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X-ray diagnostics of massive star winds

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Abstract

Nearly all types of massive stars with radiatively driven stellar winds are X-ray sources that can be observed by the presently operating powerful X-ray telescopes. In this review I briefly address recent advances in our understanding of stellar winds obtained from X-ray observations. X-rays may strongly influence the dynamics of weak winds of main sequence B-type stars. X-ray pulsations were detected in a β Cep type variable giving evidence of tight photosphere-wind connections. The winds of OB dwarfs with subtypes later than O9V may be predominantly in a hot phase, and X-ray observations offer the best window for their studies. The X-ray properties of OB supergiants are largely determined by the effects of radiative transfer in their clumped stellar winds. The recently suggested method to directly measure mass-loss rates of O stars by fitting the shapes of X-ray emission lines is considered but its validity cannot be confirmed. To obtain robust quantitative information on stellar wind parameters from X-ray spectroscopy, a multiwavelength analysis by means of stellar atmosphere models is required. Independent groups are now performing such analyses with encouraging results. Joint analyses of optical, UV, and X-ray spectra of OB supergiants yield consistent mass-loss rates. Depending on the adopted clumping parameters, the empirically derived mass-loss rates are a factor of a few smaller or comparable to those predicted by standard recipes (Vink et al., 2001). All sufficiently studied O stars display variable X-ray emission that might be related to corotating interaction regions in their winds. In the latest stages of stellar evolution, single red supergiants (RSG) and luminous blue variable (LBV) stars do not emit observable amounts of X-rays. On the other hand, nearly all types of Wolf–Rayet (WR) stars are X-ray sources. X-ray spectroscopy allows a sensitive probe of WR wind abundances and opacities.

Keywords: Blue stars; Stellar winds; X-ray emission spectra

1. Introduction

Stars much heavier than the Sun ($M_{\text{initial}} > 8M_{\odot}$) are extremely luminous and drive strong stellar winds, blowing a large part of their matter into the galactic environment before they finally explode as a supernova. By this strong feedback, massive stars ionize, enrich, and heat the interstellar medium, regulate the star formation, and affect the further development of the cluster in which they were born. Empirical diagnostics of massive star spectra provide quantitative information about stellar and wind parameters, such as the terminal wind velocity, v_∞, and the mass-loss rate, $\dot{M}$.

With the development of space based telescopes, the classical analyses of optical, and radio radiation was extended to the ultraviolet (UV) and the X-ray range. The optical range is the easiest to access. However in the vast majority of OB stars the optical spectra are dominated by photospheric lines. Only the most luminous stars with strongest stellar winds (such as Wolf–Rayet (WR) stars) show many wind lines in emission in the optical. OB stars commonly display wind signatures in their UV spectra, but UV observations are scarce. For main-sequence B stars the wind signatures are marginal and difficult to disentangle from the photospheric spectra even in the UV. In X-rays,

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on the other hand, we can observe emission lines from winds of nearly all types of massive stars, including B-type dwarfs and other stars with weak winds. Thus, X-rays provide an excellent, sometimes unique wind diagnostic.

The history of massive star X-ray astronomy begins with the UV observations. Back in the 1970s the observatory *Copernicus* made the important discovery of strong lines of highly ionized ions such as O vi, N v, and C iv in the UV spectra of massive stars as cool as spectral type B1. It became immediately clear that the stellar effective temperatures are not sufficiently high to power such high degrees of ionization. E.g. Hamann (1981) showed that the lines of O vi and N v observed in the UV spectra of the B-type star τ Sco cannot be reproduced by the standard wind models. While different theories were put forward to explain the presence of high ions in stellar spectra, it was the work of Cassinelli and Olson (1979) where the Auger ionization by X-rays was suggested as an explanation.

The first X-ray observations by the *Einstein* observatory indeed detected X-rays from OB stars, and hence proved the importance of the Auger process for stellar winds (Seward et al., 1979; Harnden et al., 1979). One of the instruments on board of the *Einstein* observatory was the Solid State Spectrometer (SSS) that was used to observe O-type stars.

Already at these early days of X-ray astronomy, Stewart and Fabian (1981) employed *Einstein* spectra to study the transfer of X-rays through a uniform stellar wind as a mean to determine stellar mass-loss rates. They applied a photoionization code to calculate the wind opacity. Using $\dot{M}$ as a model parameter, they found from matching the model and the observed X-ray spectrum of ζ Pup (O4I) that the X-ray based mass-loss rate is lower by a factor of a few than obtained from fitting the Hα emission line and the radio and IR excess. As the most plausible explanation for this discrepancy they suggested that the mass-loss rate derived from Hα is overestimated because of wind clumping. In retrospect, this was a deep insight confirmed by follow-up studies only in the 21st century.

These first low-resolution X-ray spectra of OB stars also showed emission signatures of such high ions as S xv and Si xiv, and thus revealed the presence of plasma with temperatures in excess of a few MK. From this moment on, a quest to explain X-rays from stellar winds has began. Among the first proposed explanations was a picture where the stellar wind has a very hot base zone where the plasma is constrained by a magnetic field. X-rays are produced in this base corona, and ionize the overlaying cool stellar wind. Models predict that X-rays originating from this inner part of the winds should become strongly absorbed in the overlaying outer wind. Therefore, when observations showed only little absorption of X-rays, the base corona model was seriously questioned (Long and White, 1980; Cassinelli et al., 1981; Cassinelli and Swank, 1983). A way to resolve this "too little absorption" problem was shown only much later (see discussion in Section 8).

Besides the magnetically confined hot corona scenario, other models were put forward to explain X-ray emission from single massive stars. Detailed (albeit 1-D) radiative hydrodynamic models predict the development of strong shocks (Owocki et al., 1988; Feldmeier et al., 1997a; Runacres and Owocki, 2002) as a result of the line driving instability (LDI) intrinsic to radiatively driven stellar winds (Lucy and White, 1980; Lucy, 1982). A fraction of otherwise cool ($T_{\rm cool} \sim 10$ K) wind material is heated in these shocks to a few MK, and cools radiatively via X-ray emission. In the hydrodynamic model of Feldmeier et al. (1997b), the X-rays are generated when a fast parcel of gas rams into a slower-moving dense shell, both structures resulting from the LDI. This model was successful in quantitatively explaining the observed low-resolution *Rosat* spectrum of an O supergiant, and is often invoked as the standard scenario for the origin of X-rays in stellar winds.

Another family of models suggests that radiatively driven blobs of matter plow through an ambient gas that is less radiatively accelerated (Lucy, 2012; Guo, 2010). These blobs might be the result of an instability (Lucy and White, 1980), or seeded at or below the stellar photosphere (Waldron and Cassinelli, 2009; Cantiello and Braithwaite, 2011). When these blobs propagate, forward shocks are formed, where gas is heated giving rise to X-ray emission. Cassinelli et al. (2008) and Ignace et al. (2012) calculated the temperature and density in such a bow shocks to interpret some major X-ray properties: the power-law distribution of the observed emission measure derived from many hot star X-ray spectra, and the wide range of ionization stages that appear to be present throughout the winds. One can also envisage a "hybrid" scenario to explain the X-ray emission from massive stars by a combination of magnetic mechanisms on the surface with shocks in the stellar wind (e.g. Cassinelli and Swank, 1983; Waldron and Cassinelli, 2009).

These and alternative models for the X-ray production in stellar winds are now rigorously checked by modern observations. The 21st century's X-ray telescopes *Chandra* and *XMM-Newton* made high-resolution X-ray spectroscopy possible (Brinkman et al., 2000; den Herder et al., 2001; Canizares et al., 2005). On board of *Chandra* is the High Energy Transmission Grating Spectrometer (HETGS/MEG) with a spectral resolution of 0.024 Å in its 1st order. The Reflection Grating Spectrometers (RGSs) of *XMM-Newton* have a more modest spectral resolution of 0.05 Å, but higher sensitivity. Fig. 1 shows examples of high-resolution X-ray spectra. Both telescopes also provide a possibility for low-resolution X-ray spectroscopy, imaging, and timing analysis.

In this review I briefly address the diagnostic potential of X-rays for our understanding of winds from single stars. General X-ray properties of massive stars are introduced in Section 2, and the location of X-ray plasma in their winds is discussed in Section 3. The classical UV diagnostics of stellar winds and the influence of X-rays on these diagnos-