PHAS 1102
Physics of the Universe

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(or via MOODLE)

Partial Notes, Part 2, Section 1

'Galaxies'

These partial notes should be used in conjunction with your own notes, and powerpoint slides which will be made available on-line.

The Composition of the Universe

We can examine this question on two extreme scales: the microscopic (atomic-physics particles) and the macroscopic (the major constituents of the universe). Our focus will be on the latter aspect, but to understand that we first need to review the former.

1 The Standard Model

On the small scale, the foundation of particle physics is the so-called 'Standard Model' – the current theory of fundamental particles and how they interact.

The Standard Model describes more than 200 'elementary' particles, and their interactions, using as ingredients:

6 quarks	[flavours: up, down, strange, charm, top, bottom]
6 leptons	[electron, muon, tauon, and their associated neutrinos]

(together with their antiparticles); and a few force-carrying particles:

gluon	[strong nuclear]
photon	[electromagnetic]
W+Z	[weak nuclear]
graviton?	[gravity]

The Standard Model has had great success in explaining experimental results; it predicted the existence of W and Z bosons, the gluon, and the top and charms quark before these particles had been observed. (The only fundamental particle predicted but not yet observed is the Higgs boson, discussed below.)

However, it is not a complete theory; for example:

1. The theory contains many free parameters, such as particle masses and charges, which cannot be independently calculated. (In this sense, it is a *model*, not a theory)
2. The model does not describe the gravitational interaction.
3. In its basic form it predicts neutrinos to have zero mass, which astronomical (and, much later, particle-physics) experiments have shown to be incorrect
4. It doesn't account for most of the stuff of the universe, as we shall see.
5. It doesn't explain the imbalance between matter and anitmatter

Since the completion of the basic Standard Model, many efforts have been made to address these problems, through the development of 'Grand Unified Theories' (GUTs; electroweak+strong) and 'Theories of Everything' (TOEs; GUT+gravity).

For the purposes of this course, the crucial fact to keep in mind is that, on a macroscopic scale, essentially **ALL** of the *directly observable* mass of the universe is in the form of 'baryonic matter'. Baryons are made up of three quarks[1], with neutrons and protons completely dominating the mass budget (both are baryonic particles, their quark compositions being up-down-down and up-up-down, respectively). When we see stars, planets, galaxies, plants, animals, their mass is almost entirely baryonic.[2]

1.1 Higgs, hadrons...help!

Although the basic ingredients of the Standard Model are reasonably few, the range of particles that can be built from them is bewildering large. For example, in 2008 the Large Hadron Collider (LHC) at CERN was officially opened, to great fanfare, and with much talk of the Higgs particle. What's a hadron, and what's a Higgs particle?

If you really want to know...

[1]Well, 'normal' baryons are made of three quarks – more exotic types of baryon have been postulated (but not observed).

[2]Of course, there are some electrons there, too (and electrons are leptons, not baryons), but their mass is negligible in this context.

Mesons are composed of an even number of quarks and antiquarks (all known mesons consist of equal numbers of quarks and antiquarks, usually one of each), while we have seen that all known *baryons* consist of three quarks. Mesons and baryons are collectively referred to as *hadrons* (particles made up of quarks and gluons).

[There are no mesons as familiar as the well-known baryons (i.e., protons and neutrons), because mesons are intrinsically unstable; but as an illustrative example the π^+ meson (or pion) consists of an up quark and an anti-down quark.]

The Large Hadron Collider is designed to collide protons at very high energies. Protons are a type of baryon, and baryons are a type of hadron – hence the name.[3]

All particles with half-integer spin (i.e., with spin quantum number $^1/_2, ^3/_2$, etc) are collectively called *fermions;* examples of fermions include quarks and leptons. A *boson* is any particle having an integer spin quantum number (0, 1, 2...).

[Particles with integer spin include the deuterium nucleus, and He^4 atom; the force-carrying particles (photons etc.) are also bosons.]

And the Higgs particle is more properly called the Higgs Boson. It is the only Standard Model fundamental particle not yet observed, and (if it exists) it is a key ingredient in the simplest mechanism for attributing mass to matter.

[If forces and matter particles were all there is, the simplest version of the Standard Model says that all particles must travel at the speed of light. To slow them down, Peter Higgs (and others) proposed a pervasive 'Higgs Field'. Particles that interact with the Higgs field behave as if they have mass, proportional to the strength of the field times the strength of the interaction. If the Higgs field exists, theory demands that it have an associated particle, the Higgs boson.]

1.2 Summary:

- The standard model successfully explains hundreds of different particles, and their complex interactions, with relatively few ingredients.
- It is, however, incomplete
- As far as the mass budget of the universe is concerned, the most important ingredient in the framework of the Standard Model is *Baryonic Matter* – e.g., planets and stars. (Although planets and stars also contain lots of electrons [which belong to the class of leptons] their mass is negligible compared to that of the baryons.)

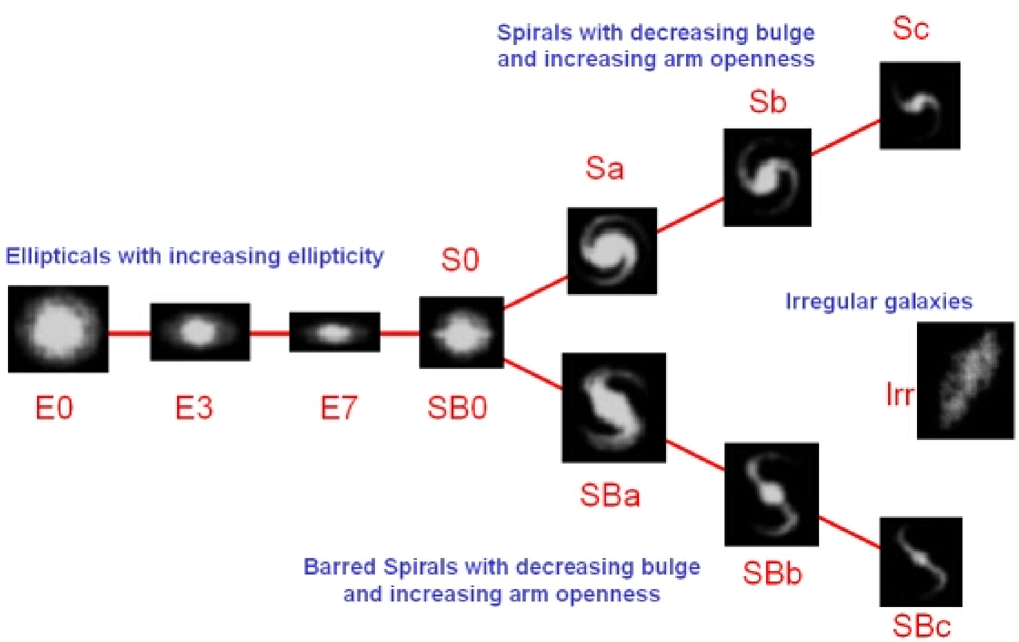
[3] I guess the Large Hadron Collider could equally well have been called the Large Baryon Collider (except that LBC is a radio station), or, more straightforwardly, the Large Proton Collider (except that 'LPC' would've confused followers of the Liberal Party of Canada).

2 Galaxies

Galaxies are the largest well-defined discrete components of the universe. They are gravitationally bound systems of, typically, $\sim 10^7$–10^{12} stars.

2.1 Classification

The wide range in mass is reflected in diverse morphologies. Galaxies were first systematically categorized by Edwin Hubble, who in 1929 classified them according to shape: the **Hubble Classification Scheme** or **'Tuning Fork Diagram'**



In the mid-20th century this was (**wrongly**) considered as a possible evolutionary scheme. By analogy with stellar spectral types, galaxies were therefore labelled as 'early-' to 'late-type'. This nomenclature persists, but it is emphasized that it does **not** imply an evolutionary sequence; rather, we now see it largely as a sequence of changing bulge:disk contribution (discussed below). Morphologically, we have:

2.1.1 Elliptical ('Early type') galaxies

E0 – E7 (0 spherical, 7 most distorted; the numerical index is calculated as $10(1 - b/a)$, where a and b are the lengths of the major and minor axes)

2.1.2 Lenticular (S0) galaxies

These galaxies are intermediate between E0 and Sa – they have disks but no spiral structure.

2.1.3 Spiral ('late type') galaxies

Classified Sa – Sc; the subclass refers to how tightly wound arms are and size of nucleus
Sa – large nucleus, tightly wound arms
Sc – small nucleus, open spiral arms

Also *barred* spiral galaxies, SBa – SBc (though bars are normal!)

2.1.4 Irregular galaxies

IrI and IrII – disorganized (Irr II are 'more disorganized'), often with associated star formation (blue regions).

Although some irregular galaxies are the result of tidal interactions or collisions between larger galaxies, in modern usage the term is most often applied to 'dwarf irregulars'.

Hubble's scheme has shortcomings (for example, doesn't take any cognizance of luminosity), and more detailed schemes have since been developed; but the basic Hubble classification remains very widely used.

2.2 Properties

Spirals:

– have large amounts of interstellar material

– show continuing star formation in the disk

– are all of *more or less* similar size and luminosity, around 10^{11} solar masses (give or take an order of magnitude!).

– consist of several distinct components. Using our own Galaxy as an example:

- *Disk*: $\sim$50 kpc in diameter[4] with a thickness of $\sim$1 kpc. The sun is located in disk, about 8 kpc from Galactic centre. The disk contains young stars (i.e., *Population I* stars) in spiral arms. The disk is supported by rotation.
- *Bulge*: Kinematically distinct (rotation *plus* velocity dispersion), contains old stars (Population II).
- *Halo*: has a diameter of $\sim$100 kpc and contains globular clusters (spherical systems of stars with diameters 10–20pc, containing about 10^5 old Population II stars. They are the oldest systems in the Galaxy, with ages $\sim 13\times10^9$ yr). The halo is supported by velocity dispersion, not rotation.

Ellipticals:

– contain old stars (Pop. II)

– have very little interstellar material

– their light is dominated by red-giant stars.

– have random internal motions ('velocity dispersion')

– show a wide range in size/luminosity, ranging from 'dwarf ellipticals' to 'giant ellipticals' ('cD' galaxies), corresponding to masses of $\sim 10^7$–10^{12} solar masses.

In modern terms, the Hubble classification scheme can be seen as reflecting the degree of present-day star formation, or (equivalently) the relative importance of the bulge and disk components (the former being essentially the sole constituent of elliptical galaxies).

	Ellipticals	Spirals	
Luminosity ($L_\odot$)	$10^5 - 10^{11}$	$10^8 - 10^{11}$	($L_\odot = 3.8 \times 10^{26}$ W)
Diameter (kpc)	3–100	5–50	
Visible Mass ($M_\odot$)	$10^5 - 10^{13}$	$10^9 - 5 \times 10^{11}$	($M_\odot = 1.989 \times 10^{30}$ kg)

[4]Only writers of science-fiction and 'popular' astronomy books use 'light-years' to measure astronomical distances. Proper astronomers use the *parsec* (3.0857×10^{13} km, or, if you must, 3.262 light-years). The nearest star (other than the Sun) is about 1 pc distant; distances within the Galaxy are conveniently measured in kpc; and intergalactic distances are conveniently measured in Mpc.

3 The Milky Way Galaxy

Our own Galaxy (usually given a capital 'G') has long been considered a 'normal' spiral galaxy, but over the last few years results from the Spitzer satellite, in particular, indicate that our Galaxy contains a substantial bar, extending $\sim$4 kpc out from the Galactic Centre (almost half the distance to the 'solar circle'). We therefore probably live in an SBc barred spiral.

3.1 Spiral arms

We now understand that spiral arms 'trail' galactic rotation.

What is the nature of spiral arms? *They cannot represent the same stars (or the same sites of star formation) over time,* as this would lead to a 'winding problem'. Spiral arms must represent a *wave* phenomenon that progresses through the galaxy. This *density wave* moves in the same direction as Galactic rotation, but more slowly than the orbital speeds. Thus stars 'catch up' with spiral arms, pass through them, and emerge out the front side.

When molecular clouds enter the compressed region of a density wave, star formation is triggered. Although stars form across a range of masses, the high-mass stars are much the brightest, and bluest, so they delineate the spiral arms in optical radiation. (Although the spiral arms are very obvious in the *light* distribution, they are much more subtle features in the *mass* distribution.)

3.2 Galactic Centre

Because of its relative proximity ($\sim$8 kpc distant), the centre of our Galaxy can be studied in greater detail than similar environments elsewhere. It is heavily obscured at optical wavelengths by intervening interstellar dust, but observable in the radio and the IR. The dynamics of stars in the central region indicates that they are orbiting a high-mass, dark object; just as with planetary orbits, we can equate centripetal and gravitational forces for a body of mass m orbiting a body of mass M at distance r with velocity v:

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

to 'weigh' the a supermassive black hole, finding $M > 10^6 \mathrm{M}_\odot$. We think this is normal: most, if not all, galaxies with a degree of axial symmetry (i.e., ellipticals and spirals, but not irregulars) are believed to host a supermassive black hole.

4 Active Galaxies

Normal galaxies emit thermal radiation and their optical spectra consist of absorption lines arising from their constituent stars.

Active galactic nuclei have the following general properties:

(1) High energy output than normal galaxies ($> 10^{37}$ W; Milky Way nucleus emits 10^{35} W) enabling them to be seen at much larger distances.

(2) Non-thermal (synchrotron) emission with excess energy at UV, IR, radio and X-ray wavelengths.

(3) Variability over time-scales from few hours to few years – indicates emitting region is few light years across.

(4) Often have jets emerging from nucleus.

(5) Have emission line spectra.

Examples are Radio Galaxies, Seyfert Galaxies and Quasars.

4.1 Seyfert Galaxies

These are spiral galaxies which show evidence for violent activity in their nuclei and are generally classed as **Active Galactic Nuclei (AGN)**.

They were discovered in the 1940s by Carl Seyfert and appear as normal spirals, but with very bright nuclei and emit strong non-thermal spectrum.

The visible spectrum contains broad (5 000–10 000 km/s) emission lines indicating clouds of gas moving at very high speeds in the nucleus of the galaxy.

$\sim$1% of spiral galaxies are Seyfert galaxies.

The light output and spectrum are highly variable on short time-scales of days to months $\rightarrow$ activity is confined to a small region at most a few light-months in diameter.

4.2 Quasars

In 1960 optical spectra of two faint stellar-like objects were obtained which were sources of radio emission – called 3C 48 and 3C 273.

Spectra showed strong emission lines which were finally interpreted in 1963 as the Balmer series of hydrogen redshifted by a (then) unprecedented amount of 100 nm for 3C 273 ($z = 0.16$; $d \simeq 650$ Mpc).

Well over 1000 Quasars (Quasi-stellar radio sources) have now been identified. It is accepted that their enormous redshifts are due to the expansion of the Universe.

They are among the most distant known objects that we can observe and they allow us to probe the early Universe. The highest redshift quasars known (to date) have $z > 6.0$

Quasars are variable on time-scales of days to months which indicates that they are very small (< 1 light-month, or $< 10^{15}$ m).
Their enormous distances indicate luminosities of $\sim 10^{12} \mathrm{L}_\odot$.
There is an energy problem – how can so much energy be generated from such a small object?
The answer is accretion, whereby energy is converted from gravitational to radiative energy as material spirals in an *accretion disk* around a black hole. The available potential energy is

$$U = \frac{GMm}{r}$$

and a supermassive black hole of $10^8 \mathrm{M}_\odot$ has a *Schwarzschild radius*,[5]

$$R_\mathrm{S} = \frac{2GM}{c^2},$$

of 3×10^8 km (easily small enough to be consistent with observations). If we suppose that most of the emitted radiation from the accretion disk comes out at $\sim 5R_\mathrm{S}$ (a reasonable number, supported by detailed calculations), then the potential energy released by infall of a particle of mass m is

$$U \simeq \frac{GMm}{5R_\mathrm{S}} = 0.1mc^2$$

(cp. nuclear fusion, efficiency = 0.007). This is a hugely efficient process! – luminosities of $10^{12} \mathrm{L}_\odot$ (bright quasars) are possible with an inflow of roughly $1\mathrm{M}_\odot$/yr.

We now believe that many 'different' types of active galaxy are underpinned by the same basic physics of accretion onto a supermassive black hole, and that the differences arise from different viewing angles, coupled with different accretion rates and accretion environments.

[5] The Schwarzschild radius marks the 'event horizon' of a norotating black hole; classically, we can get no information out from inside this radius, which in some sense represents 'the' radius of a black hole. Although it requires a full relativistic treatment to derive correctly, the same result comes out just by finding the radius at which the escape velocity from a body of mass M equals the speed of light (an exercise left for the student).

5 The Distribution of Galaxies

Galaxies are not uniformly distributed but are concentrated into
–small **groups** or larger **clusters**
which in turn form
–**superclusters**.

The Milky Way Galaxy belongs to the **Local Group** of galaxies, which consists of around 50 galaxies[6] distributed over a couple of Mpc.

Our Galaxy and the Andromeda Galaxy (M31; $d = 0.8$ Mpc) dominate; the other members are mostly irregular and dwarf galaxies – including a dozen or so satellites to our Galaxy, of which the best known are the Small and Large Magellanic Clouds. (Other satellite galaxies of note include the Sgr dwarf elliptical, about 20 kpc distant, and the CMa dwarf, now believed to be our nearest neighbour at only 8 kpc distance from us [ca. 15 kpc from the Galactic centre].)

5.1 Clusters of Galaxies

There's no formal distinction between groups and clusters, but the latter may contain hundreds to a thousand or more galaxies, in a gravitationally bound system of order 10 Mpc across. The pioneering catalogue of galaxy clusters was published by George Abell (1958), and clusters are still commonly refered to by Abell catalogue number.

The spacing of member galaxies is *relatively* close ($\sim$ 10–100$\times$ a galaxy diameter; for comparison, in our Galaxy the spacing of stars is $\sim 10^8\times$ diameter of a typical star), so galaxy–galaxy interactions must occur.

'Regular' clusters appear to be populated mainly by elliptical galaxies, while 'irregular' clusters tend to include all galaxy types. Both often have a *giant* elliptical galaxy (a so-called cD galaxy), $\sim$200 kpc in diameter, at the centre of the gravitational well.

It is thought that the large number of ellipticals is due to galaxy mergers and a cD galaxy originates by devouring other galaxies. Evidence for this is that some cD galaxies have double nuclei and extensive visible halos (up to 1 Mpc in diameter).

The Virgo Cluster is the nearest moderately rich large cluster; at a distance of about 17 Mpc and with a diameter of about 3 Mpc it covers $\sim 7^\circ$ on sky. It is an irregular cluster with many hundreds of galaxies (mostly spirals and irregulars), with a famous giant elliptical (M87) at the centre.

[6] Two large spirals (the Galaxy and M31), one small spiral (M33), two small ellipticals (M32 and M110, both satellites of M31), and a few dozen smaller objects

The Coma Cluster is a richer, regular cluster containing thousands of galaxies (mostly ellipticals and S0 spirals) in a roughly spherical distribution, again about 3 Mpc across, and ∼100 Mpc distant us. The elliptical galaxies congregate toward the central regions while the few spirals that occur are found on the outskirts. Two giant ellipticals (NGC 4874 & NGC 4889) occupy the central part of the cluster. Other rich clusters show the same segregation of the spirals from the ellipticals as the Coma Cluster: ellipticals gather together in the centre, with spirals towards the edges. Most probably both the overall shape and the ratio of ellipticals:spirals reflect interactions.

5.2 Superclusters

Over the last 10–15 years, the 3D structure of the local Universe has been mapped by measuring redshifts of clusters.

It is found that clusters of galaxies are grouped into chains or **superclusters** with large voids in between. The Universe therefore has a cell-like structure.
The superclusters are hundreds of Mpc long. Our Local Group belongs to the Virgo Supercluster (which includes the Virgo Cluster).

6 Galactic Dynamics

This topic is of greatest interest in the role it plays in determining masses.

The sun has a orbital velocity of about 220 km/s about the centre of the Galaxy. For historical reasons, astronomers often call this the 'rotational velocity', V_{rot}; it's important to realise that this doesn't refer to the velocity at which the sun rotates on its axis (which is about 2 km s^{-1} at the equator), but instead means the velocity at at which the *Galaxy* rotates at the Sun's distance from the galactic centre.

To measure the mass of a galaxy, we can use the form of Kepler's 3rd law (for circular orbits),
$V_{\mathrm{rot}}^2 = G\,M/R$
to determine the mass M inside a star's orbit at galactocentric radius R, given a rotation velocity V_{rot}.
(M is $\sim 10^{11}$–$10^{12}\mathrm{M}_\odot$ for our Galaxy.)
Plotting $V_{\mathrm{rot}}(R)$ against R gives the **rotation curve** of the Galaxy.

Our own galaxy, in common with other spiral galaxies, is observed to have a flat rotation curve – indicating large amounts of dark matter (Vera Rubin, 1985).

6.1 Masses of Clusters

Masses of clusters can be measured from
– the dynamics of the constituent galaxies;
– by gravitational lensing; and
– by X-ray observations.

6.1.1 Dynamics

Just as the motions of stars in a Galaxy are determined by the mass of the galaxy, so the motions of galaxies in a cluster of galaxies are determined by the mass of the cluster. This is formally embodied in the *Virial Theorem,* which states that:

the kinetic energy equals half the potential energy.

If a 'system' (here, a cluster of galaxies) is composed of 'particles' (here, individual galaxies) with Ω the mutual gravitational potential energy of the particles and U is the kinetic energy of the particles, then the total energy is $E = U + \Omega$, and the Virial Theorem states that

$$U = -\frac{1}{2}\Omega.$$

We can measure the velocities of galaxies in a cluster (in an average sense), and hence the kinetic energy. This gives us the gravitational potentential energy (for a virialized system), from which we infer the *total* mass (not just the mass we can see in galaxies).

(This experiment was performed by Fitz Zwicky in 1937, and provided the first strong evidence of dark matter.)

6.1.2 Gravitational Lensing

The deflection of background sources by gravitational lenses depends on the mass of the 'lens'.

6.1.3 X-ray Observations

X-ray observations allow us to infer masses through the assumption of *hydrostatic equilibrium* of hot, intergalactic gas. If we can measure the temperature, we can estimate the gas pressure, and hence the gravitational attraction (leading again to the *total* mass, not just the mass of gas).

All three methods indicates total masses $\sim 10\times$ the visible mass $\Rightarrow$ dark matter.