A FLARING X-RAY SOURCE WITH AN Hα-BRIGHT COUNTERPART TOWARD THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We report the discovery of a flaring X-ray source with an optical counterpart with H\(\alpha\) emission and red-excess, in the direction of the Small Magellanic Cloud. A 100 ks X-ray observation with Chandra detected a flare lasting \(\sim\) 6 ks in the source CXO J005428.9−723107. The X-ray spectrum during the flare was consistent with a thermal plasma of temperature \(kT = 2.4 \pm 0.4\) keV. Timing analysis did not reveal any significant periodicities or quasi-periodic oscillations. Optical images taken with the Magellan–Baade 6.5 m telescope show a single star in the (0′.9) error circle. This star has apparent magnitude \(V = 19.17\), exhibits enhanced H\(\alpha\) emission (\(H\alpha - r = -0.88 \pm 0.02\)), and has a large proper motion. Alternative explanations are explored, leading to identification as a relatively nearby (Galactic) coronally active binary star of the BY Draconis class.

Key words: Magellanic Clouds – stars: coronae – stars: flare – X-rays: stars

Online-only material: color figure

1. INTRODUCTION

The Chandra SMC Deep Fields project (Laycock et al. 2009) has observed sources in the Small Magellanic Cloud (SMC) to a flux limit of \(10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). The fields were selected as the most rich in high-mass X-ray binary (HMXB) pulsars (Deep-Field-1/DF1) and the location of the youngest stellar population (DF2). The primary aim is to locate the unseen majority of HMXBs, by detecting them in the quiescent state between outbursts. The deep observations complement ongoing weekly monitoring with RXTE that has now monitored the outburst activity of pulsars in the SMC for 10 yr (Galache et al. 2008). Other targets of great interest for the Chandra program are low-mass X-ray binaries (LMXBs), binaries containing black holes, and cataclysmic variables (CVs), none of which have yet been found in the SMC.

At the faint fluxes reached in these observations, a large by-catch of background active galactic nuclei and foreground (galactic) sources are also present in the data. The SMC lies at \(b = -60°\), so foreground contamination is sparse. The principal source of foreground stars is the galactic thick-disk and halo populations (see, e.g., Bahcall & Soneira 1984). The most probable foreground objects to be detected in X-rays are stellar coronae, including active binaries, and (to a lesser extent) CVs. Active stellar coronae are a feature of solar and subsolar-mass stars. An era marked by frequent powerful flares 10–100 times the brightness of those seen on the sun is thought to be experienced by most if not all dwarf stars, typically during the early portion of their lives (see Mathioudakis et al. 1991). In this paper, we describe our discovery of such a star, which is the most prominent representative of the sample seen in the SMC Deep Fields survey.

2. X-RAY DISCOVERY OF A FLARING SOURCE

SMC Deep Field-1 was observed observed by Chandra for 100 ks in a pair of \(\sim\) 50 ks pointings (same roll angle), over the course of 2 days, 2006 April 25–26. The Advanced CCD Imaging Spectrometer (ACIS) was used, with the ACIS-I array at the aim point. The observations and data reduction are described by Laycock et al. (2009), using the software pipeline of Hong et al. (2005).

Light curves binned by 16 times the 3.2 s ACIS frame time were visually inspected for all sources with at least 50 counts in the stacked data set. This search turned up a large flare in CXO J005428.9−723107, (R.A. = 00:54:28.91, decl. = −72:31:07.12, 95% error radius = 0′.53, including 0′′75 aspect uncertainty\(^3\) = 0′′91) lasting for \(\sim 5000\) s at the end of the first of two 50 ks exposures of Deep Field-1, shown in Figure 1. None of the other 95 sources so examined showed any similar feature. Due to the gap in coverage, it is possible that the final part of the decay phase was not observed. Subtracting the net counts for the source during the second exposure from the first (259 counts − 32 counts), we obtain an estimate of 227 counts in the flare.

X-ray variability is the hallmark of accretion and is also characteristic of flaring stellar coronae. CVs (accreting WDs) and LMXBs (both NS and BH systems) exhibit aperiodic variability (flickering) over a wide range of timescales from milliseconds up. Such variability produces a characteristic power-law distribution (red noise) in the power spectrum. The Lomb–Scargle (Scargle 1982) power spectrum of the flare is shown in Figure 2; no periods of quasi-periodic oscillations (QPOs) or red noise are evident.

We used the Quantile technique (Hong et al. 2004) to compare the source spectrum between the active/inactive states, and against other sources in the field. Energy quantiles are computed from the event list for each source. In fact, the quantiles are drawn from a cumulative photon energy distribution, from which the background distribution has been subtracted. Three values are defined, E50 is the median energy, E25 and E75 are the energies delineating the lower and upper energy quartiles. A parameter space is then defined such that the X and Y axes are representative of spectral slope and curvature, respectively.

\(^3\) http://cxc.harvard.edu/cal/ASPECT
Utilizing the detector response matrices for Chandra ACIS-I, model grids were generated for thermal bremsstrahlung (TB) and power-law spectra.

The quantile values during and post flare are plotted in Figure 3, along with other bright X-ray point sources for comparison. The flare (median energy, $E_{50} = 1.288$ keV) was harder than the quiescent emission ($E_{50} = 1.021$ keV). Using the TB grid, we see that during quiescence the quantile location is consistent with a fairly cool thermal plasma ($kT \sim 0.4$ keV) and the extinction is clearly low although poorly constrained. During the flare the quantile moves to higher temperature ($kT \sim 1.65$ keV) and we obtain a better constraint on the extinction, which is around $\sim 5 \times 10^{20} \text{ cm}^{-2}$.

Fitting an absorbed TB model to the flare spectrum produced a similar result to the quantile, $kT = 1.57 \pm 0.32$ keV, $n_H = 7.62 \pm 5.89 \times 10^{20} \text{ atom cm}^{-2}$, $\chi^2_v = 0.67$. In the quantile space, we use the TB model as it has a well behaved two-parameter grid. When a spectrum is available, more physically realistic models can be applied. The X-ray spectrum of the observation containing the flare is shown in Figure 4. The fitted model is an optically thin thermal plasma (Raymond & Smith 1977), with solar abundance (metallicity), plasma temperature $kT = 2.5 \pm 0.4$ keV, and essentially zero extinction. The reduced $\chi^2 = 1.14$ (20 degrees of freedom). Chandra has low sensitivity below 1 keV, which, combined with the faintness of the source, means that the fit cannot constrain the $n_H$ with all parameters floating. Thus, we fixed the $n_H$ at $5 \times 10^{20} \text{ atom cm}^{-2}$, resulting in $kT = 2.34 \pm 0.38$ keV, $\chi^2_v = 1.26$. Changing the metallicity to 0.5 solar, marginally improved the fit, and gave $kT = 2.06 \pm 0.26$ keV, $\chi^2_v = 0.96$.

Similar tests using the improved thermal plasma models MEKAL (Mewe et al. 1985, Liedahl et al. 1995) and APEC (Smith et al. 2001) with absorption fixed at $5 \times 10^{20} \text{ atom cm}^{-2}$, both (within rounding errors) gave $kT = 2.52 \pm 0.2$ keV, $\chi^2_v = 1.2$ for solar metallicity and $2.22 \pm 0.25$ keV, $\chi^2_v = 0.91$ for half-solar.

Next, we repeated the fit using the quiescent source spectrum as the background. For solar metallicity, APEC gave $2.62 \pm 0.30$ keV, $\chi^2_v = 0.91$ and $2.30 \pm 0.36$, $\chi^2_v = 0.77$ at half-solar.

Finally, using the APEC model and the quiescent source spectrum as background, the absorption was allowed to vary, yielding $n_H < 6.54 \times 10^{20} \text{ atom cm}^{-2}$ and $kT = 2.43 \pm 0.40$ keV.

Independent measurements of the average $n_H$ toward the SMC generated by the HEASARC online $n_H$ tool are $5 \times 10^{21}$.
The peak flux reached in the light curve binned by 16 frame intervals was 0.15 counts s\(^{-1}\). The number of counts in the peak bin is 7 or 8 (0.15 counts s\(^{-1}\) = 7.68 counts/51.2 second bin time). Applying the best-fit spectral model (RS, 2.5 keV see above), we obtain a peak flux of \(1 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\).

By binning more coarsely, a smooth light curve was obtained at 500 second per bin. Using this light curve, the flare reaches a peak of 0.0763 \(\pm 0.0125\) counts s\(^{-1}\) at 3000 s from its start. The peak flux in this case is 5.1 \(\times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\). During the rising portion of the flare, the count rate climbs at the roughly constant rate of 2.5 \(\times 10^{-5}\) count s\(^{-1}\) s\(^{-1}\). The rate of decline after peak is 1.4 \(\times 10^{-5}\) count s\(^{-1}\) s\(^{-1}\), slower than the rise-rate by a factor of 0.56. The observations stopped 2 ks after the peak, before the count rate had dropped to its quiescent level.

**3. OPTICAL COUNTERPART**

The field was observed with the IMACS imager mounted on the Magellan–Baade 6.5 m telescope at Las Campanas, Chile on 2007 August 4 (07:00 UT). The IMACS was in \(f/2\) configuration providing a circular field of view 30’ in diameter, sampled at 0.2 pixel\(^{-1}\). Long and short exposures were made through Sloan-\(g, r, i\) and hydrogen-\(\alpha\) filters.

The images were processed using standard IRAF tasks to perform the usual CCD reductions. Astrometric calibration was performed with the Two Micron All Sky Survey (2MASS) catalog as a reference. Residuals on each CCD frame were of order 0.2 rms (1 pixel) using a standard IRAF tangent-plane projection plate solution. The individual frames were reduced independently and combined using the SWARP\(^4\) utility to re-project and stack. All frames were normalized to ADU/second units and combined using weight maps constructed from flat fields and bad pixel masks. This approach combines long and short exposures into a single image.

For this paper, we restricted our analysis to a 1000 \(\times\) 1000 pixel subregion centered on the coordinates of CXO J005428.9–723107. The complete optical survey of the Chandra SMC Deep Fields will be presented by Antinou et al. (2009, in preparation). Initial identification of the optical counterpart was performed by visual inspection of the images. A single star was found in the Chandra error circle, as can be seen in Figure 5. By eye it is evident that the star is substantially redder than most of its neighbors and is bright in the \(H\alpha\) image.

Hydrogen-\(\alpha\) (6563 \(\text{Å}\)) in emission is ubiquitous in accretion-powered X-ray sources. Stars with \(H\alpha\) line emission can be swiftly identified by the image-subtraction technique, performed on a pair of images taken through a broadband red filter, and a narrowband \(H\alpha\) filter. Examination of our \(H\alpha\) and Sloan-\(r\) project and stack. All frames were normalized to ADU/second units and combined using weight maps constructed from flat fields and bad pixel masks. This approach combines long and short exposures into a single image.

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\(^4\) SWARP is a program by E. Bertin of the IAP, Paris, France that resamples and co-adds FITS images using any arbitrary astrometric projection defined in the WCS standard. http://terapix.iap.fr.
subimages showed very similar point-spread functions (PSFs), with FWHM ~ 1". An empirical flux scaling factor of 48 was applied to the Hα image to compensate for the different filter transmissions. The IMACS narrowband filter is an interference filter, which exhibits spatial variations in its bandpass when used in the steeply converging f/2 beam. The effective bandwidth of the Hα filter at the location of the subimage is accordingly calculated to be 1475/48 = 30 Å (bandwidth of the Sloan-r filter is 1475 Å). The result of subtracting the flux-scaled Hα image from the Sloan-r image is shown in the bottom right panel of Figure 5. A bright point-like residual lies in the error circle, while nearly all other stars have canceled out. The flux in the difference-image residual (ΔF) implies a magnitude difference (Δm) of −0.882 mag as given by Equation (1),

\[ \Delta m = 2.5 \log_{10}(F_r/(F_r + \Delta F)), \]

where \( F_r \) is the background-subtracted flux in the Sloan-r image. The star is red with large \( R-I \), meaning it has a steeply sloping spectrum across the bandpass of the \( r' \) filter. The Hα line is at a longer wavelength than the center of the \( r' \) bandpass; thus the Hα filter intercepts a relatively larger amount of continuum than would be the case for a flat spectrum. Zhao et al. (2005) show that photometric determinations of EW(Hα) are strongly biased by continuum shape; their Figure 5 indicates a factor of ~ 2 increase in Hα−R between G- and M-type stars at a fixed EW(Hα). Accordingly, we modeled the response of the Magellan filter set to continuum slope and equivalent width, finding the observed color indices \( r - i = 1.66, Hα - r = -0.882 \) correspond to an underlying emission line with \( \text{EW}(Hα) = -8.5 \text{ Å} \). If this effect is ignored, the EW is greatly overestimated (−38 Å). An optical spectrum is required to obtain a more accurate value.

Photometry of the IMACS subfield was calibrated against the UBVR catalog of Massey (2002). The calibration residuals between our magnitudes and the Massey magnitudes transformed to the Sloan system (Fukugita et al. 1996) were \( \text{rms}_g = 0.18 \), \( \text{rms}_r = 0.11 \), and \( \text{rms}_i = 0.18 \). For the optical counterpart of CXO J005428.9 − 723107, we measured the following magnitudes: \( g = 19.90 \pm 0.03 \), \( r = 18.63 \pm 0.01 \), and \( i = 16.97 \pm 0.01 \). After transforming back to the standard system, we obtain \( V = 19.17, B - V = 1.43, V - R = 0.80, \) and \( R - I = 1.70 \). The foreground extinction to the SMC is only \( E(B - V) = 0.08 \) (Sabbi et al. 2007), not enough to affect spectral classification. The \( B - V \) color index of the star suggests spectral type M0, while \( R - I \) supports a later subtype M5+ (see, e.g., Allen 2003). Large extinction does not work as an explanation of the star’s color because its effects would be strongest at shorter wavelengths, exactly opposite to what is observed. In addition, the X-ray spectrum shows there is little to no absorption. A pattern of rising red-excess at longer wavelengths is typical of stars with extended envelopes, an interpretation supported by the large Hα emission. Alternatively, a metal-poor star would partially explain the colors being bluer in \( B - V \) than in \( R - I \), compared to a solar metallicity star. The flux ratio \( \log(f_v/f_\alpha) \) is a useful diagnostic because it is independent of distance. Using Equation (2) (Maccacaro et al. 1988), we obtained \( \log(f_v/f_\alpha)(\text{flare}) = +0.84 \) and \( \log(f_v/f_\alpha)(\text{quiescent}) = -1.17 \), noting the X-ray and

**Figure 5.** Optical images of the location of CXO J005428.9−723107. The over-plotted circle indicates the X-ray position (2006 April 25) 95% confidence radius including contributions from ACIS/wavdetect and aspect uncertainty. The star at the center of the displayed 30′ field is the proposed optical counterpart. It is brighter at longer wavelengths and the Hα − r difference image reveals strong Hα emission compared to stars in the field. Comparison with the OGLE reference image from 1997 shows 1′/6 motion of the star in the intervening decade. Movement of OGLE 324158 is away from star “Q” and past star “P”. The 1997 position is indicated by a cross on the 2007 August IMACS images.
optical measurements were not made at the same time:

$$\log(f_\text{X}/f_\text{opt}) = \log(f_\text{opt}) + 5.5 + V/2.5.$$  \(2\)

4. DISCUSSION

We have identified an optical counterpart to the flaring X-ray source CXO J005428.9−723107 in or toward the SMC. The star has apparent V magnitude 19.17, $B - V = 1.4$, and a red-excess accompanied by Hα in emission. We explore several alternative explanations. Those motivated primarily by the X-ray data include symbiotic, LMXB, CV, magnetar, and from the optical data include young-stellar object (YSO) or foreground galactic magnetically active dwarf. Each of these scenarios is consistent with the presence of X-ray flares, plus an optical counterpart with Hα emission.

4.1. Identification as a Galactic Active Star or Binary

Dwarf M stars are the most numerous spectral class in the galaxy, with dMe subtype characterized by Hα emission making up about half (Mathioudakis et al. 1991). Observations of X-ray flaring in the dMe-star Ross 154 described by Wargelin et al. (2008) show striking similarities to the event seen in CXO J005428.9−723107. They report a flare with a rapid rise to peak in $\sim 1.6$ ks, followed by a slightly slower fading to 10% of peak in a further 2 ks, after which there is a very slow decay to quiescence. The quiescent X-ray spectrum of Ross 154 was a thermal plasma with $kT = 0.46-0.98$ keV (depending on the model used) rising to 2.95–3.71 keV during the flare. The peak X-ray luminosity was $1.8 \times 10^{32}$ erg s$^{-1}$. Ross 154 is a M3.5 dwarf at a distance of just 2.97 pc. Wargelin et al. (2008) spectral fits are nearly identical to the values estimated for CXO J005428.9−723107.

The implications of the spectral type on the implied X-ray luminosity of CXO J005428.9−723107 are as follows.

In the absence of significant extinction, assuming an M0V star, $\mu = 10$ and $D = 1$ kpc, leads to an upper limit on the peak X-ray luminosity of order $10^{32}$ erg s$^{-1}$. Instead, assuming M5V leads to distance modulus $\mu = 7.2$, $D = 275$ pc, and a lower limit on $L_X = 4.27 \times 10^{30}$.

If, on the other hand, we adopt the same luminosity as was reported in the Ross 154 flare for CXO J005428.9−723107, then the observed X-ray flux implies a distance of between 94 and 118 pc, depending on whether the 50 s or 500 s binned light curve is used for the flux estimate. The corresponding distance modulus lies in the range 4.87–5.36 mag. The absolute magnitude $M_V$ of the optical counterpart would then be $+13.8-14.3$. This is improbably faint as the observed color $(B - V = 1.43)$ indicates a spectral type M0 ($M_V = +9$).

The above line of reasoning suggests that either the flare is significantly more powerful than Ross 154, in which case it is further away to fit with an early M dwarf’s optical magnitude, or its spectral type is later than M0 (and hence is intrinsically fainter). The SMC lies at high galactic latitude, the scale height of disk dwarfs is 350 pc (Bahcall & Sonier 1984), so the preferred mid-M classification would place CXO J005428.9−723107 within the thick-disk component of the galaxy.

The range in luminosity in the above scenarios can be seen in the most active M stars, and are frequently attained in BY Draconis stars, which are a species of close binary comprising K and M dwarfs, with magnetic activity excited by tidal interaction (e.g., Singh et al. 1996). The X-ray emission in active binaries systems comes from a late-type companion which is spun up, driving a magnetic dynamo many times more powerful than the Sun’s. The Hα emission is produced in the active chromosphere and in prominences (also see Pallavicini et al. 1981). Mathioudakis (1992) shows dMe stars exhibit EW(Hα) $\lesssim -10$ Å, a plausible value according to our photometric colors. Our X-ray optical flux ratio for the star during quiescence $(\log(f_\text{X}/f_\text{opt}) = -1.2)$ is in the upper end of the normal range for M stars (Zombeck 1990).

The optical and X-ray observations described by Mathioudakis et al. (1991) for the BY Dra star G 182 before, during, and after a large flare in 1983 are similar to those found here (dM0.5e, $B - V = 1.4$, $V - R = 0.9$, and $V - I = 1.85$). They found a quiescent X-ray luminosity of $L_X = 10^{33.0}$ for G 182, and EW(Hα) $\sim 2$ Å. Our pseudo equivalent-width measure of EW(Hα) $= -8.5$ puts CXO J005428.9−723107 in the upper range for dMe stars. An optical spectrum will be interesting to determine whether CXO J005428.9−723107 shows other signs of enhanced activity, and/or extreme youth, such as prominent lithium and calcium lines.

A search of SIMBAD database revealed a high proper motion star OGLE 324153 (Soszynski et al. 2002) at J2000 coordinates 00:54:28.66, −72:31:06.5, proper motions $\mu_x = 158.1$ mas yr$^{-1}$, $\mu_y = -0.1$ mas yr$^{-1}$, $V = 19.486$, $B - V = 1.626$, and $V - I = 3.017$. Given the close match in photometry, the OGLE I-band reference image of field SMC-SC6, taken on 1997 August 11, was compared with our Magellan I-band image taken 10 yr later. The counterpart is clearly OGLE 324153 and a motion of $\Gamma = 5$ is apparent, consistent with that predicted by the OGLE proper motion (1.58). The Magellan images were taken 15 months after the Chandra observation, so the motion during that time was $+0.197$ in RA. This shift is smaller than the Chandra error circle, but, if accounted for, improves the alignment.

For our preferred distance of 275 pc the projected tangential velocity is 200 km s$^{-1}$, such a velocity is typical for members of the Galactic halo. According to Fehrenbach & Terzan (1984), the density of high-velocity foreground stars toward the Magellanic Clouds appears to be about 20 times higher than in other directions of similar galactic latitude.

4.2. Alternative Scenarios

If the star lies in the SMC, with distance modulus of 18.5, then $M_V \approx +0.7$, a red giant (MOIII) would be required to match the photometry. So-called symbiotic stars (red giant with accreting white dwarf companion) can be bright X-ray sources. Symbiotics display a great diversity of spectra, including thermal and nonthermal components, as can be seen in the ROSAT data presented by Muenset et al. (1997).

Interpreting this object as a Be–NS binary in the SMC has several problems. On the X-ray side we have the flare, a lack of pulsations, and a softer spectrum than the ubiquitous $\Gamma = 1 \pm 0.5$ power law. In the optical, the star is under-luminous for a Be star, by about 3 mag, and in addition is too red in $B - V$. According to McBride et al. (2008), of 37 spectroscopically confirmed BeX systems in the SMC all have spectral types earlier than B3; the mode is B0. From the observations listed in McBride et al. (2008), the faintest apparent V magnitude is 16.9, and the reddest color index is $B - V = +0.15$. In Be stars the $B - V$ color is relatively unaffected by the red-excess, and is representative of the intrinsic spectral type. Thus, the observed value of +1.4 rules out a Be star.

\footnote{CDS/Vizier catalog ID: J/AcA/52/143.}
The median $M_V$ for a CV secondary is +8 (Patterson 1998), which at the SMC would be $V = 26.5$. During outbursts this rises by 5 mag or more, and so a CV could become visible, but this is unlikely as the accretion disk emission would produce a blue $B - V$ index. Similar brightness arguments apply to LMXBs: the star is too bright to be a CV or LMXB at the distance of the SMC. If, however, it is a foreground galactic system, the $M_V$ constraint vanishes.

5. CONCLUSION

We found that CXO J005428.9−723107/OGLE 324153 is an active star or binary located relatively nearby, in the thick disk or halo of the Galaxy. The timescale of the X-ray flare, and the spectrum during and afterward share key characteristics with flaring M stars (see, for example, Wargelin et al. 2008 and Scholz et al. 2005). The optical magnitude and color indices of the counterpart are consistent with an M0−M5 depending on the metallicity, amount of circumstellar or chromospheric emission (indicated by the strong H$\alpha$ emission), and contribution from a companion if present. The balance of evidence points to an active M5V at $\sim 275$ pc with flare luminosity $L_X = 4.27 \times 10^{30}$. The high space velocity (200 km s$^{-1}$) and apparently low metallicity together suggest the star is in the halo. A binary is then needed to explain its highly active nature.

The discovery of a flare star in this field is a cautionary example that an X-ray source with emission line optical counterpart toward the SMC is not necessarily an HMXB. The SMC Deep Fields X-ray catalog contains several other sources whose quantiles suggest they are also stellar corona. These objects are the subject of a wider study, which includes a search for the most X-ray active stars in the SMC.

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