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LETTER

Letter to the Editor

An explanation of observed trends in the X-ray emission from single Wolf-Rayet stars

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Abstract. The O and early B star winds show empirical correlations between X-ray ($L_{\rm x}$) and Bolometric ($L_{\rm Bol}$) luminosity as well as wind properties such as wind momentum and wind kinetic energy. Wolf-Rayet stars do not. We discuss scaling relations to qualitatively explain this lack of correlation among the WR winds and to quantitatively reproduce the observed ratio of X-ray luminosities between the N-rich WN types and C-rich WC types. If (a) the filling factor of hot X-ray emitting gas varies as $(\dot{M}/v_\infty)^{-1}$ for stars of different mass loss and terminal speed and (b) the ambient Wolf-Rayet wind component is optically thick to the hot gas X-rays, then a lack of correlation between $L_{\rm x}$ and wind parameters is to be expected. The emergent X-ray emission then depends only on factors relating to relative abundances and ionization. The observed ratio $L_{\rm X}({\rm WN})/L_{\rm X}({\rm WC})$ is consistent with our scaling analysis using typical WN and WC abundances.

Key words: stars: abundances – stars: early-type – stars: mass-loss – stars: Wolf-Rayet – X-rays: stars

1. Introduction

The early type O and B star winds are well described by line-driven wind theory (Lucy & Solomon 1970; Castor et al. 1975; Pauldrach et al. 1986; Friend & Abbott 1986), and this theory also explains the observed X-ray emission from hot stars as arising from wind shocks (Lucy 1982; Cassinelli & Swank 1983; Owocki et al. 1988). However the evolved massive Wolf-Rayet (WR) stars are different from O and B stars, in that the momentum of WR winds $\dot{M}v_\infty$ typically exceeds the single scattering limit L_*/c by an order of magnitude (e.g., Barlow et al. 1981). At present, the most promising model for accelerating the high mass loss WR winds derives from multiple scattering by lines (Lucy & Abbott 1993; Springmann 1994; Gayley et al. 1995). Importantly, Gayley & Owocki (1995) have shown that even with multiple scattering, the instability mechanism that leads to shock formation in the lower mass loss OB star winds should still operate in the WR winds, and so potentially account for the observed X-ray emission.

The first quantitative X-ray information on WR stars was obtained with EINSTEIN (0.2–4.0 keV) by Seward & Chlebowski (1982). Pollock (1987) has summarized the EINSTEIN results for 48 WR stars, which consist mostly of low S/N broadband measurements. He noted that N-rich WR stars (WN) tend are more luminous than the C-rich WR stars (WC) on average, suggesting as a potential explanation the different chemical compositions between the two types. The ROSAT All-Sky Survey (RASS) has provided PSPC broadband fluxes for nearly all galactic WR stars (Pollock et al. 1995). The softer ROSAT response (0.2–2.4 keV) has led to only few quantitative results on the generation and production of shocks in WR winds, with spectra existing only for WR binaries. However, the ROSAT data has revealed that unlike the O stars (e.g., Kudritzki et al. 1996), the X-ray luminosities $L_{\rm X}$ of single WN stars are *not* correlated with Bolometric luminosity $L_{\rm Bol}$, wind momentum $\dot{M}v_\infty$, wind kinetic luminosity $0.5\dot{M}v_\infty^2$, or WN subtype (Wessolowski 1996). Although fewer in number, likewise there are no such correlations for 17 single WC stars (see Fig. 1). This paper concerns the interpretation of these observations from considerations of scaling relations.

2. Simple theory of X-rays from stellar winds

Owocki & Cohen (1999) present a scaling analysis for the X-ray emission from hot star winds. They considered an exospheric approximation, where the observed X-ray emission arising from "hot" gas emerges only from radii exterior to the optical depth unity surface of radius r_1, with X-rays at smaller radii being completely attenuated. The radius r_1 is determined primarily by K-shell photoelectric absorption in the "cool" wind. The extent of r_1 is energy dependent, with

$$r_1(E) = \frac{\dot{M}}{4\pi v_\infty}\,\kappa(E), \tag{1}$$

with the opacity

$$\kappa(E) = \frac{\sigma(E)}{\mu_{\rm N}\,m_{\rm H}} = \frac{1}{\mu_{\rm N}\,m_{\rm H}}\sum_{\rm j}\frac{n_{\rm j}}{n_{\rm N}}\,\sigma_{\rm j}(E), \tag{2}$$

Send offprint requests to: rico@astro.gla.ac.uk for the ratio $n_{\rm j}/n_{\rm N}$ the relative abundance by number for atomic species j, and $\mu_{\rm N}$ the mean molecular weight per nucleon of the cool wind. Note that for early-type winds that have essentially no neutral gas, $\mu_{\rm N} = \mu_{\rm i}$, the mean molecular weight per ion, and $\mu_{\rm i}$ is the same for both the cool and hot gas components. Typical values of r_1 at 1 keV can range from the stellar radius R_* for B and some O star winds (entirely optically thin), to around $10R_*$ for other O star winds, to hundreds or thousands of R_* in the WR case (extremely optically thick). Thus, the wind attenuation can have a major influence on the emergent X-ray spectrum of stellar winds.

Owocki & Cohen (1999) showed that for a constant expansion wind, the exospheric approximation overestimates $L_{\rm X}$ by a factor of 2 only, as compared to an exact integration. Since $r_1 \gg R_*$ over a broad range of X-ray energies for the WR stars, a constant expansion wind is an excellent approximation. We therefore assume a spherical wind with density $\rho \propto r^{-2}$ and constant filling factor $f_{\rm X}$. We take the filling factor to be the same as Kudritzki et al. (1996), such that the emitted energy from volume dV is $j_\nu\, dV$, where the emissivity for X-ray emission is

$$j_\nu(E) = \frac{1}{4\pi}\, f_{\rm X}\, (n_{\rm e}\, n_{\rm i})_{\rm w}\, \Lambda_\nu(T_{\rm X}, E). \tag{3}$$

The parameter Λ_ν is the cooling function and $T_{\rm X}$ the assumed constant temperature of the hot gas. The electron and ion number densities $n_{\rm e}$ and $n_{\rm i}$ appearing in Eq. (3) are for the cool wind. For a constant $f_{\rm X}$, the equality $(n_{\rm e}n_{\rm i})_{\rm X} = f_{\rm X}(n_{\rm e}n_{\rm i})_{\rm w}$ holds for any infinitesimal volume element dV.

The emergent X-ray luminosity arises from a spherical volume integral over the observable wind, with

$$L_{\rm X}(E) \;\approx\; \pi f_{\rm X}\Lambda_\nu(T_{\rm X}, E) \int_{r_1}^{\infty} \left(1 + \sqrt{1 - \frac{r_1^2}{r^2}}\right) \times (n_{\rm e}n_{\rm i})_{\rm w} r^2 dr \tag{4}$$

where the parenthetical accounts for occultation by the optically thick surface of radius $r_1(E)$ and a factor of $1/2$ corrects for the overestimation made in the exospheric approximation. Applying the assumption of constant expansion, the integration can be evaluated analtyically, yielding

$$L_{\rm X}(E) = \frac{1+\pi/4}{4}\, \frac{f_{\rm X}\, \dot{M}/v_\infty}{\mu_{\rm i}\, (\mu_{\rm e})_{\rm w}\, m_{\rm H}^2\, \kappa(E)}\, \Lambda_\nu(T_{\rm X}, E), \tag{5}$$

where $\mu_{\rm e}$ is the mean molecular weight per free electron of the cool wind.

There are several crucial factors that determine the total emergent X-ray luminosity from the wind: the opacity, the cooling function, and the filling factor. The opacity can be taken as $\kappa(E) \approx \kappa_0\, E^{-\gamma}$, with γ in the range 2–3 and κ_0 a constant that depends on abundances as

$$\kappa_0 = \kappa_\nu(1\,{\rm keV}) \propto \mu_{\rm i}^{-1}\, \left(N_{\rm X} + 16\, N_{\rm Y} + 2600\, N_{\rm Z}\right), \tag{6}$$

with $N_{\rm X}$, $N_{\rm Y}$, and $N_{\rm Z}$ the abundances of H, He, and metals relative to all nucleons. The K-shell absorption for a given atom depends on the fourth power of the proton number, hence the coefficient of 16 is just 2^4 for $\sigma_0({\rm He})/\sigma_0({\rm H})$, and assuming CNO are the dominant metals, $2600 \approx (6^4 + 7^4 + 8^4)/3$ is a mean for $\sigma_0({\rm metals})/\sigma_0({\rm H})$. Thus κ_0 is most appropriate at energies above the CNO edges.

For temperatures $T_{\rm X}$ in which Λ_ν is dominated by line emission (in contrast to thermal Bremsstrahlung at $T_{\rm X} \gtrsim 10^8$ K), the cooling function is roughly given by $\Lambda_\nu \approx \sum_{\rm k} P_{\rm k}(T)\, n_{\rm k}/n_{\rm i}$, where $P_{\rm k}(T)$ is a factor relating to the emitted power in the line k, and $n_{\rm k}/n_{\rm i}$ is the ratio of the number density population for the line k to the total ion number density of the hot gas. For solar abundances, the Raymond & Smith (1977; hereafter RS) cooling function is used, with $\Lambda_{\rm RS} \approx \sum_{\rm k} P_{\rm k}(T)\, (n_{\rm k}/n_{\rm H})_\odot$, where $n_{\rm H}$ is the hydrogen proton density of the hot gas. Assuming the $P_{\rm k}$'s vary weakly with density and temperature, and further that the ratio $n_{\rm k}/(n_{\rm k})_\odot = \tilde{\mathcal{A}}$ is constant for every line k, a scaling correction to the known RS cooling function for non-solar abundances is

$$\Lambda_\nu(E, T_{\rm X}) \approx \frac{\mu_{\rm i}}{\mu_{\rm H,\odot}}\, \tilde{\mathcal{A}}\, \Lambda_{\rm RS}(E, T_{\rm X}), \tag{7}$$

where $\mu_{\rm H,\odot}$ is the mean molecular weight per proton, the same for both the cool and hot gas. In the case $n_{\rm k}/(n_{\rm k})_\odot$ is not constant for every k, $\tilde{\mathcal{A}}$ is an overall average enhancement (or reduction) to the RS cooling function.

We assume the filling factor is constant throughout the wind, but it's value can vary between stars. First, it can vary with abundance as $f_{\rm X} \propto (\mu_{\rm e}\mu_{\rm i})_{\rm w}/(\mu_{\rm e}\mu_{\rm i})_{\rm X} = (\mu_{\rm e})_{\rm w}/(\mu_{\rm e})_{\rm X}$. The filling factor also varies with the ratio $\dot{M}/v_\infty$. For example, Kudritzki et al. (1996) has analyzed ROSAT observations for 42 O stars and empirically determined $f_{\rm X} \propto (\dot{M}/v_\infty)^{-1}$. They attribute this result to the expectation that larger ratios of $\dot{M}/v_\infty$ result is more efficient cooling, shorter cool zones, and consequently smaller filling factors (see also Hillier et al. 1993). The end result is that the volume filling factor scales as

$$f_{\rm X} \propto \frac{(\mu_{\rm e})_{\rm w}}{(\mu_{\rm e})_{\rm X}} \left(\frac{\dot{M}}{v_\infty}\right)^{-1}. \tag{8}$$

Combining Eqs. (5)–(8) and integrating over energy yields the overall dependence of X-ray luminosity on composition and wind parameters, viz

$$L_{\rm X} \propto \Lambda_{\rm RS}(T_{\rm X}) \cdot \frac{\tilde{\mathcal{A}}}{(\mu_{\rm e})_{\rm X}\, \mu_{\rm H,\odot}} \cdot \frac{\mu_{\rm i}}{(16 N_{\rm Y} + 2600 N_{\rm Z})} \tag{9}$$

where $N_{\rm X} = 0$ and $r_1 > R_*$ are assumed. In this expression the dependence of $L_{\rm X}$ on $\dot{M}/v_\infty$ has cancelled out (although an implicit dependence may exist through $T_{\rm X}$). We have satisfied the minimum requirement of our theory by reproducing the observed independence of $L_{\rm X}$ on $\dot{M}/v_\infty$ with our scaling result of Eq. (9). This independence is a consequence of the fact that the emissivity scales with density squared, hence $j_\nu \propto (\dot{M}/v_\infty)^2$, but r_1 and $f_{\rm X}$ are each proportional to $(\dot{M}/v_\infty)^{-1}$, thus leaving no net dependence on the wind flow parameters. We next consider how well our scaling reproduces the observed *ratio* of X-ray luminosities between WN and WC stars.

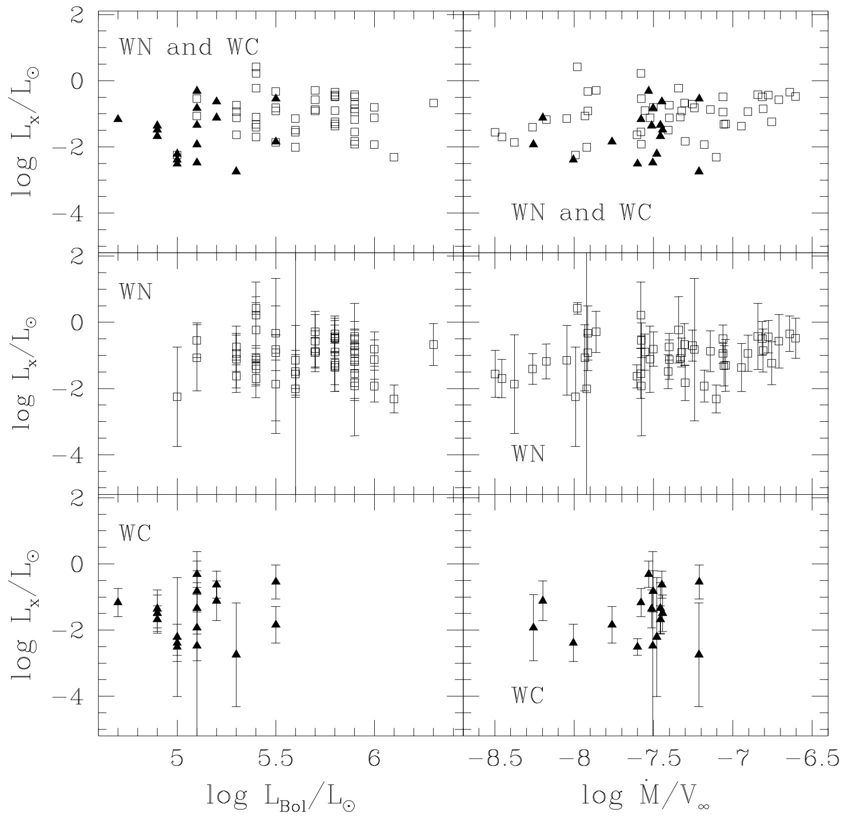

Fig. 1. A plot of ROSAT X-ray luminosities $L_{\rm X}$ for WN (squares) and WC (triangles) stars vs. Bolometric $L_{\rm Bol}$ on left and density scale $\dot{M}/v_\infty$ on right. No systematic trends are apparent, except that $L_{\rm X}({\rm WC}) < L_{\rm X}({\rm WN})$ on average. (Values of $L_{\rm Bol}$, $\dot{M}$, and v_∞ from Koesterke & Hamann 1995 and Hamann & Koesterke 1998.)

3. Application to observations

Fig. 1 summarizes the broadband ROSAT observations of X-ray emission from 48 WN and 17 WC stars (data from Pollock et al. 1995). Space does not permit a detailed explanation of this data; however, for multiple observations, the plotted points are averages. Measurements are shown only for stars that (a) are single or single-lined spectroscopic binaries and (b) have detections in contrast to upper limits. Errorbars are large, with only 1σ detections not atypical, but within the errors there are no systematic trends between $L_{\rm X}$ and $L_{\rm Bol}$ or $\dot{M}/v_\infty$.

Using a variance weighted averaging scheme, the ROSAT X-ray luminosity (0.2–2.4 keV) for WN types is $L_{\rm X}({\rm WN}) = 4.1 \pm 0.7 \times 10^{32}$ erg/s and for WC types is $L_{\rm X}({\rm WC}) = 1.4 \pm 0.5 \times 10^{32}$ erg/s. Pollock (1987) reported on EINSTEIN IPC broadband measurements (0.2–4.0 keV) of WR stars, with luminosities of $L_{\rm X}({\rm WN}) = 2.5 \pm 1.1 \times 10^{32}$ erg/s for 16 single and single-lined binaries of low mass function and $L_{\rm X}({\rm WC}) = 0.6 \pm 0.6 \times 10^{32}$ erg/s for 9 single stars. The EINSTEIN and ROSAT results are marginally consistent.

From Eq. (9), the main contributors to $L_{\rm X}$ are the emission as characterized by $T_{\rm X}$ and $\tilde{\mathcal{A}}$ from the cooling function, and the wind opacity as expressed in $\mu_{\rm i}$ and the relative abundances $N_{\rm Y}$ and $N_{\rm Z}$. Note that for complete ionization in H-poor winds, the factor $(\mu_{\rm e})_{\rm X} = 2$ is insensitive to the wind properties.

For the X-ray emission, the value of $\tilde{\mathcal{A}}$ is implicitly temperature dependent. For example, if the hot gas were typically of 10^8 K, then most atoms would be completely ionized, hence the cooling would be from Bremsstrahlung losses and $\tilde{\mathcal{A}} = 1$. It is difficult to assess the value of $\tilde{A}$ in WC stars relative to WN stars without knowing $T_{\rm X}$, but if we assume the ionization and excitation of the gas does not vary much between WN stars and WC stars (i.e., $T_{\rm X}$ is similar between the two classes), and that $T_{\rm X}$ is not exceedingly large (i.e., not much greater than 10^7 K), then we may at least expect that $\tilde{A}_{\rm WC} \geq \tilde{A}_{\rm WN}$, which will provide an upper limit to the ratio $L_{\rm X}({\rm WN})/L_{\rm X}({\rm WC})$.

To estimate values of $\tilde{A}$, we note that the primary result of O stars evolving to WN stars is to convert 4H→He leaving the metals essentially unchanged, implying $\tilde{A}_{\rm WN} \approx 1$. This is not entirely true, since C and O are underabundant but N is enhanced. However, the heavier atoms like S, Si, and Fe are not changed. For WC stars the nucleosynthesis is more complicated; however, the heavier ions of S, Si, and Fe are still not enhanced so that if the X-ray line spectrum is dominated by these metals, then $\tilde{A}_{\rm WC} \approx \tilde{A}_{\rm WN} \approx 1$. The influence of lighter ions such as O, Mg, and Ne, which are enhanced by factors of order 200, 10, and 3 in WC stars as compared to WN stars, will tend to increase $\tilde{A}_{\rm WC}$. For the attentuation of X-rays by the cool wind, the He and metals have comparable influence on the opacity for the WN winds, but for WC winds, the effect of metals is $\approx 10^2$ that of He owing to the large C and O abundances.

The quantities needed to evaluate the ratio of $L_{\rm X}({\rm WN})$ to $L_{\rm X}({\rm WC})$ using the proportionality in Eq. (9) are listed in Table 1. We used van der Hucht et al. (1986) as a guide for determining typical WR wind abundances. In the WN case, the wind is assumed to be entirely HeII in the cool wind (although the trace metals are significant for the wind opacity). In the WC case, we assumed a wind with 62% HeII, 25% CIII, and 13%

Table 1. Typical WN and WC star parameters

Parameter	WN Type	WC Type
Abundances[a]		
He	$\approx 100\%$	$\approx 62\%$
C	0.012%	$\approx 25\%$
N	0.585%	–
O	0.027%	$\approx 13\%$
$N_{\rm Y}/(N_{\rm Y})_\odot$	12.5	7.8
$N_{\rm Z}/(N_{\rm Z})_\odot$	3.2	250
Molecular Weights		
$\mu_{\rm i}$	4	7.6
$(\mu_{\rm e})_{\rm X}$	2.0	2.0
Metal Enhancements		
$\tilde{A}$	≈ 1	≥ 1

[a] Number fractions of ions; from van der Hucht et al. (1986)

O III. In both cases the hot gas is taken as completely ionized. With these abundances, we find $L_{\rm X}({\rm WN})/L_{\rm X}({\rm WC}) \leq 15$, as compared to observed ratios of 2.9 from ROSAT and 4.1 from EINSTEIN. The derived upper limit gives the correct trend with $L_{\rm X}({\rm WN})/L_{\rm X}({\rm WC}) > 1$, but exceeds the observed values by factors of 4–5. Better knowledge of the hot gas temperature would allow a more accurate assessment of $\tilde{A}$. Lines from Mg and other enhanced metals can contribute significantly to the cooling function, so that $\tilde{A} \sim$ a few is not unreasonable and would lower the predicted upper limit to near the observed values. Given the errors in both the data and our approximations, our simple scaling analysis appears capable of explaining the basic features of current X-ray data for single WR stars.

4. Discussion

The primary observational features of the ROSAT and EINSTEIN broadband measurements are (a) no correlation between X-ray luminosity and star or wind parameters and (b) evidence for WN stars being 3–4 times more luminous in X-rays than WC stars. Assuming an optically thin hot gas of small filling factor $f_{\rm X}$ embedded in a dense "cool" Wolf-Rayet wind, we have derived a simple scaling relation for the luminosity of X-ray emission. Given that the WR winds are optically thick with $r_1 \gg R_*$ at most X-ray energies, our scaling results qualitatively explain feature (a) if $f_{\rm X}$ varies from star to star as $(\dot{M}/v_\infty)^{-1}$. Note that for thin winds $(r_1 = R_*)$ with constant $f_{\rm X}$ or for winds with $f_{\rm X}$ a function of radius, $L_{\rm X}$ will generally have a dependence on the ratio $\dot{M}/v_\infty$. In fact, Owocki & Cohen (1999) appeal to a radially varying filling factor to explain the X-ray emission of O stars (however, note that they do not allow for $f_{\rm X} \propto (\dot{M}/v_\infty)^{-1}$ in their analysis).

As regards feature (b), our scaling results predict that $L_{\rm X}$ from WR winds should depend on relative abundances and ionization. Using typical parameters for the WN and WC classes, we derived an upper limit for the ratio of $L_{\rm X}({\rm WN})$ to $L_{\rm X}({\rm WC})$ that is factors of 4–5 greater than observed, but enhancement factors of a few for $\tilde{A}$(WC) would bring the prediction in line with observations. An important factor leading to the result $L_{\rm X}({\rm WN})/L_{\rm X}({\rm WC}) > 1$ is the strong influence of metals on the wind attenuation, with κ_0 for WC stars being ≈ 30 times greater than for WN stars. Although of higher emissivity, the larger r_1 values for WC stars and consequent lower emission measures result in lower X-ray luminosities than for WN stars. Better knowledge of the hot gas temperature $T_{\rm X}$ is necessary to determine $\tilde{A}$, thereby allowing a more rigorous test of our scaling results.

It is clear that a drastic improvement of data quality for WR X-ray measurements is desperately needed. There are many interesting questions on the wind driving and structure of WR winds that could be addressed with good S/N X-ray spectral data, especially the influence of multiple scattering on the formation and evolution of wind shocks. Also, since the line emission spectrum and wind absorption is dominated by metals, the X-ray band is especially apt for studying these highly enriched winds, through resolving individual line features and K-shell edges. With the better spectral response and greater collecting area of the latest X-ray telescopes, a much better data set for addressing these issues and advancing our understanding of the WR phenomenon should be forthcoming in the near future.

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