A deep Chandra observation of the hot gaseous halo around a rare, extremely massive and relativistic jet launching spiral galaxy

S. A. Walker,1* J. Bagchi2 and A. C. Fabian1

1 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
2 The Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune University Campus, Post Bag 4, Pune 411007, India

ABSTRACT
We present a deep Chandra observation of the extremely massive spiral galaxy 2MASX J23453268-0449256, the first X-ray observation of this very rare system which features the largest known relativistic jets from a spiral galaxy. We detect extended X-ray emission from the hot halo surrounding the galaxy, reaching out to 80 kpc in radius. The hot halo is elongated along the plane of the spiral galaxy, and one possibility is that the powerful relativistic jets have disrupted the hot halo gas located perpendicular to the disk. Extrapolating best fits to the hot halo out to the virial radius and including all other baryonic mass, we find a baryon fraction in the range 0.09-0.16, which is lower than the mean cosmic baryon fraction of 0.171. We also detect extended emission which appears to be associated with the inner and outer southern radio lobes, and is possibly the result of inverse Compton emission. Using the observed X-ray and radio luminosity of the central AGN, the fundamental plane of Gultekin et al. predicts a black hole mass of $5 \times 10^8 M_\odot$, with a range of $1 \times 10^8 - 3 \times 10^9 M_\odot$ when the scatter in the fundamental plane relation is taken into account.

Key words: galaxies: individual (2MASX J23453268-0449256) - galaxies: ISM - galaxies: spiral - X-rays: galaxies - X-rays: general - X-rays: ISM

1 INTRODUCTION

Galaxy formation models have made the important prediction that galaxies are surrounded by hot gaseous halos since White & Rees (1978). These hot halos are predicted to form through the accretion of matter onto the dark matter halo, with shocks raising the baryons to the virial temperature (White & Frenk 1991; Benson 2010). It is predicted that the baryonic mass in these halos is comparable to or even exceeds the baryonic mass of the galaxies themselves, depending on the levels of pre-heating, galactic feedback heating, and cooling rates that are assumed (Sommer-Larsen 2004; Fukugita & Peebles 2006). This makes the hot halos cosmologically important as reservoirs of the ‘missing baryons’ from galaxies.

Observations of nearby galaxies have found that they are missing most of their baryons (e.g., Hoekstra et al. 2005; Heymans et al. 2006; Mandelbaum et al. 2006; Gavazzi et al. 2007; Jiang & Kochanek 2007; Bregman 2007) compared to the expected mean cosmic baryon fraction determined by WMAP ($f_b = 0.171 \pm 0.009$; Dunkley et al. 2009). In other galaxies, a variety of methods has confirmed that the baryonic mass is much lower than expected (e.g., Hoekstra et al. 2005; McGaugh 2005). It is possible that these hot gas halos contain the ‘missing baryons’ from these galaxies, bringing the total baryon budget of the galaxies into agreement with expectations based on the mean cosmic baryon fraction.

Extensive observations of hot halos around early-type galaxies in soft X-rays (0.5-2 keV) have already been made (Forman et al. 1985; O’Sullivan et al. 2001; Mulchaey & Jeltema 2010). However, as these galaxies have become elliptical, coronal gas can be produced through the merging process and associated star formation (Read & Ponman 1998). This makes it very difficult to accurately connect these halos with the galaxy formation process. These ellipticals are also commonly located in the centres of groups and clusters, and it can be challenging to separate the galaxy halo emission from the surrounding intragroup medium.

Greater insight can be achieved by studying the hot halos around disk galaxies, which should be much more direct tracers of the galaxy formation process since they have not undergone major merging. Since the hot halo mass and X-ray emission scales with galaxy mass, it is necessary to observe the most massive spiral galaxies to achieve a detectable X-ray signal.

Detecting soft X-ray haloes beyond the optical radii of spiral...
galaxies has proven to be very challenging, with only upper limits being derived in early studies with ROSAT (Benson et al. 2000) and Chandra (Rasmussen et al. 2009). Detects of emission extending a few kpc above the disks of spirals have been made, but these are the result of star formation in the galaxies, and are likely due to galactic fountains (e.g. Strickland et al. 2004; Li et al. 2006; Tüllmann et al. 2006).

It is only recently that a breakthrough in the observation of hot haloes around disk galaxies has been made, using Chandra and XMM-Newton to detect the hot halos in a handful of extremely massive, fast rotating spiral galaxies: NGC 1691 (Anderson & Bregman 2011), UGC 12591 (Dai et al. 2012), NGC 6753 (Bogdán et al. 2013) and NGC 266 (Bogdán et al. 2013). For these galaxies, extended soft X-ray emission has been detected out to ~80 kpc, far outside their optical radii. When the best fitting surface brightness models for these hot haloes were extrapolated out their virial radii, the total baryon fractions inferred were, however, still below the cosmic baryon fraction for all of these galaxies. In Bogdán et al. 2013, the baryon fractions obtained for NGC 1691 and NGC 6753 were 0.11 and 0.09 respectively, while Dai et al. 2012 obtained a much lower value of 0.03-0.05 for UGC 12591. Possible explanations for the missing baryons include AGN and supernova feedback expelling gas from the galactic potential well, and the possibility that preheating of the gas has prevented it from falling into the potential well as the galaxy formed.

Here we present a deep, 100ks, Chandra observation of the extremely massive, rapidly rotating (Vrot = 429 ± 30 km s−1), relativistic jet launching, spiral galaxy 2MASX J23453268-0449256 (hereafter J2345-0449) to detect its hot halo and measure its mass content. The radio and optical properties of this extremely rare and exciting galaxy have been studied in Bagchi et al. 2014. The kinematics of the optical Balmer Hα line observed with the IUCAA Girawali Observatory (IGO) 2m telescope, reveals an extremely large rotation speed, Vrot = 371/sin(i) = 429 (±30) km s−1, in the asymptotic flat region at r ≥ 10 kpc from the galactic center. This makes J2345-0449 one of the most massive known spiral galaxies, with a mass ~4× the Milky Way mass within an equivalent radius (Rigopoulou et al. 2002). Another striking result is the exceptionally large stellar velocity dispersion σ = 326 (±59) km s−1 measured within the central (3 arcsec, or 4.3 kpcs) region, higher than for the majority of bulge-less disks on such a spatial scale. This suggests a huge central concentration of mass, including a SMBH, and the lower limit from the optical data is 2×107M⊙.

This galaxy is also currently ejecting a collimated pair of relativistic jets out to ~415kpc. There are also larger (the largest yet seen) and more diffuse older radio lobes from previous jet activity reaching over ~1.6 Mpc which lack prominent hot spots and are no longer being energized by the jets. Since radio sources appear to require diffuse hot gas to act as a working surface for making the lobes, extended X-ray emission is expected in this system.

The close alignment of the inner and outer of the radio lobe pairs indicates that the spin axis of the central black hole has remained relatively stable over the timescale of ~108 yr between jet triggering episodes (Bagchi et al. 2014). This further suggests that the galaxy and central black hole have evolved together quite, with no major merging activity. The galaxy is also located in a relatively isolated galactic environment, with no nearby luminous galaxies, and it is not in the centre of a group or galaxy cluster.

It is extremely rare for a massive spiral galaxy to eject relativistic jets, as they are nearly always launched from the nuclei of bulge dominated ellipticals and not flat spirals. It is clear that J2345-0449 is an extremely rare system whose properties challenge the standard paradigm for the formation of relativistic jets in AGN. The fact that the jets are aligned almost exactly perpendicular to the plane of the disk would also suggest that the central SMBH has a high spin. The detailed X-ray observations we present here are necessary to fully understand this system and complement the excellent GMRT and VLA radio data.

Our Chandra observation is the first time this system has been detected in X-rays, as it is not visible in the ROSAT All Sky Survey (RASS). The unrivalled, sub-arcsecond spatial resolution of Chandra is ideal for the observation of extended hot haloes around massive spiral galaxies, allowing contaminating point sources to be removed.

The way powerful relativistic jets form remains unknown, and the reason why they are launched from ellipticals and not spirals (Matthews et al. 1964) has remained a mystery since the start of radio astronomy. This dichotomy is suspected to be related to fundamental black hole properties such as spin, accretion rate and mass (Blundell & Znajek 1977; Wilson & Colbert 1995; Sikora et al. 2007), but the details remain highly uncertain. Observations of unusual systems such as J2345-0449 provide an excellent and unique means of understanding what factors are important in the formation of relativistic jets near supermassive black holes in AGN.

We use a standard ΛCDM cosmology with H0 = 70 km s−1 Mpc−1, ΩM = 0.3, ΩΛ = 0.7. For the redshift of J2345-0449, z = 0.0755, the luminosity distance is 342 Mpc and the angular scale is 85.9 kpc/arcmin. All errors unless otherwise stated are at the 1σ level.

2 OBSERVATIONS

Chandra observed J2345-0449 for 100ks between 2014-08-23 and 2014-08-24 (PI S. A. Walker), using the ACIS-S detector owing to its higher effective area than ACIS-I. As shown in Fig. 1, the Chandra observation covers the galaxy, the southern inner radio lobe and part of the southern outer radio lobe.

3 DATA REDUCTION AND IMAGES

The Chandra observation was reduced using CIAO version 4.6, using the latest calibrations. The events file was reprocessed using the task CHANDRA_REPRO to filter out periods of flaring. The task FLUX_OBS was used to extract images in a soft band (0.5-2.0 keV), which was chosen to maximise the signal to noise of the detection of the hot halo surrounding the galaxy, and a hard band (2.0-6.0 keV), which is used later to determine the contribution of the extended X-ray emission from Low Mass X-ray Binaries (LMXBs). An image was also extracted in a broad, 0.5-7.0 keV band to enable point source detection and removal. Point sources were identified from the broad band image using WAVDETECT, using a PSF (point spread function) map generated using MKPFMAP.

We detect 100 counts from the hot halo and 70 counts from the central AGN. The left panel of Fig. 1 shows the soft band, point source subtracted image which has been binned by a factor of 8 and then smoothed using a Gaussian kernel of radius 6 pixels. The central AGN has also been removed from this image. There is clear extended emission around the galaxy J2345-0449. In Fig. 2, we show a zoom in of the soft X-ray galaxy emission, compared to the SDSS image of the galaxy. The X-ray emission appears elongated along the plane of the galaxy disk, but is much larger in scale, with a diameter of around 160 kpc. This far exceeds the optical radius of the...
Figure 1. Left: Soft band (0.5-2.0 keV) image of the whole Chandra field of view. Point sources detected with WAVDETECT have been removed, the image binned by a factor of 8 and the image smoothed with a Gaussian kernel with a radius of 6 pixels. X-ray features coinciding with the inner and outer southern lobes are highlighted. Right: NVSS image of the radio emission, showing the inner and outer lobes, with the Chandra field of view shown in the left panel overplotted as the white square.

Figure 2. Left: Soft band (0.5-2.0 keV) Chandra image which is the same as the left panel of Fig. 1 but zoomed in on the galaxy. Right: SDSS image of the galaxy, with the X-ray contours overplotted in green. Both images have had their coordinate systems matched.
galaxy (25 kpc), showing that we are detecting emission from the hot halo.

The bolometric X-ray luminosity of the detected parts of the extended halo is $9.0 \pm 2.0 \times 10^{39}$ erg s$^{-1}$. This is in reasonable agreement with the total bolometric X-ray luminosities obtained in Bogdáns et al. (2013) for NGC 1691 and NGC 6753, which are $7.2 \pm 1.7 \times 10^{39}$ erg s$^{-1}$ and $7.0 \pm 0.9 \times 10^{40}$ erg s$^{-1}$ respectively (these are the total luminosities in the 0.05-0.3 keV range).

The shape of the extended X-ray halo emission is incompatible with a galactic fountain origin due to star formation activity. Galactic fountains lead to extended emission above and below the disk (where we actually observe a lack of extended emission) and do not produce extended X-ray emission outside the optical radius of the disk (e.g. Strickland et al. 2004).

There are also suggestions of extended emission from the inner southern radio lobe and part of the outer southern lobe covered by the observation. No galaxies are coincident with this southern extended emission, so it is possible that we are seeing inverse Compton emission from the inner and outer southern lobes. A zoom in comparison of the inner southern lobe X-ray and radio features is shown in Fig. 3. We detect 22 counts from the inner lobe (a 3 sigma detection), and 60 counts from the small part of the outer lobe (just 10 percent) we cover.

4 ANALYSIS

4.1 Surface Brightness profiles

The surface brightness around the galaxy appears asymmetric, with the bulk of the emission occurring in the plane of the central galaxy. It is possible that the powerful radio jets in this system have disturbed the hot halo perpendicular to the plane, removing gas from it. To maximise the signal to noise of the surface brightness profile of the hot halo, we initially consider only the directions away from the jets.

In Fig. 3, we show the soft band (0.5-2.0 keV) surface brightness profile over the halo as the black points, avoiding the regions to the north and south of the galaxy where the jets are located and where there appears to be little X-ray emission. The background level is shown as the solid horizontal line. The emission is detected out to a radius of around 80 kpc, similar to the extent found for the halo around UGC 12591 in Dai et al. (2012).

We need to account for contamination from LMXBs, which X-ray emission also declines with radius from the centre of the galaxy. To do this, we follow Anderson & Bregman (2011) and find the surface brightness profile for the same regions in a hard band, 2.0-6.0 keV, in which the emission should be dominated by LMXB emission due to the low temperature of the expected hot halo ($kT \sim 0.6$ keV). We then calculate the expected emission in the 0.5-2.0 keV band from these LMXBs, assuming them to have a powerlaw spectrum with an index of $\Gamma = 1.56$. This is motivated by Irwin et al. (2003), which found a universal spectrum for the integrated emission from low mass X-ray binaries of this form.

We subtract the calculated LMXB contamination from the soft band surface brightness profile, and this result is shown by the red points in Fig. 4. The LMXB contamination constitutes only around 10 percent of the total emission in the soft band, so the effect is not substantial.

In Fig. 5, we compare the shape of the background subtracted (and LMXB corrected) X-ray surface brightness profile with that of the background subtracted K-band profile from 2MASS data. The 2MASS profile has been scaled to match the X-ray profile in the innermost bins. We see that the X-ray surface brightness profile is clearly much more extended than the K-band profile, with X-ray emission out to at least 80 kpc from the galaxy centre.

5 HALO MASS AND BARYON FRACTION

5.1 Total galaxy mass

To determine the expected virial mass ($M_{200}$), we follow the approach of Bogdán et al. (2013) and use the baryonic Tully-Fisher relation (McGaugh 2005) for the cold dark matter cosmogony, $M_{200} \propto V_{\text{max}}^{23.23}$, which relates the virial mass to the maximum rotational velocity ($V_{\text{max}} = 430$ km s$^{-1}$). As in Bagchi et al. (2014),
we find that, scaling from the virial mass found for NGC 1961 in Bogdán et al. (2013), we obtain $M_{200} = 1.05 \times 10^{13} M_\odot$ and $r_{200} = 450$ kpc.

### 5.2 Stellar mass

In the central regions of the galaxy, the mass is dominated by the stellar mass, which can be estimated using the total K band absolute magnitude of $M_K = -26.15$ determined from 2MASS data. Using a mass to light ratio of 0.78 with a range $0.6-0.95$ (Bell et al. 2003, Dai et al. 2012), this yields a stellar mass of $4.6_{-1.0}^{+1.0} \times 10^{11} M_\odot$.

### 5.3 Hot gas mass

The hot gas mass is expected to provide a significant part of the total baryonic mass of a galaxy, with most of this residing at large radius. We can only detect the hot halo out to a radius of 80 kpc, so to calculate the total hot gas mass within the expected virial radius of 610 kpc, we must fit the observed surface brightness profile, convert it into a density profile, and extrapolate this out to $r_{200}$.

The hot halo appears asymmetric, and gas may have been removed along the jet directions. To account for this possibility, we calculate two different estimates of the hot halo mass. The first is the total hot gas mass of an original halo which we assume to have been lost along the jet directions, we then work out the total mass assuming spherical symmetry, in effect reconstructing the gas mass which we assume to have been removed to the north and south.

To do this, we fit the LMXB subtracted soft band surface brightness profile presented in Fig. 4 with a beta model:

$$S(r) = S_0 \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{-0.5-3\beta}$$  \hspace{1cm} (1)

added to a constant background level. The best fit is shown as the solid curve in Fig. 1, which has best fitting parameters of $S_0 = 1.9 \times 10^{-6}$ cts/s/arcsec$^2$, $r_0 = 1.0$ kpc and $\beta = 0.43$. The beta model is the theoretical expectation for an isothermal sphere in hydrostatic equilibrium, and has been found to provide reasonable fits to hot gas halos around elliptical galaxies, and to the large scale intracluster medium emission in galaxy clusters and groups.

Under the assumption of constant metallicity and uniform temperature, the gas density profile is then given by:

$$n(r) = n_0 \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{-1.5-3\beta}$$  \hspace{1cm} (2)

Using the ACIS-S response files, we can convert the observed surface brightness profile into the normalisation of an absorbed APEC component at each radius. We fix the APEC parameters to typically expected values of $kT=0.6$ keV (Bogdán et al. 2013) and $Z=0.5Z_\odot$. The redshift is fixed to $z=0.0755$, and we fix the absorbing column to the LAB survey (Kalberla et al. 2003) value of $3 \times 10^{20}$ cm$^{-2}$. Unfortunately, due to the low count rate, we are unable to determine these parameters accurately by direct spectral fitting. We can then find the density profile, which has the beta model form of equation (2) with $n_0 = 0.06$ cm$^{-3}$.

Integrating this density profile out to $r_{200}$ and assuming spherical symmetry to reconstruct the mass assumed to have been lost along the jet directions, we obtain a total hot gas mass of $8.1 \times 10^{11} M_\odot$, assuming a metallicity of $0.5 Z_\odot$. The hot gas mass determination depends significantly on the actual metal abundance, with a higher abundance leading to more emission from the Fe L line.
giving a lower gas density for a fixed count rate. Taking the range 0.2-1.0 Z⊙, the corresponding range in total hot gas mass is 5.9-11.7×10^{11} M⊙.

In our second hot halo mass estimate, we just find the mass of hot gas currently in the system, taking into account the possibility that the jets have removed the gas they have interacted with to the north and south. We fit a beta model to the surface brightness profile and proceed as before, but now exclude cones of opening angle 90 degrees to the north and south when performing the integration, which is a upper limit to the amount of mass removed. We find a total hot gas mass in the range 4.1-8.3×10^{11} M⊙, factoring in the uncertainty in the metal abundance as before.

5.4 Baryon Budget

Using our best fit value of the reconstructed hot gas mass (taking into account gas that may have been removed by the jets), and the stellar mass, the total baryonic mass within r_{200} is estimated to be 8.1×10^{11} M⊙. Factoring in the effect of the uncertainty in the metal abundance on the hot gas mass, the errors in the beta model fit, and the effect of the uncertainty in the mass to light ratio on the stellar mass, gives a total baryonic mass range of 9.5-17.3×10^{11} M⊙. Using the total virial mass (including dark matter) of M_{200} = 1.05×10^{13} M⊙ calculated earlier, this yields an estimate of the baryon fraction in the range 0.09-0.16, with a best fit value of 0.12. This is lower than the mean cosmic baryon fraction of 0.171±0.009 measured by WMAP, but given the large uncertainty in the baryonic mass determination, our upper bound is in reasonable agreement. Our best fit baryon fraction of 0.12 is in good agreement with the value of 0.11 obtained for the similarly massive NGC 1961 in Bogdán et al. (2013).

If we take into account the possibility that the jets have removed the halo to the north and south, and make the basic estimate that they have removed the gas within cones of opening angle 90 degrees, the hot halo mass in the system is lower, with a range of 4.1-8.3×10^{11} M⊙. This yields a lower baryon fraction in the range 0.07-0.13, which is now much lower than the mean cosmic baryon fraction of 0.171.

The AGN feedback in this system is possibly the mechanism responsible for removing gas from the potential well, accounting for the low baryon fraction. However there are other possibilities. Our estimate of the total hot halo mass has involved extrapolating the beta model fit from 80 kpc out to 450 kpc, which is clearly susceptible to systematic errors if the actual density profile differs from a beta model in the halo outskirts. It is possible that the hot halo gas is rotating rapidly with the galaxy, which may act to push gas out to larger radius, reducing the central density and observed X-ray luminosity (Negri et al. 2014), for example, found that above a velocity dispersion of 200 km s^{-1} hot haloes supported by isotropic rotation are around an order magnitude less luminous in X-rays than haloes supported fully by the velocity dispersion alone. This could put more of the hot halo mass in the unobservable outskirts beyond 80 kpc from the galaxy centre, causing the beta model fit to underestimate the amount of gas in the halo outskirts. The rotation of the hot halo may also contribute to some of the flattening of the X-ray emission in the plane of the disk we observe.

6 BLACK HOLE MASS

Bagchi et al. (2014) found that the stellar velocity dispersion within the central 2.35 kpc region of the galaxy is exceptionally large (σ = 379 ± 25 km s^{-1} along the major axis, and 351 ± 25 km s^{-1} along the minor axis), strongly suggesting the presence of a highly massive black hole. Using the black hole mass to bulge mass correlation of Marconi & Hunt (2003), the black hole mass is 2.5±0.5×10^8 M⊙, however a much larger mass of 1.4×10^{9} M⊙ can be found using the velocity dispersion in X-rays.

As the galaxy lacks a classical bulge (it has a pseudobulge), it is challenging to accurately estimate the black hole mass using scaling relations with the bulge mass.

We can now use the X-ray and radio luminosities of the central AGN to obtain another estimate the central black hole mass using the fundamental plane of Gültekin et al. (2009):

\[ \log M_{\text{BH,8}} = \mu_0 + c_1 \log L_{R,38} + c_2 \log L_{X,40} \]

where M_{BH,8} is the black hole mass in units of 10^8 M⊙, L_{R,38} is the 5GHz radio luminosity in units of 10^{38} erg s^{-1}, and L_{X,40} is the 2-10keV X-ray luminosity in units of 10^{40} erg s^{-1}. The constants are \( \mu_0 = 0.19 \pm 0.19, c_1 = 0.48 \pm 0.16 \) and \( c_2 = -0.24 \pm 0.15 \).

Using our best fit value of the reconstructed hot gas mass (taking into account gas that may have been removed by the jets), the black hole mass is 5×10^8 M⊙, though there is considerable intrinsic scatter in the mass distribution of this fundamental plane relation of 0.77 dex. The range of black hole mass taking into account the scatter is 5×10^8 - 3×10^9 M⊙, which encompasses the possibility that the central black hole is exceptionally massive (i.e. > 10^{9} M⊙).

7 CONCLUSIONS

Using deep Chandra observations we detect an extended X-ray halo around the massive spiral galaxy J2345-0449, reaching out to 80 kpc from the galaxy centre, far in excess of the the extent of the optical emission. The X-ray halo appears elongated along the plane of the galaxy, which is possibly the result of the powerful jets removing gas above and below the galactic plane. We also detect extended X-ray emission which is spatially coincident with the inner and outer radio lobes, and may by the result of inverse Compton scattering.

Assuming spherical symmetry to reconstruct the halo mass before the interaction with the jets, we find that the total mass in hot gas is 8.1×10^{11} M⊙, and that the baryon fraction for the galaxy as a whole is 0.12, with a range of 0.09-0.16 when systematic uncertainties are taken into account. This is lower than the mean baryon fraction of 0.171, as has been found for other massive spiral galaxies (NGC 1961, UGC 12591, NGC 6753 and NGC 266). In J2345-0449, we may be seeing first hand the way AGN feedback expels gas from massive spiral galaxies, contributing to at least some of the baryon deficit below the mean baryon fraction.

The rotation of the hot halo may also cause our determination of the baryon fraction to be an underestimate. It is possible that the rotation pushes out gas to larger radii, lowering the gas density and observed X-ray luminosity in the central regions. This would lead to more of the hot halo mass being in the unobservable outskirts of the halo, in the range 80-450 kpc from the galaxy centre. Extrapolating the beta model fit from the central regions may therefore be underestimating the mass of gas in the outskirts. It is possible that the rotation of the halo may also contribute to its flattened appearance in X-rays.

Using the X-ray and radio luminosities of the central AGN, the fundamental plane of Gültekin et al. (2009) gives a central black hole mass of 5×10^8 M⊙, with a range of 1×10^8 - 3×10^9 M⊙ when the scatter in the plane is taken into account.
ACKNOWLEDGEMENTS

SAW and ACF acknowledge support from ERC Advanced Grant FEEDBACK. This work is based on observations obtained with the Chandra observatory, a NASA mission.

REFERENCES

Anderson M. E., Bregman J. N., 2011, ApJ, 737, 22
Bagchi J., Vivek M., Vikram V., Hota A., Biju K. G., Sirothia S. K., Srianand R., Gopal-Krishna Jacob J., 2014, ApJ, 788, 174
Bell E. F., McIntosh D. H., Katz N., Weinberg M. D., 2003, ApJS, 149, 289
Benson A. J., 2010, Physics Reports, 495, 33
Benson A. J., Bower R. G., Frenk C. S., White S. D. M., 2000, MNRAS, 314, 557
Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433
Bogdán Á., Forman W. R., Kraft R. P., Jones C., 2013, ApJ, 772, 98
Bogdán Á., Forman W. R., Vogelsberger M., Bourdin H., Sijacki D., Mazzotta P., Kraft R. P., Jones C., Gilfanov M., Churazov E., David L. P., 2013, ApJ, 772, 97
Bregman J. N., 2007, ARA&A, 45, 221
Dai X., Anderson M. E., Bregman J. N., Miller J. M., 2012, ApJ, 755, 107
Dressler A., 1980, ApJ, 236, 351
Dunkley J., Komatsu E., Nolta M. R., Spergel D. N., Larson D., Hinshaw G., Page L., Bennett C. L., Gold B., Jarosik N., Weiland J. L., Halpern M., Hill R. S., Kogut A., Limon M., Meyer S. S., Tucker G. S., Wollack E., Wright E. L., 2009, ApJS, 180, 306
Forman W., Jones C., Tucker W., 1985, ApJ, 293, 102
Fukugita M., Peebles P. J. E., 2006, ApJ, 639, 590
Gavazzi R., Treu T., Rhodes J. D., Koopmans L. V. E., Bolton A. S., Burles S., Massey R. J., Moustakas L. A., 2007, ApJ, 667, 176
Gültekin K., Cackett E. M., Miller J. M., Di Matteo T., Markoff S., Richstone D. O., 2009, ApJ, 706, 404
Heymans C., Bell E. F., Rix H.-W., Barden M., Borch A., Caldwell J. A. R., McIntosh D. H., Meisenheimer K., Peng C. Y., Wolf C., Beckwith S. V. W., Häußler B., Jahnke K., Jogee S., Sánchez S. F., Somerville R., Wisotzki L., 2006, MNRAS, 371, L60
Hoekstra H., Hsieh B. C., Yee H. K. C., Lin H., Gladders M. D., 2005, ApJ, 635, 73
Irwin J. A., Athey A. E., Bregman J. N., 2003, ApJ, 587, 356
Jiang G., Kochanek C. S., 2007, ApJ, 671, 1568
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R., Pöppel W. G. L., 2005, A&A, 440, 775
Li Z., Wang Q. D., Irwin J. A., Chaves T., 2006, MNRAS, 371, 147
Mandelbaum R., Seljak U., Kauffmann G., Hirata C. M., Brinkmann J., 2006, MNRAS, 368, 715
Marconi A., Hunt L. K., 2003, ApJ, 589, L21
Matthews T. A., Morgan W. W., Schmidt M., 1964, ApJ, 140, 35
McGaugh S. S., 2005, ApJ, 632, 859
Mulchaey J. S., Jeltema T. E., 2010, ApJ, 715, L1
Negri A., Posacki S., Pellegrini S., Ciotti L., 2014, MNRAS, 445, 1351
O’Sullivan E., Forbes D. A., Ponman T. J., 2001, MNRAS, 328, 461
Rasmussen J., Sommer-Larsen J., Pedersen K., Toft S., Benson A., Bower R. G., Grove L. F., 2009, ApJ, 697, 79
Read A. M., Ponman T. J., 1998, MNRAS, 297, 143
Rigopoulou D., Franceschini A., Aussel H., Genzel R., Thathe N., Cesarsky C. J., 2002, ApJ, 580, 789
Sikora M., Stawarz L., Lasota J.-P., 2007, ApJ, 658, 815
Sommer-Larsen J., 2006, ApJ, 644, L1
Strickland D. K., Heckman T. M., Colbert E. J. M., Hoopes C. G., Weaver K. A., 2004, ApJS, 151, 193
Tüllmann R., Pietsch W., Rossa J., Breitschwerdt D., Dettmar R.-J., 2006, A&A, 448, 43
White S. D. M., Frenk C. S., 1991, ApJ, 379, 52
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
Wilson A. S., Colbert E. J. M., 1995, ApJ, 438, 62