Relativistic baryonic jets from an ultraluminous supersoft X-ray source

Ji-Feng Liu1,2, Yu Bai1, Song Wang1, Stephen Justham1,2, You-Jun Lu1,2, Wei-Min Gu3, Qing-Zhong Liu4, Rosanne Di Stefano5, Jin-Cheng Guo1, Antonio Cabrera-Lavers6,7, Pedro Álvarez6,7, Yi Cao8 & Shri Kulkarni8

The formation of relativistic jets by an accreting compact object is one of the fundamental mysteries of astrophysics. Although the theory is poorly understood, observations of relativistic jets from systems known as microquasars (compact binary stars)1,2 have led to a well-established phenomenology3–4. Relativistic jets are not expected to be produced by sources with soft or supersoft X-ray spectra, although two such systems are known to produce relatively low-velocity bipolar outflows5,6. Here we report the optical spectra of an ultraluminous supersoft X-ray source (ULS7,8) in the nearby galaxy M81 (M81 ULS-1; refs 9, 10). Unexpectedly, the spectra show blueshifted, broad Hα emission lines, characteristic of baryonic jets with relativistic speeds. These time-variable emission lines have projected velocities of about 17 per cent of the speed of light, and seem to be similar to those from the prototype microquasar SS 433 (refs 11, 12). Such relativistic jets are not expected to be launched from white dwarfs13, and an origin from a black hole or a neutron star is hard to reconcile with the presence of M81 ULS-1’s soft X-rays14–20. Thus the unexpected presence of relativistic jets in a ULS challenges canonical theories of jet formation3,4, but might be explained by a long-speculated, supercritically accreting black hole with optically thick outflows14–20.

Initial spectroscopic observations21 of M81 ULS-1, made at the W.M. Keck Observatory in 2010, found broad Balmer hydrogen emission lines (as wide as 400 km s⁻¹) on top of a power-law-like blue continuum. A very broad emission line (as wide as 30 Å, corresponding to 2,000 km s⁻¹) was detected at around 5,532 Å and 5,543 Å in both observations, but was not identified with any known spectral lines. We followed up with new spectra obtained at the Gran Telescopio Canarias in 2015, which again showed the Balmer emission lines and the blue continuum; however, the previously unidentified broad emission line was now at a notably changed wavelength of 5,648 Å (Fig. 1). This change in observer-frame wavelength immediately suggests that the previously unidentified emission line is a blueshifted Hα emission line emitted by an approaching baryonic relativistic jet, at projected velocities of 17% of the speed of light (~0.17c). Subsequent spectra reveal ongoing changes in the projected velocity of the blueshifted jet, for which we suggest that the best explanation is jet precession, as observed in the prototype microquasar SS 433.

SS 433 has exhibited time-variable blueshifted and redshifted optical emission lines from its precessing jets, the long-term monitoring of which has revealed11,12 a precession period of 164 days, and an intrinsic jet velocity of 0.26c. M81 ULS-1 is only the second microquasar

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Figure 1 | Spectra obtained from the W.M. Keck Observatory and the Gran Telescopio Canarias (GTC) for the optical counterpart of M81 ULS-1. a, The Keck/LRIS (Low Resolution Imaging Spectrometer) spectrum taken on 13 April 2010 (blue channel; shown in black) and the GTC/OSIRIS (Optical System for Imaging and Low/Intermediate-Resolution Integrated Spectroscopy) spectrum taken on 8 April 2015 (shown in blue) for M81 ULS-1. Labelled are the broad Balmer lines (Hβ and Hα), and the very broad blueshifted Hα lines at 5,530 Å (Keck/LRIS) and 5,648 Å (GTC/OSIRIS). The power-law-like continuum and the broad Balmer lines are characteristic of an accretion disk around a compact object, confirming the physical association between the X-ray source and its optical counterpart. b, The blueshifted Hα emission lines from six Keck and GTC observations, with time-variable, observer-frame central wavelengths. The intensities also change with time in proportion to the intensities of the stationary Hα emission line from the accretion disk, suggesting a link between the accretion and the jet. See Methods for details. Both the spectra and the fits are normalized by the underlying continuum, and are shifted vertically for clarity.
energies below 1 keV (Fig. 2). For the Galactic microquasars, only a few per cent to less than 35 per cent of the photons have energies below 1 keV. Because the response matrix is not well calibrated below 0.3 keV for Chandra/ACIS, only photons with energies greater than 0.3 keV are shown here.

to be identified through measuring directly the blueshifting of $\text{H}_\alpha$ lines emitted by its baryonic jets. Other known microquasars\textsuperscript{1,2} have mostly been identified through direct imaging of their radio jets, or by interpreting strong non-thermal radio emission as arising from their relativistic jets with velocities above 0.1c. M81 ULS-1 has not previously been detected by radio surveys, but this is not surprising given the great distance to the galaxy M81. Were SS 433 placed in M81, its radio flux at Earth would be about 1 μJy—below the detection sensitivity of current radio facilities, but achievable in the future with the Square Kilometer Array\textsuperscript{22}.

From its X-ray properties\textsuperscript{10}, M81 ULS-1 seems to be a truly unique jet source, different to all other known microquasars\textsuperscript{1,2}. Since the launch of the Chandra X-Ray Observatory, all observations of M81 have detected ULS-1, which exhibits high-flux and low-flux states with count rates ranging from 1 to 70 photons per kilosecond. When in high-flux states, M81 ULS-1 clearly exhibits supersoft spectra with blackbody temperatures of 65–100 eV and bolometric luminosities greater than $10^{39}$ erg s\textsuperscript{-1}. Somewhat surprisingly, the low-flux state of M81 ULS-1 appears to be as supersoft as the high-flux state, with more than 95% of the photons having energies below 1 keV (Fig. 2). In contrast, all other known microquasars\textsuperscript{1,2} are low-mass or high-mass X-ray binaries, each shown or thought to contain a neutron star or black hole, emitting abundant hard photons with energies above 1 keV. Observations by the Chandra X-Ray Observatory show that only a few per cent to 35 per cent of the photons from these microquasars have energies below 1 keV (Fig. 2).

Luminous supersoft sources\textsuperscript{23} have supersoft X-ray spectra, and those with luminosities below the Eddington limit for a solar-mass object are conventionally interpreted as white dwarfs accreting at a rate of about $10^{-7} M_\odot$ yr\textsuperscript{-1} to $10^{-6} M_\odot$ yr\textsuperscript{-1} (where $M_\odot$ is the mass of the Sun), where hydrogen fusion within the accreted material proceeds steadily\textsuperscript{24,25}. But for M81 ULS-1, the presence of relativistic jets suggests otherwise: such jets are simply not expected for typical white dwarfs\textsuperscript{13}. Indeed, although bipolar outflows with low velocities of a few thousand kilometres per second are possible and have been observed in supersoft sources such as RX J0513.9-6951 (ref. 5) and RX J0019.8+2156 (ref. 6), no relativistic jets have ever, to our knowledge, been observed from supersoft sources other than M81 ULS-1. These considerations suggest that the accreting object in M81 ULS-1 is not a white dwarf, adding strong evidence to the idea\textsuperscript{26,27} that supersoft sources, especially the ultraluminous ones, do not necessarily contain accreting white dwarfs.

If, instead, the central engine of M81 ULS-1 is a neutron star or a black hole—as is the case for all other known microquasars—established phenomenology\textsuperscript{1,2} would predict steady jets to be generated when X-ray emissions are in the low-hard state, with episodic jets generated when emissions are in the very high state, or during the transitions between soft and hard states. In the case of M81 ULS-1, the blueshifted $\text{H}_\alpha$ emission lines emitted from the relativistic jets were present in all six optical spectroscopic observations in 2010 and 2015. Standard presumptions would therefore be that M81 ULS-1 is in the low-hard or very high states for a substantial fraction of the time, during which abundant hard photons (with energies above 1 keV) would be expected, as for other microquasars (Fig. 2). However, X-ray emissions from ULS-1 have been supersoft in all 19 Chandra observations, regardless of whether ULS-1 is displaying a low-flux or a high-flux state—suggesting that its relativistic jets are not generated in the canonical ways. In fact, the persistently supersoft appearance of ULS-1 would not be expected in any spectral states in the standard accretion scenarios\textsuperscript{28,29} for neutron-star or black-hole X-ray binaries, which are known to be accreting below the critical (that is, Eddington) rate.

This unusual combination of relativistic jets and persistently supersoft X-ray spectra is completely unexpected, posing a challenge to the conventional understanding of jet formation\textsuperscript{3,4}. One possible identity for M81 ULS-1 is a long-s Gespräch\textsuperscript{4,15}, supercritically accreting black hole with optically thick outflows. Recent magnetohydrodynamic simulations of such systems, although still under development and the subject of heated debate\textsuperscript{16,17}, can generate super-Eddington luminosities, and necessarily\textsuperscript{30} generate disk winds and funnels along the rotation axis, from which radiation pressure will drive baryon-loaded relativistic jets with velocities of up to 0.3c, regardless of the black-hole spin\textsuperscript{32}. Observations of M81 ULS-1 qualitatively match the predictions of high luminosities and baryon-loaded relativistic jets, and its supersoft X-ray spectra might be expected from optically thick outflows under suitable conditions of outflow geometry, wind velocities and outflow mass rates\textsuperscript{18,20}. Thus, ULS-1 might be a manifestation of recent predictions of supercritical accretion onto black holes, and so reveal the nature of extreme accretion in extreme conditions.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 17 June; accepted 11 September 2015.

Published online 25 November 2015.

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Acknowledgements We thank K. Blundell, R. Narayan, Z. Li, T. Wang, F. Yuan, X. Fang, J. Irwin, T. Maccarone and D. Swartz for helpful discussions. We acknowledge support from the Chinese Academy of Sciences (grant XDB09000000), from the 973 Program (grant 2014CB845705), and from the National Science Foundation of China (grants NSFC-11333004/11425313). This work is based partly on observations made with the Gran Telescopio Canarias, installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, on the island of La Palma. Some of the data were obtained at the W.M. Keck Observatory, which is operated through a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. This Observatory was made possible through the financial support of the W.M. Keck Foundation.

Author Contributions J.-FL. proposed the observations. J.-FL., Y.B., S.W. and J.-C. G. reduced the optical and X-ray data and carried out the analysis. J.-FL., S.J., Y.-J.L. and R.D.S. discussed the results and drafted the manuscript. A. C.-L., J.-C. G. reduced the optical and X-ray data and carried out the analysis. J.-FL., S.J., Y.-J.L. and R.D.S. discussed the results and drafted the manuscript. All authors commented on and helped in improving the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.-F. Liu (jfliu@nao.cas.cn).
METHODS

GTC/OSIRIS and Keck/LRIS data reduction. Initial optical spectroscopic observations of M81 ULS-1 were carried out with Keck/LRIS on 13 April and 17 April 2010, revealing broad Balmer emission lines as if from an accretion disk. The blueshifted Hα emission line (Hα−) is shown at 5,530 Å in the spectra, with a shift in the line centre of 10 Å ± 2 Å between those two observations (that is, two epochs separated by four nights). M81 ULS-1 was later observed using GTC/OSIRIS on 8 April, 7 May and 8 May 2015, masked with the 0.6″ slit followed by the R1000R grating, which yields a resolution of about 7 Å. The spectra were reduced in a standard way with IRAF (Image Reduction and Analysis Facility) software (http://iraf.noao.edu). After bias subtraction and flat correction, dispersion correction was carried out on the basis of the line lists given in the OSIRIS manual (http://www.gtc.iac.es/instruments/osiris/). Raw spectra were then extracted with an aperture size of 1″, and a standard star taken at each night was used to make the flux calibration.

On 22 April 2015, another observation of M81 ULS-1 was carried out using Keck/LRIS with the 1.0″ slit. The light was split with a beam diroch of 6,800 Å to the blue and red sides, followed by using the 300/5,000 and 400/6,500 gratings, which yields a resolution of ~8 Å. The spectrum was reduced with the IDL (Interactive Data Language) pipeline designed for the W.M. Keck Observatory.

Extended Data Table 1 lists the basic information obtained from the 2010 and 2015 observations. Both Hα and Hδ emission lines are detected in all the spectra, and their line properties are calculated from Gaussian line profile fitting. Extended Data Table 2 lists the central wavelength, the full width at half-maximum (FWHM) and the equivalent width for each fitted emission line. The observed Hα central wavelengths, λc, correspond to projected velocities, v∥, from −0.17c to −0.14c in these observations, given by λc = 5,530 Å + 1.5 × v∥/c.

Properties of the emission lines. In the case of SS 433, the equivalent widths of Hα emission lines are tightly correlated with the phases of the precession, and those of the Hβ− emission lines follow a similar trend but with a phase delay. We use the power of the emission lines, calculated from the area of the Gaussian fitting, as representative of the emission intensity, because the observed continuum from M81 ULS-1 varies markedly between observations. Extended Data Fig. 1 shows that the power of the Hα emission lines from the accretion disk is positively correlated with that of the Hβ emission lines, suggesting a link between the accretion and the jet. The variations in the power of the emission lines are asymmetrical, with smooth rises and steeper declines around 7 May 2015 (Extended Data Fig. 2)—similar to the variations seen in the SS 433 emission lines.

The rate at which the projected Hα− velocity changes seems to be slower during 2015 than it was during 2010. The rate of change in 2015 was roughly 0.8 Å per day, whereas it was 2.6 Å per day in 2010; if the velocity shift is due to precession, this difference may be explained naturally, because the 2015 observations are sampling a different part of the precession cycle. We can estimate a minimum likely precession period by assuming that the turning point of the precession cycle occurred at around the time of the observations of 7 and 8 May 2015 (see Extended Data Figs 2, 3). If so, then, after the wavelength of the emission lines reached the maximum on 8 April (Extended Data Fig. 2), the Hα emission probably turned back to the short wavelength with the rate of roughly 0.8 Å per day, indicating that the half-precession period must be longer than 30 days.

Theoretical predictions of the Hα− emission lines. The existence of blueshifted Hα− emission lines from the approaching jets, redshifted Hα emission lines (Hα+) would be expected from receding jets, albeit with much lower intensities (because of Doppler boosting effects). Assuming symmetrical and steady jets, the boosting factors (D) for the lines emitted from the approaching and the receding jets are given by D+ = (1 − β cos θ)/[1 + β cos θ] > 1 and D− = (1 + β cos θ)/[1 − β cos θ] < 1, respectively. The total flux of a blueshifted or redshifted line in the observer frame is boosted by a factor of D2. The expected central wavelengths of the two lines are given by λc = λ0 / Dc and λc = λ0 / Dc and the corresponding redshifts are z = λc / λ0 − 1 > 0 and z = λc / λ0 − 1 < 0. D and z values for Hα− in all observations are listed in Extended Data Table 3.

We have searched for the redshifted Hα− emission lines in all observations. A weak emission line feature was detected at ~5 Å around 7,524 Å (Fig. 1), roughly symmetrical to Hα+ at 5,648 Å, in one of the GTC exposures during the night of 8 April 2015. If this marginal detection were the redshifted Hα+ line, its boosting factor would be D− = λc / λ0 = 0.8722, and the ratio of the received total flux of the blueshifted line to that of the redshifted line should be D2 = 2.5, which is roughly consistent with the observed flux (~2 × 10^3 Å^-1).

However, the observed wavelength is not consistent with the expected Hα+ wavelength given the blueshifted Hα− at 5,648 Å, that is, 6.56 × 10^-3 Å^-1. Assuming the extreme case, θ = 0°, then we have β = 0.149.1. If the receding jet has the same velocity, then the expected central wavelength of Hα+ should be 7,626 Å, which is about 104 Å larger than the detected line. If we assume that θ = 10°20′30″, then β = 0.152/0.160/0.177, and the expected central wavelength of Hα+ is 7,632 Å, 7,650 Å, 7,688 Å, which is about 108 Å/126 Å/164 Å larger than the detected line. The discrepancy becomes larger for larger inclination angles.

This casts doubt on the identification of the 7,524 Å line feature as Hα+, unless the jets are asymmetrical or fast-changing. We may have not detected the redshifted Hα+, but the non-detection is not surprising given the Doppler boosting effects, and other realistic explanations. For example, the receding jets may be blocked by the optically thick outflows if this system is a supercritically accreting black-hole system, as described in the text. No candidate Hα+ emission lines were detected in all the 7 and 8 May GTC observations, or in the Keck spectrum. Even if the 8 April line were a true Hα+ emission line, this non-detection would not be surprising, given the lower equivalent widths of Hα− on 7 and 8 May, and the relatively lower sensitivity in the red channel of LRIS.

Analysis of Chandra data. There have been 19 Chandra/ACIS observations of the nuclear region of M81, where ULS-1 resides. All of these observations were derived from the Chandra archive and analysed uniformly with CIAO 4.7 software tools (http://cxc.harvard.edu/ciao/). Point sources were detected with WAVDETECT on the individual Chandra images. As listed in Extended Data Table 4, the photon counts were extracted from the source ellipses enclosing 95% of the total photons as reported by WAVDETECT, which was run with scales of 1″, 2″, 4″ and 8″ in the 0.3 to 8.0 keV band.

The spectra in the high-flux states (>10 counts per kilosecond) were fitted by absorbed blackbody models, with the spectral parameters presented in Extended Data Table 4, all of which show that M81 ULS-1 has been persistently supersoft in these observations. In addition, the spectra in the high-flux and low-flux states were added together into combined high- and low-state spectra, and were also fitted in the band 0.3–8.0 keV. Using the fitted absorbed blackbody model, we calculated the 0.3–8.0 keV flux, the 0.3–8.0 keV luminosity and the bolometric luminosity with the distance of 3.63 megaparsecs for M81 (ref. 32).

As plotted in Extended Data Fig. 4, M81 ULS-1 displays a soft excess below 0.3 keV as compared to the best-fit model for 0.3–8.0 keV. However, considering that the response matrix for Chandra observations is not well calibrated below 0.3 keV, we refrain from interpreting this soft excess. Nonetheless, it is clear that M81 ULS-1 has very different spectral properties from the other known microquasars. Moreover, these uncertainties in calibration below 0.3 keV might merely make the intrinsic spectral differences between M81 ULS-1 and the other known microquasars even larger (that is, the energy distribution from M81 ULS-1 might be even softer than observed).

Code availability. The optical spectra were reduced with IRAF, available at http://iraf.noao.edu/. All of the emission lines in Extended Data Table 2 were fitted with the curve-fitting toolbox based on Matlab (http://www.mathworks.com/help/curvefit/index.html). The Chandra archive data were analysed with CIAO 4.7, which can be downloaded from http://cxc.harvard.edu/ciao/download/.

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Extended Data Figure 1 | The power of Hα$^{-}$ emission versus that of Hα emission for M81 ULS-1, in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. The error bars denote 68.3% uncertainty. Observations are given as year followed by month followed by day.
Extended Data Figure 2 | Variation in the power of emission lines from M81 ULS-1, in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. The error bars denote 68.3% uncertainty. The x-axis gives the observation date as a Heliocentric Julian Date (HJD).
Extended Data Figure 3 | The centre of Hα− emission as a function of the relative observational date. The dates of observations are marked in the figure; the ‘relative observational date’ refers to the date relative to the first observation of 2010 or 2015. The error bars denote 68.3% uncertainty.
Extended Data Figure 4 | The M81 ULS-1 spectra and model fitting. The spectra from Chandra observation ID 735, the combined high-state observations, and the combined low-state observations are shown with red, blue, and black crosses respectively. The corresponding blackbody models in the energy range 0.3–8.0 keV are shown with red, blue, and black dotted lines. The yellow dashed line indicates photon energy of 0.3 keV. The error bars denote 68.3% uncertainty.
## Extended Data Table 1 | Observations of M81 ULS-1

| Date    | Telescope | Exposure Time | $\Delta \lambda$ |
|---------|-----------|---------------|------------------|
| 2010.4.13 | Keck     | 1000×3        | 5                |
| 2010.4.17 | Keck     | 1200×2        | 5                |
| 2015.4.08 | GTC      | 1800×3        | 7                |
| 2015.4.22 | Keck     | 2800×2        | 8                |
| 2015.5.07 | GTC      | 1800×3        | 7                |
| 2015.5.08 | GTC      | 1800×4        | 7                |

$\Delta \lambda$ indicates spectral resolution.
## Extended Data Table 2 | Properties of Hα⁺/Hα⁻ and Hα for M81 ULS-1

| HJD-2450000 | Hα⁺ |   | Hα⁻ |   | Hα  |   |
|-------------|-----|---|-----|---|-----|---|
|             | Center | FWHM | E.W. | Power | Center | FWHM | Power |
| 5299.83     | 5532.3 ± 1.5 (−0.17c) | 33 ± 4 | 41 ± 5 | 1.55 ± 0.20 | 6562.9 ± 0.2 | 10.8 ± 0.5 | 1.69 ± 0.09 |
| 5303.77     | 5543.1 ± 1.6 (−0.17c) | 33 ± 4 | 24 ± 3 | 0.94 ± 0.13 | 6562.8 ± 0.2 | 9.4 ± 0.3 | 1.30 ± 0.05 |
| 7121.47     | 5647.5 ± 2.3 (−0.15c) | 32 ± 6 | 21 ± 5 | 0.65 ± 0.15 | 6564.9 ± 0.3 | 6.7 ± 0.6 | 0.31 ± 0.04 |
| 7134.88     | 5683.0 ± 3.0 (−0.14c) | 34 ± 7 | 33 ± 9 | 1.07 ± 0.31 | 6564.4 ± 0.9 | 8.9 ± 2.1 | 0.86 ± 0.27 |
| 7150.42     | 5696.0 ± 3.1 (−0.14c) | 46 ± 8 | 16 ± 4 | 1.08 ± 0.24 | 6564.1 ± 0.1 | 7.6 ± 0.3 | 1.60 ± 0.09 |
| 7151.46     | 5695.2 ± 2.3 (−0.14c) | 29 ± 6 | 13 ± 3 | 0.57 ± 0.15 | 6564.4 ± 0.2 | 7.4 ± 0.5 | 0.79 ± 0.06 |
| 7121.47     | 7522.1 ± 2.7 (+0.14c) | 20 ± 6 | 27 ± 7 | 0.16 ± 0.05 |

The centre, FWHM and equivalent width are in units of angströms. The numbers in parentheses are velocities, in units of the speed of light (c). The power is in units of \(10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\). All of the error bars denote 68.3% uncertainty. The bottom row shows Hα⁺ emission; the other rows show Hα⁻ emission.
Extended Data Table 3 | Doppler boost factors for each observation of M81 ULS-1

| Date    | $\lambda(H_{\alpha}^- \text{ or } H_{\alpha}^+ ?)$ | $D$   | $z$    |
|---------|-----------------------------------------------|-------|--------|
| 20100413 | 5532.5                                        | 1.1862| -0.1570|
| 20100417 | 5543.1                                        | 1.1840| -0.1554|
| 20150408 | 5647.5                                        | 1.1621| -0.1395|
| 20150422 | 5683.0                                        | 1.1548| -0.1341|
| 20150507 | 5696.0                                        | 1.1522| -0.1321|
| 20150508 | 5695.2                                        | 1.1523| -0.1322|
| 20150408 | 7524.0                                        | 0.8722| 0.1465 |

The second column gives the wavelength of the blueshifted/redshifted $H_{\alpha}$ emission. $D$ is the Doppler boost factor; $z$ is the redshift.
**Extended Data Table 4 | Chandra observations of M81 ULS-1**

| ObsID   | Obs Date  | ExpT (ks) | $C_{\text{NET}}$ | $C_{\text{Soft}}$ | Count Rate (count ks$^{-1}$) | $kT_{bb}$ (eV) | $n_H$ (10$^{20}$ cm$^{-2}$) | Flux (ergs s$^{-1}$) (10$^{38}$) | $L_X$ (10$^{38}$ ergs s$^{-1}$) | $L_{bol}$ | $\chi^2$/dof | State |
|---------|-----------|-----------|------------------|------------------|-----------------------------|----------------|-----------------------------|-----------------------------|-----------------------------|----------|-------------|-------|
| acis390 | 2000 Mar 21 | 2.4 | 140 | 25 | 60.81±5.74 | 145±40.9 | 12.5±20.0 | 1.42e-13 | 2.3 | 6.7 | 1.390/4 | high |
| acis735 | 2000 May 07 | 50.7 | 3679 | 2141 | 67.16±1.19 | 78±1.6 | 9.5±1.0 | 1.99e-13 | 3.1 | 21.3 | 1.086/4 | high |
| acis5935 | 2005 May 26 | 11.1 | 11 | 2 | 1.06±0.43 | low |
| acis5936 | 2005 May 28 | 11.6 | 11 | 2 | 0.82±0.40 | low |
| acis5937 | 2005 Jun 01 | 12.2 | 22 | 6 | 1.63±0.46 | low |
| acis5938 | 2005 Jun 03 | 12.0 | 485 | 185 | 37.69±1.87 | 81±6.2 | 12.0±5.8 | 1.89e-13 | 3.0 | 25.6 | 2.041/17 | high |
| acis5939 | 2005 Jun 06 | 12.0 | 364 | 181 | 27.53±1.61 | 76±5.6 | 8.3±4.2 | 1.62e-13 | 2.6 | 17.7 | 0.857/13 | high |
| acis5940 | 2005 Jun 09 | 12.1 | 70 | 20 | 4.90±0.73 | low |
| acis5941 | 2005 Jun 11 | 12.0 | 429 | 187 | 32.16±1.74 | 91±5.8 | 6.5±4.0 | 1.74e-13 | 2.8 | 10.6 | 1.004/17 | high |
| acis5942 | 2005 Jun 15 | 12.1 | 405 | 206 | 30.30±1.68 | 70±5.4 | 14.1±5.1 | 1.68e-13 | 2.7 | 42.5 | 0.724/14 | high |
| acis5943 | 2005 Jun 18 | 12.2 | 525 | 187 | 41.30±1.94 | 91±5.4 | 8.8±3.8 | 2.10e-13 | 3.3 | 16.0 | 1.096/21 | high |
| acis5944 | 2005 Jun 21 | 12.0 | 356 | 85 | 28.71±1.64 | 96±9.8 | 20.6±8.6 | 1.16e-13 | 1.8 | 20.3 | 1.128/15 | high |
| acis5945 | 2005 Jun 24 | 11.7 | 415 | 220 | 32.04±1.75 | 65±4.4 | 19.8±5.3 | 1.69e-13 | 2.7 | 97.4 | 1.028/14 | high |
| acis5946 | 2005 Jun 26 | 12.2 | 287 | 167 | 20.75±1.40 | 70±7.1 | 10.6±5.9 | 1.29e-13 | 2.0 | 22.5 | 1.160/8 | high |
| acis5947 | 2005 Jun 29 | 10.8 | 40 | 29 | 2.81±0.62 | low |
| acis5948 | 2005 Jul 03 | 12.2 | 77 | 51 | 4.93±0.73 | low |
| acis5949 | 2005 Jul 06 | 12.2 | 54 | 33 | 3.36±0.62 | low |
| acis9805 | 2007 Dec 21 | 5.2 | 44 | 28 | 7.55±1.43 | low |
| acis9122 | 2008 Feb 01 | 10.0 | 55 | 18 | 5.40±0.87 | low |
| Total high | 149.3 | 7085 | 3384 | 37.85±2.53 | 84±1.3 | 8.2±0.1 | 1.98e-13 | 3.1 | 16.9 | 1.739/31 |
| Total low | 97.4 | 384 | 189 | 3.61±0.81 | 82±8.3 | 5.6±11.3 | 2.03e-14 | 0.3 | 1.4 | 1.069/12 |

Column 1 shows the observation identification number. Column 2 shows the observation date. Column 3 shows the on-time (exposure time, ExpT) without dead-time correction. Column 4 shows the net number of photon counts in the range 0.1 to 8.0 keV ($C_{\text{NET}}$). Column 5 shows counts in the supersoft band ($C_{\text{Soft}}$), 0.1–0.5 keV. Column 6 shows the count rate after vignetting correction. Column 7 shows the temperature for the blackbody fit to the spectrum ($kT_{bb}$) in the range 0.3 to 8.0 keV. Column 8 shows the neutral hydrogen column density ($n_H$). Column 9 shows the 0.3–8.0 keV flux for the blackbody fit to the spectrum. Column 10 shows the luminosity ($L_X$) at 0.3–8.0 keV. Column 11 shows the unabsorbed bolometric luminosity ($L_{bol}$). Column 12 shows the reduced $\chi^2$ and degree of freedom (dof) for the spectral fit. Column 13 shows whether the observations indicate a high-flux or a low-flux state (10 counts per kilosecond separate these two states).