MAGNETIC FIELDS OF 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. These exciting discoveries have significant implications for massive star structure and evolution (Maeder & Meynet 2005), including implications for he 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[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 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 (Gagne 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[2].

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 θ^1 Ori C, HD 191612, shows X-ray emission that is soft, not especially luminous, and has broad emission lines (Naze 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.

[1]The program has been granted over 500 hours (?) of observing time using the Espadons spectropolarimeter at the CFHT, and we are also supplementing that with observations using 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?*

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

The puzzle of diverse X-ray behavior in magnetic massive stars has continued as we look at the X-ray properties of two new magnetic massive stars we found during a systematic survey of Orion Nebula Cluster: NU Ori and LP Ori (Petit et al. 2008). Although they have magnetic fields of similar strength, their X-ray properties (observed as part of the COUP program) differ greatly. Notwithstanding its strong magnetic field, NU Ori has X-ray properties that appear typical of a non-magnetic star: soft and non-variable, with only a little excess luminosity. LP Ori, on the other hand, shows hard, significantly variable X-ray emission, with higher-than-average X-ray efficiency for its B2 spectral subtype (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 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[3], as well as five additional stars of later B spectral subtypes, and two A0p stars of special interest[4]. All of the stars in our sample are being intensively studied with spectropolarimetric obervations as part of the MiMeS program. The proposed *Chandra* observations will nicely complement the direct studies of their magnetic field properties. And as part of our proposed research program, we will also model these ojects using steady-state RRM calculations as well as dynamical RFHD simulations that will directly simulate their X-ray emission via hydrodynamic models that include a detailed energy equation. The ongoing spectropolarimetric observations will constrain the surface field distribution and field geometry, that will inform the numerical magnetospheric modeling and the analysis of the X-ray emission.

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. In addition to providing the magnetic information (strength, geometry, topology, period) that is necessary to simulate the magnetoshere of these stars, we will obtain exquisite spectra with Espadons and Narval covering the whole optical range that will allow for precise photospheric parameter determination, and also allows us to search for the presence of spectroscopic companions that could potentially contribute to the X-rays.

We will then compare the predictions of the magnetosphere simulations to the observed X-ray properties. To do this, we will need an accurate determination of the X-ray luminosity of these stars and some information about the temperature distribution of the X-ray emitting plasma in their magnetospheres. The high sensitivity of ACIS is therefore important, along with its high spatial resolution which will enable the observation of massive stars in crowded regions and also allows us to resolve potential visual binaries that could be contributing to the X-ray emission. The moderate spectral resolution of ACIS will enable us to estimate plasma temperatures, which are

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

[4] *Co-authors: Is 12 stars too many? Shall we cut this list a bit?*

Table 1: MiMeS X-ray Sample

name	alt. name	sp. type	x-ray observation status	comments
HD 163472	V 2052 Oph	B2 IV (He-strong)	rosat upper limit	
HD 184927	V 1671 Cyg	B2 V (He-strong)	none	
HD 37776	V 901 Ori	B2 IV (He-strong)	none	
HD 3360	ζ Cas	B2 IV (SPB)	rosat upper limit	
HD 212076	31 Peg	B2 IV-Ve	none (XMM?)	
HD 125823	a Cen	B2 - B9 (He var.)	rosat upper limit	
HD 208057	16 Peg	B3 Ve	none (XMM?)	
HD 58260		B3 III (He-strong)	none	
HD 35502		B5 V (He-weak)	none	
HD 175362	V 686 CrA	B8 IV (He-weak)	rosat upper limit	
HD 124224	CU Vir	A0Vp	rosat measurement	
HD 34452	IQ Aur	A0p	rosat measurement	

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. 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?

key observables that can be confronted with magnetospheric simulations. Finally, we will search for X-ray variability, hence addressing all the major predictions from the magnetically channeled wind model.

0.1 Observing strategy:

Up to now, there are 23 stars of spectral type B2 or earlier which are confirmed magnetic field detections. All these stars will be studied by MiMeS, except 3 stars situated in the Southern hemisphere, and 2 stars whose magnetic fields have already been studied in details (Tau Sco and Zeta Ori, Donati et al. ;Bouret et al.).

Of these 23 stars, only 13 have determination of their X-ray properties (several just with *ROSAT*). We thus propose to observe the remaining 10 stars, in order to not only double the sample of magnetic massive stars with known X-ray properties, but also to obtain a complete sample of *all* the magnetic massive stars which are supposed to have non-negligeable winds.

(*Co-authors, these numbers must be a little off. The 13/23 leaving 10, doesn't account for the three southern stars not on the MiMeS target list; and I think it might include one or two stars with later spectral subtypes than listed in the spreadsheet. In any case, maybe this numerical information has been discussed sufficiently earlier in the proposal (or it could be fleshed out up there, with a few (accurate) numbers). Then this "observing strategy" section could be focused on the exposure time justifications.*)

Co-authors: What figures to show? (1) Related to the Espadons observations – something that demonstrates our magnetic field measurements. (2) X-ray simulations – a simulated ACIS spectrum or two? (3) At least one simulation figure, from Rich?