DARK MATTER HALOS OF EARLY-TYPE GALAXIES

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ABSTRACT

Cosmological simulations of galaxy formation predict a universal form for the mass profile of dark matter (DM) halos from cluster to galaxy scales. Remarkably few interesting constraints exist, however, on DM halos in early-type galaxies. Using *Chandra* we present the temperature, density and mass profiles of a small sample of early-type galaxies, revealing significant DM in each case. When a component is included to account for stellar mass and the DM halo is allowed to respond adiabatically to the baryonic condensation into stars, the mass profiles are well-fitted by the universal profile, with Virial masses and concentrations in agreement with simulations. However, only ∼half, or less, of the mass within R_e seems attributable to the stars, implying stellar M_*/L_B ∼1–5.

Key words: galaxies: elliptical and lenticular, cD—galaxies: ISM— dark matter.

1. INTRODUCTION

The nature of DM within the Universe is one of the fundamental problems facing modern physics. N-body cosmological simulations predict a "universal" profile for DM halos over a wide range of mass-scales (Navarro et al., 1997, hereafter NFW). In an hierarchical formation scenario the early epoch of formation of low-mass halos should "freeze in" more tightly concentrated halos at the galaxy scale than are observed in clusters (Bullock et al., 2001). What is less clear, however, is the way in which the DM halo responds to the condensation of baryons into stars. If the galaxy is assembled by a series of mergers, however, the baryonic and dark matter may be mixed in such a way that the total gravitating mass follows the NFW profile (Loeb & Peebles, 2003). Alternatively, present-day ellipticals may retain the "memory" of the original contraction (Gnedin et al., 2004). We present X-ray determined mass profiles for 7 early-type galaxies, spanning the mass range $\sim 10^{12}$–$\sim 10^{13} M_\odot$, chosen from the *Chandra* archive to be sufficiently bright and relaxed enough to yield interesting mass constraints. Two companion posters, Gastaldello et al and Zappacosta et al (both this volume) address DM halos at galaxy and group scales.

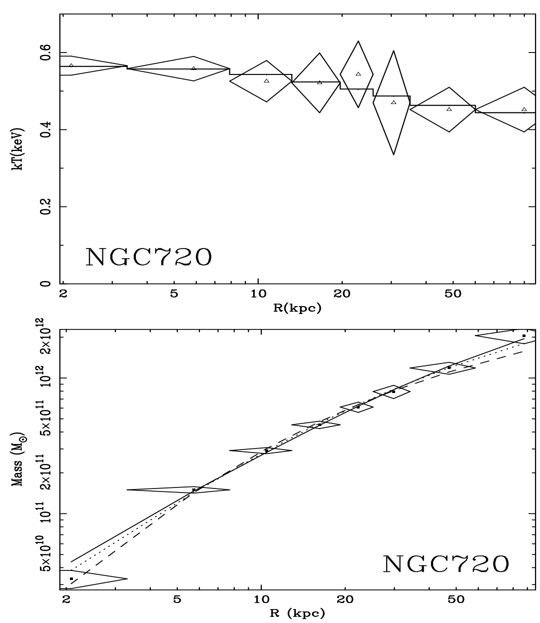

Figure 1 Temperature *(upper panel)* and mass *(lower panel)* profiles of NGC 720. The mass data are shown with models comprising simple NFW (dashed line), NFW plus stellar (dotted line) and compressed NFW plus stellar (solid line) potentials.

2. DATA ANALYSIS

The *Chandra* data were processed with *CIAO* 3.2.2, following standard procedures. Due to the low surface brightness of the data, special care was taken in treating the background, for which we adopted a modelling procedure (see Humphrey et al, 2005). We fitted the spectra from concentric annuli with an APEC model (plus unresolved point-source component in D_{25}) to determine temperature and density. The best-fitting abundances were

Table 1: Best-fit values of $\mathrm{M_{vir}}$, in units of $10^{12}\mathrm{M_\odot}$, and c for the different mass models fitted. Where no error is quoted the parameter value was fixed. Error bars are at 1-σ. Figures in square parentheses are systematic error estimates (see text). Other figures in parentheses represent the change in the best-fit value if $\mathrm{M_*/L_B}$ is varied by $\pm$20%.

Galaxy	NFW			Compressed NFW+ stars			
	χ^2/dof	$\mathrm{M_{vir}}$	c	χ^2/dof	$\mathrm{M_{vir}}$	c	$\mathrm{M_*/L_B}$
NGC 720	2/9	$3.4^{+1.5}_{-0.9}$	47$\pm$15	1/9	$6.1^{+5.2}_{-2.4}$	19^{+8}_{-6}	3.3
		$[^{+1.7}_{-0.7}]$	[$\pm$8]		$[^{+15}_{-1.2}](^{+1.4}_{-0.9})$	$[^{+2}_{-7}]$($\pm$4)	
NGC 1407	23/11	$9.0^{+6.3}_{-3.5}$	36^{+13}_{-9}	18/11	300(>30)	4.6$\pm$4.2	4.7
		$[^{+4.3}_{-3.7}]$	$[^{+14}_{-8}]$		[-250](-230)	$[^{+7.2}_{-1.9}]$($\pm$4.1)	
NGC 4125	23/11	$1.0^{+0.2}_{-0.1}$	88$\pm$14	19/11	$1.8^{+0.8}_{-0.4}$	25^{+8}_{-6}	2.4
		$[^{+0.3}_{-0.4}]$	$[^{+44}_{-7}]$		$[^{+0.2}_{-1.1}](^{+0.7}_{-0.3})$	[+38]($\pm$10)	
NGC 4261	23/12	$1.5^{+0.3}_{-0.2}$	160$\pm$20	21/12	$2.6^{+1.8}_{-1.0}$	38^{+23}_{-14}	4.6
		$[^{+0.4}_{-0.2}]$	$[^{+10}_{-30}]$		[$\pm$1.2]$(^{+2.0}_{-0.7})$	$[^{+23}_{-18}]$($\pm$26)	
NGC 4472	53/21	10^{+4}_{-3}	30^{+7}_{-5}	30/20	55^{+160}_{-28}	11$\pm$4	0.87$\pm$0.14
		$[^{+0.4}_{-0.6}]$	$[^{+20}_{-2}]$		$[^{+2}_{-30}]$	$[^{+1.7}_{-0.8}]$	
NGC 4649	30/7	$2.5^{+0.4}_{-0.3}$	140$\pm$10	21/7	17^{+36}_{-9}	24$\pm$8	4.7
		$[^{+0.1}_{-1.0}]$	$[^{+30}_{-4}]$		$[^{+2}_{-11}](^{+130}_{-10})$	$[^{+13}_{-1}]$($\pm$18)	
NGC 6482	0.6/5	$2.3^{+0.4}_{-0.3}$	99$\pm$16	0.4/5	$3.5^{+1.3}_{-0.9}$	36^{+9}_{-7}	1.2
		$[^{+0.2}_{-0.1}]$	[$\pm$4]		[$\pm$0.3]$(^{+0.6}_{-0.4})$	[$\pm$2]($\pm$9)	

similar to other early-type galaxies (Humphrey & Buote, 2005).

3. MASS PROFILES

The gravitating mass profiles were inferred from the temperature and density profiles in two ways. First, we used parameterised models for each, although we did not find a universal profile fitted either, and derived mass profiles under the assumption of hydrostatic equilibrium (we discuss the possible impact of low-significance asymmetries in some systems— e.g. Randall et al. 2004— in Humphrey et al, 2005, in prep). The mass profiles were clearly more extended than the optical light, indicating significant DM. Within $\mathrm{R_e}$, we found $\mathrm{M/L_B}$ for the gravitating matter varied from 2.3–9.3 $\mathrm{M_\odot/L_\odot}$. In Fig. 1, we show the best-fit temperature and mass profiles for NGC 720. Alternatively, we also used the temperature profile, and an assumed mass profile (see below) to derive a density model, which we fitted to the data. This procedure gave more robust mass constraints. These techniques are outlined in Humphrey et al (2005).

Simple NFW fits to the data gave very large ($\gg 20$) values for c, the halo concentration, in contrast to the typical values predicted by simulations ($\sim$15 e.g. Bullock et al., 2001). To investigate whether baryonic matter affects the mass profile, we included an Hernquist (1990) mass component to trace the stars and allowed the DM halo to be compressed due to baryonic condensation (Gnedin et al., 2004). Assuming all mass within $\mathrm{R_e}$ is stellar did not give meaningful fits. Fixing stellar mass ($\mathrm{M_*}$) within $\mathrm{R_e}$ to be half of the total reduced c, bringing $\mathrm{M_{vir}}$ and c into better agreement with simulations. This model fitted all the galaxies well. We note that if adiabatic compression of the DM halo was turned off, for a fixed $\mathrm{M_*/L_B}$, c was significantly higher.

Our results were very sensitive to $\mathrm{M_*/L_B}$, which could only be constrained in NGC 4472 (in which it was $\sim$1). In general, though, we found $\mathrm{M_{vir}}$ and c were consistent with simulations (Bullock et al., 2001), albeit very uncertain. In Table 1 we show a summary of our results and, in addition, the sensitivity to $\mathrm{M_*/L_B}$ and the spectral analysis choices (e.g. N_H or background modelling).

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