CHANDRA–MIMES: X-RAYS FROM MAGNETIC MASSIVE STARS

Very strong magnetic fields have long been known to exist in a handful of chemically peculiar B stars [1]. However, they are not supposed to exist generally in massive stars, due to the absence of convective envelopes and presumed lack of a magnetic dynamo. Thanks to new, sensitive spectropolarimetric observations, though, a small trickle of magnetic field detections has increased to a torrent, with positive detections now totaling about 25 O and (mostly) B stars. These exciting discoveries have significant implications for massive star structure and evolution [2], including implications for the highly debated question of the origin of the fields of neutron stars, pulsar and magnetars [3,4]. The presence of magnetic fields in OB stars also has important implications for the physics of these luminous stars' atmospheres and winds and the X-ray emission that arises in them. By studying the X-ray properties of magnetic massive stars, we can learn about the high energy processes around these objects, and determine how magnetic fields affect X-ray emission mechanisms. With sufficient understanding, our community may, with the next generation of X-ray telescopes, be able to use X-ray properties as a means of discovering new magnetic massive stars.

Our group, the Magnetism in Massive Stars (MiMeS) collaboration, is an effort by an international team of researchers to investigate the magnetic properties of massive stars, both observationally and theoretically [5]. The primary pathway to this investigation is the MiMeS Large Program, which is collecting a tremendous database of high-resolution spectropolarimetric observations of massive stars as part of a 5-year project at the Canada-France-Hawaii Telescope (PI Gregg Wade). A sizable fraction of the MiMeS observing program is dedicated at the intensive observation of known magnetic massive stars in order to characterize their fields in great detail[1]. Here we are proposing to use new *Chandra* observations (in combination with archival data) to measure the X-ray properties of nearly every known magnetic massive star in the MiMeS sample with a strong wind – that is, having spectral subtype B2 or earlier – as well as a few additional later-type stars of special interest.

The first studies of magnetic massive star X-rays have shown that some have quite different X-ray properties than normal massive stars. The wind of the magnetic O-type star θ^1 Ori C is confined by its strong magnetic field, resulting in a X-ray emission that is more luminous, more energetic, and more variable than other stars of similar spectral type [6]. The Bp star σ Ori E is another archetype of an extreme wind-field interaction with bright and hard X-ray emission that can be understood in the context of the rigidly field hydrodynamics model [7], and which shows periodic X-ray flaring that may be due to centrifugally driven breakout of magnetically trapped and torqued material that drives magnetic reconnection and associated heating [8].

Our group's work in modeling the X-ray emission related to the magnetic fields on these stars has been quite successful [6,7,8,9], but as more magnetic massive stars are discovered, the diversity of their X-ray properties becomes more pronounced. The next magnetic O star discovered after θ^1 Ori C, HD 191612, shows X-ray emission that is soft, not especially luminous, and has broad emission lines [10]. Similarly, the X-ray emission from the magnetic B star β Cep, seems to be like that from other, presumably non-magnetic, early B stars [11]. Petit et al. [12] recently discovered two new magnetic B stars in the ONC – NU Ori and LP Ori – one with hard X-ray emission and one with soft X-ray emission [13].

This apparent diversity of X-ray behavior in these magnetic massive stars reflects a picture that

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[1] The program has been granted 640 hours of observing time using the ESPaDOnS spectropolarimeter at the CFHT, and we are also supplementing that with observations using ESPaDOnS's twin, the Narval spectropolarimeter at Pic du Midi Observatory. While we are mapping out the magnetic field properties of most of the known magnetic massive stars (omitting only those that are inaccessible from our two observing sites), the MiMeS program also includes a survey component that should lead to the discovery of many new magnetic massive stars.

is more complex than workers in the field had anticipated. This diversity could be related to many effects: the field geometry and topology, the wind speed and properties, the presence of a companion or colliding winds, etc. But for the moment, the sparsity of X-ray observations of magnetic massive stars make it impossible to determine under which circumstances anomalous X-ray emission will manifest itself. Many of the early B stars with measured magnetic fields have never been detected with X-ray telescopes – some have upper limits from the ROSAT All-Sky Survey, and some simply have never been observed with any X-ray telescope.

> *We therefore propose to systematically study the X-ray properties of the magnetic massive stars whose magnetic properties also are being studied by the MiMeS collaboration.*

The program we are proposing here will provide a complete set of X-ray observations for every known magnetic hot star of spectral type B2 and earlier[2], as well as five additional stars of later B spectral subtypes, and two A0p stars of special interest. All of the stars in our sample are being intensively studied with spectropolarimetric observations as part of the MiMeS program. We are mapping out the surface magnetic fields on these stars (for an example of what we have done with the magnetic hard X-ray source, τ Sco, see Fig. 1). And we are making precise measurements of photospheric abundances using the exquisite spectra from which we also measure the magnetic fields.

These observational constraints on the atmosphere properties and magnetic fields will serve as inputs for the theoretical component of our research program. We will model the magnetospheric X-ray emission using the Rigid Field Hydrodynamics [7], as demonstrated in Fig. 2. With the addition of *Chandra* observations to the magnetic observations of MiMeS, we will have all the ingredients needed to exploit the theoretical framework developed by our group in order to provide a strong bridge between magnetic characteristics and observed properties of massive stars. By doubling the number of magnetic massive stars observed in X-rays, the proposed *Chandra* observations of a eleven magnetic B stars and two A0p stars will enable four key milestones to be reached:

1. Push down the detection limits of a few times 10^{28} ergs s^{-1}, which in the case of non-detections, will improve upon the *ROSAT* upper limits by factors of 20 to 40. *Does field geometry correlate with X-ray luminosity?*

2. Characterize the temperature distribution in the emitting plasma. Magnetic massive stars already measured with X-ray telescopes have dominant plasma temperatures that vary from 3 million K to 50 million K. *Do X-ray temperatures correlate with wind properties?*

3. Characterize the short-term variability of the X-ray emission. *Of the massive stars with grating spectra, the magnetic stars θ^1 Ori C and τ Sco show significantly more short-term variability that non-magnetic O stars like ζ Pup. Is this generally true of magnetic massive stars?*

4. Test for binarity. The spatial resolution of *Chandra*, which far exceeds XMM or *ROSAT* will enable us to detect visual X-ray companions down to at least 0.5 arcseconds. Czesla & Schmitt [14] recently used *Chandra* to investigate whether the X-ray emission in several non-magnetic late B stars is intrinsic to the massive star or rather arises in a binary companion. In many cases at least some of the X-rays were intrinsic to the late B star. We will perform a similar analysis, and also use Czesla & Schmitt's sample as something of a control group, to compare to the X-ray properties of our thirteen magnetic B stars.

Observation planning: Most of our sample stars have never been detected in X-rays, and several have ROSAT upper limits. We used PIMMS to predict the *Chandra* ACIS-S count rate correspond-

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[2] With three exceptions, that are too far south for us to observe with ESPaDOnS.

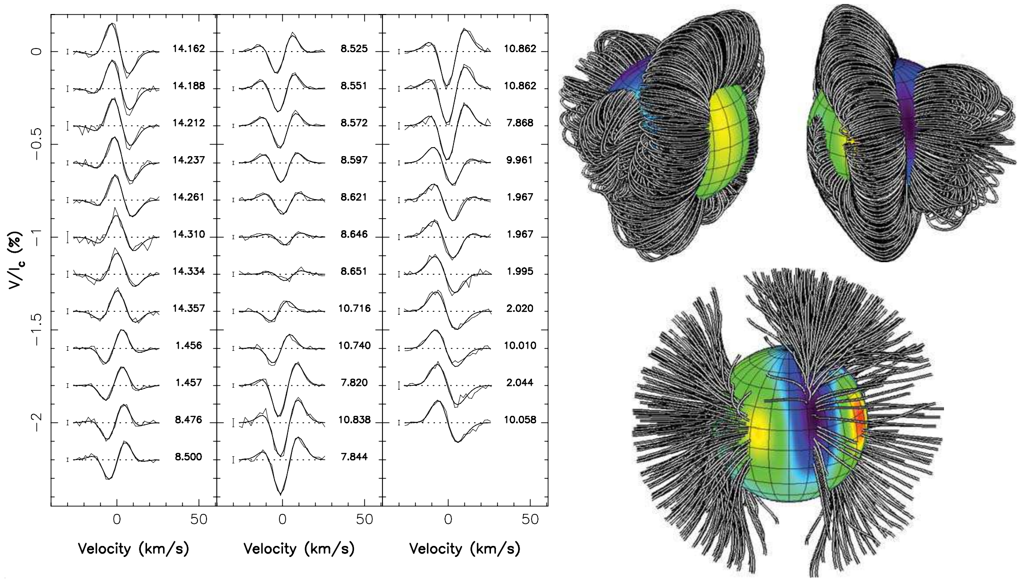

Figure 1: Detailed magnetic field mapping obtained with ESPaDOnS for the B0.2V star τ Sco (Donati et al. 2006, MNRAS 370, 629). On the left, time-resolved variations of the observed circular polarization Zeeman signature (thin lines) and maximum-entropy fit (thick lines). On the right, extrapolation of the magnetic map obtained from the spectropolarimetric observations.

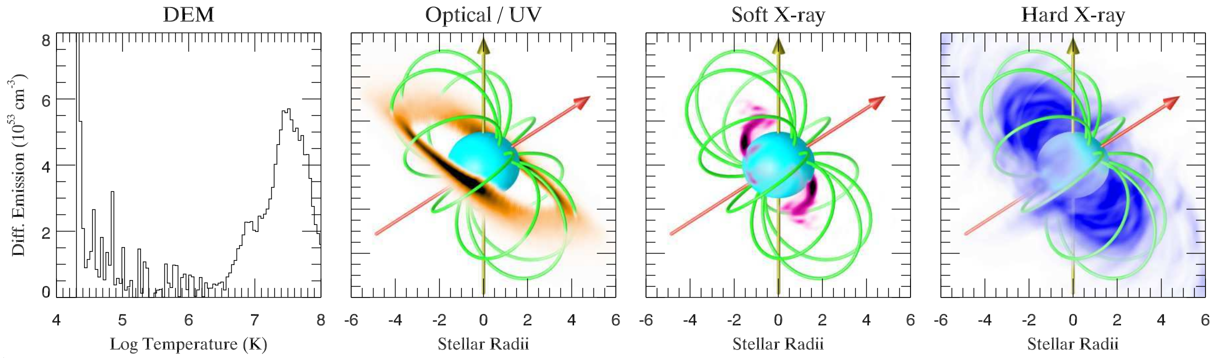

Figure 2: A snapshot of a rigid field hydrodynamics simulation [7], showing the differential emission measure in the magneosphere (left panel), which can be used to predict X-ray emission levels. The other three panels are visualizations of material in the magnetosphere in three different temperature regimes.

Table 1: MiMeS X-ray Sample

name	sp. type	x-ray observation status	comments	d (pc)
ξ^1 CMa	B1 III	rosat (0.11 c/s), xmm		629
V 2052 Oph	B2 IV	rosat upper limit	250 G; β Cep, per. UV var.	254
V 1671 Cyg	B2 V	none	-700:1800 G	559
V 901 Ori	B2 IV	none	-2140:2540 G; dip. & qdr.; rot. br.	510
ζ Cas	B2 IV	rosat upper limit	335 G; SPB	183
31 Peg	B2 IV-Ve	none	newly detected B-field	298
a Cen	B2 - B9	rosat upper limit	-430:375 G	128
16 Peg	B3 Ve	none	-156:104 G	157
HD 58260	B3 III	none	8100 G	826
HD 35502	B5 V	none	2250 G; radio source	408
V 686 CrA	B8 IV	rosat upper limit	-6860:4020 G	130
CU Vir	A0Vp	rosat (.08 c/s)	-437:811; rot. braking	80
IQ Aur	A0p	rosat (.026 c/s)	860 G	126

ing to these upper limits. Our exposure times of 10 ks are designed to push these limits down by between one and two orders of magnitude. Our strongest source is ξ^1 CMa, with a predicted 10,000 counts. Most stars will likely have 1000 or fewer counts. Even with a few hundred, though, we will be able to do rudimentary spectral (and time-variability) analysis. We request the ACIS-S mode for the enhanced sensitivity to soft X-rays.

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DAVID H. COHEN: PREVIOUS CHANDRA PROJECTS (year in parentheses denotes graduating class of undergraduate co-author)

AO1 - τ Sco (PI) - publication: Cohen, de Messieres ('04), MacFarlane, Miller, Cassinelli, Owocki, & Liedahl, "Chandra Spectroscopy of τ Scorpii: A Narrow Lined Spectrum from a Hot Star," 2003, *Ap.J.*, 586, 495

A01 - ζ Pup and δ Ori (co-I) - publications: 1. Cassinelli, Miller, Waldron, MacFarlane, & Cohen, "Chandra Detection of Doppler Shifted X-ray Line Profiles from the Wind of ζ Puppis (O4f)," 2001, *Ap.J.L.*, 554, L55; 2. Miller, Cassinelli, Waldron, MacFarlane, & Cohen, "New Challenges for Wind Shock Models: The Chandra Spectrum of the Hot Star δ Orionis," 2002, *Ap.J.*, 577, 951; 3. Kramer ('03), Tonnesen ('03), Cohen, Owocki, ud-Doula, & MacFarlane, "X-ray Emission Line Profile Modeling of Hot Stars," 2003, *Rev. Sci. Inst.*, 74, 1966; 4. Kramer ('03), Cohen & Owocki, "X-ray Emission Line Profile Modeling of O Stars: Fitting a Spherically-Symmetric Analytic Wind-Shock Model to the Chandra Spectrum of ζ Puppis," 2003, *Ap.J.*, 592, 532

AO2 - γ Cas (co-I) - publication: Smith, Cohen, Gu, Robinson, Evans, & Schran, "High-Resolution Chandra Spectroscopy of γ Cassiopeia (B0.5e)," 2004, *Ap.J.*, 600, 972

AO3 - θ^1 Ori C (co-I) - publication: Gagne, Oksala, Cohen, Tonnesen, ud-Doula, Owocki, Townsend, & MacFarlane, "Chandra HETGS Multi-phase Spectroscopy of the Young Magnetic O star θ^1 Ori C," 2005, *Ap.J.*, 628, 986

AO3 - β Cru (PI) – publication: Cohen, Kuhn ('07), Gagne, Jensen, & Miller, "Chandra Spectroscopy of the Hot Star β Crucis and the Discovery of a Pre-Main-Sequence Companion," 2008, *MNRAS*, 386, 1855

AO4 - DoAr 21 (co-I) - manuscript in preparation for submission to *Ap.J.*, AAS presentation available at: astro.swarthmore.edu/~cohen/projects/doar21/DoAr21 AAS2005.jpg

AO6 - archive (PI) - publications: 1. Owocki & Cohen, "The Effects of Porosity on X-ray Emission Line Profiles from Hot-Star Winds," 2006, *Ap.J.*, 684, 565; 2. Cohen, Leutenegger, Grizzard ('06), Reed ('05), Kramer ('03), & Owocki, "Wind Signatures in the X-ray Emission Line Profiles of the Late O Supergiant ζ Orionis," 2006, *MNRAS*, 368, 1905

AO6 - theory (co-I) - publications: 1. Gagne, Oksala, Cohen, Tonnesen, ud-Doula, Owocki, Townsend, & MacFarlane, "Chandra HETGS Multi-phase Spectroscopy of the Young Magnetic O star θ^1 Ori C," 2005, *Ap.J.*, 628, 986; 2. ud-Doula, Townsend, & Owocki, "Centrifugal Breakout of Magnetically Confined Line-Driven Stellar Winds," 2007, *Ap.J.L.*, 640, L191

AO8 - archive (PI) - publications: 1. Leutenegger, Paerels, Kahn, & Cohen, "Measurement and Analysis of Helium-Like Triplet Ratios in the X-ray Spectra of O-Type Stars," 2006, *Ap.J.*, 650, 1096; 2. Cohen, "X-ray Emission from O Stars," 2008, in *IAU 250: Massive Stars as Cosmic Engines,* Cambridge University Press, p. 17; 3. Zsargo, Hillier, Bouret, Lanz, Leutenegger, & Cohen, "On the Importance of the Interclump Medium for Superionization: O VI Formation in the Wind of ζ Pup," 2008, *Ap.J.L.*, 685, L149; 4. Skinner, Sokal, Cohen, Gagne, Owocki, & Townsend, "High-Resolution Chandra X-ray Imaging and Spectroscopy of the Sigma Orionis Cluster," 2008, *Ap.J.*, 683, 796.; 5. Cohen, Leutenegger, Wollman ('09), Zsargo, Hillier, Townsend, & Owocki, "A Mass-Loss Rate Determination for ζ Puppis from the Quantitative Analysis of X-ray Emission Line Profiles," 2009, *MNRAS*, submitted (astro.swarthmore.edu/zPupCohen.pdf)

DAVID H. COHEN: biographical sketch

EDUCATION

University of Wisconsin-Madison Ph.D. in Astronomy, 1996, “High-Energy Emission from B Stars and Its Relationship to Stellar Winds,” under the direction of Prof. Joseph Cassinelli

Harvard College A.B. in Astronomy and Astrophysics, *magna cum laude*, 1991, senior honors thesis, “Disentangling Double-Line Spectroscopic Binaries,” under the direction of Dr. David Latham

EMPLOYMENT

Associate Professor Swarthmore College, 2006–present

Assistant Professor Swarthmore College, 2000–2006

Research Scientist Bartol Research Institute, University of Delaware and Prism Computational Sciences 1998–2000

Post-doc, Assistant Scientist Fusion Technology Institute and Astronomy Department, University of Wisconsin-Madison, 1996–1998

RESEARCH INTERESTS

X-ray spectroscopy and **numerical modeling** of hot plasmas in laboratory and astrophysical settings

Stellar winds high-energy observations and analysis, collisional-radiative and hydrodynamic modeling, analytic modeling

X-ray/EUV astronomy spectral analysis, time-variability analysis, hot stars, young stars, interstellar medium

Laboratory astrophysics ionization/excitation kinematics modeling, spectroscopy, and experiment design of x-ray photoionized plasmas; plasmas heated by magnetic reconnection

Inertial confinement fusion experiment design and modeling—shock physics, ionization dynamics, and non-LTE physics

SELECTED PUBLICATIONS (more information at astro.swarthmore.edu/~cohen)

Cohen, Kuhn (’07), Gagne, Jensen, & Miller, “Chandra Spectroscopy of the Hot Star β Crucis and the Discovery of a Pre-Main-Sequence Companion,” 2008, MNRAS, 386, 1855

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Owocki & Cohen, “X-ray Line Profiles from Parameterized Emission Within an Accelerating Stellar Wind,” 2001, *Ap. J.*, 559, 1108