CHANDRA–MIMES: X-RAYS FROM MAGNETIC MASSIVE STARS

Magnetic fields are not supposed to exist in massive stars, due to their lack of convective envelopes and presumed lack of a magnetic dynamo. However, thanks to new, sensitive spectropolarimetric observations, magnetic fields are unexpectedly starting to be discovered in a range of massive stars, with positive detections now totalling about 25 O and (mostly) B stars[1]. These exciting discoveries have significant implications for massive star structure and evolution (Maeder & Meynet 2005), including implications for the highly debated question of the origin of the fields of neutron stars, pulsar and magnetars (Ferrario & Wickramasinghe 2006; Hu & Lou 2009). 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 on 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. The primary pathway to this investigation is the MiMeS Large Program, which is collecting a tremendous database of high-resolution spectropolarimetric observations of hot stars as part of a 5-year project at the Canada-France-Hawaii Telescope (PI Gregg Wade). A part 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[2]. 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 stars of special interest with later spectral subtypes.

The first studies of magnetic 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 (Gagné et al. 2005). 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 rotating magnetosphere model (Townsend et al. 2007), 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[3].

Our group's work in modeling the X-ray emission related to the magnetic fields on these stars has been quite successful, but as more magnetic massive stars have been discovered, a diversity of X-ray properties in these objects has been observed. The next magnetic O star discovered after

[1] A handful of chemically peculiar B stars have been known for some time to have kilogauss scale magnetic fields, thought to be fossil in origin. Shore & Brown's seminar work on B star magnetospheres was motivated by these stars. The MiMeS project is mapping out the fields in many Bp stars in great detail.

[2] 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 obseving sites), the MiMeS program also includes a survey component that should lead to the discovery of many new magnetic massive stars. *Co-authors: I think somewhere in this proposal, we need to use numbers to assert that our team is* **the** *team for discovering and studying magnetic massive stars. Verinonique, what can we say about how many of the known magnetic massive stars – or those discovered in the last five years, say – have been discovered by our group, for example?*

[3] *Co-authors: should we mention the recent detection of a low mass companion?*

θ^1 Ori C, HD 191612, shows X-ray emission that is soft, not especially luminous, and has broad emission lines (Nazé et al. 2006). 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 (ref). Petit et al. (2008) 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 (Stelzer et al. 2005).

This apparent diversity of X-ray behavior in these magnetic massive stars reflects a picture that 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 a massive magnetic star will show anomalous X-ray emission. 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 simultaneously are being intensively 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[4], 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 obervations 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 wind-field interactions using the Rigidly Rotating Magnetosphere model and Rigid Field Hydrodynamics simulations to study the wind channeling of the fields and the X-ray production from the wind channeling, shock heating, and confinement. (*Show figure, including DEM(s), which we will then use to generate simulations of the ACIS spectra.*)

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 theoretical bridge between magnetic characteristics and observed properties of massive stars. The proposed *Chandra* observations of a dozen magnetic B stars (including two A0p stars) will do four things while nearly doubling the number of magnetic massive stars observed in X-rays:

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*

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

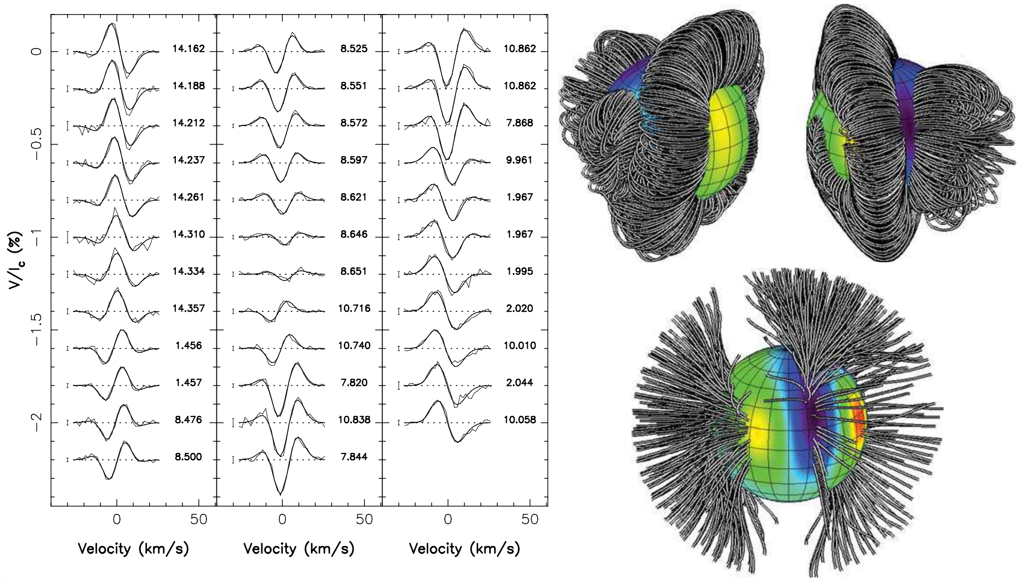

Figure 1: Detailed magnetic field mapping obtained with ESPaDOnS for the B0.2V star τ Sco (Donati et al. 2006, MNRAS 370, 629). On the left, time-resolved variations of the observed circular polariation Zeeman signature (thin lines) and maximum-entropy fit (thick lines). On the right, extrapolation of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

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 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 the X-rays were intrinsic to the late B star. We will perform a similar analysis, and also can use Czesla & Schmitt's sample as somthing of a control group, to compare to the X-ray properties of our dozen magnetic B stars.

Observation planning: Count rate estimates, exposure time justifications, observing modes...

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 (He-strong)	rosat upper limit	250 G; β Cep, per. UV var.	254
V 1671 Cyg	B2 V (He-strong)	none	-700:1800 G	559
V 901 Ori	B2 IV (He-strong)	none	-2140:2540 G; dip. & quadr.; rot. braking	510
ζ Cas	B2 IV (SPB)	rosat upper limit	335 G	183
31 Peg	B2 IV-Ve	none	newly detected B-field	298
a Cen	B2 - B9 (He var.)	rosat upper limit	-430:375 G	128
16 Peg	B3 Ve	none	-156:104 G	157
HD 58260	B3 III (He-strong)	none	8100 G	826
HD 35502	B5 V (He-weak)	none	2250 G; radio source	408
V 686 CrA	B8 IV (He-weak)	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	629

Co-authors: We could provide comments about individual stars in the last column or, better still I think, in foonotes to this table, as needed. But for the table column, how about listing magnetic properties? At least the field strength (and if there's variability or evidence for non-dipole fields, we can put that in the footnotes. – OK, I've got them from Veronique. I just have to put them in the table. Finally, what do you think about having a column in the table listing how many hours of observing time have been or will be dedicated to each target in the MiMeS program?