XMM-NEWTON DETECTS A HOT GASEOUS HALO IN THE FASTEST ROTATING SPIRAL GALAXY UGC 12591

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ABSTRACT

We present our XMM-Newton observation of the fastest rotating spiral galaxy UGC 12591. We detect hot gas halo emission out to 80 kpc from the galaxy center, and constrain the halo gas mass to be smaller than $4.5 \times 10^{11} M_\odot$. We also measure the temperature of the hot gas as $T = 0.64 \pm 0.03$ keV. Combining our x-ray constraints and the near-infrared and radio measurements in the literature, we find a baryon mass fraction of $0.03-0.05$ in UGC 12591, suggesting a missing baryon mass of $70\%$ compared with the cosmological mean value. Combined with another recent measurement in NGC 1961, the result strongly argues that the majority of missing baryons in spiral galaxies do not reside in their hot halos. We also find that UGC 12591 lies significantly below the baryonic Tully–Fisher relationship. Finally, we find that the baryon fractions of massive spiral galaxies are similar to those of galaxy groups with similar masses, indicating that the baryon loss is ultimately controlled by the gravitational potential well. The cooling radius of this gas halo is small, similar to NGC 1961, which argues that the majority of the stellar mass of this galaxy is not assembled as a result of cooling of this gas halo.

Key words: galaxies: halos – galaxies: individual (UGC 12591) – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Observations show that nearby galaxies 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) when compared to the cosmological baryon to matter ratio (e.g., $f_0 = 0.171 \pm 0.009$ from Wilkinson Microwave Anisotropy Probe (WMAP); Dunkley et al. 2009). For example, the Milky Way is missing two-thirds of its baryon allotment (e.g., Sakamoto et al. 2003) and less massive galaxies have retained less than $10\%$ of their baryons (e.g., Corbelli & Sommer-Larsen 2006; Fukugita & Peebles 2006; also see the review by Benson 2010). This component can be difficult to detect for spiral galaxies due to its faintness, especially if the gas density profile is flat. As another possibility, the missing baryons from galaxies may have escaped from the potential wells of the galaxies but reside in their parent groups or clusters (e.g., Humphrey et al. 2011). Finally, the missing baryons can be in the form of warm–hot intergalactic medium (Cen & Ostriker 1999, 2006). Deep x-ray observations are needed to distinguish these different scenarios.

The situation is different for rich galaxy clusters, where the gas mass dominates the baryon content, and the baryon fractions in these massive systems are close to the cosmological value after combining the gas and stellar baryon contributions (e.g., Vikhlinin et al. 2006; Allen et al. 2008). The measurements of the baryon fraction in different systems suggest that the fraction depends on the dynamical mass of the systems: rich clusters retain their cosmological allotment of baryons, while galaxies are baryon-poor. We summarize the situation in Dai et al. (2010) by combining the archival data points reported in the literature and our stacking analysis result using the ROSAT All-Sky Survey (RASS) data of 4000 nearby galaxy groups and clusters (Dai et al. 2007). We find that the baryon fractions from dwarf galaxies to rich galaxy clusters can be fit by a broken power-law model with the break at the circular velocity of $V_c \sim 440$ km s$^{-1}$. The scatter of the fractions about the mean relation is small considering the huge dynamic range of the systems. Examining the relation further, we find that the baryon fractions are similar for different systems with similar total masses but different compositions. For example, the baryon fractions of poor galaxy groups, where the baryon mass is still dominated by the gas mass, are close to those of massive galaxies, where the baryon mass is dominated by the stellar mass. Such a coincidence is puzzling considering the differences between their mass compositions and energy feedback mechanisms.

To test whether the missing baryons reside in galaxy halos and further constrain the baryon loss in different mass scales, we focus on the massive galaxy UGC 12591 ($z = 0.0232$, R.A.: 23 25 21.7, decl.: +28 29 43 J2000). UGC 12591 is a spiral galaxy with the largest measured rotational velocity to date (466–500 km s$^{-1}$; Giovanelli et al. 1986; Paturel et al. 2003). Figure 1 shows the Two Micron All Sky Survey (2MASS) K-band (Skrutskie et al. 2006) and DSS V-band images of the galaxy in the left and middle panels, respectively, where the optical image clearly shows a dust lane across the galaxy. To appreciate this galaxy, its optical–IR luminosity is nine times that of M31. Therefore, this individual galaxy is more luminous than the Hickson groups, and half as luminous as the Fornax cluster, though obviously its stellar emission is much more compact than these systems. Besides the optical–IR emission, UGC 12591 is also detected as a point source ($<3^\prime\prime$) in the Very Large Array (VLA) image attributed to a supermassive black hole (Condon et al. 1991). In this paper, we combine our XMM-Newton observation of UGC 12591 with
2MASS and other data to determine the baryon fraction and the composition of this massive spiral galaxy. Throughout the paper, we use the cosmological parameters from WMAP with $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.26$, and $\Omega_{\Lambda} = 0.74$ (Dunkley et al. 2009).

2. XMM-NEWTON OBSERVATION AND DATA REDUCTION

We observed UGC 12591 with the XMM-Newton X-ray Observatory (Jansen et al. 2001) on 2008 December 15 for 80 ks. The observation log is listed in Table 1. We reprocessed the PN and MOS data using the SAS9.0.0 software tools epchain and omcchain, and filtered the events with the patterns $\leq 4$ and $\leq 12$ for the PN and MOS chips, respectively. We filtered background flares by excluding the intervals with background count rates of $CR > 0.4$ counts s$^{-1}$ and $CR > 0.2$ counts s$^{-1}$ in the 10–12 keV band in PN and MOS observations, respectively, following the standard suggestion from SAS. We also applied a low energy flare filter to exclude flares in the 0.6–1.4 keV band (Table 1). We obtained net exposure times of 31.2, 50.0, and 46.0 ks for PN, MOS1 and MOS2 CCDs, respectively. We detected serendipitous sources in the field using the SAS tools, and masked the bright serendipitous source regions in the subsequent analysis with a flux limit of $1.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. The central region of UGC 12591 is clearly detected in x-rays in all PN (Figure 1, right) and MOS CCDs. However, a detailed analysis of the background is needed to determine the extent to which the outer region is detected.

2.1. Background Determination

We estimated the PN and MOS backgrounds by directly fitting the background spectra (e.g., Kuntz & Snowden 2008; Leccardi & Molendi 2008), a 7’–10’ ring from the center for PN and an 11’–13’ ring for MOS. We did not use the outermost ring of the PN spectra because it is close to the edge of the CCD and the background is much more difficult to model. Here, we briefly describe the method. The XMM-Newton background is composed of several components induced by soft protons, cosmic rays, galactic, and extragalactic background photons (e.g., Carter & Read 2007). After filtering the background flares in the hard and the soft energy bands, we had removed most of the variable soft proton background. We then extracted the spectrum from an outer annulus background region, and the remaining background components in this spectrum are from quiescent soft protons, cosmic rays, galactic, and extragalactic background photons. The cosmic-ray background can be subtracted by comparing the surface brightnesses in the outer ring and out-of-FOV (OFOV) regions. We can then decompose the contributions from the photon background and quiescent soft proton background through spectral analysis.

We modeled the quiescent soft proton induced background as an unfolded (not convolved with the instrument response) power law with $\Gamma = 0.4$ fixed for PN and an unfolded broken power law with parameters fixed at $\Gamma_1 = 0.4$, $\Gamma_2 = 0.8$, and $E_b = 5$ keV for MOS, and allowed the normalizations to vary (e.g., Leccardi & Molendi 2008). There was a small difference between the PN and MOS models at high energies $E > 5$ keV, and we found that a single power-law model for PN provided a better fit. This could be attributed to the differences in the flare exclusion procedure or the residual background from cosmic rays. We modeled the extragalactic background as a folded power law with $\Gamma = 1.4$ fixed and Galactic background with a folded APEC model with parameters fixed at temperature $T = 0.197$ keV, metallicity $Z = 1 Z_\odot$, and redshift $z = 0$ (Leccardi & Molendi 2008). We allowed the normalizations of these two components to vary during the spectral fitting process and independently for the PN, MOS1, and MOS2 spectra, such that we could have three independent measurements. Figure 2 shows the PN and MOS spectra of the outer ring background region, where we used the OFOV spectra as backgrounds, and the fitting parameters are listed in Table 2. The spectra are reasonably fit by the combination of photon background, quiescent soft proton background, and residual metal emission.

![Figure 1. Images of UGC 12591 in the 2MASS K, DSS V, and XMM-Newton PN x-ray bands.](image1)

![Table 1. XMM-Newton Observation of UGC 12591](table1)
This is consistent with the unresolved extragalactic background (e.g., Cowie et al. 2002), which predicts a flux of $1.2 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ by integrating to our bright source exclusion limit of $2.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ for the outer ring. The consistency between the PN, MOS1, and MOS2 measurements and with that from the Chandra Deep Field suggests that we have decomposed the extragalactic emission successfully. We also calculated fluxes for the extragalactic and Galactic component in the ROSAT R45 band (0.47–1.21 keV) with the extragalactic component flux of $3.1 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ and the Galactic component flux of $1.2–2.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ for PN, MOS1, and MOS2. This difference between the Galactic background measured in PN and MOS spectra may arise from the difficulty to separate the Galactic background and proton induced background in the soft energy band below 1 keV. We compared this flux range with the one estimated from the x-ray Background Tool (Snowden et al. 1997) provided by NASA HEASARC using RASS. In particular, we queried the soft x-ray background from an annulus centered at UGC 12591 with inner and outer radii of 0.8 and 1 and obtained a background flux of $4.9 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ in the ROSAT R45 band. This is consistent with the sum of our measured extragalactic and Galactic backgrounds. We estimated that the ratios between the quiescent soft proton background and photon background are 0.389, 0.200, and 0.087 for PN, MOS1, and MOS2, respectively, in the 0.6–1.4 keV band. The differences in the ratios reflect the differences between the instrument response and flare exclusion thresholds used in the analysis. After this step, we can scale the two components to inner regions using the corresponding vignetting profiles.

### 2.2. Surface Brightness Profile of UGC 12591

We measured the surface brightness profile of UGC 12591 by extracting events in consecutive annuli of 0.5 widths (13.6 kpc). For the region within 1′ from the center, we further divided the annuli using 0.25 widths. We measured average exposure times within each annulus. To maximize the signal-to-noise ratio (S/N) of the surface brightness profile, we measured it in the soft x-ray (0.6–1.4 keV) band, since we expect most of the hot halo emission in this band. We first subtracted the surface brightness of the OFOV region, which is unvignetted, from the surface brightness profile. We then subtracted the photon- and non-photon-induced background based on our background decompositions obtained by fitting the outer background spectra. We plot the net surface brightness profiles and their uncertainties of UGC 12591 after correcting for vignetting measured from PN and MOS CCDs, in Figures 3–5, respectively. UGC 12591 is detected out to $\sim$3′ in the PN data and $\sim$1.5 in the MOS data. We also extracted the surface brightness profile of UGC 12591 in the hard x-ray band between 2 and 8 keV to measure the contribution from point sources. The hard component from point sources is detected to 1′ and 0.5, respectively, in the PN and MOS data. After scaling the 2–8 keV count rate to the 0.6–1.4 keV count rate for the point-source contribution, assuming $\Gamma = 1.56$ (Irwin et al. 2003), we found the contribution from point sources in the 0.6–1.4 keV band flux is 45% within the central 1′ region.

### 2.3. Spectral Analysis

We extracted the central spectra of UGC 12591 within 50″ from the PN and MOS data. The background regions were chosen in a region with large off-axis angles to avoid possible contamination from the extended halo emission detected in UGC 12591. We chose to fit the central 50″ region because

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**Figure 2. XMM-Newton PN and MOS spectra extracted from an outer annulus background region.** We fit the spectra using the OFOV spectra as backgrounds, and modeled the spectra as a combination of photon, quiescent soft proton, and residual metal emission line induced backgrounds. The three lines represent the unfolded component, the folded component, and the total emission, respectively.
Table 2

Spectral Fitting Results for the Outer Ring

| Model Name     | Model Parameter | Fixed/Free | PN     | MOS1   | MOS2   |
|----------------|-----------------|------------|--------|--------|--------|
| Folded pow     | Γ               | Fixed      | 1.4    | 1.4    | 1.4    |
| 2–8 keV flux (10^{-11} erg cm^{-2} s^{-1} deg^{-2}) | Free | 1.2    | 1.3    | 1.3    |
| 0.47–1.21 keV flux (10^{-12} erg cm^{-2} s^{-1} deg^{-2}) | Free | 3.0    | 3.0    | 3.1    |
| Folded apec    | T (keV)         | Fixed      | 0.197  | 0.197  | 0.197  |
| Metallicity Z (Z⊙) | Fixed | 1    | 1    |        |
| Redshift       |                | Fixed      | 0      | 0      | 0      |
| 0.47–1.21 keV flux (10^{-12} erg cm^{-2} s^{-1} deg^{-2}) | Free | 1.7    | 1.2    | 2.5    |
| Folded wabs    | Galactic N_H (10^{20} cm^{-2}) | Fixed | 1.62   | 1.62   | 1.62   |
| Γ₁             |                | Fixed      | 0.4    | 0.4    | 0.4    |
|                | E₀ (keV)       | Fixed      | 20.0   | 5.0    | 5.0    |
| Γ₂             |                | Fixed      | 0.8    | 0.8    | 0.8    |
| Unfolded gau   | Al Kα E (keV)  | Fixed      | 1.487  | 1.487  | 1.487  |
| Unfolded gau   | Al Kβ E (keV)  | Fixed      | ...    | 1.557  | 1.557  |
| Unfolded gau   | Si Kα E (keV)  | Fixed      | ...    | 1.74   | 1.74   |
| Unfolded gau   | Au Mα E (keV)  | Fixed      | ...    | 2.11   | 2.11   |
| Unfolded gau   | Au Mβ E (keV)  | Fixed      | ...    | 2.2    | 2.2    |
| Unfolded gau   | Cr Kα E (keV)  | Fixed      | ...    | 5.412  | 5.412  |
| Unfolded gau   | Fe Kα E (keV)  | Fixed      | 6.4    | 6.4    | 6.4    |
| Unfolded gau   | Ni Kα E (keV)  | Fixed      | 7.47   | 7.47   | 7.47   |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 8.04   | ...    | ...    |
| Unfolded gau   | Ni Kβ E (keV)  | Fixed      | 8.265  | ...    | ...    |
| Unfolded gau   | Zn Kα E (keV)  | Fixed      | 8.63   | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 8.9    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kα E (keV)  | Fixed      | 9.2    | ...    | ...    |
| Unfolded gau   | Cu Kβ E (keV)  | Fixed      | 9.2    | ...    | ...    |

Notes. We modeled the spectra with a folded component (modified by instrument response) and an unfolded component. The folded component includes photon backgrounds, and a power-law and an apec model both modified by Galactic absorption. The unfolded component includes the particle-induced backgrounds, and a broken power-law model plus several metal emission lines. We used the OFOV spectra as backgrounds.

a The normalizations of the unfolded components are all free in our fits. Since they are instrument specific, we do not list them here.

Figure 3. Surface brightness profile of UGC 12591 from the XMM-Newton PN observation. The circles represent the raw surface brightness profile, and the triangle the OFOV surface brightness. The cross symbols are results of subtracting the raw surface brightness profile by the OFOV surface brightness. The dashed line is our model for the background including the contributions of photon, quiescent soft proton, and residual metal emission lines, which fit the outer regions well. The squares and their associated error bars denote the net surface brightness profile and its uncertainty of UGC 12591 (crosses minus the dashed line) corrected for vignetting. We also plot the uncertainties as dotted lines.

Figure 4. Surface brightness profile of UGC 12591 from the XMM-Newton MOS1 observation. Combining an APEC model for the extended gas emission and a power-law model for point sources, modified by Galactic absorption and absorption at the source. We fixed the photon index of the power-law component as Γ = 1.56 and scaled its normalization based on the 2–8 keV count rate of the central 50″ region, since the expected gas emission (the APEC model) in this band is negligible. We also fixed the Galactic absorption based on the value obtained by Dickey & Lockman (1990). Since our spectra cannot constrain the gas metallicity reliably, we fixed it at 0.5 solar metallicity. The free parameters left are the temperature and normalization of the gas emission and the N_H column density of the absorption at the source. Figure 6 shows our simultaneous fit to the PN and MOS spectra using this
model in the 0.4–8 keV band, where we used the 0.4–2 keV band as the fitting range. We obtained an acceptable fit to the spectra with $\chi^2/\text{dof} = 129.2/115$, and constrained the gas temperature as $T = 0.64 \pm 0.03$ keV and the absorption at the source as $N_{\text{H}} = (9 \pm 2) \times 10^{20}$ cm$^{-2}$. Table 3 lists the best-fit parameters. Therefore, there are both hot and cold gas in the galaxy, where the cold gas is possibly confined in the disk as suggested by the dust lane in the optical image. The 0.2–10 keV luminosity for the point-source component is $1.1 \times 10^{41}$ erg s$^{-1}$. At this luminosity, the central source is possibly dominated by an active galactic nucleus (AGN), which is supported by the VLA image with a point source at the center (Condon et al. 1991).

We also fit the spectra in the 0.4–8 keV range such that we can measure the normalization of the power-law component from the hard x-ray band (2–8 keV). We found that the power-law component contributes to 35% of the 0.6–1.4 keV flux using this method, 10% less than the value by directly converting from the hard band count rate. Besides the normalizations, we obtained consistent fitting results in the gas temperature and the intrinsic absorption at the source. The 10% difference in the contribution of the power-law component can be attributed to the difference in the treatment of the particle-induced background, which is more important in the hard x-ray band. In the spectral analysis in this subsection, we did not differentiate the photon background and particle-induced background, where the latter one has a flatter vignetting profile. Thus, we could oversubtract the particle-induced background resulting in a smaller hard band count rate. However, in our analysis for surface brightness profiles, we decomposed different backgrounds and scaled them using different vignetting profiles. Therefore, we adopted results from the first method in our subsequent analysis. At any rate, this difference is not able to account for the missing baryons as obvious in the discussion section.

3. MASS OF THE HOT GASEOUS HALO

We fit the surface brightness profile in the 0.6–1.4 keV band using three components, the hot gas, AGN/accretion binaries, and the contribution from the stellar population (including cataclysmic variables). The AGN/binaries contribution can be measured using the surface brightness profiles from the 2–8 keV band, as described above. We estimated the x-ray emission from the stellar population (e.g., M stars, but excluding the AGN/binaries) using the stellar mass to x-ray luminosity conversion factor of Revnivtsev et al. (2008). This relation is calibrated for old stellar populations, and since UGC 12591 is fairly bulge-dominated, the relation should still work approximately. To compute the radial surface brightness profile from the stellar population in the x-ray band, we derived a $K$-band radial surface brightness profile from the $K$-band magnitudes within circles of different angular sizes for this galaxy listed in the 2MASS Extended Source Catalog. We used a distance modulus of 35.0 and a $K$-band mass-to-light ratio of 0.6 (Bell & de Jong 2001) for this galaxy, and then applied the Revnivtsev et al. (2008) conversion to derive an x-ray surface brightness profile. We also added a systematic uncertainty of 0.08 counts ks$^{-1}$ arcmin$^{-2}$ in each data point to account for the uncertainties in modeling...
the particle included background. The remaining emission contributes to the hot gas in the halo. We fit the surface brightness profile of this emission using a standard $\beta$-model. Figure 7 shows the XMM-Newton PN and MOS data, after vignetting correction and background subtraction, as well as the estimates of the various components we fit to the surface brightness profile. It is clear that out to 30 or 40 kpc the x-ray binary and stellar components are insufficient to account for all the emission, and therefore that a hot halo component is necessary. We only allowed $\beta$-models for the hot gas if they cannot be excluded at greater than 95% confidence. This results in a narrow range of acceptable fits for the hot halo profile. The true uncertainties in the surface brightness profile are probably somewhat larger than the statistical errors, however, due to inevitable systematic errors in the flat fielding and background subtraction. This means that the range of formally acceptable fits for the hot halo might be a little wider than we have indicated (Figure 7). Deviations from a simple $\beta$-model for the hot gas distribution are also possible, and we tested by adding a second flatter $\beta$-model component in our fits.

The acceptable fit with the highest enclosed mass has $\beta = 0.40, r_0 = 0.53$ kpc, and $S_0 = 87.0$ counts ks$^{-1}$ arcmin$^{-2}$. This corresponds to a count rate within a projected radius of 50 kpc of 0.0039 counts s$^{-1}$. Assuming an APEC model with $kT = 0.64, Z = 0.5 Z_\odot$, and $N_H = 9 \times 10^{20}$ cm$^{-2}$, we constrained the mass within 50 kpc as $5.1 \times 10^9 M_\odot$. The acceptable fit with the lowest enclosed mass has $\beta = 0.83, r_0 = 10.6$ kpc, and $S_0 = 6.1$ counts ks$^{-1}$ arcmin$^{-2}$. This corresponds to a count rate within a projected radius of 50 kpc of 0.0025 counts s$^{-1}$, yielding a mass of $3.3 \times 10^9 M_\odot$. The best-fit profile has $\beta = 0.48, r_0 = 3.04$ kpc, and $S_0 = 14.2$ counts ks$^{-1}$ arcmin$^{-2}$. The best-fit profile has $\chi^2$ is 2.7 for 6 degrees of freedom. This corresponds to 0.0032 counts s$^{-1}$, yielding a mass of

![Figure 7. Background-subtracted and unvignetted XMM-Newton PN and MOS radial surface brightness profiles of the 0.6–1.4 keV emission around UGC 12591.](image)

**Notes.** We modeled the PN and MOS spectra simultaneously with a power-law and an apec component both modified by Galactic absorption and intrinsic absorption in UGC 12591.

- The redshift of the intrinsic absorption is at $z = 0.0232$.
- The apec model has the metallicity $Z = 0.5 Z_\odot$ and redshift $z = 0.0232$ fixed.

### Table 3

| wabs | zwabs* | apec$^b$ | pow | $\chi^2$/dof |
|------|--------|----------|-----|-------------|
| $N_H (10^{20}$ cm$^{-2}$) | $N_{HW} (10^{20}$ cm$^{-2}$) | $T$ (keV) | $L_{bol} (0.1–10$ keV$)$ (erg s$^{-1}$) | $\Gamma$ | $0.2–10$ keV $L_X$ (erg s$^{-1}$) |
| 1.62 (fixed) | 9 ± 2 | 0.64 ± 0.03 | 3.9 \times 10^{41} | 1.56 (fixed) | 1.1 \times 10^{41} (fixed) | 129.2/115 |

...
4.4 × 10^9 M_☉ and an unabsorbed luminosity of 2.3 × 10^{40} erg s^{-1}. If we integrate these profiles out to 500 kpc, then the fit with the highest enclosed mass contains 3.1 × 10^{11} M_☉ with an unabsorbed luminosity of 1.1 × 10^{44} erg s^{-1}. The fit with the lowest enclosed mass contains 1.9 × 10^{10} M_☉ with an unabsorbed luminosity of 1.9 × 10^{40} erg s^{-1}. The best fit contains 1.5 × 10^{11} M_☉ with an unabsorbed luminosity of 4.7 × 10^{40} erg s^{-1}.

We also examined the possibility of a higher-entropy halo as predicted by many simulations (Maller & Bullock 2004; Kaufmann et al. 2009; Crain et al. 2010; Guedes et al. 2011). Such a halo would have a flatter density profile than the β ~ 0.5 models we find above, and it would therefore be both more difficult to detect in emission and also more massive than a lower-entropy halo. As in Anderson & Bregman (2011), we chose to model a flattened profile with a two-component fit to the data. The “flattened” component is a β-model with fixed β = 0.35 and r_e = 50 kpc, but with free normalization, and the other component is a more concentrated β-model with all three parameters free, used to model the emission at smaller radii. For this galaxy, there is very little statistical space left to add a flattened profile, so the most mass that can be included by adding a flattened component is 4.5 × 10^{11} M_☉. As before, however, we caution that this statistical constraint depends on understanding all the systematic uncertainties perfectly, especially the background in XMM-Newton PN/MOS CCDs. These profiles can be independently tested in absorption profiles instead of emission due to the linear dependence on density in absorption. In addition, we note that the metallicity assumed can be another uncertainty in our analysis since the total mass will depend on the metallicity.

4. DISCUSSION

4.1. Baryon Mass Components in UGC 12591

We list the various baryon mass components in UGC 12591 in Table 4. We have constrained the hot gas mass of UGC 12591 using the XMM-Newton observation as (4.1 ± 0.3) × 10^7 M_☉ within 50 kpc with an average temperature of T = 0.64 ± 0.03 keV. We have also constrained the hot gas mass of 1.5 × 10^{11} M_☉ within 500 kpc regions using our best-fit β-model, and the hot gas mass is below 4.5 × 10^{11} M_☉ within 500 kpc even if we add another flatter β-model component in our fits. Beside the hot gas mass, there are other baryon mass components in the galaxy including the stellar mass and cold gas mass components. For the cold gas mass component, Giovanelli et al. (1986) measure the H_1 mass of 5.3 × 10^9 h_7^{−2} M_☉ from the radio data. Assuming the H_1 mass is 75% of the total cold gas mass, we find that the total cold gas mass is M_g = 7.1 × 10^9 M_☉, where we ignore the contribution from the molecular gas component. We estimate the stellar mass of UGC 12591 as (4.5 ± 1.0) × 10^{11} M_☉ within a 29 kpc radius, using its K-band total magnitude (K = 8.89 mag) from the 2MASS Extended Source Catalog and a range of mass-to-light ratio from 0.6 to 0.95 (e.g., Bell et al. 2003). The 2MASS team calculates the total magnitude by integrating the surface brightness profile out to ~4 disk scale lengths from the isophotal aperture well below the 1σ noise level. For the mass-to-light ratio, Bell et al. (2003) measure a value of 0.95 as the cosmic mean value. However, since UGC 12591 is a late-type galaxy and could have a lower mass-to-light ratio, we choose to use 0.78 ± 0.18 in our calculation. We find the largest uncertainties in the baryon mass are from the systematical uncertainty in the stellar mass-to-light ratio and the flattened gas halo. Combining the two effects, we find an uncertainty of 2.4 × 10^{11} M_☉ for the total baryon mass within 500 kpc.

In the central region within ~50 kpc, the baryon mass is clearly dominated by the stellar mass, and the stellar-to-total mass ratio is r_g ≥ 39. Using the rotational velocity of 466–500 km s^{-1}, we measure a total mass of m_g = 2.7 × 10^{12} M_☉ within 50 kpc and a baryon mass fraction of f_b ≥ 0.17, consistent with the cosmological baryon fraction. Out to the 500 kpc region (r_500 ≅ 550 kpc), we use the gravitational mass m_g = 1.9 × 10^{13} M_☉ estimated from the x-ray data using the hydrostatic equation, because the rotational curve is only constrained within 28 h_7^{−2} kpc (Giovanelli et al. 1986), smaller than the total mass m_g = 2.7 × 10^{13} M_☉ estimated using the rotational curve. The baryon mass within 500 kpc is m_b = 6.1 × 10^{11} M_☉, and we measure a baryon fraction of f_b ≥ 0.03. Considering a second flattened gas component, the baryon fraction within 500 kpc can reach to f_b ≥ 0.05. Since we use the smaller total mass estimate in the calculation, the baryon fraction quoted should be treated as a conservative upper limit. The stellar mass component is still more important with r_g ≥ 2.9 within 500 kpc, or r_g ≥ 1.0 with the additional flattened gas component.

To summarize, combining our XMM-Newton observation and the 2MASS and radio data in the literature, we have constrained that UGC 12591 has lost at least 70% of the baryons compared to the cosmological value. The missing baryons do not reside in the hot halos for spiral galaxies. Our result confirms the recent measurements in another giant spiral NGC 1961 using Chandra by Anderson & Bregman (2011), who find that NGC 1961 has also lost 75% of its baryon content.

One major challenge in this analysis is to separate the particle-induced background from the gas emission. By fitting the outer ring spectra, which include mostly various backgrounds, we have obtained reasonable fits to the background spectra, decomposing them to several components. Although the final fitting statistics is not optimal, our fits have successfully measured the extragalactic x-ray background within 10% from the measurement of the Chandra Deep Field, independently from the PN and MOS spectra. As for the Galactic background, our measurements are within 50% from the estimate based on RASS. Since the Galactic background has larger spatial variations, it is possible that a portion of the Galactic background can be from the gas emission. However, this small uncertainty cannot hide the missing baryons. If the hot halo contains all the missing baryons, then we would easily detect the emission in the PN or MOS spectra in the outer ring. For example, Figure 8 shows such a model for the PN spectra in the outer ring, where we replaced...
the Galactic background by a halo emission with $T = 0.64$ keV, $Z = 0.5 \, Z_\odot$, $z = 0.0232$, and a normalization to account for the missing baryons. This model is consistent with the data in Figure 8, which shows the PN spectrum for the outer ring fit with the same model as in Section 2.1 but with the Galactic background replaced by a halo emission with $T = 0.64$ keV, $Z = 0.5 \, Z_\odot$, $z = 0.0232$, and a normalization to account for the missing baryons. The three lines represent the unfolded component, the folded component, and the total emission, respectively. We would have easily detected this halo emission at larger radius from the galaxy center.

Another challenge arises from the estimate of the total mass. Since we only detect cluster emission out to 80 kpc and the rotational velocity measurement is also measured in the central region, our total mass estimates out to 500 kpc are based on extrapolations. To match the cosmic baryon fraction, the total mass within 500 kpc needs to be $\sim 5 \times 10^{12} \, M_\odot$. This is only two to four times the total mass of the Milky Way or M31 with the mass range of $1.2-2.7 \times 10^{12} \, M_\odot$ (e.g., Sakamoto et al. 2003; Watkins et al. 2010), while UGC 12591 has nine times the optical–IR luminosity of the Milky Way or M31 and a higher rotational velocity. Simply scaling from optical–IR luminosity, the total mass of UGC 12591 is in the range of $1.1-2.5 \times 10^{13} \, M_\odot$. On the other hand, since the mass of UGC 12591 is comparable to poor groups of galaxies, we use the $M_{200}-T$ relation measured from local groups and clusters to estimate the total mass of UGC 12591. In particular, we use the log ($M_{200}/M_\odot$) = 13.56 ± 0.05 + (1.59 ± 0.17) log ($T/1$ keV) relation of Dai et al. (2007), who measure the ensemble average of several hundred groups with the group temperature measured out to $r_{500}$, and find $M_{200} = 1.8 \times 10^{13} \, M_\odot$ for UGC 12591, consistent with our previous estimated range.

4.2. Baryonic Tully–Fisher Relationship

Using the fastest rotating galaxy UGC 12591, we are able to extend the baryonic Tully–Fisher relationship (BTF), a correlation between the baryon mass and rotational velocity of galaxies (McGaugh 2005, 2011) to the high rotational velocity regime of 500 km s$^{-1}$. We plot UGC 12591 in the BTF diagram together with the galaxies in McGaugh (2005) and the other massive galaxy NGC 1961 (Anderson & Bregman 2011) with a rotational velocity of 402 km s$^{-1}$ in Figure 9. Anderson & Bregman (2011) find that NGC 1961 deviates slightly from the linear fits to BTF. However, the authors caution that the offset can be caused by systematic uncertainties. Indeed, assuming a $K$-band mass-to-light ratio of 0.95, NGC 1961 would be on the BTF relation. Here, UGC 12591 provides another challenge to the linear BTF relation, which predicts a baryon mass of $2.2 \times 10^{12} \, M_\odot$ for UGC 12591, whereas we measure a baryon mass in the range of $(6.1-9.1) \times 10^{11} \, M_\odot$ with an uncertainty of $2.4 \times 10^{11} \, M_\odot$. Thus, UGC 12591 is $5\sigma$ below the BTF relation. If the offset from the BTF relation is caused by the uncertainties in the $K$-band mass-to-light ratio, then a ratio of 3.0 is needed to put UGC 12591 on the BTF relation, which is extremely unlikely (e.g., Bell et al. 2003). Thus, it is possible that the BTF relation turns over for massive galaxies with $v_c \gtrsim 400$ km s$^{-1}$. However, measurements from a larger sample of massive spiral galaxies are needed to confirm this result.

4.3. Overall Relationship of Baryon Fractions with Total Mass

We plot the baryon fractions of UGC 12591 and NGC 1961 against their rotational velocities, a proxy for the depth of the gravitational potential well, in Figure 10. We include the data
Figure 10. Baryon fraction as a function of the gravitational potential well indicated by the circular velocity at $r_{200}$. We plot the new measurements from massive spiral galaxies UGC 12591 and NGC 1961 (Anderson & Bregman 2011) over the archival data from Sakamoto et al. (2003), McGaugh (2005), Flynn et al. (2006), Vikhlinin et al. (2006), Gavazzi et al. (2007), Walker et al. (2007), Stark et al. (2009), Sun et al. (2009), and Dai et al. (2010). The dotted line is the cosmological baryon fraction measured from cosmic microwave background, and the dashed line is our best-fit broken power-law model for baryon losses. For massive spiral galaxies like UGC 12591 and NGC 1961, the baryon loss is at least 70%.

The overall baryon fractions for all systems can be fit by a broken power-law model (Dai et al. 2010). With the addition of new measurements, especially from those gas-rich late-type galaxies (Begum et al. 2008; Trachternach et al. 2009) and the Milky Way (Sakamoto et al. 2003; Flynn et al. 2006), and the recent addition of gas-rich late-type galaxies (Begum et al. 2008) and the Milky Way (Sakamoto et al. 2003; Flynn et al. 2006), we can better fit the power-law slope for baryon fractions in less massive systems. Thus, we re-fit the data with a broken power-law model for baryon fractions in less massive systems. This allows us to confirm the stacking results of Dai et al. (2010).

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$$f_b = \frac{0.16(v_c/643 \text{ km s}^{-1})^a}{(1 + (v_c/643 \text{ km s}^{-1})^b)^{bc}},$$

where $a = 1.26$, $b = 1.24$, and $c = 2$. The baryon fraction, $f_b$, scales as $f_b \propto v_c^{a-b} = 0.02$ above the break and $f_b \propto v_c^{a-b} = 1.26$ below the break, and the parameter $c$ in the equation is the smoothness of the broken power-law model, which is fixed in our fit. Comparing with the fit in Dai et al. (2010), we find the major difference lies in the shallower slope $f_b \propto v_c^{1.26}$ for the baryon loss in galaxies. We also find a larger break location and a shallower slope for galaxy clusters.

4.4. Cooling of the Gas Halo

The gas halo is predicted to play an important role in galaxy formation and evolution. With our detection of the gas halo emission in UGC 12591, we can estimate the cooling time of this hot halo and the implied accretion rate onto the galaxy, which can provide constraints on the gas available for new star formation. We define the cooling radius as the radius where the cooling time is 10 Gyr, using the expression of the cooling time (Fukugita & Peebles 2006),

$$\tau(r) = \frac{1.5nkT}{\Lambda n_e (n - n_e)} \approx \frac{1.5kT \times 1.92}{\Lambda n_e \times 0.92},$$

where the latter expression assumes a primeval He abundance resulting in a total particle density of $n = 1.92 n_e$. For $T = 10^6.85$ K, $Z/Z_\odot = 0.5$, and $\Lambda = 10^{-20.85}$ erg cm$^{-3}$ s$^{-1}$ (Sutherland & Dopita 1993), the cooling radius is at $n_e = 6.8 \times 10^{-4}$ cm$^{-3}$. For the range of best-fit $\beta$-model profiles constrained in this paper, this corresponds to a cooling radius between 15.6 and 18.0 kpc, and a hot halo mass of 6.2–9.2 $\times 10^8 M_\odot$ within that radius. We can roughly estimate the cooling time and rate by dividing the thermal energy in the hot gas within the cooling radius by the luminosity within that radius, and this yields a wide range in cooling time of $2.8–6.3$ Gyr for material within the cooling radius, but a fairly narrow range in the effective cooling rate of $0.15–0.21 M_\odot$ year$^{-1}$. This halo accretion rate is two orders of magnitude too low to assemble the stellar mass of this galaxy within a Hubble time. Therefore, significant accretion must have occurred via some other mode, such as cold flows or mergers, to produce the stellar mass seen in this galaxy today, confirming the conclusion drawn in NGC 1961 (Anderson & Bregman 2011).
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REFERENCES

Allen, S. W., Rapetti, D. A., Schmidt, R. W., et al. 2008, MNRAS, 383, 879
Anderson, M. E., & Bregman, J. N. 2011, ApJ, 737, 22
Begum, A., Chengalur, J. N., Karachentsev, I. D., Sharina, M. E., & Kaisin, S. S. 2008, MNRAS, 386, 1667
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Benson, A. J. 2010, Phys. Rep., 495, 33
Bregman, J. N. 2007, ARA&A, 45, 221
Carter, J. A., & Read, A. M. 2007, A&A, 464, 1155
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Cen, R., & Ostriker, J. P. 2006, ApJ, 650, 560
Condon, J. J., Frayer, D. T., & Broderick, J. J. 1991, AJ, 101, 362
Corbelli, E. 2003, MNRAS, 342, 199
Cowie, L. L., Garmire, G. P., Bautz, M. W., et al. 2002, ApJ, 566, L5
Crain, R. A., McCarthy, I. G., Frenk, C. S., Theuns, T., & Schaye, J. 2010, MNRAS, 407, 1403
Dai, X., Bregman, J. N., Kochanek, C. S., & Rasia, E. 2010, ApJ, 719, 119
Dai, X., Kochanek, C. S., & Morgan, N. D. 2007, ApJ, 658, 917
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Dunkley, J., Komatsu, E., Nolta, M. R., et al. 2009, ApJS, 180, 306
Flynn, C., Holmberg, J., Portinari, L., Fuchs, B., & Jahreiß, H. 2006, MNRAS, 372, 1149
Fukugita, M., & Peebles, P. J. E. 2006, ApJ, 639, 590
Gavazzi, R., Treu, T., Rhodes, J. D., et al. 2007, ApJ, 667, 176
Giovanelli, R., Haynes, M. P., Rubin, V. C., & Ford, W. K., Jr. 1986, ApJ, 301, L7
Guedes, J., Callegari, S., Madau, P., & Mayer, L. 2011, ApJ, 742, 76
Heymans, C., insBell, E. F., Rix, H.-W., et al. 2006, MNRAS, 371, L60
Hoekstra, H., Hsieh, B. C., Yee, H. K. C., Lin, H., & Gladders, M. D. 2005, ApJ, 635, 73
Humphrey, P. J., Buote, D. A., Canizares, C. R., Fabian, A. C., & Miller, J. M. 2011, ApJ, 729, 53
Irwin, J. A., Athey, A. E., & Bregman, J. N. 2003, ApJ, 587, 356
Jansen, F., Lumb, D., Alteri, B., et al. 2001, A&A, 365, L1
Jiang, G., & Kochanek, C. S. 2007, ApJ, 671, 1568
Kaufmann, T., Bullock, J. S., Maller, A. H., Fang, T., & Wadsley, J. 2009, MNRAS, 396, 191
Kuntz, K. D., & Snowden, S. L. 2008, A&A, 478, 575
Leccardi, A., & Molendi, S. 2008, A&A, 486, 359
Maller, A. H., & Bullock, J. S. 2004, MNRAS, 355, 694
Mandelbaum, R., Seljak, U., Kauffmann, G., Hirata, C. M., & Brinkmann, J. 2006, MNRAS, 368, 715
McGaugh, S. S. 2005, ApJ, 632, 859
McGaugh, S. S. 2011, Phys. Rev. Lett., 106, 121303
Patrício, G., Theureau, G., Bottinelli, L., et al. 2003, A&A, 412, 57
Revnivtsev, M., Churazov, E., Sazonov, S., Forman, W., & Jones, C. 2008, A&A, 490, 37
Sakamoto, T., Chiba, M., & Beers, T. C. 2003, A&A, 397, 899
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Snowden, S. L., Egger, R., Freyberg, M. J., et al. 1997, ApJ, 485, 125
Sommer-Larsen, J. 2006, ApJ, 644, L1
Stark, D. V., McGaugh, S. S., & Swaters, R. A. 2009, AJ, 138, 392
Sun, M., Voit, G. M., Donahue, M., et al. 2009, ApJ, 693, 1142
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Trachternach, C., de Blok, W. J. G., McGaugh, S. S., van der Hulst, J. M., & Dettmar, R.-J. 2009, A&A, 505, 577
Vikhlinin, A., Kravtsov, A., Forman, W., et al. 2006, ApJ, 640, 691
Walker, M. G., Mateo, M., Olszewski, E. W., et al. 2007, ApJ, 667, L53
Watkins, L. L., Evans, N. W., & An, J. H. 2010, MNRAS, 406, 264
White, S. D. M., & Frenk, C. S. 1991, ApJ, 379, 52