A LARGE X-RAY OUTBURST IN MIRA A

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ABSTRACT

We report the Chandra ACIS-S detection of a bright soft X-ray transient in the Mira AB interacting symbiotic-like binary. We have resolved the system for the first time in X-rays. Using Chandra and Hubble Space Telescope images, we determine that the unprecedented outburst is likely associated with the cool asymptotic giant branch (AGB) star, Mira A, the prototype of the Mira class of variables. X-rays have never before been detected from an AGB star, and the recent activity signals that the system is undergoing dramatic changes. The total X-ray luminosity of the system is several times higher than the luminosity estimated using previous XMM-Newton and ROSAT observations. The outburst may be caused by a giant flare in Mira A associated with a mass ejection or a jet and may have long-term consequences on the system.

Subject headings: binaries: symbiotic — stars: activity — stars: AGB and post-AGB — stars: individual (Mira AB) — stars: winds, outflows — X-rays: general

1. INTRODUCTION

Mira AB is an interacting binary system composed of an aging cool giant (Mira A) losing mass at a rate of \( \sim 10^{-7} \ M_\odot \) yr\(^{-1} \) (Bowers & Knapp 1988) and an accreting companion (Mira B) about \( \sim 70 \) AU (\( \sim 0.06 \)) away. This detached binary is one of very few wind-accreting systems that has been spatially resolved and for which the energy distribution of both components can be determined unambiguously (Karovska et al. 1997). Studies of Mira AB’s wind accretion and mass transfer at wavelengths ranging from X-rays to radio provide a basis for understanding wind accretion processes in many other astronomical systems that currently cannot be resolved. Therefore, this nearest symbiotic-like system offers a test bed for detailed studies of wind accretion processes and accretion theory (Livio 1988).

In 1995, using the Hubble Space Telescope (HST) Faint Object Camera, we resolved the system for the first time spatially and spectrally at UV and optical wavelengths and studied the interacting components individually (Karovska et al. 1997). In the past few years, we have been witnessing changes in the spectral energy distribution (SED) of Mira AB, especially in the UV (Karovska et al. 1997; Wood et al. 2001). In addition to a general fading of the accretion luminosity, another baffling development was the appearance of a forest of Lyα-fluoresced H\(_2\) emission lines, which dominated the HST spectra in 1999 despite not being seen at all in the 1995 spectra or by IUE (Wood et al. 2001, 2002). A similar drop in the accretion luminosity and appearance of a set of Lyα-fluoresced H\(_2\) emission lines were also seen in FUSE spectra from 2001 (Wood & Karovska 2004). Variable mass loss from Mira A could have caused the changes in the UV flux of Mira B observed in the past 10 years, signaling that the system is undergoing dramatic changes.

In 1993, a ROSAT observation of Mira AB resulted in the first unambiguous detection of X-ray emission from the system (Karovska et al. 1996). This observation resolved the contradictory results from analysis of the Einstein observation: Jura & Helfand (1984) marginally detected an X-ray source, while Maggio et al. (1990) set an upper limit of \( f_X < 1.4 \times 10^{-13} \) ergs s\(^{-1}\) cm\(^{-2}\). The ROSAT X-ray luminosity of the Mira AB system was estimated to be \( \sim 10^{30} \) ergs s\(^{-1}\) (Karovska et al. 1996), which is similar to the luminosity estimated from XMM-Newton observations carried out about 10 years later (Kastner & Soker 2004b).

In this Letter, we report initial results from recent Chandra observations and coordinated HST and ground-based observations of Mira AB, including the discovery of a soft X-ray outburst in Mira A.

2. OBSERVATIONS AND ANALYSIS

On 2003 December 6, we carried out a 70 ks pointed Chandra observation of Mira AB using the ACIS-S instrument (Weisskopf et al. 2002). The source was placed at the nominal aim point of ACIS-S, on CCD S3. We analyzed the Chandra observations using CIAO data reduction and analysis routines.\(^5\)

The source spectrum was extracted using an aperture of 12\(^\prime\) radius centered on Mira AB; the background came from a surrounding annulus of inner radius 14\(^\prime\) and outer radius 30\(^\prime\). Figure 1 shows the Chandra spectrum and the best spectral fit (described in detail in § 3.2). The source contained 515 counts, for a count rate of 0.073 ± 0.001 counts s\(^{-1}\). The background rate was 0.0007 counts s\(^{-1}\). In the 0.2–0.7 keV band, the count rate was 0.066 ± 0.001 counts s\(^{-1}\) (background: 0.0003 counts s\(^{-1}\)); in the 0.7–4 keV band, the detected rate was 0.008 counts s\(^{-1}\) (background: 0.0004 counts s\(^{-1}\)).

The combination of the declining effective area below 0.5 keV and the excess absorption layer (Chandra Proposers’ Observatory Guide)\(^6\) ensures minimal or zero photon pileup. Pushing all the model parameters to their most pileup-favorable extremes yields a pileup estimate of less than 4%.

We detected several thousand counts below 1 keV associated with a new bright soft source in the system, which was not reported a few months before by XMM (Kastner & Soker 2004b), or by ROSAT in 1993 (Karovska et al. 1996). The high-energy component (>1 keV) is similar in appearance to the quiescent XMM and ROSAT spectra. However, a detailed comparison shows that a clear evolution has occurred in this portion of the spectrum (\(\sim 1.2–1.8 \) keV) as well. The count rates

\(^{5}\) CIAO is the Chandra Interactive Analysis of Observations data analysis system (http://cxc.harvard.edu/ciao/).

\(^{6}\) See http://asc.harvard.edu/proposer/POG/index.html.
Further details of the analysis and the results of the X-ray outburst, indicating velocities of the (∼100 km s\(^{-1}\)) for the CO edge at 0.3 keV, where the response matrix is known to have errors.

The ACIS-S raw image of Mira AB binned at the detector 0.6 pixel resolution shows an elongation along the Mira AB system axis (Fig. 2a). We made soft (<0.7 keV) and hard (0.7–2 keV) images of Mira AB, filtered based on the major components detected in the ACIS-S spectrum. Figure 2b shows the image of the hard source (to the east) with an overlay of the contours of the soft component (to the west). The centroids of these sources are displaced by ∼0.6″.

We attempted further spatial analysis using the HRC zeroth-order image. The image appears extended and is shifted ∼0.3″ from the soft ACIS image, in the direction toward the hard ACIS image. It could therefore be associated with Mira A or Mira B (or both). However, the low counts and lack of spectral resolution make it difficult to determine if there is a component associated with a remnant of the outburst. Although the HRC pixels (∼0.14″) are indeed smaller than the ACIS pixels, the actual resolution of the HRC is in fact comparable to ACIS. Furthermore, there are additional artifacts in the HRC images that make it very difficult to decide whether the extension in the image to the south and an additional source 0.5″ to the west are real.

We explored the spatial extent of the emission in the ACIS-S (0.3–4 keV) image of the system at 0.2 resolution using a new multiscale deconvolution technique, EMC2, and model Chandra point-spread function (PSF). This was possible because the Chandra data include information about the photon energies and positions, which was used to obtain filtered images and carry out subpixel-resolution analysis. The Chandra PSF varies as a function of energy and off-axis angle; we carried out PSF simulations using CIAO software and threads, including the ChaRT PSF simulator.\(^7\) The PSF simulation was carried out using information on the spectral distribution and off-axis location of the system as inputs to ChaRT. The EMC2 deconvolution technique, described in detail by Esch et al. (2004), was developed for low count statistics data, and it provides error estimates in addition to the reconstructed images.

The deconvolved image (Fig. 3) shows two sources separated by ∼0.6″. The pixel size is 0.1″ (0.2 times the ACIS-S pixel size). This is the first image of an interacting binary that has been spatially resolved at X-ray wavelengths. We note that the location of the brighter source in the deconvolved image (to the west) corresponds to the position of the soft source (as determined using filtered ACIS-S images), and the fainter source (to the east) corresponds to the hard-band ACIS-S image.
We compared the X-ray images with the \textit{HST} images of the Mira AB components obtained 2 months later, showing two sources separated by \(\sim 0\text{"0.6} \). In the \textit{HST} images, Mira A is to the west of Mira B. Figure 3 displays an overlay of the contours of the \textit{HST} 3729 \(\AA\) image on the \textit{Chandra} deconvolved image, showing that the soft X-ray source is in the vicinity of Mira A. The soft source is therefore likely associated with the asymptotic giant branch (AGB) star rather than with the accreting companion, Mira B.

When the X-ray image is compared with the \textit{HST} image of Mira A and Mira B, one can see a slightly larger separation of the X-ray components (\(\sim 0\text{"1.1}\)) and a possible small rotation of the axis between the sources. This difference could be real, but it could also be due to uncertainties in the deconvolution or to the limited resolution of the \textit{Chandra} data. It could also be a result of \textit{HST} absolute positioning uncertainties.

The X-ray images of Mira A and Mira B appear extended. Furthermore, the \textit{Chandra} image shows a faint “bridge-like” feature extending between the components. A similar structure was detected in the 1995 \textit{HST} images and indicates possible mass flow between the components (Karovska et al. 1997). Although the features in the X-ray image are uncertain because of the low count level and possible PSF and deconvolution artifacts, we note that very similar structures can be seen in the overlaid \textit{HST} contours.

We determined that some of the extended structure in the \textit{HST} image to the right of Mira A, in the opposite direction from Mira B, is due to an undocumented red leak of the F28X500II filter. Following the \textit{HST} observations, we discovered and confirmed the red leak in other very red sources. For example, F28X500II filter images of CH Cyg, which contain a very red component, show similar structure, and we have a detected similarly structured PSF in the [O iii] \(\lambda 5007\) filter during the 1999 observation of Mira AB.

The evidence of extended structure in both components in both X-ray and UV images is uncertain, and further analysis and modeling are required. In order to determine if there was a mass ejection during the outburst, it will be necessary to carry out further high angular resolution monitoring, including at X-ray and UV wavelengths.

3.2. X-Ray Spectroscopy

The spectrum was binned to a minimum of 20 counts per channel. The effective area was corrected for the energy- and time-dependent instrumental absorption, and XSPEC version 11.0 was used to fit the spectra (Arnaud 1996) as detailed below. The X-ray spectrum shows strong soft emission and potentially multiple harder components. Standard continuum models (bremsstrahlung, blackbody, power-law) did not provide good fits to the soft component. We describe the spectral fit below with 90\% errors on the model parameters.

We fitted the low-energy portion of the spectrum using an absorbed model spectrum consisting of a sum of Gaussians, each with a fixed center and zero width to represent an unresolved line. We included several C, N, and O lines. The line centers (in keV) are at C \(\lambda 0.299, 0.304, 0.308;\) N \(\lambda 0.319, 0.426, 0.431;\) and O \(\lambda 0.561, 0.569, 0.574;\). For each line, only the normalization was fitted. The initial fit showed that the O line normalizations were all consistent with zero, as were approximately half the C and N normalizations; a subsequent fit used a model containing only the C and N lines. Figure 1 shows the result with lines at C \(\lambda 0.367\) keV, N \(\lambda 0.426, 0.459\) keV, and N \(\lambda 0.500\) keV (line normalizations of 4.9, 6.2, 50.8, and 33.1, respectively, in units of \(10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\)).

Because of the limited spectral resolution, we cannot determine if there are any specific lines detected, or if the fit is unique. When we added a continuum component, its model normalization was consistent with zero. The apparently large residuals near 0.3 keV may be explained by the known problems with corrections for the contaminant near the carbon edge (Marshall 2003).8 The best-fit spectrum is therefore most easily explained as blended emission of C and N lines.

The hard component was best fitted with a bremsstrahlung continuum of \(kT \sim 0.78^{+0.15}_{-0.22}\) keV to mimic an optically thin thermal plasma, plus two zero-width Gaussians representing emission lines at 1.02\(^{+0.06}_{-0.04}\) and 1.36\(^{+0.03}_{-0.04}\) keV, all absorbed by a column \(N_{\text{H}} \sim 9.0^{+0.15}_{-0.12} \times 10^{22}\) cm\(^{-2}\). Other models provided very poor fits, including models containing additional Gaussians at the positions of expected line emission. The fitted bremsstrahlung temperature is nearly identical to the value determined from the XMM spectrum (Kastner & Soker 2004b). The fitted column is about a factor of 2 higher than the XMM-determined value. A specific error range is not shown for the XMM value, but the authors claim “formal uncertainties of \(\sim 20\%\).” A 20\% error range on the XMM value places it outside the 90\% range of the fitted value determined here, suggesting that the column may have increased by a factor of \(\sim 2\) between the two observations. The hard Gaussians have equivalent widths of \(236^{+244}_{-110}\) and \(124^{+124}_{-50}\) eV, and we attribute them to Ne and Mg emission lines, respectively. We note that Ne ix and Ne x lines were also detected by XMM (Kastner & Soker 2004b), but the Mg line is not pronounced in the XMM spectrum. These results are similar to the enhanced Ke H-like Ne and He-like Mg lines observed in an ASCA spectrum of the symbiotic system CH Cyg showing jet activity (Ezuka et al. 1998) corresponding to \(T \approx 6.8\). Our signal-to-noise ratio is insufficient to fit for the He-like Si line (found in the CH Cyg spectrum). These high-temperature lines may indicate shock-heated emission or could be associated with the flare or a jetlike ejecta.

We calculated the total flux from the system to be \(5.6 \times 10^{-13}\) \((0.2–4\text{ keV}), 5.5 \times 10^{-13}\) (soft component only, in 0.2–0.7 keV), and \(2.7 \times 10^{-14}\) (hard component only, in 0.7–4 keV) ergs s\(^{-1}\) cm\(^{-2}\) for the bands defined. The unabsorbed fluxes are very sensitive to the adopted column. The fitted column toward the soft source is \(\sim 8.0 \times 10^{19}\) cm\(^{-2}\). This value, if adopted as the column toward the system, is not consistent with the column

\footnote{8 Available at http://space.mit.edu/ASC/calib/letg_acis/ck_cal.html.}
obtained from the ROSAT spectrum (Karovska et al. 1996) or the XMM observation (Kastner & Soker 2004b). However, the fitted column is only a lower limit. The 90% confidence contour is closer to $2.8 \times 10^{23}$ cm$^{-2}$. Within this upper limit, the column remains inconsistent with the XMM value but is consistent with the column determined from the UV H$_2$ line spectroscopy (Wood et al. 2002). If we adopt the formal-fit column from the soft spectrum, then the unabsorbed fluxes are $6.4 \times 10^{-13}$ (0.2–4 keV), $6.2 \times 10^{-13}$ (0.2–0.7 keV), and $2.7 \times 10^{-14}$ (0.7–4 keV) erg s$^{-1}$ cm$^{-2}$. If we adopt the upper limit value for the column, the unabsorbed fluxes are $8.3 \times 10^{-13}$ (0.2–4 keV), $8.0 \times 10^{-13}$ (0.2–0.7 keV), and $2.7 \times 10^{-14}$ (0.7–4 keV) erg s$^{-1}$ cm$^{-2}$. Adapting the fitted value of the column for the hard component, we find that the unabsorbed hard-band flux is $9.9 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ (0.7–4 keV).

We emphasize that the appropriate $N_{\text{H}}$ value could be completely different for the hard and soft sources, since the emissions originate from different places. It is conceivable that a persistent low-energy X-ray source exists and that it was made from Mira A resulting from the recent outburst could help renew the accretion disk around the companion, following the low state observed by $HST$ and FUSE in 1999–2001.

The increased accretion rate into Mira B could also cause instabilities in the accretion disk and jetlike activity (e.g., Soker 2002) similar to that detected in several nearby unresolved symbiotic systems (e.g., CH Cyg [Corradi et al. 2001] and R Aqr [Kellogg et al. 2001]). An outburst in Mira B associated with accretion disk instabilities could be analogous to a dwarf nova outburst, except that the much larger size of the wind-fed disk in this well-separated binary would increase the duration from about a week to many months. Further multiwavelength observations are necessary in order to determine the nature and characteristics of instabilities in the system or in its individual components that may have caused the outburst, and to understand the long-term consequences of this outburst on the system.

We are grateful to H. Tananbaum and S. Beckwith for granting Director’s time on Chandra and HST. This work is part of a long-term collaboration with several colleagues on a coordinated multiwavelength campaign, including R. Stefanik, M. Marengo, J. Drake, A. Henden, D. Esch, L. Matthews, E. Guinan, E. Waagen, and the AAVSO. We thank the referees, N. Soker and J. Kastner, for helpful suggestions. This work was supported by NASA grants GO4-5024A and NAS8-39073. M. K. and E. S. are members of the Chandra X-Ray Center, which is operated by the Smithsonian Astrophysical Observatory under NASA contract NAS8-39073.

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