SOFT CORONAL X-RAYS FROM \( \beta \) PICTORIS

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ABSTRACT

A-type stars are expected to be X-ray dark, yet weak emission has been detected from several objects in this class. We present new \emph{Chandra}/HRC-I observations of the A5 V star \( \beta \) Pictoris. It is clearly detected with a flux of \((9 \pm 2) \times 10^{-4}\) counts s\(^{-1}\). In comparison with previous data this constrains the emission mechanism and we find that the most likely explanation is an optically thin, collisionally dominated, thermal emission component with a temperature around 1.1 MK. We interpret this component as a very cool and dim corona, with \( L_X/L_{bol} = -8.2 \) (0.2–2.0 keV). Thus, it seems that \( \beta \) Pictoris shares more characteristics with cool stars than previously thought.

Key words: stars: activity – stars: chromospheres – stars: coronae – stars: individual: \( \beta \) Pictoris – X-rays: stars

Online-only material: color figure

1. INTRODUCTION

Stars across the main sequence (MS) produce X-ray emission by two fundamentally different mechanisms. Late-type stars have convective envelopes, thus they develop a solar-like dynamo which creates a magnetic field. In turn, they display magnetic activity in a corona. All late-type MS stars close enough to be detected in X-ray surveys are confirmed X-ray emitters (Schmitt & Liefke 2004). Similarly, all stars earlier than mid-B to be detected in X-ray surveys are confirmed X-ray emitters and do not drive a solar-like dynamo and thus are, at least in principle, X-ray dark (Schmitt 1997).

It is no contradiction that some of these systems are detected in the ROSAT All-Sky Survey (RASS) because they often have unresolved late-type companions. Due to the shorter lifetime of the A-type star the companion is still at an early stage of its evolution and thus X-ray bright. The RASS catalog contains 312 bright A-type stars, a detection rate of 10\%–15\% (Schröder & Schmitt 2007). Most of those sources that have been re-observed at higher spatial resolution turn out to be multiple (Huelamo et al. 2000; Stelzer et al. 2003), but the possibility remains that a fraction are bona fide X-ray emitting A stars.

We mention two classes as exceptions to the rule of X-ray dark mid-B to mid-A stars: (1) Ap/Bp stars such as IQ Aur have strong magnetic fields and can funnel their winds to collide in the equatorial plane, forming shocks (Babel & Montmerle 1997; Robrade & Schmitt 2011) and (2) Herbig Ae/Be stars are young pre-MS stars of spectral type A or B with ages of only a few Myr. Herbig Ae/Be stars have significant mass accretion and sometimes strong jets. X-ray grating spectroscopy indicates both a coronal component from primordial fields or a turbulent dynamo and a soft X-ray component that is formed above the stellar surface, which has been interpreted as a jet base shock (Telleschi et al. 2007; Günther & Schmitt 2009).

Recently, Altair, spectral type A7, has been observed with \emph{XMM-Newton} (Robrade & Schmitt 2009). The star shows modest variability on the 30\% level, which is due to stellar rotation. The plasma temperature is 1–4 MK and the luminosity \( L_X = 1.4 \times 10^{27} \) erg s\(^{-1}\). The activity level of \( \log L_X/L_{bol} = -7.4 \) is far below that of saturated late-type stars which show \( \log L_X/L_{bol} = -3 \). In contrast, all single, earlier A stars remain undetected; the most prominent example is the A0V star Vega, where 29 ks of \emph{Chandra} ACIS and HRC observations place a 99.7\% upper limit as low as \( 2 \times 10^{25} \) erg s\(^{-1}\) or \( \log L_X/L_{bol} < -10 \) (assuming a corona with \( T = 1.5 \) MK), one of the lowest limits ever obtained for an X-ray luminosity (Pease et al. 2006; Ayres 2008). Vega is thought to be up to 500 Myr old and it seems natural to expect higher luminosities from younger stars. We have recently observed the 8 Myr old early A-type star HR 4796A but failed to detect it down to a limit of \( L_X = 1.3 \times 10^{27} \) erg s\(^{-1}\) (J. J. Drake et al., in preparation).

This article presents new \emph{Chandra}/HRC-I observations of the only known isolated mid-A-type star with detected X-ray emission: the A5 star \( \beta \) Pic (Hempel et al. 2005) at a distance of 19.4 pc. \( \beta \) Pic is the eponymous member of the \( \beta \) Pic moving group (BPMG) of coeval stars. The age is somewhat uncertain and ranges from 12 (Zuckerman et al. 2001) to 40 Myr (Macdonald & Mullan 2010). \( \beta \) Pic harbors a bright debris disk (Smith & Terrile 1984), further characterized by many groups and telescopes, including Subaru (Honda et al. 2004) and Spitzer (Chen et al. 2007). The disk of \( \beta \) Pic has been subject to intensive study, including IR interferometry, which excludes any companion more massive than 50 \( M_{Jup} \) in the inner few AU at 90\% level (Absil et al. 2010). However, Lagrange et al. (2009) imaged a giant planet in the debris disk at around 8 AU from the primary, which can account for some of the disk substructure, and two other planets are probably located near the other dust belt concentrations (Honda et al. 2004). The entire disk extent is some 1000 AU, and is dominated by icy dust in an extended Kuiper Belt full of primitive comets and icy dwarf planets. From this disk comets, or “falling evaporating bodies (FEBs),” appear to impact on the star on a daily basis (Ferlet et al. 1987).

Observations with \emph{FUSE} in the FUV show strong and superrotationally broadened lines of highly ionized species up to O VI. These lines consist of several components. Their emission mechanism is uncertain, but could be related to some sort of a chromosphere or cool corona a few stellar radii above the photosphere (Deleuil et al. 2001; Bouret et al. 2002) or to
accretion of mass from the debris disk. A further peculiarity is that β Pic shows δ Scuti-type pulsations (Koen et al. 2003).

2. OBSERVATIONS AND DATA REDUCTION

We performed X-ray observations with Chandra/HRC-I to confirm the XMM-Newton detection of β Pic and constrain the X-ray emission mechanism. The HRC is a microchannel plate detector with excellent timing and spatial resolution, but only very limited energy resolution. The spatial size of the digitized pixels is 0′.13175. This is well matched to the intrinsic point-spread function (PSF), which can be described by a Gaussian with FWHM of 0′.4 (Murray et al. 2000). It also has excellent sensitivity to soft X-rays. Additional Chandra/ACIS data were retrieved from the archive. In contrast to the HRC, the ACIS CCDs have an intrinsic energy resolution. Chandra data for the HRC-I and ACIS-I observations were reprocessed with CIAO 4.4 (Fruscione et al. 2006) to extract event lists. The background light curves for both observations are flat confirming that no flaring of the ambient spacecraft proton impact rate was present.

Table 1 contains details of all Chandra and XMM-Newton observations of β Pic. Existing ROSAT data are dominated by UV contamination but could have detected β Pic if it were a few times brighter than in the XMM-Newton observation (Hemel et al. 2005). We reprocessed the archival XMM-Newton data with the current version 11.0.0 of the standard Science Analysis System (SAS) software (Gabriel et al. 2004) with all standard selection criteria and refer the reader to Hempel et al. (2005) for further details of the XMM-Newton observation.

3. SOURCE PROPERTIES

The XMM-Newton/PN spectrum shows strong UV contamination due to the insufficient UV blocking used, but β Pic can be detected in a very narrow energy filter around the O vii triplet in the MOS. Our analysis confirms the published results by Hempel et al. (2005), who detect the source with a total count number of 17 (of which 6.1 are expected to be background photons) in both MOS detectors, a detection with a formal significance of 99.99%. The flux of the O vii triplet is 3 × 10^{-5} erg s^{-1}.

In the ACIS-I observation there are four counts within a source extraction region of 1′ radius centered on the optical position of β Pic (05:47:17.08858–51:03:59.2035). The individual photon energies are 280 eV, 300 eV, 720 eV, and 11 keV, the last one is certainly a background event. From a large background region we estimate the background within the source region to be 1.5 counts, predominantly at high energies. The UV contamination of the ACIS data is negligible (Bautz & Nousek 1999, with a 2001 update to account for an optical light leak for very red stars).

If we scale the O vii flux in the 465–665 eV range from Hempel et al. (2005) to the shorter exposure time in the Chandra observation and the lower effective area of the ACIS detector, we estimate that one photon from the O vii triplet should be recorded in 10 ks. β Pic indeed remains undetected in an energy filter centered on O vii with 0 counts observed and an estimated background of 0.25 counts.

Source detection on the HRC-I data is performed using the celldetect algorithm as implemented in CIAO. Our target β Pic is detected with 17 counts in a circle of 1′ radius (90% encircled energy), while the background is estimated from a larger annulus around the source position (Figure 1) to be 0.90±0.02 counts. In addition to the uniform background, there is also a contribution caused by optical and UV light from β Pic which leaks through the UV/Ion shield of the HRC-I. Scaling down the observed count rate of Vega4 of 0.0005 counts s^{-1} to the B and V magnitude of β Pic yields an estimated contribution of 0.5 counts over our exposure time. We also estimate the UV leak following Kenter et al. (2000) and Zombeck et al. (2000), who developed a model for the out-of-band UV–optical effective area and folded them with UV and optical stellar spectra. This calculation gives 1 count over our exposure time, but we note that, again in comparison to Vega, this model is known to overestimate the light leak by a factor of 2–4.

The net source count rate is thus (8 ± 2) × 10^{-4} s^{-1}, which leads to (9 ± 2) × 10^{-4} counts s^{-1} considering that our extraction region contains 90% of the PSF. The detected source position is R.A. = 86.82109 ± 0.00003, decl. = −51.06622 ± 0.00002. The distance to the SIMBAD position of β Pic at the time of observation (including proper motion) is 0′.08, which is well within the absolute Chandra pointing accuracy.

While the error on the flux is large, the detection itself is significant because counts are distributed according to Poisson statistics which deviates from the Gaussian approximation for low count numbers. The formal probability to observe 17 or more counts by chance, if only 1.5 counts are expected from the background and UV leak, is negligibly small.

Thus, we conclude that β Pic is clearly detected in the HRC-I data. According to a Kolmogorov–Smirnov test, the photon arrival times are compatible (on the 86% level) with a constant luminosity during the observation.

The low intrinsic energy resolution of the HRC-I and the low number of counts do not allow the calculation of any meaningful

\footnote{http://cxc.harvard.edu/contrib/juda/memos/uvis_monitor/index.html}
hardness ratios. The detector is sensitive from a few keV down to \(\approx 0.06\) keV, although the effective area drops from a peak of over 200 cm\(^2\) at 1 keV to below 10 cm\(^2\) for energies below 0.15 keV.

4. DISCUSSION

In all X-ray observations \(\beta\) Pic either remained undetected or was seen only with very few photons. The number of photons observed in the XMM-Newton and the Chandra/ACIS observations are consistent with the ROSAT limit, although \(\beta\) Pic is not formally detected in ACIS. This shows that \(\beta\) Pic was not significantly brighter in 1996 or 2002 than in 2004. If we assume that the emission is constant, we can estimate the count rate expected in the HRC-I due to the O \(\text{vii}\) flux seen in XMM-Newton to be \(5 \times 10^{-4}\) s\(^{-1}\) according to WebPIMMS\(^5\). This is about half of the observed count rate. Since the upper limits on flux at other bands are relatively strict in the XMM-Newton observations (Hempel et al. 2005), most of the remaining count rate must be caused by very soft emission in the 0.06–0.2 keV range where the MOS detectors are not sensitive. Because the effective area of the HRC-I depends strongly on the photon energy, a model is required to turn the count rate into an energy flux. Adopting a photon energy of 0.1 keV for all photons (monochromatic emission) we estimate the HRC-I flux to be \(3 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), i.e., \(\log L_X = 27.1\).

4.1. A Thermal Plasma

The easiest explanation for the detected data is optically thin thermal emission. Figure 2 shows the ratio of HRC-I counts (full band) and MOS counts (O \(\text{vii}\)) as a function of plasma temperature for an optically thin, collisionally excited thermal plasma with solar abundances. Count rates for this figure were calculated using an APEC model (Brickhouse et al. 2005) and convolved with the respective effective areas using the WebPIMMS tool. A plasma with a temperature of 1.1 \(\times 10^6\) K would explain the MOS and HRC-I data. This model gives \(\log L_X = 26.5\) (0.2–2.0 keV) and \(\log L_X = 27.5\) (0.06–0.5 keV).

In the following we use the energy band 0.2–2.0 keV, which allows for easy comparison to other observations. This leads to the following ratio of X-ray to bolometric luminosity: \(\log L_X/L_{\text{bol}} = -8.2\), where we use \(L_{\text{bol}} = 5.0 \times 10^{34}\) erg s\(^{-1}\) (Allen 2000). Coronae of typical late-type stars with magnetic activity are generally much hotter than \(\beta\) Pic, and even the MS A7 star Altair has a mean temperature twice as high and shows a small flare (Robrade & Schmitt 2009). Altair is of later spectral type and the equatorial bulge is even cooler than the stellar impactus \(T_{\text{eff}}\) (Mommert et al. 2007) and thus it will have a thin outer convective layer (Landstreet et al. 2009). Altair’s fast rotation could provide a magnetic field to drive magnetic activity on a similar level as on the quiescent Sun. \(\beta\) Pic rotates more slowly than Altair, but still has \(v \sin i = 124 \pm 3\) km s\(^{-1}\) (Koen et al. 2003) and might operate a similar mechanism, \(\beta\) Pic is fainter than Altair which has \(\log L_X = 27.1\) in the 0.2–2 keV band. Also, because \(\beta\) Pic is younger there are alternative possibilities to explain a magnetic field, which could be primordial or formed by a dynamo which feeds of residual shear in the stellar atmosphere (Spruit 2002; Tout & Pringle 1995). Alternatively, the \(\delta\) Scuti pulsations might supply energy to heat a chromosphere (Koen et al. 2003) and possibly a cool and weak corona. In both cases the magnetically active regions can be distributed unevenly on the surface. Impacting FEBs might provide additional energy to excite waves which can heat a transition region and a corona.

The described thermal component can also account for some of the O \(\text{vii}\) emission seen by \(\text{FUSE}\) (Deleuil et al. 2001) but this fraction is strongly temperature dependent. Alternatively, Bouret et al. (2002) present a model for the corona and the transition region that explains the observed UV lines very well. If the chromosphere covers a significant part of the stellar surface and rotates rigidly with the photosphere, then the large O \(\text{vii}\) line width is due to rotational broadening. Based on a comparison of the chromospheric activity on \(\beta\) Pic and \(\alpha\) Aql they predict an X-ray activity level on \(\beta\) Pic of \(\log L_X/L_{\text{bol}} = -7\), close to the value we observe.

In summary, the X-ray emission from \(\beta\) Pic is fully consistent with a corona. The activity level is below that of Altair which is of slightly later type and much older. A convective dynamo that fades to earlier spectral types can explain both observations. In contrast, a shear dynamo scenario would be unique to \(\beta\) Pic, since Altair is so old, that any initial shear would have decayed already (Tout & Pringle 1995).

4.2. Accretion

Hempel et al. (2005) suggested accretion of gas from the disk onto \(\beta\) Pic itself as one possibility for the energy source of the observed UV and X-ray emission. While small mass accretion rates consistent with optical observations release sufficient power, the accretion streams would originate at the inner truncation radius of the disk and accelerate to the free fall velocity, which is not observed (Deleuil et al. 2001). To avoid this problem Hempel et al. (2005) propose a disk reaching down to the star, so that the accretion can proceed more gradually. This model predicts a boundary layer with lower velocities and thus lower temperatures around 0.3 MK. However, gas at this temperature would be much brighter in the HRC-I than observed (Figure 2) and it should cause additional UV continuum emission, again contrary to observations (Deleuil et al. 2001). Thus, an accretion scenario is unlikely to explain the observations.

\(^5\) http://heasarc.nasa.gov/Tools/w3pimms.html
4.3. Charge Exchange

Soft X-ray emission, typically dominated by a strong O vii triplet, has been observed for over 20 comets to date (see reviews by Krasnopolsky et al. 2004; Bhardwaj et al. 2007). Ranging in luminosity from $5 \times 10^{13}$ to $5 \times 10^{15}$ erg s$^{-1}$ in the $300$–$1000$ eV range, comets shine in the X-ray range as the neutral gas sublimating from their surface close to perihelion passage collides with the highly ionized solar wind and exchanges electrons. The electrons are transferred from the neutral gases into the heliosphere as a whole, produced when instreaming neutral interstellar medium (ISM) H and He atoms collide with the solar wind. The total luminosity for the latter process is on the order of $10^{23}$ erg s$^{-1}$. Thus, CXE could be producing the observed X-ray emission, if $10^{10}$ to $10^{12}$ solar system-like comets were extant in the disk; while the FEB detection suggests there may be many comets and KBOs in the disk, this seems like a huge number and would add up to as much as $1 M_{\odot}$.

A second possibility is astrospheric emission detection from an interaction of the stellar wind and the infalling ISM. A star with a strong wind would cause a large heliosphere, so that a charge exchange can happen over a large region.

However, both these scenarios require a strong stellar wind with highly ionized ions. A-type stars in general are expected to show only weak radiatively driven winds and on $\beta$ Pic Bruhweiler et al. (1991) observed a slow wind with an outflow velocity of only $60$ km s$^{-1}$ and mass-loss rates of $1 \times 10^{-14} M_{\odot}$ yr$^{-1}$. The stellar radiation field is insufficient to produce highly ionized ions like O vii in the wind and Beust & Tagger (1993) showed that shocks between the stellar wind and the infalling comets are not strong enough to heat the gas to high ionization stages.

In summary, it is unlikely that highly ionized ions are present in the wind from $\beta$ Pic and even if there are charge-exchange reactions with comets or the ISM they are still unable to explain the observed X-ray luminosity.

5. SUMMARY

We have detected $\beta$ Pic in a Chandra/HRC-I observation with a count rate of $(9 \pm 2) \times 10^{-4}$ counts s$^{-1}$ (corrected for the encircled fraction of the PSF). For a thermal model with $kT = 0.1$ keV this corresponds to log $L_X = 26.5$ in the $0.2$–$2.0$ keV band. Ninety percent of this emission comes from outside of the O vii line. The emission can be explained by optically thin thermal emission of a cool corona with a temperature of $1.1$ MK which sits on top of a solar-like chromosphere. Several dynamo scenarios could supply the energy for modest magnetic heating. We find that a dynamo in a weak convection zone (e.g., on the equatorial bulge) as proposed for Altair can explain all X-ray observations of A-type stars consistently. Thus, the high energy emission of $\beta$ Pic might resemble our Sun more closely than previously thought, despite the fact that $\beta$ Pic is surrounded by a massive debris disk and has a much earlier spectral type. With the exception of the accreting HAeBes, $\beta$ Pic is now the hottest star known with a solar-like corona.

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Facilities: CXO (HRC/ACIS), XMM

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