X ray emission line profile modeling of hot stars

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Abstract

The launch of high-spectral-resolution x-ray telescopes (*Chandra*, *XMM*) has provided a host of new spectral line diagnostics for the astrophysics community. In this paper we discuss Doppler-broadened emission line profiles from highly supersonic outflows of massive stars. These outflows, or winds, are driven by radiation pressure and carry a tremendous amount of kinetic energy, which can be converted to x rays by shock-heating even a small fraction of the wind plasma. The unshocked, cold wind is a source of continuum opacity to the x rays generated in the shock-heated portion of the wind. Thus the emergent line profiles are affected by transport through a two-component, moving, optically thick medium. While complicated, the interactions among these physical effects can provide quantitative information about the spatial distribution and velocity of the x-ray-emitting plasma in stellar winds. We present quantitative models of both a spherically-symmetric wind and a wind with hot plasma confined in an equatorial disk by a dipole magnetic field.

I. INTRODUCTION

Ultraviolet spectra of O and B stars (with luminosities up to $L = 10^6$ L_{sun} and surface temperatures $T \gtrsim 3$ T_{sun}) show the signatures of rapidly expanding winds, with velocities on the order of a few 1000 km s^{-1}, densities of order 10^{10} cm^3, and mass-loss rates up to 10^{-5} M_{sun} yr^{-1}. These stars are detected to have soft-x-ray luminosities of 10^{-7} times their total (bolometric) luminosities.[1] In cooler stars, like the Sun, x rays are produced in coronae, high-temperature regions near the surface of the star, and line widths are primarily indicative of thermal broadening. The line widths observed in x-ray spectra of hot stars, however, provide evidence that the emission originates in an extended, high-velocity wind.[2]

The *Chandra X-ray Observatory* has the spectral resolution to resolve Doppler-broadened lines from hot stars, providing quantitative information about the geometry and kinematics of the wind and putting important constraints on physical models that may explain the observed x rays. *Chandra* uses concentric parabolic and hyperbolic mirrors with an effective area of about 10 cm^2 to focus x rays on its instrument package. The High Energy Transmission Grating (HETG) provides a resolution of $\lambda/\Delta\lambda \lesssim 1000$ from 0.4 to 10keV.

II. SPHERICALLY-SYMMETRIC WIND MODELS

An optically-thin, spherically-expanding, x-ray-emitting plasma produces symmetric line profiles centered on the rest wavelengths of the lines with a shape determined entirely by the velocity and emissivity structure of the plasma. Two effects can change the symmetry of the line. The star itself occults part of the plasma, while cold components of the wind absorb x rays, meaning photons traveling along longer lines of sight or through more dense wind regions will be less likely to reach the observer. In a radially expanding wind, the observer sees blue-shifted emission from the approaching material on the near side of the wind and red-shifted emission from the receding material on the far side. Thus an optically thick wind has the effect of removing photons from the red side of the profile, shifting the line center blueward and altering the shape of the line.

Owocki and Cohen[3] have numerically integrated a spherically-symmetric wind model to determine the shape of line profiles produced in a wind characterized by four parameters. The wind velocity at a distance r from the center of the star is assumed to be of the form

$v(r) = v_\infty(1 - R_*/r)^\beta$, where R_* is the stellar radius, v_∞ is the terminal velocity of the wind (determined from ultraviolet spectra), and β is a free parameter. Given a constant mass loss rate, the density at any point in a smoothly-expanding, spherically-symmetric wind can be determined from the velocity law. The emissivity of the wind is taken to be zero below some radius R_0, and to fall off like $n^2 r^{-q}$ above that, where n is the density of the wind and q is a free parameter. The optical depth of the wind is characterized by the parameter τ_*, which is defined so that, in a constant velocity wind ($\beta = 0$, $v = v_\infty$) τ_* is the radial optical depth at the surface of the star and the radius of optical depth unity is $r|_{\tau=1} = \tau_* R_*$. The parameters β, q, R_0, and τ_* offer enough flexibility to characterize a variety of physical models, including coronal models (by setting q and β to high values and $R_0 = R_*$).

All lines produced in an extended wind of this form will be skewed to the blue side of line center by the removal of photons from the red edge of the profile. *Chandra* observations of the star ζ Puppis[4] reveal broad lines with a significant blueward skew, suggesting an extended, spherical wind model may be able to explain the shape of the profiles.

Preliminary work on fitting the Owocki and Cohen model to lines in ζ Puppis suggest that good fits may be obtained with physically reasonable parameters. Figure 1 (a) shows the *Chandra* HETG (sum of +1, and −1 order) spectrum of the Ne X line of ζ Puppis along with the best fit line profile.

Other hot stars, however, show much more symmetric profiles. Figure 1 (b) shows the Ne X line of θ^1 Orionis C along with the model that fit the same line in ζ Puppis. No spherically-symmetric wind model that includes absorption can fit the relatively narrow and symmetric line from this star.

III. MODELING NON-SPHERICALLY-SYMMETRIC WINDS

A promising alternative to spherically-symmetric models is the Magnetically Confined Wind Shock (MCWS) model in which a strong (kG), large-scale dipole magnetic field originates from the star's surface and directs the stellar outflow. This field directs the wind toward the magnetic equator, where flows from opposite hemispheres collide, causing strong shocks and heating the wind plasma to 10^7 K. This theory, originally proposed by Babel and Montmerle[5], lately has gained currency due to the direct detection of an 1100 G field on θ^1 Orionis C[6] and the detailed magnetohydrodynamic modeling by ud-Doula and Owocki.[7]

As an initial exploration of this model, we have numerically synthesized emission line profiles of equatorial x-ray-emitting flows. In figure 2 we show the results of a simple model based on a radially directed flow confined to the magnetic equator of a hot star (using a standard beta-velocity law, with the flow confined to within 20 degrees of the equator). Because stellar magnetic fields are often tilted with respect to the rotation axis, our viewing orientation changes with rotation phase. In the figure we show a simulated line profile from three different angles: 0 degrees (magnetic pole-on), 45 degrees, and 90 degrees (equator-on). The characteristics of these profiles are due to (the changing) projected radial velocity of the x-ray-emitting wind, as well as (viewing-angle dependent) occultation by the star.

Clearly, the rotation phase can affect the line profiles, which is a conclusion we will be testing against recently obtained multi-phase Chandra observations of θ^1 Orionis C itself. This star has a 45 degree angle between the magnetic and rotation axes[8], and a viewing angle that is also tilted by 45 degrees with respect to the rotation axis, giving us a full range of viewing angles with respect to the star's magnetic axis. Future modeling work will include the effects of absorption by the cold wind and also take into account more realistic and complex flow morphologies, including the spectral post processing of numerical MHD simulations.

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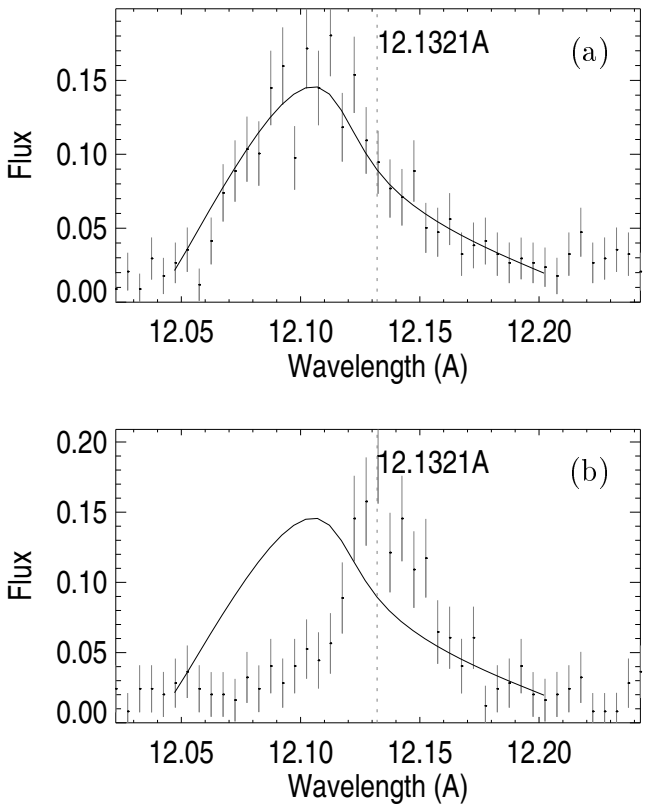

FIG. 1: *Chandra* HETG (+1 and −1 order summed) spectra (with error bars) of (a) ζ Puppis, and (b) θ^1 Orionis C, with the best-fit spherically-symmetric wind model for ζ Puppis (in black). The parameters for the best-fit model are $\beta = 1$, $q = 0$, $R_0 = 1.4R_*$, and $\tau_* = 4$. The area under the model curve is normalized to the area under the data curve.

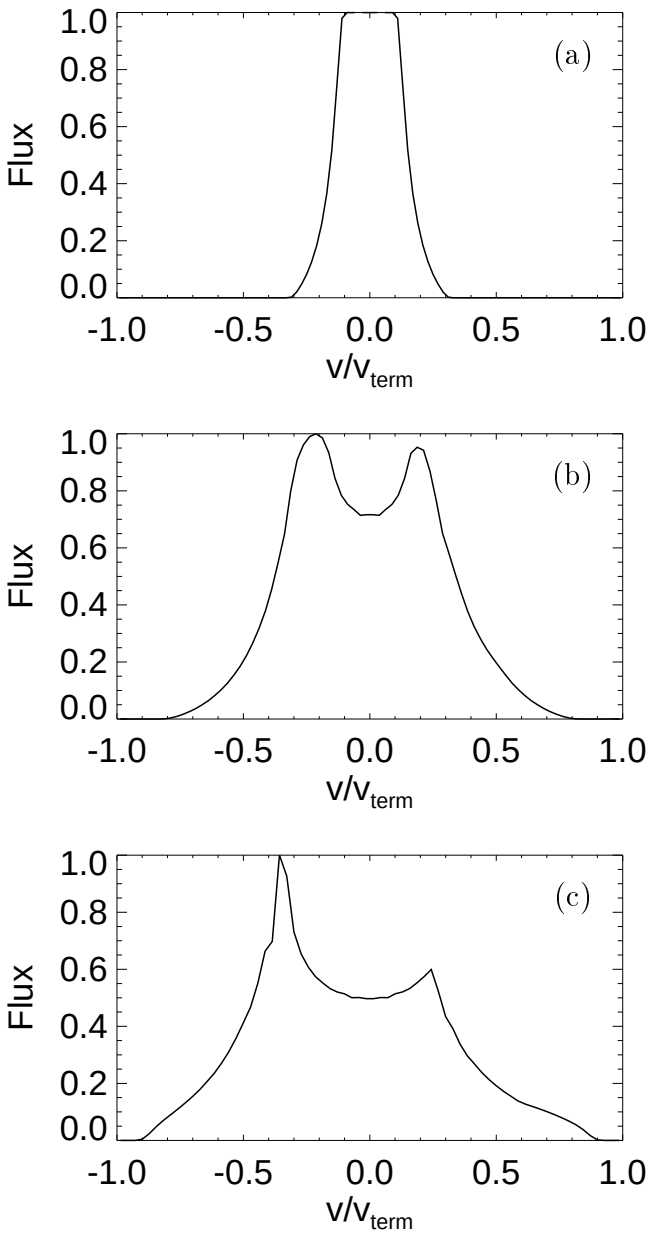

FIG. 2: Line profiles of an equatorial disk for an observer at three different viewing angles (a) 0^o (magnetic-pole on), (b) 45^o, and (c) 90^o (along magnetic equator). The horizontal axis shows the wavelength scaled to the terminal velocity of the wind, $v/v_{\rm term} = v/v_\infty = \Delta\lambda c/\lambda v_\infty$. The flux is normalized to the maximum value.