1. Abstract

High-resolution x-ray spectra of single and binary high-mass stars observed with the Chandra and XMM grating 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 locate the x-ray emitting regions around many hot, massive stars. The /I/ ratios have been used to show that the x-rays from magnetic stars like θ Orionis C (O5.5 V) arise close to the stellar photospheres, 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 X-ray 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 x-ray microcalorimeter will allow us to detect rapid changes in temperature, column density, and emission measure at the unsampled spectral resolution of the XRT at high energies will probe the very hottest, most ionized lines of Ca XIX, Fe XXV, Fe XXVI and Fe Xa.

2. Colliding wind shocks: WR 48a

The prototype for colliding wind shocks is the WC8+B4a WR 140 located at only 1.1 kpc with A_V = 3.6. Its Chandra HETG spectra obtained near periastron show highly processed WR abundances and lower line widths for cooler ions, suggesting non-equilibrium ion and electron temperatures (Puls et al. 2005). WR 48a is a dusty WC8+B Wolf-Rayet star in the galactic star-forming region G305 and associated with dense 1–5 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 ROSAT spectrum is weak, but suggests broad lines: v_a = 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 = 15 mag. Its spectrum before 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 to continue to look for radiative recombination continua, further evidence of collionless winds.

3. Extragalactic massive stars: the SMC LBV HD 5980

HD 5980 is located at 50 kpc in the Small Magellanic Cloud and is associated with the giant H II region N66B and the dense cluster NGC 346). HD 5980 was an exciting WR star in the 6-30 Å region. The 2001 Chandra ACP 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 x-ray spectrum of HD 5980 by assuming a spectrum like that of WR 48a with an unabsorbed L_x = 1.3*10^{38} ergs s^{-1} and a column N_H = 2.2*10^{20} cm^{-2} (Nazé et al. 2002). A 150-ksec XMM simulation shows 4 bright emission lines near 0.7, 0.8, 0.6, and 0.5 keV, corresponding to the wavelengths of the x-ray optical depth for atomic and bound-continuous bremsstrahlung emissions with a model of the wind opacity.

Most notably, the bright lines below 0.5 keV are blended Fe XXV and O VII lines. The He-like ions in non-ionization equilibrium plasma are strong: the /O/ 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 will provide an exploration of high-S/N spectra of Li, Be, and other light elements.

4. Chandra grating spectra of two nearby O stars

Long HETG and ROS 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 ORO 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 bluewind O5.5V θ Puppis shows a cool, thin plasma, broad, asymmetric line profile and lower column density. The line profiles are being used to probe high-S/N 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. The XMS will reveal shock temperatures, emission measure, radial velocity, width and column density variations on time scales of 1–3 days.

5. IXO Spectra of ζ Pup and θ Ori

5.1 ζ Pup - x-ray spectra of ζ Pup (O3.5 I)

25-ks CAT grating spectra of ζ Pup show a cool, thin plasma, broad, asymmetric lines, sub-solar abundances of C, O, Mg, Ne, Si, and Fe. The line profiles are being used to probe high-S/N 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. The XMS will reveal shock temperatures, emission measure, radial velocity, width and column density variations on time scales of 1–3 days.

5.2 θ Ori - x-ray spectra of θ Ori (O7.5 V)

25-ks CAT grating spectra of θ Ori show a cool, thin plasma, broad, asymmetric lines, sub-solar abundances of C, O, Mg, Ne, Si, and Fe. The line profiles are being used to probe high-S/N 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. The XMS will reveal shock temperatures, emission measure, radial velocity, width and column density variations on time scales of 1–3 days.

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

The XMM and CATGAS will be used to measure the diagnostically important resonance, intercombination and forbidden (f) lines of the He-like ions: O VI to O VII and O VIII to Fe XXV. The XMM resolves 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 XMM spectrum is shown in the 0.5–20 keV range. The XMM 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. The XMS will reveal shock temperatures, emission measure, radial velocity, width and column density variations on time scales of 1–3 days.

7. Probing magnetically confined wind shocks: θ Ori C

Top panel: 850-ks Chandra Ultraviolet Orbit Project image of θ Ori C (center) and the other components of θ Ori. The soft (orange) source at lower left is θ Ori C. Like 1 Ori C it is thought to possess a large-scale magnetic field modulating its x-ray emission. Tough IXO will likely achieve 5–10 times higher resolution, individual sources in crowded star-forming regions will be resolved. Legacy Chandra data will be needed to model IXO spectra.

Lower panel: radial velocity snapshots in a long 3D magnetic field model of magnetically confined wind shocks. To 1 Ori C. Plasma, driven off the star by radiation, distorts and is channeled along the fields lines. Like 30–50 Myr shocks near the magnetic equator, above the photosphere. The XMS will reveal shock temperature, emission measure, radial velocity, width and column density variations on time scales of 1–3 days.

8. High-resolution spectroscopy of massive stars with IXO

Our simulations of colliding wind binaries, single O stars, and massive 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 (18.3–23 Å) range. XMS spectra will provide:

1. High S/N emission-line spectra to determine temperature and abundance and He-like f/r lines to measure shock locations.
3. High S/N 0.3–3 keV spectra of extragalactic colliding wind binaries in the LMC and SMC with 100–200-ks exposures.

CAT grating spectra will be useful for line-profile analyses of massive stars with column densities N_H < 10^{23} cm^{-2}. CATGAS 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. Tracking the mass-loss history of massive stars will be achieved with high-resolution x-ray spectroscopy.

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