A ULX associated with a cloud collision in M 99

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\section*{ABSTRACT}
The Sc galaxy M 99 in the Virgo cluster has been strongly affected by tidal interactions and recent close encounters, responsible for an asymmetric spiral pattern and a high star formation rate. Our XMM-\textit{Newton} study shows that the inner disk is dominated by hot plasma at \(kT \approx 0.30\) keV, with a total X-ray luminosity \(\approx 10^{41}\) erg s\(^{-1}\) in the 0.3–12 keV band. At the outskirts of the galaxy, away from the main star-forming regions, there is an ultraluminous X-ray source (ULX) with an X-ray luminosity \(\approx 2 \times 10^{40}\) erg s\(^{-1}\) and a hard spectrum well fitted by a power law of photon index \(\Gamma \approx 1.7\). This source is close to the location where a massive H\(_1\) cloud appears to be falling onto the M 99 disk at a relative speed \(> 100\) km s\(^{-1}\). We suggest that there may be a direct physical link between fast cloud collisions and the formation of bright ULXs, which may be powered by accreting black holes with masses \(\sim 100 M_\odot\). External collisions may trigger large-scale dynamical collapses of protoclusters, leading to the formation of very massive (\(\gtrsim 200 M_\odot\)) stellar progenitors; we argue that such stars may later collapse into massive black holes if their metal abundance is sufficiently low.

\section*{Key words:} X-rays: galaxies — radio lines: galaxies — galaxies: individual (NGC 4254) — X-rays: binaries — black hole physics

\section*{1 INTRODUCTION}
The Sc galaxy M 99 (NGC 4254), located a distance of about 17 Mpc (Tully 1988), is the brightest spiral in the Virgo Cluster (\(M_B = -20.8\)), with a gas mass \(\approx 5 \times 10^9 M_\odot\) and a kinematic mass \(\approx 10^{11} M_\odot\) (Vollmer, Huchtmeier & van Driel 2005; Phookun, Vogel & Mundi 1993). It shows a peculiar spiral structure\(^1\), with one arm less tightly wound and much brighter than the other two. Another unusual feature of M 99 is the presence of a string of H\(_1\) “blobs” to the south and west of the stellar disk, and a low-surface-density H\(_1\) gas tail to the north-west; the total gas mass in those extra-disc structures is \(\approx 2 \times 10^9 M_\odot\) (Phookun et al. 1993). It is likely that there is a physical connection between the unusual spiral structure and the disturbed gas distribution. In one scenario (Vollmer et al. 2005), the spiral structure was affected by a close encounter with another Virgo Cluster galaxy \(\approx 280\) Myr ago; the surrounding H\(_1\) clouds are due to ongoing, face-on ram-pressure stripping, and are mostly moving away from the galaxy. An alternative scenario (Phookun et al. 1993) suggests that the H\(_1\) clouds and tail are tidal debris of an entity that was at least partly disrupted in a close encounter with M 99; that debris is now falling and merging with the galactic disk. Simulations show (Bekki, Koribalski & Kilborn 2005) that tidal debris could also have been stripped from the outer disk of M 99 itself, by the Virgo Cluster potential as the galaxy crossed the central region of the cluster; part of the stripped gas would later fall back onto the same galaxy. In this scenario, heavy gas infall onto the M 99 disk would be responsible for the lopsided spiral structure (Phookun et al. 1993; Bournaud et al. 2005).

Intriguingly, a large H\(_1\) cloud (VIRGOHI 21), with a gas mass \(\approx 2 \times 10^8 M_\odot\) but without any associated stars, located \(\approx 120\) kpc to the north-west of M 99, has recently been discovered (Davies et al. 2004). One interpretation (Minchin et al. 2005, 2006) is that it is an old, bound “dark galaxy” that has never formed stars because of its low hydrogen surface density. In this scenario, VIRGOHI 21 would be dark-matter dominated, with a kinematic mass \(\approx 10^{11} M_\odot\); if so, it would likely be the same galaxy responsible for the suspected close encounter with M 99 and possible tidal gas stripping. Alternatively, VIRGOHI 21 could itself be simply another, larger piece of tidal debris (without a dark matter halo), stripped from the outer H\(_1\) disk of M 99 by the Virgo Cluster poten-
Gas-rich galaxies with recent tidal interactions generally show particularly active star formation, and M 99 is no exception, with a rate $\approx 10 M_\odot$ yr$^{-1}$ inferred from its Ho luminosity (Kennicutt et al. 2003), or $\approx 10$–20$M_\odot$ yr$^{-1}$ from an optical/near-IR photometric study (Gonzales & Graham 1996). As a comparison, this is twice as high as in M 82 (Kennicutt et al. 2003), and three times the current total rate in our Local Group (Hopkins, Irwin & Connolly 2001). Another phenomenon often associated with tidal interactions and high star formation is the presence of ultraluminous X-ray sources (ULXs) with apparent isotropic X-ray luminosities $\sim 10^{39}$–$10^{40}$ erg s$^{-1}$ (for recent reviews, see King 2006; Fabbiano & White 2006; Colbert & Miller 2004). They are interpreted as accreting binary systems, an order of magnitude more luminous than the Eddington limit for typical stellar-mass black holes (BHs) in the Local Group. Two ULXs were detected by ROSAT/HRI within the $D_{25}$ region of M 99, on 1997 June 30 (Colbert & Ptak 2002; Liu & Bregman 2005). In this paper, we use XMM-Newton to have a better understanding of the X-ray properties of M 99, and in particular of its brightest ULX. We compare radio and X-ray information to investigate the possible connection between ULX formation, star formation and collisional events in this galaxy. Finally, we outline a possible general scenario for the nature of ULXs, to be tested by future studies.

2 XMM-NEWTON STUDY

2.1 Data analysis

M 99 was observed with all instruments on-board XMM-Newton on 2003 June 26 (Revolution 651; observation ID 0147610101); the thin filter, full-frame mode was used for the European Photon Imaging Camera (EPIC) detectors. We processed the Observation Data Files with standard tasks in the Science Analysis System (SAS), version 6.5.0. Unfortunately, most of the X-ray observation was disrupted by strong solar flares: after inspecting the background lightcurves, we retained a good live-time interval of 17.0 ks for the pn and 20.5 ks for the MOSs, out of the total 51-ks exposure. In addition, Optical Monitor (OM) images were taken in the $UVW1$, $UVM2$ and $UVW2$ filters, with exposure times of 3.0, 6.0 and 17.8 ks, respectively. We filtered the EPIC event files, selecting only the best-calibrated events (pattern $\leq 12$ for the MOSs, pattern $\leq 4$ for pn), and rejecting flagged events.

We used the Chandra Interactive Analysis of Observations (CIAO) task wavdetect to identify discrete sources in the combined EPIC image, in different energy bands$^3$. We selected a source extraction region of radius 25$''$ around the brightest point-like source (the only one of the two ROSAT ULXs that is seen again by XMM-Newton, see Section 2.2). We built response functions with the SAS task rmfgen, and auxiliary response functions with arfgen, for pn and the two MOSs. We then coadded the three spectra, with the method described in Page, Davis & Salvi (2003), in order to increase the signal-to-noise ratio. Similarly, we obtained combined EPIC spectra of the X-ray emission from the whole galaxy (excluding the ULX) and from the star-forming region within 1$'$ from the galactic centre. Finally, we fitted the background-subtracted spectra with standard models in XSPEC version 11.3.1 (Arnaud 1996).

2.2 Discrete X-ray sources and unresolved emission

The X-ray emission from M 99 is dominated by hot gas, as expected from its high star formation rate (SFR). The modest spatial resolution of XMM-Newton and the strength of the diffuse component make it difficult to resolve individual point-like sources (essentially, high-mass X-ray binaries and young supernova remnants), especially in the inner arcmin (4.8 kpc at the assumed distance), where most of the X-ray emission is concentrated (Figure 1). A few point-like sources are instead detected (Table 1) from the combined EPIC image in the 1.5–12 keV band, where the diffuse emission is negligible$^4$. The location of the detected sources is shown in Figure 2, overplotted on a true-colour OM image. Of the two ULXs found by ROSAT inside the $D_{25}$ ellipse in 1997, one (X-1 in the ROSAT catalogue, Liu & Bregman 2005) is no longer detected: hence, we estimate that it must now be fainter than $\approx 5 \times 10^{38}$ erg s$^{-1}$ in the 0.3–12 keV band; its luminosity is $\approx 6 \times 10^{39}$ erg s$^{-1}$ in 1997, extrapolated to the same band. The other ULX (IXO 46 in Colbert & Ptak 2002, or X-2 in Liu & Bregman 2005) is instead recovered, with a 0.3–12 keV luminosity $\approx 2 \times 10^{40}$ erg s$^{-1}$ (detailed analysis of this source in Section 2.4).

We estimate that the total unabsorbed X-ray luminosity (not including the bright ULX) from inside the $D_{25}$ ellipse is $\approx (1.2 \pm 0.2) \times 10^{41}$ erg s$^{-1}$ in the 0.3–12 keV band, of which only $\approx 10^{40}$ erg s$^{-1}$ in the 2–12 keV band. About 70% of the X-ray emission comes from within a projected radius of $1' \approx 4.8$ kpc. The unresolved emission is dominated by thermal plasma at a temperature $\lesssim 30$ keV; a two-temperature thermal-plasma fit (vapec in XSPEC) gives temperatures $kT_1 = (50 \pm 5)$ eV and $kT_2 = (0.30 \pm 0.01)$ keV (Figure 3). Gas temperatures $\lesssim 0.3$ keV are typical of disk emission in normal spirals, and are also one of the plasma components in starburst galaxies. We do not detect any additional thermal-plasma component at $\approx 0.7$–0.8 keV, which is instead characteristic of starbursts (e.g., Ott, Walter & Brinks 2005; Jenkins et al. 2005; Summers et al. 2003, 2004). The diffuse, soft X-ray emission, which traces recent star formation, appears to be uniformly distributed over the inner disk, and only weakly peaked in the nuclear region.

An additional, harder component of the unresolved emission is well fitted by a power-law of photon index $\Gamma = 1.70 \pm 0.25$. As is generally the case for star-forming galaxies, the power-law component can be interpreted as emission from unresolved X-ray binaries. The contribution of the discrete sources (both resolved and unresolved, but not including the ULX) to the total emitted luminosity in

$^2$ See http://www.xmm.ac.uk/onlines/uhb/XMM_UHB/node66.html for a plot of the OM filter throughput curves.

$^3$ A comparison between the source-finding algorithms in CIAO and SAS can be found in Valtchanov, Pierre & Gastaud (2001).

$^4$ The same five sources listed in Table 1 are also found when we use the SAS source-finding routine emldetect.
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Table 1. Point-like X-ray sources detected at > 3-sigma significance in the 0.3–12 keV band inside the D25 ellipse of M99. Fluxes and luminosities are isotropic, emitted values, assuming a power-law spectrum with \( \Gamma = 1.7 \) and a line-of-sight Galactic column density \( N_{H,\text{Gal}} = 2.7 \times 10^{20} \) cm\(^{-2} \).

| No. | R.A.(2000) | Dec.(2000) | \( f_{1.5-12} \) \((10^{-14}\ erg\ \text{cm}^{-2}\ \text{s}^{-1})\) | \( f_{0.3-12} \) \((10^{-14}\ erg\ \text{cm}^{-2}\ \text{s}^{-1})\) | \( L_{0.3-12} \) \((10^{39}\ erg\ \text{s}^{-1})\) |
|-----|------------|------------|------------------|------------------|------------------|
| 01  | 12 18 45.58| 14 26 43.1 | 1.71 ± 0.35      | 2.46 ± 0.50      | 0.85 ± 0.20      |
| 02  | 12 18 51.13| 14 26 30.4 | 2.09 ± 0.38      | 3.01 ± 0.55      | 1.0 ± 0.2        |
| 03  | 12 18 51.36| 14 24 24.5 | 3.02 ± 0.51      | 4.35 ± 0.73      | 1.5 ± 0.3        |
| 04  | 12 18 52.61| 14 25 47.8 | 2.44 ± 0.38      | 3.52 ± 0.55      | 1.2 ± 0.2        |
| 05  | 12 18 56.15| 14 24 18.0 | 39.5^{+28}_{-12} | 56.1^{+3.4}_{-1.7} | 19.4^{+1.2}_{-0.6} |

Table 2. Best-fitting parameters to the combined XMM-Newton/EPIC spectrum of the inner-disk emission; the source region is a circle of radius 1\('\). The XSPEC model is \( \text{tbabs}_{\text{Gal}} \times \text{tbabs} \times (\text{powerlaw} + \text{vapec} + \text{vapec}) \). The quoted errors are the 90% confidence limit and \( N_{H,\text{Gal}} = 2.7 \times 10^{20} \) cm\(^{-2} \) (Dickey & Lockman 1990). \( K_1 \) and \( K_2 \) are the normalisation constants of the two \text{vapec} components; \( f_0^{\text{obs}} \) is the observed flux; \( f_0^{\text{em}} \) the unabsorbed flux; \( L_0.3-12 \) the relative contribution of the point-like accreting sources (resolved and unresolved) to the total X-ray emission, clearly dominated here by hot thermal plasma.

| Parameter | Value |
|-----------|-------|
| \( N_H \) \((10^{20} \text{ cm}^{-2})\) | 18.1^{+6.4}_{-1.3} |
| \( \Gamma \) | 1.70^{+0.24}_{-0.23} |
| \( K_{po} \) \((10^{-5})\) | 3.3^{+1.0}_{-1.2} |
| \( kT_1 \) \((\text{keV})\) | 0.050^{+0.05}_{-0.05} |
| \( K_1 \) \((10^{-3})\) | 350^{+500}_{-110} |
| \( kT_2 \) \((\text{keV})\) | 0.30^{+0.01}_{-0.02} |
| \( K_2 \) \((10^{-3})\) | 1.5^{+1.1}_{-0.2} |
| \( \langle Z/Z_\odot \rangle \) | 0.13^{+0.12}_{-0.06} |
| \( \chi^2 \) | 0.96(81.0/84) |
| \( f_0^{\text{obs}} \) \((10^{-12} \text{ CGS})\) | 0.39^{+0.02}_{-0.06} |
| \( f_0^{\text{em}} \) \((10^{-12} \text{ CGS})\) | 2.5^{+2.4}_{-1.5} |
| \( L_0.3-12 \) \((10^{39} \text{ erg s}^{-1})\) | 8.6^{+8.3}_{-5.2} |
| \( (L_{po}/L)_{0.3-12} \) | \( \approx 0.10 \) |

Figure 2. True-colour UV image from XMM-Newton/OM; red corresponds to the UVW1 filter, green to the UVM2 filter, and blue to the UVW2 filter. Point-like X-ray sources detected with XMM-Newton/EPIC are marked with green circles, of radius 1\('\). The peak of the X-ray emission in the nuclear region is indicated with a red circle, of radius 3\(')\).

2.3 Nuclear morphology: an old conundrum

The nucleus itself is not unequivocally resolved as a point source. We do clearly detect X-ray emission in the hard band at the nuclear position (Figure 1, middle panel), for an estimated emitted luminosity \( \approx 10^{39} \text{ erg s}^{-1} \) extrapolated to the 0.3–12 keV band. However, because of the low number of counts and low spatial resolution, we cannot tell whether it is the true nuclear source, or instead a number of unresolved X-ray binaries in the region where star formation is more active.

On an historical note, the nature of the nuclear source in M99 was the subject of intense investigations by Carl Lampland at the Lowell Observatory, many decades ago (Lampland 1921). Lampland noted that the peak of the optical emission in his photographic plates (which have peak sensitivity at \( \approx 4200\lambda \), in the standard B band) appeared sometimes shifted from the position corresponding (as we know today) to the true galactic nucleus, to another point located \( \approx 2\) to the southeast. This variability was re-examined and confirmed by Walker (1967), who found that the off-nuclear source was brighter in 10 of the 30 Lowell plates taken between 1921 and 1948, with changes occurring sometimes on a timescale of a few days. Spectroscopic observations (Walker 1967) also suggested that the true optical nucleus is redder, corresponding to a stellar type G0–G2, while the off-nuclear source appears much bluer.

We can now shed further light on the nuclear morphology. An HST/WFPC2 image in the F606W filter (Figure
The true explanation of this effect, if real, remains a mystery. The brightness of a nuclear BH would also be very peculiar. Stars are clearly unsatisfactory explanations; variations in days apart. Repeated supernovae or variability of individual sources in the same field have a width of 0′.10 ± 0′.01. An approximate conversion to standard colours gives an absolute magnitude $M_V \approx -13.5$ mag. Within 200 pc from the nucleus, there are a few, fainter, unresolved stellar clusters with typical absolute magnitudes $M_V \approx -11$ mag. The secondary optical peak described by Lampland (1921) and Walker (1967) corresponds to the stellar complex labelled as A in Figure 4 (unresolved from ground-based telescopes), and sometimes (at least in plates with worse seeing) to the unresolved blend of A and B. When we compare the HST image with an XMM-Newton/OM image of the same field, in the near-UV (UVW2 filter, with an effective wavelength of 2120 Å), we note that the true nucleus is undetected: the brightest UV sources in the nuclear region are the young stellar complexes labelled as A, B and C (Figure 4, right panel). The optical nucleus remains undetected even in the UVW1 filter (effective wavelength of 2910 Å). Unfortunately, the XMM-Newton/EPIC image does not provide enough information to determine whether the X-ray emission peaks at the true optical nucleus or at any of those three UV-bright sources nearby. It is plausible that the true nucleus and source A would appear of comparable brightness in the standard $U$ band. The nuclear cluster is the brighter source in the $B$ band, as evident from the archival images in the NASA/IPAC Extragalactic Database (NED). Of course, this does not explain how the peak brightness could be perceived to shift between the two sources several times over a few decades, in plates with the same density, taken a few days apart. Repeated supernovae or variability of individual stars are clearly unsatisfactory explanations; variations in the brightness of a nuclear BH would also be very peculiar. The true explanation of this effect, if real, remains a mystery for now.

4. Left panel) is dominated by a bright nuclear star cluster (a nuclear structure typical of late-type spiral galaxies), located at the dynamical centre, as can be inferred from the morphology of the dust filaments. The cluster is spatially resolved in the HST image, with a full width half maximum of $0′.15 \pm 0′.02$ corresponding to $(12 \pm 2)$ pc; point sources in the same field have a width of $0′.10 \pm 0′.01$. An approximate conversion to standard colours gives an absolute magnitude $M_V \approx -13.5$ mag. Within 200 pc from the nucleus, there are a few, fainter, unresolved stellar clusters with typical absolute magnitudes $M_V \approx -11$ mag. The secondary optical peak described by Lampland (1921) and Walker (1967) corresponds to the stellar complex labelled as A in Figure 4 (unresolved from ground-based telescopes), and sometimes (at least in plates with worse seeing) to the unresolved blend of A and B. When we compare the HST image with an XMM-Newton/OM image of the same field, in the near-UV (UVW2 filter, with an effective wavelength of 2120 Å), we note that the true nucleus is undetected: the brightest UV sources in the nuclear region are the young stellar complexes labelled as A, B and C (Figure 4, right panel). The optical nucleus remains undetected even in the UVW1 filter (effective wavelength of 2910 Å). Unfortunately, the XMM-Newton/EPIC image does not provide enough information to determine whether the X-ray emission peaks at the true optical nucleus or at any of those three UV-bright sources nearby. It is plausible that the true nucleus and source A would appear of comparable brightness in the standard $U$ band. The nuclear cluster is the brighter source in the $B$ band, as evident from the archival images in the NASA/IPAC Extragalactic Database (NED). Of course, this does not explain how the peak brightness could be perceived to shift between the two sources several times over a few decades, in plates with the same density, taken a few days apart. Repeated supernovae or variability of individual stars are clearly unsatisfactory explanations; variations in the brightness of a nuclear BH would also be very peculiar. The true explanation of this effect, if real, remains a mystery for now.

5 http://nedwww.ipac.caltech.edu/
half of the ULX flux; however, that background source was clearly stronger than the ULX in the Einstein image. We estimate that at the time of the Einstein observations (1980 June 25), the ULX must have been at least a factor of 5 fainter than in 1997 and 2003.

We estimate that the XMM-Newton/EPIC astrometry is accurate to $\approx 1.5''$. There are no other point-like X-ray sources in the field that can allow a better registration with optical positions. We searched for optical counterparts within the X-ray error circle in the XMM-Newton/OM images and in several optical images from public archives but found none. The bright optical source suggested as a possible counterpart by Colbert & Ptak (2002), based on the ROSAT/HRI position, is now clearly ruled out (Figure 1, right panel). Its brightness and colours are consistent with a G0 foreground star (Kharchenko 2001). We took optical spectra of this source with the LRIS spectrograph on the Keck telescope, confirming the spectral identification and verifying that its radial velocity is consistent with a foreground star, ruling out the possibility that it belongs to M99. Using the best high-resolution optical images available in public archives (in particular, a 30-s VLT/FORS1 observation in the Bessel-R band; a 720-s B-band image from the 2.1-m telescope at Kitt Peak National Observatory; a 200-s B-band image from the 2.5-m Isaac Newton Telescope at La Palma), we conclude that there are no optical counterparts brighter than $M_B \approx -9.5$ mag and $M_R \approx -9$ mag. This is not a very stringent limit, and does not even rule out an old globular cluster. None the less, we can confidently say that the ULX is right at the outer edge of the stellar disk (the limit beyond which the gas density is too low to collapse and form stars spontaneously), and that there are no super star-clusters or massive OB associations at that position or within $\approx 800$ pc.

![Figure 4. Morphology of the nuclear region in the optical and near-UV. Left panel: HST/WFPC2 image in the F606W filter; right panel: the same region, seen by XMM-Newton/OM in the UVW2 filter. At the dynamical center, an old nuclear star cluster dominates the optical image but is undetected in the near UV. The labels identify smaller, younger clusters of OB stars, and are given simply to facilitate a comparison between the two images.](image)

### Table 3. Best-fitting parameters to the combined XMM-Newton/EPIC spectrum of the ULX. The XSPEC model is $tbabs_{\text{Gal}} \times tbabs \times po$. The quoted errors are the 90% confidence limit and $N_{\text{H,Gal}} = 2.7 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990).

| Parameter     | Value       |
|---------------|-------------|
| $N_{\text{H}}$ (10$^{20}$ cm$^{-2}$) | 23.3$^{+3.8}_{-3.4}$ |
| $\Gamma$   | 1.67$^{+0.10}_{-0.10}$ |
| $K_p$ (10$^{-5}$) | 7.5$^{+0.9}_{-0.8}$ |
| $\chi^2_0$ | 0.89(86.0/97) |
| $f_{0.3-12}^{\text{obs}}$ (10$^{-13}$ CGS) | 4.4$^{+0.2}_{-0.3}$ |
| $f_{0.3-12}^{\text{mod}}$ (10$^{-13}$ CGS) | 5.6$^{+0.4}_{-0.2}$ |
| $L_{0.3-12}$ (10$^{40}$ erg s$^{-1}$) | 1.9$^{+0.2}_{-0.1}$ |

### 3 RADIO STUDY: A COLLIDING CLOUD?

If the optical data offer no clue on the nature of the ULX, the radio data may instead suggest a complex, intriguing story. H I 21-cm line observations of M 99 were carried out by Phookun et al. (1993), using the C and D arrays (exposure times of 8 hr and 4 hr, respectively) of the Very Large Array$^6$ (VLA). The size of the synthesized beam was 23''03 x 23''56. See Phookun et al. (1993) for details of the observations and data analysis. As expected, the H I disk is $\approx 40\%$ larger than the stellar disk, and extends slightly beyond the location of the ULX (Figure 6). The total H I flux from the galaxy corresponds to a gas mass $\approx 5 \times 10^8 M_\odot$ (Vollmer et al. 2005).

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$^6$ The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.
Figure 5. Coadded XMM-Newton/EPIC spectrum and best-fit residuals of the ULX spectrum, fitted with a power law of index $\Gamma = 1.7 \pm 0.1$. See Table 3 for the best-fitting parameters.

Phookun et al. 1993), using a standard conversion between H I flux and mass (e.g., Rohlfs & Wilson 2006).

Interestingly, the ULX is located close to where a large H I spur or cloud apparently joins the gas disk (Figure 6). The gas mass of this cloud is $\approx 10^7 M_\odot$, considering only the fraction that visibly “sticks out” from the disk. More likely, its mass could a factor of two higher, considering that part of it overlaps with the disk (see also Fig. 5 in Phookun et al. 1993). This cloud represents $\approx 10\%$ of the gas mass outside the galactic H I disk: either infalling onto the disk, or in the process of being shredded from it, according to alternative models (recall Section 1). It may be possible that the association is simply a coincidence: there is no definitive way to tell from the data available. It is none the less remarkable that, while there are various other gas clouds around the galaxy (references in Section 1), the cloud near the ULX is the only one that overlaps and probably impacts the stellar disk; all the others are at larger radial distances, at the edge of the galactic H I disk. We estimate that only $\approx 3\%$ of the projected area of the stellar disk overlaps with this (or any other) external cloud.

The H I velocity map (Phookun et al. 1993) tells a more dramatic picture (Figure 7). The gas cloud is strongly blueshifted with respect to the galactic disk, with a difference in the projected radial velocity $> 100$ km s$^{-1}$, and is clearly overlapping with the disk. From the inferred radial velocities, the cloud could be either in the process of being ejected (ram-pressure stripped) from the disk towards us, or, more likely in our opinion, it is tidal debris infalling onto the disk from behind. In the latter case, we have no elements to determine whether the cloud is actually hitting and merging with the disk. But is is interesting to note that the possible impact point is very close to the projected ULX position. We shall discuss in Section 4 whether there may be a direct physical connection between collisional processes and the formation of ULXs.

Figure 6. Top panel: H I 21-cm radio flux, represented in greyscale over the galactic disk, and as contours for the outer (less dense) regions. Contour levels are on a square-root scale from 0.02 to 0.3 Jy km s$^{-1}$ beam$^{-1}$. Bottom panel: the same H I radio flux contours overlapped over a VLT/FORS1 R-band image.

4 DISCUSSION

4.1 Hard state of ULXs

With an X-ray luminosity $\approx 2 \times 10^{40}$ erg s$^{-1}$, the ULX in M 99 is among the brightest of this mysterious class of sources: the cut-off in the luminosity function is at $\approx 3 \times 10^{40}$ erg s$^{-1}$ (Gilfanov, Grimm & Sunyaev 2004; Swartz et al. 2004). If the emission is isotropic and Eddington-limited, the mass of the accreting BH is $\gtrsim 100 M_\odot$. Apart from its extreme brightness, there is a notable, unexplained feature associated with this source and other bright ULXs: the X-ray spectrum is well fitted by a simple power-law with a rather hard photon index ($\Gamma = 1.7 \pm 0.1$). In stellar-mass BH binaries, such spectra are characteristic of the low/hard state (e.g., McClintock & Remillard 2006), with typical X-
ray luminosities in the standard XMM-Newton or Chandra bands less than a few per cent of the Eddington luminosity. At higher mass accretion rates and luminosities, stellar-mass BH binaries are dominated by either an accretion disk component (thermal, or high/soft state) or by a steep power-law component (thermal, or high/soft state) or by a steep power-law classification as stellar-mass systems, the inferred spectral exponent (thermal, or high/soft state) or by a steep power-law (thermal, or high/soft state) or by a steep power-law or by a steep power-law slope and luminosity of the source in M 99 would suggest the disk is truncated (as in the standard low/hard state), we expect a different spectral behaviour; for example, they might be found in a steady high/hard state which is not known in Galactic X-ray binaries. For other examples of bright ULXs with relatively hard power-law-like spectra, see Winter et al. (2005), and Stobbart, Roberts & Wilms (2006); see also the discussion in Gonçalves & Soria (2006) and references therein.

The underlying problem is how to explain the lack of evidence or the relative weakness of the accretion disk component in such bright sources. If the disk is faint because it is truncated (as in the standard low/hard state), we expect a low radiative efficiency, as well as a dimensionless accretion rate much below Eddington; therefore, a very high accretion rate (in physical units) and an even higher BH mass are needed to explain the observed luminosity. If the disk extends to the innermost stable circular orbit, the efficiency may be higher (standard efficiency ~ 0.1); however, most of the detected photons must have been reprocessed in a comptonizing medium, because we do not see the thermal disk spectrum directly. This requires that most of the gravitational energy is released in or transferred to the upscattering medium, for example via magnetic coupling (Kuncic & Bicknell 2004). Finally, especially for a pure power-law source, we cannot rule out that the X-ray emission comes from a relativistic jet pointing towards our line of sight (microblazar) (Körding, Falcke & Markoff 2002). However, physical and statistical arguments make the strong-beaming scenario rather implausible as a general explanation for the whole population of ULXs (Davis & Mushotzky 2004). Direct evidence against beamed emission is provided in some cases by the energy requirements of a photoionized nebula surrounding a ULX (Pakull & Mirioni 2003). Relativistic beaming has also been ruled out, in one case, by the presence of quasi-periodic oscillations (M 82 X-1; Strohmayer & Mushotzky 2003), and in another case by the radio/X-ray flux ratio (Holmberg IX X-1; Miller, Fabian & Miller 2004).

4.2 ULXs and galaxy collisions

Bright ULXs are preferentially associated with tidally interacting or collisional systems, or actively star-forming galaxies, or both (e.g., Swartz et al. 2004 for a population study). For example, many bright ULXs have been found in the Antennae (Zezas & Fabbiano 2002), the cartwheel (Gao et al. 2003), the Mice (Read 2003), NGC 7714/15 (Smith, Struck & Nowak 2005), NGC 4485/90 (Robert et al. 2002) the M 81/M 82 group (in M 82, Holmberg II and Holmberg IX).

The simplest explanation is that galaxy collisions trigger or enhance star formation, which, in turn, increases the birth rate of high-mass X-ray binaries (hence, the normalization of the point-source X-ray luminosity function). This also increases the probability of forming very luminous sources, near the upper cut-off. For example, it explains the large number of X-ray sources with luminosities $\gtrsim 10^{39}$ erg s$^{-1}$ in the Antennae (Zezas & Fabbiano 2002).

While this is probably a correct argument, it cannot be the whole story, especially for the small sample of ULXs with luminosities $\gtrsim 10^{40}$ erg s$^{-1}$. Some of them (e.g., Holmberg II X-1: Dewangan et al. 2004; Holmberg IX X-1; Miller et al. 2004) are in dwarf galaxies with relatively small star-formation rates. Others, such as the ULX in M 99 or the brightest ULXs in NGC 7714 (Soria & Motch 2004) and NGC 4559 (Soria et al. 2005), are in strongly star-forming galaxies but far away from the main star-forming regions. There are no ULXs in the inner disk of M 99 despite an SFR $\sim 10 M_\odot$ yr$^{-1}$; instead, the bright ULX object of our study is at the outer edge of the stellar disk, where the star formation rate is and probably has always been orders of magnitude lower. And yet, the ULX does seem to be associated with a collisional event between the disk and an infalling gas cloud (Section 3). How can we make sense of this apparently contrasting evidence? Here, we try to speculate one possible scenario for ULX formation, consistent with the sketchy observational evidence available so far. The following statements are conjectures to be tested with further observational and theoretical modelling.

i) Most ULXs are not strongly beamed. They are powered by BHs with masses $\sim 20-200 M_\odot$; the upper limit can easily be reduced to $\lessapprox 100 M_\odot$ if mild anisotropy or mild super-Eddington emission are allowed. The donor is likely to be a Roche-lobe-filling OB donor star, which can supply the required amount of accreting gas over its nuclear timescale.
(Rappaport, Podsiadlowski & Pfahl 2005; Copperwheat et al. 2006). If so, ULXs represent the upper end of high-mass X-ray binaries, consistent with their preferential location in young stellar environments; the accreting BHs are a factor of a few more massive than Galactic systems, and require stellar progenitors with masses \(\sim 50–400 M_\odot\).

i) A starburst or high SFR may favour but is not a sufficient condition for the formation of bright ULXs; other conditions may be required. For example, low metal abundance is essential to allow the evolution of a very massive star into a massive BH (Pakull & Mirioni 2003; Heger et al. 2003). A high SFR is not a necessary condition, either, as proved by the occasional presence of ULXs in gas-rich but low-SFR environments. Super star-clusters are also not a necessary condition for ULX formation.

ii) Galaxy-galaxy or cloud-galaxy collisions may induce the formation of bright ULXs, as well as trigger intense star formation, as separate, parallel consequences. This could explain why the two phenomena (ULXs and starbursts) are often, but not always, associated with each other. For example, local collisional events in NGC 4559 (Soria et al. 2005) and M 99 may be responsible for their respective ULXs in metal-poor regions at the very edge of their stellar disks.

The key issue we need to explain is why a collisional event would directly (i.e., not simply through enhanced star formation) favour the formation of a very massive star, which may then become a ULX progenitor if other conditions (e.g., low metal abundance) are also satisfied. A possible explanation is suggested by studies of the star-formation process in the Galactic protocluster NGC 2264-C, in the Cone Nebula (Peretto, André & Belloche 2006). In that case, a molecular clump with a mass \(\approx 1700 M_\odot\) is undergoing a large-scale collapse onto its central region, on a dynamical timescale (essentially in free fall). This results in the formation of a few massive protostars, one of which has already reached a mass \(\sim 40 M_\odot\) but is still accreting at a rate \(\sim 10^{-3} M_\odot\) yr\(^{-1}\) (Peretto et al. 2006). It is plausible that two or three protostars would accrete a few \(100 M_\odot\) of gas and coalesce even before ending their protostellar phase (\(\approx 3 \times 10^5\) yr).

Based on this scenario, we speculate that the formation of a star with an initial mass of a few \(100 M_\odot\) may occur in a protocluster such as NGC 2264-C, via massive global gas infall and mergers already during the protostellar phase (Soria et al. 2006); this is perhaps a more common process than the runaway merger of O stars in the core of super star-clusters (Portegies Zwart & McMillan 2002; Freitag, Gürkan & Rasio 2006).

It can be shown that an external shock or pressure wave can trigger the global, dynamical collapse of a molecular clump such as NGC 2264-C; instead, an isolated clump in hydrostatic equilibrium would have fragmented into much smaller Jeans-mass protostars (for recent reviews, see for example Struck 2005, Elmegreen 2002, 2004). The critical momentum required to trigger the collapse of a molecular clump is of order of the clump mass times its sound speed; moreover, the accretion rate onto the protostellar cores is proportional to the momentum imparted to the collapsing molecular clump (Motoyama & Yoshida 2003). Supernova shocks are a possible trigger of dynamical collapses in nearby molecular clumps; a fast, colliding gas cloud may carry even more energy and momentum than a supernova. Thus, we speculate that collisional events (such as the cloud-disk collision at the outer edge of M 99, or the possible dwarf galaxy-disk collision in NGC 4559: Soria et al. 2005) may lead to the formation of extremely massive protostars, via dynamical collapse and protostellar mergers on a timescale \(\sim 10^3\) yr.

The second step of the process to form a ULX would then be to ensure that the massive stellar progenitor retains most of its gas until core collapse. We speculate that this is where low metal abundance comes into play, because it strongly reduces the mass loss rate through line-driven stellar winds (e.g., Eldridge & Vink 2006, and references therein) and therefore leaves behind a bigger BH. This is why the (metal-rich) Pistol star in the Quintuplet Cluster (initial mass \(\approx 200–250 M_\odot\); Figer et al. 1998), the Wolf-Rayet stars in the Arches cluster, or the massive protostars in the NGC 2264-C protocluster will never form massive BHs, and perhaps why there are no ULXs in that part of our Galaxy. Conversely, we expect metal abundance to be much lower at the outer edge of the disk in M 99, perhaps made even lower by the infalling gas clouds (see, e.g., Chen, Hou & Wang 2003, and Andrievsky et al. 2003, for recent studies of metal abundances as a function of galactocentric distance in the Milky Way; and MacArthur et al. 2004 for similar trends in other disk galaxies).

In summary, our suggested scenario differs from models based on the runaway coalescence of O stars in super star-clusters, because it does not require such massive systems. We speculate that the formation of a massive stellar progenitor may occur in smaller \((\sim 10^3–10^4 M_\odot)\) protoclusters, during their embedded phase, through infall and merger processes similar to what is currently observed in NGC 2264-C. Protoclusters of that size are massive enough to produce O stars, but would by no means be classified as super clusters; in fact, they may not even be massive enough to survive their embedded phase as bound systems (Kroupa & Boily 2002).

Our scenario also differs from ULX formation models based on Population-III stars, because it only requires low but not primordial abundances, and therefore it can work at any redshift. At zero metallicity, stars with initial masses \(\approx 140–300 M_\odot\) may be disrupted by pair-instability supernovae that leave no remnants (Heger et al. 2003). Instead, at \(Z \sim 0.1 Z_\odot\), stars in that mass range may become the progenitors of accreting BHs in ULXs, via direct collapse, precisely in the mass range required by the X-ray observations. Further discussion of each of those speculations, and detailed comparisons with the observations, is beyond the scope of this paper.

5 CONCLUSIONS

We studied the X-ray properties of M 99, the most massive spiral galaxy in the Virgo Cluster. As expected from its high SFR \((\approx 10 M_\odot\) yr\(^{-1}\)), the X-ray emission is dominated by a soft thermal-plasma component. The total unabsorbed luminosity (not including a bright ULX) inside the \(D_{25}\) ellipse is \(\approx (1.2 \pm 0.2) \times 10^{41}\) erg s\(^{-1}\) in the 0.3–12 keV band; about 15% of this is due to resolved or unresolved discrete sources. The emission appears almost uniformly diffused across the inner disk (at \(\lesssim 5\) kpc from the nucleus), and there is no
starburst core. The temperature of the hot gas, \( kT \lesssim 0.30 \) keV, is also rather low, typical of disk emission rather than of a starburst environment.

We briefly discussed the morphology of the nucleus in the optical and UV bands, showing the presence of a (redder) massive nuclear star cluster and a few smaller, much bluer clusters of young stars around it. The spatial resolution of XMM-Newton does not reveal whether there are faint point-like X-ray sources in the nuclear region, and if so, whether they are located in the old nuclear cluster or associated to the young stars around it.

The main goal of this paper was a study of the properties and origin of a bright ULX at the outer edge of the stellar disk. Its unabsorbed luminosity of \( \approx 2 \times 10^{40} \) erg s\(^{-1}\) in the 0.3–12 keV band, together with a pure power-law spectrum with photon index \( \Gamma \approx 1.7 \), are difficult to interpret in the framework of classical spectral states for stellar-mass BHs. Such high/hard states are not uncommon in ULXs but are not generally seen in Galactic BHs. It suggests that we are not seeing the accretion disk directly, and that most of the gravitational power is efficiently transferred to a comptonizing region.

An intriguing new discovery is that there is a massive gas cloud (H\(^1\) mass \( \approx 10^7 M_\odot \)) seen in projection very close to the ULX position. From its radial velocity, we suggested that this cloud is falling onto the galactic disk (from behind) and perhaps impacting it near the ULX location. The cloud occupies \( \approx 3\% \) of the projected area of the stellar disk; therefore, we cannot entirely rule out the possibility that it is a chance association. However, we explored the speculative idea that there is a direct connection between collisional events and ULX formation, and not simply an indirect effect due to an enhancement in star formation. We suggested a possible scenario of ULX formation that would be consistent with this interpretation. We argued that cloud collisions may trigger a large-scale dynamical collapse of molecular clumps, rather than Jeans-mass fragmentation; in turn, this may lead to the formation of very massive stellar progenitors in the cluster core. If the metal abundance is low (\( Z \approx 0.1 Z_\odot \), not primordial abundances), we speculate that the star might retain enough of its gas to directly-collapse into a BH massive enough (up to \( \approx 100 M_\odot \)) to explain the luminosity of the brightest ULXs.

This scenario has to be tested with further individual and population studies of ULXs. At the individual level, the suggestion that ULXs have masses up to an order of magnitude higher than Galactic BHs (but not more) needs to be tested with more advanced X-ray spectral modelling, and a better understanding of the thermal disk and comptonized emission components in such systems. At the population level, we need a more systematic study of the spatial association between ULXs, low-metallicity environments and collisional events. Further work on this issue is currently under way (D. Swartz et al., in preparation).

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