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Detailed ADM-based Modeling of Shock Retreat and X-ray Emission of τ Sco

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Abstract. Leveraging the improvement of spectropolarimeters over the past few decades, surveys have found that about 10% of OB-type stars host strong ($\sim$ kG) and mostly dipolar surface magnetic fields. One B-type star, τ Sco, has a more complex surface magnetic field than the general population of OB stars. Interestingly, its X-ray luminosity is an order of magnitude higher than predicted from analytical models of magnetized winds. Previous studies of τ Sco's magnetosphere have predicted that the region of closed field loops should be located close to the stellar surface. However, the lack of X-ray variability and the location of the shock-heated plasma measured from forbidden-to-intercombination X-ray line ratios suggest that the hot plasma, and hence the closed magnetic loops, extend considerably farther from the stellar surface, implying a significantly lower mass loss rate than initially assumed. We present an adaptation of the Analytic Dynamical Magnetosphere model, describing the magnetic confinement of the stellar wind, for an arbitrary field loop configuration. This model is used to predict the shock-heated plasma temperatures for individual field loops, which are then compared to high resolution grating spectra from the Chandra X-ray Observatory. This comparison shows that larger closed magnetic loops are needed.

Key words: magnetic fields – stars: massive – x-rays: general – stars: winds, outflows

1. Introduction

With recent spectropolarimetric advancements, the number of magnetic OB stars has grown rapidly (Wade et al., 2016; Schöller et al., 2017). These stars host strong (~ kG), mostly dipolar magnetic fields. The magnetically confined wind shock (MCWS) paradigm, first developed by Babel & Montmerle (1997) and refined by ud-Doula & Owocki (2002), explains the formation of a circumstellar magnetosphere by the competition of the magnetic field with the stellar wind. For regions close to the photosphere, the magnetic field energy density is larger than the stellar wind kinetic energy density, resulting in closed magnetic loops. In these regions, the stellar wind is forced to flow along the magnetic loop from the surface footpoints until it collides with the corresponding flow from the opposite hemisphere. Since the velocity of the stellar wind is supersonic, the collision will result in a shock. As the shocked material cools radiatively, it will emit photons in the X-ray waveband.

The Analytic Dynamical Magnetosphere (ADM) model was developed by Owocki et al. (2016) to provide an analytical scaling for the MCWS model that could reproduce time-averaged results from MHD simulations and be used to quickly calculate observable diagnostics at many wavelengths. A key parameter of the ADM model is the wind magnetic confinement parameter (η_*), relating the stellar kinetic energy density to the magnetic field energy density near the stellar surface, and providing a simple way to find the apex heights of the last closed field loops for a dipolar magnetic field (ud-Doula & Owocki, 2002).

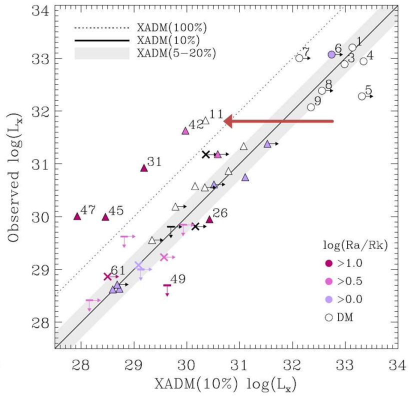

Figure 1. A comparison of the observed and XADM-predicted X-ray luminosity for all the magnetic OB stars with modern X-ray observations (Nazé et al., 2014). τ Sco is #11 in the small group of overluminous stars shown with the red arrow.

For typical O-type stars, the stellar wind is dense and cools efficiently once shocked. The post-shock material will cool quickly as it expands from the shock front to the loop apex, resulting in a narrow post shock region. However, for B-type stars with low-density stellar winds that do not cool as efficiently, the post shock region will be larger pushing the shock front down the field loop closer to the stellar radius. Since the velocity of the stellar wind increases monotonically with radial distance from the stellar surface, a retreat of the shock front towards the stellar surface will result in lower shock jump velocities and lower post-shock temperatures. This phenomenon is called "shock retreat" and is addressed by the X-ray ADM (XADM, ud-Doula et al., 2014) model. The XADM model uses a similar analytical scaling as presented by the ADM model but focuses on determining the X-ray properties.

Nazé et al. (2014) performed a study of all of the known magnetic OB-type stars with existing modern X-ray observations. The observed X-ray luminosity was then compared to that predicted by the XADM model. This study identified a small group of X-ray "overluminous" stars shown in Fig. 1. The majority of these overluminous stars are rapid rotators, except for τ Sco (#11 in Fig. 1). One hypothesis proposed to explain why τ Sco appears overluminous is that it has a more complex magnetic field than the dipolar approximation made by the XADM model.

2. An ADM Model for an Arbitrary Field Topology

Donati et al. (2006) observed that the magnetic field of τ Sco was significantly more complex than a dipole. Using Zeeman-Doppler imaging surface field topology maps, the magnetic field loops can be extrapolated to give a three dimensional model using the assumption that the field can be expressed as the gradient of a scalar potential (Jardine et al., 1999). An important parameter in extrapolating the magnetic field is the so-called "source radius", corresponding to the radius of the last closed field loop.

The last closed field loop depends directly on η_* and therefore the mass loss rate. Mass loss rates for main sequence B-type stars are uncertain, especially for magnetic stars. Donati et al. (2006) used a source radius of $2R_*$ corresponding to a mass loss rate of $\dot{M} = 2\times10^{-8}\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ with a polar magnetic field strength of 100G.

As the ADM model was previously developed for dipolar field configurations, we adapted the ADM scaling relations for arbitrary field loops to determine the temperatures and velocities of the confined wind plasma. We then applied this model to the field extrapolation of τ Sco's surface field maps (Fig. 3) and compared with the observed time variability, f/i-inferred radii and modeled APEC plasma temperatures.

The high resolution grating spectrum from the Chandra X-ray Observatory of τ Sco (Cohen et al., 2003) was modeled with APEC plasma temperature models using XSPEC to determine the temperatures needed to reproduce features present in the spectrum (Fig. 2). Comparing the modeled temperatures to the shock temperatures determined by the arbitrary ADM model (Fig. 3), it is shown that compact closed field loops, as implied by the $2R_*$ source radius, do not produce strong enough shocks to create the observed short wavelength line

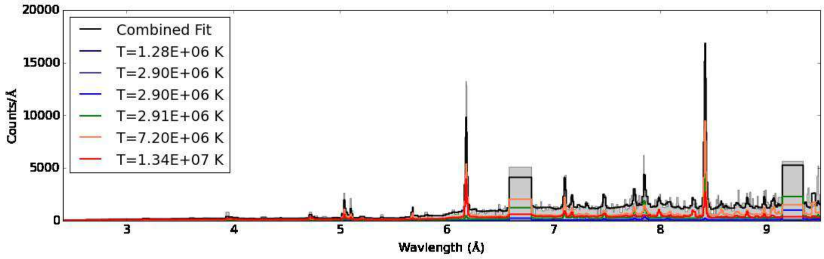

Figure 2. Part of the Chandra high resolution grating spectrum for τ Sco modeled with APEC plasma models (V. Petit et al. in prep.). The modeled temperatures are compared to the post-shock temperatures produced in the arbitrary XADM model.

emission.

With the compact field loops of the $2R_*$ source radius model, we should also expect to see periodic variations in the X-rays produced as the star rotates. However, from Suzaku observations obtained at various phases, Ignace et al. (2010) reported that there appears to be no periodic variations in the X-ray counts, suggesting a larger source radius, and therefore a smaller mass loss rate, is needed. Our calculations seem to agree with this hypothesis.

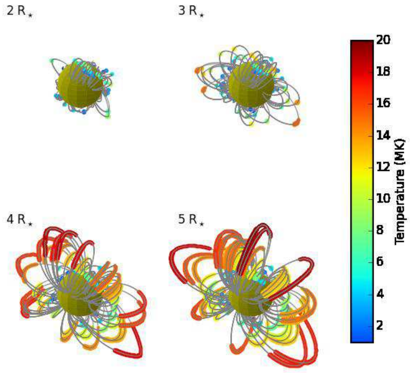

Figure 3. 3-dimensional magnetic field plots of τ Sco for some source radii. The immediate post-shock temperature for each loop and the extent of the shock region along the loop are displayed with the color scheme. As the field loops get larger, the shock temperatures increase (V. Petit et al. in prep.).

By analyzing the ratio of the forbidden line to the intercombination line (f/i ratio) found in helium-like ions such as magnesium, or silicon, we can predict the location of the X-ray emitting plasma. For τ Sco, the f/i ratios from the high resolution Chandra spectrum determined for magnesium indicate the X-rays to be emitted around $2.65R_*$ above the photosphere and the silicon f/i ratios provide a lower limit of $2.44R_*$ above the photosphere (V. Petit et al. in prep.). These results further support the need for a source radius larger than $2R_*$. Therefore, a field extrapolation for source radii of $3R_*$, $4R_*$, and $5R_*$ was performed (Fig. 3). The largest source radius requires a reduction of the Donati et al. (2006) mass loss rate by a factor of 42, which we adjust accordingly when determining the shock retreat. The mass loss rate for $5R_*$ is on the low end of predicted values, but comparable to those determined by Oskinova et al. (2011).

Applying the arbitrary ADM model to the 3-dimensional magnetic field loops for the other three source radii shows that the post-shock temperatures will increase for a larger source radius. Although the shock retreat for the larger loops extends further toward the stellar surface, it is not enough to quench the higher post-shock temperatures needed to reproduce the observed spectral features seen in Fig.2. The bulk of the X-rays are well above the surface, resulting in less variability than observed due to the star producing less occultation. Constraining the source radius would help to constrain the mass loss rate for τ Sco, however, more work is needed to directly recover the X-ray luminosity from the arbitrary ADM model.

References

Babel, J. & Montmerle, T. 1997, *Astron. Astrophys.*, **323**, 121

Cohen, D. H., de Messières, G. E., MacFarlane, J. J., et al. 2003, *Astrophys. J.*, **586**, 495

Donati, J.-F., Howarth, I. D., Jardine, M. M., et al. 2006, *Mon. Not. R. Astron. Soc.*, **370**, 629

Ignace, R., Oskinova, L. M., Jardine, M., et al. 2010, *Astrophys. J.*, **721**, 1412

Jardine, M., Barnes, J. R., Donati, J.-F., & Collier Cameron, A. 1999, *Mon. Not. R. Astron. Soc.*, **305**, L35

Nazé, Y., Petit, V., Rinbrand, M., et al. 2014, *Astrophys. J., Suppl. Ser.*, **215**, 10

Oskinova, L. M., Todt, H., Ignace, R., et al. 2011, *Mon. Not. R. Astron. Soc.*, **416**, 1456

Owocki, S. P., ud-Doula, A., Sundqvist, J. O., et al. 2016, *Mon. Not. R. Astron. Soc.*, **462**, 3830

Schöller, M., Hubrig, S., Fossati, L., et al. 2017, *Astron. Astrophys.*, **599**, A66

ud-Doula, A., Owocki, S., Townsend, R., Petit, V., & Cohen, D. 2014, *Mon. Not. R. Astron. Soc.*, **441**, 3600

ud-Doula, A. & Owocki, S. P. 2002, *Astrophys. J.*, **576**, 413

Wade, G. A., Neiner, C., Alecian, E., et al. 2016, *Mon. Not. R. Astron. Soc.*, **456**, 2