**Wolf-Rayet Stars**
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# Diffuse X-ray Emission within Wolf-Rayet Nebulae

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We discuss our most recent findings on the diffuse X-ray emission within Wolf-Rayet (WR) nebulae. The best-quality X-ray observations of these objects are those performed by *XMM-Newton* and *Chandra* towards S 308, NGC 2359, and NGC 6888. Even though these three WR nebulae might have different formation scenarios, they all share similar characteristics: i) the main plasma temperatures of the X-ray-emitting gas is found to be $T$=[1–2]×$10^6$ K, ii) the diffuse X-ray emission is confined inside the [O III] shell, and iii) their X-ray luminosities and electron densities in the 0.3–2.0 keV energy range are $L_\mathrm{X}$ ≈$10^{33}$–$10^{34}$ erg s$^{-1}$ and $n_\mathrm{e}$ ≈0.1–1 cm$^{-3}$. These properties and the nebular-like abundances of the hot gas suggest mixing and/or thermal conduction is taking an important rôle reducing the temperature of the hot bubble.

## 1 Introduction

Massive stars represent the main source of feedback that govern the physics of the Interstellar Medium (ISM). The most massive stars ($M_\mathrm{i}$ $\gtrsim$25 M$_\odot$) will evolve through the red supergiant or yellow supergiant (RSG or YSG) or luminous blue variable (LBV) phase depositing up to half their masses into the ISM, to finally become Wolf-Rayet (WR) stars (e.g., Ekström et al. 2012, and references therein). During the intermediate RSG/YSG or LBV phase, the star develops a slow and dense wind ($\dot{M}$=$10^{-4}$–$10^{-3}$ M$_\odot$ yr$^{-1}$, $v_\infty$=10–100 km s$^{-1}$) with no significant UV flux. The final WR phase is characterized by a strong wind ($\dot{M}$=$10^{-5}$ M$_\odot$ yr$^{-1}$, $v_\infty$=1500 km s$^{-1}$) that sweeps up, shocks, and compresses the RSG/LBV slow material, while a newly developed ionising photon flux ionises the material. This combination of effects will lead to the formation of the so-called WR nebulae (or ring nebulae).

Before the current generation of X-ray satellites (e.g., *XMM-Newton*, *Chandra*, and *Suzaku*) the only WR nebulae reported to harbor diffuse X-ray emission were S 308 and NGC 6888 around WR 6 and WR 136, respectively (see, e.g., Wrigge 1999; Wrigge et al. 2005) but with low resolution X-ray maps. The reported plasma temperatures and X-ray luminosities of the X-ray-emitting gas were $T$ ≈$10^6$ K and $L_\mathrm{X}$ ≈$10^{34}$ erg s$^{-1}$, respectively.

In this talk we review the most recent *Chandra* and *XMM-Newton* observations towards S 308, NGC 2359, and NGC 6888 around WR 6, WR 7 and WR 136, respectively.

## 2 On the origin of the diffuse X-ray emission

An adiabatically shocked stellar wind can form a hot bubble inside a nebula with an estimated temperature of $k_\mathrm{B}T = 3\mu m_\mathrm{H} v_\infty^2/16$ (see Dyson & Williams 1997), where $\mu$ is the mean particle mass for fully ionised gas, $m_\mathrm{H}$ is the hydrogen mass, and $k_\mathrm{B}$ is the Boltzmann's constant. That is, for the estimated stellar wind velocities of WR 6 and WR 136 of $v_\infty$ ≈1700 km s$^{-1}$ (Hamann et al. 2006), hot bubbles with temperatures of $T$ ∼$10^7$–$10^8$ K are expected, which are in clear mismatch with the observed X-ray temperatures.

It was always argued that thermal conduction between the outer cold ($10^4$ K) nebular material and the hot bubble would lead to temperatures as those as reported by X-ray observations. In particular, the often cited work of Weaver et al. (1977), which assumes classical thermal conduction (e.g., Spitzer 1962), predicts higher luminosity values than those observed ($L_\mathrm{X}$ $\geqslant$$10^{35}$ erg s$^{-1}$). Recent numerical studies have shed light into this problem showing that as a result of the slow-wind/fast-wind interaction, the swept up shell will break up due to the formation of Rayleigh-Taylor and thin shell instabilities and will be a source of mass, reducing the temperature of the hot bubble, raising the density to observed values, and reproducing the observed X-ray luminosities (Toalá & Arthur 2011; Dwarkadas & Rosenberg 2013).

## 3 Notes on individual objects

To date, five WR nebulae have been reported in the literature to be observed with the current generation of X-ray satellites: S 308, NGC 2359, RCW 58, and NGC 6888 around WR 6, WR 7, WR 40, and WR 136, respectively, and the WR nebula around WR 16, but only diffuse X-ray emission has been detected in S 308, NGC 2359, and NGC 6888 (see Figure 1). In this section we will present a summary of the best-quality X-ray observations towards these three objects as performed with *XMM-Newton* and *Chandra* satellites.

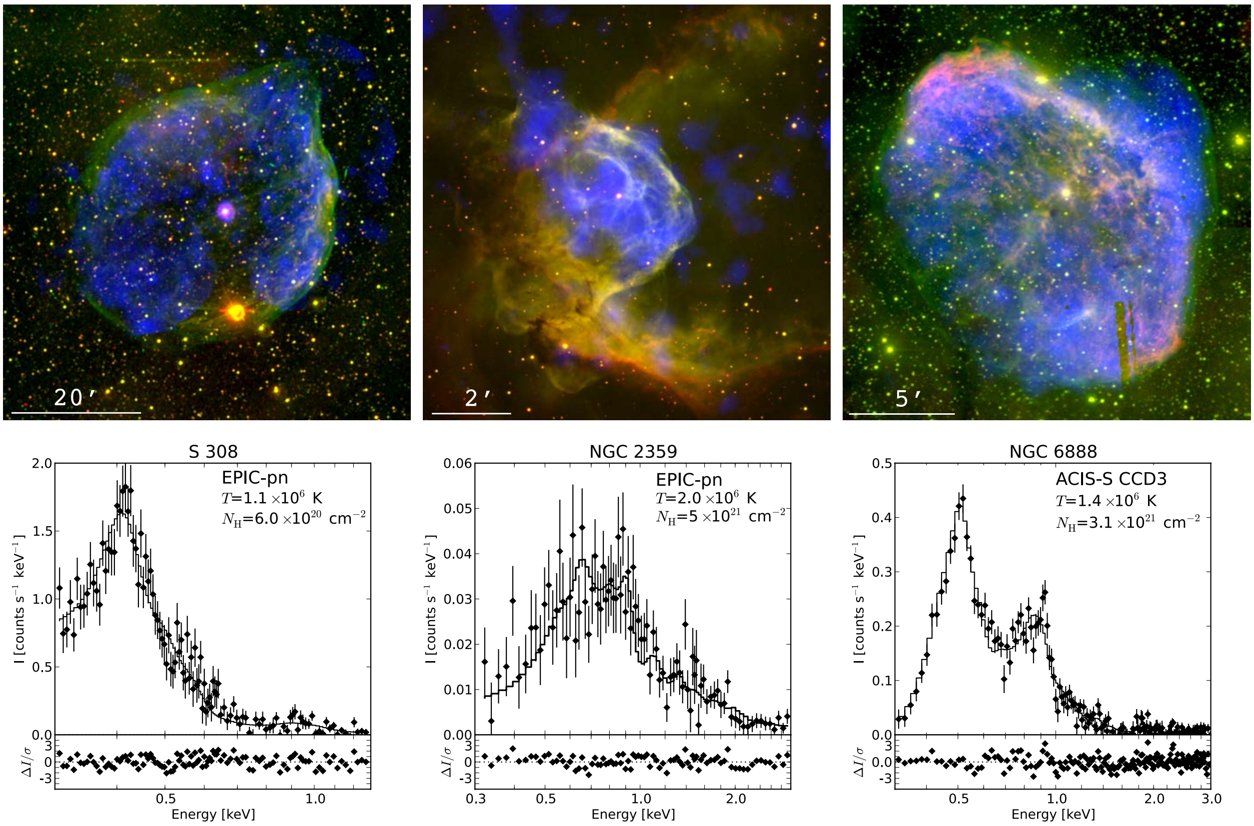

**Fig. 1:** X-ray emission from the WR nebulae S 308 (left panels), NGC 2359 (central panels), and NGC 6888 (right panels) around WR 6, WR 7 and WR 136, respectively. Top panels: Colour-composite pictures. Red, green, and blue correspond to the H$\alpha$, [O III], and diffuse X-ray emission as detected by *XMM-Newton*. Bottom panels: Background-subtracted spectra of the diffuse X-ray emission overplotted with their best-fit optically thin plasma model (solid line).

## 3.1 S 308 (WR 6)

S 308 around WR 6 is a nearly spherical nebula with an angular size of $\sim$40′ (in diameter) rendering it the most extended object of this class. Because of this, it had to be observed with 4 *XMM-Newton* pointings that mapped 90% of its total extension. The diffuse X-ray emission was found to be confined by the [O III] emission and displays a clear limb-brightened morphology (Toalá et al. 2012, see Figure 1 – upper left panel). The EPIC-pn background-subtracted spectrum presented in Fig. 1-bottom left panel shows that it is mainly dominated by the He-like triplet of N VI at 0.43 keV declining towards higher energies.

Toalá et al. (2012) presented a spectral study of S 308 concluding that spectra extracted from different regions can be modeled by an optically thin plasma model with nebular abundances and a main temperature of $T$=1.1$\times$10$^6$ K. The averaged luminosity and rms electron density are $L_\mathrm{X}$=2$\times$10$^{33}$ erg s$^{-1}$ and $n_\mathrm{e}$=0.1 cm$^{-3}$.

Toalá & Arthur (2011) argued that the most probable scenario formation of this nebula is that the central star, WR 6, might have evolved through a YSG phase in order to create such an extended nebula ($\sim$9 in radius) using a stellar evolution model with initial mass of 40 M$_\odot$ and initial rotation of 300 km s$^{-1}$ (Meynet & Maeder 2003).

## 3.2 NGC 2359 (WR 7)

The WR nebula NGC 2359 presents an interesting morphology: it displays a main central bubble with several blisters and filaments (see Fig. 1, upper central panel). The X-ray-emitting gas seems to fill the main cavity and the northeast blister. It is probable that this is also the case for the southeast blister, but molecular material in the line of sight towards this region precludes a clear view of the total distribution of the X-ray-emitting gas (see Rizzo et al. 2003, and references therein). Furthermore, as different velocity components have been reported by Rizzo et al. (2003) and the complex shape of the nebula points out an eruptive and non-isotropic origin as an LBV (Toalá et al. 2015a).

The EPIC-pn background-subtracted spectrum presents a broad peak around 0.5–0.9 keV, with two apparent maxima at 0.65 keV and ∼0.9 keV (Fig. 1, bottom central panel). Toalá et al. (2015a) estimated a main temperature of $T$=2×10$^6$ K adopting nebular abundances. The luminosity and rms electron density were estimated to be $L_{\rm X}$=2×10$^{33}$ erg s$^{-1}$ and $n_{\rm e}$ $\lesssim$0.6 cm$^{-3}$.

### 3.3 NGC 6888 (WR 136)

NGC 6888 is the most studied WR nebula in optical and X-rays. Its H$\alpha$ emission shows a nearly elliptical distribution of clumps but the [O III] emission reveals a more spherical morphology with a blowout towards the northwest (Fig. 1, upper right panel). Toalá et al. (2014) reported the study of the spectral properties as observed with *Chandra* ACIS-S CCD#3 and #4. Even though the spectral responses of these CCDs are not the same and the observations only covered 60% of the nebula, they manage to derive the physical parameters of the X-ray-emitting gas. Toalá et al. (2014) argued that there should be an extra maximum in the spatial distribution of the X-ray emission towards the northwest blowout.

The *Chandra* ACIS-S CCD#3 spectrum shows that there are two main components, one at the N VII at 0.5 keV and a secondary peak at 0.7–0.9 keV which could be associated to the Fe complex and Ne lines (see Fig. 1, bottom right panel). The estimated main plasma temperature was $T$=1.4×10$^6$ K assuming an optically thin plasma model with nebular abundances. The luminosity and rms electron density were estimated to be $L_{\rm X}$=7.7×10$^{33}$ erg s$^{-1}$ and $n_{\rm e}$ $\gtrsim$0.4 cm$^{-3}$.

We have recently obtained *XMM-Newton* observations of this nebula and have confirmed that the distribution of the X-ray-emitting gas presents three maxima: two associated to the caps and an extra spatially correlated to the northwest blowout as suggested by the *Chandra* observations (see Fig. 1, top right panel). The global physical properties of the X-ray emission in NGC 6888 are very similar as those obtained for the *Chandra* observations, but due to the superior spectral capabilities of the EPIC cameras we are able to detect spectral variations (temperature and nitrogen abundance) when studying in detail different regions within the nebula (Toalá et al. in prep.). It is probable that the variations in nitrogen abundance might be due to different mixing efficiencies in different regions of the nebula as suggested by the possible interaction with a cold filament as seen in infrared wavelengths (see discussion by Toalá et al. 2014).

## 4 Remarks

Even though these three WR nebula might have formed as the result of different stellar evolutionary paths, they all exhibit diffuse X-ray emission with soft temperatures. The main reason of this it is now understood: mixing of nebular material into the hot bubble by instabilities and/or thermal conduction, but the contribution of each effect has not been critically assessed so far. It would be also interesting to test numerically the effect of cooling due to the dust present in the nebula (Toalá et al. 2015b).

It is worth noting that the WR nebulae reported to harbor diffuse X-ray emission have very similar central stars: WN4–6 type stars with terminal wind velocities of $v_\infty$ ≈1700 km s$^{-1}$ and mass-loss rates of $\dot{M}$=2–5×10$^{-5}$ M$_\odot$ yr$^{-1}$ (Hamann et al. 2006). Those that do not exhibit diffuse X-ray emission have WN8h stars (e.g., WR 16 and WR 40) with lower stellar wind velocities ($v_\infty$=650 km s$^{-1}$) but similar mass-loss rates. In addition, our recently obtained *XMM-Newton* observations of the WR nebula NGC 3199 around WR18 also follow this trend (Toalá et al. in prep.): diffuse X-ray emission is detected in a WR nebula around a WN4-type star ($v_\infty$ ≈1700 km s$^{-1}$, $\dot{M}$=3×10$^{-5}$ M$_\odot$ yr$^{-1}$). A detailed analysis on these observations is still lacking in order to assess the physical properties of the diffuse X-ray emission and put it in context with S 308, NGC 2359 and NGC 6888.

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**Anthony Marston:** Please be careful with NGC 3199. It has ISM abundances and large masses almost certainly *not* associated with ejecta from the star. More likely, the X-rays are associated with a cluster/association of hot stars.

Jesús A. Toalá (left) with session chair Isabelle Cherchneff