IV. Baryon Fraction Tests
Course Overview

Observations of galaxy clusters (primarily in X-rays) for cosmological tests

☆ Cosmological primer
  ▶ incomplete overview of parts of cosmology important for cluster studies

☆ Galaxy clusters and their observation
  ▶ mass determinations

☆ Cluster baryon fraction tests
  ▶ constraints on matter density and standard bucket

☆ Cluster mass function
  ▶ growth of structure and volume tests
Baryon Fraction Tests

★ Early constraints on $\Omega_M$
★ Clusters as a “standard bucket”
★ Observational results
★ Caveats
Constraining $\Omega_M$

Standard big bang theory accurately predicts abundances of light elements produced in first few minutes via nucleosynthesis

- Tight theoretical and observational constraints on $\Omega_b$
  - ratio of baryon density to critical density

$$\Omega_b = \frac{\rho_b}{\rho_c}$$
Constraining $\Omega_M$

Present abundances of light element isotopes depends on $\Omega_b$

- curves show theoretical dependence
- lines show measured abundances
- current best estimate $\Omega_b = 0.044$
  (e.g. Kirkman et al, 2003, ApJS, 149)

http://www.astro.ucla.edu/~wright/BBNS.html
Constraining $\Omega_M$

Theory + observations strongly suggest Universe is flat ($\Omega_{tot} = 1$)

★ $\Omega_b << 1$ so majority of matter/energy density is non-baryonic

Matter density comprises baryonic and dark matter:

$$\Omega_M = \Omega_b + \Omega_{dark}$$

In early 1990's, flat models with $\Omega_{tot} = \Omega_M = 1$ popular
Galaxy clusters are largest objects for which masses determined
  ★ large enough to assume enclose representative volume of Universe

This means ratio of baryonic mass to total mass in cluster ($f_b$) should match universal ratio:

$$f_b = \frac{M_b}{M_{tot}} = \frac{\Omega_b}{\Omega_M}$$

Thus can attempt to measure $f_b$ and use $\Omega_b$ to determine $\Omega_M$
Constraining $\Omega_M$

White et al (1993, Nature, 366) made one of first attempts to measure $\Omega_M$ using $f_b$:

- used X-ray surface brightness profile to estimate gas mass

$$M_{\text{gas}} = 1.3 \times 10^{14} M_\odot$$

- used total optical luminosity, and mass to light ratio to estimate stellar mass

$$M_{\text{stars}} = 1.4 \times 10^{13} M_\odot$$

- used various methods (velocity dispersion, $kT$) to estimate total mass

$$M_{\text{tot}} = 1.6 \times 10^{15} M_\odot$$
Constraining $\Omega_M$

$$f_b = \frac{M_b}{M_{tot}} = \frac{M_{gas} + M_{stars}}{M_{tot}}$$

This gave $f_b \sim 0.1$
★ implied $\Omega_M \sim 0.15$
★ strong evidence to abandon $\Omega_M = 1$

“Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.”

(White et al 1993; Nature, 366, 429)
Constraining $\Omega_M$

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“Either the density of the Universe is less than that required for
closure, or there is an error in the standard interpretation of element
abundances.”

(White et al 1993; Nature, 366, 429)

More recently, similar tests give $\Omega_M \sim 0.3$ (e.g. Sanderson &
Constraining $\Omega_M$

In 1930's, galaxy cluster observations showed
★ $M_b << M_{tot}$
i.e. dark matter required
★ $\Omega_b << \Omega_M$

In 1990's cluster observations showed
★ $\Omega_M < 1$
i.e. open Universe, or cosmological constant

In 2000's clusters used as standard buckets...
Standard Buckets

Assuming that clusters large enough to be representative, expect $f_b$ to be same at all $z$

★ at least until reach $z$ clusters forming
★ “standard bucket”
★ observational determination of $f_b$ depends on distance to cluster
  ▶ sensitive to $E(z)$
Standard Buckets

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☆ at least until reach $z$ clusters forming
☆ “standard bucket”
☆ observational determination of $f_b$ depends on distance to cluster
  ▶ sensitive to $E(z)$

If we know $f_b$, and measure $z$, then infer distance to cluster
☆ constrain $E(z)$, hence $\Omega_M, \Omega_\Lambda, w$

For strongest constraints, measure $f_b$ for set of clusters at different $z$

Artificial evolution in $f_{\text{gas}}$ for different cosmologies

Only get constant $f_{\text{gas}}$ with $z$ if using correct cosmology
Distance Dependence of $f_b$

\[ f_b = \frac{M_b}{M_{tot}} = \frac{M_{\text{gas}} + M_{\text{stars}}}{M_{tot}} \]

- Measure $M_{\text{stars}}$ from optical and $M_{\text{gas}}$ from X-ray
- Dominated by $M_{\text{gas}}$ – measured value depends on $d$
Distance Dependance of $f_b$

$$f_b = \frac{M_b}{M_{tot}} = \frac{M_{gas} + M_{stars}}{M_{tot}}$$

- Measure $M_{stars}$ from optical and $M_{gas}$ from X-ray
- Dominated by $M_{gas}$ – measured value depends on d

Consider spherical region of cluster, angular radius $\theta$

- Physical (proper) radius of region is
  $$R = \theta d_A$$

  where $d_A$ is angular diameter distance.

- The proper volume of the region is just
  $$V = \frac{4}{3} \pi (\theta d_A)^3$$
Now $M_{\text{gas}}$ is given by

$$M_{\text{gas}} = \rho_{\text{gas}} V$$

so

$$M_{\text{gas}} \propto \rho_{\text{gas}} (\theta d_A)^3$$
Distance Dependence of $f_b$

Now $M_{\text{gas}}$ is given by

$$M_{\text{gas}} = \rho_{\text{gas}} V$$

so

$$M_{\text{gas}} \propto \rho_{\text{gas}} (\theta d_A)^3$$

and recall that gas density is related to the X-ray luminosity

$$L \propto \int n_p n_e dV \propto \rho_{\text{gas}}^2 V$$

and we can relate $L$ to the observed flux $F$:

$$L = F \times 4\pi d_L^2$$

where $d_L$ is the luminosity distance to the cluster
Distance Dependence of $f_b$

\[
L \propto \int n_p n_e dV \propto \rho_{gas}^2 V \quad L = F \times 4\pi d_L^2
\]

Rearrange for $\rho$ in terms of observables $F$ and $\theta$

\[
\rho_{gas} \propto \left(\frac{L}{V}\right)^{1/2}
\]

\[
\rho_{gas} \propto \left(\frac{F d_L^2}{\theta^3 d_A^3}\right)^{1/2}
\]

and finally

\[
M_{gas} \propto \rho_{gas} (\theta d_A)^3 \propto (F \theta^3)^{1/2} d_L d_A^{3/2}
\]
Distance Dependence of $f_b$

$$M_{gas} \propto (F \theta^3)^{1/2} d_L d_A^{3/2}$$

For a cluster with observed F within angular radius $\theta$

$$M_{gas} \propto d_L d_A^{3/2}$$
Distance Dependence of $f_b$

\[ M_{gas} \propto (F \theta^3)^{1/2} d_L d_A^{3/2} \]

For a cluster with observed $F$ within angular radius $\theta$

\[ M_{gas} \propto d_L d_A^{3/2} \]

Can also show that if total mass is determined from X-ray hydrostatic analysis

\[ M_{tot} \propto d_A \]

so the estimated value of the baryon fraction depends on distance as

\[ f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2} \]

Distance Dependance of $f_b$

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2}$$

So to determine $f_{gas}$ (or $f_b$) from X-ray observation of cluster at redshift $z$

* need to know $d_A$, $d_L$ to $z$

Instead, if we know $f_b$ from theory, can determine $d_A$, $d_L$ to $z$

* constrain $E(z)$
FIELDS ARRANGED BY PURITY

MORE PURE

Sociology is just applied psychology. Psychology is just applied biology. Biology is just applied chemistry. Which is just applied physics. It's nice to be on top. Oh, hey, I didn't see you guys all the way over there.

Sociologists  Psychologists  Biologists  Chemists  Physicists  Mathematicians
Experimental Results

Allen et al. (2002) used 6 clusters for first study of $f_{\text{gas}}(z)$

Data favour $\Omega_M = 0.3, \Omega_\Lambda = 0.7$
Experimental Results

Solve for cosmological parameters that give constant $f_{\text{gas}}(z)$

$$\Omega_M = 0.30 \pm 0.04, \quad \Omega_\Lambda = 0.95^{+0.48}_{-0.72}$$
Experimental Results

More recently Allen et al (2008) used 42 clusters at $0.05 < z < 1.1$

\[ \Omega_M = 0.3, \Omega_\Lambda = 0.7 \quad \Omega_M = 1, \Omega_\Lambda = 0 \]
Experimental Results

More recently Allen et al (2008) used 42 clusters at $0.05 < z < 1.1$

$\Omega_M = 0.28 \pm 0.06$

$\Omega_\Lambda = 0.86 \pm 0.21$

$w = -1.14 \pm 0.31$

★ N.B. $\Omega_M$ also constrained by overall fgas
   ▪ improves constraints from fgas(z)
★ best constraints if combine with SNIa and CMB data
Cautions & Caveats

Method relies on determination of $M_{\text{tot}}$

- hydrostatic masses – are clusters really relaxed?

Cautions & Caveats

Method relies on determination of $M_{\text{tot}}$
★ hydrostatic masses – are clusters really relaxed?

★ Hard to tell for distant clusters
  ▶ bright relaxed clusters biased towards line of sight mergers?

Method relies on determination of $M_{\text{tot}}$:
- are X-ray masses accurate?

Nagai et al (2007) analysed mock X-ray observations of simulated clusters:
- for relaxed clusters $M_{\text{gas fine}}$
- $M_{\text{tot}}$ underestimated by $\sim 10\%$
Cautions & Caveats

Nagai et al. (2007) analysed mock X-ray observations of simulated clusters

- for relaxed clusters $M_{\text{gas}}$ fine
- $M_{\text{tot}}$ underestimated by $\sim$10%

Due to **non-thermal pressure** support

- thermal pressure observed in X-ray
- extra pressure from bulk motions allows for larger $M$

Method relies on determination of $M_{\text{tot}}$

- are X-ray masses accurate?

\[ M(r) = \frac{-r^2}{G \rho(r)} \frac{dP}{dr} \]
Is $f_{\text{gas}}$ the same for all clusters?

- radial profiles of $f_{\text{gas}}$

- some variation at small radius, but consistent with same value at R2500
  - statistical variation at R2500 gives 5% distance uncertainty
  - c.f. 7% intrinsic distance uncertainty from SNIa
Cautions & Caveats

Is $f_{\text{gas}}$ the same for all clusters?

★ simulations also support small variation in $f_{\text{gas}}$ (Nagai et al 2007)

★ variation <6% for relaxed clusters
★ lower still for more massive clusters
Allen et al. derived $f_b$ in R2500

★ is this large enough to be a standard bucket?

Assumed clusters large enough that ratio of mass components is universal

★ but $f_{\text{gas}}$ increases with R

★ still increasing at R2500

Cautions & Caveats

Allen et al. derived $f_b$ in R2500
★ is this large enough to be a standard bucket?

Simulations used to estimate bias factor $b$
★ ratio of enclosed $f_b$ to universal value
★ relaxed clusters in sims agree with observed $f_{\text{gas}}$

Use sims to correct $f_b$ at R2500 by bias factor $b \approx 0.8$
★ does $b$ vary with $z$?
★ sims suggest not, but could be important

Summary

Assuming clusters large enough to be representative, mass composition should match Universe

\[ f_b = \frac{M_b}{M_{tot}} = \frac{\Omega_b}{\Omega_M} \]

★ observe \( f_b \) and constrain \( \Omega_M \)

Assuming \( f_b \) redshift independent, any observed variation with \( z \) due to assumed cosmology

\[ f_{gas} = \propto d_L d_A^{1/2} \]

★ constrain \( E(z) \) and from observed \( f_b(z) \)

★ combined with CMB and SNIa and including possible systematics:

\[ \Omega_M = 0.253 \pm 0.021 \quad w = -0.98 \pm 0.07 \]