Bright radio emission from an ultraluminous stellar–mass microquasar in M 31

Matthew J. Middleton, James C. A. Miller–Jones, Sera Markoff, Rob Fender, Martin Henze, Natasha Hurley–Walker, Anna M. M. Scaife, Timothy P. Roberts, Dominic Walton, John Carpenter, Jean–Pierre Macquart, Geoffrey C. Bower, Mark Gurwell, Wolfgang Pietsch, Frank Haberl, Jonathan Harris, Michael Daniel, Junayd Miah, Chris Done, John S. Morgan, Hugh Dickinson, Phil Charles, Vadim Burwitz, Massimo Della Valle, Michael Freyberg, Jochen Greiner, Margarita Hernanz, Dieter H. Hartmann, Despina Hatzidimitriou, Arno Riffeser, Gloria Sala, Stella Seitz, Pablo Reig, Arne Rau, Marina Orio, David Titterington & Keith Grainge

A subset of ultraluminous X-ray sources (those with luminosities of less than $10^{40}$ erg s$^{-1}$; ref. 1) are thought to be powered by the accretion of gas onto black holes with masses of $\sim 5-20 M_\odot$, probably by means of an accretion disk$^{2,3}$. The X-ray and radio emission are coupled in such Galactic sources; the radio emission originates in a relativistic jet thought to be launched from the innermost regions near the black hole$^{4,5}$, with the most powerful emission occurring when the rate of infalling matter approaches a theoretical maximum (the Eddington limit). Only four such maximal sources are known in the Milky Way$^2$, and the absorption of soft X-rays in the interstellar medium hinders the determination of the causal sequence of events that leads to the ejection of the jet. Here we report radio and X-ray observations of a bright new X-ray source in the nearby galaxy M 31, whose peak luminosity exceeded $10^{49}$ erg s$^{-1}$. The radio luminosity is extremely high and shows variability on a timescale of tens of minutes, arguing that the source is highly compact and powered by accretion close to the Eddington limit onto a black hole of stellar mass. Continued radio and X-ray monitoring of such sources should reveal the causal relationship between the accretion flow and the powerful jet emission.

XMM-Newton first detected XMUM J004243.6+412519 on 15 January 2012 (ref. 7) at an X-ray luminosity of $2 \times 10^{40}$ erg s$^{-1}$ (for a distance to M 31 of 0.78 Mpc; ref. 8), with an X-ray spectrum that could be fully described by a hard power-law, characteristic of sub-Eddington accretion (mass accretion rates $<70$% of the Eddington limit$^{9,10}$). The source then rose to $>10^{40}$ erg s$^{-1}$ in two subsequent detections, fulfilling the traditional definition of an ultraluminous X-ray source (ULX; although other definitions exist, the term ULX is numerical rather than physically motivated)$^{11}$ and significantly above the cutoff luminosity of the X-ray luminosity function of M 31 (ref. 12), which shows no sources more luminous than $2 \times 10^{38}$ erg s$^{-1}$.

At the peak luminosity of $(1.26 \pm 0.01) \times 10^{40}$ erg s$^{-1}$, the X-ray spectrum seemed similar to that of Galactic black-hole X-ray binaries (BHXBs) at mass accretion rates close to or above the Eddington limit$^{11,12}$. In such cases, the emission is dominated by an optically thick accretion disk$^2$ whose spectrum may appear broadened because the accretion process is no longer radiatively efficient$^{11}$. This can be accompanied by a second, weaker, thermal component at higher energies, possibly due to Compton up-scattering of disk photons in a wind or photosphere. These two components are also required to fit high-quality spectra of nearby ‘low-luminosity’ ULXs$^{13,14}$, implying that similar accretion processes are taking place. Although the intrinsic emission can potentially be amplified through geometrical beaming$^9$, this is thought to be important only for ULXs above $10^{40}$ erg s$^{-1}$.

After the X-ray outburst, the source was monitored by the Swift and Chandra missions for more than 8 weeks (see Fig. 1 and Supplementary Table 1), until the source was no longer observable because of the Sun angle. The X-ray luminosity decreased slightly to $\sim 10^{39}$ erg s$^{-1}$, with the spectrum evolving to be fully described by emission from a standard accretion disk$^2$ with a peak temperature characteristic of high-mass-accretion-rate Galactic BHXBs$^6$. Both the timescale for the X-ray spectral variations and the temperature of the disk component rule out an interpretation as a background active galaxy.

A subsequent period of X-ray monitoring showed the source to remain disk-dominated while decaying to a luminosity of $\sim 7 \times 10^{37}$ erg s$^{-1}$. The correlation of luminosity with disk temperature as $L \propto T^4$ is a well-established observational tracer of sub-Eddington accretion. We find that the best-fitting spectral parameters (see Supplementary Table 2) deviated strongly from this correlation when the source was brightest: the temperature decreased with luminosity (Supplementary Fig. 2). Such behaviour is well documented in ULXs$^{15}$, strengthening our identification of this object as a member of this class, albeit a low-luminosity one.

The X-ray detection of this nearby bright source motivated a series of radio observations by the Karl G. Jansky Very Large Array (VLA; see Supplementary Table 3), Very Long Baseline Array (VLBA) and Arcminute Microkelvin Imager Large Array (AMI-LA). The radio light curves are shown in Fig. 2 (observational details are provided in Supplementary Information). The source was initially detected by the VLA at a highly significant level ($>40\sigma$), with a 4–5e AMI-LA detection the following day. The spectral index (defined by $S_\nu \propto \nu^{-\alpha}$) measured by the VLA was slightly inverted, at $\alpha = 0.27 \pm 0.16$.

The AMI-LA monitoring demonstrated that the radio emission was variable on timescales of days, as confirmed by a detection of strongly

©2013 Macmillan Publishers Limited. All rights reserved

10 JANUARY 2013 | VOL 493 | NATURE | 187
instead observed to undergo flaring periods, associated with transitions
hole. At these high accretion rates, the radio emission from BHXRBs is
(dot–dashed blue line) and a second, weaker thermal component (dot–dashed red).
This size limit, together with the variability on a timescale of days,
in Fig. 2 constrains the size of the emitting region to be
XMMU J004243.6 | NATURE | VOL 493 | 10 JANUARY 2013
be powered by the bright accretion flow18. The radio variability from
combined Array for Research in Millimeter-wave Astronomy (CARMA).
reduced emission by the VLA (Fig. 2) and a non-detection by the Com-
source dims to
412519 demonstrates that the emission cannot be
10–5 shows clearly
105 shows clearly
reduced emission by the VLA (Fig. 2) and a non-detection by the Com-
source may be looking closer to the jet axis in
XMMU J004243.6+412519. This physical picture is supported by
both of which have reached similarly high radio luminosities and prob-
this source is therefore fully consistent with analogous behaviour, and
the radio emission is probably associated with shock acceleration of
This size limit, together with the variability on a timescale of days,
3 keV. If the short-timescale radio variability we observe is intrinsic (see
Supplementary Information), it could be an analogue of this behaviour,
we favour a more conservative mass estimate of
105 shows clearly
105 shows clearly
from hard to soft X-ray spectral states5. Indeed, scaling the radio and
X-ray flux from this source to be within our Galaxy would give fluxes
similar to soft, bright, radio-flaring BHXRBs such as GRS 1915+105 and
1.3
10–5 and other BHXRBs5. We can therefore make a secure identification of the compact object in
this source as a black hole of stellar mass (\(<17M_\odot\)).

BHXBs accreting at sub-Eddington rates produce powerful, per-
dependent radio jets; the radio and X-ray emission are strongly correlated
and are linked to black-hole mass through the ‘fundamental plane of
black hole activity’19,20. However, the thermal, disk-dominated X-ray
spectrum after the peak of the outburst implies accretion at a relatively
high fraction of the Eddington limit10 (3–100%). The fundamental
plane relation does not hold for sources accreting at such high mass
accretion rates and so cannot be used to constrain the mass of the black
hole. At these high accretion rates, the radio emission from BHXBs is
instead observed to undergo flaring periods, associated with transitions
from hard to soft X-ray spectral states5. Indeed, scaling the radio and
X-ray flux from this source to be within our Galaxy would give fluxes
similar to soft, bright, radio-flaring BHXRBs such as GRS 1915+105 and
Cygnus X-3 (ref. 21). The observed X-ray and radio emission of this source is therefore fully consistent with analogous behaviour, and
the radio emission is probably associated with shock acceleration of
particles within ejections moving away from the black hole22 with a
high Lorentz factor (\(\gamma \geq 2\); ref. 5).

The AMI-LA light curve (Fig. 2) suggests multiple ejection events,
although the observed inverted, optically thick, spectrum is at odds
with the optically thin emission expected from the later stages of an
expanding synchrotron-emitting plasma. Either the VLA observed the
early, self-absorbed stage of a flare or there is additional, free-free
absorbing material in the environment of the source.

A search for shorter-timescale fluctuations in the VLA data revealed
significant variability in the first epoch, on a characteristic timescale of
several minutes (Fig. 2). Regardless of whether we attribute this to
intrinsic variability or to scintillation (see Supplementary Information),
this timescale implies a source size of only ~5 AU (a few micro-
arcseconds at the distance of M 31), constraining the emitting region
to be highly compact.

There are clear similarities between the behaviour of XMMU
J004243.6+412519 and the few ‘super-Eddington’ Galactic BHXBs.
Of these, the canonical microquasar GRS 1915+105 is the only one
whose luminosity regularly exceeds 1039 erg s\(^{-1}\) and that would
sometimes appear as a ULX to an extragalactic observer23. Multiwavelength
studies of the disk–jet coupling in GRS 1915+105 (ref. 24) have
identified both ‘plateau’ states with steady jet emission at lower mass accre-
tion rates and ‘flaring’ states with rapid radio oscillations at accretion
rates around the Eddington limit, accompanied by an extremely soft
X-ray spectrum. The latter, minute-timescale22 radio flaring, has been
observed to occur immediately after a major radio flare, accompanied
by X-ray brightness changes that are dominated by variability above
3 keV. If the short-timescale radio variability we observe is intrinsic (see
Supplementary Information), it could be an analogue of this behaviour,
although we would not expect to detect the X-ray variability in our
observations because the flux above 3 keV is extremely low as a result of
the greater source distance. Although GRS 1915+105 shows clearly
analogous behaviour, when scaled to a similar distance our source is
approximately an order of magnitude more luminous in the radio band,
with a variability brightness temperature for the flares of ~7 10^{12} K
(see Supplementary Information). Such a discrepancy can readily be
explained by differences in the inclination angle of the jets to our
line of sight; GRS1915+105 is highly inclined and thus Doppler-
deboosted, whereas we may be looking closer to the jet axis in
XMMU J004243.6+412519. This physical picture is supported by
comparison with the Galactic BHXBs, Cygnus X-3 and V4641 Sgr,
both of which have reached similarly high radio luminosities and
probably have low angles to the line of sight26,27. Our source seems
particularly well matched to V4641 Sgr, which reached ~0.5 Jy in its 1999
outburst23, and has also shown similarly high brightness temperatures.

The coupled radio and X-ray behaviour in this source is fully
consistent with a picture of a BHXB rising above the Eddington limit in
outburst then dimming to a bright sub-Eddington state, with radio
flaring analogous to that seen in GRS 1915+105 and other BHXBs5.
We can therefore make a secure identification of the compact object in
this source as a black hole of stellar mass (<70M_\odot). Because the source remains in a disk-dominated state down to
~7 10^{37} erg s\(^{-1}\), and the lower limit for such a state is ~3% of the
Eddington limit10, this constrains the mass of the black hole to <17M_\odot.
However, because the joint radio and X-ray behaviour implies
Eddington-rate accretion at the peak luminosity of ~1.3 10^{39} erg s\(^{-1}\),
we favour a more conservative mass estimate of ~10M_\odot.

We can also constrain the nature of the companion star from archival
optical data29. The field does not contain a source within 3 arcsec (where
the positional accuracy from the VLBA observations is extremely high;
larger population of low-luminosity ULXs (a substantial component onto a black hole of stellar mass in XMMU J004243.6
we confidently extend the identification of Eddington-rate accretion this regime will allow us to address outstanding cosmological problems
understanding of Eddington accretion and associated phenomena.
Jet coupling studies and in doing so will significantly expand our un-
galaxies, using sensitive radio telescopes, will permit detailed disk–
low-mass companions whose outbursts reach the Eddington lumin-
is roughly consistent with the observed rate of Galactic BHXRBs with
unbeamed. The X-ray monitoring cadence for M 31 has yielded two
similarly relativistically beamed event out to 4 Mpc, or 0.5 Mpc if
events in future. The sensitivity of the VLA would allow us to detect a
larger population, we can consider the possibility of detecting similar
outflows from quasars redistributed matter and energy in
the early Universe.
Assuming that the properties of this source are representative of the
larger population, we can consider the possibility of detecting similar
events in future. The sensitivity of the VLA would allow us to detect a
similarly relativistically beamed event out to 4 Mpc, or 0.5 Mpc if
unbeamed. The X-ray monitoring cadence for M 31 has yielded two
candidates in 10 years; although the monitoring was not constant, this
is roughly consistent with the observed rate of Galactic BHXRBs with
low-mass companions whose outbursts reach the Eddington lumin-
sity. It is therefore a realistic prospect (see Supplementary Informa-
tion) that future observations of transient ULX systems in nearby
galaxies, using sensitive radio telescopes, will permit detailed disk–
jet coupling studies and in doing so will significantly expand our un-
derstanding of Eddington accretion and associated phenomena.

Received 10 May; accepted 22 October 2012.
Published online 12 December 2012.

1. Walton, D., Roberts, T., Mateos, S. & Heard, V. 2XMM ultraluminous X-ray source candidates in nearby galaxies. Mon. Not. R. Astron. Soc. 416, 1844–1861 (2011).
2. Shakura, N. & Sunyaev, R. Black holes in binary systems. Observational appearance. *Astron. Astrophys.* **24**, 337–355 (1973).
3. Middleton, M., Sutton, A., Roberts, T., Jackson, F. & Done, C. The missing link: a low-mass X-ray binary in M 31 seen as an ultraluminous X-ray source. *Mon. Not. R. Astron. Soc.* **420**, 2969–2977 (2012).
4. Mirabel, I. & Rodriguez, L. A superruminal source in the Galaxy. *Nature* **371**, 46–48 (1994).
5. Fender, R., Belloni, T. & Gallo, E. Towards a unified model for black hole X-ray binary jets. *Mon. Not. R. Astron. Soc.* **355**, 1105–1118 (2004).
6. Grimm, H., Gilfanov, M. & Sunyaev, R. The Milky Way in X-rays for an outside observer. Log(N)–log(S) and luminosity function of X-ray binaries from RXTE/ASM data. *Astron. Astrophys.* **391**, 923–944 (2002).
7. Henze, M. et al. XMMU J004243.6–412519—a new X-ray transient in M 31 seen with XMM-Newton. *Astronomer’s Telegram* #3890, http://www.astronomerstelegram.org/?read=3890 (2012).
8. Monachesi, A. et al. The deepest Hubble Space Telescope color–magnitude diagram of M32. Evidence for intermediate-age populations. *Astrophys. J.* **727**, 55 (2011).
9. Remillard, R. & McClintock, J. X-ray properties of black-hole binaries. *Annu. Rev. Astron. Astrophys.* **44**, 49–92 (2006).
10. Dunn, R., Fender, R., Körding, E., Belloni, T. & Cabanac, C. A global spectral study of black hole X-ray binaries. *Mon. Not. R. Astron. Soc.* **403**, 61–82 (2010).
11. Feng, H. & Soria, R. Ultraluminous X-ray sources in the Chandra and XMM-Newton era. *N. Astron. Rev.* **55**, 166–183 (2011).
12. Kong, A., Di Stefano, R., García, M. & Greiner, J. Chandra studies of the X-ray point source luminosity functions of M 31. *Astrophys. J.* **585**, 298–304 (2003).
13. Ueda, Y., Yamaoka, K. & Remillard, R. GRS 1915+105 in ’soft state’: nature of accretion disk wind and origin of X-ray emission. *Astrophys. J.* **695**, 888–899 (2009).
14. Abramowicz, M., Czerny, B., Lasota, J.-P. & Suszczewicz, E. Slim accretion disks. *Astrophys. J.** **332**, 646–658 (1988).
15. Middleton, M., Sutton, A. & Roberts, T. X-ray spectral evolution in the ultraluminous X-ray source M3 X-3. *Mon. Not. R. Astron. Soc.* **417**, 464–471 (2011).
16. King, A. Masses, beaming and Eddington ratios in ultraluminous X-ray sources. *Mon. Not. R. Astron. Soc.* **393**, L41–L44 (2009).
17. Feng, H. & Kaaret, P. Spectral states and evolution of ultraluminous X-ray sources. *Astrophys. J.* **696**, 1712–1726 (2009).
18. Cseh, D. et al. Black hole powered nebulae and a case study of the ultraluminous X-ray source IC 342 X-1. *Astrophys. J.* **749**, 17 (2012).
19. Merloni, A., Heinz, S. & di Matteo, T. A fundamental plane of black hole activity. *Mon. Not. R. Astron. Soc.* **345**, 1057–1067 (2003).
20. Plotkin, R., Markoff, S., Kelly, B., Körding, E. & Anderson, S. Using the fundamental plane of black hole activity to distinguish X-ray processes from weakly accreting black holes. *Mon. Not. R. Astron. Soc.* **419**, 267–286 (2012).
21. Gallo, E., Fender, R. & Pooley, G. A universal radio-X-ray correlation in low/hard state black hole binaries. *Mon. Not. R. Astron. Soc.* **344**, 60–72 (2003).
22. Kaiser, C., Sunyaev, R. & Spruit, H. Internal shock model for microquasars. *Astron. Astrophys.* **356**, 975–988 (2000).
23. King, A. The brightest black holes. *Mon. Not. R. Astron. Soc.* **335**, L13–L16 (2002).
24. Fender, R. & Belloni, T. GRS 1915+105 and the disc–jet coupling in accreting black hole systems. *Annu. Rev. Astron. Astrophys.* **42**, 317–364 (2004).
25. Pooley, G. & Fender, R. The variable radio emission from GRS 1915+105. *Mon. Not. R. Astron. Soc.* **292**, 925–933 (1997).
26. Corbel, S. et al. A giant radio flare from Cygnus X-3 with associated γ-ray emission. *Mon. Not. R. Astron. Soc.* **421**, 2947–2955 (2012).
27. Orosz, J. A. et al. A black hole in the superluminal source SAX J1819.3–2525 (V4641 Sgr). *Astrophys. J.* **555**, 499–503 (2001).
28. Hjellming, R. M. et al. Light curves and radio structure of the 1999 September transient event in V4641 Sagittarii (~ XTE J1819–254–SAX J1819.3–2525). *Astrophys. J.* **544**, 977–992 (2000).
29. Vilarelld, F., Ribas, I. & Jordi, C. Eclipsing binaries suitable for distance determination in the Andromeda galaxy. *Astron. Astrophys.* **459**, 321–331 (2006).
30. Soria, R. et al. The birth of an ultraluminous X-ray source in M83. *Astrophys. J.* **750**, 152 (2012).

**Supplementary Information** is available in the online version of the paper.

**Acknowledgements** We thank C. Trott and R. Soria for discussions, and C. Gough for making his code available. This work was supported by a Science and Technology Facilities Council (STFC) standard grant (M.J.M.), Netherlands Organization for Scientific Research Vidi Fellowship (S.M.), European Research Council partial funding (R.F.) and grant number BMWI/DLR, FKZ 50 OR 1010 (M. Henze). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. We thank the staff of the Mullard Radio Astronomy Observatory for their assistance in the commissioning and operation of AML, which is supported by Cambridge University and the STFC. This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. This research has also made use of data obtained from NASA’s Swift and Chandra satellites.

**Author Contributions** M.J.M. wrote the manuscript with comments from all authors. J.C.A.M.-J. designed and analysed the VLA and VLBA observations. The remaining authors either assisted with various aspects of the science case or are contributing members of the M 31 group. J.C., G.C.B. and M.G. provided support and contributions directly funded by ESA Member States and NASA. This research has making his code available. This work was supported by a Science and Technology Facilities Council (STFC) standard grant (M.J.M.), Netherlands Organization for Scientific Research Vidi Fellowship (S.M.), European Research Council partial funding (R.F.) and grant number BMWI/DLR, FKZ 50 OR 1010 (M. Henze). The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. We thank the staff of the Mullard Radio Astronomy Observatory for their assistance in the commissioning and operation of AML, which is supported by Cambridge University and the STFC. This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. This research has also made use of data obtained from NASA’s Swift and Chandra satellites.

**Author Contributions** M.J.M. wrote the manuscript with comments from all authors. J.C.A.M.-J. designed and analysed the VLA and VLBA observations. N.H.-W. and A.M.M.S. analysed the AMI-LA observations; J.-P.M. and J.C.A.M.-J. conducted the scintillation analysis. S.M., R.F. and M. Henze made significant contributions to the overall science case and manuscript. J.C., G.C.B. and M.G. provided support and analysis for the CARMA observations. The remaining authors either assisted with various aspects of the science case or are contributing members of the M 31 group.

**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 M.J.M.

(m.j.middleton@durham.ac.uk).