Galaxy Masses as Constraints of Formation Models
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X-Ray Measurements of the Mass Profiles in Massive Isolated Elliptical Galaxies

David A. Buote[1], **Ewan O'Sullivan**[2] **and Trevor J. Ponman**[3]

[1]Department of Physics and Astronomy, 4129 Frederick Reines Hall, University of California, Irvine, Irvine, CA 92697-4575 USA. email: buote@uci.edu
[2]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-50 Cambridge, MA 02138, USA. email: eosullivan@cfa.harvard.edu
[3]School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK. email: tjp@star.sr.bham.ac.uk

Abstract. We discuss some results for mass profiles that we have obtained from hydrostatic studies of the hot gas in isolated, massive elliptical galaxies.

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1. Introduction

The mass profiles of elliptical galaxies are important probes of galaxy formation and cosmology via measurements of their total baryon fraction and the relationship between halo concentration and virial mass. Only a few elliptical galaxies have detailed mass measurements from X-rays because of the lack of suitable targets in terms of total mass ($\lesssim 10^{13}\, M_{\odot}$), ISM X-ray flux, and relaxed dynamical states appropriate for hydrostatic analysis (e.g., for a review see Buote & Humphrey 2012a). We have identified a sample of 11 (hot) gas-rich isolated elliptical galaxies, most of which were discovered from previously awarded *XMM-Newton* and *Chandra* snapshot programs to search for optimal targets for X-ray studies of mass profiles on the galaxy scale.

2. Hydrostatic Equilibrium

Since the primary tool to obtain mass profiles of elliptical galaxies from X-rays is through the hydrostatic equilibrium approximation, we discuss briefly its validity. Recall that for a given fluid element hydrostatic equilibrium is the balance between the inward force of gravity and the outward force due to thermal gas pressure. One would like to know the importance of correction terms to this equation. Ideally, any non-thermal gas motions could be measured by Doppler shifts and broadening of the many strong emission lines in the X-ray–emitting plasma. This will be possible for the brightest systems with the launch of *Astro-H* in 2015. Kinematic constraints with current data are challenging but suggest that gas motions near the centers of elliptical galaxies are sub-sonic (e.g., Werner *et al.* 2009; Sanders *et al.* 2011).

Although presently one cannot rely on direct kinematic constraints on non-thermal gas motions, there are still reasonable steps that can be taken to mitigate their impact on mass-profile studies (Buote & Humphrey 2012a). First, for the hydrostatic equilibrium approximation to be most accurate, one should focus on those systems that are the most regular in terms of their image morphology. If there is a disturbance, such as from AGN feedback, it is best if the disturbance is confined to a spatial scale much smaller than the region of interest. Next, it is important that the X-ray emission be dominated by that from the hot gas not from background sources. This is especially important in elliptical galaxies (as opposed to galaxy clusters), where sometimes the emission from unresolved discrete sources can masquerade as diffuse gas. The third guideline is to examine whether a reasonable hydrostatic model is able to provide an acceptable description of the X-ray data. While this does not prove hydrostatic equilibrium, it is a necessary consistency check. Finally, until the day arrives when precise constraints on detailed gas kinematics are routinely available, the best means to gauge the reliability of hydrostatic equilibrium is to compare to mass measurements obtained by other methods such as stellar dynamics and gravitational lensing.

Comparisons have been performed between stellar dynamics and X-rays where it was assumed that all differences between the mass profiles obtained by the two techniques were due solely to non-thermal gas motions. A study by Churazov *et al.* (2010) of six galaxies and one galaxy by our team (Humphrey *et al.* 2013) find significant offsets leading to approximately a 30% non-thermal pressure fraction. These results pertain to galaxies at the centers of group-scale halos with total virial masses of a few $\times 10^{13}\ M_\odot$. It is unclear whether they hold for smaller, galaxy-scale halos.

3. Isolated Elliptical Galaxy Sample

Here we are interested in the properties of elliptical galaxies outside of any group or cluster. This leads us to focus on isolated elliptical galaxies. Isolation guarantees a galaxy-scale dark matter halo provided the ratio of X-ray to optical luminosity is not too large (otherwise one would have a fossil group). In the most isolated ellipticals the hydrostatic equilibrium approximation is expected to hold most accurately, since the gas has had ample time to settle down from past mergers. Unfortunately, only a few isolated elliptical galaxies with large hot gas halos have been observed previously in X-rays. To remedy this, we constructed an optically selected sample of isolated elliptical galaxies from the LEDA catalog with various criteria. Our total sample consists of 35 galaxies within 100 Mpc. Only 10 were previously observed with deep X-ray observations. We conducted a snapshot campaign with *XMM-Newton* and *Chandra* of the rest of the sample to ascertain their fluxes more accurately. Our survey is now completed, and we have now identified 11 isolated elliptical galaxies with substantial X-ray halos, 8 of which presently have deep *Chandra* observations. We will focus on these systems in this proceedings.

4. Results

4.1. *Spatially Resolved Spectral Analysis*

First we will summarize results we obtained previously for two of the brightest systems in our sample using traditional spatially resolved X-ray spectroscopy (Humphrey *et al.* 2011, 2012). NGC 720 is a well-known object which has been studied extensively in the past. The extended X-ray emission in NGC 1521 was discovered in our snapshot campaign. For these galaxies we also have deep *XMM-Newton* or *Suzaku* observations to complement the *Chandra* data allowing for constraints out close to R_{2500}, which is about 1/4 the virial radius. In Figure 2 of Humphrey *et al.* (2011) we present some representative *Chandra* and *Suzaku* spectra of NGC 720 at different radii. In these spectra one can notice that at the largest radius the background exceeds the source clearly indicating that accurate background subtraction is essential for constraining the gas properties. Nevertheless, even in the outermost aperture the gas properties can be constrained because the spectral "bump" near 1 keV is visible. This feature arises from the unresolved emission from the strong, temperature-sensitive Fe-L shell lines. Indeed, the well-constrained temperature and density profiles of the hot gas of NGC 720 obtained by fitting these *Chandra* and *Suzaku* spectra are shown in Figure 3 of Humphrey *et al.* (2011). To constrain the mass profile, we fitted these temperature and density profiles with hydrostatic models. Shown in that Figure 3 are the results of fitting a model without any dark matter halo. The fit is obviously very poor and is formally excluded at very high significance; i.e., about 20σ using the Bayesian evidences.

Hydrostatic equilibrium can be applied in many different ways. We find an entropy-based procedure is particularly effective since it allows us to easily enforce the additional constraint of convective stability (e.g., Buote & Humphrey 2012a). We begin by assuming parameterized forms for the entropy and mass profiles which are input into the equation of hydrostatic equilibrium. Then we compute the gas density and temperature profiles which are fitted to the observations. We also mention that provided the system is approximately a triaxial ellipsoid, we have shown previously that the assumption of spherical symmetry translates into only small errors in the derived properties (Buote & Humphrey 2012b). Finally, we note that we use the NFW profile for the dark matter halo in our default analysis while a 2-break power-law model (with a constant) is used for the entropy profile. For NGC 720, e.g., we have 9 free parameters constrained by 26 data points.

For both NGC 720 and NGC 1521 we obtain very tight constraints on the mass within the region where we have data (see Figure 6 of Humphrey *et al.* 2011 and Figure 7 of Humphrey *et al.* 2012). When we evaluate our models self-consistently out to the virial radius the error bars increase but we clearly find a total masses below $10^{13}\ M_\odot$ indicative of a galaxy-scale halo in each case. We also find good constraints on the global baryon fractions that are very consistent with the cosmic value. These results provide interesting evidence that the so-called "Missing Baryons" may exist in the outer parts of galaxy halos as hot gas – at least for massive ellipticals. It also shows that any non-gravitational heating did not push much gas outside of the virial radius.

Finally, we mention that we have constructed detailed error budgets for our measured parameters considering how different analysis choices affect our results for both galaxies. For NGC 720 the largest effect at the virial radius is the choice of dark matter profile. If instead of NFW we use a cored logarithmic potential (equivalent to a β model when the gas is isothermal) then at the virial radius the baryon fraction is shifted down by 0.11 to a value about 0.05. This alternative model, where the dark matter density $\sim r^{-2}$ at the virial radius, can be tested against the NFW model. Examining the bayesian evidences we find that NFW is preferred over the cored logarithmic potential by about 4σ.

4.2. *Narrow-Band Surface Photometry*

It is not always possible or even necessary to conduct detailed spectral fitting in each spatial bin to extract the global properties of the hot gas. In Humphrey & Buote (2013) we have studied the utility of narrow-band X-ray photometry for studies of the hot gas in elliptical galaxies and galaxy clusters. In essence, one is exploiting a tradeoff in spectral degrees of freedom for spatial degrees of freedom – ideal for high resolution *Chandra* data. This approach also has the significant advantage of typically having a far simpler background subtraction involving essentially constant components. We have applied this method to the *Chandra* data of 8 of our isolated elliptical galaxies using the following 3 energy bands: 0.5-0.9, 0.9-2.0, and 2.0-7.0 keV. In Figure 1 we show a fit to one of the galaxies in our sample. Notice the hard band, shown in green, reaches the constant

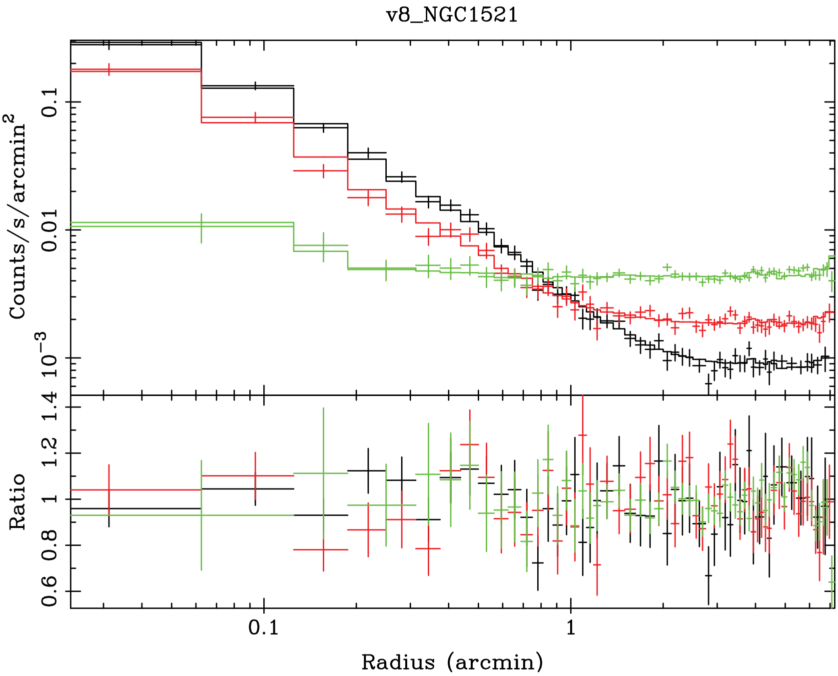

Figure 1. Galaxy + background fitted jointly to the 3-band Chandra surface brightness profile of NGC 1521: soft band (black, 0.5-0.9 keV), medium band (red, 0.9-2.0 keV) and hard band (green, 2.0-7.0 keV). The bottom panel shows the ratio data/model.

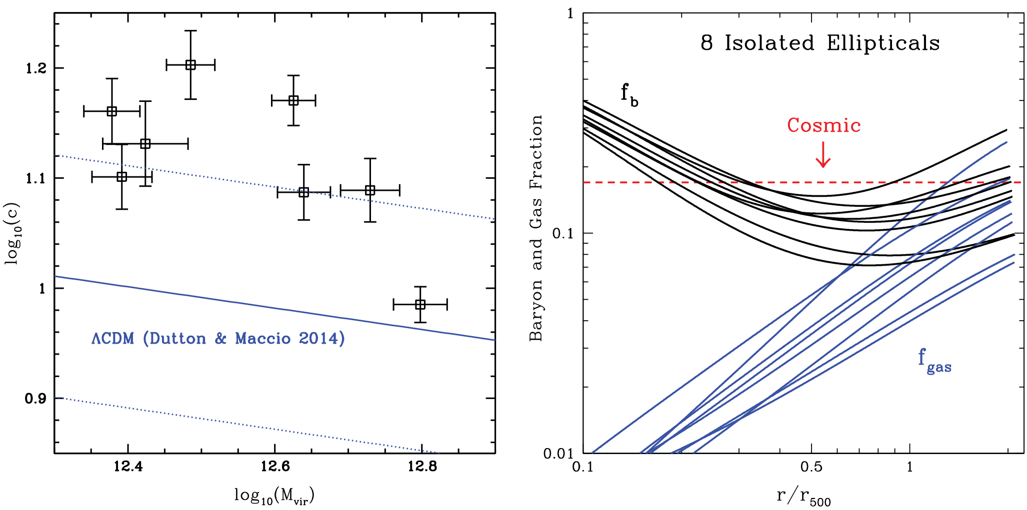

Figure 2. (*Left Panel*) Concentration-mass relation where each quantity is defined at the virial radius ($\Delta \sim 101$). (*Right Panel*) Radial profiles of the gas (blue) and baryon (black) fractions.

background level very quickly. But in softer bands the gas dominates the emission in the stellar region and does not reach the background level until a radius of about 50 kpc.

We display the key results for the mass profiles in Figure 2. In the left plot we show the concentrations and virial masses. A simple average of the virial masses of the 8 galaxies gives a value of $4 \times 10^{12}\ M_{\odot}$. The measurements lie systematically above the ΛCDM concentration-mass relation from Dutton & Macciò (2014) which may be expected since

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our galaxies were selected to be isolated, presumably early forming systems. As for the baryon and gas fractions (Figure 2), the behavior is also very similar to what we found for NGC 720 and NGC 1521 from the traditional spatially resolved spectral analysis. At the virial radius – which is about twice r_{500} – a simple average of the 8 values yields a value for the baryon fraction consistent the cosmic value but with large scatter ($\sigma = 0.07$).

5. Conclusions

We emphasize that the results presented for the narrow-band surface photometry are still preliminary, and we are currently constructing detailed systematic error budgets. Nevertheless, taking the results presented in §4.2 at face value we find that there is no core-cusp controversy for these systems, and these galaxies are consistent with, on average, having retained their cosmic fraction of baryons; i.e., no "Missing Baryons" problem in these systems.

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