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X-rays from Magnetically Channeled Winds of OB Stars

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OB stars with strong radiation-driven stellar winds and large-scale magnetic fields generate strong and hard X-ray emission via the Magnetically Channeled Wind Shock (MCWS) mechanism, as first described in detail by Babel & Montmerle (1997), building on the concept applied to chemically peculiar B stars by Shore & Brown (1990). In the MCWS model, oppositely directed wind flows from the two magnetic hemispheres collide at the magnetic equator, generating strong shock heating of the confined wind plasma. This shock-heated plasma then radiatively cools while it is confined by the closed magnetic field structures near the star and by the wind ram pressure. Because the collision is relatively head-on, the shock temperatures can be quite high ($T > 10^7$ K), in contrast with the line-driven instability wind shocks in unmagnetized OB stars, that are significantly weaker. And the emission levels are high, due to the confinement and the high shock efficiency. If the magnetic axis is inclined with respect to the rotation axis of the star, rotational modulation of the X-ray emission will also be present.

Understanding the X-ray production via MCWS in magnetized OB stars may enable us to identify magnetized OB stars via their X-ray emission, even if direct field detections are not possible, and it could also enable us to study the evolution of magnetic fields as young OB stars age (via the comparison of X-ray properties in clusters of different ages, for example). But here I will focus on the detailed physical constraints that can be placed on the MCWS process in a star with a measured magnetic field, θ^1 Ori C, via high-resolution X-ray spectroscopy.

There are four separate X-ray diagnostics that confirm the MCWS scenario for θ^1 Ori C and constrain the physical properties of the X-ray emitting magnetosphere:

1. High X-ray temperatures (determined from thermal spectral model fitting). The differential emission measure of θ^1 Ori C peaks at temperatures above 10 MK, which is in contrast to the few million K peak temperatures in mature, unmagnetized O stars, and which is well reproduced by MHD simulations of the MCWS mechanism (Cohen, 2008, these proceedings). The detailed temperature distribution provided information about the pre-shock wind speed and the magnetic geometry.

2. Relatively narrow X-ray emission lines. The X-ray emitting plasma in the MCWS scenario is predominantly in the closed magnetic field regions and thus the plasma velocity is relatively low and the associated Doppler line broadening is modest. This is seen in the MHD simulations and confirmed by the Chandra grating observations (Cohen, 2008, these proceedings).

3. The rotational modulation of the X-ray emission is consistent with part of the magnetosphere being eclipses near phase 0.5, when the viewing orientation is magnetic equator-on. The depth of the eclipse provides information about the location of the X-ray emitting plasma (deeper eclipses imply more plasma close to the star). The observed eclipse depth for θ^1 Ori C implies that the bulk of the plasma is within a stellar radius of the photosphere (this is a somewhat closer than the MHD simulations predict).

4. The ratio of the forbidden to intercombination line strengths in helium-like ions also puts a constraint on the location of the X-ray emitting plasma, via the sensitivity of these line ratios to the local UV mean intensity. The closer the hot plasma is to the photosphere, the stronger the UV photoexcitation of electrons from the upper level of the forbidden line to the upper level of the intercombination line, and the weaker the f/i ratio. This is demonstrated in Fig. 1 for the Mg XI complex in the co-added (over four observations) Chandra grating spectrum of θ^1 Ori C, where we see that the very weak forbidden line requires a plasma location below $r \approx 2$ R$_*$.

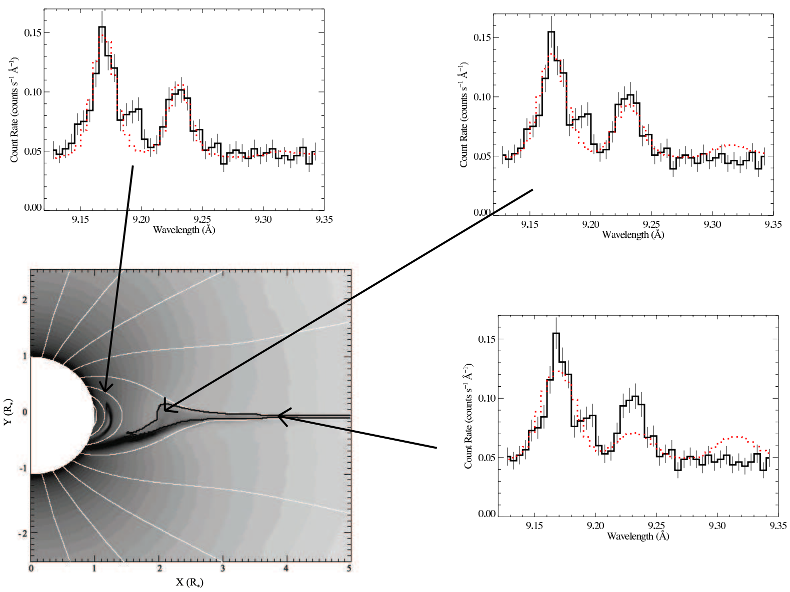

Figure 1. A snapshot from a 2-D MHD simulation of θ^1 Ori C, taken from Gagné et al.(2005), showing emission measure in grayscale and with a thick contour enclosing plasma with temperature above 10^6 K (lower left). The three other panels show the coadded *Chandra* spectra in the vicinity of the helium-like Mg XI complex, with a model of the resonance, intercombination, and forbidden lines overplotted. The relative strengthes of the f and i lines are different in each of the three panels, as the three models were calculated assuming a source location of 1.2 R$_*$, 2.1 R$_*$, and 4.0 R$_*$, respectively, starting at the top left and moving clockwise.

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