X-ray emission from the Ultramassive Black Hole candidate NGC 1277: implications and speculation on its origin

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ABSTRACT
We study the X-ray emission from NGC 1277, a galaxy in the core of the Perseus cluster, for which van den Bosch et al. have recently claimed the presence of an UltraMassive Black Hole (UMBH) of mass $1.7 \times 10^{10} M_\odot$, unless the IMF of the stars in the stellar bulge is extremely bottom heavy. The X-rays originate in a power-law component of luminosity $1.3 \times 10^{40} \text{ erg s}^{-1}$ embedded in a 1 keV thermal minicorona which has a half-light radius of about 0.36 kpc, typical of many early-type galaxies in rich clusters of galaxies. If Bondi accretion operated onto the UMBH from the minicorona with a radiative efficiency of 10 per cent, then the object would appear as a quasar with luminosity $10^{46} \text{ erg s}^{-1}$, a factor of almost $10^6$ times higher than observed. The accretion flow must be highly radiatively inefficient, similar to past results on M87 and NGC3115. The UMBH in NGC 1277 is definitely not undergoing any significant growth at the present epoch. We note that there are 3 UMBH candidates in the Perseus cluster and that the inferred present mean mass density in UMBH could be $10^5 M_\odot \text{ Mpc}^{-3}$, which is 20 to 30 per cent of the estimated mean mass density of all black holes. We speculate on the implied growth of UMBH and their hosts, and discuss the possibility that extreme AGN feedback could make all UMBH host galaxies have low stellar masses at redshifts around 3. Only those which end up at the centres of groups and clusters later accrete large stellar envelopes and become Brightest Cluster Galaxies. NGC 1277 and the other Perseus core UMBH, NGC 1270, have not however been able to gather more stars or gas owing to their rapid orbital motion in the cluster core.

Key words: X-rays: galaxies — galaxies: clusters — intergalactic medium — galaxies:individual (NGC 1277)

1 INTRODUCTION
The discovery of UltraMassive Black Holes (UMBH), with masses above $10^{10} M_\odot$ by McConnell et al. (2011, 2012) has challenged our understanding of black hole growth. Their objects lie at the centres of Brightest Cluster Galaxies, which have the highest stellar masses known. The mystery has now deepened by the recent claim of a UMBH in the lenticular galaxy NGC 1277 (van den Bosch et al 2012). The estimated black hole mass of $1.7 \times 10^{10} M_\odot$ corresponds to 14 per cent of the total stellar mass of that galaxy, much larger than the 0.1 per cent found in a normal massive galaxy. Moreover, van den Bosch et al. (2012) imply that there may be many more such objects, based on a Table including 5 other galaxies with similar properties. All of the known examples lie within about 100 Mpc from us.

Presumably they were among the most luminous quasars when they were growing but are certainly not quasars now. NGC 1277 lies in the core of the Perseus cluster where we have amassed a very deep X-ray exposure with Chandra (Fabian et al 2006; 2011). It appears as a weak compact source with properties similar to other early-type galaxies in the cores of clusters, showing a power-law continuum in an extended thermal minicorona (Sun et al 2007; Santra et al 2007). We present here a re-analysis of the X-ray data. The minicorona of 10 million K gas lies within the Bondi radius so should be accreting. If the accretion flow were radiatively efficient with a radiative efficiency of 10 per cent then the luminosity should exceed $10^{46} \text{ erg s}^{-1}$, i.e. it should be a quasar. It clearly is not, since the power-law component has an X-ray luminosity of only $1.3 \times 10^{40} \text{ erg s}^{-1}$. We discuss possible ways in which accretion may be reduced. We then briefly look at NGC 1270 which is another object from the Table of UMBH candidates of van den Bosch (2012) and lies also in the Perseus core and has roughly similar properties.

We note the surprisingly large mean black hole mass density implied by the newly discovered UMBH candidates. We then consider the possibility in which extreme Active Galactic Nucleus
feedback (Silk & Rees 1998; Fabian 2012) during the growth phase of a UMBH pushes all surrounding gas away, except in the directions along the filaments fuelling the black hole accretion. Star formation would then be inhibited close to the UMBH and when growth ceases around redshift 3, all UMBH are surrounded by whatever compact stellar bulge has survived from the earliest growth phases. Those UMBH which now lie at the centre of a cluster or group of galaxies will have since been able to accrete a large stellar envelope due to cannibalism, cooling flows etc and now appear as a BCG. Those orbiting in the core of a cluster, like NGC 1277, will have been unable to accrete much of a stellar envelope and so have a large fraction of their mass in the central black hole.

We concentrate on the UMBH interpretation of NGC 1277, but briefly note and discuss the possible influence of a bottom-heavy stellar mass function, which may reduce the black hole mass required by the observations.

2 THE CHANDRA DATA

The core of the Perseus cluster has been observed several times with Chandra ACIS-S, centred on the Brightest Cluster Galaxy NGC 1275 Fabian et al (2006, 2012). 4345 background-subtracted counts are detected in a 3 arcsec radius aperture on NGC 1277 (Fig. 1), 3.75 arcmin to the North of NGC 1275, with a total exposure time of 698,800 s. The source flux in the 0.5–7 keV band is $4.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

Since the source is about 3 arcmin from the aimpoint of the telescope, the point spread function is slightly worse than on axis. Fitting the profile of the source by a gaussian gives a width, $\sigma$, of about 1 arcsec, which is slightly larger than the nominal width for this off-axis distance. Using a simulation with the Chandra tool MARX, we can compare it to the observed profile of the source (Fig. 2). The Chandra data can be fitted by the simulated point source of gaussian width (standard deviation) $\sigma_1 = 0.41$ arcsec plus an extended part of intrinsic gaussian width $\sigma_2 = 0.8$ arcsec. The ratio of the flux in the two components is $\sim 1.6$. Adopting a cluster redshift of 0.018 the angular scale is 360 pc per arcsec, so the extended component has a half-light radius of approximately 0.36 kpc.

The spectrum (Fig. 3) is characteristic of minicorona (Vikhlinin et al 2001; Sun et al 2007). It is well-modelled by thermal gas plus a power-law continuum ($\chi^2/dof = 103.7/127$, the thermal model alone gives 144.1/129 and the power-law alone...
A deep dust lane is clearly visible.

Figure 3. Chandra X-ray spectrum of NGC 1277, fitted with Galactic absorption applied to an APEC thermal model (red) and a power-law continuum (green).

Figure 4. Preview image of HST-ACS image of NGC 1277 taken through the F550M filter. A deep dust lane is clearly visible.

The peak just below 1 keV is due to Fe-L emission lines from the hot gas. We obtain a temperature for the gas of $kT = 1.02 \pm 0.06$ keV. The best-fitting metal abundance is 0.6 but is poorly constrained provided that it is at least 0.05 (the thermal continuum is degenerate with the power-law). Galactic absorption of $1.28 \times 10^{22} \text{cm}^{-2}$ is included, which is typical for the core of the Perseus cluster (Fabian et al 2006). The power-law component has a photon index $\Gamma = 1.92^{+0.20}_{-0.19}$, if the metallicity is fixed at 1 $Z_{\odot}$ (Anders & Grevesse 1982), and the absorption-corrected 0.5–7 keV luminosity is $1.3 \times 10^{40} \text{erg s}^{-1}$. The normalization of the power-law component correlates with both $\Gamma$ and metal abundance $Z$. Provided that $Z > 0.5 Z_{\odot}$ (i.e. at least comparable to the ICM) then the uncertainty of the normalization is less than 30 per cent. These results are similar to those obtained previously (Sun et al 2007). The ratio of the flux of the power-law to the thermal power-law component is about 2, in fair agreement with the power-law arising from an unresolved central point source and the thermal emission being extended, as expected. A good fit is also obtained with two thermal components, at 0.96 and 4.6 keV.

3 THE ACCRETION POWER

Modelling the thermal component as a sphere of uniform density and radius $r$ kpc gives a density of $0.023 r^{-1.5} \text{cm}^{-3}$. The half-light radius of a sphere is 0.36 kpc if $r = 0.6$. The Bondi radius $r_B = GM/c^2$ for a black hole of mass $1.7 \times 10^{10} M_{\odot}$ is 840 pc for gas at $10^7$ K, which is slightly larger than the radius at which most of the thermal gas is found. Assuming that the gas is flowing inward at its sound speed, at a radius of about 0.6 kpc, we obtain an approximate accretion rate,

$$\dot{M} \sim 4\pi \lambda r^2 n_m c_s = 1.4 M_{\odot} \text{yr}^{-1},$$

which gives an accretion luminosity of

$$L_B \sim 10^{46} \eta_{0.1} \text{erg s}^{-1},$$

where we use 0.25 for the factor $\lambda$, which is appropriate for Bondi accretion of an adiabatic gas. The radiative efficiency of accretion is $0.1 \eta_{0.1}$, the gas density $n$, the sound speed $c_s$. $M$ and $m_p$ are the mass of the black hole and the proton, respectively.

There is then a mismatch between the predicted accretion luminosity and the observed luminosity of the power-law source, by a factor of nearly $10^8$. Some of this could be in bolometric corrections, but a factor of more than $10^8$ will remain. We see no obvious disturbance in surrounding intracluster gas so there is no major mechanical energy loss through winds or jets. The overall accretion efficiency must be $10^{-6}$ or less. Inefficient accretion flows have been inferred before for Sgr A* at the centre of our Galaxy (Rees 1983; Narayan & Yi 1994). The flow can become convectively unstable at low accretion rates leading to a convectively dominated accretion flow (Narayan et al 2000; Quartet & Gruzinov 2000). Mismatches with supermassive black holes have been observed before, from M87 (Di Matteo et al 2003) and NGC 3115 (Wong et al 2011) at $\eta < 10^{-7}$. The most massive black holes provide therefore stringent tests of accretion theory.

We note that there is a very deep dust lane (Fig. 4) in the centre of NGC 1277, with a radius of $\sim 300$ pc. This presumably indicates that matter is orbiting the black hole there, with a velocity of at least $480 \text{km s}^{-1}$, if the black hole mass is $1.7 \times 10^{10} M_{\odot}$. Any cold accretion flow may be stalled at the location of the dust lane: thermal gas at a temperature of 1 keV will however be in a thick atmosphere. NGC 1277 is listed as a radio source with flux $2.7 \text{mJy}$ at $1.4 \text{GHz}$ by Miller & Owen (2001; from work by Sijbring 1993).

The presence of UMBH in galaxies with stellar masses as low as that of NGC 1277 needs to be confirmed. This can be done by spectroscopy of the stellar bulge at higher spatial resolution. If the dust ring in NGC 1277 is accompanied by gas, as is likely, then the high expected circular velocity ($\sim 480 \text{km s}^{-1}$) of that ring would provide convincing confirmation. We shall proceed assuming that there is a UMBH in NGC 1277.

Van den Bosch et al (2012) list a further 5 galaxies which are candidates for hosting ultramassive black holes, including 2 more in the Perseus cluster (NGC 1270 and UGC 2689). NGC 1270 is also in the core of the cluster and lies in some of the deep Chandra images. It is also characterised by a minicorona of temperature 1.07 keV plus a power-law component of 0.5–7 keV luminosity $6.3 \times 10^{40} \text{erg s}^{-1}$ (Sun et al 2007; Pearce et al 2012 submitted). NGC 1270 is nearly 10 arcmin away from the Chandra aimpoint so the PSF is too broad for an extent analysis. We note that NGC 4889, a BCG in the Coma cluster with a black hole of mass of $2 \times 10^{10} M_{\odot}$ (McConnell et al 2011) also has a minicorona, one of the first discovered (Vikhlinin et al 2001).
4 DISCUSSION

If we add the 6 candidate ultramassive black holes (UMBH) in the Table of van den Bosch (2012) to the 2 found by McConnell et al. (2012), then we have 8 within about 105 Mpc. This represents a mass density of $2 \times 10^4 \text{M}_\odot \text{Mpc}^{-3}$ assuming a mean mass of $10^{10} \text{M}_\odot$. If they are all $2 \times 10^{10} \text{M}_\odot$ the mass density would be a factor of two larger and if we account for the fact that they are all Northern objects, which is the minimum selection effect operating, then the mass density increases by another factor of two. Their mass density could then easily be $10^5 \text{M}_\odot \text{Mpc}^{-3}$ which is a significant fraction of the mean mass density of black holes, estimated by e.g. Marconi et al (2004) at $4.6 \times 10^5 \text{M}_\odot \text{Mpc}^{-3}$ or Hopkins et al (2006) at $2.9 \times 10^5 \text{M}_\odot \text{Mpc}^{-3}$. The above 8 objects translate to a present UMBH space density of at least $4 \times 10^{-6} \text{Mpc}^{-3}$. With three UMBH in the Perseus cluster they appear to be strongly clustered.

The objects of McConnell et al. (2012) are BCGs, 3 of the van den Bosch (2012) sample are in the Perseus cluster and one other is in Abell 347. Hlavacek-Larrondo et al. (2012) have indirect arguments for UMBH in a distant population of BCGs. There is thus some evidence that the environment of a cluster, or whatever turns into a cluster, is conducive to the growth of UMBH. The galaxies that host them are of two types, the first are BCGs, with a high stellar mass, the second are unconditiously early-type galaxies with relatively low stellar mass, such as NGC 1277.

4.1 The growth of UMBH and their hosts

If there is a UMBH in NGC 1277 it is growing little at the present epoch, since its current mass doubling time is many Hubble times. Its bolometric Eddington limit is $3 \times 10^{46} \text{erg s}^{-1}$, which rivals the most luminous objects known and requires an accretion rate of $100 \text{M}_\odot \text{yr}^{-1}$. Even if it took billions of years to grow, we can expect that it was a powerful quasar or blazar in the past. Hopkins et al (2006), Ghisellini et al (2010) and Volonteri et al (2011) have all considered the growth of black holes of mass exceeding $10^7 \text{M}_\odot$, based on observations of quasars and blazars. The present number density they estimate for black holes above that mass is less than we are inferring for the UMBH, which are ten times more massive. This may indicate that the UMBH, if real, are now too numerous to have been regular quasars or blazars, but must have lost their accretion energy through mechanical means, for example powerful winds, or been highly obscured.

A possible scenario then emerges where the enormous power of the accreting UMBH stops any significant star formation in its neighbourhood. Such extreme AGN feedback could have been too fierce for new star formation to occur and only a compact stellar region or bulge survives from the earliest stages of growth. Of course the black hole has to be fuelled, which requires relatively low angular momentum gas to be fed into the centre, more or less continuously. Dubois et al (2012) show that this can occur at high redshifts. This would require that feedback occurs in a bipolar fashion, as expected if jets or winds from an accretion disc are involved, in order that the fueling along filaments can continue undisturbed. The large mass of the black hole means that the orientation of the object will be relatively fixed.

In this model, where the major UMBH growth phase is likely to happen in deep potential wells before a redshift of 3, we are left at the most massive black holes lying in compact bulges. At redshift 3, most UMBH would then resemble NGC 1277. (Van den Bosch et al 2012 have already noted the resemblance between NGC 1277 and typical red, passive galaxies at earlier times.) What the host galaxy eventually looks like then depends on how that bulge accretes more gas and stars, and how further feedback shapes the gas and thus star formation. Such a scenario is consistent with recent observational evidence that the growth of massive galaxies from redshifts of 2.5 to 1 occurs in an inside-out mode (van Dokkum et al 2010, Szomoru et al 2011 and references therein).

If the UMBH host lies in a cluster then it only later accretes or accumulates significant gas for star formation if it lies at the centre of the potential well and so has a low velocity with respect to its surroundings. Cannibalism, cooling flows and mergers can supply that object with an extensive halo of stars and gas. The object thus becomes a BCG. If the UMBH bulge orbits in the core of a cluster at $1000 \text{km s}^{-1}$, then it accumulates few stars and little gas and could end up resembling NGC 1277. Its outer dark matter halo will have dissolved into the general cluster halo.

Note that there is a requirement in the model, which is not easy to fulfill, that fuelling can proceed while powerful feedback is taking place and we have appealed to a special geometry to allow this to occur. This special requirement may be why few galaxies host a UMBH. Only when the geometry of the fuelling filaments is appropriate can a UMBH form, otherwise the central black hole is 10 to 100 times less massive.

The energy released in growing a black hole of mass $2 \times 10^{10} \text{M}_\odot$ is $4 \times 10^{43} \text{erg}$, which will heat $10^{13} \text{M}_\odot$ of gas, comparable to the gas in the present-day Perseus cluster, to $\sim 10$ keV. This could expel much of the gas in any early subcluster if the energy is widely distributed and little is radiated. Widespread heating to a few keV per particle by the growth of black holes has been invoked to explain the the X-ray properties of groups and clusters (e.g. the X-ray luminosity – temperature relation, Wu, Fabian & Nulsen 2000), but 10 keV is too much. Some inefficiency in the heating is required, such as could occur due to infrared radiation in an obscured scenario, or if the accretion process is intrinsically inefficient ($\epsilon < 0.1$).

4.2 An alternative interpretation: a bottom-heavy IMF

The data on NGC 1277 presented by van den Bosch et al (2012) indicate that it is an unusual galaxy with a high central mass-to-light ratio. Future observations will confirm whether this is due to a UMBH. An alternative possibility is that the Initial Mass Function (IMF) of the stars formed in the core of the galaxy is very bottom heavy, i.e. it has much of its mass in low mass stars which are not directly detected. Recent work by van Dokkum & Conroy (2010), Conroy & van Dokkum (2012) and Cappellari et al (2012) have shown that the IMF in early type galaxies is increasingly skewed to low mass stars as the velocity dispersion of the stars increases. This could be due to the higher pressure of extended gaseous atmospheres in deep potential wells (Krumholz 2012).

The high velocity dispersions found in the UMBH host galaxies already imply a bottom-heavy IMF in the candidate UMBH hosts. It is possible that the observations can be explained by a combination of low-mass stars and a less massive black hole than a UMBH. van den Bosch et al (2012) do however show that the mass-to-light ratio of the stellar component needs to be exceptional (e.g. $M/L > 10$) for the black hole mass to be significantly reduced.
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