Whittle : EXTRAGALACTIC ASTRONOMY

13. GALAXY GROUPS & CLUSTERS

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(1) Introduction

Lets start by identifying some of the salient features of galaxy clusters.

- Typical cluster sizes are $\approx$ 1 - 3 Mpc :
  → they are the **largest virialized structures** in the Universe (ie $\Sigma KE \approx \frac{1}{2} \Sigma PE$)
  Structures larger than clusters have not had time to "turn around", collapse, and virialize.

  Galaxies : $t_{virial} \approx 10^8$ yr <<< t_{Hubble}
  Clusters : $t_{virial} \approx 10^9$ yr << t_{Hubble}
  Superclusters : $t_{virial} \approx 10^{10.5}$ yr > t_{Hubble}

  Note that clusters are not necessarily the largest **bound** structures in the universe
  → superclusters may be bound, but haven't yet turned around and virialized.

- On these large scales, components have not had a chance to separate during collapse
  → a cluster is probably a **representative sample of the Universe**
  This is important when, for example, we measure their Dark Matter (DM) content :

  $$(M_{DM} / M_{baryons})_{cluster} = (M_{DM} / M_{baryons})_{Universe}$$

  So a measurement in clusters can be scaled up to derive Ω_{matter} for the universe

- Cluster are part of a continuous range of structures :
  galaxies → groups → clusters → superclusters → large scale structure
  However, clusters are **rare extremes** in the galaxy distribution, with $\Delta\rho / <\rho> \approx 10^3$:
  Very roughly (depending on definitions) the total galaxy content of the universe is divided :
  1-2% in rich clusters
  5-10% in clusters
  50-100% in "Local Group"s &/or looser groupings

- The richest clusters are typically found at the **intersection** of sheets and filaments of galaxies
  (eg Coma is located at an intersection in the great wall :[image])

→ Ongoing **heirarchical assembly** : small things merge to make bigger things, on all scales.
→ Clusters **continue to grow** (and form), even today

- The four principal constituents of clusters include :
  - Galaxies
    $\approx 10^2$ large galaxies; $\gtrsim 10^3$ total galaxies
    typical speeds $\approx 10^3$ km/s
  - Intracluster Stars
    very faint ($\approx$1% sky) diffuse light (distinct from cD halo light)
    comprises →10-50% total galaxy light (in rich clusters; much less in poor clusters)
    probably tidally stripped stars
  - Hot Gas
    Hydrostatic atmosphere
    $T \approx 10^{7\text{-}8}$K → X-ray emitter
    $n \approx 10^{-3}$ cm^{-3}
    $L \approx 10^{43\text{-}46}$ erg/s $\approx 10^{-2} - 10^{-4}\ L_{opt}$
    $M_{gas} \approx 5 \times M_{gals}$
    $Z \approx 0.3\ Z_{\odot}$ → enriched : not all primordial
  - Dark Matter
    Dominates the total mass
    $M_{DM} \approx 4 \times M_{gas + gals}$

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(2) Cluster Surveys and Catalogs

(a) Optical Identification

One needs to identify an "overdense" region of galaxies
Early steps : Herschel(s); Hubble; Shapley; Reynolds.
Significant improvement following publication of the northern Palomar Sky Survey (PSS-I)

(i) Abell (1958) : Catalog of Rich Clusters

A definitive work (ApJ Supp **3** 211) which has survived to current times
Visual inspection of 10^4 deg^2 from PSS yielding 2712 clusters
Southern extension using SRC-J : 1364 clusters (Abell, Corwin & Olowin, 1989, ApJ Supp, **70** 1)
Robust criterion :
  estimate distance using m_{10} (10^{th} brightest galaxy)
  exclude clusters with $0.02 < z > 0.2$ (note : Virgo excluded -- too close/big)
  define region of radius 1.5 h^{-1} Mpc (an "Abell Radius", R_A)
  count galaxies within R_A between magnitudes m_3 and $m_3 + 2$
  subtract a background count evaluated nearby
  $N > 50$ → "complete catalog" (adding : $800 > \sigma < 1200$ km/s eliminates $\approx$10% superpositions)
  Richness classes 1-2-3-4 : N = 50 - 80 - 130 - 200 - 300 (comprising 1224, 383, 68, 6 clusters)
  N = 30 - 49 → "incomplete catalog" (1030 clusters, Richness class 0)
Data on the Abell clusters compiled by Struble & Rood : 1987 ApJ Supp **63**, 543 & 555
Basic data and links to SDSS images of all Abell clusters is here: o-link

(ii) Zwicky (1961-68) : Catalog of Galaxies and Clusters of Galaxies

18 inch Schmidt gave m_B for 31,000 galaxies, visual inspection of PSS gave 10,000 clusters.
  Assigned cluster type : Compact, Medium-Compact, Open
  Assigned cluster distances : Very Near, Near, Distant, Very Distant, Extremely Distant.
  Gave number of galaxies, cluster boundary size, coordinates etc.
Uses "isopleth" density contrast of $N / N_{background} = 2$ to define cluster
however, statistically incomplete : cluster sizes are distance dependent

→ rarely used compared to Abell's lists

(iii) Automated Digital Catalogs

Possibly more objective selection criterion uses automated recognition of galaxies and clusters.
Main effort : scanning of UK schmidt plates (SRC J & R) by two UK groups :
APM (Automatic Plate Measuring Machine) : Cambridge (Mike Irwin et al)
COSMOS : Edinburgh/Durham

(b) X-ray Identification

Rich clusters with deep potentials have hot gas (§ 10)
→ X-ray emission is an effective way to find relaxed clusters
Since emissivity $\propto n^2$, we have ≈ no forground X-ray emission (though smooth X-ray background)
→ problems of spurious identification from superposition is **greatly reduced** compared to optical surveys.
At high redshifts, this is increasingly important
→ X-ray surveys may be the best way to identify (rich) high-z clusters (if they exist)
Several surveys currently exist :

EMSS (Einstein Medium Sensitivity Survey : serendipitous, 800 deg^2, $z \approx 0.05 - 0.55$)
RDCS (ROSAT Deep Cluster Survey : serentipitous, 100 deg^2, $z \lesssim 1$)
RASS (ROSAT All Sky Survey)

(c) Other (Future) Methods of Identification

There are a few other methods which show great promise for the future :

- SZ (Sunyaev-Zeldovich) effect :
  hot cluster gas Compton scatters CMB photons, increasing their energy
  Look for brightening of CMB at mm-wavelengths (reduces point source confusion)
  promising for detecting very high-z clusters
  currently very difficult, but possible (future) instruments : MMA, (MAP, PLANCK ?)

- Weak Gravitational Lensing :
  faint background galaxies suffer slight distortion by matter along the line of sight
  intervening clusters give slight azimuthal image elongation
  Many galaxies → statistically detectable
  allows mapping of intervening mass distribution.
  still early days, but quite promising.
  Possible database : SDSS (?)

- Color Search for Red Galaxies :
  (Red) Ellipticals formed very early
  → so concentrations of faint red objects should yield high-z clusters
  redshift modifies colors, so good color information should also yield approximate redshift.
  Some deep multicolor surveys begun, but still early days.

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(3) Cluster Classification

- Clusters are not all the same !
  One might classify clusters according to one of several possible properties :
  eg shape, richness, lumpiness, Hubble mix, dominant galaxy types, etc
  it transpires (see below) that many of these are equivalent,
  so in practice we need only keep track of one (or two) underlying properties.

- A couple of classification schemes are in common use :
  - Bautz-Morgan (BM) type :
    Compares the prominence of the brightest galaxy to the other galaxies.

BM I	single central dominant cD galaxy	(eg A 2199)
BM II	several bright galaxies between cD and gE	(eg Coma)
BM III	no dominant galaxy	(eg Hercules)

- Rood-Sastry (RS) type :
  Describes the distribution of the 10 brightest galaxies
  Can be arranged in a "tuning fork" sequence (image / viewgraph)

cD	dominated by a single cD galaxy	(eg A 2029)
B	dominated by a bright binary	(eg Coma)
L	line of several bright galaxies	(eg Perseus)
C	core of > 4 bright galaxies	(eg A 2065)
F	flattened distribution	(eg A 397)
I	irregular with no center	(eg Hercules)

These two systems are closely related
it seems there is a **primary factor** which defines a cluster : its degree of **relaxation**
from most relaxed to least relaxed we have :
    BM : I → II → III
    RS : cD → B → L → C → F → I
A number of other properties follow this sequence :
    Hubble type mix : Elliptical rich → Spiral Poor → Spiral rich
    Overall Shape : Spherical → Intermediate → Irregular
    X-ray Luminosity : High → intermediate → low

Here is a more specific table (condensed from Bahcall's entry in Allen's AQ)

Property/Class	Regular	Intermediate	Irregular
Zwicky type	Compact	Medium-Compact	Open
Bautz-Morgan type	I, I-II, II	(II), II-III	(II-III), III
Rood-Sastry type	cD,B, (L,C)	(L),(F),(C)	(F), I
Content	Elliptical-rich	Spiral-poor	Spiral-rich
E:S0:S ratio	3:4:2	1:4:2	1:2:3
Symmetry	Spherical	Intermediate	Irregular shape
Central concentration	High	Moderate	Very little
Central profile	Steep	Intermediate	Flat
Mass segregation ?	Marginal	Marginal	None
Radio detection ?	≈50%	≈50%	≈20%
X-ray luminosity	High	Intermediate	Low
Examples	A2199, Coma	A194, A539	Virgo, A1228

It is very likely that this sequence reflects, at least in part, stages in **cluster evolution** :
most evolved → intermediate → least evolved
Stated slightly differently : given a few Gyr, Hercules will resemble Coma
of course, more clusters like Hercules will form out of yet lower density regions.

(Warning !! regular / irregular clusters are sometimes called "early" / "late"
although this matches their E / Sp content, it is **opposite** to the likely evolutionary sequence)

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(4) Important Timescales

(a) Crossing Time

Obviously, given the velocity dispersion and cluster size, we have :
(recall, the ever handy rule of thumb : A km/s is a pc in a Myr !)

$$t_{cross} \approx R / \sigma \approx 10^9 \text{ yr} \times R_{Mpc}\, \sigma_{1000}^{-1}$$

So, for clusters that formed at $z \approx 1$, galaxies might have experienced a few orbits
(dont forget, though, many (spiral) galaxies may be falling in for the first time)

(b) Violent Relaxation Time

This refers to the time for a chaotic collapse to "sort itself out" and reach steady state
(it is also the time for two similar sized clusters to merge) :

$$t_{violent} \approx \text{few } (2\text{-}5) \times t_{cross} \approx (2\text{-}5) \times 10^9 \text{ yr} \times R_{Mpc}\, \sigma_{1000}^{-1}$$

Given the observed range in cluster properties (R, σ, and possibly age) :
we expect (and find) a significant range in relaxation : quite unrelaxed → well relaxed.

(c) 2-Body Relaxation and Dynamical Friction Times

From Topic 8.10.a.iii we derived a simple formula for 2-body relaxation (eq 8.38c) :

$$t_{2\text{-}body} \approx t_{cross}\, N / 6 \ln N$$

where N is the total number of interacting bodies in the system.
This gives $\approx 3 \times 10^9$ yr (Table in 8.9.b) which is **quite short**
However : lets not forget the Dark Matter --- how does this change things ?
When we have a background medium, the 2-body and dynamical friction processes get entwined.
The timescale for significant energy loss becomes :

$$t_{relax} \approx t_{cross}\, N / f_g\, 6 \ln N$$

where f_g is the fraction of mass in galaxies (≈ 0.1) and N is the total number of galaxies
For individual galaxies we get $t_{relax} \approx 10^{11\text{-}12}$ yr while for subgroups (3-30 galaxies) this becomes $10^{9\text{-}11}$ yr
So relaxation is generally **not significant for most galaxies**
However, for subgroups or galaxies near the center, some relaxation is expected
Dont forget, this kind of relaxation leads to equipartition (in energy), so **massive galaxies will settle**
Although massive galaxies **are** often found in cluster cores, it is unclear if this is due to relaxation or merging.

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(5) Cluster Shapes & Kinematics

(a) "Smoothed" Properties

- The RS classification divides clusters by shape and concentration :
  irregular/unconcentrated → intermediate (eg flat/linear) → circular/concentrated

- Statistical analysis of aspect ratios :
  → clusters are **prolate** or **triaxial**
  → richer clusters are **less elongated**

- Radial profiles : azimuthal averaging gives $\Sigma(R)$
  clusters can be **stacked** by cluster type &/or galaxy Hubble type to give $\Sigma(R)$:
  Paramterize $\Sigma(R)$ using :
    central surface density : $\Sigma(0)$
    scale length (or core radius) : R_c
    steepness of concentration gradient : slope

  From rich → sparse :

    $\Sigma(0)$ **decreases** (by definition !)
    R_c **increases** (0.1 - 0.5 Mpc)
    slope becomes **flatter**
  Variation by Hubble type :
    Ellipticals are **more concentrated** and have **lower velocity dispersion** than spirals
    Velocity dispersion of spirals **decreases** at larger radius
    → outer spirals not yet crossed cluster
    → radial orbits, infalling for first time ?
    → cluster continues to be constructed

  A more theoretical approach can be adopted :
  Analytically :

    Following violent relaxation, we **expect** :
    isothermal and isotropic velocity distribution
    an equilibrium stellar dynamical system of this kind has $\rho(r)$ with :
      ≈flat core, core radius, & steep r^{-2} envelope
    appropriate solutions include (Topic 8.10.b&c) :
      isothermal profile or King profile or analytic equivalents eg $\rho(r) = \rho(0)\,[1 + (r/r_c)^2]^{-3/2}$
    These lend themselves to simple estimates of core M/L (see Topics 8.10.b.ii and 7.7)
  Numerically :
    Collisionless collapse simulations suggest a profile more similar to $\Sigma(R) \propto R^{1/4}$ deVaucouleurs law
    (not surprisingly, since the calculation is similar to collapse/merger in elliptical formation)
    Observed profiles fit both this and the analytic profiles equally well.
    The $R^{1/4}$ profile is more peaked at the center,
    although this fits the galaxy luminosity distribution well, the dark matter profile is less certain here.

- To first order, the distribution of projected galaxy velocities is **Gaussian**
  This is as expected : violent relaxation leaves an isothermal distribution with $N(v) \propto \exp(-v^2 / 2\sigma^2)$
  σ is an important parameter and measures the potential depth (as it does in galaxies).
  The velocity histogram is useful in eliminating foreground/background galaxies
  however, ambiguities result for galaxies in the Gaussian wings
  Example : velocity distribution in the Coma region, with velocity color coded map (from Huchra et al)

(b) Substructures

- **very few** clusters are completely smooth, in either surface distribution, Σ or velocity space, σ
  → there are often **close** pairs &/or small sub-groups with **similar velocities**
- Sometimes the outer parts of the cluster include significant concentrations of galaxies with lower σ
- Velocity histograms, while Gaussian overall, may have statistically significant substructure; even bimodal.
- There are clear examples of "**binary clusters**", or elongated clusters with two centers : ie **merging clusters**

  We conclude :
  → Clusters **continue to be assembled** (via heirarchical merging)

→ Relaxation is **not yet complete** in many/most clusters.

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(6) Two Nearby Examples : Virgo & Coma

Virgo and Coma provide nice examples of unrelaxed (Virgo) and relaxed (Coma) clusters.
I did not have time to go over these in class, so for the moment I'll leave this blank.
I'll include this section next time, since there are many interesting things to learn from these two clusters.

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(7) The Morphology-Density Relation

It is well known that the Spiral/Elliptical ratio is often lower in clusters than the field.
We discussed this in terms of Luminosity Functions in Topic 4 § 6 (< link >)
It seems the morphology of a galaxy depends (statistically) on its **environment**
This "Morphology-Density Relation" is important since it clearly plays a role in galaxy evolution :

- Perhaps environmental density affects what kind of galaxy can form ?
- Perhaps spirals are converted to ellipticals in dense environments ?

Lets look more closely at this topic.

(a) Early Work at Low Redshift

- Hubble and Humason (1931) notice that clusters have a higher fraction of Es and S0s than the field.
  >>> The morphological mix of galaxies depends on **galaxy environment**.
- Oemler (1974) recognised three types of cluster :
  "spiral rich" (eg Hercules); "spiral poor" (eg Virgo); "cD" (eg Coma);
  He suggests they represent a sequence in cluster dynamical evolution.
  Here is a typical census :

Type:	cD	E+S0	S+I
Rich clusters	93	56	38
Poor clusters	6	20	14
Field	< 6	< 24	48

- Dressler (1980) classified 6000 galaxies in 55 clusters plus 15 field regions.
  He recorded positions and **local projected galaxy density**
  (area enclosing nearest 10 galaxies brighter than Mv=-21.4 [Ho=50]).
  He found :
  - Strong dependencies of f(Sp), and f(E) on projected local galaxy density (figure)
  - In poor clusters, the trend is stronger with local density than with simple cluster radius (figure)
  - The dependency of f(S0) is weaker than f(E) or f(Sp)
  - The effect occurs in regions of sufficiently low density that gas stripping (see below) or encounters cannot operate.
- He concluded :
  - The primary effect is with local galaxy density NOT cluster radius.
  - The effect occurs at **galaxy formation**, and is not an ongoing **evolutionary process**.
- Both these conclusions have been subsequently questioned, and it now seems that :
  - Both global cluster conditions and local galaxy density play roles
  - While some of the effect occurs at galaxy formation, some is continuous.

(b) Possibly Relevant Physical Processes

Overall, the interpretation of the morphology-density relation is still unclear.
Possibilities include :

- High densities inhibit the **formation** of spirals.
- Spirals may be stripped of gas (see below) to make S0s
  - c.f. Amemic spirals (van den Bergh) are common in clusters
  - **But** : B/D ratios in S0s are systematically higher than in spirals.
  - **However**, maybe disks fade faster than bulges (since younger)
  - Bulges may "grow" by accretion of dwarfs
  - S0s may not be a homogeneous class : some originate as spirals, others not
- Spirals experiencing "harrassment" (Moore et al 1996) can resemble S0s.
  rapid gravitational shocks disturb spiral structure and "heat" the disk stars.
- Spiral mergers may create S0s and/or Es.

(c) HI Deficiency - Stripping of Spiral HI Gas

One of the (several) possible environmental effects on galaxies in clusters is the stripping of ISM due to ram pressure as the galaxy moves through the ICM. Observational work in the 80s focussed on HI and CO :

- HI deficiency is defined as (M - <M>)/<M>, where <M> is the mean HI mass for galaxies of the same Hubble type.
- HI deficiency is found to **increase**
  (a) towards the center of clusters (picture)
  (b) in richer clusters of higher X-ray luminosity (picture)
- However, whether this is sufficiently efficient is unclear :
  (a) Studies show CO is **not** removed (denser and deeper in galaxy potential)
  (b) Only the outer HI is stripped (eg HI map of virgo shows smaller sizes in the core)

(d) Recent Work at High Redshift

Only with HST has it been possible to study morphology at high-z (z ~ 0.5; lookback times ~6-8 Gyr).
This gives insight into whether the morphology-density relation stems from galaxy **formation** or galaxy **evolution**.

HST studies find :

- f(E) is the **same** as low-z
- f(S0) is **lower** by factor 2-3
- f(Sp) is **higher** by factor 2-3
- The morph-density relation is **absent** in irregular clusters.

We conclude from this :

- Ellipticals formed earlier (at even higher z)
- For Es, the density at formation is most important
- Spirals are converted into S0s, in an ongoing process which depends on density (still to be identified)
- These results are broadly consistent with the "Butcher-Oemler Effect" (1978)
  in which the fraction of **blue** galaxies is found to be higher in distant clusters

(e) Caveat

This is an active area of research, with many details and uncertainties.
The outline I have given here is cleaner than the true situation at this time.

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(8) Luminosity Functions

We have looked at the Luminosity function for cluster galaxies in Topic 4

Recall : the cluster LF can be constructed by combining the LFs for each galaxy type
Ellipticals : Gaussian skewed to high luminosities
Spirals and S0s : Gaussian
dE's : Schechter function with steep slope
dSp/dIrr : Schechter function with shallower slope

For increasing densities :

→ the contribution of Es, S0s and dEs increases
→ the contribution of Spirals and dIrr decreases.

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(9) cD Galaxies

cD galaxies are **anomalies** in the galaxy population :

- very **luminous** Elliptical galaxies
  $L_{cD} \approx 10 \times L_*$ which is unusually bright
  They contribute to the LF **above** the normal exponential cutoff in the Schechter function
  Significantly more luminous than expected from the population of other cluster galaxies (ie a statistical anomaly)
  → cD galaxies have a qualitative different formation history than other cluster galaxies
- always found at the **cluster center** at the projected local density maximum
  they have essentially zero velocity w.r.t. the cluster mean
  → they lie at the cluster center of gravity
- very **large** with an extended halo (50 - 100 kpc in scale)
  the light profile rises **above** the normal $R^{1/4}$ deVaucouleurs law at large radii
  The halo is usually oriented similarly to the overall cluster shape
  velocity dispersion **increases with radius** to match the cluster dispersion
  → halo contains stars in the **cluster potential**
- Images often show double/triple merging nuclei within cDs : [image]
- Origin : mergers of cluster galaxies in the cluster core
  Since cluster velocities are so high, merging should be inefficient → occurred earlier ??
- cD galaxies can be at the center of a **Cooling flow** (see below)
  These can be associated with significant emission line filaments (10^4 K gas)
  cD radio sources/jets are FR-I and exhibit significant interaction with a high pressure IGM.
  if cooling gas end up as stars, they may account for a significant fraction of the cD mass.
  (a few cDs do have patchy blue light (eg A 1795) -- but only a few)

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(10) The Hot Inter-Cluster Medium (ICM)

Clusters are the most luminous extended X-ray sources in the Universe : $10^{43\text{-}46}$ erg/s
→ emission from **hot hydrostatic gaseous "atmosphere"** : ($10^{7\text{-}8}$K)

(a) Simple Physics

- Bremsstrahlung (breaking) radiation from hot gas
  electrons scattered by nuclei → acceleration → EM radiation (photons)

(acceleration is impulsive → ≈ flat spectrum ≡ Fourier Transform of delta function)

$$\epsilon_\nu = 10^{-11}\ T^{-½} \exp(-E/kT)\ n_e\ n_Z\ Z^2\ g(E) \quad \mathrm{erg/s/cm^3/erg}$$

$g(E) \approx \ln T/E$ for $E << kT$
$g(E) \approx (E/kT)^{-0.4}$ for $E \approx kT$
for several ions, replace $n_e\ n_Z Z^2$ by $\Sigma\ n_e\ n_Z Z^2$
For cosmic abundances, integrate over energy to get :

$$\epsilon = 2.4\times10^{-27}\ T^{½}\ n_e^2 \quad \mathrm{erg/s/cm^3}$$

$$L_{tot} \approx 10^{-23}\ \mathrm{erg/s} \times \int n_e^2 dV \quad \text{for } T \approx 5\times10^7 K \approx 7\ \mathrm{keV}$$

Note : emissivity $\propto n_e^2$ → weights dense regions strongly → strong cooling in core

- Shape of spectrum → Temperature = 2 - 30 × 10^7K (ave : 7×:10^7K ≈ 7 keV)
  Intensity → n_e = 10^{-4} - 10^{-1} cm^{-3} (ave : 10^{-3} cm^{-3})
  + Volume → Mass = 0.2 - 5 × 10^{14} $M_\odot$ (ave = 10^{14} $M_\odot$)

  $M_{gas} \approx M_{gals}$ (groups) increasing to $M_{gas} \approx 7\ M_{gals}$ (rich clusters)
  On average :

  $M_{gas} \approx 5\ M_{gals}$ → ICM significantly outweighs galaxies !
  $M_{gas} \approx 1/3\ M_{tot}$ → however, dark matter still dominates overall

- Origin of gas and gas's thermal energy :
  Two obvious origins :
  - infall (deep potential) : $3/2\ kT \approx m_p\Delta\Phi$ → $T \approx 7\times10^7$ K
  - mass loss from galaxies : $3/2\ kT \approx ½\ m^p V_{gal}^2$ → $T \approx 7\times10^7$ K

  (obviously equivalent, since galaxies are in approximate virial equilibrium)

  Using abundances (see below) it seems that **both** contribute :
  → ≈80% primordial infall, ≈20% ejected from galaxies

(b) Hydrostatic Atmosphere & "Beta" Models

- Given the hot ICM is radiating X-rays, how long will it take the gas to cool down ?
  Cooling time = Thermal capacity / cooling rate

$$t_{cool} = 3\ N_e\ k\ T / \epsilon = 10^{11}\ N_e^{-1}\ T^{½} \ \mathrm{sec} = 2.7\times10^{10}\ N_{e,3}^{-1}\ T_7^{½} \ \mathrm{yr}$$

  This is longer than t_{Hubble} except, possibly, at the center.
  → the gas **remains hot**, even with no additional heating

- Sound speed : $c_s \approx 10^3$ km/s ≈ V_{gals}
  Sound crossing time : $t_{s\text{-}cross} \approx 10^9$ years << 10^{10} years

  → the atmosphere can adjust to the potential and achieve equilibrium
  → we have a **hydrostatic atmosphere**

- What is the structure of such an atmosphere : ie what is $\rho_{gas}(r)$ and $T_{gas}(r)$?
  The appropriate equations for hydrostatic support and the equation of state are :

$$dP_{gas} / dr = -G\ M(<r) / r^2 \times \rho_{gas} \quad \text{and} \quad P_{gas} = nkT = \rho_{gas}\ kT / \mu m_p$$

  Which together give :

$(1 / \rho_{gas})\, d\, \rho_{gas}(kT/\mu m_p) / dr = - GM(<r) / r^2$

Obviously, we can view this in two ways :

knowing ρ_{gas} and T_{gas} we can derive M(r) $\rightarrow$ ultimately very important (§11)
knowing M(r) **or its equivalent** (and assuming T), we can derive $\rho_{gas}(r)$

- Although we dont know M(r) we do have another tracer of Φ : **the galaxies**
  Since galaxies are $\approx$collisionless they obey an equivalent equation (T8.8.c.i eq 8.37b)

  $(1 / \rho_{gal})\, d\, (\rho_{gal}\sigma_{r,gal}^2) / dr + 2\, \beta\, \sigma_{r,gal} / r = - GM(<r) / r^2$

  (Here, β referes to **orbit anisotropy** and $\sigma_{r,gal}$ is the **radial** galaxy dispersion)
  notice that in both these equations we do **not** assume that either ρ_{gal} or ρ_{gas} define the potential (they dont, the dark matter does)
  The gas and galaxies do, however, sample the **same** potential

- To proceed, we make **three** assumptions :
  - the galaxies have isotropic orbits : $\beta = 0$, so $\sigma_{r,gal} \equiv \sigma_{gal}$
  - the galaxies are isothermal : $\sigma_{gal} = \text{const}$
  - the gas is isothermal : $T = \text{const}$

  Notice that we do **not** assume $T_{gas} = T_{gals}$
  Since $T_{gas} \neq T_{gals}$ we expect a **different** (but still isothermal) profile for the gas.

  Combining the hydrostatic fluid and stellar equations, we get :

$$\boxed{\sigma_{\rm gal}^2\, \frac{d\ln\rho_{\rm gal}}{dr} = \frac{kT}{\mu m_p}\left(\frac{d\ln\rho_{\rm gas}}{dr}\right) = -\frac{GM(<r)}{r^2}} \qquad (13.1)$$

  from which we see :

  $\rho_{gas} \propto \rho_{gal}^{\ \beta}$ with $\beta = \sigma_{gal}^2 / (kT/\mu m_p) = T_{gal} / T_{gas}$

  Here β refers to T_{gal} / T_{gas} (and should **not** be confused with the anisotropy parameter)

- One approach is to compare $N_{gal}(R)$ with $S_X(R)$ to extract β and test the various assumptions.
  Early on, considerable effort went into this but ultimately firm conclusions were illusive :
  - too few galaxies to get smooth N(R)
  - deprojection amplifies uncertainties in both $\rho_{gas}(r)$ and $\rho_{gal}(r)$
  - unknown mass segregation may render σ_{gal} **not** constant

- Instead, the above reasoning is **assumed** to be valid, and an isothermal profile is **adopted** directly.
  An adequate approximation is the "Analytic King Profile"

  $\rho_{gal} \propto (1 + (r / r_c)^2)^{-3/2}$

  so

  $\rho_{gas} \propto (1 + (r / r_c)^2)^{(-3/2)\beta}$

  recall, from T5 and T8.10.b.ii, that this is in fact the density law behind the "Hubble Profile"
  $\rightarrow$ it does **not** fit the isothermal r^{-2} profile at large radii, but
  $\rightarrow$ it does fit the general isothermal profile within a few core radii.
  One nice advantage, however, is that **all integrals are analytic** (including deprojections)

- Fits to X-ray brightness profiles are reasonably good, except :
  - when substructure is strong (not hydrostatic)
  - at the centers when a cooling flow occurs (see §10e)

  Fits yeild $\beta \approx 0.7$ (rich clusters) $\rightarrow \approx 0.4$ (less rich clusters)
  giving halo gas density gradients r^{-1} (rich clusters) $\rightarrow$ $r^{-0.7}$ (less rich clusters)

- In terms of gas temperature : $T_{gas} / T_{gal} \approx \beta^{-1} \approx 1.5$ (rich) $\rightarrow$ 2 (less rich)

  $\rightarrow$ It seems the gas is **hotter** than the galaxies,
  $\rightarrow$ the temperature difference is **greater** for shallower potentials.
  These results are also supported by (spectroscopic) measurements of T_{gas}

  conclusion : There is a non-gravitational source of heating for the ICM.

  What is it ? $\rightarrow$ not yet known
  Possibilities include :

  - AGN jets (in the past, not current radio sources)
  - Starburst driven superwinds
  - Shocks arising from cluster mergers
  - Early inhomogeneous ICM : cooler parts become galaxies, hotter parts stay ICM

(c) X-ray Correlations

Given that X-rays arise from a hydrostatic atmosphere, we expect (and find) correlations with **other** measures of potential depth.

- L_X increases with increasing central galaxy density
- L_X increases with increasing E/S0/Sp fraction
- T_{gas} increases with L_X (cluster potential depth)
- M_{gas} / M_{gal} increases with L_X and T $\rightarrow$ gas **retained** in deeper potentials
- Metallicity increases with **lower** L_X & T $\rightarrow$ greater loss of primordial gas

(d) Abundances (and Temperatures)

- **Atomic emission lines** provide information on **temperature** and **abundances**
  At 10^6 K X-ray lines originate from **highly ionized** ions (eg Fe??, Si??)
  also inner shell transitions (eg n=1,2 $\equiv$ K,L)

- The quality of X-ray spectra has gradually improved in both sensitivity and resolution.
  Initially, **proportional counters** (eg ????satellites) gave few ($\lesssim$ 5 - 10) resolution elements
  $\rightarrow$ slope and absorbing column (confirms Bremms)
  Early spectrographs gave high resolution, but cluster ICM too faint.
  examples
  more examples

- **Temperatures** from continuum shape agree with temps from ionization degree
  $\rightarrow$ gas is **collisionally ionized** (& in **LTE**)
  Spatial resolution of Temp measurements still poor (exampes)
  However, some results have emerged :
  - confirm isothermal to 0^{th} order
  - identify cooler central gas $\rightarrow$ cooling flows (see below)
  - find mild Temperature gradients $\rightarrow$???

- Abundances are modest but certainly not zero : $Z \approx 1/3\ Z_\odot$
  Abundances **decrease** with radius (figure from Keel)
  Mass in ICM metals **increases** with luminosity (mass) of spheroids (Es & S0s)

→ origin of metals is galactic winds

- M_Z(gas) ≈ M_Z(gals) which is quite remarkable, (M_Z means total mass of metals)
  → the ICM gas has experienced as much toal processing as all the galaxies.
  → galaxies lose a significant fraction of their initial gas (≈30% - 50%) in winds

- However, recall that $M_{gas} \approx 3 - 5 \times M_{gals}$
  → early SN fraction **higher** than today ie **flatter** IMF → more SN per $M_\odot$ SF
  also
  → only **part** of the ICM originates as winds :
  → ≈ 20% ejected from galaxies
  → ≈ 80% primordial

- **Relative** abundances can help distinguish Type Ia (Si/Fe "low") from Type II (Si/Fe "high")
  → most metals come from Type II SN (massive star core collapse)

- However, Si/Fe **decreases** for poorer clusters (figure from Keel)
  → **lost** some of their initial Type II ejecta
  → ongoing input from Type Ia which is retained

(e) Cooling Flows

- Not all parts of the ICM have $t_{cool} > t_{Hubble}$
  Since emissivity $\epsilon \propto \rho^2$ & $t_{cool} \propto \rho kT/\mu m_p \epsilon$ we have $t_{cool} \propto \rho^{-1}$
  we expect the **centers** of ICM (high ρ) to have **shortest** t_{cool}
  → ≈ 2/3 clusters have $t_{cool} \lesssim 10^{10}$ yr at 100 kpc and $t_{cool} \lesssim 10^9$ yr at 10 kpc
  → this is quite a **small region** : R ≈ 10% Abell Radius (2-3 × cD radius)
  → if the density profile **doesn't** rise steeply (eg affected by merger) then **won't** get rapid cooling (eg Coma compared to A 478 : figure from Fabian EAA)
  → given rapid cooling, get L_X (cooling flow) ≈ 10% - 40% L_X(total)

- If gas cools → T decreases → ρ increases ($P \propto \rho \times T$)
  So gas **slowly moves inwards** (highly subsonic, gas still in hydrostatic eqlm)
  modest heating by release of PE is **not enough** to halt the flow
  Spectra confirm : $T_{inner} \approx 1$ keV ; $T_{outer} \approx 5$ keV

- knowing $\rho_{gas}(r)$, $L_X(r)$ & $T_X(r)$ gives the deposition rate of cool gas M(dot)(<r)
  → one can show that M(dot)(<r) ∝ r with $M(dot)_{total} \approx 10 - 1000\ M_\odot\ yr^{-1}$
  → this is comparable to star formation rates in SB → LIG → ULIG starbursts ! (see Topic 11)
  Unlike starbursts, however, this mass deposition is **long lived**
  → integrated over 5 Gyr → $5 \times 10^{10-12}\ M_\odot$
  → could contribute **significantly** to the central (gE or cD) galaxy !

- 64 k$ question : where does the matter go ??
  below 10^6 K / 10^3 K $t_{cool} \approx 10^6 / 10^3$ yr → T ≈ 3 - 30 K
  expect small dense molecular clouds ?
  → low mass stars ?
  → dense clouds fall through the ICM & merge → high mass stars
  (**some** examples of blue/young regions : eg A 1795)
  → Hα filaments are common (≈50%)
  however, M_{HII} is less than expected, & $L_{H\alpha}$>> recombinations from M(dot)
  suggests that the 10^4 gas is kept ionized by something (hot stars ? shocks ?)

(f) Radio Sources & the ICM

WATs & NATs

Radio halos & the link to ICM shocks
Not yet written up

(g) ICM Substructures and Cluster Mergers

Not yet written up

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(11) Cluster Masses

There are a number of methods for measuring the gravitational field in clusters
To some extent, this topic overlaps with Topic 17 on Dark Matter and Gravitational Lensing
So we will be quite brief here.

- **Galaxy Velocities** :
  Assuming clusters to be in gravitational equilibrium, we can use the Virial Theorem :

  $\langle KE\rangle = -\tfrac{1}{2}\langle PE\rangle \rightarrow \langle v^2\rangle = \alpha\, GM_{clus} / R_{clus}$ ($\alpha \approx 1$ depending on orbit geometry)

  Zwicky (1933) was the first to apply this (to Coma) and recognised that $M_{clus} >> \Sigma M_{gals}$
  at the time, interpretation was unclear since it was not known if clusters were in gravitational equilibrium
  The result was controversial until the 1970s when evidence for dark matter began to build

  Today, Zwicky's approach has been vindicated, though there are still some caveats :

  a well sampled velocity field is rare (usually too few galaxy redshifts measured)
  eliminating foreground/background galaxies is difficult (though velocity outliers are influencial)
  orbits of galaxies are unknown (so α is not well known; cf Topic 13 measuring BH masses)

- **Hydrostatic Hot Gas**
  Since the hot ICM is hydrostatically supported, its structure is defined by the potential :

  $(1 / \rho_{gas})\, d P_{gas} / dr = - GM(<r) / r^2$

  This requires measuring :
  $\rho_{gas}(r)$ from X-ray images (eg ROSAT; XMM; Chandra)
  $T_{gas}(r)$ from X-ray spectra (eg ASCA; Chandra)

  This method also has some caveats :

  Presently, spatial resolution is poor for spectra (hopefully Temp gradients are slight)
  There may be both small and/or large scale inhomogeneities in the ICM

- **Gravitational Lensing**
  The light from distant galaxies is deflected (slightly) by the gravitational field of the cluster
  Image **distortion** $\rightarrow$ **projected, total** mass density : $\Sigma_{tot} = \int \rho_{tot}\, dl$

  There are **two** rather different regimes :

  - Strong Lensing
    Background galaxies are **strongly** distorted $\rightarrow$ they appear as small arcs or arclets (figure)
    Detailed modelling can provide a **map** of the projected density (figure)
    This method is good for massive clusters, and can provide maps of the inner potential

  - Weak Lensing
    Background galaxies are only slightly distorted
    For a symmetric potential, the galaxies are elongated slightly in the axial direction
    This is a "shearing" effect and only reveals the **gradient** in the potential, not its integrated depth

By measuring thousands of faint galaxy images, the effect is identified statistically.

In addition to being distorted, the galaxies are also slightly **brighter**.
→ the surface **number density** at different magnitudes can yield similar information.

- **Results Summary**

Naturally, there is a range of cluster masses found
Here is the cluster mass function : < graph >
Total masses range over 10^{14} - 10^{15} $M_{\odot}$ with fewer of higher mass
More important are mass **ratios** : M_{tot} is typically $\approx$ $4 \times M_{gas + gals}$
Comparing the mass to the galaxy light : $(M / L_B) \approx 200\ M_{\odot} / L_{B,\odot}$
this is **much** larger than the optical part of individual galaxies (1-10 depending on type)
This provides some of the strongest evidence for Dark Matter.

Oort (1958) first suggested that cluster M/L ratios were representative of the Universe as a whole
Using a total galaxy luminosity density and a typical cluster M/L ratio we find $\Omega_{matter} \approx 0.2$
If the gas and galaxies comprise all the **baryonic** matter in the cluster, we then expect $\Omega_{baryons} \approx 0.06$
which is nicely consistent with the value from cosmic nucleosynthesis.

As you probably know, a variety of methods have established that we are in a flat universe, with :
$\Omega_{total} \approx 1$ which itself comprises $\Omega_{vacuum} \approx 0.7$; $\Omega_{matter} \approx 0.3$; $\Omega_{baryons} \approx 0.04$

Clusters have played an important role in establishing these cosmological numbers

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