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The crucial role of high resolution X-ray spectroscopy in studies of massive stars and their winds

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Abstract: High-resolution X-ray spectroscopy has proven to be a crucial tool for addressing a wide range of problems relating to massive stars: measurement of fundamental stellar parameters, including mass-loss rates and chemical composition; characterization of magnetospheres of magnetic massive stars; and studies of shocks in colliding wind binaries. Progress is limited by the collecting area of existing observatories, and future studies require spectroscopy with square-meter class collecting area, both to expand existing techniques to a larger sample of objects, and to allow time-domain studies on the brightest objects.

1 Introduction

Massive stars of type O, B, and WR are crucial objects in the evolution of the universe. They impart enormous quantities of ionizing radiation into their circumstellar environments, as well as kinetic energy and momentum from their powerful stellar winds. They thus continuously feed back into the star formation process in their natal environments even before the powerful supernova explosions at the ends of their lives, which chemically enrich their environments through nucleosynthesis occurring during the explosion. Massive stars are the progenitors of neutron stars and stellar-mass black holes, objects of great interest as probes of ultra-high density matter, general relativity in the limits of strong gravity, and as the source of gravitational wave events resulting from their mergers.

Understanding the role of populations of massive stars in all of these cases depends on a good quantitative understanding of their stellar winds, as the lost mass has a strong influence on their evolution. Furthermore, the winds are themselves of interest as laboratories of radiation hydrodynamics, sites of strong shocks and particle acceleration, as well as dust formation.

The evolution of massive stars is further affected and diagnosed by changes in surface elemental composition, as well as the presence of large scale, ordered magnetic fields.

O stars and early B stars are known to be X-ray emitters, typically with $L_X/L_{bol} \sim 10^{-7}$, but in some cases significantly more. X-rays are generated in shocks caused by instabilities in all radiatively driven stellar winds. Additionally, binary massive stars, which comprise a large fraction of the population, often show even stronger X-ray emission from powerful shocks caused by the collision of the winds of the two stars. Finally, about 10% of massive stars harbor strong ($\sim$ 1 kG) surface magnetic fields, leading to partial confinement of the wind and resulting in multiple possible mechanisms for generation of X-ray producing shocks.

High resolution X-ray spectroscopy is a key tool for studying the winds of massive stars, and one that has only begun to be exploited. Although the fraction of the total luminosity emerging in the X-ray band is small, the diagnostic potential is large for two reasons: line formation and radiative transfer processes are relatively simple, offering the opportunity to make measurements of key stellar and wind parameters independent of commonly used diagnostics in the UV, optical, IR, and radio bands; and the X-rays are tracers of shocks in stellar winds, and therefore give the most direct insight into wind instabilities and wind-wind collisions.

Furthermore, a good understanding of the spatial distribution of X-ray emission in stellar winds is also crucial for accurate modeling of commonly used UV, optical, and IR diagnostics, since the ionization balance is very sensitive to the local X-ray flux (Pauldrach et al., 1994; Carneiro et al., 2016).

2 Mass-loss rates of massive stars

Mass-loss rates in massive stars have been estimated using a wide variety of diagnostic tools (Puls et al., 2008). The strength of Hα recombination emission lines is widely used, as is the radio free-free continuum excess. Both of these diagnostics have been shown to be sensitive to wind inhomogeneities, with mass-loss rates overestimated by the square root of the clumping factor $f \equiv \langle\rho^2\rangle/\langle\rho\rangle^2$. UV absorption lines do not suffer directly from density inhomogeneities; however, use of non-saturated lines typically implies reliance on non-dominant charge states, which introduces sensitivity to the ionization balance, which *is* density dependent. Seminal studies using non-saturated lines from the dominant charge state of the low abundance element phosphorus showed evidence for much lower mass-loss rates than were previously found (Fullerton et al., 2006); however, even these diagnostics can be affected by inhomogeneities in the velocity distribution of the wind (Sundqvist et al., 2010).

X-ray measurements of mass-loss rates work quite differently. X-rays are emitted in shocks distributed throughout the wind, with a large fraction of the flux coming in a small number of strong emission lines; these lines are broadened by the projected velocity distribution of the wind. The bulk of the (relatively cool) wind attenuates the X-rays through photoelectric continuum absorption; for most OB stars, the typical continuum X-ray optical depth through the wind is on the order of unity. Thus, the red side of the line profile (being formed in the back hemisphere of the wind) is more absorbed than the blue side, with the degree of asymmetry tracking the wind optical depth and thus the mass-loss rate (Owocki & Cohen, 2001; Cohen et al., 2010, 2014). This diagnostic is robust against uncertainties in the ionization balance, since the photoelectric opacity of the wind with respect to X-rays relies on inner-shell electrons. It is also robust against some forms of wind inhomogeneities: if the inhomogeneities are not coherent on large scales (*microclumping*), then there is no effect, as photoelectric absorption measures only the line-of-sight integral of density; but if the inhomogeneities are coherent on sufficiently large scales (*macroclumping*), then the wind may also become *porous* (Feldmeier et al., 2003; Oskinova et al., 2004, 2006; Owocki & Cohen, 2006), allowing a reduction in the effective optical depth for a given mass-loss rate. If porosity is important, then there may be some degeneracy between model-derived mass-loss rates and the assumed degree of porosity (Sundqvist et al., 2012). Models with strong porosity do not appear to be compatible with the limited body of existing high-quality high-resolution X-ray spectra of (presumably) single massive stars (Hervé et al., 2013; Leutenegger et al., 2013).

The current state of the field thus points in two directions: first, more thorough studies must better quantify the level of systematic uncertainty in X-ray mass-loss rate determinations due to porosity; and second, a much larger sample of stars must be studied, and the results used to benchmark diagnostics from other wavelength bands, as well as theoretical estimates of mass-loss rates based on fundamental stellar parameters.

3 Time domain diagnostics of the structure of winds

Winds of massive stars are known to exhibit clumpy structure resulting from the instability of the radiative driving mechanism. They are also known to exhibit large-scale structure with recurrence timescales on the order of the rotation period, and persistence over multiple consecutive rotation periods, but not over long timescales. These large scale phenomena primarily manifest via variability of discrete absorption components (DACs) in UV/optical absorption lines (e.g., Kaper et al., 1999). These corotating interaction regions (CIRs, Mullan, 1986) are speculated to originate in photospheric bright spots (Cranmer & Owocki, 1996; David-Uraz et al., 2017), for which there is evidence from precision optical photometry with the MOST and BRITE satellites (Ramiaramanantsoa et al., 2014, 2018). Over recent years it was found that some beta Cep pulsating stars exhibit pulsations with the period of their optical pulsations also in their X-ray emission (Oskinova et al., 2014; Cazorla & Nazé, 2017), and variability has been found in a number of other stars (Cohen et al., 2008; Massa et al., 2014; Rauw et al., 2015; Nazé et al., 2018). Studying the pulsational modulation of their high-resolution X-ray spectra will provide unique information on the connection between the photosphere and the stellar wind.

4 The elemental composition of massive stars

Elemental abundances of massive stars are of great interest for two reasons: first, they offer stringent tests of models of stellar evolution, in particular for transport mechanisms; second, they are good candidates for accurate measurements of abundances in the local universe.

Massive stars burn hydrogen via the CNO cycle, which converts carbon and oxygen present at the time of formation into nitrogen on timescales much shorter than the duration of the hydrogen-burning phase. Because their envelopes transfer heat radiatively, material that is CNO processed in the core should naively not appear at the surface; however, processes driven by rotation and mass-loss are thought to drive strong mixing, allowing nitrogen and helium enhancements to be observed at the surface.

Testing the correlation of these predicted enhancements with rotational velocity has been a key focus of recent work (Hunter et al., 2007, 2008, 2009; Cazorla et al., 2017a,b), but this is hampered by relatively large uncertainties in elemental abundance determinations derived from modeling of UV and optical spectra, where analysis of different photospheric lines originating from the same ion can result in factors of two differences in inferred abundances.

X-ray abundance determinations are much more reliable, since they rely on optically thin emission lines produced in shocks at much lower densities than the photosphere. Furthermore, because the emission comes from dominant charge states, abundance measurements are relatively insensitive to ionization balance modeling systematics.

While X-rays can be used to measure the abundances of C, N, and O relative to Fe, thus probing element transport in the stellar interior, it is not much more ambitious to obtain accurate abundances relative to Fe for the most abundant elements with $Z < 30$, including Ne, Mg, Si, S, Ar, and Ni. Abundance determinations for OB stars are not biased by coronal first ionization potential (FIP) or inverse-FIP effects. Therefore, accurate X-ray abundance determinations for massive stars may be the most reliable available in the local universe.

5 The structure of magnetospheres of massive stars

About 10% of massive stars have been found to harbor large-scale, ordered magnetic fields, typically dominated by the dipole component, and with equatorial field strengths typically of hundreds of G to kG (Aurière et al., 2007; Wade et al., 2016). The exact mechanism for the generation of these fields is not certain, although there is strong evidence that they are of fossil origin.

The presence of a strong magnetic field in a sub-population of massive stars may have profound impacts on stellar evolution and endpoints. Mass loss is suppressed from parts of the stellar surface near the magnetic equator, where the field lines remain closed, and it has been suggested that this can thus allow significantly larger stellar masses at the end of main sequence, and correspondingly larger masses of black holes formed in the subsequent core collapse supernova

(Petit et al., 2017). Thus, magnetic massive stars are candidate progenitors of the relatively large (several tens of $M_{\odot}$) black holes that have been repeatedly observed in mergers by LIGO and LIGO-Virgo.

Because the optical spectropolarimetric capability to intensively study magnetic massive stars is still relatively new, surveys for detection of candidate stars are still ongoing (Wade et al., 2016; Fossati et al., 2015), and while some systems have been studied in the UV (Stahl et al., 1996; Grunhut et al., 2009, 2012; Martins et al., 2012; Marcolino et al., 2012, 2013; David-Uraz et al., 2019), multiwavelength characterization of the detected systems is still in its infancy (Nazé et al., 2015; Shenar et al., 2017). The number of stars available to study is relatively small, and it is therefore crucial to characterize their magnetospheres as fully as possible, thereby validating observational diagnostics of stellar and magnetic parameters.

X-ray spectroscopy is a critical component of this multiwavelength suite (ud-Doula & Nazé, 2016). X-rays trace energetic shocks that occur when the trapped wind is accelerated along closed field lines to collide with accumulated material in the magnetic equatorial plane (Babel & Montmerle, 1997b,a; Gagne et al., 1997; ud-Doula & Owocki, 2002). A large sample of magnetic OB stars has been characterized in X-rays by Nazé et al. (2014).

Kinematic and plasma diagnostics allow independent measurement of the location of the shocks, constraining the closure radius of the magnetosphere, and thus the mass-loss rate reduction with respect to a comparable non-magnetic system. Characterizing the mass-loss rate reduction is crucial in evaluating the place of magnetic massive stars as potential progenitors of unusual compact stellar endpoints.

Progress in this field will depend on expanding the first few detailed multiwavelength studies of massive stars magnetospheres to the larger sample of stars detected in optical spectropolarimetric surveys and characterized in the first X-ray surveys. This crucially depends on the existence of future large collecting area X-ray observatories featuring high resolution spectroscopy.

6 Colliding wind shocks in massive binary systems

A number of massive binary systems are known which exhibit strong, often phase-dependent emission from the shock that forms where the stellar winds collide (Stevens et al., 1992; Pittard, 2009; Rauw & Nazé, 2016). In fact, this is the primary X-ray generation mechanism for most WR stars. Shock temperatures of several 10s of MK are not uncommon in such systems. Studies of nearby systems to date have focused on kinematic information contained in emission lines Henley et al. (2003, 2008); Rauw et al. (2016), as well as studies of temperature distributions.

These systems are ideal laboratories for testing shock physics, and in particular offer the possibility to study the importance of non-equilibrium ionization and non-thermal electron energy distributions via the dielectronic recombination satellite lines of He-like Fe XXV.

7 Summary and instrument needs

Observations of massive stars with the high resolution X-ray diffraction grating spectrometers on Chandra and XMM have revealed tantalizing opportunities for advanced diagnostics of the properties of these stars that are difficult to obtain with any other methods. To take advantage of these opportunities, significant new capabilities are needed that can only be provided by major new X-ray observing facilities.

The single most important feature required for new observatories to make an impact in this field is increased collecting area. Pilot studies have been carried out on the several brightest objects, but what is needed is to make X-ray spectroscopy a routine tool used throughout the Galaxy. To carry out this vision **requires collecting area of order 1 m^2 at 1 keV**, combined with resolving powers of at least a few hundred, and angular resolution of $5''$, allowing resolution of massive stars in all but the most crowded fields. Such large effective area also opens up the time domain, enabling collection of high quality spectra for nearby objects with exposure times of order few ks, comparable to the wind flow time $t_{flow} \equiv R_*/v_\infty$.

The most important part of the bandpass is near 1 keV, where rich diagnostics are available from Fe L-shell lines, as well as K-shell transitions of astrophysically abundant elements. It is essential to retain good performance down to 0.3 keV, allowing access to the K-shell transitions of C, N, and O, and up to 10 keV, allowing Fe K-shell line diagnostics.

Beyond these basic requirements, it would be desirable to combine such a large aperture with angular resolution of $1''$ or better, and high spectral resolving power of at least 1000. Improved angular resolution would allow resolution of the most crowded fields in the Galaxy as well as in the Magellanic Clouds, enabling studies at low metallicity. Improved spectral resolution would allow full resolution of the wind-broadened emission lines of massive stars. A combination of high resolving power with large effective area is required for the most ambitious time domain studies of emission lines, as is routine in ground-based UV/optical spectroscopy.

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