

XMM-Newton Observations of the 2003 X-ray Minimum of η Carinae

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Abstract. The *XMM-Newton* X-ray observatory took part in the multi-wavelength observing campaign of the massive, evolved star η Carinae in 2003 during its recent X-ray minimum. This paper reports on the results of these observations, mainly from the aspect of spectral change. Hard X-ray emission from the point source of η Carinae was detected even during the minimum. During the minimum the observed flux above 3 keV was $\sim 3 \times 10^{-12}$ ergs cm⁻² s⁻¹, which is about one percent of the flux before the minimum. Changes in the spectral shape revealed two X-ray emission components in the central point source. One component is non-variable and has relatively cool plasma of $kT \sim 1$ keV and moderate absorption, $N_H \sim 5 \times 10^{22}$ cm⁻². The plasma is probably located far from the star, possibly produced by the high speed polar wind from η Carinae. The other high temperature component has $kT \sim 5$ keV and is strongly variable. This component shows an increase in the apparent column density from 5×10^{22} cm⁻² to 2×10^{23} cm⁻², probably originating near the heart of the binary system. These changes in N_H were smaller than expected if the minimum is produced solely by an increase of hydrogen column density. The X-ray minimum seems to be dominated by a decrease of the apparent emission measure, suggesting that the brightest part of the X-ray emitting region is completely obscured during the minimum in the form of an eclipse. A “partial covering” model might explain the residual emission seen during the minimum.

1. Introduction

The supermassive star, η Carinae, is now widely described as a binary system with a period of 5.5 years (e.g. Ishibashi et al. 1999; Daminieli et al. 2000). A collision between the wind from the primary star and the hidden companion forms a strong bow shock, which will produce hot X-ray emitting plasma. The emission undergoes a flux minimum apparently coincident with periastron passage, which may be caused by partial or full eclipse by the wind of the primary star and/or collapse of the bow shock. During the minimum in 1997–98, the *ASCA* satellite detected hard X-ray emission, characterized by similar kT and N_H to the pre-minimum state with reduced plasma emission measure (*E.M.*). The lim-

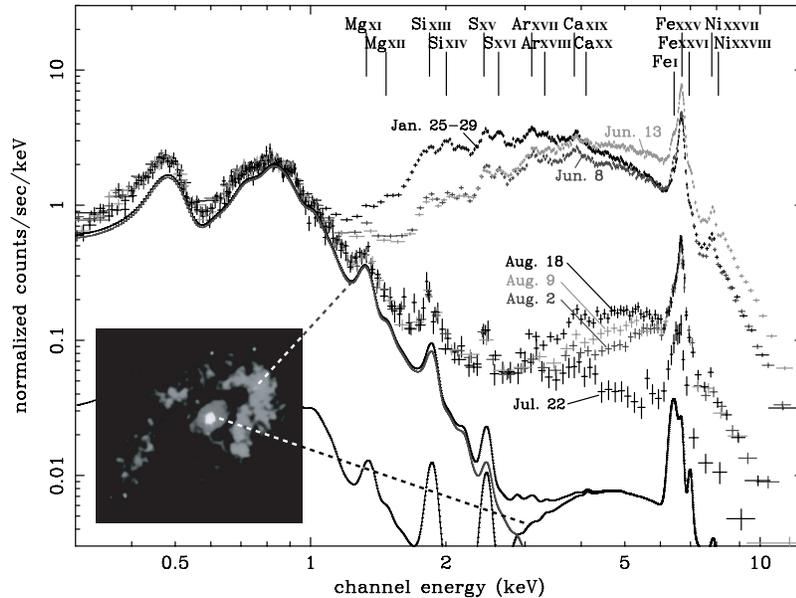


Figure 1. EPIC pn spectra of η Carinae in 2003. Spectra from each observation are shown as individual points with error bars. Spectra of the “Outer Debris Field” and the Homunculus Nebula, and their summed spectrum are shown as solid lines. The bottom left panel displays a *Chandra* image during the X-ray minimum (Corcoran et al. 2004). Strong emission lines from individual elements are shown at the top of the figure.

ited spatial resolution of *ASCA*, however, left the possibility that the observed emission was contaminated by emission from unresolved nearby sources.

The latest X-ray minimum began at 2003 June 29. It was monitored with three X-ray observatories, *RXTE*, *Chandra*, and *XMM-Newton* (see Corcoran et al., this meeting, for the results of the *RXTE* and *Chandra* campaigns.) Of these observatories, *XMM-Newton* has the largest effective area, with moderate spatial and spectral resolution, and therefore is suitable for tracing changes in N_{H} and kT . *XMM-Newton* observed η Carinae 1) 5 times in January 2003 before the minimum, which are treated as one set of data in our analysis, 2) twice in June 2003 prior to the minimum, near the X-ray maximum, 3) four times during the minimum in July and August 2003, for a total of 11 observations. This paper reports on the results from the EPIC pn and MOS CCD detectors.

2. Results

A *Chandra* observation by Corcoran et al. (2004) confirmed that hard X-ray emission during the X-ray minimum comes mainly from a point source at the position of η Carinae and partly from faint X-ray emission reflected from the Homunculus Nebula around η Carinae (see the bottom left panel in Figure 1). Unfortunately, *XMM-Newton* cannot spatially resolve these components nor well separate the soft X-ray emission from the “Outer Debris Field” beyond the

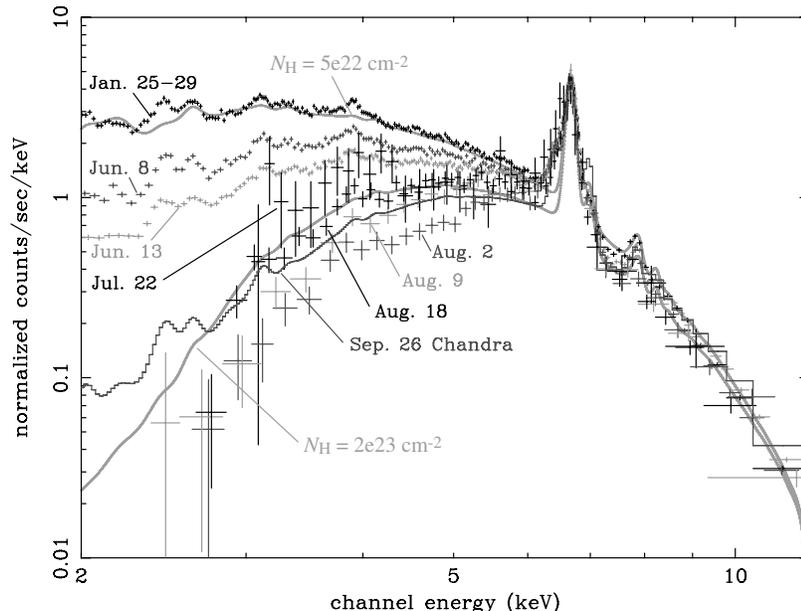


Figure 2. *XMM-Newton* EPIC pn spectra and the best-fit model of the *Chandra* spectrum on September 26, normalized at the Fe_{XXV} line intensity. The vertical unit is correct for the data on January 25–29. Smooth gray lines with indications of N_{H} represent absorbed 1T thin-thermal plasma (MeKaL) models with $kT = 5$ keV, $N_{\text{H}} = 5 \times 10^{22} \text{ cm}^{-2}$ (upper line) and $= 2 \times 10^{23} \text{ cm}^{-2}$ (lower line), $E.M. = 1.7 \times 10^{57} \text{ cm}^{-3}$ and abundance $Z/Z_{\odot} = 0.87$.

Homunculus, which is made by ancient ejecta interacting with the interstellar medium or previous ejecta. We therefore included all these components in the source region when extracting source events, and took background events from source free regions on the same CCD chip.

Background subtracted light curves above ~ 2 keV exhibited variation up to $\sim 5\%$ on timescales of ~ 30 msec, which reflects emission from the central point source. The variation roughly agrees with the interpolated daily fluxes monitored with RXTE

The EPIC pn spectra in Figure 1 demonstrate a strong decrease in hard X-ray emission up to a factor of ~ 100 above 1 keV during the minimum, with no variation in the emission below 1 keV. This is similar to the *ASCA* results from the previous X-ray cycle (Corcoran et al. 2000). The contribution of the X-ray emission from the outer debris field and the Homunculus Nebula, neither of which varied on timescales of a month or longer, was estimated from the *Chandra* data on 2003 July 20 during the minimum, and is overlaid in Figure 1. Except for the excess below 1 keV (which is produced by the poor absolute flux calibration between *Chandra* and *XMM-Newton*), the excess above 1 keV should represent emission from the central source.

During the minimum, this emission shows a non-variable component between 1–3 keV. To estimate the physical properties of this non-variable component, we subtracted the X-ray emission from the outer debris field and the

reflected emission from the Homunculus from the spectra during the minimum, and simultaneously fit them by a two-temperature (2T) optically thin-thermal plasma (APEC) model with independently absorbed 1T non-variable and 1T variable components. We also used the *Chandra* spectra of the central region for the fitting. The best-fit parameters of the non-variable component are $kT \sim 1$ keV, $N_{\text{H}} \sim 5 \times 10^{22}$ cm $^{-2}$, and $\log L_{\text{X}} \sim 34.2$ ergs s $^{-1}$.

We extracted spectra of the variable component by subtracting this non-variable component in addition to the X-ray debris field and Homunculus emission components (Figure 2). In the figure, we also display the best-fit model of the *Chandra* spectrum from September 26 when the minimum had just ended, and normalized all the spectra at the Fe_{XXV} line energy. Interestingly, the normalized spectra do not show any significant change in hard band slope above 7 keV, which is equivalent to a continuum temperature of $kT \sim 5$ keV. Meanwhile, the relative flux in the lower energy band decreased, with N_{H} increasing from 5×10^{22} cm $^{-2}$ to 2×10^{23} cm $^{-2}$. The N_{H} increase was moderate, and is not large enough to account entirely for the strong flux decrease during the minimum, especially at energies > 3 keV. The flux decrease is more consistently described as an apparent decrease of *E.M.* as suggested in the earlier *ASCA* observations (Corcoran et al. 2000). This could either represent a real reduction in the amount of X-ray emitting plasma, or an obscuration of X-ray emitting plasma. The flux during the minimum started to increase around July 22, though N_{H} was still increasing, and N_{H} continued to increase through the recovery on September 26. The N_{H} increase seems to lag the apparent *E.M.* decrease. In the spectra near the X-ray intensity maximum, the Fe_{XXV} emission line seems to have a lower energy tail, which is also seen in the *Chandra* HETG high resolution spectra (see Corcoran et al., this meeting). The feature seemed to be enhanced during the minimum though photon statistics were rather limited. This low energy tail may suggest that the ionization of the X-ray emitting plasma during the X-ray minimum may have been out of collisional equilibrium. The EWs of the Fe fluorescent line were 140–220 eV before the minimum and were restricted to less than 700 eV during the minimum.

3. Discussion

3.1. What is the Non-Variable X-ray Source?

The non-variable X-ray emission was stable for about two months during the minimum when the X-ray emission from the colliding winds exhibited prominent variation. The N_{H} of $\sim 5 \times 10^{22}$ cm $^{-2}$ is smaller than the columns to the colliding wind X-rays around the minimum and are the same as those in January and near apastron (e.g. Leutenegger et al. 2003). These results suggest that this emission component is remote from the binary system and not affected by the increasing column to the colliding wind source. On the other hand, *Chandra* images during the minimum between 1–3 keV, dominated by the non-variable X-ray emission, did not show any extended structure. The plasma size is therefore restricted to within $\sim 1''$, equivalent to a physical size of ~ 2300 AU assuming $d \sim 2.3$ kpc. These results suggest that the X-ray plasma is produced by collision of a fast outflow with ambient gas relatively far from the star. A good candidate for this outflow is the polar wind from η Carinae, which has a high speed outflow up to

$\sim 1000 \text{ km s}^{-1}$ (Smith et al. 2003), which can produce plasma at temperatures near 1 keV.

3.2. What Caused the X-ray Minimum?

The series of the *XMM-Newton* observations confirmed that the spectral variations during the minimum are caused by a change in $E.M.$, and not the observed increase in N_H (which is too low to provide the observed decline at $E > 5 \text{ keV}$). There are a number of ways in which this apparent reduction in X-ray brightness can be produced. One scenario is that the X-ray activity decayed close to the periastron passage, perhaps due to strong instabilities near periastron (Davidson 2002). However, while the behavior of the Fe_{XXV} line suggests that the ionization balance of the plasma may be changing during the minimum, the hottest plasma temperature appears so stable that it does not support a dramatic decay of X-ray activity. An alternative is that the X-ray emission is only partially blocked by an optically thick absorber. In this scenario, the plasma $E.M.$ is apparently reduced during the X-ray minimum because the volume is mostly obscured from our line of sight. A partial or annular eclipse geometry seems unlikely because of the rapid change in geometry caused by the motion of the companion near periastron. A possible solution is a "leaky absorber" consisting of optically thick clumps immersed in a lower-density gas which obscures 95–99% of the emitting region.

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