XMM-Newton observation of 4U 1543–475: The X-ray spectrum of a stellar-mass black-hole at low luminosity

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1. Introduction

4U 1543–475 is a recurrent X-ray transient containing a black hole. It was discovered during an outburst in 1971 (Matilsky et al. 1972) and observed in outburst again in 1983 (Kitamoto et al. 1984), in 1992 (Harmon et al. 1992) and in 2002 (Park et al. 2004; Kalemci et al. 2004). In the decade-long quiescence periods the flux is lower than 0.1 μCrab, while the source brightens by a factor greater than 2 × 10^7 in outburst (Garcia et al. 2001). In the latest outburst, between June and July 2002, the measured flux reached a peak value of 4.2 Crab in the 2–12 keV energy band, comparable to the peak intensities observed in the three previous outbursts (Tanaka & Lewin 1995). The source light curve along the whole outburst showed the characteristic shape of the “classic” X-ray novae, i.e. a fast rise to the outburst peak followed by an exponential decay, with e-folding decay time of ≈14 days (Mc Clintock & Remillard 2003). The spectrum was soft and dominated by the emission from the accretion disk: its continuum part was fit with a multi-colour disk blackbody ($kT_{\text{col}} = 1.04$ keV) and a power-law (photon index $\Gamma ~ 2.7$).

The optical counterpart of 4U 1543–475, IL Lupi, has been classified as spectral type A2V (Chevalier & Ilovaisky 1992). During the X-ray outbursts it brightens by ≈1.8 mag (van Paradijs & Mc Clintock 1995), but during the quiescent periods it was possible to perform detailed studies. This allowed to derive the orbital period $P_{\text{orb}} = 26.8$ h, the black-hole mass $M_1 = 9.4 \pm 2.0 M_\odot$, the secondary star mass $M_2 = 2.7 \pm 1.0 M_\odot$, the source distance $d = 7.5 \pm 1.0$ kpc and the orbit inclination $i = 20.7 \pm 1.0^\circ$ (Orosz et al. 1998; Orosz 2003).

Here we present the results of an XMM-Newton observation obtained after the most recent outburst of 4U 1543–475. The spectrum obtained with the EPIC instrument has an unprecedented statistics for a galactic black-hole at this level of luminosity, allowing for the first time to investigate the spectral details of a black-hole binary approaching the quiescent phase.

2. Observations, data reduction and spectral analysis

4U 1543–475 was observed by XMM-Newton on 2002 August 18, between 12:30 and 20:42 UT. The source was on-axis and the observation lasted about 29.5 ks. The three EPIC cameras (Turner et al. 2001; Strüder et al. 2001) were all active during the observation: the PN, MOS1 and MOS2 instruments were operated in Small Window, Timing Uncompressed and Full Frame mode, respectively. For all of them, the Thin filter 1 was used.

We used the version 5.4.1 of the XMM-Newton Science Analysis System (SAS) to process the event files. After the standard processing pipeline of the data, we looked for possible periods of high background due to soft proton flares with energies less than a few hundred keV. For the two MOS cameras this was done by inspecting the light curves of the events with energy above 10 keV detected in the peripheral CCDs and with pixel patterns from 0 to 4. In this way, we selected only those background events whose high energy is distributed in one or two pixels at most, which presumably are due to low energy protons focused on the focal plane by the telescope mirrors. These light curves showed a large increase of the count-rate.
Table 1. Best-fit parameters for a power-law model in the case of the PN, MOS2 and PN+MOS2 data.

| Instrument | \(N_H\) (\(\times 10^{21}\) cm\(^{-2}\)) | Photon index | Normalization at 1 keV (ph keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\)) | \(\chi^2\) | d.o.f. | \(f_X\) (0.3–10 keV)\(^{\prime}\) (erg cm\(^{-2}\) s\(^{-1}\)) |
|-----------|-----------------|--------------|-----------------|--------|-------|-----------------|
| PN        | 3.6 ± 0.2       | 1.92 ± 0.04  | (9.9 ± 0.5) \(\times 10^{-4}\) | 1.104  | 297   | (3.7 ± 0.2) \(\times 10^{-12}\) |
| MOS2      | 4.5 ± 0.3       | 1.99 ± 0.07  | (11.2 ± 0.9) \(\times 10^{-4}\) | 1.131  | 146   | (3.7 ± 0.3) \(\times 10^{-12}\) |
| PN+MOS2   | 3.8 ± 0.2       | 1.94 ± 0.04  | (10.3 ± 0.3) \(\times 10^{-4}\) | 1.069  | 442   | (3.7 ± 0.1) \(\times 10^{-12}\) |

Note – Errors are at 90% c.l. for a single interesting parameter; \(^{\prime}\) absorbed flux.

For the MOS2 camera\(^3\) we applied the same source extraction radius of the PN camera (30\(\prime\)), while, thanks to the larger size of the MOS CCDs, we could accumulate the background spectrum using a circular area of 2.5\(\prime\) radius. Also in this case the spectrum was rebinned with a minimum of 30 counts in each energy bin and fitted over the 0.3–8.5 keV energy range. The fit with a power-law yielded a comparable photon-index but a higher hydrogen column density than the PN one (Table 1). This discrepancy is likely due to the uncertainties still remaining in the calibration of the two instruments, especially at low energies (Kirsch 2004). We also fitted the PN and MOS2 data simultaneously, after including a systematic error of 5% in the spectral bins. Again a satisfactory fit was obtained with a power-law model (see Table 1) while thermal models gave worse \(\chi^2\) values.

In conclusion, although the exact value of the absorption is still subject to some uncertainty\(^4\), all our data point to a power-law spectrum with photon index ~2. In the following analysis, aimed to assess the possible presence of additional components in the spectrum, we will consider only the PN data, due to their higher statistics (~12 000 source counts are detected in the PN compared to ~5600 in the MOS2). We checked that similar

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1. The PN pixels are larger than the MOS ones; therefore, no multipixel events are expected by the soft-protons.
2. This is smaller than the MOS one due to the reduced live-time of the Small Window mode used for the PN.
3. We have not used the MOS1 data since the spectral response in Timing Mode is not yet well calibrated.
4. Note, however, that this is one of the best measurements of \(N_H\) for this source obtained so far; our value is comparable with the value of \((4.26 ± 0.15) \times 10^{21}\) cm\(^{-2}\) obtained by van der Woerd et al. (1989) with EXOSAT data.
results would be obtained using the MOS2 data, although with
looser upper limits (usually a factor 2–5 times higher).

To look for a possible Fe Kα emission line, we tried to
improve the spectral fit by adding a Gaussian component at
four different fixed energies between 6 and 7 keV, with σ be-
tween 0 and 0.5 keV. In all the cases we found no evidence
for it: the Gaussian normalization was always consistent with
zero. The upper limit on the line equivalent width is always
below ~0.25 keV at a 3σ confidence level (Table 2).

Although not formally required by the data, which are sat-
satisfactorily fit by the power-law model, we investigated the
possible presence of an additional multi-colour disk emission
(Mitsuda et al. 1984; Makishima et al. 1986). To this aim we
added a disk blackbody component and obtained $N_H = (4.4 \pm
0.7) \times 10^{21}$ cm$^{-2}$, $\Gamma = 1.94 \pm 0.05$, $K_{PL} = (1.0 \pm
0.1) \times 10^{-3}$, $kT_{col} = 0.16 \pm 0.03$ keV and $K_{DBB}
= 141 \pm 289$ as best-fit parameters, with $\chi^2$/d.o.f. = 325.5853/295. This result would
imply an absorbed flux $f^{0.3-10}_{DBB} = 8.44 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for
the thermal component (i.e. ~2% of the total flux), but the large
error on its normalization clearly demonstrates that this com-
ponent is only marginally present. The F-test proves that the fit
quality improves only at a 0.3σ level.

We have therefore computed an upper limit to the disk
emission component. This is shown in Fig. 2, where the upper-
limit on the disk bolometric luminosity is shown as a func-
tion of the colour temperature $T_{col}$ (assumed a source dis-
cance $d = 7.5$ kpc). The power-law best-fit parameters imply
an unabsorbed flux $f_X = (5.83 \pm 0.29) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in
the energy range 0.3–10 keV, which corresponds to $L_X =
(3.92 \pm 0.20) \times 10^{34}$ erg s$^{-1}$. This means that any possible disk
contribution is well below 10% of the total source luminosity.

3. Discussion and conclusions

The XMM-Newton data reported here were obtained just
two months after the start of the source outburst observed
by Rossi-XTE (RXTE) on MJD 52445 (2002 June 20). The
source was monitored by RXTE during all this period: Park
et al. (2004) analysed the data collected between MJD 52442
and 52477 (i.e. before the transition to the low-hard state),
while Kalemci et al. (2004) considered the data between
MJD 52464 and 52498 (i.e. during and after the transition
to the LH state). Both Park et al. (2004) and Kalemci et al.
(2004) used the sum of a power-law and a multi-colour disk
blackbody to fit the continuum part of the spectra, finding that
the photon index decreased from 3.85 (at the outburst peak)
to 2.21 (just ~6 days before the XMM-Newton observation),
while the temperature at the inner disk edge decreased from 1
to 0.35 keV. Using the best-fit parameters reported by these
authors, we computed the 2–10 keV fluxes as a function of time
for the total emission and for the power law component only,
which are shown in Fig. 3. The last point in the figure in-
cidates our XMM-Newton flux value, converted to the same
energy range. Even if this flux is below the extrapolation of the
last RXTE measurements, the plot shows that it is in general
agreement with the overall decreasing rate measured by RXTE.

The luminosity observed with XMM-Newton corresponds
to $\sim 1.5 \times 10^{-5}$ of the Eddington luminosity, still well
above the typical quiescent level of BH candidates $L_{q} \sim 10^{-9.5}L_{EDD}$
(Mc Clintock & Remillard 2003), where we assumed $d =
7.5$ kpc and $M = 9.4 M_{\odot}$. At the time of the XMM-Newton
observation (i.e. two months after the outburst), 4U 1543–475

| $E$ (keV) | 6   | 6.4  | 6.7  | 7   |
|----------|-----|------|------|-----|
| $\sigma$ (keV) | U.L. (eV) | U.L. (eV) | U.L. (eV) | U.L. (eV) |
| 0        | 173 | 117  | 37   | 97  |
| 0.1      | 209 | 130  | 48   | 99  |
| 0.2      | 255 | 150  | 71   | 91  |
| 0.3      | 262 | 161  | 90   | 97  |
| 0.4      | 254 | 173  | 113  | 111 |
| 0.5      | 235 | 176  | 138  | 134 |

Fig. 2. 3σ upper-limit on the bolometric luminosity of the multi-colour
disk as a function of the colour temperature.

Fig. 3. X-ray flux observed by RXTE and XMM-Newton during the
2002 outburst of 4U 1543–475. The open circles refer to the total
source flux, the crosses to the power-law component. The last point
to the right is our XMM-Newton total flux.
was not yet in quiescence but still in the low-hard state, which is characterized by $1.5 < \Gamma < 2.1$ and a power-law flux contribution higher than 80% of the total flux.

According to Kalemci et al. (2004) some emission from an accretion disk is still required by the last RXTE spectra of 4U 1543–475 obtained six days before the XMM-Newton observation reported here. Their data cannot yield a disk temperature for such a faint and soft component. Therefore Kalemci et al. fix it at the value of 0.35 keV. Assuming $d = 7.5$ kpc and $i = 21^\circ$, for such a temperature our upper limit on the disk blackbody normalization corresponds to a disk colour radius of 0.08 $R_g$ (where $R_g = GM/c^2$ is the BH gravitational radius).

The value of $r_{\text{col}}$ obtained from the best fitting procedure of the multi-colour disk blackbody model systematically underestimates the actual disk radius (Shimura & Takahara 1995; Merloni et al. 2000). In fact $r_{\text{in}} = \eta \times g \times f_{\text{col}}^2 \times r_{\text{col}}$, where $\eta = 0.6$–0.7 is the ratio between the inner radius and the effective radius (i.e. the radius at which the temperature of the disk peaks), $g = 0.7$–0.8 takes into account the general relativistic corrections and $f_{\text{col}} = T_{\text{col}}/T_{\text{eq}}$ is the spectral hardening factor, whose value can be about 3 for low accretion rates. If we consider the maximum value for all the parameters, from $r_{\text{col}} = 0.08R_g$ we obtain $r_{\text{in}} \sim 0.4R_g$. This value is incompatible with the innermost stable circular orbit around a black-hole, which is $R_{\text{ISCO}} = 6R_g$ for a Schwarzschild BH and $R_{\text{ISCO}} = R_g$ for a Kerr BH (Shapiro & Teukolsky 1983). Note that the same would be true for lower normalizations at the same temperature. Only for disk temperatures $kT_{\text{col}} < 0.25$ keV our normalization upper limits give acceptable values for the inner disk radius. For example, for $kT_{\text{col}} = 0.2$ keV we obtain $r_{\text{col}} = 0.43R_g$, which corresponds to $r_{\text{in}} \sim 2.2R_g$. A similar conclusion was noted in a short report on this XMM-Newton observation by Miller et al. (2003), but contrary to these authors we do not find a significant improvement by the inclusion of the disk component in the fit to the spectrum of 4U 1543–475.

In conclusion the observation reported here provides one of the best quality spectra for a black hole X-ray binary accreting at a low level, but still far from the quiescent state. The featureless power law energy spectrum does not give any evidence for the presence of an accretion disk. If a disk is present, it is constrained to have a luminosity of $(2–3) \times 10^{-5}$ erg s$^{-1}$ and a temperature smaller than 0.25 keV. This is an interesting result since little is known on the possible presence and the properties of accretion disks around black-holes at these relatively low luminosities. Even if a multi-colour disk is not strictly required in the hard state from the theoretical point of view, there are some arguments in favour of it: on one hand, most common accretion models foresee the presence of a disk with a large (i.e. $\geq 100R_g$) inner radius (Esin et al. 1997; Mc Clintock & Remillard 2003); on the other hand, a soft X-ray excess, which can be modeled with a large and cool accretion disk, has been observed in GX 339–4 (Wilms et al. 1999) and XTE J1118+480 (Mc Clintock et al. 2001; Frontera et al. 2003), albeit at higher luminosities than that reported here for 4U 1543–475.

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References

Chevalier, C., & Illovaisky, S. A. 1992, IAU Circ., 5520, 1

Esin, A. A., Mc Clintock, J. E., & Narayan, R. 1997, ApJ, 489, 865

Frontera, F., Amati, L., Zdziarski, A. A., et al. 2003, ApJ, 592, 1110

Garcia, M. R., Mc Clintock, J. E., Narayan, R., et al. 2001, ApJ, 553, L47

Harmon, B. A., Wilson, R. B., Finger, M. H., et al. 1992, IAU Circ., 5504, 1

Kalemci, E., Tomsick, J. A., Buxton, M. M., et al. 2004, ApJ, submitted [arXiv:astro-ph/0409992]

Kirsch, M. 2004, XMM-SOC-CAL-TN-0018 Issue 2.3

Kitamoto, S., Miyamoto, S., Tsunemi, H., Makishima, K., & Nakagawa, M. 1984, PASJ, 36, 799

Makishima, K., Maejima, Y., Mitsuda, K., et al. 1986, ApJ, 308, 635

Matilsky, T. A., Giaconi, R., Gursky, H., Kellogg, E. M., & Tananbaum, H. D. 1972, ApJ, 174, L53

Mc Clintock, J. E., Haswell, C. A., Garcia, M. R., et al. 2001, ApJ, 555, 477

Mc Clintock, J. E., & Remillard, R. A. 2003, Black Hole Binaries, Chap. 4 of Compact Stellar X ray Sources, ed. W. H. G. Lewin, & M. van der Klis (Cambridge University Press) [arXiv:astro-ph/0306213]

Merloni, A., Fabian, A. C., & Ross, R. R. 2000, MNRAS, 313, 193

Miller, J. M., Fabian, A. C., & Lewin, W. H. G. 2003, The Astronomer’s Telegram, 212, 1

Mitsuda, K., Inoue, H., Koyama, K., et al. 1984, PASJ, 36, 741

Orosz, J. A., 2003, in IAU Symp., 365

Orosz, J. A., Jain, R. K., Bailyn, C. D., Mc Clintock, J. E., & Remillard, R. A. 1998, ApJ, 499, 375

Park, S. Q., Miller, J. M., Mc Clintock, J. E., et al. 2004, ApJ, 610, 378

Shapiro, S. L., & Teukolsky, S. A. 1983, Black holes, white dwarfs, and neutron stars: The physics of compact objects (New York: Wiley-Interscience), 663

Shimura, T., & Takahara, F. 1995, ApJ, 445, 780

Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18

Tanaka, Y., & Lewin, W. H. G. 1995, in X-ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge University Press)

Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27

van der Woerd, H., White, N. E., & Kahn, S. M. 1989, ApJ, 344, 320

van Paradijs, J., Mc Clintock, J. E. 1995, in X-ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge University Press)

Wilms, J., Nowak, M. A., Dove, J. B., Fender, R. P., & di Matteo, T. 1999, ApJ, 522, 460