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A Report on the X-ray Properties of the τ Sco Like Stars

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ABSTRACT

An increasing number of OB stars have been shown to possess magnetic fields. Although the sample remains small, it is surprising that the magnetic and X-ray properties of these stars appear to be far less correlated than expected. This contradicts model predictions, which generally indicate that the X-rays from magnetic stars to be harder and more luminous than their non-magnetic counterparts. Instead, the X-ray properties of magnetic OB stars are quite diverse.

τ Sco is one example where the expectations are better met. This bright main sequence, early B star has been studied extensively in a variety of wavebands. It has a surface magnetic field of around 500 G, and Zeeman Doppler tomography has revealed an unusual field configuration. Furthermore, τ Sco displays an unusually hard X-ray spectrum, much harder than similar, non-magnetic OB stars. In addition, the profiles of its UV P Cygni wind lines have long been known to possess a peculiar morphology.

Recently, two stars, HD 66665 and HD 63425, whose spectral types and UV wind line profiles are similar to those of τ Sco, have also been determined to be magnetic. In the hope of establishing a magnetic field – X-ray connection for at least a sub-set of the magnetic stars, we obtained XMM-Newton EPIC spectra of these two objects. Our results for HD 66665 are somewhat inconclusive. No especially strong hard component is detected; however, the number of source counts is insufficient to *rule out* hard emission. longer exposure is needed to assess the nature of the X-rays from this star. On the other hand, we do find that HD 63425 has a substantial hard X-ray component, thereby bolstering its close similarity to τ Sco.

Key words: stars: early-type; stars: individual: HD63425, HD66665; stars: magnetic field; X-rays: stars

1 INTRODUCTION

In spite of their apparent simplicity, near main sequence B stars exhibit a range of properties that are not well understood. Among the challenges include: surprisingly low wind mass-loss rates and wind terminal speeds (Petit et al. 2011; Oskinova et al. 2011), a full understanding of the causes and evolution of the Be phenomenon (e.g., Porter 1999; Brown, Cassinelli, & Maheswaran 2008; Townsend, Owocki, & Howarth 2004; Carciofi et al. 2009; Wisniewski et al. 2010), and the nature of magnetism being detected among some B stars (Hubrig et al. 2006; Rivinius et al. 2010; Petit et al. 2011; Oksala et al. 2012; Grunhut et al. 2012).

In regard to their mass loss, a number of main sequence B stars display mass-loss rates $\dot{M}$ that are an order of magnitude lower than theoretical expectations. Examples include detailed spectral analyses of five B stars described in Oskinova et al. (2011): τ Sco, β Cep, ξ^1 CMa, V2052 Oph, and ζ Cas. Although β Cep is a giant, the other four are B0–2 main sequence stars. In addition, the early BV stars HD 66665 and HD 63425, which are the subject of this paper, were analyzed by Petit et al. (2011) and found to have low $\dot{M}$ values, an order magnitude lower than predicted by Vink, de Koter, & Lamers (2000). Notably, the presence of X-rays in their winds played an important, if not central, role in achieving satisfactory fits to observed UV and optical spectra. It seems then that at least some B stars exhibit the same "weak wind" problem seen in the less luminous O stars (e.g., Martins et al. 2005; Marcolino et al. 2009; Muijres et al. 2012; Lucy 2012; Huenemoerder et al. 2012).

Then there is the occurrence, properties, and evolutionary influence of magnetic fields among B stars. Our contribution to this issue has been to study the X-ray emissions from magnetic B stars in order to identify relationships (or the absence thereof) between known magnetic properties and measured X-ray characteristics (Ignace et al. 2010; Oskinova et al. 2011).

Our attempt to draw connections between magnetism and X-rays among the B stars was inspired by several by successes in relating X-ray properties to magnetospheric models for early-type

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stars with strong magnetic fields. Magneto-hydrodynamical simulations of the early O star θ Ori[1] appear capable of matching the observed X-ray variations, both in broad band terms as well as in emission lines (Gagne et al. 2005; ud-Doula 2012). The Bp star σ Ori E has a very strong surface magnetic field of $\approx 20,000$ G that motivated a semi-analytic approach called the Rigidly Rotating Magnetosphere (RRM) model (Townsend & Owocki 2005). The RRM has been broadly successful in explaining observed Hα variations, the polarization light curve, and with extension to time-dependent hydrodynamics, the star's broad X-ray properties (Townsend, Owocki, & ud-Doula 2007). Indeed, the approach has even been able to explain the *measured* rotational spin-down rate of the star (Townsend et al. 2010). Although MHD simulations still face challenges with producing detailed quantitative matches to observed X-rays of magnetic massive stars (e.g., Nazè et al. 2010), the models are a work in progress that offer a promising framework in which to interpret the observations.

With this framework, it was thought that deeper insights into the relationship between magnetic and X-ray characteristics could be gained through a study of B stars with weaker yet moderately strong surface magnetic fields and lower wind mass-loss rates. To this end, the efforts of the MiMeS (e.g., Grunhut & Wade 2012) and Magori (Scholler et al. 2011) collaborations to detect, characterize, and catalog the magnetic properties of early-type stars have been indispensable. Unfortunately, a clear relation between stellar magnetism and X-ray fluxes has not emerged. Indeed, the apparent *absence* of expected relationships between magnetic and X-ray properties has been a surprise (Favata et al. 2009; Ignace et al. 2010; Oskinova et al. 2011).

Despite the lack of an overall connection, it may be that certain types of magnetic stars do exhibit one. For example, τ Sco is a magnetic star with unusual UV wind lines, and is also notable for having an unusually hard component to its X-ray emission for a massive star, especially for an early B type star that is believed to be single (e.g., Cassinelli et al. 1994; Cohen et al. 2003; Mewe et al. 2003; Ignace et al. 2010). Recently, two other stars, HD 66665 and HD 63425, were identified as having UV wind lines with the same peculiar morphology seen in τ Sco. This motivated Petit et al. (2011) to observe both stars, and both yielded significant positive detections of surface magnetic fields. We refer to Petit et al. (2011) for a discussion and spectral analysis of HD 66665 and HD 63425, and to Oskinova et al. (2011) for a spectral analysis of τ Sco.

The question that naturally arises is whether or not HD 66665 and HD 63425 are also hard sources of X-rays like τ Sco. If so, the discovery would produce a rare example among massive stars of a relationship involving stellar magnetism, X-ray emissions, and UV line profile morphology. We report here on data obtained with the *XMM-Newton* in an effort to characterize the X-ray luminosities and hot plasma temperatures for HD 66665 and HD 63425. Section 2 details the acquisition and reduction of data obtained with the EPIC detectors. Section 3 presents an analysis of the X-ray spectra. An assessment of whether HD 66665 and HD 63425 are indeed hard sources is given in Section 4, followed by concluding remarks in section 5.

2 OBSERVATIONS AND DATA REDUCTION

We obtained dedicated *XMM-Newton* observations of HD 63425 and HD 66665. Stellar and wind properties of our target stars are given in Table 2. All three (MOS1, MOS2, and PN) European Photon Imaging Cameras (EPICs) were operated in the standard, full-frame mode and a medium UV filter. A log of observations is shown in Table 2. The data were analyzed using the software SAS 10.0. The time periods when the particle background was high were excluded from the analysis. Both stars were detected by the standard source detection software. The exposure times and EPIC PN count rates for our program stars are given in Table 2.

Table 1. Properties of Analogue Stars[†]

	HD 63425	HD 66665
Type	B0.5V	B0.5V
$T_{\rm eff}$ (K)	29,500	28,500
$\log g$ (cgs)	4.0	3.9
$\log L_*/L_\odot$	4.50	4.25
$M_*/M_\odot$	17	9
$R_*/R_\odot$	6.8	5.5
$v \sin i$ (km/s)	< 15	< 10
$\dot{M}$ ($M_\odot$/yr)	$< 7.5 \times 10^{-10}$	$< 4.5 \times 10^{-10}$
v_∞ (km/s)	~ 1700	~ 1400
d (kpc)	1,136	1–2
$\log N_H$ (cm^{-2})	20.64	20.15
V magn	6.9	7.8

[†] Values taken from Petit et al.(2011), except for the hydrogen column density that comes from Diplas & Savage (1994)

Table 2. *XMM-Newton* Observations of τ Sco-Analogue Stars

Star	MJD	useful exposure [ksec]	PN count-rate[a] [s^{-1}]
HD 63425	55687.8474	12	0.064 ± 0.002
HD 66665	55077.0906	25	0.022 ± 0.001

[a] In the 0.3-7.0 keV band; background subtracted.

A bright patch of diffuse X-ray emission with diameter of ≈ 4 arcmin is present in the EPIC images of HD 63425. The spectrum of the diffuse emission was found to be well fitted with a two temperature plasma having components $kT_1 \approx 0.7$ keV and $kT_2 \approx 5.4$ keV. The X-ray temperature, flux, brightness distribution, and comparison with optical and IR images indicate that this diffuse emission is most likely due to a massive galaxy cluster at $z > 0.3$ (A. Finoguenov, private comm.). The spectrum of HD 63425 was extracted from a region with a diameter of $\approx 15''$. The X-ray background was chosen from a nearby area in the diffuse X-ray source. Thus, it is possible that the hard stellar X-ray emission for HD 63425 is *over-subtracted* because of the hard background diffuse radiation. Therefore, the X-ray spectrum of HD 63425 presented here provides only a conservative estimate of the hottest temperature plasma component.

The X-ray point source with the coordinates of HD 66665 is well isolated, and there was no difficulty in obtaining its spectrum using the standard procedure and determining the X-ray background from a nearby region free of X-ray sources.

3 RESULTS

To analyze the spectra we used the standard spectral fitting software XSPEC (Arnaud 1996). The number of counts per bin in the spectra of HD 63425 and HD 66665 is small; therefore, we used the Cash-statistic (Cash 1979) for spectral fitting. Using the neutral hydrogen column density as a fitting parameter does not yield a sensible con-

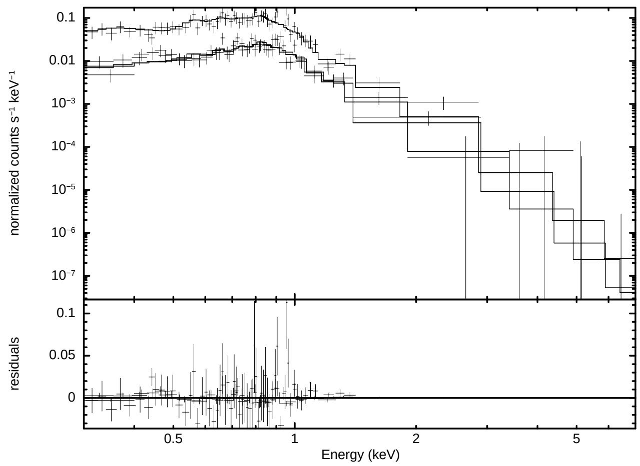

Figure 1. *XMM-Newton* PN (upper curve), and MOS1 and MOS2 (lower curves) spectra of HD 63425 with the best fit three-temperature model (solid lines). The model parameters are shown in Table 3.

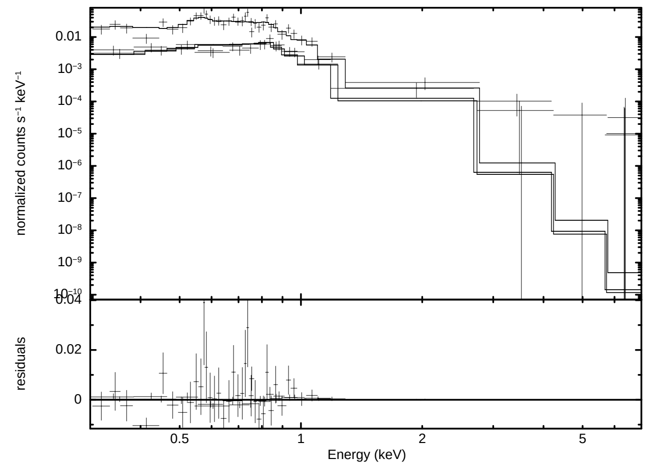

Figure 2. *XMM-Newton* EPIC-PN spectrum of HD 66665 and the best fit two-temperature model. The model parameters are shown in Table 3.

straint on its value; therefore, $N_{\rm H}$ was fixed at its interstellar value (see Tab. 1).

Our targets are known magnetic stars, and peculiar abundances are often found in such stars, typically explained as arising from diffusion processes which allow heavier elements to sink in the atmosphere under the influence of gravity, while lighter elements are elevated to the surface by radiation pressure (e.g., Morel et al. 2008). It is usual for a magnetic star to show an overabundance of nitrogen, and sometimes helium. For example, Morel (2011) find that the abundance ratio [N/C] is higher than solar in HD 66665, while [N/O] is nearly solar. We are not aware of any abundance studies for HD 63425. The quality of the X-ray spectra of our program stars are not sufficient to constrain abundances. We carried out tests that showed that the overabundance of N by a factor of a few does not significantly change the results of our spectral fits. Therefore, abundances for our two target stars were set to solar values based on Asplund (2009).

3.1 HD 63425

Our *XMM-Newton* observation detected the X-ray emission from HD 63425 for the first time. The 90% confidence range for the unabsorbed X-ray flux, meaning the intrinsic flux of the star after correcting for interstellar absorption, is $1.31 - 1.71 \times 10^{-13}$ erg s^{-1} cm^{-2}. Assuming a distance of $d = 1.136$ kpc, the X-ray luminosity of HD 63425 is $L_{\rm X} \approx 2 \times 10^{31}$ erg s^{-1} with an error of about 15%; this X-ray luminosity is comparable to the value for τ Sco. The observed EPIC spectra of HD 63425 and the fitted model are shown in Figure 1. A two temperature plasma model can reproduce the observed spectrum quite well (see Tab. 3).

3.2 HD 66665

Our *XMM-Newton* observation detected the X-ray emission from HD 66665 also for the first time. The source has only a modest count rate (see Tab. 2). The unabsorbed X-ray flux is $2.0 - 4.8 \times 10^{-14}$ erg s^{-1} cm^{-2}. Assuming a distance of $d = 1 - 2$ kpc, the X-ray luminosity of HD 66665 falls in the conservative range of $L_{\rm X} \approx 2 - 22 \times 10^{30}$ erg s $^{-1}$. The EPIC spectra of HD 66665 can be well described using a two temperature plasma model (see Tab. 3). The observed spectra and a model fit are shown in Figure 2. It is interesting to note that the emission measures of hotter and cooler plasma components are quite similar. This is in contrast to other magnetic B-type stars, where the softer component usually has much larger emission measure (c.f., Oskinova et al. 2011); however, τ Sco is one notable exception to this rule.

Although the two-temmperature fit is statistically acceptable, it seems that the model doesn't reproduce well the spectral shape at energies above 2 keV. We attempted to find a three-temperature model fit or a power-law fit, but these additional model components were essentially unconstrained. Thus, while it appears that there are indications of a harder component being present in the spectrum of HD 66665, it must be confirmed by better quality data.

4 DISCUSSION

4.1 Comparison of Spectra

Figure 3 displays a comparison of the X-ray spectra of the two τ Sco analogues against τ Sco itself, as well as two other reference objects, ξ^1 CMa and β CMa. Each source spectrum has been normalized to unit area for the sake of comparison. The spectrum of τ Sco is shown as the hatched region in each panel of this figure. The two analogue objects are shown at bottom; the other two reference objects at top. The B star ξ^1 CMa is a magnetic star with a surface field of about 1,450 G (Hubrig et al. 2006; Fortune-Ravard et al. 2011); its X-ray properties have been reported in Oskinova et al. (2011). The source β CMa is a giant B star that does not, so far, have a detectable magnetic field (Hubrig 2006). The star has been observed with the XMM-EPIC (PI: W. Waldron), but a detailed analysis has not been reported in the literature. Here we present only a preliminary spectrum of β CMa for the purpose of having a high signal-to-noise X-ray spectrum with (a) the same instrument as our analogues sources and (b) which is known not to have a significant surface magnetic field.

Normalization of the spectrum accentuates differences in the spectral energy distributions between the repective sources and τ Sco. (Note: With an EPIC/PN spectrum of over 100,000 X-ray counts, the S/N of τ Sco's spectrum is so much higher than the other stars that we do not show error bars.) The spectra of both HD 63425 and ξ^1 CMa closely hug the shape of τ Sco's spectrum. By contrast both HD 66665 and β CMa show peak values that are

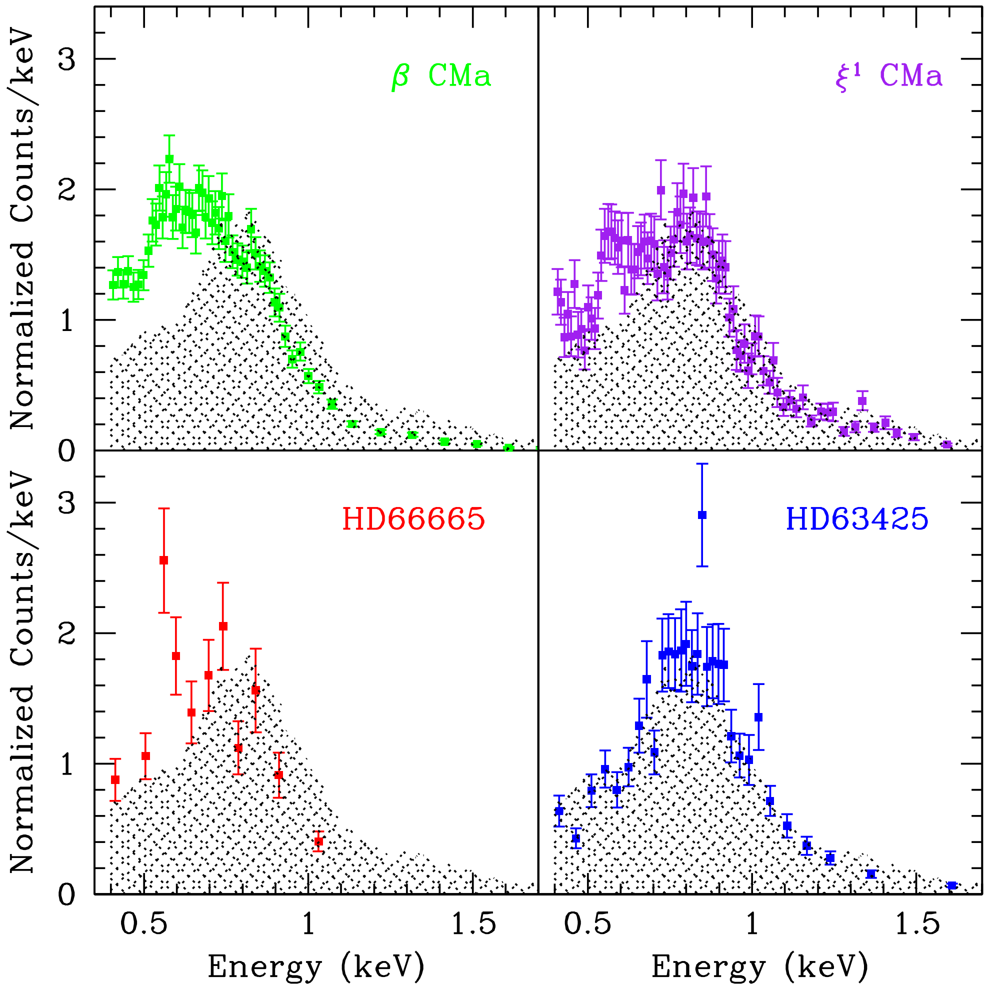

Figure 3. A comparison of XMM-Newton spectra of five B stars from the PN instrument, as labeled. Only β CMa is known not to be magnetic; all the others are magnetic stars. For reference the spectrum of τ Sco is displayed as the hatched area in each figure. All of the spectra have been normalized to unit area for comparisons of spectral shape.

shifted to softer energies and a relative deficit of quite hot gas as compared to τ Sco.

There are two main comments to be made at this point. First, β CMa is at an extremely low interstellar hydrogen column density, approximately two orders of magnitude lower than the other four stars (see Tab. 3). In fact, because of its low column density, β CMa was one of only two massive stars observed with the EUVE (Cassinelli et al. 1996). For the present analysis, the low column results in minimal attenuation of the softer X-ray emissions from this star, which naturally shifts the X-ray spectral peak of β CMa to lower energies. Still, as will be discussed, β CMa lacks a substantial hard component to its X-ray spectrum.

The second point is that the overall counts for HD 66665 are low, lowest of all five sources in this report. The lower-than-expected count rate of HD 66665 suggests that hard emission could be present but not detected. In effect, a low level of hard emission above 1.5 keV could be present intrinsically, but lost in the background noise owing to insufficient counts. As a result, only the dominant softer component survives in the data reduction. Our main conclusion for HD 66665 is that its spectrum does not provide evidence of hard emission, but that a longer exposure is needed to determine confidently whether or not hard emission is produced by the system.

4.2 Statistical Analysis

With the exception of τ Sco, we have made two-temperature fits to our sources. For τ Sco, the quality of the spectrum is so high, at over 100,000 counts detected, that a two-temperature fit produces a poor match to the spectrum. In this case we use the four-temperature fit of Mewe et al. (2003) in the following discussion of source X-ray properties.

X-ray spectral characteristics are given for the five stars under discussion in Table 3. The table lists the hydrogen column density, X-ray count rate in EPIC/PN, the X-ray luminosity from EPIC/PN, and the temperatures (as kT in keV) and relative emission measures of the two temperature fits. Also listed is an emission-measure-weighted average temperature, defined by

Table 3. X-ray Characteristics of Sources[a]

	τ Sco[b]	HD 63425	HD 66665	ξ^1 CMa	β CMa
N_H^c (10^{20} cm^{-2})	2.0	4.4	1.4	1.4	0.02
PN Count Rate (cps)	7.99	0.063	0.023	0.67	0.73
d (kpc)	0.145	1.11	1–2	0.420	0.151
L_X (10^{30} erg/s)	32	12 ± 2	2–23	31	3.2 ± 0.2
L_X/L_* (10^{-7})	4.0	1.6	$2-22$	2	0.4
B_* (G)	500	$\sim 1,100$	600	1,450	0
kT_1 (keV)	0.141 ± 0.005	0.19 ± 0.01	0.16 ± 0.04	0.121 ± 0.004	0.111 ± 0.004
EM_1/EM_T	0.17 ± 0.02	0.54 ± 0.10	0.50 ± 0.31	0.65 ± 0.14	0.61 ± 0.12
kT_2 (keV)	0.85 ± 0.06	0.60 ± 0.02	0.39 ± 0.06	0.564 ± 0.009	0.353 ± 0.007
EM_2/EM_T	0.83 ± 0.06	0.46 ± 0.08	0.50 ± 0.34	0.35 ± 0.04	0.39 ± 0.05
$\langle kT \rangle$ (keV)	0.73 ± 0.07	0.38 ± 0.05	0.28 ± 0.15	0.28 ± 0.03	0.21 ± 0.02
$\Delta kT/\sigma_\Delta^d$	7.3	3.1	0.5	1.9	N/A

[a] Values based on fits to the EPIC-PN spectral data, unless indicated otherwise.
[b] Values based on RGS/MOS analysis by Mewe et al. (2003); see text.
[c] Values fixed as based on measures found in the literature.
[d] See text for an explanation of this ratio.

$$\langle kT \rangle = \frac{\sum_i kT_i\, EM_i}{\sum_i EM_i} = \sum_i \left(\frac{EM_i}{EM_T}\right) kT_i, \quad (1) \quad (2)$$

where EM_T is the total emission measure. In the case of τ Sco, the star has one measure of temperature of relatively low value, typical of other OB stars, and three higher temperature components. Those three higher ones have been emission-measure averaged according to the values quoted by Mewe et al. (see their Tab. 2), and given in the table simply as kT_2.

Table 3 also gives the measured surface magnetic field values, the X-ray luminosities, and the ratios of X-ray to Bolometric luminosity. The surface fields show a large range. Not counting the non-magnetic star β CMa, field values range from about 500 G for τ Sco to one that is 3× that for ξ^1 CMa. Although none of the stars are exceptional in their value of $L_X/L_{\rm Bol}$, having ratios of order 10^{-7} that is reflective of the standard found for other O stars and early B stars (e.g., Berghoefer et al. 1997), it is interesting to note that the ratio for β CMa is smaller than all of the magnetic stars being considered.

As mentioned in the previous section, there is some concern for HD 66665 that its apparent lack of quite hard emission is an artifact of its low quality spectrum. To illustrate Figure 4 plots the two kT values for each source against the total number of detected X-ray counts. It seems clear that the *failure* to detect a hot component in β CMa, the lone non-magnetic star in this sample, is not a question of sufficient counts. Both HD 63425 and ξ^1 CMa have lower total counts in EPIC/PN yet substantially hotter kT_2 values. The kT_2 value for HD 66665 is lowest among the magnetic stars, but suspiciously also has the lowest total counts. The fact that the spectrum of HD 66665 is fit by roughly equal amounts of soft and hard emissions is anomalous among single OB stars, and tantalizingly suggestive that hotter gas may be present in HD 66665 but was simply not detected. We feel strongly that a longer exposure spectrum is needed to determine whether or not HD 66665 has a hot component, similar to τ Sco. Clearly, HD 63425 does have a hot component similar to τ Sco.

To place these claims on a more quantitative level, consider the following analysis of the emission-measure-weighted kT values, $\langle kT \rangle$, for our sources as compared to our reference non-magnetic B star, β CMa. For this purpose we introduce a difference parameter ΔkT as

$$\Delta kT = \langle kT \rangle_{\rm star} - \langle kT \rangle_{\beta\ {\rm CMa}}. \quad (3)$$

The error in the difference ΔkT is given by σ_Δ, with

$$\sigma_\Delta^2 = \sigma_{\rm star}^2 + \sigma_{\beta\ {\rm CMa}}^2. \quad (4)$$

Then the significance of the difference in weighted kT values can be evaluated from the ratio $\Delta kT/\sigma_\Delta$, as provided in Table 3. The overall harder emission observed in τ Sco and HD 63425 as distinct from β CMa is found to be significant at confidence levels of roughly $7\sigma_\Delta$ and $3\sigma_\Delta$, respectively. For ξ^1 CMa the significance is actually less at just under $2\sigma_\Delta$. For HD 66665 the distinction is formally not significant at all because of the larger error in the determination of $\langle kT \rangle$ for this star.

5 CONCLUSIONS

The two B stars HD 63425 and HD 66665 have been identified as analogues to the B star, τ Sco, initially owing to similarity between UV P Cygni spectral lines. Given the successful detection of magnetism in τ Sco (Donati et al. 2006), Petit et al. (2011) reported the search and detection of magnetism in HD 63425 and HD 66665 that strengthens the physical connection that these three stars appear to share.

The magnetic detections prompted an investigation of the X-ray properties of HD 63425 and HD 66665. The detection of

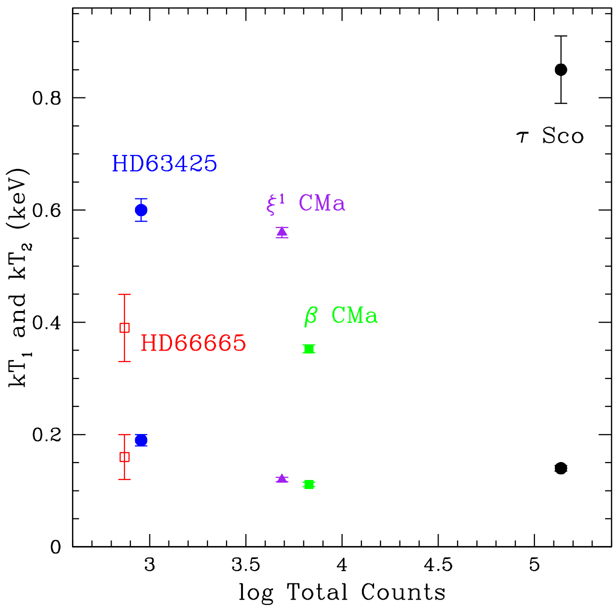

Figure 4. A plot of the two temperature components from spectral fits, provided as kT in units of keV, versus the total counts for the source. For τ Sco, the higher temperature component is an emission measure weighted average from the three hot components described in Mewe et al. (2003; see text). Note that all five stars have low temperature components of similar value. τ Sco, ξ^1 CMa, and HD 63425 all have high temperature components, more so than β CMa. The hot component of HD 66665 appears consistent with that of β CMa; however, the former has an order of magnitude fewer counts than the latter. The error bars are 1σ values.

hard emission with a substantial relative emission measure for HD 63425 appears to solidify its observational status as a bona fide τ Sco analogue by virtue of having (a) peculiar UV wind lines, (b) a substantial surface magnetic field, and (c) hard X-ray emission well in excess of values typically seen in single OB stars.

For HD 66665 our analysis does not provide evidence of a substantial hard component. However, our observation led to fewer counts than expected, and we view the experiment as inconclusive. A longer exposure is needed to verify whether or not the star possesses significant plasma of abnormally high temperature as in the case of τ Sco.

Given the success in verifying the analogue nature of HD 63425, it now seems ripe, from an empirical point of view, to suggest that τ Sco may be a prototype for a new class of magnetic B stars. Exactly how the wind and magnetic field interacts to produce the observed hard X-ray emissions and pecular UV line morphologies remain important open questions. Zeeman Doppler imaging of τ Sco has revealed a quite complex magnetic field topology (Donati et al. 2006). The star's surface distribution is more complicated than a simple dipole field like those used in current models of magnetized stellar winds ud-Doula & Owocki 2002; Townsend, Owocki, & ud-Doula 2007). What can be concluded is that there is a subset of magnetic B stars taht share the properties of τ Sco; and that adopting β CMa as a reference non-magnetic B star, it appears that the magnetic stars τ Sco, HD 63425, and ξ^1 CMa are all comparatively hard and X-ray luminous (in terms of L_X/L_*), as one might generally expect from models of magnetically channeled wind flow. In the future more intensive monitoring of HD 63425 and HD 66665 is needed to discern the detailed magnetic field geometries of these stars, and more data are needed to confirm the X-ray nature of HD 66665.

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