IXO Spectroscopy of High-mass Stars: Wind Shocks, Magnetic Confinement, and Colliding-Wind Binaries

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1. Abstract

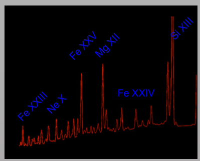
High-resolution x-ray spectra of single and binary high-mass stars observed with the *Chandra* and XMM gratings in the 6−30 Å region show resolved, sometimes asymmetric line profiles of highly ionized N, O, Ne, Mg, Si, S and Fe. The line profiles are being used to probe mass-loss in the winds of some of the most luminous single stars like ζ Puppis (O4 If). Meanwhile, the forbidden-to-intercombination line ratio of the He-like ions are being used to localize the X-ray emitting regions around many hot, massive stars. The *f/i* ratios have been used to show that the x-rays from magnetic stars like θ¹ Orionis C (O5.5 V) arise close to the stellar photosphere, suggesting magnetic confinement, while the x-rays from Wolf-Rayet binaries are produced further away, in a wind interaction zone between the stars. The superior effective area of the XMS and CAT grating spectrometers on IXO will allow similar studies to be undertaken for a larger, more distant sample of stars spanning a range of masses, mass-loss rates, ages, and binary separation and with higher time cadence to look for dynamic phenomena. The high efficiency of the XMS microcalorimeter will allow us to detect rapid changes in temperature, column density and emission measure. The unsurpassed spectral resolution of the XMS at high energies will probe the very hottest, time variable lines of Ca XIX, Fe XXV, Fe XXVI and Fe Kα.

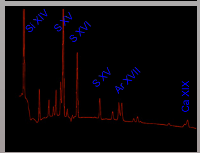
2. Colliding wind shocks: WR 48a

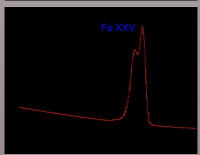
The prototype for colliding wind shocks is the WC8+O4 binary WR 140 located at only 1.1 kpc with $A_V \approx 3.8$. Its *Chandra* HETG spectra obtained near periastron show highly processed WC8 abundances and lower line widths for cooler ions, suggesting non-equilibrium ion and electron temperatures (Pollack et al. 2005).

WR 48a is a dusty WC8+? Wolf-Rayet star in the galactic star-forming region G305 and associated with dense 1−3 Myr−old star clusters located at 3−4 kpc. The XMM EPIC spectra show a line-rich non-ionization equilibrium spectrum from 4 keV shocks. The RGS spectrum is weak, but suggests broad lines: $v_{\rm HWHM} \approx 700$ km s^{-1}.

Like many of the very massive stars in the plane of the Galaxy that we would like to study with IXO, WR 48a has $A_V \approx 15$ mag: its spectrum below 1 keV is strongly absorbed. A high-S/N CAT grating spectrum would require >300 ks. However, a 25-ks XMS spectrum of WR 48a will reveal hundreds of resolved lines with enough S/N in the continuum to look for radiative recombination continua, further evidence of collisionless shocks.





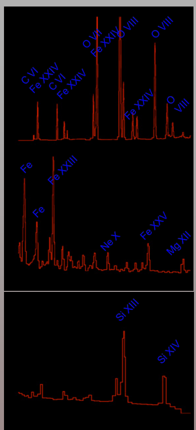


3. Extragalactic massive stars: the SMC LBV HD 5980

HD 5980 is located at 59 kpc in the Small Magellanic Cloud and is associated with the giant H II region N66 and the dense cluster NGC 346. HD 5980 was an eclipsing WN+O system that evolved into a WN+WN and later underwent a Luminous Blue Variable eruption in 1994. The 2001 *Chandra* ACIS image of HD 5980 is remarkable: it shows a point source surrounded by soft, bright, diffuse x-ray emission nearly 2′ across: most likely a supernova remnant.

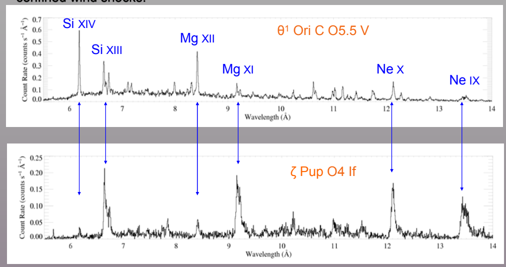
We simulate the XMS spectrum of HD 5980 by assuming a spectrum like that of WR 48a with an unabsorbed $L_X \approx 1.3\times10^{34}$ ergs s^{-1} and a column $N_H \approx 2.2\times10^{21}$ cm^{-2} (Nazé et al. 2002). A 150-ks XMS simulation shows 42 bright emission to measure line widths for ions from C VI to Fe XXV.

Most notably: the bright lines below 0.9 keV are blended Fe XXIV and O VII lines. The He-like lines in non-ionization equilibrium plasma are strong; the *f/i* ratio of O VII could be used to locate the x-ray shocks relative to the O-star photosphere. Though long exposures will be needed, massive stars in the LMC and SMC



4. *Chandra* grating spectra of two nearby O stars

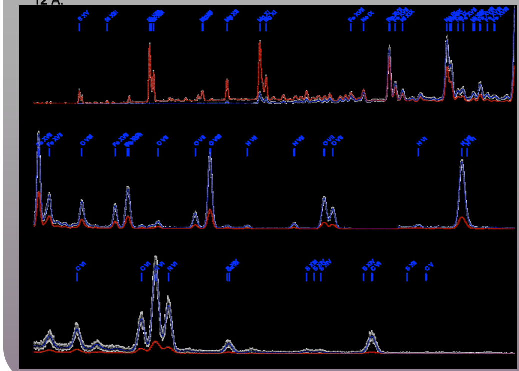
Long HETG and RGS observations of the O4 supergiant ζ Pup show a cool, thin plasma, broad, asymmetric lines, sub-solar abundances of C, O, Mg, Ne, Si and Fe, and enhanced N, suggesting CNO processed elements in the wind. The x-ray line profiles have been modeled to provide independent estimates of the mass-loss rate, porosity, and opacity of the radiation-driven wind. In contrast, the magnetic O5.5 star θ¹ Ori C shows a harder x-ray spectrum, 15-day periodic variations and narrower, symmetric line profiles suggesting magnetically confined wind shocks.



θ¹ Ori C: $T \approx 33$ MK, $R_{\rm shock} \approx 2R_\star$, $v_{\rm turb} \approx 300$ km s^{-1}
ζ Pup: $T \approx 4$ MK, $R_0 \approx 1.5R_\star$, $v_{\rm HWHM} \approx 1{,}000$ km s^{-1}

5. IXO Spectra of ζ Pup (O4 If)

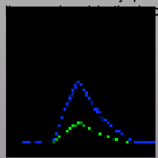
25-ks CAT grating spectra: zeroth order (red), coadded orders 1−5 (blue). The XMS calorimeter will provide more effective area and higher spectral resolution from 1.5-12 Å. The CAT will provide velocity resolution of 60−100 km s^{-1} above 12 Å.

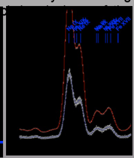


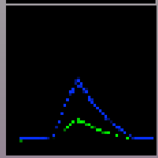
6. ζ Pup line profiles: mass-loss, resonant scattering, porosity

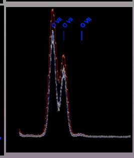
The XMS and CATGS will be used to measure the diagnostically important resonance, intercombination and forbidden (*fir*) lines of the He-like ions: S XV to N VI (Ne IX and O VII are shown in the right panels). CAT grating resolution will be used to measure mass-loss rates and the effects of clumping in the winds of massive stars. The wind optical depth, which is proportional to the mass-loss rate, controls the asymmetry of emission lines by preferentially attenuating photons on the red wing of the line ... wind. The mass-loss rate is derived by fitting the wavelength-dependent x-ray optical depths for an ensemble of broad, asymmetric emission lines with a model of the wind opacity:

In the left panels, the XMS (black), CAT order 2, 3 (green, blue) data points were simulated with no clumping or resonant scattering. In the top panel, the model (solid lines) has some clumping. In the lower panel the model O VIII line has a resonant opacity $\tau_{0,\star} = 1$.



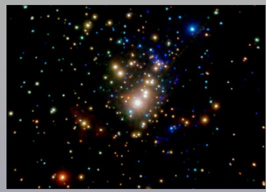




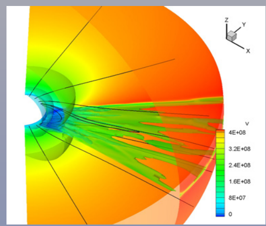


7. Probing magnetically confined wind shocks: θ¹ Ori C

Top panel: 850-ks *Chandra* Ultradeep Orion Project image of θ¹ Ori C (center) and the other components of θ Ori. The soft (orange) source at lower left is θ² Ori A. Like θ¹ Ori C, it is thought to posses a large-scale magnetic field modulating its x-ray emission. Tough IXO will likely achieve 5″ resolution, individual sources in crowded star-forming regions will not be resolved. Legacy *Chandra* data will be needed to model IXO spectra.



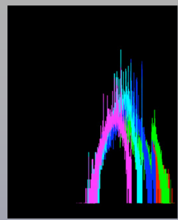
Lower panel: radial velocity snapshot in a long 3D magneto-hydrodynamic simulation of magnetically confined wind shocks on a θ¹ Ori C. Plasma, driven off the star by radiation, distorts and is channeled along the field lines, leading to 30−50 MK shocks near the magnetic equator ≈1$R_\star$ above the photosphere. The IXO XMS will reveal shock temperature, emission measure, radial velocity, line width and column density variations on time scales of 1−3 hours.

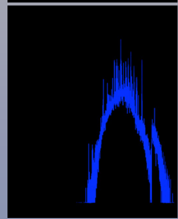


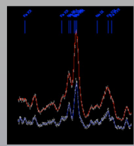
8. IXO spectra: θ¹ Ori C

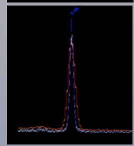
25-ks XMS (no grating, black) and CAT grating simulations of the O5.5 star. Model (red), CAT orders 1−5 (red-magenta) and coadded orders (blue). For moderate absorption (N_H = 4.5×10^{21} cm^{-2}) the XMS provides a large S/N advantage, except at O VIII (fourth panel).

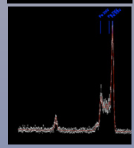
The CATGS will resolve Fe XIX and Ne IX blends and better measure line widths. The hottest lines of Fe XXV may reveal rapid time variations. XMS will resolve the Fe XXV *fir* lines and dielectronic recombination lines (fifth panel). XMS could also detect 6.4 keV fluorescence from cool gas in the magnetic equatorial plane. CAT grating spectra will be needed for detailed line-profile work.











9. High-resolution spectroscopy of massive stars with IXO

Our simulations of colliding wind binaries, single O stars, and magnetic O stars suggest that studies of massive stars will benefit enormously from the high collecting area of the IXO telescope and the high efficiency and spectral resolution of the XMS microcalorimeter in the 0.5−6.9 keV (1.8−23 Å) range. XMS spectra will provide:

1. High S/N emission-line spectra to determine temperature and abundance and He-like *fir* lines to measure shock locations.
2. High S/N in relatively short 10−25-ks exposures to probe dynamic, high-temperature phenomena including 6.4 keV emission.
3. High S/N 0.3-3 keV spectra of extragalactic colliding wind binaries in the LMC and SMC with 100−200-ks exposures.
4. high S/N spectra of radiative recombination and bremsstrahlung continua to probe non-equilibrium shock physics.

CAT grating spectra will be useful for line-profile analyses of massive stars with column densities $N_H < 10^{22}$ cm^{-2}. CATGS line profiles will be used to measure mass-loss rates and clumping in massive star winds, and to measure line shifts in magnetically confined wind shocks to compare with numerical simulations. Tracing the mass-loss history of massive stars will be achieved with high-resolution x-ray spectroscopy.