account for the UV and optical spectra. The wind abundances are used for the X-ray spectral analysis of the CSPN and the diffuse emission. The X-ray emission from the CSPN in A78 can be modeled by a single CVI emission line, while the X-ray emission from its diffuse component is better described by an optically thin plasma emission model with temperature kT=0.088 keV ($T \approx 1.0 \times 10^6$ K). We estimate X-ray luminosities in the 0.2–2.0 keV energy band of $L_{\rm X,CSPN}=(1.2\pm0.3)\times10^{31}$ erg s⁻¹ and $L_{\rm X,DIFF}=(9.2\pm2.3)\times10^{30}$ $erg s^{-1}$ for the CSPN and diffuse components, respectively.

Subject headings: planetary nebulae: general – planetary nebulae: individual (A78) – stars: winds, outflows - X-rays: ISM

1. INTRODUCTION

Born-again planetary nebulae (PNe) are thought to have experienced a very late thermal pulse (VLTP) when the central star (CSPN) was on the white dwarf (WD) track. The VLTP event occurs when the thermonuclear burning of hydrogen in the stellar envelope has built up a shell of helium with the critical mass to ignite its fusion into carbon and oxygen (Herwig et al. 1999; Lawlor & MacDonald 2006; Miller Bertolami & Althaus 2006; Miller Bertolami et al. 2006). As the WD envelope is shallow, the increase of pressure from this last helium shell flash leads to the ejection of newly processed material inside the old PN, leaving the stellar core intact. As the stellar envelope expands, its effective temperature decreases and the star goes back to the asymptotic giant branch (AGB) region in the HR diagram. The subsequent stellar evolution is fast and will return the star back to the post-AGB track in the HR diagram (e.g. Miller Bertolami et al. 2006): the envelope of the star contracts, its effective temperature and ionizing photon flux increase, and a new fast stellar wind develops. This canonical model, however, has notable difficulties to reproduce the relatively low C/O ratio and high neon abundances found in born-again PNe (e.g., Wesson et al. 2003, 2008). Alternative scenarios, invoking the possible evolution through a binary system or a nova event immediately after the late helium shell flash, have been discussed by Lau et al. (2011), although none of them are completely satisfactory.

The born-again phenomenon is rare, with A30, A58

(Nova Aql 1919), A78, and the Sakurai's object (V 4334 Sgr) being the most studied objects of this class. These PNe harbor complex physical processes: the hydrogenpoor material ejected by the star during the born-again event will be photoevaporated by the ionizing photon flux from the CSPN and swept up by the current fast stellar wind (see Guerrero et al. 2012; Fang et al. 2014). These objects evolve very fast after the VLTP, thus, they provide a rare opportunity to study such complex phenomena and their real-time evolution (e.g., Evans et al. 2006; Hinkle et al. 2008; Clayton et al. 2013; Hinkle & Joyce 2014).

Among these PNe, A30 and A78 share similar characteristics suggesting that they are at a comparably late stage after the born-again event. They exhibit large $(\sim 2' \text{ in size})$ limb-brightened outer shells that surround an ensemble of H-poor clumps that are prominent in [O III] narrow band images (Jacoby 1979, see Figure 1). The outer hydrogen-rich shells are ellipsoidal in shape and expand at $\sim 40 \text{ km s}^{-1}$, while the H-deficient knots detected in [O III] have velocities up to 200 km s⁻¹ (Meaburn & Lopez 1996; Meaburn et al. 1998). The central parts in A30 and A78 were imaged by the Hubble Space Telescope (HST; Borkowski et al. 1993; Fang et al. 2014). The detailed HST WFPC2 [O III] images revealed cometary structures distributed on an equatorial plane (a few arcsec from the star) and polar features, which, in the case of A78, are more diffuse and are located at $\sim 12-14''$ from its CSPN (see Figure 1-right panel).

X-ray emission has been detected within a number of PNe, including A30 (e.g., Guerrero et al. 2012; Kastner et al. 2012; Ruiz et al. 2013; Freeman et al. 2014, and references therein). This born-again PN has

[†]Now at the Institute of Astronomy and Astrophysics, Academia Sinica (ASIAA), Taipei 10617, Taiwan



FIG. 1.— He II (left) and [O III] (center) narrow-band images of A78 as obtained at the Nordic Optical Telescope (see Section 3 for details), and (right) *HST* WFPC2 F502N image of the central part of A78. The equatorial plane and the bipolar flows are marked with a dashed-line ellipse and arrows, respectively.

been studied with *ROSAT* (PSPC and HRI), *Chandra*, and *XMM-Newton* X-ray satellites (Chu & Ho 1995; Chu et al. 1997; Guerrero et al. 2012). Its X-ray emission originates from the CSPN, but there is also diffuse emission spatially coincident with the cloverleaf-shaped H-poor structure detected in [O III]. The X-ray emission from both the CSPN and the diffuse extended emission are extremely soft.

The X-ray properties of A30 and the similarities of this nebula to A78 motivated us to obtain XMM-Newton observations, as the only previous X-ray observations of A78 by Einstein yielded a rather insensitive upper limit (Tarafdar & Apparao 1988). In this paper we present the analysis of new XMM-Newton observations that reveal the existence of hot gas associated with the H-poor knots inside the eye-shaped inner shell of A78, and also a point-like source of X-ray emission at its CSPN. The outline of this paper is as follows. The stellar wind properties and abundances of A78 CSPN are derived in §2. The XMM-Newton observations are presented in §3, and the spatial distribution and spectral properties of the X-ray emission in §4 and §5, respectively. A discussion is presented in §6 and we summarize our findings in §7.

2. NLTE ANALYSIS OF THE CENTRAL STAR

We analyzed the optical and UV spectra of the CSPN of A78 using the most recent version of the Potsdam Wolf-Rayet (PoWR) model atmosphere¹. The PoWR solves the NLTE radiative transfer problem in a spherical expanding atmosphere simultaneously with the statistical equilibrium equations and at the same time accounts for energy conservation. Iron-group line blanketing is treated by means of the superlevel approach (Gräfener et al. 2002), and a wind clumping in first-order approximation is taken into account (Hamann & Gräfener 2004). We did not calculate hydrodynamically consistent models, but assumed a velocity field following a β -law with $\beta = 1$. We also performed tests with different β -laws, e.g., $\beta = 0.8$, $\beta = 2$, and a double- β law, but we found the impact of different β -laws to be much smaller than the change of other parameters, such as effective temperature and mass-loss rate. Our

computations applied here include complex atomic models for helium, carbon, nitrogen, oxygen, neon, fluorine, hydrogen, and the iron-group elements.

The synthetic spectrum was corrected for interstellar extinction due to dust by the reddening law of Cardelli et al. (1989), as well as for interstellar line absorption for the Lyman series in the UV range.

The UV spectrum of the CSPN of A78 has been observed by the Far Ultraviolet Spectroscopic Explorer (FUSE) and the International Ultraviolet Explorer (IUE) satellites. Data from these observations have been retrieved from MAST, the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute². We used the FUSE observation with ID e1180101000 (PI: J. Kruk) obtained on 2004 November 11 in the spectral range 916-1190 Å for a total exposure time of 58 ks. The *IUE* observations in the spectral range 1150-1975 Å consists of two datasets with IDs SWP19879 and SWP19906. both taken with the large aperture at high dispersion with total exposure times of 25.5 ks and 25.2 ks, respectively. Only low dispersion *IUE* observations were available for the spectral range 2000-3300 Å. The data set with ID LWP23314LL obtained through the large aperture for a total exposure time of 600s was used. Optical spectra of $R \approx 6000$ were obtained by K. Werner using the TWIN spectrograph on the 3.5m-telescope at Calar Alto in October 1990 and in September 1991 (see Werner & Koesterke 1992).

Since the stellar spectra of the CSPN of A30 (Guerrero et al. 2012) and A78 are similar, the spectral fits resulted in similar wind properties and abundances (see Table 1). For the determination of the stellar temperature we used mainly the ratio of the line strengths of O VI vs. O V wind lines. The best fit to these lines was obtained with an effective temperature of $T_* = 117 \pm 5$ kK (see Figures 2 and 3).

From the strengths of the emission and P Cygni lines we derived the mass-loss rate under the assumption of a typical central star luminosity and mass of $L = 6000 L_{\odot}$ and $M = 0.6 M_{\odot}$ (see e.g. Schönberner et al. 2005;

¹ http://www.astro.physik.uni-potsdam.de/PoWR

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Parameter	Value	Comment		
$T_{\rm eff} (\rm kK)^{a}$	117			
$\log(L/L_{\odot})$	3.78	Adopted		
$M_{*}(M_{\odot})$	0.6	Adopted		
$R_* (R_{\odot})^{\rm b}$	0.19	$R_* \propto L^{1/2}$		
$R_{\tau=2/3}(R_{\odot})$	0.19			
$v_{\infty} (\mathrm{km} \mathrm{s}^{-1})$	3100			
D (clumping factor)	10	Adopted		
$\log \dot{M} (M_{\odot} \text{ yr}^{-1})$	-7.8	$\dot{M} \propto D^{-1/2} L^{3/4}$		
d (kpc)	1.40	$d \propto L^{1/2}$		
E_{B-V} (mag)	0.12			
Ab	undances (mass fraction	on)		
He	0.55			
С	0.30			
Ν	0.015			
0	0.10			
Ne	0.04			
F	1.3×10^{-5}			
Fe-group	1.4×10^{-4}			

TABLE 1 PARAMETERS OF THE CSPN OF A78

^a T_{eff} is defined as the effective temperature at the radius R_* .

^b The stellar radius R_* refers to, by definition, the point where the radial Rosseland optical depth is 20.



FIG. 2.— Details of the normalized UV spectrum of A78. Observations (blue thin line) from *FUSE* (upper panels) and *IUE* (lower panel) are shown together with the synthetic spectrum of our model (dashed lines) with parameters as in Table 1. The model spectrum was convolved with a Gaussian with 0.5 Å FWHM to match the resolution of the observation. *Top-left panel:* A model with 4% Ne (red dashed) compared to a model with only solar Ne abundance (green dashed). *Top-middle panel:* Best-fit model with $v_{\infty} = 3100 \text{ km s}^{-1}$ plus depth dependent microturbulence (red dashed). *Top-right panel:* Best-fit model to the Fe VII 1141.43 Å line with 10% solar Fe abundance (green dashed). This panel also includes the F VI 1139.5 Å line, where the vertical lines in the *FUSE* spectrum indicate different Doppler shifts with respect to the F VI line. *Bottom panel:* Our best-fit model (red dashed) vs. *IUE* observation.



FIG. 3.— Optical spectrum of the central star of A78. Normalized observation (blue) vs. synthetic spectrum of our best-fit model (red dashed). The model spectrum was convolved with a Gaussian with 2 Å FWHM to match the resolution of the observation, inferred from the interstellar Na I doublet.



FIG. 4.— Details of the optical spectrum of A78: Observation (blue thin solid lines) vs. models without hydrogen (red thick dashed), with 10% H (green thick dotted), and with 30% H (black thin dashed).



FIG. 5.— Spectral energy distribution (SED) of the central star of A78 from the UV to the infrared range. Observations (blue) are photometric measurements in the indicated bands and calibrated IUE and FUSE UV spectra. The theoretical SED derived from our stellar model with the parameters compiled in Table 1 is also shown.

Miller Bertolami & Althaus 2007). The inferred value of $\dot{M} = 1.6 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ is about half of the value from Werner & Koesterke (1992) and Leuenhagen et al. (1993), also because we account for clumping and use a different luminosity (see Table 1 for scaling relations). Indeed, the mass-loss rate determined by Koesterke & Werner (1998) is the same as ours, if rescaled to the values of distance and stellar luminosity used in our analysis.

The blue edge of the P Cygni profiles was used to estimate a terminal wind velocity of about 3100 ± 100 km/s, consistent with that found by Guerrero & De Marco (2013). Additional broadening due to depth-dependent microturbulence with $v_{\rm D} = 50$ km s⁻¹ in the photosphere up to $v_{\rm D} = 300$ km s⁻¹ in the outer wind was taken into account and allows to fit the widths of the O VI and the C IV resonance lines simultaneously (see Figure 2).

The strong Ne VII line at 973.33 Å (Herald et al. 2005) observed in the UV spectrum (see Figure 2) can only be reproduced by models with a supersolar Ne abundance. Similarly, the strength of the N v lines (Figures 2 and 3) implies a supersolar nitrogen abundance of 1.5% by mass. To reproduce the observed strength of the F vI 1139.5 Å line a fluorine abundance of at least $25 \times$ the solar value is needed, similar to what was found by Werner et al. (2005) for the same object as well as for other H-deficient post-AGB stars. They also mentioned an asymmetry of this line meaning that the line is partly formed in the wind, as reproduced by our wind models (see Figure 2).

Initial solar abundances of the iron group resulted in Fe VII lines more intense than those observed in the FUSE spectrum (see Figure 2-top right panel). Accordingly, the abundance of the iron group elements had to be reduced down to 1/10 of the solar value to obtain a consistent fit of the Fe VII lines. Our iron estimate is in contrast to that found by Werner et al. (2011), who suggested that the strong Fe VIII 1148.22 Å line would imply solar Fe abundances. They recognize, however, that the Fe VIII line profile, much broader than the prediction from their static NLTE models, called for an analysis using expanding atmosphere models as that performed here. Following the interpretation of the subsolar Fe/Ni ratio reported in Sakurai's object (Asplund et al. 1999), the iron deficiency in A78 can be explained by the conversion of iron into heavier elements by s-process neutron captures.

We also tried to constrain the hydrogen abundance. The best fit to the Balmer lines is obtained by models without hydrogen. However, at the given resolution and S/N of our optical observation, a hydrogen abundance below 10% by mass would escape detection (Figure 4).

The absolute flux of the model is diluted by the distance to the central star, which we consider to be a free parameter. We obtain a consistent fit of the spectral energy distribution from the far UV to the near infrared range (see Figure 5) for a reddening of $E_{B-V} = 0.12$ mag and a distance of d = 1.4 kpc. These values are consistent with the reddening of $E_{B-V} = 0.15$ mag and the distance of d = 1.5 kpc reported by Jeffery (1995) and Harrington et al. (1995), respectively. We note, however, that our distance estimate is 30% smaller than that of Frew (2008).

3. Observations

XMM-Newton observed A 78 on 2013 June 3 (Observation ID 0721150101, PI: M.A. Guerrero) using the European Photon Imaging Cameras (EPIC) and Reflective Grating Spectrographs (RGS). The observations were performed in the Full Frame Mode with the thin optical filter for a total exposure time of 59.4 ks. The data were reprocessed with the XMM-Newton Science Analysis Software (SAS) 13.5 with the most up-to-date XMM-Newton calibration files available on the Current Calibration File as of 2014 January 7. The net exposure times were 59.4, 59.1, 59.1, 59.4, and 59.4 ks for the EPICpn, EPIC-MOS1, and EPIC-MOS2, RGS1, and RGS2, respectively. After processing the effective times were reduced to 23.9, 43.6, 42.5, 59.1, and 59.0 ks for the EPIC-pn, MOS1, MOS2, RGS1, and RGS2 respectively.

To help study the distribution of the X-ray emission, we obtained He II and [O III] narrow-band images of A78 on 2014 July 19 using the Andalusian Faint Object Spectrograph and Camera (ALFOSC) at the Nordic Optical Telescope (NOT). The central wavelengths and bandpasses (FWHM) of the filters are 4687 Å and 43 Å for He II, and 5010 Å and 35 Å for [O III], respectively. The images have total exposure times of 1800 s each. The average seeing during the observation was ~0".7. The final processed images are shown in the left and middle panels of Figure 1.

4. SPATIAL DISTRIBUTION OF THE X-RAY EMISSION

For direct comparison with the XMM-Newton observations of A30, we created EPIC images of A78 in four different energy bands: soft 190-275 eV, medium 275–450 eV, hard 450–600 eV, and total 190–600 eV. Individual EPIC-pn, EPIC-MOS1, and EPIC-MOS2 images were extracted, merged together, and corrected for exposure maps. The final smoothed exposure-corrected images of the four energy bands are show in Figure 6.

Figure 6 reveals a bright source associated with the CSPN and diffuse X-ray emission within A78. Both the point-like source and diffuse emission seem to fade away at energies >450 eV. Other point-like sources are present in the panels shown in Figure 6, in particular the point-like X-ray source detected in all energy bands $\sim 37''$ north of the CSPN of A78. The optical counterpart of this X-ray source is detected faintly in the optical images in Figure 1 with coordinates (R.A,Dec.)=(21^h 35^m 28.76^s, +31° 42' 31.2''). No counterpart is identified in the NED and SIMBAD databases. This source is most likely a background source, as it does not have any morphological correlation with A78.

In Figure 7 we compare the spatial extent of the Xray emission with the optical H α and [O III] images presented in Figure 1. The diffuse X-ray emission in A78 does not fill the elliptical outer shell, but it seems to be bounded by the [O III] bright eye-shaped shell, as it was also the case for the distribution of diffuse X-rays in A30. Furthermore, there is a local peak in the diffuse X-ray emission that seems to be associated with a H-poor clump toward the SW direction from the CSPN. In a similar manner, A30 also presents a maxima in the X-ray emission associated with the H-poor clumps, suggesting that the two born-again PNe may have similar origins of X-ray emission.



FIG. 6.— Exposure-corrected XMM-Newton EPIC images of A78 in different bands. The images have a pixel size 1". The images are centered at the central star in A78. Other point-like sources are presented on the images. The black lower contours correspond to 1, 3, 5, and 10σ over the background level, while the white upper contours represent 20% and 60% of the peak intensity.

To better assess the extent and intensity of the diffuse X-ray emission, we have used the SAS task *eradial* to extract a radial profile of the X-ray emission centered on the CSPN of A78 and compare it to the theoretical point-spread function (PSF) of the observation. This comparison is shown in Figure 8, where the PSF scaled to the radial profile fits nicely the emission from the CSPN until a radius of 12". An excess of diffuse emission is detected above the PSF profile between 17–35". To estimate the contribution of the CSPN emission to the diffuse emission obtained with *eradial* for distances smaller than 34", and computed the percentage to the total emission from the

CSPN using the PSF model. The contribution of the CSPN to the total emission is 99% for radial distances <12'', 79% for distances <34'', and only 24% for distances between 17'' and 34''.

5. SPECTRAL PROPERTIES OF THE X-RAY EMISSION

To study the global spectral properties of the X-ray emission from A78, we have extracted the EPIC-pn, EPIC-MOS, and combined RGS1+RGS2 spectra shown in Figure 9. The EPIC spectra have been extracted from an elliptical region that encloses the whole emission from A78. These spectra (Figure 9-top) are very soft and resemble those presented by Guerrero et al. (2012) for A30. The EPIC-pn spectrum peaks at 0.3-0.4 keV with a rapid



FIG. 7.— Composite color picture of the XMM-Newton EPIC 190-600 eV (blue) and NOT ALFOSC [O III] (green) and He II (red) images of A78. To emphasize the comparison between the spatial distributions of the X-ray-emitting gas and nebular component in A78, X-ray contours of the same energy band have been overplotted. The emission to the north of A78 corresponds to a point-like X-ray source in the field of view of the observations (see text).



FIG. 8.— EPIC-pn radial profile of the X-ray emission from A78 extracted using *eradial*. The dashed line is the fitted PSF to the radial profile.

decay at energies greater than 0.5 keV. This spectrum shows evidence for an emission line at ~ 0.58 keV, absent in the EPIC-pn spectrum of A30, which would correspond to the O VII triplet. The count rates for the EPIC-pn, EPIC-MOS1, and EPIC-MOS2 in the 0.2–2.0 keV energy range are 18.2, 2.4, and 2.1 counts ks⁻¹, respectively.

The combined RGS1+RGS2 background-subtracted spectrum of A78 can help us identify the emission detected around 0.3-0.4 keV in the EPIC-pn camera. Fig-



FIG. 9.— XMM-Newton EPIC (top) and combined RGS1+RGS2 (bottom) background-subtracted spectra of A78. The best-fit models to the EPIC-pn and MOS cameras are shown with solid lines in the top panel (see § 5.1). Residuals of these fits are also shown. The RGS spectrum displays the CVI emission line at 33.7 Å(=0.37 keV).

ure 9-bottom panel shows that this is mostly due to the C VI emission line at 33.7 Å (=0.37 keV). However, because of the low MOS and RGS count rates, we will mainly focus on the spectral analysis from the spectrum extracted from the EPIC-pn camera for further discussion.

We have extracted separately EPIC-pn spectra for the CSPN and for the diffuse X-ray emission. The spectrum from the CSPN was extracted using a circular aperture of radius 12'' centered at the position of the star with a background extracted from regions with no contribution of diffuse emission. The spectrum from the diffuse emission was extracted using an elliptical aperture that covered the extension of the [O III] filamentary shell with a minor axis of 34'' to avoid contamination from the point-like source to the North. According to §4, a circular region of radius 17'' centered at the position of the CSPN was excised to reduce the contamination from the CSPN. The resultant background-subtracted EPICpn spectra of the CSPN and that of the diffuse component, shown in Figure 10, have net count rates of 8.8 and $8.0 \text{ counts } \text{ks}^{-1}$, respectively.

Figure 10 shows subtle differences in the spectral shapes from the CSPN and diffuse emission. For example, the spectrum from the diffuse component (Figure 10-right) shows the spectral line at ~0.58 keV, whilst that of the CSPN (Figure 10-left) does not. As for A30, both spectra seem to peak at the energy ~0.37 keV of the C VI line.

5.1. Spectral analysis

The spectral analysis of the X-ray emission from A78 was performed using XSPEC v.12.7.0 (Arnaud 1996). The spectral fits include one or two of the following components: (1) an emission line at ~0.37 keV, and (2) an *apec* optically thin plasma emission model with abundances as those listed in Table 1. The estimates of the luminosity and electron density assume a distance of 1.4 kpc (see §2).

The emission model needs to be absorbed by the material along the line of sight whose origin can be interstellar, but also circumstellar. Manchado et al. (1988) measured a nebular extinction towards the dusty, inner filaments of $E_{B-V} = 0.15$ mag, which is in agreement with the UV absorption towards the CSPN derived in \S 2, but these measurements do not help disentangle the relative contributions of interstellar and circumstellar absorptions. To determine these contributions, we have used long-slit intermediate-dispersion optical spectroscopic observations (Fang et al., in preparation) of the outer ellipsoidal shell to derive the interstellar extinction towards the outer nebular regions. Our measurements indicate a negligible extinction, $E_{B-V} = 0.014$ mag, thus proving that most of the absorption towards the central regions of A78 has a circumstellar origin, i.e., as in A30. The absorption would be produced by the dust in the central regions of A78. Since the IR emission of the dust (Kimeswenger et al. 1998; Phillips & Ramos-Larios 2007) shares the same spatial distribution of the H-poor knots, the chemical composition of the dust is expected to be similar to that of the H-poor knots. Given the large metal-to-hydrogen ratio of this absorbing material, a relatively small hydrogen column density, $N_{\rm H} \approx 2 \times 10^{16}$ $\rm cm^{-2}$, will contain similar amounts of carbon and oxygen as the interstellar hydrogen column density required to produce the observed absorption.

As a first inspection, the spectra of the three EPIC cameras were fit simultaneously using an *apec* component and an emission line at 0.37 keV. This gives a good quality fit (χ^2 =72.6/77=1.06) with a plasma temperature of kT=0.072 keV and ΔE =26 eV³. The model is compared to the observed spectra in the 0.2–1.5 keV energy range in Figure 9-top, and the plasma temperature (kT), fluxes (f), emission line central energy (E), and normalization factors (A) of the best-fit models are listed in Table 2. The absorbed flux and intrinsic luminosity in the 0.2–2.0 keV energy range of this model are f_{TOT} =(2.2±0.8)×10⁻¹⁴ erg cm⁻² s⁻¹ and $L_{\text{TOT},X}$ =(2.1±0.6)×10³¹ erg s⁻¹.

Another emission model consisting of an *apec* component and two emission lines at 0.37 keV and 0.58 keV was tried in an attempt to reproduce the emission ex-

cess at ~0.58 keV, but it did not improve statistically the results of the previous fit. A simpler model, involving just one *apec* component, resulted in a poorer fit, $\chi^2/dof^4=70.26/45=1.56$, for a similarly low plasma temperature of kT=0.086 keV.

We next proceeded to perform spectral fits of the Xray emission from the CSPN and from the diffuse component separately. The different emission models used to describe these components are described in the next sections. We want to emphasize that the spectrum of the diffuse emission is contaminated by emission from the CSPN. This is not the case for the spectrum of the CSPN, which corresponds mostly to emission from the CSPN.

5.1.1. X-ray emission from the CSPN

The X-ray emission from the central star in A78 was first modeled by an *apec* plasma model. This resulted in a fit with reduced χ^2 greater than two and plasma emission model of kT=0.071 keV. The absorbed flux in the 0.2–2.0 keV energy range is $f_{\rm X}=(1.08\pm0.35)\times10^{-14}$ erg cm⁻² s⁻¹.

A second fit was performed using only the contribution of an emission line around ~0.37 keV. This model results in an improved fit with $\chi^2/dof=1.30$. The corresponding absorbed flux is $(1.12\pm0.20)\times10^{-14}$ erg cm⁻² s⁻¹, very similar to the flux level derived for the single *apec* model described above. The intrinsic X-ray luminosity of this model is $(9.9\pm2.4)\times10^{30}$ erg s⁻¹.

A third model including the combination of an *apec* model and an emission line at 0.37 keV model was also attempted, but this model does not improve the previous fits (χ^2 /dof=0.65). Indeed, XSPEC cannot constrain the temperature of the *apec* component.

The three resultant models are compared with the background-subtracted spectrum in the 0.2-1.5 keV energy range in Figure 10-left. The parameters of the best-fit models are summarized in Table 2.

5.1.2. The diffuse and extended X-ray emission

Similarly, the diffuse X-ray emission in A78 was first fit using an *apec* optically thin plasma model. The fit has a reduced χ^2 of 1.40, for a plasma temperature of kT=0.086 keV and an absorbed flux of $(9.70\pm0.25)\times10^{-15}$ erg cm⁻² s⁻¹.

The second fit adopted a single emission line at ~0.37 keV. This model resulted in a similar quality fit, with χ^2/dof of 1.38, for an emission line with energy 0.362 keV and $\Delta E=36$ eV. The corresponding absorbed flux is $(8.8\pm0.5)\times10^{-15}$ erg cm⁻² s⁻¹.

The third model used a combination of an *apec* plasma model and an emission line at 0.37 keV. This model gives a reduced χ^2 of 1.32, but the plasma temperature is basically unconstrained and the line width implies it is unresolved. Still, the resultant absorbed flux, $(1.0\pm0.6)\times10^{-14}$ erg cm⁻² s⁻¹, is consistent with those implied by the other two models.

One final spectral fit was attempted taking into account that the CSPN contributes significantly to the emission registered in this region. This contribution was

 $^{^3}$ It is worth noting that, in the cases in which an emission line is used to model the X-ray emission, its line width is a few tens of eV, which means that the line is not resolved by EPIC-pn.

⁴ The degrees of freedom, dof, is equal to the number of spectral channels which are used into the fit minus the number of free parameters in the adopted model.



FIG. 10.— EPIC-pn background-subtracted spectra of the CSPN (left) and diffuse emission (right) of A78. Different line colors represent the different fits described in Table 2. The dotted histogram in the right panel illustrates the contribution of the CSPN to the diffuse emission.

Region	Model	kT	A_1^{**}	E	ΔE	A_2^{**}	$f_{\rm X}$	$\chi^2/{ m dof}$
		(keV)	(cm^{-5})	(keV)	(keV)	(cm^{-5})	$({\rm erg} {\rm cm}^{-2} {\rm s}^{-1})$	
A78	line+apec	$0.072^{+0.017}_{-0.013}$	1.60×10^{-9}	0.37	$2.6{\times}10^{-2}$	6.7×10^{-5}	2.20×10^{-14}	72.58/72 = 1.06
CSPN	apec	$0.071^{+0.003}_{-0.003}$	1.60×10^{-9}				1.1×10^{-14}	35.18/17 = 2.07
	line			$0.363^{+0.017}_{-0.018}$	3.0×10^{-2}	7.3×10^{-5}	1.1×10^{-14}	20.78/16 = 1.30
	line+apec	1-64	4.20×10^{-10}	$0.368\substack{+0.014\\-0.010}$	$2.1{\times}10^{-2}$	$6.6{\times}10^{-5}$	1.3×10^{-14}	$9.03/14 {=} 0.65$
Diffuse emission	apec	$0.086\substack{+0.010\\-0.012}$	7.20×10^{-10}				9.7×10^{-15}	33.80/24 = 1.40
	line			$0.362^{+0.025}_{-0.023}$	3.6×10^{-2}	5.8×10^{-5}	8.8×10^{-15}	31.75/23 = 1.38
	line+apec	1 - 40	5.95×10^{-11}	0.37	1.3×10^{-4}	4.6×10^{-5}	1.0×10^{-14}	29.09/22 = 1.32
Diffuse +CSPN spillover ^{***}	diffuse+line	$0.088^{+0.019}_{-0.017}$	5.20×10^{-10}	0.37	2.3×10^{-2}	1.4×10^{-5}	9.6×10^{-15}	31.38/23=1.36

TABLE 2 Best-fit models for the X-ray emission in $A78^*$

^{*} All models were computed assuming an absorbing column density of $N_{\rm H} = 2 \times 10^{16} {\rm ~cm^{-2}}$.

^{**} The normalization parameter A is defined as $A=1\times10^{-14}\int n_{\rm e}n_{\rm H}dV/4\pi d^2$, where d is the distance, $n_{\rm e}$ is the electron number density, and V the volume, all in cgs units.

*** The line component is for the spillover CSPN emission.

estimated to be $\approx 1/4$ of the emission detected in the region defined for the CSPN. We then scaled the CSPN line emission model listed in Table 2 to this flux level and added it as an additional spectral component to the model of the diffuse emission, which consisted of an *apec* model. The best-fit parameters of this model are listed in the last row of Table 2. The quality of the fit is similar to the previous ones, but the temperature of the plasma is constrained to kT=0.088 keV. Its corresponding flux is $(9.6\pm1.6)\times10^{-15}$ erg cm⁻² s⁻¹, but only $(7.4\pm1.7)\times10^{-15}$ erg cm⁻² s⁻¹ corresponds to the diffuse X-ray emission. The intrinsic X-ray luminosity of the net diffuse emission is $(6.8\pm1.7)\times10^{30}$ erg s⁻¹.

The best-fit models are compared to the backgroundsubtracted spectrum from the diffuse emission in the 0.2–1.5 keV in Figure 10-right, and the parameters listed in Table 2.

6. DISCUSSION

The present *XMM-Newton* observations have discovered very soft X-ray emission in the born-again PN A78. These X-ray observations reveal the existence of a point-like source associated with the CSPN and a source of extended X-ray emission within A78. The spatial distribution of the diffuse X-ray emission does not fill the elliptical outer shell; instead, this emission can be associated with the H-poor knots and is enclosed by the filamentary cavity detected in [O III] narrow band images.

The best-fit model for the CSPN of A78 seems to be that including only a line emission at ~0.37 keV; models including a plasma component cannot produce an acceptable fit to the data. The estimated total flux for the CSPN, accounting for the fraction of the PSF not included in the source aperture of radius 12", is $f_{\rm X,CSPN}=(1.32\pm0.24)\times10^{-14}$ erg cm⁻² s⁻¹ which corresponds to an intrinsic X-ray luminosity of $L_{\rm X,CSPN}=(1.2\pm0.3)\times10^{31}$ erg s⁻¹. The X-ray emission from the diffuse component in A78 is better explained by a thermal plasma with temperature of kT=0.088 keV ($T \approx 1.0 \times 10^6$ K). Its corresponding total flux, after subtracting the contribution from the CSPN and adding that of regions with aperture radius <17'', is $f_{\rm X,DIFF}=(1.0\pm2.2)\times10^{-14}$ erg cm⁻² s⁻¹, which corresponds to an intrinsic luminosity of $L_{\rm X,DIFF}=(9.2\pm2.3)\times10^{30}$ erg s⁻¹. The normalization parameter for the *apec* component ($A_1=5.20\times10^{-10}$ cm⁻⁵) has been used to estimate an electron density of the diffuse X-ray-emitting gas for a distance of 1.4 kpc as $n_{\rm e}=0.002 \ (\epsilon/0.1)^{1/2}$ cm⁻³, with ϵ as the gas-filling factor.

6.1. Comparison with A30

The four *bona fide* born-again PNe, A30, A58, A78, and Sakurai's object, represent different stage of the same evolutionary path. A30 and A78 are very similar in many ways. The morphology and spectral similarities between A30 and A78 and their central stars are remarkable. Their optical narrow band images show similar limb-brightened outer nebulae which correspond to the expected shell in the canonical formation of a PN (Kwok et al. 1978; Balick 1987), with estimated dynamical ages, $\tau_{\rm dyn}{}^5$, of 12,500 and 10,700 yr for A30 and A78, respectively. The processed H-poor material is thought to have been ejected around a thousand years ago (e.g., Guerrero et al. 2012; Fang et al. 2014), which means that the stellar wind velocity must have increased very rapidly within this time-lapse in both cases. The interaction of this stellar wind with the material ejected in the born-again event is responsible for the shaping of the cloverleaf and eye-shaped H-poor clumpy distributions in A30 and A78, respectively (see Fang et al. 2014).

The X-ray properties of A30 and A78 are very much alike. The diffuse X-ray emission can be modeled by an optically thin plasma model with similarly low temperatures for both PNe, besides the different relative importance of an emission line at ~ 0.58 keV attributable to O VII in their spectra. The origin of this hot plasma may be due to pockets of shocked and thermalized stellar wind, as the current fast wind from the CSPNe $(V_{\infty} \lesssim 4000 \text{ km s}^{-1})$ interacts with the processed material from the born-again ejection. The plasma temperature from an adiabatic shocked stellar wind can be determined by $kT = 3\mu m_{\rm H} V_{\infty}^2/16$, where μ is the mean particle mass (Dyson & Williams 1997). Therefore, for the stellar winds of A30 and A78, the temperature expected from the shocked material would be $T \sim 5 \times 10^8$ K, in sharp contrast with the observed temperatures. This discrepancy is found in all PNe in which diffuse X-ray emission is detected (see Ruiz et al. 2013, and references therein) and it is always argued that thermal conduction is able to reduce the temperature of the shocked stellar wind and to increase its density to observable values (Soker 1994). Even though one-dimension radiativehydrodynamic models on the formation of hot bubbles in PNe as those presented by Steffen et al. (2008) and Steffen et al. (2012) are able to explain this discrepancy, they are not tailored to the specific evolution of a star

that experiences a VLTP and creates a born-again PN. The fact that the diffuse X-ray emission of A30 and A78 is confined within filamentary and clumpy H-poor shells is a clear indication that a variety of physical processes are taking place to reduce its temperature. These processes may include mass-loading and photoevaporation from the H-poor clumps (Meaburn & Redman 2003), which mix the material with the thermalized shocked wind. The realization of numerical simulations on the formation of born-again PNe including these complex interactions and accounting for their singular abundances is most needed to understand the puzzling X-ray emission in these objects (Toalá & Arthur in prep.).

The X-ray emission from the point sources at the CSPNe of A30 and A78 is dominated by the C VI line. As discussed by Guerrero et al. (2012), the origin of the X-ray emission associated with the CSPNe of born-again PNe is inconclusive. Several mechanism are capable of producing this X-ray emission (e.g., charge transfer reactions from highly ionized species of carbon, oxygen, and nitrogen), but the present observations cannot provide a definite answer.

It is worth mentioning here that, given the large opacity of this material (see figure 11 in Guerrero et al. 2012), the C VI 0.37 keV emitting-region must be located at least a few stellar radii above the surface of the CSPN, which is consistent with the carbon-rich wind implied by our optical and UV spectral modeling.

6.2. On the origin of the hydrogen-poor material

The origin of the newly processed hydrogen-poor material inside the old PN is still a matter of debate (Lau et al. 2011). The Ne abundance of the ejecta can hold important clues. The Ne abundances of A30 and A58 (Wesson et al. 2003, 2008) seem to point to a nova eruption on an O-Ne-Mg WD (Lau et al. 2011). This hypothesis was invoked by Maness et al. (2003) to interpret the high Ne abundances in the X-ray-emitting gas in BD+30°3639.

That is an interesting possibility worth to be explored in A78. First, we have to note that there is no significant contribution of Ne lines ($\sim 0.9 \text{ keV}$) to the observed spectrum of A78. This does not necessarily imply a low Ne abundance, because the temperature of the hot plasma in A78 is low to produce bright Ne IX and Ne X emission lines. To test this, we have compared the observed X-ray spectrum with models with Ne abundance enhanced by 5, 10, and 20 times the value reported in §2, where the mid values in this range implies Ne abundances by mass similarly high to those reported in A30 and A58. These changes in the abundances do not produce noticeable effects in the synthetic spectrum, revealing a fundamental insensitivity of the X-ray spectrum of A78 to the Ne abundance due to its low plasma temperature.

7. SUMMARY AND CONCLUSIONS

We report the XMM-Newton discovery of X-ray emission in A78, making it the second born-again PN detected in X-rays, besides A30 Guerrero et al. (2012). The X-ray data of A78 have been analyzed in conjunction with narrow-band optical images of the nebula to determine the spatial distribution of the hot gas. Multiwavelength spectral observations of its CSPN have also been analyzed using a NLTE code for expanding atmospheres

⁵ The dynamical age can be estimated as $\tau_{\rm dyn} = R/v_{\rm exp}$, where R and $v_{\rm exp}$ are the radius and velocity of the outer optical shell, respectively.

to assess its stellar parameters and wind properties. In particular we find:

- The spatial distribution and spectral properties of the X-ray emission detected towards A78, and the chemical abundances and stellar wind parameters of its CSPN are very similar to those reported for A30 by Guerrero et al. (2012).
- The X-ray emission from A78 consists of a pointlike source and diffuse emission. The point-like source is coincident with the position of the CSPN. The distribution of diffuse X-ray emission does not fill the outer nebular shell, instead it traces the H-poor clumps and eye-shaped cavity detected in [O III] narrow band images. An apparent maximum in the diffuse X-ray emission is detected at the location of one H-poor clump toward the southwest.
- The X-ray emission from A78 is very soft. Most of the X-ray emission has energies lower than 0.5 keV, pointing at the C VI 0.37 keV emission line. There is evidence for a weaker emission line at ~0.58 keV, which would correspond to the O VII triplet.
- The analysis of the optical and UV spectra of the CSPN of A78 helped us to constrain its abundances and stellar wind parameters. These have been used for the analysis of the X-ray spectra of A78.
- The best-fit model for the diffuse X-ray emission resulted in a plasma temperature of kT=0.088 keV $(T \approx 1.0 \times 10^6 \text{ K})$ with an estimated absorbed flux of
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 $f_{\rm X,DIFF}=1.0\times10^{-14}$ erg cm⁻² s⁻¹. The estimated X-ray luminosity is $L_{\rm X,DIFF}=9.2\times10^{30}$ erg s⁻¹. A variety of processes may have played significant roles in lowering the plasma temperature (e.g., mixing, ablation and photoevaporation) of the diffuse X-ray emission.

- The X-ray spectra of A78 cannot be used to constrain the Ne abundance of the hot plasma due to its low temperature.
- The main X-ray spectral feature in the CSPN in A78 is the C VI emission line, as revealed by the EPIC and RGS spectra. Its estimated flux in the 0.2–2.0 keV energy band is $f_{X,CSPN}=1.32\times10^{-14}$ erg cm⁻² s⁻¹ which corresponds to a luminosity of $L_{X,CSPN}=1.2\times10^{31}$ erg s⁻¹. The physical mechanism for the production of the emission associated with the CSPN of A78 is elusive, as it is also the case for the CSPN of A30.

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