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Rigid Field Hydrodynamic Simulations of the Magnetosphere of σ Orionis E

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Abstract. We present Rigid Field Hydrodynamic simulations of the magnetosphere of σ Ori E. We find that the X-ray emission from the star's magnetically confined wind shocks is very sensitive to the assumed mass-loss rate. To compare the simulations against the measured X-ray emission, we first disentangle the star from its recently discovered late-type companion using *Chandra* HRC-I observations. This then allows us to place an upper limit on the mass-loss rate of the primary, which we find to be significantly smaller than previously imagined.

Keywords. hydrodynamics, stars: magnetic fields, stars: mass loss, X-rays: stars

1. Introduction

The B2Vpe star σ Ori E has long been known to possess a strong ($\sim 10\,$kG), dipolar magnetic field (e.g., Landstreet & Borra 1978). It is widely believed that the star's strong, relatively hard X-ray emission (e.g., Sanz-Forcada et al. 2004; Skinner et al. 2008) arises when wind streams, channeled and confined by the strong field, collide with each other and shock-heat to millions of Kelvin. To test this hypothesis, Townsend et al. (2007) formulated a new Rigid Field Hydrodynamic (RFHD) approach for simulating the time-dependent wind flow along field lines, which are assumed rigid in accordance with the star's very large magnetic confinement parameter, $\eta_* \sim 10^7$ (see ud-Doula & Owocki 2002).

2. RFHD Analysis

We have modified the RFHD code described in Townsend et al. (2007) to incorporate energy transport by field-parallel electron thermal conduction. We have also introduced an algorithm that limits the time-step to the smallest characteristic time scale of the differing processes (hydrodynamic and energetic) in the simulation; this is to improve coupling between these processes.

The most notable result from these modifications is an overall cooling of the magnetosphere, relative to simulations based on previous versions of the RFHD code. This is due to thermal conduction, which transfers heat from the hot, low-density post-shock regions to the cool, high-density equatorial accumulation disk, where it can be radiated away efficiently. As a consequence, typical magnetospheric temperatures do not reach the levels reported by Townsend et al. (2007).

A further significant finding, illustrated in Fig. 1, is that the X-ray differential emission measure (DEM) is very sensitive to changes in the mass-loss rate, as parametrized via the $\bar{Q}$ introduced by Gayley (1995) to characterize the overall opacity available for line driving in the Castor, Abbott & Klein (1975) wind formalism.

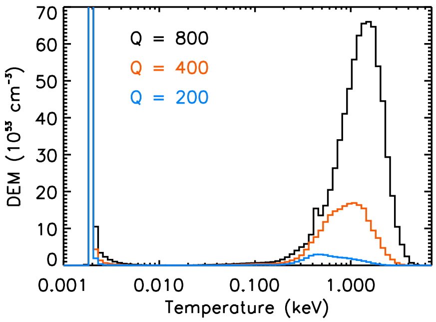

Figure 1. The time-averaged DEM from three 20 Msec RFHD simulations of σ Ori E, each differing only in the choice of opacity parameter $\bar{Q}$. Increasing $\bar{Q}$ (bottom curve to top curve) leads to disproportionately stronger X-ray emission, and also hardens the spectrum.

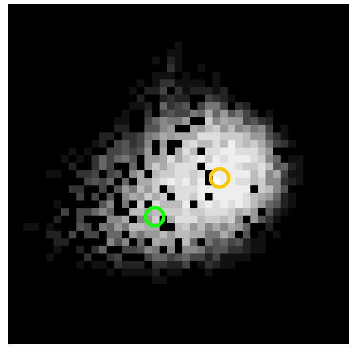

Figure 2. Lucy-Richardson deconvolution of the *Chandra* HRC-I image of σ Ori E. The lower-left circle marks the position of the primary, and the upper-right circle the position of the companion as measured by Bouy et al. (2009).

3. Observational Comparison

When comparing our simulated DEMs against X-ray observations of σ Ori E, we must contend with the possibility of emission from the late-type companion claimed by Bouy et al. (2009). Using a Lucy-Richardson deconvolution of the *Chandra* HRC-I observations of the star (PI: S. Wolk), we find that approximately two-thirds of the observed X-rays (during quiescence) come from a source at the same offset and position angle as the proposed companion (see Fig. 2). This both confirms the companion's existence, and indicates that only one-third of the observed X-rays originate from the primary.

Complementary *Chandra* ACIS-I observations (Skinner et al. 2008) indicate an overall X-ray emission measure ($0.2-3$ keV) of $\sim 2\times10^{53}$ cm^{-3}, so the emission measure of the primary should be on the order 7×10^{52} cm^{-3}. This is approximately half that predicted by our $\bar{Q}=200$ simulation, indicating that the mass loss rate of the primary must be *less* than the $\sim 2.4\times10^{-11}\,M_\odot\,\mathrm{yr}^{-1}$ derived from this simulation. Standard CAK theory predicts significantly higher mass-loss rates for a B2V star, on the order of $10^{-9}\,M_\odot\,\mathrm{yr}^{-1}$; thus, we conclude that there is something unusual about the wind of the σ Ori E primary.

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