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# Studying massive stars with the International X-ray Observatory

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**Abstract:** *Chandra* and *XMM-Newton* have deeply changed our view of the X-ray emission of massive stars. However, the majority of the massive stars being rather faint sources, the number of high-resolution X-ray spectra of massive stars remains rather limited and obtaining these spectra requires rather long exposure times. ESA, NASA and JAXA are currently designing the International X-ray Observatory (*IXO*) that will provide a quantum leap in collecting area compared to the current missions. In this contribution, we highlight the capabilities of *IXO* and its instrumentation for the study of massive stars in our Galaxy and beyond.

## 1 Introduction

X-ray astrophysics is currently in a "golden age" with two major observatories (*XMM-Newton* and *Chandra*) and several other missions (e.g. *Suzaku*, *Swift*,...) flying. These facilities have revolutionized our views of the X-ray universe, including our understanding of massive stars (see e.g. Güdel & Nazé 2009, Oskinova et al. 2011, and Nazé 2011). At the same time, new questions came up, that cannot be addressed with the present generation of X-ray observatories, but require a significant increase in collecting area. The science case for a large collecting area X-ray observatory led to two independent projects. In the USA, the NASA project *Con-X* came up second behind *JWST* in the 2000 Decadal Survey, whilst in Europe, *XEUS* was selected as a candidate mission for the first L-mission launch slot of ESA's Cosmic Vision programme, with contributions from JAXA. In 2008, both concepts were merged into the *International X-ray Observatory* (*IXO*).

In this paper, we first provide a general description of *IXO*, before we describe a few possible studies of massive stars that could be carried out with *IXO*. We conclude by summarizing the current status of the project.

## 2 The International X-ray Observatory

The key features of the *IXO* project are (Lumb & Bookbinder 2010, see also Fig. 1):

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- an effective collecting area of 3 m$^2$ at 1.25 keV (to be compared to 400 cm$^2$ and 1400 cm$^2$ at 1 keV for *Chandra*/ACIS-I and *XMM-Newton*/EPIC-pn respectively),
- an angular resolution (half-energy width) better than 5 arcsec (to be compared to 0.5 arcsec and 15 arcsec for *Chandra* and *XMM-Newton* respectively),
- an unprecedented spectral resolution of 3000 over the 0.3 – 1.0 keV energy domain,
- a focal length of 20 m to be achieved through an extensible optical bench[1],
- a halo orbit around the second Lagrangian point of the Sun - Earth system with a nominal mission lifetime of 5 years and consumables for 10 years.

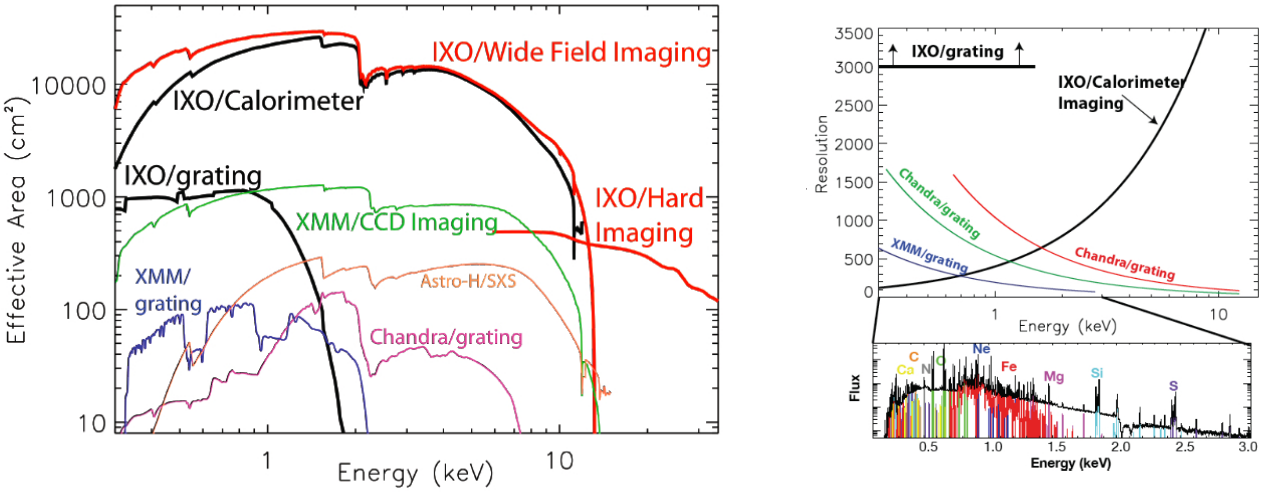

Figure 1: Left: effective collecting area of the *IXO* instruments in comparison to *XMM-Newton* and *Chandra*. Right: same for the spectral resolution. The bottom panel illustrates the emission lines of the various elements in the 0.1 - 3.0 keV energy range. Both figures are taken from the *IXO* website http://constellation.gsfc.nasa.gov/science/performanceRequirements.html

The key ingredients to achieve these performances are the grazing incidence mirrors. They must have a large effective area and a good angular resolution with a mass that should not exceed 2000 kg. This is an extremely challenging requirement. Currently, two technologies are being considered: slumped glass and silicon pore optics. Both technologies represent a quantum leap compared to previous missions, since their mass per unit collecting area is reduced by a factor 10 with respect to the mirrors onboard *XMM-Newton* (Nandra 2010).

The current design of the *IXO* focal plane features several instruments (Martin 2010):

- XGS, the X-ray Grating Spectrometer (0.3 – 1.0 keV, $R \geq 3000$) which is located on a fixed platform and is operated all the time.
- XMS, a cryogenic X-ray Micro-calorimeter imaging Spectrograph (0.2 – 10 keV, with an energy resolution of 2.5 eV over its inner field of view of $2 \times 2$ arcmin and 10 eV over the outer field of view of $5 \times 5$ arcmin).

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[1] Whilst the *XEUS* mission concept was based on two spacecraft operated in formation flight, the *IXO* mission concept features a single spacecraft.

- WFI, a Wide Field Imager (0.1 – 15 keV, with an energy resolution of $< 150$ eV over a field of view of 18 arcmin), operated in conjunction with HXI, a Hard X-ray Imager (10 – 40 keV, with an energy resolution of $< 1$ keV).
- HTRS, the High Time Resolution Spectrograph (0.3 – 15 keV, with an energy resolution $<$ $200$ eV) which has a time resolution of 10 $\mu$s for very bright sources, up to 12 Crab.
- X-POL, an X-ray POLarimeter (2 – 10 keV) able to detect polarization down to the 1% level.

Whilst XGS will be located on a fixed platform and will be operated all the time, the other instruments (XMS, WFI/HXI, HTRS and X-POL) will be on a moveable instrument platform and will observe one at a time.

# 3 What can we learn about massive stars using *IXO*?

In this section, we highlight a few possible applications of the XGS and XMS instruments to studies of massive stars. We stress that this list is by no means exhaustive.

## 3.1 Single O and Wolf-Rayet stars

To date, only about a dozen presumably single O-type stars have medium-quality *XMM-Newton* or *Chandra* grating spectra. These are actually the X-ray brightest objects of their class, but they already require minimum exposure times of 100 – 200 ksec. By far, the best quality high-resolution X-ray spectrum of a single O-type is the one of $\zeta$ Pup (O4 Ief) which has been observed, as a calibration source, for a total of 700 ksec with the RGS onboard *XMM-Newton* (Nazé et al., in preparation). The mean spectrum has a unique quality and provides the possibility to perform detailed line profile analyses. With *IXO*, we should be able to collect good-quality X-ray spectra for about 100 O-type stars with exposure times of a few 10 ksec. These high-resolution spectra will provide important clues about the properties of clumps in stellar winds, they will allow us to constrain the abundances of the X-ray emitting plasma[2] and to probe the impact of magnetic confinement, etc.

Observations with *IXO* will also open up an entirely new field. Indeed, the individual observations that make up the $\zeta$ Pup RGS dataset suggest some low-level line profile variability. However, the present data do not have sufficient statistics to address this issue. With *IXO*, we will be able, for the first time, to study the actual link between wind structures and X-rays through a monitoring of the line profile variability on the relevant time scales.

Since massive stars are usually found in open clusters, often in association with X-ray bright pre-main sequence stars, spatial resolution is important in these studies. The imaging spectrograph XMS will provide an instrument of choice for the investigation of massive stars (see Fig. 2).

Single Wolf-Rayet stars, unlike O-type stars do not exhibit a tight relation between their X-ray and bolometric luminosity. Actually, we currently ignore whether all types of WR stars emit X-rays and if so, by what mechanism. In this context, an interesting result was the detection with *XMM-Newton* of a very faint, but very hard X-ray emission from the WO star WR 142 (Oskinova et al. 2009). With XMS we will be able to collect high-resolution spectra of WR 142 allowing to distinguish between an intrinsically hard emission and a strongly absorbed one.

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[2] Lower resolution CCD X-ray spectra frequently suggest sub-solar metal abundances, although the photospheric abundances are essentially consistent with solar metallicity. It remains to be established whether this effect is real, or due to an insufficient spectral resolution in the CCD spectra.

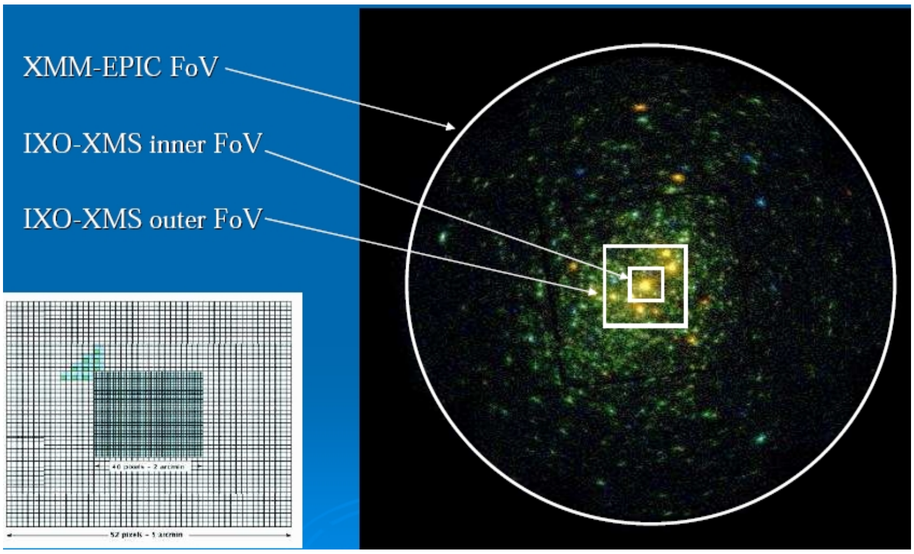

Figure 2: Illustration of the XMS field of view overlaid on an EPIC image of the very young open cluster NGC 6231 (from Sana et al. 2006).

## 3.2 Massive binary systems

The interactions of stellar winds in massive binary systems can produce a strong X-ray emission due to the heating of the winds in the interaction zone (see e.g. the review in Pittard 2011). Some colliding wind binary systems indeed feature a rather hard X-ray spectrum with a prominent Fe K line which is mainly formed in the wind interaction zone. This line should display profile variations with orbital phase (Henley, Stevens & Pittard 2003). Provided one obtains high-resolution, phase-resolved spectroscopy of this line, one can build a Doppler map of the line emission region. For this purpose, one can use the Doppler tomography technique (Horne 1991, Kaitchuk et al. 1994). The latter uses a reference frame centered on the centre of mass of the binary with the $x$-axis pointing from the primary to the secondary and the positive $y$-axis pointing along the direction of the secondary's orbital motion (see Fig. 3). The phase dependence of the radial velocity $v(\phi)$ of any gas flow that is stationary in the rotating frame of reference of the binary can be described by a so-called 'S-wave' relation:

$$v(\phi) = -v_x \cos{(2\,\pi\,\phi)} + v_y \sin{(2\,\pi\,\phi)} \tag{1}$$

Here $\phi$ stands for the orbital phase, whilst $(v_x, v_y)$ are the velocity coordinates of the gas flow. $v_x$

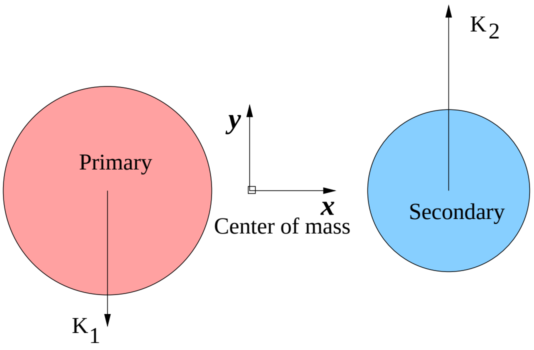

Figure 3: Orientation of the axes used in the Doppler tomography.

and $v_y$ simply reflect the projected velocity components along the $x$ and $y$ axes: $v_x = V_x \sin i$ and

$v_y = V_y \sin i$, where $V_x$ and $V_y$ are the actual velocities in the orbital plane of the binary and $i$ is the orbital inclination. Each pixel in a Doppler map, specified by its velocity coordinates is associated with a particular S-wave (see e.g. Horne 1991 for a detailed discussion of the method).

This technique is already commonly used to study phase-locked profile variations of emission lines (H$\alpha$, He II $\lambda$ 4686,...) in the optical spectra of early-type binaries (e.g. Thaller et al. 2001, Rauw et al. 2005). Applying it to the Fe K line in the X-ray spectra will allow to trace the cooling of the material in the wind interaction zones and will thus provide unprecedented insight into the physics of wind-wind interactions.

# 4 The way forward

Although stars, and massive stars in particular, are not the main science drivers of *IXO*, this high-throughput X-ray observatory will be a tremendously powerful tool to study the physics of massive stars, as we have shown by selecting only a few examples of possible applications.

Pre-phase A studies are under way at ESA and NASA. They indicate that the mission design is feasible, well on track for a launch in 2021 and should be within the budget (Nandra 2010). Recently (August 2010), the Astro2010 Decadal Survey acknowledged that many high-priority science questions require a high-throughput X-ray observatory. Although the ranking of the mission was somewhat ambiguous, its status mainly depends on the outcome of the ESA Cosmic Vision down-selection process that will take place this autumn and during the first half of 2011. Our community needs to support *IXO* to make sure it will indeed be launched in 2021!

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# References

Güdel, M., & Nazé, Y. 2009, A&ARv 17, 309

Henley, D.B., Stevens, I.R., & Pittard, J.M. 2003, MNRAS 346, 773

Horne, K., 1991, in *Fundamental Properties of Cataclysmic Variable Stars: 12th North American Workshop on Cataclysmic Variables and Low Mass X-ray Binaries*, SDSU Press, ed. A.W. Shafter, 23

Kaitchuck, R.H., Schlegel, E.M., Honeycutt, R.K., Horne, K., Marsh, T.R., White, J.C., & Mansperger, C.S. 1994, ApJS 93, 519

Lumb, D., & Bookbinder, J. 2010, http://ixo.gsfc.nasa.gov/resources/Paris2010/01_Lumb.pdf

Martin, D. 2010, http://ixo.gsfc.nasa.gov/resources/Paris2010/10_Martin.pdf

Nandra, K. 2010, http://ixo.gsfc.nasa.gov/resources/Paris2010/36_Nandra.pdf

Nazé, Y. 2011, in Proceedings of the 39th Liège Astrophysical Colloquium, eds. G. Rauw, M. De Becker, Y. Nazé, J.-M. Vreux & P.M. Williams, BSRSL 80, 109

Oskinova, L.M., Hamann, W.-R., Feldmeier, A., Ignace, R., & Chu, Y.-H. 2009, ApJ 693, L44

Oskinova, L.M., Hamann, W.-R., Ignace, R., & Feldmeier, A. 2011, in Proceedings of the 39th Liège Astrophysical Colloquium, eds. G. Rauw, M. De Becker, Y. Nazé, J.-M. Vreux & P. Williams, BSRSL, 80, 54

Pittard, J.M. 2011, in Proceedings of the 39th Liège Astrophysical Colloquium, eds. G. Rauw, M. De Becker, Y. Nazé, J.-M. Vreux & P. Williams, BSRSL, 80, 555

Rauw, G., Crowther, P.A., De Becker, M., et al. 2005, A&A 432, 985

Sana, H., Gosset, E., Rauw, G., Sung, H., & Vreux, J.-M. 2006, A&A 454, 1047

Thaller, M.L., Gies, D.R., Fullerton, A.W., & Kaper, L. 2001, ApJ 554, 1070

# Discussion

**M. Corcoran**: Can you say something about the use of the polarimeter for massive star research, at least for the brightest systems?
**G. Rauw**: XPOL should be able to detect polarization down to 1% for 1 mCrab sources in 100 ksec. The possibilities to use it for massive star research will critically depend upon the degree of polarization on the one hand and the brightness of the source on the other.

**A. Willis**: Can you comment on the drivers in the choice of the angular resolution of *IXO* of around 5 arcsec - 10 times poorer than *Chandra*, with science implications. Is this driven by the cost of mirror fabrication?
**G. Rauw**: The angular resolution of 5 arcsec is determined by the constraints on the mass of the mirrors and the effective area requirement. To reach the 3m$^2$ of effective area, it is mandatory to assemble a large number of smaller elements into the final mirror assembly. Although the metrology of these stacking processes has been greatly improved, they lead eventually to an angular resolution which is poorer than the one of *Chandra*, but still a factor 3 better than the one of *XMM*. The science implications are of course that source confusion in crowded regions such as young open clusters featuring a large number of X-ray emitting PMS stars will be more of an issue than for *Chandra*.

**W.R. Hamann**: My question is rather a political one. In Potsdam we have a neighbouring Institute for gravitational Physics. Talking with the colleagues there, they seem to be 100% confident that the *LISA* experiment will fly. But as I understand, *LISA* and *IXO* are directly competing within the ESA planning. How optimistic are you that *IXO* will be launched?
**G. Rauw**: The bottom line of my talk is that there are currently no obstacles (neither technological nor financial) that would render a launch of *IXO* in 2021 impossible within the budgetary framework of an ESA L-type mission. I do not know whether the same statement can be made about *LISA*. In the end, the choice of what mission will fly first, will depend a lot on technological and financial aspects, but it will also be affected by the size of the corresponding community and its enthusiasm for the mission. This is why I think it is important that we support *IXO*.