Astronomy & Astrophysics

XMM–Newton observations of the ultraluminous nuclear X-ray source in M 33[⋆]

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Abstract. We present observations with *XMM-Newton* of M 33 X-8, the ultraluminous X-ray source ($L_{0.5-10 \text{ keV}} \approx 2 \times 10^{39}$ erg/s) closest to the centre of the galaxy. The best-fit model is similar to the typical model of Galactic black holes in very high state. Comparison with previous observations indicates that the source is still in a very high state after about 20 years of observations. No state transition has been observed even during the present set of *XMM-Newton* observations. We estimate the lower limit of the mass of the black hole $>6 \, M_\odot$, but with proper parameters taking into account different effects, the best estimate becomes 12 $M_\odot$. Our analysis favours the hypothesis that M 33 X–8 is a stellar mass black hole candidate, in agreement with the findings of other authors. In addition, we propose a different model where the high luminosity of the source is likely to be due to orientation effects of the accretion disc and anisotropies in the Comptonized emission.

Key words. X-rays: binaries – X-rays: galaxies – galaxies: individual: M 33 – galaxies: nuclei

1. Introduction

About 20 years ago, with the early observations of nearby spiral galaxies by the *Einstein* satellite, a new class of intermediate luminosity ($L_X = 10^{39}-10^{40}$ erg/s) X–ray sources was discovered (cf. Fabbiano 1989). These sources, later defined as ultraluminous X–ray sources (ULX, Makishima et al. 2000), were immediately intriguing, since one of the proposed model is that they could be intermediate mass black holes ($10^2-10^4 \, M_\odot$) accreting at sub–Eddington rates, the missing link between stellar mass X–ray binaries and active galactic nuclei (see Miller & Colbert 2003 for a review on intermediate mass black holes and their relationship with ULX). However, there are also other explanations available, which do not require a new class of object. According to these models, the ULX are stellar mass X–ray binaries, but either with truly super–Eddington accretion rate (e.g. Watarai et al. 2000; Begelman 2002), or with sub–Eddington rate, but with some type of collimated emission, either simply anisotropic (King et al. 2001) or relativistic (Körding et al. 2002; Georganopoulos et al. 2002) to increase

the observed luminosity. The threshold to define an ULX is now generally set to $10^{39.0}$ erg/s, without any reference to the physical mechanism responsible for this value (see Miller & Colbert 2003 for a review).

Surveys of ULX (e.g. with *ROSAT* Colbert & Ptak 2002, with *XMM–Newton* Foschini et al. 2002, with *Chandra* Colbert et al. 2003) can give gross information about these sources, their statistical properties, their relationships with the host galaxy. However, to improve the understanding of these sources, a detailed study of nearby ULX with high signal–to–noise data are needed.

M 33 (NGC 598) is one of the nearest spiral galaxies ($d = 795$ kpc). Classified as SA(s)cd, it has an inclination angle of 55° (Ho et al. 1997). Since the first observations with the *Einstein* satellite (Long et al. 1981), it was clear that the central source (M 33 X-8) had particular features (luminosity in the 0.2−4 keV energy range of about 10^{39} erg s^{-1}, soft spectrum, excess of absorption along the line of sight) suggesting that the source is somewhat different from an active galactic nucleus (Trinchieri et al. 1988). The authors suggested the possibility that M 33 contains a new type of X-ray binary system.

Later on, *ASCA* (Takano et al. 1994) observations extended up to 7 keV and strengthened the early results of Trinchieri et al. (1988). The best-fit model was composed of a multicolour disc (MCD) plus a power law at high energies,

Table 1. *XMM-Newton* observation Log. Columns: (1) observation identifier; (2) date of the observation; (3) duration of the observation [s]; (4)–(6) observing mode of MOS1, MOS2, and PN, respectively (FF: Full Frame; SW: Small Window); (7) Position with respect to the centre of the field of view.

| Obs. ID | Date | Exposure | MOS1 | MOS2 | PN | Position |
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0102640101	04 Aug. 2000	18672	SW	SW	FF	on axis
0102640301	07 Aug. 2000	14862	FF	FF	FF	off axis
0102640601	05 Jul. 2001	12525	FF	FF	FF	off axis
0102641001	08 Jul. 2001	13275	FF	FF	FF	off axis
0102642001	15 Aug. 2001	12266	FF	FF	FF	off axis
0102642101	25 Jan. 2002	13001	FF	FF	FF	off axis
0102642301	27 Jan. 2002	12999	FF	FF	FF	off axis

consistent with that of Galactic black holes in their high state. However, Schulman & Bregman (1995), based on *ROSAT* observations, conclude that the probability of such an unusual X-ray binary close to the centre of M 33 is very small.

Another point which makes M 33 X-8 an unusual source is the steadiness of its flux, except for a modulation of ∼20% with a period of 106 days (Dubus et al. 1997). This discovery strengthened the hypothesis of a binary system, since the modulations can be due to the precession motion of the accretion disc (cf. Maloney et al. 1996). It is important to add that there is a lack of information at wavelengths other than X-rays for the source, since the source is located in a crowded region, so that it is difficult to find the right counterpart or the companion star.

The recent increase of interest for ultraluminous X-ray source phenomenon gave new light to the study of M 33 X-8. Indeed, since the spatial resolution of *Einstein*, *ROSAT*, and *ASCA* were not sufficient to rule out the possibility of a small offset of the source from the optical centre, Makishima et al. (2000) suggested that X-8 could be an ULX. However, *Chandra* observations put the tightest constraints on the position of X-8 (Dubus & Rutledge 2002). The authors found a possible counterparts at radio wavelengths: it was identified with the point source n. 102 discovered by Gordon et al. (1999) with the VLA at 20 and 6 cm. In the near-IR, M 33 X–8 is at the 2MASS position of the nucleus (2MASS J01335089 + 3039365) within 0.6″, which corresponds to about 2.3 pc at the distance of 795 kpc (Dubus & Rutledge 2002).

The hypothesis of an active galactic nucleus (AGN) in the centre of M 33 is inconsistent with the upper limits on the central black hole mass obtained from the velocity dispersion measurements of the nuclear region: Kormendy & McClure (1993) gave an upper limit of 5×10^4 $M_\odot$, by using the Canada-France-Hawaii Telescope. Recently, Gebhardt et al. (2001) set, with the *Hubble Space Telescope (HST)*, an upper limit to only 1500 $M_\odot$. Moreover the 106 days periodicity is not consistent with the AGN hypothesis. The possibility that M 33 X-8 is an ULX is the best explanation, as already suggested by Makishima et al. (2000), although the source is very close to the centre of M 33.

We present a detailed analysis of observations of the source M 33 X-8 with *XMM-Newton*. This work is organized as follows: after the introduction (Sect. 1), the X-ray data reduction and analysis are described in Sect. 2. Section 3 deals with the observations of the nuclear region of M 33 in the near-IR and radio wavelengths. The interpretation of the X-ray data is divided in Sects. 4 and 5: the evaluation of the mass of the compact object is extensively dealt with in the first part, while the second discusses the main characteristics of the source.

2. *XMM-Newton* observation and data reduction

A set of observations of the central region of M 33 is available in the *XMM-Newton* Public Data Archive (see Table 1), with the nucleus in several position angles (on-axis and off-axis). For the processing, screening, and analysis of the data from the EPIC MOS1 and MOS2 cameras (Turner et al. 2001) and PN camera (Strüder et al. 2001), we used the standard tools of XMM-SAS software v. 5.4.1 and HEAsoft Xspec (11.2.0) Xronos (5.19) and followed the standard procedures described in Snowden et al. (2002). In some cases, the observations were affected by solar soft-proton flares, so that a preliminary cleaning was necessary.

2.1. Time analysis

To study the evolution of M 33 X−8 and check for possible state transitions, we extracted from the observations reported in Table 1 EPIC-PN light curves with ∼73 ms time resolution. We extracted the data from a circle with 35″ radius and centered in the position of M 33 X-8 (RA = 01 : 33 : 50.89, Dec = +30 : 39 : 37.2, J2000, uncertainty <4″).

The background was derived from a region 2′ wide near the source in the PN camera. Except for the third observation, during which the soft-proton flares limit the good time to about 5 ks, the others had a net exposure time of ∼9−10 ks.

From all these light curves, but one, we produced power density spectra (PDS) on interval of ∼300 s, and all the resultant PDS of a single observation were averaged and Leahy normalized (cf. Leahy et al. 1983). The resultant PDS are thus fitted between 3.3 mHz and 6.8 Hz (Fig. 1). Although the PDS above ∼20 mHz is flat and compatible with white noise, evidence for a red-noise component is found below that value: our best fit with a power law gives an index $-1.5^{+0.3}_{-0.2}$ ($\chi^2 = 130.6$, 137 d.o.f.). The red noise that appears to be present is apparently not due to the source.
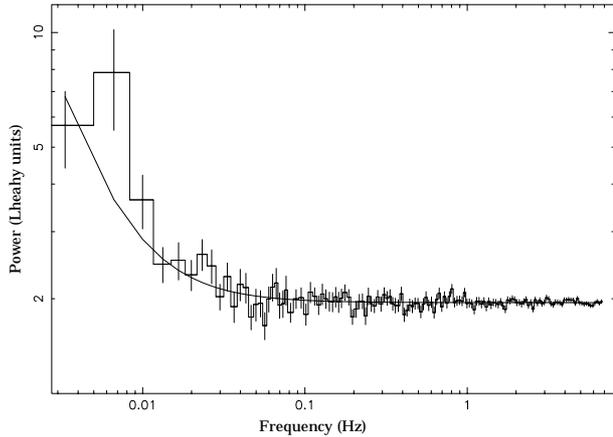
Fig. 1. Power density spectrum of M 33 X-8 build from all the *XMM-Newton* observations, except for ObsID 0102640101, which showed instrumental noise.

Fig. 2. Global light curve of M 33 X-8 (all the observations) folded with a period of 5000 s. Error bars are at 1σ.

Fig. 3. (*top*) Best-fit spectrum of M 33–X8 with EPIC MOS1, MOS2, and PN data. The model used is the multicolour disc plus a power law. See Table 2 and the text for details. The ratio data/model is shown in the bottom panel. (*bottom*) Corresponding unfolded spectrum.

Given the present statistics, it is not possible to have sufficient frequency resolution below 3.3 mHz to study the signal at 0.2 mHz (5000 s) reported by La Parola et al. (2003), but the folding of the light curve on this timescale indicates the presence of signal (see Fig. 2). Although the exposure time is not sufficient to have a highly significative detection, the χ^2 test gives a probability of 4% for the constancy of the source, with an excess variance <2.1% (3σ), thus confirming the results obtained by La Parola et al. (2003).

No state transitions were observed: we detect only a flux increase in the observation of 15 August 2001, without significant spectral changes with respect to the best-fit model described in the Sect. 2.1, and the flux variation was consistent with the well-known modulation of ~20% already observed by early satellites.

2.2. Spectral analysis

For the spectral analysis, we retrieved the on-axis observation of M 33 performed on August 4th, 2000. The EPIC MOS cameras were set in the small-window mode, and the net exposure was 12.5 ks long. The PN camera was in full-frame mode, and the exposure was 13.5 ks long. We extracted the data from the same regions described in the Sect. 2.1. The background was derived from a region 2′ wide near the source in the PN camera, but for the MOS cameras, since they operated in small-window mode, we used the background in the closest chip. The spectra were rebinned so that each energy bin contained a minimum of 30 photons, and we fitted only in the 0.5−10 keV energy range because of the uncertainties in the MOS cameras calibration at low energies (cf. Kirsch 2003). The photon redistribution matrix and the related ancillary file were created appropriately with the `rmfgen` and `arfgen` tasks of XMM-SAS.

We tried to fit the spectrum obtained with EPIC PN and MOS cameras with several models. Results of this are reported in Table 2. The best-fit model is composed of a multicolour accretion disc with temperature at the inner disc $T_{\rm in} = 1.16$ keV plus a power law with $\Gamma = 2.5$ (Fig. 3). The flux in the band 0.5−10 keV is of 1.7×10^{-11} erg cm^{-2} s^{-1} and is in agreement
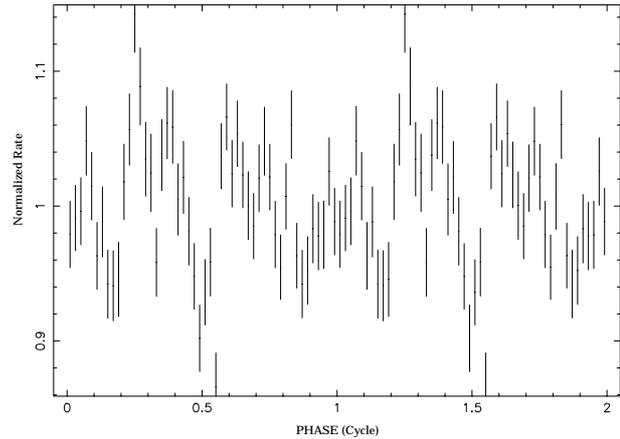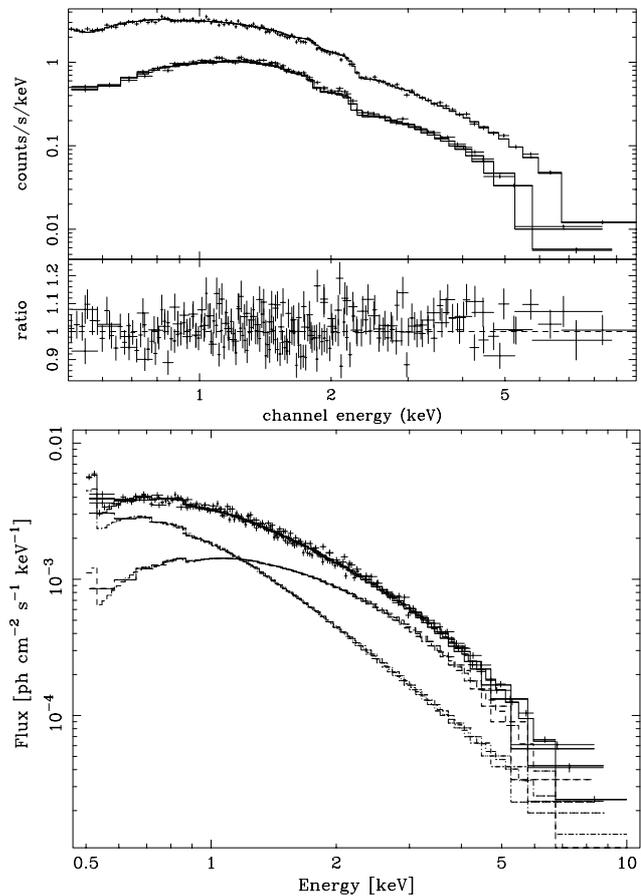
with earlier observations of other satellites. The power law accounts for about 57% of the total flux.

The absorption column is higher than the Galactic value of $N_{\rm H} = 5.6 \times 10^{20}$ cm^{-2} along the direction of observation, the latter being evaluated according to Dickey & Lockman (1990). In past observations, intrinsic absorption was never mandatory: Schulman & Bregman (1995) with *ROSAT* and

Table 2. Results from the fit of the X-ray data. Columns: (1) model: power law (PL), power law with high-energy cutoff (COPL; `cutoffpl` model in `xspec`), multicolour black body disc (MCD; `discbb` model in `xspec`), Raymond-Smith (RAY), unsaturated Comptonization (CST; `compst` model in `xspec`); (2) absorption column [10^{21} cm^{-2}]; (3) free parameters of the model: (PL) photon index Γ; (COPL) photon index Γ and cutoff energy E_{cut} [keV]; (MCD) temperature [keV] at the inner disc (T_{in}); (RAY) plasma temperature [keV] and metal abundances a; (CST) temperature [keV] and optical depth τ; (4) χ^2 and degrees of freedom of the spectral fitting; the reduced χ^2 is reported between brackets; (5) flux in the 0.5–10 keV band (10^{-11} erg cm^{-2} s^{-1}); (6) X-ray luminosity in the 0.5–10 keV band (10^{39} erg s^{-1}) calculated for $d = 795$ kpc and corrected for the absorption. The Galactic column is $N_H = 5.6 \times 10^{20}$ cm^{-2}. The uncertainties in the parameters are at the 90% confidence level.

Model (1)	N_H (2)	Parameters (3)	χ^2/d.o.f. (4)	F_X (5)	L_X (6)
MCD+PL	1.8 ± 0.2	$\Gamma = 2.5^{+0.2}_{-0.1}$	1221.5/1175	1.7	1.7
		$T_{in} = 1.16 \pm 0.04$ keV	(1.04)		
MCD+COPL	$1.4^{+0.5}_{-0.4}$	$\Gamma = 1.8^{+0.7}_{-0.8}$	1219.4/1174	1.7	1.5
		$T_{in} = 1.2^{+0.2}_{-0.1}$ keV	(1.04)		
		$E_{cut} > 2.3$ keV			
RAY+COPL	$1.0^{+0.2}_{-0.8}$	$\Gamma < 0.8$	1216.8/1173	1.7	1.4
		$a < 0.97$	(1.04)		
		$kT = 1.3^{+0.5}_{-0.3}$ keV			
		$E_{cut} = 1.8^{+0.3}_{-0.2}$ keV			
CST	1.65 ± 0.07	$kT = 1.13 \pm 0.03$ keV	1244.6/1176	1.7	1.6
		$\tau = 20.9 \pm 0.6$	(1.06)		

Dubus & Rutledge (2002) with *Chandra* found that no absorption was required in addition to the Galactic hydrogen column. On the other hand, Gottwald et al. (1987) with EXOSAT, Trinchieri et al. (1988) with *Einstein*, Takano et al. (1994) with *ASCA*, Parmar et al. (2001) with *BeppoSAX*, and La Parola et al. (2003) with *Chandra* found that it was necessary to include an additional absorption component.

In the present case, the additional absorption is required with statistical significance greater than 99.99% (see Fig. 4 for the 2-dimensional fit-statistic contour plot of the power-law photon index and the absorption column). The absorption along the line of sight appears to be the same for both the multicolour disc and the power law model.

It is most probable that the earlier negative detections were due to low statistics, rather than other effects: indeed, the *Chandra* spectrum with no absorption (Dubus & Rutledge 2002) was 10 ks long and had 23 degrees of freedom; the observation from which La Parola et al. (2003) found additional absorption was 92 ks long and had 333 degrees of freedom. It is worth noting too that the better statistics obtained thanks to the large collecting area of *XMM-Newton* results in a smaller error range with respect to the previous measurement of the additional absorption. The measured value of 1.24×10^{21} cm^{-2} (already subtracted for the Galactic value) corresponds to an optical reddening of $E(B-V) = 0.21$ mag, in agreement with the latest *HST* observations that found $E(B-V) = 0.22$ mag (Long et al. 2002).

La Parola et al. (2003) found that they needed to add a thermal plasma component. However, substituting the multicolour disc model with a thermal plasma model (e.g., Raymond-Smith) leads to a worse result, with parameters not properly constrained. If the thermal plasma model is added to, instead of substituting, the MCD, the results (not reported in Table 2) are even worse.

Furthermore, using a power law with an exponential cutoff, a model successfully used by some authors (e.g., Gottwald et al. 1987; Trinchieri et al. 1988) did not improve the fit, and in this case some parameters are also not properly constrained.

The only real alternative model to the reported best fit appears to be the unsaturated Comptonization model of Sunyaev & Titarchuk (1980). The plasma temperature is compatible with that obtained from the multicolour accretion disc and the optical depth τ, which is known to vary according to the disc inclination (θ), is compatible to a high value $\theta \approx 60°$. This agreement is expected in the case of steady accretion discs around black hole candidates, as shown by Ebisawa et al. (1991).

There is, however, no evidence of any anomalous Comptonization as found by Kubota et al. (2001) in GRO J1655 − 40. By adding to the best-fit model a Comptonized blackbody component (`compbb` model in `xspec`) and linking the blackbody temperature to the temperature of the inner disc (T_{in}), the new three-component model does not converge.

We tried also the bulk motion Comptonization model (`bmc` model in `xspec`, Laurent & Titarchuk 1999), which has been used successfully to fit the soft state of several Galactic black hole candidates (Borozdin et al. 1999), but also some ULX, with M 33 X–8 among them (Schrader & Titarchuk 2003); however, in the present case, the fit gives unphysical results, with pegged parameters. We therefore do not mention this in Table 2.

Having detected flux variations in the observation of 15 August 2001, we extracted the source spectrum to investigate the possibility of state transitions. The data were affected by pile-up, mildly for the PN and strongly for the MOS cameras. Therefore, we analyzed the data from PN only, and we extracted the source spectrum from an annulus centered on the nucleus coordinate and with radii 10″ and 40″, thus

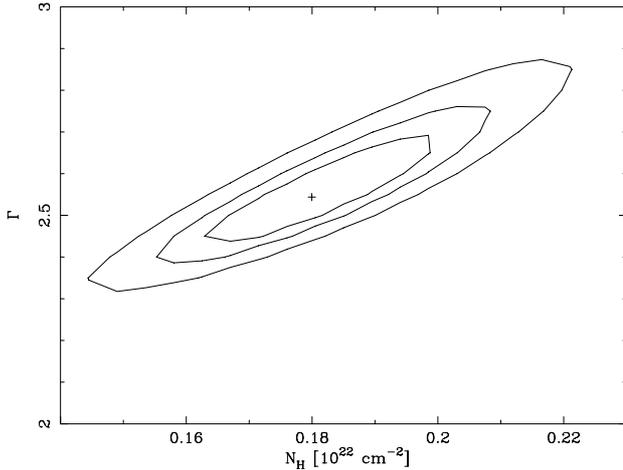**Fig. 4.** 2-dimensional fit-statistic contour plot of Γ versus N_{H}. The contours are with $\Delta\chi^2 = 2.3, 4.61, 9.21$, corresponding to the confidence levels of 68%, 90%, and 99%.

excluding the central region affected by pile-up. The background was extracted from a nearby region of $2'$ radius.

The data were fitted to the best-fit model, i.e. multicolour accretion disc and power law. The present fit gave $\chi^2 = 182$ for d.o.f. $= 191$, with $N_{\mathrm{H}} = (1.9 \pm 0.5) \times 10^{21}$ cm^{-2}, $\Gamma = 2.3^{+0.8}_{-0.4}$, and $T_{\mathrm{in}} = 1.4^{+0.3}_{-0.4}$ keV. Their results are consistent with the reference spectrum within the measured errors. No state transition was observed, but the measured unabsorbed x flux in the energy band 0.5–10 keV is 2.8×10^{-11} erg cm^{-2} s^{-1}, which is 27% higher than the flux measured during observation 0102640101, consistent with the well-known modulation of ~20%.

3. Observations of the nuclear region at other wavelengths

Observations of the nuclear region of M 33 at wavelengths other than X-rays are very difficult because the stellar density in the nuclear region of M 33 is so high. Even with the highest available resolution, the innermost region of the nucleus remains unresolved (Lauer et al. 1998).

Chandra observations by Dubus & Rutledge (2002) placed the X-ray position within $0.6''$ (2.3 pc at the distance of 795 kpc) of the near-IR position from 2MASS and the radio position from the VLA observations. The *Chandra* coordinates are compatible with what has been found by *ROSAT* and the present observation with *XMM-Newton*.

The reference radio observation has been performed by Gordon et al. (1999). They observed M 33 with the VLA at 6 and 20 cm with $7''$ resolution and detected the centre of M 33 at RA = 01 : 33 : 50.89 and Dec = +30 : 39 : 37.33 (J2000). The flux density at 20 cm was $S_{20} = 0.6 \pm 0.1$ mJy, while it was 0.2 ± 0.1 mJy at 6 cm (signal-to-noise ratio > 3). The spectral index was $\alpha = -0.8 \pm 0.2$, where $S_\nu \propto \nu^\alpha$. By comparing the radio data with optical observations performed with the 4 m telescope at the Kitt Peak Observatory, Gordon et al. (1999) exclude the possibility that the M 33 centre is related to supernova remnants or H II regions. Intermediate-age stars, common in the nuclear region (Lauer et al. 1998), should not

generate strong radio emission; the only other type of source that can display an $\alpha = -0.8$ spectrum would be a background AGN. But the periodicity of 106 days in X-rays excludes the possibility of an AGN. Therefore, it is reasonable to assume that the VLA detection is genuinely linked with M 33 X-8, although the current spatial resolution of either the X-ray or radio data cannot yet definitively prove this.

However, there are problems to accept the 2MASS detection as simply the *counterpart* of X-8. In the 2MASS All Sky Data Release Catalog[1] (released on March 2003) the centre of M 33 is located at RA = 01 : 33 : 50.9 and Dec = +30 : 39 : 36.6 (J2000, spatial resolution $3''$). The apparent magnitudes are $J = 12.06 \pm 0.03$, $H = 11.44 \pm 0.03$, and $K = 11.22 \pm 0.03$. The detection flags of the catalog indicate a good quality processing of a pointlike source, although $3''$ at 795 kpc is equivalent to about 11 pc.

The total absorption column measured by the present work ($N_{\mathrm{H}} = 1.8 \times 10^{21}$ cm^{-2}) allows us to calculate a visual extinction of $A_{\mathrm{V}} = N_{\mathrm{H}} \cdot 5.3 \times 10^{-22} = 0.954$ mag (by using $R_{\mathrm{V}} = 3.1$; cf. Cox 2000). Then, it is possible to calculate the extinction factors at the 2MASS wavelengths according to Cardelli et al. (1989): $A_J = 0.27$, $A_H = 0.18$, and $A_K = 0.11$ mag. The dereddened magnitudes are $J = 11.79$, $H = 11.26$, and $K = 11.11$, which yield colours of $J - H = 0.53$ mag and $H - K = 0.15$ mag, indicating an infrared excess that cannot be due to a single star. The near-IR emission is consistent with the light expected from the known nuclear star cluster of M 33. According to Kormendy & McClure (1993), the central cluster has a *B*-band magnitude of ~14.6. Long et al. (2002) recently concluded that M 33's nucleus has an age of ~10^7–10^9 yrs. From the population synthesis models of Bruzual & Charlot (2003), we anticipate that a cluster in this age range should have $B - V \approx 0$–0.6 mag and $V - K \approx 2$–3 mag. Hence, the nuclear star cluster of M 33 is expected to have a *K*-band magnitude of ~11–12, consistent with the value seen by 2MASS. Therefore, the 2MASS detection is likely to be dominated by the integrated stellar emission of the nuclear star cluster, not by near-IR emission intrinsic to X-8.

4. Discussion

The source shows interesting similarities with other well known Galactic BHC (see, e.g., McClintock & Remillard 2003). The radio spectral index of M 33 X–8 is very similar to the ones of the famous microquasars 1E1740.7 − 2942 (cf. Mirabel et al. 1992) or SS433 (cf. Dubner et al. 1998). Moreover we confirm the 5000 s modulation of the emission of the source. If this period refers to a signal propagating at the speed of sound (with a typical value of $c_{\mathrm{s}} = 10$ km s^{-1}) or at the speed of light, the corresponding physical dimensions are between 5×10^9 and 1.5×10^{14} cm. A similar variability has been observed also in SS433 (jet 1000 s) and for this source

the typical dimension has been calculated to be about 10^{13} cm (Kotani et al. 2002).

Moreover the source X–ray flux recorded by *XMM–Newton* is almost equal to that previously measured. The only change observed is in good agreement with the 106 days modulation previously measured (Dubus et al. 1997). By this evidence, we may assess that the source has been observed to be almost stable during the last 20 years. No particularly strong variation in the spectral and/or flux state of the source has ever been observed. These characteristics are very similar to what is observed in the BHC LMC X–1 (cf. Nowak et al. 2001; Wilms et al. 2001).

From these indications we are led to classify the ULX M 33 X–8 as a black hole with stellar mass. This picture is supported also by the X–ray spectra we obtained with *XMM–Newton*. In particular, the temperature of the thermal component seems to be too high to be referred to an intermediate mass BH unless one assumes relativistic effects (see the next subsection).

4.1. Evaluation of the mass of M 33 X-8

To calculate the mass of M 33 X-8, we have to take into account that it cannot be greater than the upper limit of the non-luminous mass of the nucleus, 1500 $M_\odot$ (Gebhardt et al. 2001).

From the X-ray analysis, it is obvious that X-8 is in a very high state, with a thermal component with $kT \sim 1$ keV and a power law with photon index ~2.5. According to some authors (e.g. Done & Gierlinski 2003), these spectral characteristics are the typical signature of the accretion disc around a black hole.

In the present work, the best model to fit the ultrasoft component is the multicolour accretion disc (MCD) by Mitsuda et al. (1984). The MCD model require, to be correctly used, some additional parameters (cf. Merloni et al. 2000; Ebisawa et al. 2003). Therefore, we recall some basic definitions to explain the values of the parameters we used to calculate the mass of the compact object in the present case. We refer to the works of Makishima et al. (2000) and Ebisawa et al. (2003) for further details and deeper analysis on the MCD model applied to ULX.

The normalization of the MCD model A_{MCD} allows a direct estimate of the inner disc radius R_{in}, by means of $A_{MCD} = R_{in}^2 \cos\theta / D^2$, where D is the distance of the source in units of 10 kpc, θ is the inclination of the disc ($\theta = 0°$ means face-on; $\theta = 90°$ refers to the disc edge-on). R_{in} is expressed in km and depends on the spin of the black hole. In the case of a Schwarzschild black hole (spin 0), R_{in} is equal to three times the event horizon radius $R_S = 2GM/c^2$ (that is twice the gravitational radius), while for a Kerr black hole, the radius of the inner disc can be down to $1.24R_S$ in the most extreme case of spin +1.

Two more correction parameters should be taken into account: the first correction, indicated with the parameter ξ, is to represent the fact that T_{in}, the temperature at the innermost disk boundary, is related to a radius a bit larger than R_{in} ($\xi \approx 0.41$, Kubota et al. 1998). The second parameter is the spectral hardening factor f of Shimura & Takahara (1995), which takes into account the fact that in the MCD model T_{in} is the maximum

disc colour temperature, and therefore it has to be converted into the effective temperature. The hardening factor weakly depends on the accretion rate and the viscous parameter α of the standard model (Shakura & Sunyaev 1973). For Galactic black holes, f is generally constant and within the range 1.7–1.9 (see Ebisawa et al. 2003 for a discussion on these values). We assume $f = 1.7$.

The mass of the compact object is therefore given by $M = (R_{in}\xi f^2 / 8.86s) \, M_\odot$, where s is a coefficient depending on the spin of the black hole. In the case of a Schwarzschild black hole $s = 1$. A further uncertainty in the evaluation of the mass is given by the inclination of the accretion disc, which is generally unknown. By assuming $\cos\theta = 1$, we obtain a lower limit of the mass. The MCD normalization in the best-fit model of M 33 X-8 gives $R_{in} = 46 \pm 3$ km, which corresponds to a mass of $(6.2 \pm 0.4) \, M_\odot$.

It is worth noting that the inclination of the accretion disc and the corresponding relativistic corrections can increase the value of the mass. To have an estimate of the possible inclination of the accretion disc, we note in Table 2 that the X–ray spectrum of M 33 X–8 is also well fitted by the unsaturated Comptonization model by Sunyaev & Titarchuk (1980), with a temperature compatible with that of the MCD model. Therefore, it is reasonable to think that the power law component of the MCD+PL model could be due to the Comptonization. From the data of fit with unsaturated Comptonization and the studies performed by Ebisawa et al. (1991), we can infer that a possible value for $\theta = 60°$. If true, the mass would be $M = (8.7 \pm 0.5) \, M_\odot$.

If we include also relativistic effects of the disc inclination, including Doppler boosting and gravitational focusing, by assuming that the accretion disc shares the same behavior as that seen in AGNs (see Sun & Malkan 1989), the mass might rise to $M = (12 \pm 1) \, M_\odot$.

Defining $L_{Edd} = 1.3(M/M_\odot) \times 10^{38}$ erg/s (e.g. Frank et al. 2002), and assuming $L_{0.01-100keV} = 2.7 \times 10^{39}$ erg/s (extrapolated from the X–ray data) as the best approximation of the bolometric luminosity, it results that we are observing the source at about 1.7 L_{Edd} for a 12 $M_\odot$ black hole. To reach such a super–Eddington luminosity there are two possibilities: to have genuine super–Eddington accretion rate or sub–Eddington rate with some type of anisotropies or collimation. The bolometric luminosity of the accretion disc only can be calculated by using the Stefan–Boltzmann law with the dimension and temperature of of the innermost stable region. In the case of the inclination angle $\theta = 60°$, the disc can account for $L_{disc} = 1.0 \times 10^{39}$ erg/s. The remaining part of the accretion, related to the power law component, is more difficult to explain, since it depends on the physical interpretation. In the case of sub–Eddington rate, a little anisotropy (solid angle of the emission $<1.6\pi$) is sufficient to account for the observed flux. These values are similar to those of the Galactic microquasar GRS1915 + 105, where the inclination angle is 70° and the solid angle of the emission is about 2.4π (see King et al. 2001). We cannot exclude at all that the M 33 X–8 could accrete at super–Eddington rates, although, in this case, we would expect values of the excess variance greater than those observed.

We caution that the mass evaluation is only as good as the MCD model, the present best fit, and the parameters adopted/inferred for the correction of the MCD.

The above value is the best estimate, according to the *XMM–Newton* observation and in the hypothesis of a Schwarzschild black hole. It is worth noting in case of intermediate mass black hole, the temperature of the inner disc is expected to be much lower than the 1 keV measured in the present case. Miller et al. (2003) found a temperature of $kT_{in} = 0.15$ keV for the two ULX in NGC 1313 from which they inferred the presence of a black hole of $\approx 10^3\ M_\odot$. It is possible to reach a high value of the mass only if the black hole is maximally rotating ($s = 1/6$, Kerr black hole). In this case, taking into account all the effects and parameters described above, the mass of M 33 X–8 could be as high as $M = (147 \pm 8)\ M_\odot$.

4.2. A mildly relativistic jet or a Compton heated wind?

We propose two possible hypotheses to explain the power law component of M 33 X-8. The first is the presence of *collimated emission (mildly relativistic jets)*. The dimensions of the variable region appear to be compatible with the X-ray emitting region from jets in microquasars: e.g. for SS433 (jet speed $0.26c$, time variability 1000 s), this region has dimension $\sim 10^{13}$ cm (Kotani et al. 2002). The radio spectral index is compatible with the values found in the hot spots of some Galactic microquasars, like 1E1740.7 − 2942 (Mirabel et al. 1992) or SS433 (Dubner et al. 1998). Although it is not possible to resolve the radio emission from the nucleus of M 33, the steep spectral index is consistent with the synchrotron emission from charged particles accelerated in shocks generated by the propagation of a jet in a diffuse region. But a cautionary note should be stressed, which is the great uncertainty in the determination of the counterpart of M 33 X-8.

The second hypothesis takes into account the presence of *Compton-heated winds*, like, for example, the Galactic black hole GRO J0422 + 32 (van Paradijs et al. 1994). This model was never proposed to explain the high luminosity of ULX. In this case, the hard X-ray emission represents the signature of a specific physical process, generally taken to be inverse-Compton scattering of photons of thermal origin on a population of hot electrons. The geometry of the region where this process occurs is rather difficult to understand. The two-phase model by Haardt & Maraschi (1991) of a corona in hydrostatic equilibrium around the accretion disc is one of the standard solutions. In this case, thermal radiation emitted by the accretion disc enters the hot corona and is Comptonized into hard X-rays. Part of this radiation is then reprocessed by the accretion disc, and a small fraction is reflected. The fact that the spectrum of M 33 X-8 is well fitted also by the unsaturated Comptonization model strengthens the importance of the corona for this source (cf. Table 2).

We consider, as a reference, the model developed by Begelman et al. (1983). A nearly hydrostatic corona exists at a distance r from the centre of the accretion disc system if the Compton temperature T_{IC} is less than the escape temperature. This occurs inside the radius $R_{IC} = (1.0 \times 10^{10}/T_{IC8})M/M_\odot$,

where R_{IC} is in cm and T_{IC8} is the inverse-Compton temperature expressed in units of 10^8 K (Begelman et al. 1983). If $r > R_{IC}$, Compton heating can cause a strong wind (see Begelman et al. 1983; Begelman & McKee 1983; Shields et al. 1986). In this case, a wind-driven relaxation cycle is set up, causing oscillations in the interplay of the disc accretion rate and the wind ejection rate. In the standard disc model, these oscillations have a period $P = (3400\ \mathrm{s}) \cdot M^{14/9}/(\alpha^{7/9} T_{IC8}^{4/3} \dot{M}_{a17}^{1/3})$, where $\dot{M}_{a17}$ is the disc accretion rate in units of 10^{17} g s^{-1}. In the hypothesis that M 33 X–8 is accreting at about 60% the Eddington limit, from the above equation, it is possible to calculate T_{IC8}, which in turn gives us R_{IC}. For the values of mass of the compact object $M = (6-12)\ M_\odot$, we infer a value of $R_{IC} \approx 7 \times 10^9$ cm. Therefore, if the oscillation occurs at this distance, the perturbation speed is about 14 km s^{-1}, compatible with the sound speed in a isothermal plasma at a temperature of about 2×10^4 K. This value can be compared with what has been found in the case of GRO J0422 + 32, where the temperature of the plasma is $\sim 3 \times 10^4$ K (van Paradijs et al. 1994).

It is worth mentioning that outflows have been invoked to account for the high luminosity in ULXs (e.g., Begelman 2002; King 2002; King & Pounds 2003) and the Compton-heated winds solution proposed here can be considered a variant of these models.

5. Final remarks

We presented the spectral and temporal analysis of *XMM-Newton* observations of M 33 X-8. The present analysis of X-ray data suggest that M 33 X-8 is a stellar mass black hole, whose luminosity is only apparently super–Eddington for geometrical reasons. The lower limit for the mass of $M > 6\ M_\odot$, and a best estimate of $M = 12 \pm 1\ M_\odot$, although we cannot completely exclude a mass of $\approx 150\ M_\odot$ if X–8 is a maximally rotating BH. These conclusions are in agreement with the X–ray binary interpretation already found by several other authors (Makishima et al. 2000; Dubus & Rutledge 2002; King 2002; La Parola et al. 2003, just to mention the latest).

We confirm the oscillation with a period of 5000 s discovered by La Parola et al. (2003), and we suggest that this oscillation is associated with the interplay between the mass loss from a Compton-heated wind and the accretion rate. It is worth noting that also a mildly relativistic jet could explain as well most of the observed data. In this case, the 5000 s variability is due to oscillations at the basis of the jet.

The case of M 33 X-8 sheds new light on ULX studies. The interpretation proposed here for M 33 X-8 – a stellar-mass black hole whose luminosity is boosted by orientation effects of the accretion disc and Compton-heated winds (or even a mildly relativistic jet) – may serve as a useful template for understanding other ULXs. To date, ULXs with little or no variability have generally been associated with young supernovae remnants. M 33 X-8 illustrates that steady X-ray sources, with weak short term variability, can be stellar-mass black holes.

It is also of interest to note that environments rich in hot plasma, coming from hot winds of young stars or from stellar collisions, as might occur in compact young star clusters or the

nuclei of galaxies, may be particularly conducive to fueling and sustaining ULX sources.

Finally, we would like to emphasize that very high resolution, multiwavelength, simultaneous observations of M 33 X-8 are required to draw definitive conclusions on the nature of this enigmatic source.

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