RESOLVING X-RAY SOURCES FROM B STARS SPECTROSCOPICALLY: THE EXAMPLE OF $\mu$ LEPORIS

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ABSTRACT

We present high-resolution X-ray observations of the chemically peculiar late-type B star $\mu$ Lep. However, we find spectroscopic and astrometric evidence, which shows that the X-rays are not traced back to the B star itself but rather to a previously unresolved companion, $\mu$ Lep-B, whose X-ray spectrum resembles that of a coronally active source. We discuss the possibility that $\mu$ Lep-B is a pre–main-sequence companion, most likely of the nonaccreting magnetically active type.

Subject headings: stars: activity — stars: chemically peculiar — stars: coronae — stars: pre–main-sequence — X-rays: stars

Online material: color figures

1. INTRODUCTION

Bright X-ray emission from isolated late-type B stars (and early A stars) remains enigmatic, as conventional stellar theory predicts these stars neither to have the magnetically active coronae of cool stars nor to eject sufficiently intense stellar winds like those of hot O and early B stars. Therefore, it was surprising that a deep ROSAT survey detected as many as 86 late B stars (Berghöfer et al. 1996). In an effort to explain these results, Hubrig et al. (2001) searched for companions to the alleged X-ray–bright B stars. A companion, it was presumed, could be the actual X-ray source. In 24 cases out of a selected list of 49 B stars, evidence of an active late-type companion was not found, leaving the high level of X-ray flux associated with these B stars a mystery. Until recently, the discussion in the community on whether B stars are intrinsic X-ray emitters or not has suffered from the limitations on our ability to resolve the B stars from their putative low-mass companions.

The superb angular resolution available for imaging with the Chandra X-ray telescope has allowed Stelzer et al. (2003) to resolve a handful of B stars, previously suspected as intrinsic X-ray emitters or not has suffered from the limitations on our ability to resolve the B stars from their putative low-mass companions.

The superb angular resolution available for imaging with the Chandra X-ray telescope has allowed Stelzer et al. (2003) to resolve a handful of B stars, previously suspected as intrinsic X-ray emitters, from the position of their associated X-ray sources. However, in some cases even the angular resolution of Chandra is insufficient (e.g., HD 1685 A in Stelzer et al. 2003), and a different approach is required. We have constructed and proposed a series of X-ray spectroscopic tests, which provide a scheme to determine whether the X-rays emanate from the immediate vicinity of the B star or not. These methods are particularly useful in the cases in which the source cannot be angularly resolved by direct imaging.

Some of the X-ray brightest, presumably isolated, late-type B stars are chemically peculiar (CP) stars, whose atmospheric composition is significantly enriched with peculiar elements. Since highly charged ions of any heavy element emit bright lines in the X-ray band, the potential observation of peculiar elements in the X-ray spectrum provides a powerful tool for testing whether or not the X-rays are due to the B star. With that in mind, we chose to observe $\mu$ Lep, a late-type B9, nonmagnetic, CP HgMn B star, also known as HR 1702 or HD 33904, with the XMM-Newton and Chandra grating spectrometers. As detected by ROSAT (Berghöfer et al. 1996), $\mu$ Lep is the X-ray–brightest late-type HgMn B star. Most importantly, $\mu$ Lep was included in the survey of Hubrig et al. (2001) in which an X-ray active companion was searched for but not found.

2. OBSERVATIONS

The target $\mu$ Lep was observed with XMM-Newton on 2003 March 23–24 for 47 ks. All three EPIC cameras were operated in full-frame mode with a thick filter, and the two Reflection Grating Spectrometers (RGS) were operational simultaneously. The EPIC and RGS data were processed with SAS version 5.4.1. Standard event filtering procedures were followed including background subtraction using off-target CCD regions. $\mu$ Lep was also observed with Chandra in the Low Energy Transmission Grating Spectrometer (LETGS) with the High Resolution Camera (HRC) configuration on 2003 December 1–2 for 64 ks and on 2004 January 12 for 37 ks. The data were processed with CIAO version 3.0.

2.1. Astrometry and Timing

Using the zero-order LETGS image to determine the position of the X-ray source, we obtain R.A. = $5^h12^m55^s.85$, decl. = $-16^\circ12'19".91$. The Hipparcos catalog position corrected for proper motion is R.A. = $5^h12^m55^s.913$, decl. = $-16^\circ12'19".749$ (Perryman et al. 1997). The discrepancy of 0.93 is about a 3 $\sigma$ offset from the astrometric accuracy of HRC-S.7 This already hints to the X-ray source not being associated with the B star. Nevertheless, we proceed with the spectroscopic diagnostics below. If indeed there is a secondary source separated by about 1" from $\mu$ Lep, it has to be faint in the K band, as the separation achieved by Hubrig et al. (2001) was as low as 0"3 and increasingly sensitive for larger separations. Alternatively, the separation may be variable. At $\mu$ Lep’s distance of 56.5 pc, 0"93 corresponds to a projected distance of 52 AU.

The EPIC MOS 1 and LETGS zero-order light curves are...
shown in Figure 1. In the MOS light curve, two short-duration flares (~10 ks) are observed in which the peak flux is about 1.5 and 2.0 times what seems to be the average nonflare flux level. LETGS just catches a similar flare (times 1.8) declining, with subsequent flux variations of as much as 40% thereafter. The variability is observed on timescales of a few hours.

2.2. Spectroscopic Diagnostics

The LETGS spectrum is of insufficient quality because of the high background level of the HRC. We focus therefore on the RGS spectrum. RGS 1 and RGS 2 recorded 1400 and 1635 source counts, respectively. The total flux measured from 6 to 37 Å (0.34–2.1 keV) is (1.15 ± 0.03) × 10^{-12} ergs s^{-1} cm^{-2}. This can be compared with the flux of (2.4 ± 0.23) × 10^{-12} ergs s^{-1} cm^{-2} measured over the 0.1–2.0 keV band with ROSAT (Berghofer et al. 1996). The discrepancy is reasonable considering the slightly wider ROSAT band and the fact that the source flux varies typically by a factor of 2. Assuming the X-ray source to be at the same distance as μ Lep (56.5 pc), the RGS flux translates into an X-ray luminosity in the RGS band of $L_x = (4.4 ± 0.1) × 10^{39}$ ergs s^{-1}.

The full RGS spectrum is presented in Figure 2 along with a simple model that serves mainly to highlight the identified bright lines. The model is an ion-by-ion fit to the data, similar to the method used in Behar et al. (2001) and in Brinkman et al. (2001). The spectrum features many emission lines and little continuum. O vii Lyα appears to be slightly (red)shifted from its rest-frame position of 18.969 Å. It is measured with RGS 1 at 18.988 ± 0.007 Å and with RGS 2 at 18.998 ± 0.006 Å, i.e., redshifted by 300 ± 110 and 460 ± 90 km s^{-1}, respectively. This could hint to rapid orbital motion of a late-type companion or to a wind. However, the positions of other bright lines are all formally consistent with the rest-frame wavelengths to within 200 km s^{-1}. Therefore, we prefer to interpret the O vii Lyα anomaly as a calibration/statistics artifact. Line widths are unresolved, providing only a not-very-constraining upper limit of $σ = 500$ km s^{-1} at 19 Å for the turbulent velocity width.

The He-like triplets are vital to the determination of the distance of the X-ray source from the B star. In the presence of the high UV flux of the B star, intensity would be transferred from the forbidden line ($f$) to the intercombination line ($i$) (Gabriel & Jordan 1969). The best measured He-like triplet in the RGS spectrum is that of O vii. The unperturbed (low-density, no-UV) value of the O vii $f/i$ intensity ratio is ~4.4, which then decreases rapidly as the distance between the UV (B star) and X-ray sources is reduced.

The region of the spectrum containing the bright O vii lines is shown in Figure 3. Although the moderate statistics hamper accurate determination of the line fluxes, the $f/i$ ratio is obviously high and a lower limit for this ratio can be readily obtained. The $i$ line ($λ = 21.801$ Å) barely can be identified in Figure 3. Indeed, the best-fit $i$-line flux is nil with an error of $2.0 × 10^{-3}$ photons s^{-1} cm^{-2}. The best-fit fluxes for the $r$ (21.602 Å) and $f$ (22.097 Å) lines are $10.5 × 10^{-3}$ and $6.0 × 10^{-3}$ photons s^{-1} cm^{-2}, respectively, neither of which is tightly constrained. The upper limit of $2.0 × 10^{-3}$ photons s^{-1} cm^{-2} for the $i$-line flux yields a lower limit to the $f/i$ ratio of 3.0, although a higher value (greater than 4.0) is much more likely. The three-line model in Figure 3 shows the best-fit fluxes for the $r$ and $f$ lines but the above upper limit for the $i$-line flux.

The implication of this measurement is demonstrated in Figure 4, where we show the theoretical $f/i$ ratio as a function of the distance of the X-ray source from μ Lep assuming it is a perfect blackbody at $T = 12,400$ K (Adelman & Pintado 2000). It can be seen that even at the conservative limit of $f/i = 3.0$, the X-ray source has to be at least 10.4 stellar radii ($R_*$) away from the B star. We take this as evidence for the X-
rays not originating from the B star itself but rather from a previously unresolved companion: \( \mu \) Lep-B. With a surface gravity of \( \log g = 3.7 \) \( \text{cm s}^{-2} \) (Adelman & Pintado 2000) and a mass of \( 3.5 \, M_\odot \) (from Schaller et al. 1992), \( 10.4R_\odot \) for \( \mu \) Lep corresponds to \( \approx 0.2 \) AU, which is much less than the estimate of \( \approx 50 \) AU obtained in \$2.1. Indeed, the separation is probably much larger than \( 10.4R_\odot \), only that the moderate statistics of the spectrum call for caution. A similar result: \( f/i > 3.0 \) is found using the Ne ix triplet, where the \( f \) line is even stronger relatively; only the blending of the \( i \) line with Fe xix lines makes the exact determination of the Ne ix \( f/i \) ratio more model dependent.

Another powerful diagnostic tool is the potential detection of emission lines of peculiar elements. As a HgMn star, the abundances of elements such as Hg and Mn are enriched in the atmosphere of \( \mu \) Lep and by a few orders of magnitude compared to solar composition. If the X-ray source is on \( \mu \) Lep, we would naively expect to observe lines of these elements in the X-ray spectrum. The strongest isolated line expected is that of Ne-like Mn xvi at 16.62 \( \AA \), which is the isoelectronic analog of the 15.01 \( \AA \) resonant line of Fe xvii. No clear Mn line is found using the Ne ix triplet, where the \( f \) line is even stronger relatively; only the blending of the \( i \) line with Fe xix lines makes the exact determination of the Ne ix \( f/i \) ratio more model dependent.

Having established that the X-rays are not coming from \( \mu \) Lep, the X-ray source companion \( \mu \) Lep-B is of interest by its own merits. The goal of this section is to try and shed some light on the nature of \( \mu \) Lep-B although the absence of optical or IR detections impedes conclusive results. Hence, \( L_{\text{bol}} \) for \( \mu \) Lep-B is unknown, and since the X-ray emission \( (L_X) \) is not due to winds or directly related to the B star, \( L_X \) should not be compared to \( L_{\text{bol}} \) (B star) is not a meaningful parameter. Thus, \( \mu \) Lep-B may be a cool pre-main-sequence (MS) or pre-MS (PMS) companion. PMS stars have been suggested as the X-ray companions of B stars, as the B star system is naturally young enough for a low-mass companion to be in its early evolutionary stages. Assuming \( L_{\text{bol}} = 8.7 \times 10^{35} \text{ ergs s}^{-1} \) for \( \mu \) Lep (Berghöfer et al. 1996), the tables of Schaller et al. (1992) give an estimated age of 19 Myr. IR detections provide evidence for PMS companions to B stars of similar ages (Stelzer et al. 2003). PMS stars are usually also radio sources, but \( \mu \) Lep has not been observed properly in the radio. The X-ray emission mechanism in PMS stars is thought to be magnetic (Feigelson & Montmerle 1999), proof that the X-ray source is not on \( \mu \) Lep. We note that strong emission by highly ionized Hg is also expected at \( \approx 43 \) \( \AA \) (Doron et al. 2002), which is just outside the RGS range.

In short, there is accumulating spectroscopic evidence, namely, the high \( f/i \) ratios and the absence of peculiar elements, which demonstrates that the X-ray source is not on \( \mu \) Lep but rather at an appreciable distance from it. Furthermore, the X-ray source is not due to stellar winds from the B star, nor to any other form of gas that has undergone chemical fractionation inside the B star atmosphere. Wind shocks are also ruled out by the short flares and by the observed high X-ray temperatures (see \$3).

3. DISCUSSION: THE NATURE OF \( \mu \) LEP-B

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although shocks have also been suggested (Kastner et al. 2002). Either way, it is well established that PMS stars are bright X-ray sources.

For MS stars, there is a strong correlation between X-ray emission and rotational velocity: \( L_x = 10^{32}(v \sin i)^2 \) ergs s\(^{-1}\) (Pallavicini et al. 1981). If \( \mu \) Lep is a tidally locked binary, a plausible scenario that could explain the chemical peculiarity, its low rotational velocity, \( v \sin i < 10 \) km s\(^{-1}\) (Abt & Morrell 1995), would imply \( L_x < 10^{19} \) ergs s\(^{-1}\) for a cool star companion. This is significantly lower than observed: \( L_x = (4.4 \pm 0.1) \times 10^{25} \) ergs s\(^{-1}\). On the other hand, PMS stars have an opposite, although not as tight, correlation where X-ray emission decreases with rotational velocity (see Fig. 7 in Feigelson et al. 2003). Estimating the rotational period of \( \mu \) Lep to be \( 2\pi R, /v > 22 \) sin \( i \) days, we find that the present \( L_x \)-value is consistent with the correlation of Feigelson et al. (2003). Therefore, we favor the identification of \( \mu \) Lep-B as a PMS star. The X-ray luminosity and variability of \( \mu \) Lep-B are also consistent with previous X-ray observations of PMS stars: The X-ray luminosity is well within the PMS range of \( L_x = 10^{23}–10^{24} \) ergs s\(^{-1}\), and the variability (Fig. 1) is in line with the fact that X-ray emission of PMS stars is dominated by flares. If indeed \( \mu \) Lep-B is a PMS star, at 56.5 pc it is arguably the closest one to Earth.

The X-ray thermal and chemical structure of \( \mu \) Lep-B can be tested against general characteristics of PMS stars. Although we leave a more elaborate spectral analysis for future work, there are a few points that already can be made here. A range of temperatures is observed in the RGS spectrum. High temperatures above 1 keV are observed through the well-identified Fe-L ions up to Fe xxiv (see Fig. 2) and by Mg, Si, and S K-shell lines clearly detected with the EPIC (not shown). Conversely, the 2p–3d lines of Fe xvi are identified at \( \sim 15.2 \) Å (Behar et al. 2001) and are indicative of temperatures as low as \( kT_e = 0.2 \) keV. Even lower temperatures may be probed after we do a careful job of identifying the L-shell lines of mid-Z elements, e.g., Ca, Ar, and S (Leepson et al. 2003).

Higher temperatures, \( kT_e \geq 2 \) keV, have been suggested in X-ray measurements of PMS stars (Feigelson & Montmerle 1999). There is no evidence in our spectrum for such high temperatures. Since two other state-of-the-art grating observations of T Tauri stars (TTs; Kastner et al. 2002, 2004) do not show such high temperatures either, we suspect that temperatures as high as 2 keV may not be ubiquitous to PMS stars.

A robust method for distinguishing between accreting and nonaccreting PMS stars by means of X-ray spectra alone has yet to be established. Nonetheless, between the two well-studied TTs—TW Hydrae (accreting) and HD 98800 (non-accreting; Kastner et al. 2002, 2004, respectively)—the present spectrum is more similar to that of HD 98800. The emission measure distributions of both \( \mu \) Lep-B and HD 98800 are broad, the latter covering the temperature range of 0.2–1.0 keV. The strong O and Ne lines compared to those of Fe in the present spectrum (Fig. 2) also resemble the ratios observed in HD 98800 and are very different from the abundance anomaly found in TW Hya. Finally, the high densities \( (10^{13} \text{ cm}^{-3}) \) observed for TW Hya through quenched forbidden lines are not observed for \( \mu \) Lep-B. In short, \( \mu \) Lep-B is probably a non-accreting magnetically active PMS star.

4. CONCLUSIONS

Using high-resolution grating spectroscopy, we have discovered the X-ray source \( \mu \) Lep-B to be distinct from the B star \( \mu \) Lep. This result is based on the X-ray source being 0.93° from the nominal position of the B star, but even more conclusively by two spectroscopic findings: (1) the observed forbidden lines of the He-like triplets are unaffected by the B star’s UV light and therefore cannot originate from close to the B star, and (2) there is no significant evidence in the X-ray spectrum for Mn, which is known to be extremely abundant on \( \mu \) Lep. The methods used here are most general and could be used to test whether other CP B stars are intrinsic X-ray emitters. The X-ray luminosity and variability indicate that \( \mu \) Lep-B could be a PMS star, although it is impossible to totally rule out a faint late-type cool star. By comparison with grating observations of other PMS stars, we suspect that the X-ray emission of \( \mu \) Lep-B is magnetically driven.

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