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Observations of the recurrent M 31 transient XMMU J004215.8+411924 with *Swift*, *Chandra*, HST, and *Einstein*

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ABSTRACT

Context. The transient X-ray source XMMU J004215.8+411924 within M 31 was found to be in outburst again in the 2010 May 27 *Chandra* observation. We present results from our four *Chandra* and seven *Swift* observations that covered this outburst.
Aims. X-ray transient behaviour is generally caused by one of two things: mass accretion from a high mass companion during some restricted phase range in the orbital cycle, or disc instability in a low mass system. We aim to exploit *Einstein*, HST, *Chandra* and *Swift* observations to determine the nature of XMMU J004215.8+411924.
Methods. We model the 2010 May spectrum, and use the results to convert from intensity to counts in the fainter *Chandra* observations, as well as the *Swift* observations; these data are used to create a lightcurve. We also estimate the flux in the 1979 January 13 *Einstein* observation. Additionally, we search for an optical counterpart in HST data.
Results. Our best X-ray positions from the 2006 and 2010 outbursts are 0.3″ apart, and 1.6″ from the *Einstein* source; these outbursts are likely to come from the same star system. We see no evidence for an optical counterpart with $m_B \lesssim 25.5$; this new limit is 3.5 mag fainter than the existing one. Furthermore, we see no V band counterpart with $m_V \lesssim 26$. The local absorption is ∼7 times higher than the Galactic line-of-sight, and provides ∼2 mag of extinction in the V band. Hence $M_V \gtrsim -0.5$. Fits to the X-ray emission spectrum suggest a black hole primary.
Conclusions. We find that XMMU J004215.8+411924 is most likely to be a transient LMXB, rather than a HMXB as originaly proposed. The nature of the primary is unclear, although we argue that a black hole is likely.

Key words. X-rays: general – X-rays: binaries – galaxies: individual: M 31

1. Introduction

The bulge region of M 31, the nearest spiral galaxy neighbour, is one of the best laboratories in the Universe for studying X-ray binaries. Accordingly, it has been observed hundreds of times by various X-ray observatories over the past 30 years. In the last ∼10 years alone, it has been observed 120 times by *Chandra*, 90 times by *Swift* and 31 times by *XMM-Newton*. Most of the *Chandra* and *XMM-Newton* observations were short, monitoring observations looking for transient X-ray sources, while the *Swift* observations generally followed these transients (see e.g. Williams et al. 2005, 2006).

XMMU J004215.8+411924 was identified as a new X-ray transient in the 2006, August 9 observation of M 31 (Haberl et al. 2006), with a positional uncertainty of 2″. Haberl et al. (2006) found that the emission spectrum was well described by a power law with photon index 1.57, suffering absorption equivalent to 4.2×10^{21} H atom cm^{-2}; the unabsorbed 0.5−10 keV luminosity was 9.1×10^{37} erg s^{-1}, assuming a distance of 780 kpc. The follow-up *Swift* observation made on 2006 September 1 revealed a UV counterpart within the X-ray error circle, leading Haberl et al. (2006) to identify XMMU J004215.8+411924 as a high mass X-ray binary (HMXB). A further *Swift* observation on 2006 September 11 yielded only three photons from XMMU J004215.8+411924 (Pietsch et al. 2006); this corresponded to a 0.5−10 keV luminosity of $<5 \times 10^{36}$ erg s^{-1} when assuming the above emission model.

Galache et al. (2006) subsequently reported a *Chandra* detection of XMMU J004215.8+411924 in a July 31 observation, finding the 0.9−6 keV spectrum to be well modeled by a power law model with photon index ∼1.8, with absorption equivalent to 4.4×10^{21} H atom cm^{-2}. They found the 0.5−10 keV luminosity to be 1.1×10^{38} erg s^{-1}.

Voss et al. (2008) examined the *Chandra*, *Swift* and *XMM-Newton* observations of three transients in M 31, including XMMU J004215.8+411924. The June 2 *XMM-Newton* observation made no firm detection of J004215.8+411924; hence Voss et al. (2008) constrainted the outburst duration to 40−79 days. They refined the source position by registering the *Chandra* data with the 2MASS catalogue of Skrutskie et al. (2006). They obtained RA(J2000) = 00:42:16.1, Dec(J2000) = +41:19:26.7, with a 1σ uncertainty of 0.5″. This new position was ∼4″ from the counterpart identified by Haberl et al. (2006), allowing Voss et al. (2008) to reject this association. They searched for a counterpart in the local group galaxy survey (LGGS) images provided by Massey et al. (2006), and found nothing with $V \lesssim 22$; using a distance modulus of 24.46 and 0.4 mag of extinction, they could not rule out a Be companion star.

In Nooraee et al. (2010) we reported a new outburst in the 2010 May 27 *Chandra* observation within 0.5″ of the position of

Table 1. Journal of observations.

Instrument	Obs	Date	Exposure	Net counts
Einstein HRI	579	1979-01-13	29 ks	29
Chandra ACIS-I	7139	2006-07-31	4 ks	433
Chandra ACIS-I	11279	2010-03-05	4 ks	5
Chandra ACIS-I	11838	2010-05-27	4 ks	279
Swift XRT	0031255012	2010-06-06	4 ks	44
Swift XRT	0031255013	2010-06-09	4 ks	37
Swift XRT	0031255014	2010-06-12	4 ks	24
Swift XRT	0031255015	2010-06-15	1.7 ks	9
Swift XRT	0031255016	2010-06-18	3 ks	6[a]
Chandra ACIS-I	11839	2010-06-23	4 ks	27
Swift XRT	0031255018	2010-06-24	4 ks	1[a]
Chandra ACIS-I	11840	2010-07-20	4 ks	∼0[a]

Notes. For each observation we give the instrument, observation number, date, exposure time and number of net source photons.
[(a)] Not a secure detection. Derived luminosities are 3σ upper limits.

XMMU J004215.8+411924, and identified it as a recurring transient. In this paper we present detailed analysis of the seven *Swift* and four *Chandra* observations made between 2010 March 5 and 2010 July 20. We also search for a counterpart in the 2006 August 27 HST observation, and present evidence for a previous outburst in 1979 detected with *Einstein*.

We discuss the observations and data analysis in Sect. 2. We then present our results in Section 3 and discuss in Sect. 4 whether XMMU J004215.8+411924 is a HMXB displaying orbital variability, or a transient low mass X-ray binary (LMXB) with unstable disc accretion.

2. Observations and data analysis

A journal of observations is provided in Table 1.

2.1. Analysis of Chandra data

The 2006 July 31 *Chandra* observation (7139) of XMMU J004215.8+41192 has already been discussed by Voss et al. (2008). However, we registered the image to the LGGS *B* band image of M 31 Field 6, which has positional uncertainties of 0.25″, using globular clusters (GCs) in the Revised Bologna Catalogue V4 (Galleti et al. 2004, 2006, 2007, 2009) that were X-ray bright. To do this, we used the IRAF tool IMCENTROID to determine the position of each cluster in the *Chandra* and LGGS observations in image coordinates, then checked the positional uncertainties of each GC. We then used XY2SKY to get the sky coordinates for each GC in the X-ray and LGGS images. This allowed us to map the LGGS coordinates to the X-ray positions with CCMAP. The position of XMMU J004215.8+41192 was determined in the corrected image using IMCENTROID, and the positional uncertainties were combined with the 0.25″ of the LGGS coordinate system.

For the 2010 May 27 *Chandra* observation (11838), we located XMMU J004215.8+41192 as above. In addition, we extracted source and background spectra, with related products, using CIAO ver 4.2. These spectra were analysed with XSPEC VER 12.6. XMMU J004215.8+41192 was too faint for spectral modelling in the 2010 March 5, 2010 June 24 and 2010, July 20 observations; instead, we derived a conversion from intensity to flux for each observation using the best fit emission model from Obs 11838, as described below.

2.2. Analysis of Swift data

We were awarded seven observations of M 31 with *Swift* during 2010, June at three day intervals to monitor the transient CXOM 31 J004253.1+4122 (Henze et al. 2009); results from that transient will be presented by Nooraee et al. (in prep). This work uses data from the X-ray Telescope (XRT), taken in photon counting (pc) mode. Unfortunately, the 2010 June 21 observation had an exposure time of just 35s in pc mode, so this observation was ignored. XMMU J004215.8+411924 was at a large off-axis angle that varied between observations (∼7−10′).

The *Swift* data were analysed with XSELECT version 2.4a. We were unable to use the recommended source extraction radius of 47″ (containing ∼90% of the source photons) due to crowding. Instead we used a circular source extraction region with radius 20″, and a concentric, annular background region with inner radius 20″ and outer radius 28.28″. Lightcurve analysis was not productive, since the *Swift* data are obtained in chunks of a few hundred seconds, and very few photons were collected each time.

Since there were too few photons for spectral analysis in each *Swift* observation, we converted from background-subtracted intensity to 0.5−10 keV flux by calculating the flux equivalent to 1 count s^{-1} assuming the best fit model derived from our analysis of the Obs 11838 *Chandra* data. To do this we obtained source and background spectra for each observation, and created an ancillary response file using the tool XRTMKARF; the appropriate canned response matrix was used. For each observation we loaded these files into XSPEC version 12.6 and normalised the best fit emission model to give 1 count s^{-1}. This enabled us to obtain the unabsorbed 0.5−10 keV flux equivalent to 1 count s^{-1}, which we refer to as the conversion factor.

2.3. Analysis of HST data

We triggered two HST observations after the 2006 outburst, designed to observed the counterpart in the on phase phase and off phase. The first observation was made with the ACIS/WFC on 2006 August 27 using the *F435W* filter. Unfortunately, the ACS was not operational during our second observation in 2007 July, and the observation was made with WFPC/FIX-1 using the *F439W* filter. However, the position of XMMU J004215.8+411924 was serendipitously covered by an ACS/WFC1 observation in 2004, October using the *F555W* filter.

We obtained the drizzled images of these observations from the Hubble legacy archive, and registered them with the B image of M 31 Field 6 in the LGGS; we used stars that were visible in both images, but not so bright that the centroid determination had large uncertainties.

3. Results

3.1. Fitting the 2010 May Chandra spectrum

The 2010 May observation of XMMU J004215.8+411924 yielded 279 net source counts. We grouped the source spectrum to get a minimum of 15 counts per bin. The best fit power law emission model had a photon index of 1.8 ± 0.5, with absorption equivalent to $6 \pm 3 \times 10^{21}$ H atom cm^{-2}; χ^2/d.o.f. = 7/15. These parameters are entirely consistent with those found by Voss et al. (2008).

The *XMM-Newton* observation analysed by Voss et al. (2008) yielded the tightest constraints on the absorption (4.2 ± 0.5 × 10^{21} H atom cm^{-2}); we therefore fixed the absorption

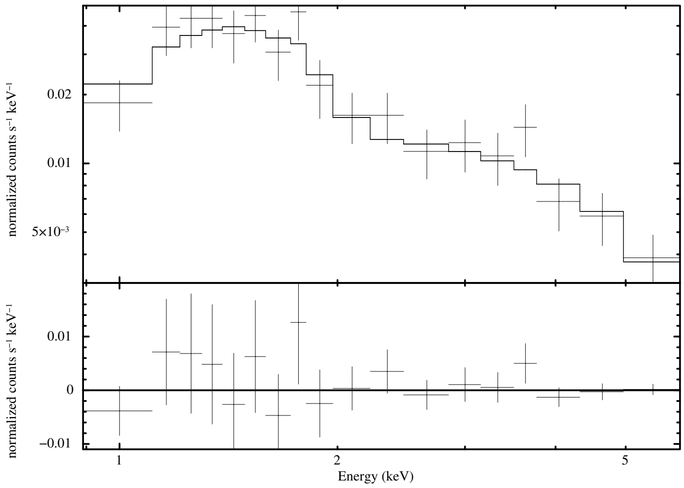

Fig. 1. Best fit power law model to the Obs 11838 *Chandra* spectrum, with residuals; χ^2/d.o.f. = 7/16. N_H was fixed to 4.2×10^{21} atom cm^{-2}.

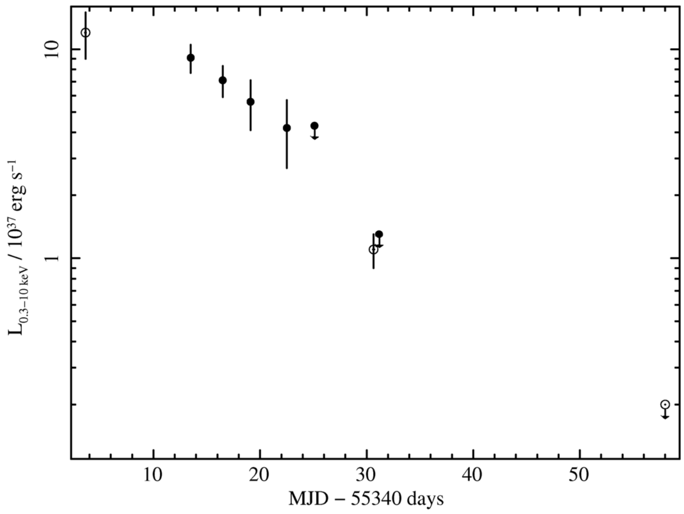

Fig. 2. 0.3−10 keV lightcurve of XMMU J004215.8+411924 from *Swift* (filled circles) and *Chandra* (hollow circles). Arrows represent 3σ upper limits. The y axis is log scaled for clarity.

to 4.2×10^{21} H atom cm^{-2} for our *Chandra* spectrum. This gave a best fit photon index of 1.6 ± 0.2, and χ^2/d.o.f. = 8/16. This yielded an unabsorbed 0.5–10 keV luminosity of $1.2 \pm 0.3 \times 10^{38}$ erg s^{-1}. This fit is presented in Fig. 1.

We also fitted the spectrum with a disk blackbody model, since black holes in outburst are often in the high soft state, with thermal emission spectra (see e.g. McClintock & Remillard 2006, and references within). The best fit spectrum had an inner disc temperature of 1.4 ± 0.3 keV; N_H was fixed to 4.2×10^{21} atom cm^{-2} as before; χ^2/d.o.f. = 10/16. This temperature is somewhat high for a high state black hole binary (McClintock & Remillard 2006), and the fit is rather worse than the power law fit. Hence we prefer the power law fit, but cannot rule out a thermal fit.

A neutron star accreting at $\sim 10^{38}$ erg s^{-1} has a two component emission spectrum, often characterised as a blackbody and a power law, with the blackbody contributing ∼10−50% of the luminosity (see e.g. Church & Bałucińska-Church 1995; Church et al. 2002). Hence, we fitted the spectrum with a blackbody + power law model. The best fit gave $kT \sim 1$ keV, and a power law slope 1.6 ± 0.6; χ^2/d.o.f. = 7/14; however, the blackbody component was not well constrained, and only contributed ∼5% of the flux, significantly less than expected for a neutron star system. We infer from the lack of a strong thermal component that the primary is more likely to be a black hole than a neutron star; however, we cannot rule out a neutron star primary.

3.2. The X-ray lightcurve

We obtained the conversions from intensity to 0.5−10 keV flux for each *Swift* observation and the 2010 June *Chandra* observation, assuming a power law with photon index 1.6, with N_H = 4.2×10^{21} atom cm^{-2}. The conversion factor varied by up to 25% between observations, due to changes in off-axis angle.

We present the lightcurve of XMMU J004215.8+411924 covering the outburst from 2010 May 27 to 2010 July 20 in Fig. 2. Each point is plotted at the midpoint of the observation; the points from the June 18 and June 24 *Swift* observations, and the July 20 *Chandra* observation, are 3σ upper limits. The 2010 July *Chandra* observation yielded a 3σ upper limit of 2×10^{36} erg s^{-1}, suggesting that XMMU J004215.8+411924 may have returned to its pre-outburst level.

The deepest observation made of XMMU J004215.8+411924 is *Chandra* Obs 1575, with a ∼40 ks duration. The 3σ upper luminosity limit is 6×10^{35} erg s^{-1}. Hence, the variation in luminosity is a factor $\gtrsim 200$ between the outburst peak and quiescence.

XMMU J004215.8+411924 was observed by *Chandra* three times in 2010 prior to the detection of the outburst, in January, February and March; no observation was made in April, as M 31 was behind the sun. We found no strong detections in any of these observations; the 3σ upper limit for the March observation was $\sim 2 \times 10^{36}$ erg s^{-1}. Hence the 2010 outburst lasted at least 30 days, but not more than 140 days. The outburst appears to be of similar duration to the one in 2006.

We have found no evidence of additional outbursts in the 120 *Chandra* observations and 90 *Swift* observations of XMMU J004215.8+411924.

3.3. The X-ray position of XMMU J004215.8+411924

For the 2006 July *Chandra* observation, we chose 12 bright X-ray sources associated with GCs for the registration. Five GCs had unacceptably large uncertainties in their X-ray positions (>0.2″), and these were removed from the registration process. Additionally, one of the GCs showed an unusually large discrepency between the X-ray and optical positions, so it was discarded and a new solution was found; the final rms offset between *Chandra* and LGGS was 0.07″ in RA and 0.12″ in Dec. Our best registration solution yielded RA = 00:42:16.063 Dec = +41:19:26.73, with 0.17″ uncertainty in RA and 0.2″ uncertainty in Dec. Combining these with the position uncertainties of the LGGS images gives an error circle with 0.3″ radius.

Our final registration of the 2010 May *Chandra* observation utilised five GCs; the final rms offset between *Chandra* and LGGS was 0.19″ in RA and 0.16″ in Dec. Our best location in this observation was RA = 00:42:16.037, Dec = +41:19:26.63, with 0.17″ uncertainty in RA and 0.28″ uncertainty in Dec. Combining these with the LGGS uncertainties results in a 0.3″ × 0.4″ ellipse. The best fit positions in the two observations are offset by 0.3″. Therefore it is most likely that both X-ray outbursts come from the same source.

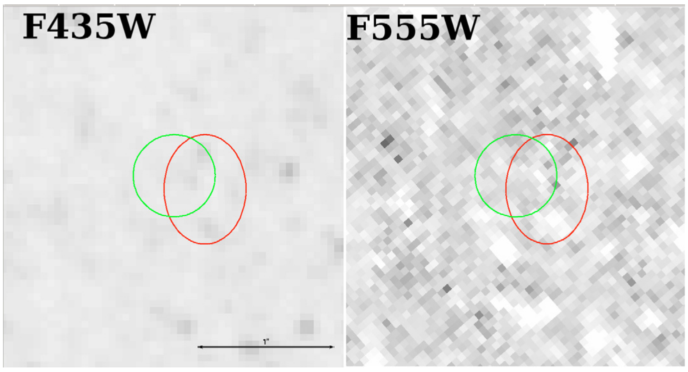

Fig. 3. Details of HST images of the environs of XMMU J004215.8+411924 from 2006, August, i.e. during outburst (*left*) and 2004, October, in quiescence (*right*). Uncertainties in the X-ray position are represented by a circle for the 2006 *Chandra* observation and by an ellipse for the 2010 May *Chandra* observation.

3.4. The Einstein outburst

We note that our 2010 position is 1.6″ from an X-ray source detected in the *Einstein* HRI ∼30 years previously (source 17 in Crampton et al. 1984); the uncertainty in *Einstein* position is ∼10″, and includes no known X-ray sources other than XMMU J004215.8+41192 This source was not detected by Trinchieri & Fabbiano (1991), who used a source detection radius of 6.7″ for the *Einstein* HRC; however, XMMU J004215.8+41192 was observed at a high off-axis angle, and the photons were spread over a wider area than the detection cell.

Extracting a circle with 20″ radius around the position of XMMU J004215.8+41192 yields 76 counts, while a nearby source free region of the same size yields 47 counts. The net exposure time for the observation is 28 564 s. We calculated a conversion from 0.2−4.0 keV intensity in the HRC to 0.5−10 keV unabsorbed flux using WEBPIMMS: 1 count s^{-1} = 7.1×10^{-10} erg cm^{-2} s^{-1}. Hence we estimate the 0.5−10 keV luminosity of XMMU J004215.8+41192 to have been $\sim 5 \times 10^{37}$ erg s^{-1} in the 1979 January 13 observation.

3.5. The search for counterparts

The 2006, August HST observation was registered to the LGGS using seven stars, with a r.m.s offset of 0.02″ in both RA and Dec. The 2005, May HST observations was registered with 5 stars, resulting in rms offsets of 0.019″ and 0.05″ in RA and Dec respectively.

In Fig. 3 we present details of the HST images from 2006, August (left) and 2005, May (right). These images are superposed with a circle that represents the X-ray position from the 2006, July *Chandra* observation, and an ellipse to represent the 2010, May position. We find no compelling evidence for a counterpart during outburst down to $m_B \sim 25.5$, or $m_V \sim 26$, let alone evidence for variability that would confirm the association.

At a distance of 780 kpc, M 31 has a distance modulus of 24.45 mag. The observed column density is significantly higher than the Galactic line-of-sight absorption (6×10^{20} H atom cm^{-2}); using the empirical relationship obtained by Predehl & Schmitt (1995), we can expect ∼2 mag of V band extinction, and ∼3 mag in B band. Hence we place upper limits on the counterpart of $M_B \gtrsim -2$, and $M_V \gtrsim -0.5$.

4. Discussion

Two mechanisms could be responsible for the huge variation in mass accretion that resulted in the observed outburst (see e.g. Williams et al. 2006, for a discussion of M 31 transients). The system could be a HMXB with a long, eccentric orbital period where accretion is intensified near periastron; this scenario was initially favoured by Haberl et al. (2006) after mistakenly identifying a counterpart in the *Swift* UVOT image. Alternatively, the system could be a low mass X-ray binary (LMXB) with an unstable accretion disc that oscillates between a cold state (quiescence) and a hot, ionised state (outburst), see e.g. Dubus et al. (2001, and references within). Here we consider the observational constraints on both scenarios.

4.1. Constraints on a HMXB system

The known counterparts of HMXBs in the SMC have apparent V magnitudes in the range $13 \lesssim m_V \lesssim 18$, and $B - V$ in the range $-0.32 \leq B - V \leq 0.06$ (see e.g. Coe et al. 2005; Antoniou et al. 2009). For a distance of ∼60 kpc, this equates to $-6 \lesssim M_V \lesssim -1$, all brighter than our threshold of $M_V \gtrsim -0.5$. It is therefore unlikely that a Be star is hidden by the local absorption.

Furthermore, variations in accretion rate on the orbital cycle are of course periodic, and we see no evidence for other outbursts in our ∼120 other *Chandra* monitoring observations. Since the outbursts lasted at least ∼30 days, and the frequency of our monitoring is once per ∼30 days, we would expect coverage of other outbursts.

If the outbursts in 1979, 2006 and 2010 were due to periodic accretion near perihelion, then a whole number of orbital cycles every ∼1430 days would be required. Hence, XMMU J004215.8+41192 would have had an unabsorbed 0.5−10 keV luminosity $\sim 10^{38}$ erg s^{-1} during the 2006, July 2 *XMM-Newton* observation. However, Voss et al. (2008) did not detect XMMU J004215.8+4119 during that observation. We therefore conclude that XMMU J004215.8+411924 is likely to be a LMXB.

4.2. Constraints on a LMXB system

The optical emission of X-ray bright LMXBs is dominated by the accretion disc; since larger discs exist in systems with longer orbital periods, van Paradijs & McClintock (1994) derived an empirical relation between the optical luminosity (L_V), the X-ray luminosity (L_V) and the disc radius (R): $L_V \propto L_X^{1/2} R$. The range in absolute magnitudes of the sample was $-5 \lesssim M_V \lesssim 5$.

Including the relation between R and orbital period, and defining Σ as $(L_X/L_{Edd})^{1/2}\,(P/1\mathrm{hr})^{2/3}$, they further found that the relation

$$M_V \ = 1.57 \pm 0.24 - 2.27\,(\pm 0.32) \log \Sigma \tag{1}$$

produced good results over three orders of magnitude in Σ. This relation allows us to estimate the range in orbital period for XMMU J004215.8+411924. Due to the high local absorption, the upper limit to the orbital period is not particularly constraining: ≲40 h for a neutron star and ≲130 h for a black hole, longer than typical LMXB periods.

The X-ray spectrum from Observation 11838 is best fitted by a power law fit with spectral index ∼1.6; this is seen in neutron star and black hole binaries at low accretion rates (van der Klis 1994). However, Gladstone et al. (2007) showed that neutron star LMXBs don't exhibit this behaviour at 0.01−1000 keV luminosities ≳10% of the Eddington limit. Neutron star LMXBs at higher luminosities have two component emission spectra, with a thermal component contributing ∼10−50% of the flux (Church et al. 2002). Since the 0.5−10 keV luminosity of XMMU J004215.8+411924 is ∼70% of the Eddington limit for a 1.4 $M_{\odot}$ neutron star, the primary is likely to be a black hole (Barnard et al. 2008); this conclusion is supported by the lack of a strong thermal component in the two component model. However, the quality of the data prevents us from excluding a neutron star primary.

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