RESOLVING COMPONENTS OF THE MIRA AB INTERACTING BINARY SYSTEM

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ABSTRACT

Mira AB is the the nearest symbiotic binary and the only interacting binary that has been resolved from X-ray to radio wavelengths. In this paper I describe results from multiwavelength observations of Mira AB carried over the past 20 years. These include recent Chandra observations that resolved this interacting system for the first time at X-ray wavelengths. A Chandra spectrum of Mira AB and follow-up HST and ground-based observations showed evidence for an unprecedented outburst from Mira A likely associated with magnetic flare followed by a mass ejection or jet-like activity. Chandra and HST images also detect a bridge between the components, showing that Mira B is also accreting *via* direct mass exchange. These results have major impact on our understanding of accretion processes in other currently unresolved "wind" interacting systems.

Key words: X-rays; binaries: symbiotic.

1. INTRODUCTION

Mira AB is one of the very few interacting binaries that has been resolved at wavelengths ranging from X-rays to radio (Karovska *et al.* 1991, Karovska *et al.* 1997, Karovska *et al.* 2005; Matthews & Karovska 2005). Mira AB is the nearest symbiotic system consisting of an evolved Asymptotic Giant Banch (AGB) star, Mira A, and an accreting compact object, likely a white dwarf, Mira B. Symbiotic systems are a very important class of interacting binaries since they are likely progenitors of Planetary Nebulae (PNs). In addition, they have been invoked as possible progenitors of SN type 1a, key distance indicators in the Universe (e.g., Munari & Renzini 1992; Corradi *et al.* 2000). In these systems, believed to be detached for most of their long orbital periods, the interaction between components is assumed to be via wind accretion. The cool component, a giant or a Mira-type star, loses its mass *via* a powerful wind; A fraction of the wind mass (∼few %) is accreted by the compact hot accretor, often a white dwarf (e.g., Whitelock 1987; Livio 1988).

As in many other wind accreting systems, the accretion processes in symbiotics are currently not very well understood, and the theoretical models are limited by lack of knowledge of important input parameters such as wind mass and velocity, characteristics of the individual components (including radius and mass), orbital velocity and characteristics of the flow. These parameters can be accurately measured only when the system can be resolved and the components studied individually. Even in the case of the nearby symbiotic systems such as R Aqr and CH Cyg, neither the central region in the proximity of the binary, nor the binary itself have been resolved.

Mira AB is the only symbiotic systems that has been resolved so far. There are two reasons for this: first, the binary is nearby (∼130 pc, Perryman *et al.* 1997); second, the components are separated by at least 70AU. This angular separation is significantly greater than in other unresolved symbiotics (the nearest symbiotic systems are at a distance beyond ∼250 pc) in which the components seem to be much closer then in Mira AB. Thus, Mira AB is an easier target for imaging with current high-angular resolution ground- and space-based telescopes.

Therefore, the Mira AB system provides a unique laboratory to study the individual components of an interacting binary, as well as accretion processes in detached systems with extended atmosphere donors.

In the following we highlight results from multiwavelength observations of Mira AB, and also present results from our recent Chandra observations that resolved the system for the first time at X-ray wavelengths.

2. RESOLVING MIRA AB

2.1. UV and Optical Observations

Mira AB was discovered by A.H. Joy in 1923 (Aitken 1923) at optical wavelengths. However, it took another 60 years before the components of the system were clearly separated for the first time using speckle interferometry observations in 1983 (Karovska *et al.* 1991). The "speckle" images obtained in the optical detected for the

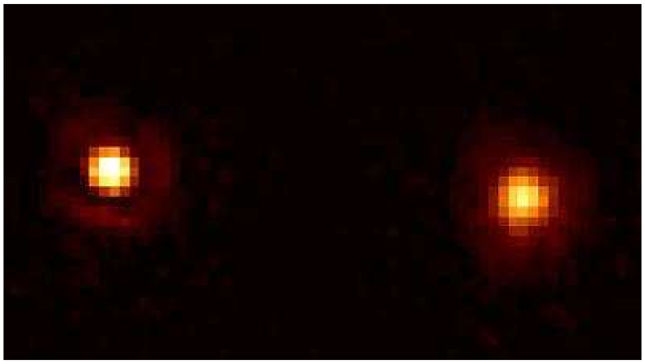

Figure 1. 1995 HST observations of Mira AB resolved the components of this 0.6” binary at optical and UV wavelengths (Karovska et al. 1997). North is up and East to the left.

first time an asymmetry in Mira A, the prototype of Mira-type variables.

Since 1983, observations of the system from X-ray to radio have provided unprecedented information about the characteristics of the components, Mira A and Mira B, and of the system as a whole. Specifically, they reveal a complex interacting system with tremendous changes in the components and the circumbinary environment.

For example, HST observations of Mira AB clearly resolved the components of the system at UV and optical wavelengths, and separated for the first time their spectra (Karovska *et al.* 1997). The HST images of Mira A (Fig. 1) confirmed the asymmetry in its extended atmosphere detected in the “speckle” images. Furthermore, the first UV image of Mira A showed a hook-like feature stretching toward Mira B, indicating possible mass flow toward the companion - an unexpected result given the large separation between the components (Karovska *et al.* 1997), see Fig.2.

Spectral observations carried out with the IUE in the early nineties, and HST observations carried out in 1995 and 1999, show tremendous changes in the UV luminosity of Mira AB (Fig. 3). Over an order of magnitude change in brightness was detected in the continuum and the line emission between 1999 and 1991. Furthermore, modeling of the Mg h&k line emission showed a decrease of Mira B mass loss of at least 2 magnitudes between 1991 and 1999, and a drop of the wind velocity by a factor of ∼2 (Fig. 4). The 1999 HST observations and the followup FUSE observations in 2001 detected a forest of Lyα-fluoresced H_2 emission lines at wavelengths below 1600 $\AA$ which dominated the spectra, despite not being seen at all in the 1995 HST observations or by IUE (Wood, Karovska, & Hack 2001; Wood, Karovska, & Raymond, 2002, Wood and Karovska 2004)). These dramatic changes indicate that Mira B may have been approaching a low state in the late nineties, and/or that the accretion characteristics in the system have changed in a very significant way.

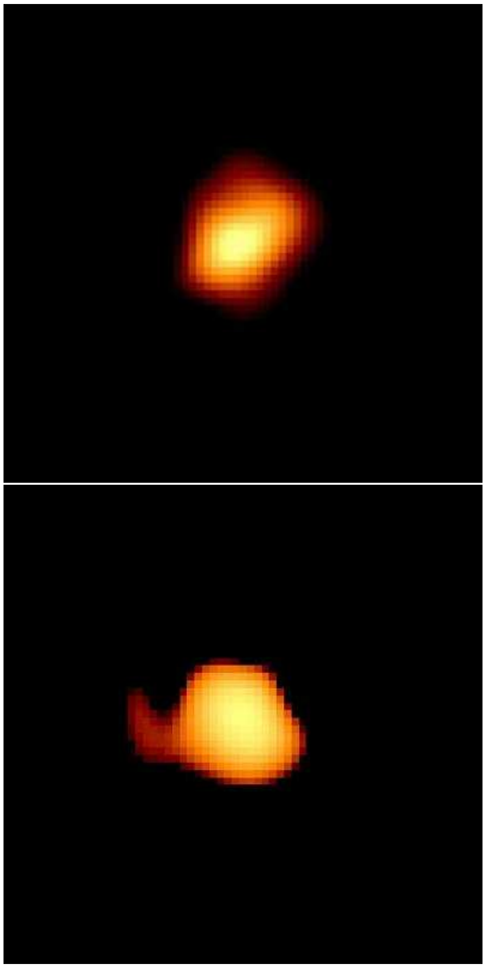

Figure 2. Deconvolved images of Mira A from the 1995 HST observations: (top panel) an optical image of Mira A showing a strong asymmetry in its envelope; (bottom panel) a UV image of Mira A showing an extension toward Mira B - an indication of a possible mass flow between the components (Karovska et al. 1997)

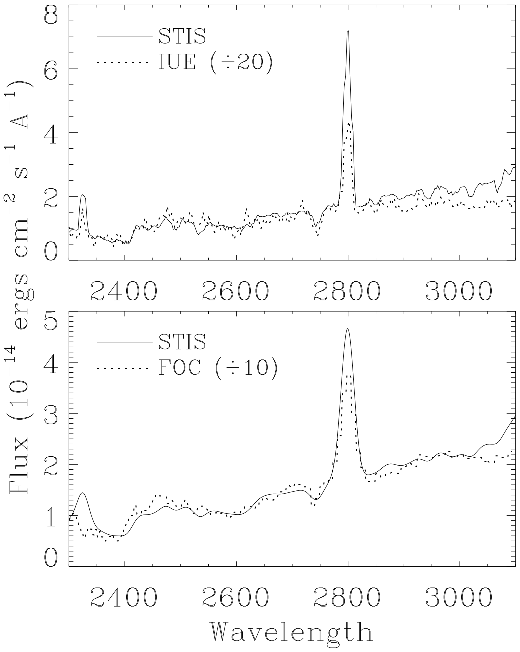

Figure 3. Comparison of the HST/STIS near-UV spectrum of Mira B with previous observations from IUE (top panel) and HST/FOC (bottom panel). In both panels, the STIS spectrum is rebinned and deresolved to match the resolution of the other observation. The peaks at 2325 Å and 2800 Å are C II] and Mg II lines, respectively. Note that the IUE and FOC fluxes had to be reduced by factors of 20 and 10, respectively, to match the STIS data (Wood et al. 2001).

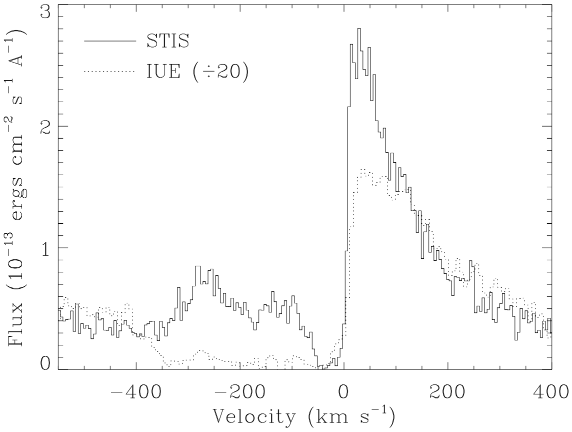

Figure 4. Comparison of the Mg II k line profile observed by HST/STIS (solid line) and one observed by IUE (dotted line), shown on a velocity scale centered on the rest frame of the star. The IUE fluxes are reduced by 20 to roughly match the STIS fluxes. Note the larger wind opacity between 0 and -400 km s^{-1} in the IUE spectrum (Wood, Karovska, & Hack 2001).

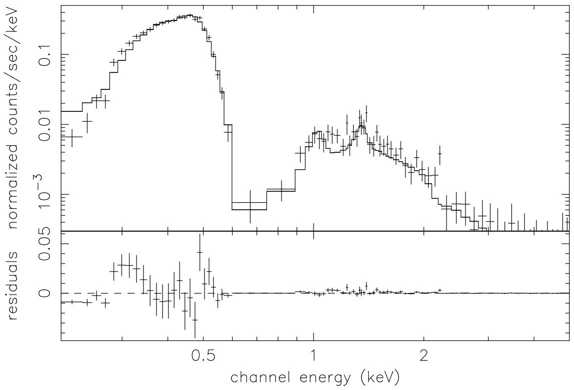

Figure 5. Chandra ACIS-S spectrum of Mira AB (plus signs) fit with a combination of gaussians for the soft spectral component and a bremsstrahlung plus gaussians for the hard component. Residuals fall mostly near the C edge at 0.3 keV where the response matrix is known to have errors (Karovska et al. 2005).

2.2. X-ray Observations

In 1993, a ROSAT observation resulted in the first unambiguous detection of X-ray emission from Mira AB (Karovska *et al.* 1996). This observation resolved the contradicting results from the analysis of the EINSTEIN observation; Jura & Helfand (1984) marginally detected an X-ray source, while Maggio et al. (1990) set an upper limit of $f_x<1.4\times10^{-13}$ erg s^{-1} cm^{-2}. The ROSAT X-ray luminosity of the Mira AB system was estimated $\sim10^{29}$erg s^{-1} (Karovska *et al.* 1996) which is similar to the luminosity estimated from the XMM observations carried out about ten years later (Kastner & Soker 2004).

On 2003 December 6 we carried out a 70 Ksec pointed Chandra observation of Mira AB using the ACIS-S instrument (*vis* Karovska *et al.* 2005). We detected several thousand counts below 1 keV (see Fig. 5), associated with a new bright soft source in the system, which was not seen a few months before by XMM (Kastner & Soker, 2004), or by ROSAT in 1993 (Karovska *et al.* 1996).

The high-energy component (>1keV) 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 (∼1.2-1.8 keV) as well. Figure 6 shows the Chandra spectrum and the best spectral fit to the XMM data obtained on 2004 July 23 (Kastner & Soker, 2004).

The best-fit spectrum is most easily explained as blended emission of C + N lines. We fit the low-energy portion of the Chandra 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. The best fit was obtained with lines at C VI 0.367 keV, N VI 0.426 keV, C VI 0.459 keV, and N VII 0.500 keV (line normalizations = 4.9, 6.2, 50.8, and 33.1, respectively, in units of 10^{-5} photons cm^{-2} s^{-1}). Fitting with a continuum component in the model resulted in a normalization

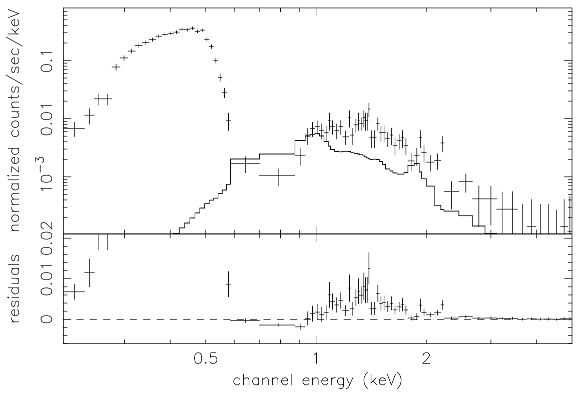

Figure 6. Chandra ACIS-S spectrum of Mira AB (plus signs). Histogram shows the best fit XMM spectrum (Kastner & Soker 2004). Note the flux below 1 keV associated with the outburst, and the increased flux above ∼ 1keV

consistent with zero.

The hard component was best-fit with a bremsstrahlung continuum of kT ∼0.78 keV to mimic an optically thin thermal plasma, plus two zero-width gaussians representing emission lines at ∼1 and ∼1.35 keV, all absorbed by a column $N_H \sim 9.0 \times 10^{22}$ cm^{-2}. The gaussians have equivalent widths of ∼240 and ∼120 eV, respectively. We attribute these emission to Ne and Mg lines. The total X-ray luminosity of the Mira AB system was estimated ∼2x10^{30}erg s^{-1}, and has increased by ∼ 5 times since the XMM observations few months before.

A major further insight into the origin of the observed outburst came from the Chandra images. Given the Chandra high-angular resolution capabilities, and the fact that the data include information about the photon energies and positions, we were able to obtain images of each component by filtering according to the information derived from the spectrum. We obtained a "soft" image from 0.3 to 0.7 keV, and "hard" image from 0.7-2 keV. Figure 7 shows a comparison between the ACIS image of the system (0.3-2keV)and the filtered images showing two separate components shifted by ∼0.5"; The "hard" image is shifted to the East of the "soft" image.

We further explored the spatial extent of the X-ray sources using PSF models and a new multiscale deconvolution technique *EMC2* (Esch *et al.* 2004). This technique was specifically developed for low-count statistics data, and it provides error estimates in addition to the reconstructed images. This enabled us to search for additional sources of X-rays in the system at a resolution 0.1" (less then the ∼ 0.5" ACIS-S pixel size).

The deconvolved image (Fig. 8) shows two sources separated by ∼0.6". This is the first image of an interacting binary that has been spatially resolved at X-ray wavelengths. The location of the brighter source in the deconvolved image corresponds to the centroid position of the soft source as determined using filtered images.

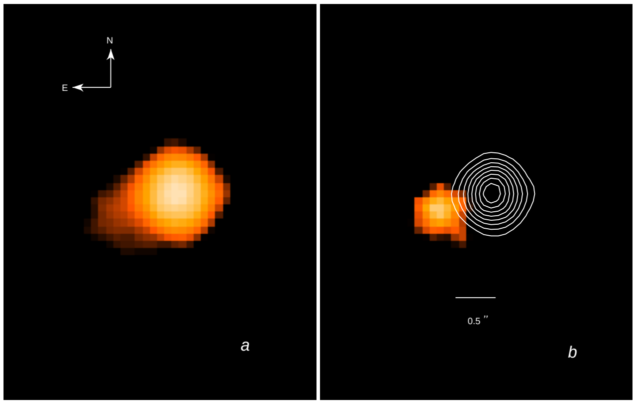

Figure 7. Chandra images of Mira AB: (a) ACIS-S raw image of Mira AB filtered from 0.3 to 2 keV. Mira A is toward the West (see Fig. 10); (b) contours of the ACIS-S soft image (0.3-0.7keV) (toward the West) overlayed on the image of the hard image (0.7-2 keV) (toward the East) (Karovska et al. 2005).

We compared the X-ray images with the HST images of the Mira AB components (Fig. 9) obtained two months later in the near-UV (3729 $\AA$ filter). The overlay of the HST and Chandra images obtained by shifting the HST image to match the X-ray components of the binary is shown in Fig. 10. The Chandra image of the soft X-ray source is in the vicinity of the 3729 $\AA$ image of Mira A and therefore likely associated with the AGB star rather then with the accreting companion Mira B. Before these observations, it was assumed that all the X-rays came from the accretion disk surrounding the white dwarf, so the detection of an X-ray outburst from the giant star came as a surprise.

The soft X-ray outburst in Mira A could be caused by a magnetic flare followed by a large mass ejection. This outburst is possibly associated with jet-like activity, as evidenced by ground-based Hα spectroscopy, and the changes in the Mgh&k lines in the 2004 HST spectra (Karovska *et al.* 2005). Furthermore, both HST and Chandra images show extended structures toward the North-West that could be associated with ejected material (e.g. Karovska *et al.* 2005; Karovska *et al.* 2006, in preparation).

In the case of mass ejection we could expect changes in the Spectral Energy Distribution (SED) of both components on a time scale of years. For example, we would expect increased dust formation in the system in the years following the outburst. Furthermore, assuming that the flow is propagating toward Mira B with speed of few hundred km/s, we would expect a dramatic response of the accretion disk on a time scale of few years.

The Chandra image also shows a faint "bridge-like" feature extending between the components. Similar structure can be seen in the HST image. This is consistent with the 1995 HST observations of Mira AB which showed extension from Mira A toward Mira B indicating possible

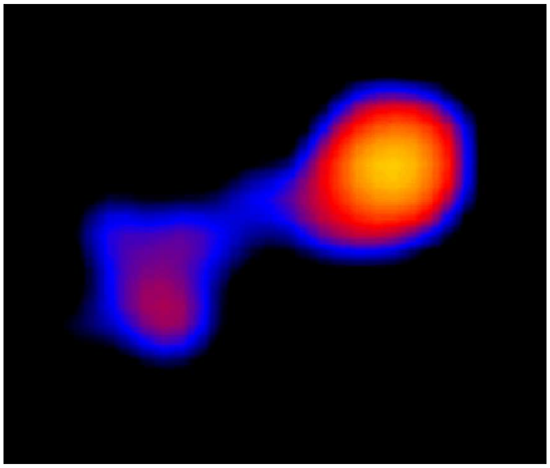

Figure 8. Chandra deconvolved image of Mira B (left) and Mira A (right), separated by ∼ 0.6", showing a bridge between the components. The Mira A image shows an elongation to the NW possibly associated with the outburst

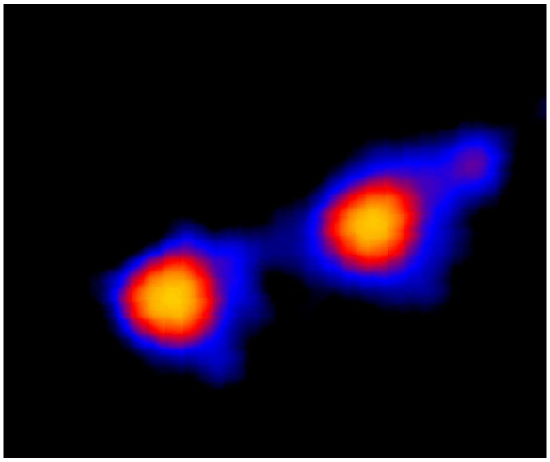

Figure 9. HST image of Mira AB obtained in February 2004 in the near-UV showing a possible extension in Mira A and a faint "bridge" between the components.

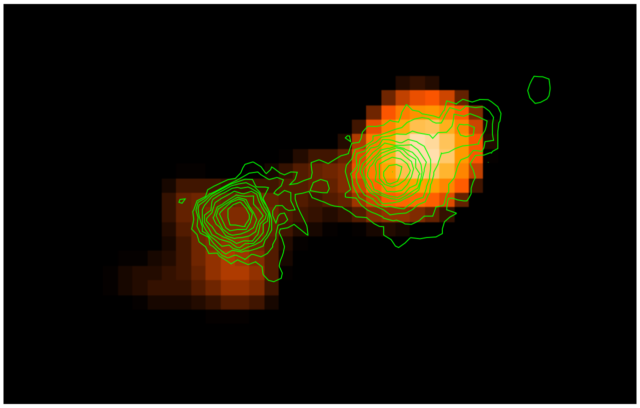

Figure 10. Chandra image of Mira B (left) and Mira A (right), separated by ∼ 0.6", with overlayed contours of the HST 3729 Å image of the system. North is up, East is to the left (Karovska et al. 2005).

Figure 11. The mass exchange between the components of Mira AB: in addition to wind accretion there is evidence for Roche-lobe like overflow (CXC PRC 05-06 2005).

mass flow between the cool giant and the hot companion (Karovska *et al.* 1997; STScI-PRC1997-26). This was also an unexpected result, because the components are separated by at least ∼70 AU, and it has been assumed in the past that the interaction between the components in such systems can be carried out *only via* wind accretion. The observations show that in addition to wind accretion this system interacts *via* direct mass exchange between the components as well (Fig. 11).

These results further challenge our understanding of accretion processes in detached systems and have important implications for understanding of accretion processes in other wind accreting systems in the Universe. This is very important since the flow of material from one component into the potential well of the other is a key in determining the future evolutionary histories of each component and the system itself, and particularly the production of degenerate companions and supernovae.

The key to further advances in accretion studies is resolving and directly imaging a wide range of interacting binaries, and studying their components and mass flows.

Increasing the resolution to *sub-milliarcsecond* level in the UV and X-rays will revolutionize the observational astrophysics of the 21st century and provide unprecedented opportunities for studies of many interacting binaries (Karovska *et al.* 2006).

For now it is very important to continue multi-wavelength studies of Mira AB and its dramatic transformations. Further monitoring of Mira AB at X-ray wavelengths is critical for understanding the accretion processes and the impact of the outburst on the surrounding circumstellar and circumbinary material and on the accreting companion and on the stability of the accretion disk.

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