

Whittle : EXTRAGALACTIC ASTRONOMY

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1. HISTORY & PRELIMINARIES

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(1) Introduction

Let's start this course with the suggestion that the subject is of fundamental importance.

For reasons not yet fully understood, matter in the universe is organized into three basic structures:

- Atoms
- Stars
- Galaxies -- the subject of this course

Our understanding of each has grown in rough synchrony :

- ~1750 - 1850 : recognition of basic existence
- ~1850 - 1930 : recognition of basic properties
- ~1930 - present : deeper understanding (structure, creation, evolution, sociality)

It is probably fair to say that our understanding of galaxies has lagged behind atoms and stars, mainly because they are difficult to observe, being so faint.

- atoms & stars : understanding now mature
- galaxies : becoming mature; now ± 30 yrs is a golden time.
 - currently fertile area (astronomy is prominent amongst physical sciences)
 - your careers will witness significant growth
 - these notes will be of limited use when **you** teach the course, in ~20 yrs.

Let's first look briefly at some historical highlights.

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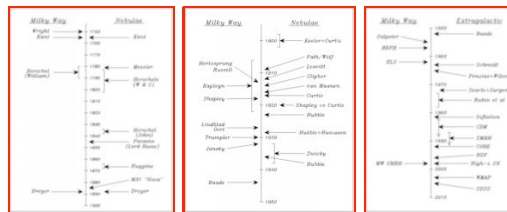
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(2) Discovering Galaxies : Ours & Others

(a) Early Aims

- Early thinking (before 1923) focussed on two main questions :
 - What is the **Milky Way** (Latin : Via Lactea)
 - initially : what is its shape and where is the sun
 - later : what is its size and internal motion
 - What are the **Nebulae** (Latin : clouds)
 - initially : use "large" telescopes to find, catalog, and describe them
 - later : are they unresolved star groups, or genuinely nebulous (gaseous)
 - finally : are they internal to the MW, or external "island universes"
- As telescope apertures increased, the methods developed :
 - Visual → photographic → visual spectra → photographic spectra
- The path of discovery was NOT linear, with discussion often polarized and ambiguous.
- Here are some simple time-line sketches identifying the key people/work

1750 - 1900 [figure]
 1900 - 1950 [figure]
 1950 - present [figure]
 all combined: [figure]



(b) Before 1850 : Search & Discovery

- **before 1750** : essentially no references to galaxies, except :
 Australian dreamtime narratives include "Magellanic" Clouds
 ~ 950 **al-Sufi** (Persian) includes M31 in star charts : [images]
- **1610** : **Galileo Galilei** (Italian) uses early telescopes
 realises Milky Way is composed of many stars
- **1750** : Thomas **Wright** (English) : [images]
 Publishes "An Original Theory of the Universe" in 1750
giant spherical shell; we see tangent plane; God @ center
 stars orbit around, preventing them falling onto God
- **1755** : Immanuel **Kant** (German)
 writes : "General Natural History & Theory of the Heavens"
 (1) rejects spherical shell
 (2) MW like huge solar system, rotating
 (3) stars far from plane on different orbits
 (4) disks (like MW) project to ellipses
 (5) oval nebulae (seen by de Maupertius) = separate galaxies
 → remarkably precient, but not widely accepted through 1800s

- **1780s** : William **Herschel** (English) : [images]
star counts → MW = flat disk with sun @ center
no size estimate
ultimately recognizes wrong assumptions & retracts
- **1781** : Charles **Messier** (French) completes first catalog of nebulae (109) [image]
- **1770 - 1810** : William & Caroline & John **Herschel** (English) : [images]
all-sky survey → 2500 nebulae
used 18" (20 foot) reflecting telescope, diurnal sweeps
extended to southern skies by son John at Cape of Good Hope (1834-9)
some resolve into stars (clusters) others don't (gas?)
speculation : uniform distribution of stars will gravitationally cluster
- **1845** : William **Parsons** (3rd Earl of Rosse) : [images]
English Lord resident in central Ireland : Birr Castle
36" then 72" (Leviathan of Parsonstown; largest until 100" Mt Wilson, 1917)
spiral structure (eg M51, M33, M101)
some have stars and gas (eg M42) → supports Kant's rotation idea
1840s potato famine stops work; never achieves its potential

(c) 1850 - 1925 : The Great Debates

- **1864-68** : William **Huggins** (English) : [images]
telescopic visual spectra of nebulae
1/3 emission lines (gaseous); 2/3 continuous (stellar)
- **1885** : **Nova** (actually Supernova) in M31
10% brightness of entire nebula
seen as strong evidence against "island universes"
- **1888** : John **Dreyer** (Danish) [image] working at Birr Castle, compiles
New General Catalog (NGC) : 7840 nebulae
Index Catalog (IC) : 5086 more
- **1900s** : James **Keeler** and Herber **Curtis** (USA, Lick) use **photography**
36" Crossley reflector @ Lick : [images]
estimates ~120,000 nebulae accessible; ~50% are spiral
- **1910** : E. **Fath** (USA, Lick) and Max **Wolf** (Germany, Heidelberg)
photographic spectra of many spirals
many have absorption lines → stellar systems → external?
- **1906-22** : Jacobus **Kapteyn** (Dutch) : detailed study of MW : [images]
surveys 200 areas : star counts, proper motions, radial velocities
concludes : MW = thick disk, 5kpc radius, sun @ center
considers absorption and finds some reddening, but
assumes Rayleigh scattering so infers (wrongly) absorption unimportant
- **1912** : Henrietta **Leavitt** (USA, Harvard) : [images]
Period-Luminosity relation for Cepheids in Magellanic Clouds
tool for measuring distances
- **1913** : Ejnar **Hertzsprung** (Danish) and Henry **Russell** (USA, Princeton) [image]
first color-magnitude (CM) diagrams for stars
- **1914** : Vesto **Slipher** (USA, Lowell) : [image]
spectra of spirals (take 80 hours!)

finds large velocities (eg M31 is -300 km/s)
much larger than any MW stars

- **1916** : Adriaan **van Maanen** (USA, Mt Wilson) :
finds proper motion rotation in M101 (!!)
→ must be local to avoid super-luminal speeds
- **1917** : Herber **Curtis** (USA, Lick [PhD Virginia!]) :
measures more novae in spirals → 100 x farther than galactic novae
suggests 1885 "nova" in M31 was anomalous
- **1918** : Harlow **Shapley** (USA, Princeton/Harvard) :
uses Globular Clusters (GCs) to infer "Big Galaxy"
diameter 100 kpc, sun ~15 kpc off-center
10 x Kapteyn's galaxy; suggests absorption was the problem
- **1920** : **Shapley (no) - Curtis (yes) Debate** : "Are Spiral Nebulae Island Universes" [\[image\]](#)
public debate @ National Academy of Science, Washington DC.
Short (30min) presentations, but summary articles published 1921
surprisingly, Shapley "won" the debate, though Curtis was right.
Shapley :
 new MW so big, inconceivable universe so much bigger
 van Maanen rotation rules out distant spirals
Curtis :
 doubted Shapley's MW size
 range in size (0.01-2 deg) → range in distance (1000x more than MW)
 Novae in M31 → 100 kpc away and size of Kapteyn's MW
 spectra show large doppler shifts, yet no proper motions
 some edge on spirals have dust lanes → similar to MW (zone of avoidance) → external
- **1923** : Edwin **Hubble** (USA, Mt Wilson) : uses the new 100"
finds Cepheids in M31 → 300 kpc (now, 770 kpc) → **external galaxy**
(centennial review of Hubble's career by Sandage : [\[o-link \]](#))

(d) 1925 - 1950 : Expanding Horizons

- **1927** : Bertil **Lindblad** (Sweedish) and Jan **Oort** (Dutch) :
Lindblad predicts differential rotation near sun; Oort find it
supports Shapley's MW with sun off-center (against Kapteyn's MW)
however, derives smaller size than Shapley
suggests disk flattened by rotation + spherical system non-rotating
resembles bulge/disk of external galaxies
- **1929** : Edwin **Hubble** and Milton **Humason** (USA, Mt Wilson) : galaxy spectra
Finds **redshift-distance relation** (Hubble's Law) (Original paper: [\[o-link \]](#))
already expected from de Sitter's solutions to GR
looked for by others; Hubble used **distance ladder**, including Cepheids
1931 - includes many more galaxies
 $H \sim 530 \text{ km/s/Mpc}$ → 2 Gyr age (less than earth !?)
attempts (failed) to find alternative to Hubble Law
- **1930** : Robert **Trumpler** (USA, Lick) :
compares sizes and CM diagrams of open clusters
concludes absorption pervasive (~0.5mag/kpc, close to correct)
nail in the coffin of Kapteyn's Milky Way
- **1932** : Carl **Jansky** (USA) : detects **radio** from MW
(HI predicted 1945; observed 1951; map of MW plane 1958)

- **1936** : **Hubble** : publishes galaxy classification (tuning fork)
uses names (early, late) influenced by Jean's theory of gravitational collapse
eg E's = large gas cloud, evolves into spiral
- **1930s** : Fritz **Zwicky** (Swiss/USA, Cal Tech) : [images]
measures galaxy velocities in Coma;
infers **dark matter** needed if clusters are bound
no one believes him
- **1944** : Walter **Baade** (German/USA, Mt Wilson) :
observes Spiral bulges & Ellipticals (war time black-outs help)
uncovers **stellar populations** :
 - Pop I : blue supergiants in disks
 - Pop II : red giants in bulges and Ellipticals
- **1939** : Hans **Bethe** (German/USA, Cornell) : p-p chain
- **1946** : Fred **Hoyle** (English) : SN generation of elements
- **1957** : **Burbidge, Burbidge, Fowler & Hoyle** (B²FH) : Nucleosynthesis

(e) 1950 - Present : Modern Developments

- **1952** : **Baade** : uses 200" to recalibrate Cepheid P-L relation
depends on Pop I or II; previous work used wrong relation
→ all distances doubled
→ M31 is similar in size to MW
→ Universe doubles in size (!)
- **1955** : Edwin **Salpeter** (USA, Cornell) :
introduces Initial Mass Function (IMF) for frequency of star masses
- **1962** : **Eggen, Lynden-Bell & Sandage** (ELS) :
Collapse model for formation of MW galaxy
Accounts for position/kinematic/metallicity gradients
Importance of ELS picture still debated
- **1963** : Maartin **Schmidt** (German/USA, Cal Tech) :
Discovers **Quasars**
- **1965** : Arno **Penzias** & Robert **Wilson** (USA, Bell Labs) :
Discover Cosmic Microwave Background (**CMB**)
Strong support for **Hot Big Bang** model
- **1972** : Leonard **Searle** & Wal **Sargent** (USA, Cal Tech) :
measure 24% He baseline in low metallicity Dwarfs
consistent with Big Bang nucleosynthesis
- **1970s** : Vera **Rubin et al.** (USA, Carnegie) :
infers **dark matter** from spiral rotation curves
inspires **Cold Dark Matter** (CDM) models of 80s-90s
- **1992** : **COBE** (NASA) :
measures stunningly accurate black body spectrum
finds slight (10^{-5}) anisotropies in CMB → pregalactic structure
- **1996** : **HST's HDF** (NASA) :
galaxies down to 29^m; out to z~3; total ~10¹⁰
young galaxies visibly different

early star formation rate is high ("Madau" plot)

- **1998 : High-z SN Projects** (USA, Berkeley & Harvard) :
Two groups use Type Ia SN as standard candles out to $z \sim 1$
Both find evidence for non-zero **cosmological constant** (universe accelerating)
- **2003 : WMAP** (NASA) :
CMB power spectrum measured; includes acoustic peaks 1,2,(~3)
inspires **concordance model** with "high" accuracy (few %)
combines : WMAP; SN-1a; 2dFGRS; HST- H_0 ; BBNS; to find :
 - flat geometry
 - 70% Dark Energy; 26% Dark Matter; 4% Baryonic Matter
 - age 13.7 Gyr
 - initial fluctuation spectrum is power law, index -1 (consistent with inflation)
 - epoch of reionization starts near $z \sim 20$

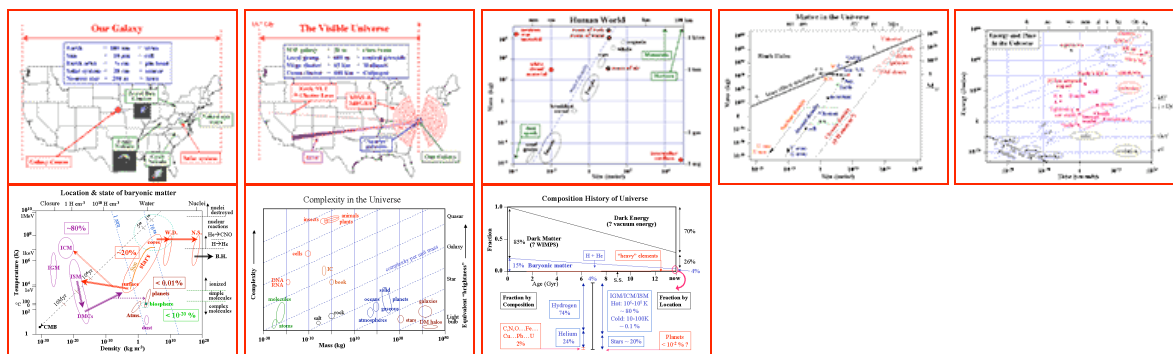


(3) Preliminaries

Before delving into the subject proper, its useful to review some basic themes
These will set the stage, and help guard against some common misconceptions.

(a) The Big Picture

The following diagrams help integrate a wide range of physical processes into a whole.
You probably "know" most of what's in them, but it is good to grasp the bigger picture.
Usually, our intuition spans only a small fraction of what Nature offers.



- Remind yourself, using simple **scale models**, just how BIG the Universe is.
- A more physically revealing diagram plots **Size vs Mass** on exponential axes.
- The Universe is incredibly dynamic; as seen in a **Time-Energy** diagram.
- See the atomic and nuclear cycles in a **Density-Temperature** diagram.
- Regain a sense of your own significance in a **Mass-Complexity** diagram.

In a course of this type, it can be too easy to develop myopia.

Keep trying to see your subject in a "global" context -- see where it fits on the grandest scales.

(b) Galaxies are Multicomponent Systems

- Three **constituents**, with rough mass ratio 1/10/100 : **Gas / Stars / Dark Matter**

The first two have complex identity :

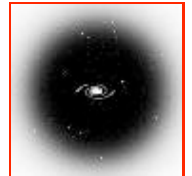
- **Gas**: different phases; dynamics; composition; (like "weather")
- **Stars**: different ages; locations; kinematics; metallicities; (like "cars")

The third is simpler but more enigmatic:

- **DM**: collisionless "gas" (of WIMPs?); huge; ~smooth; centrally concentrated

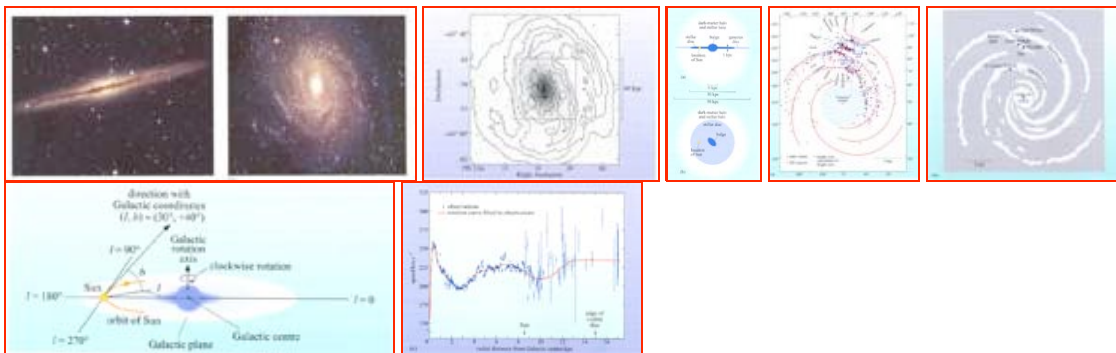
- Several **components**, with varying prominence depending on galaxy type
 - **Nucleus**: dense; star formation; supermassive black hole
 - **Bulge**: spheroidal; mixed ages; kinematically "hot" & little rotation
 - **Disk**: gas & stars; younger; star formation; spiral arms; kinematically "cold" & rotates
 - **Halo**: low density; GCs present; old; Dark Matter dominates; [sketch]

Note : Dark Matter dominates on **large scales only**
bulge & disk dynamics determined by **stars & gas alone**



(c) The Milky Way - A Typical Large Spiral

To get oriented, let's look at the basic properties of the Milky Way
NGC 891 & NGC 6744 are thought to be Milky-Way look-alikes [images]



Masses and luminosities are in solar units (V band; B&T Tables 1-1, 1-2, 1-5)

- Global Properties:
 - Type: Sbc/SBbc, with weak bar.
 - Total luminosity: $1.4 \times 10^{10} L_{\odot}$; disk / bulge $1.2 / 0.2 \times 10^{10} L_{\odot}$
 - Disk: exponential scale length: 3.5 kpc; mass: $6 \times 10^{10} M_{\odot}$; $M/L_V \sim 5$
 - Spiral structure is difficult to identify with certainty, but 2-3 arms known.
 - Like many spirals, the MW probably has a large HI disk.
- Milky Way Coordinates and Rotation:
 - The North Galactic Pole (NGP) and Galactic Center (GC) have RA, Dec (J2000):
 $6^{\text{h}}35^{\text{m}}, +46.4^{\circ}$ and $6^{\text{h}}35^{\text{m}}, +46.4^{\circ}$.
 - These define **galactic longitude** and **latitude** (l, b): $l = 0^{\circ}$ towards the GC
increasing **eastwards**: 0 (Sagittarius) $\rightarrow 90$ (Cygnus) $\rightarrow 180$ (Lyra) $\rightarrow 270$ (Grus).
 - The MW rotates **clockwise** viewed from the NGP
(opposite to the direction of earth's rotation and orbit around the sun).
 - The rotation curve is normal for a spiral of our type and luminosity.
- Solar Neighborhood and the LSR:
 - The sun resides ~ 8.5 kpc from the GC, and is slightly above the plane, $z \sim +40$ pc.

- Mass & luminosity **volume** density : $0.18 M_{\odot} \text{pc}^{-3}$ & $0.067 L_{\odot} \text{pc}^{-3}$
- Mass & luminosity **surface** density : $75 M_{\odot} \text{pc}^{-2}$ & $15 L_{\odot} \text{pc}^{-2}$
- The circular rotation rate and period of the solar neighborhood are $\sim 220 \text{ km/s}$ & 240 Myr
- The Local Standard of Rest (LSR) is a frame moving at 220 km/s towards $l, b = 90^{\circ}, 0^{\circ}$.
- The local velocity coordinates are: U,V,W (towards $l = 180^{\circ}; 90^{\circ}; \text{NGP}$):
Relative to the LSR, typical disk star random velocities are $\sim 40 \text{ km/s}$.
The sun's motion is: U;V;W = -10; 20; 7 km/s (16.5 km/s towards Leo: $l = 53, b = 25$).
- Galaxy Center Properties :
 - Core radius : $\sim 1 \text{ pc}$ (human cell in middle of)
 - Stellar density : $5 \times 10^6 M_{\odot} \text{pc}^{-3}$
 - Velocity dispersion (1-D sigma) : $\sim 150 \text{ km/s}$
 - Total mass : $10^8 M_{\odot}$
 - Black Hole Mass (MW) : $3.4 \times 10^6 M_{\odot}$

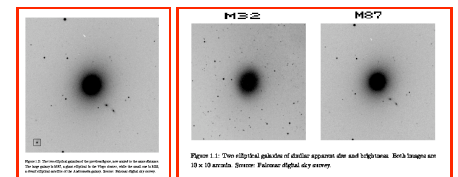
(d) A Wide Variety of Size, Mass & Form

Pretty galaxy posters give a very biased view of the galaxy population.

- Huge range in mass, size, and luminosity : (in units of MW)

| Type | Mass | Diameter | Luminosity |
|-------------|-----------------------------|-----------------|--------------------------|
| Spirals | 0.005 - 1.5 | 0.2 - 2.0 | 0.005 - 10.0 |
| Ellipticals | 10^{-4} - 5.0 | 10^{-2} - 5.0 | 5×10^{-5} - 5.0 |
| Irregulars | $< 5 \times 10^{-4}$ - 0.15 | 0.01 - 0.25 | 5×10^{-5} - 0.1 |

Note that spirals span a **narrower range** in all three parameters. See M87 (Giant E) and M32 (dwarf E) at same physical scale [\[images\]](#)



- Relative numbers of galaxies described by :
 - luminosity functions** (e.g. the Schechter Function: [\[Topic 4\]](#))
 - mass functions** (in practice, more difficult to evaluate)
 Typically, these are **steep functions**, increasing for **smaller** galaxies
 → dwarfs **far outnumber** large galaxies (by 100s to 1)
- Many galaxies do not have cleanly defined Hubble type
Galaxies (particularly disks) are **fragile** and easily disturbed
 → many cluster galaxies are "peculiar"
 → disturbed/interacting field galaxies are not uncommon
 → many high-z galaxies look peculiar (not yet relaxed/assembled)

(e) Useful Units

Calculations of galaxy properties are greatly simplified with sensible units (see also: [Toolbox](#)). Rather than "mks" or "cgs" for length/mass/time, we can use:

"psm" : parsec, solar mass, Megayear : pc, M_{\odot} , Myr

There are a number of nice features to this system:

1. **Velocity** in psm units, pc/Myr, is the same as **km/s** (within 2%; 1pc/Myr = 0.9778 km/s) (recall the mnemonic: "a kilometer per second is a parsec in a million years ")
2. Newton's constant: $G = 4.50 \times 10^{-3}$ (4.49846 $\times 10^{-3}$)
its units are: $(\text{pc}^3/\text{M}_\odot) \text{Myr}^{-2} \equiv \rho^{-1} \text{Myr}^{-2} \approx (\text{km/s})^2 \text{pc M}_\odot^{-1}$
3. Equations, such as $M = R V^2 / G$, directly accept and yield **observational values**
4. Densities, ρ_{psm} , are in $\text{M}_\odot/\text{pc}^{-3} = 6.76 \times 10^{-23} \text{ gm cm}^{-3} = 40.4 m_p \text{ cm}^{-3} = 3.60 \times 10^6 h^2 \rho_{\text{crit}}$
5. **Frequencies**, Myr^{-1} , are also **velocity gradients: km/s/pc**
6. **Crossing/collapse times**: $R(\text{pc}) / V(\text{km/s}) = 1 / (G \rho)^{1/2}$ are in Myr.

Some examples illustrate psm units, and introduce basic galaxy properties : (see homework for further examples).

- Estimate the mass interior to the sun's orbit ($R \sim 8 \text{ kpc}$; $V \sim 220 \text{ km/s}$)
use (3): $M \sim R V^2 / G \rightarrow 8000 \times 220^2 / 4.5 \times 10^{-3} \sim 8.6 \times 10^{10} \text{ M}_\odot$
- What's the density at the galactic center, where $V \sim 100 \text{ km/s}$ @ $R \sim 1 \text{ pc}$?
use (6) : $R^2/V^2 = 1 / (G \rho)$
 $\rightarrow \rho = V^2 / (G R^2) = 100^2 / (4.5 \times 10^{-3} \times 1^2) = 2.2 \times 10^6 \text{ M}_\odot/\text{pc}^{-3}$
- What's the Schwarzschild radius of a 10^8 M_\odot black hole ?
use $R_s = 2GM/c^2 = 2 \times 4.5 \times 10^{-3} \times 10^8 / (3 \times 10^5)^2 = 1.0 \times 10^{-5} \text{ pc} = 2 \text{ AU}$
- What's the Hubble time for $H_0 = 75 \text{ km/s/Mpc}$?
use (5) : $t_H(\text{Myr}) = 1 / (75 \text{ km/s/Mpc}) = 1 \text{ Mpc} / (75 \text{ km/s})$
 $= 10^6 / 75 = 1.33 \times 10^4 \text{ Myr} = 13.3 \text{ Gyr}$

There are a few extensions to the psm system which can, at times, be useful:

7. psm energy units: $\text{peu} (\text{M}_\odot \text{pc}^2 \text{Myr}^{-2}) = 1.89 \times 10^{36} \text{ Joules}$
8. psm luminosity units: $\text{plu} (\text{peu/Myr}) = 5.97 \times 10^{22} \text{ Watt} = 1.56 \times 10^{-4} L_\odot$
9. mass/luminosity units: $\text{M}_\odot/\text{plu} = 3.33 \times 10^7 \text{ kg/Watt} = 6400 (\text{M}_\odot/L_\odot)$
10. linear momentum: $\text{pmu} (\text{M}_\odot \text{pc/Myr} \approx \text{M}_\odot \text{km/s}) = 1.85 \times 10^{33} \text{ kg m s}^{-1}$
11. angular momentum: $\text{pamu} (\text{M}_\odot \text{pc}^2 \text{Myr}^{-1} \approx \text{M}_\odot \text{km/s pc}) = 5.71 \times 10^{49} \text{ kg m}^2 \text{ s}^{-1}$
12. force (momentum flux): $\text{pflu} (\text{M}_\odot \text{pc/Myr}^2 \approx \text{M}_\odot \text{km/s/Myr}) = 5.86 \times 10^{19} \text{ N}$
13. acceleration: $\text{pau} (\text{pc/Myr}^2 \approx \text{km/s Myr}^{-1}) = 3.09 \times 10^{-11} \text{ m s}^{-2}$

A few more examples help illustrate:

- What's the gravitational luminosity of a galaxy merger ($M \sim 10^{11} \text{ M}_\odot$ in $R \sim 10 \text{ kpc}$)
Use (6) for collapse time $\sim (G \rho)^{-1/2} \sim (4.5 \times 10^{-3} \times 10^{11} / 20000^3)^{-1/2} \sim 130 \text{ Myr}$
Energy of collapse $\sim GM^2/R \sim 4.5 \times 10^{15} \text{ peu}$
Gravitational luminosity $= 3.5 \times 10^{13} \text{ plu} = 5.4 \times 10^9 L_\odot$
(much less than $\sim 10^{11} L_\odot$ from typical star formation).
- What's the ejection velocity of a 10 M_\odot supernova envelope of energy 10^{46} J ?
Energy is $\sim 5 \times 10^9 \text{ peu} \sim \frac{1}{2} M V^2 \rightarrow V \sim 32,000 \text{ km/s}$
- What's the mechanical luminosity and force of a 1000 km/s AGN jet carrying $10 \text{ M}_\odot \text{ yr}^{-1}$?
 $L = \frac{1}{2} \dot{M} V^2 = \frac{1}{2} \times 10^7 \times 10^6 = 5 \times 10^{12} \text{ plu} = 3 \times 10^{42} \text{ erg s}^{-1}$
 $F = \dot{M} V = 10^7 \times 10^3 = 10^{10} \text{ pflu} = 5.9 \times 10^{34} \text{ dyne}$

(f) Magnitude Systems and Surface Brightness

The previous section deals only with dynamical variables : V , R , t , M .
Let's introduce **starlight** into the mix, not least because it is easy to measure.

Astronomers use **two** systems: magnitudes and fluxes (each with apparent and intrinsic)
it can sometimes be tricky jumping back and forth between these systems.

- **Magnitudes:**

The generic magnitude is defined:

$$m = \text{const} - 2.5 \log_{10}[\text{flux}] = -2.5 \log_{10}[\text{flux} / \text{flux}_0] \quad (1.3f - 1)$$

where flux_0 is a reference flux for a star with $m = 0.0$ (usually Vega), and is filter-specific.
Typically, $m \sim 12 - 14$ (nearby galaxies); $16 - 18$ (distant galaxies); $21 - 25$ (very distant galaxies).

Absolute magnitude (M) is defined as the apparent magnitude (m) were the object at 10pc, hence:

$$M = m - 5 \log d_{\text{pc}} + 5 \quad (1.3f - 2)$$

Typically, $M \sim -10$ to -17 (dwarfs); -18 to -21 (normal galaxies); -22 to -24 (giant galaxies & QSOs).

- **Solar magnitudes and fluxes:**

Often, we express luminosities relative to the sun (e.g. $3 \times 10^8 L_{V,\odot}$)

The sun's absolute magnitude in band $X = U, B, V, R, I$ is $M_{X,\odot} = 5.66, 5.47, 4.82, 4.28, 3.94$.

Hence, an object with absolute magnitude M_X , has luminosity:

$$L_X = \text{dex}[-0.4(M_X - M_{X,\odot})] L_{X,\odot} \quad (1.3f - 3)$$

- **Surface Brightness:**

Extended objects have **surface brightness**, μ in mag arcsec^{-2} (mag/ss; sometimes written Σ)

Since μ is **independent of distance** it immediately gives the **surface luminosity density**, $I L_{\odot} \text{pc}^{-2}$
e.g. using $M_{\odot,B}$ from above, we find (see homework) :

$$\mu_B = 27.04 - 2.5 \log(I_B) \quad (1.3f - 4)$$

and in general, for U, B, V, R, I , the constant is: 27.23, 27.04, 26.39, 25.85, 25.51.

- **Example:**

M87 has a central surface brightness $\mu_V = 17 \text{ mag/ss}$.

→ the core has projected luminosity density: $\text{dex}[-0.4(17 - 27.04)] = 10,400 L_{V,\odot} \text{pc}^{-2}$.

if the core radius is 10 arcsec, what's the core's total luminosity?

→ $m_{\text{core}} \sim 17 - 2.5 \log [7\pi \times 10^2] = 10.75$, giving $L_{\text{core}} = 3.26 \times 10^6 L_{V,\odot}$

for a distance of 15 Mpc, what's the luminosity density in M87's core?

→ 10 arcsec = 730 pc, so $j_{\text{core}} \sim I_{\text{core}} / 2 r_{\text{core}} \sim 7.1 L_{V,\odot} \text{pc}^{-3}$.

to find the mass density requires a mass-to-light ratio, which is our next topic:

(g) Mass to Light Ratios

Light and dynamics are coupled using "Mass to Light Ratios (M/L)".

- "Mass to Light" (M/L) ratios are important for **two** reasons :
 - they allow us to estimate mass (important but difficult to measure) using **light** (easy to measure)
 - they tell us about the **content** of a system, eg (M/L) values differ : pop I < pop II < galaxy+halo < clusters
- **Solar units** are used : where $(M/L)_{\odot} \equiv M_{\odot}/L_{\odot} \equiv 1$
Physical units : kg/Watt are *not* generally used
[conversion : $(M/L)_{\odot, \text{bol}} = 5173 \text{ kg/Watt} = 0.5173 \text{ gm/(erg/s)}$]
(M/L) is expressed at a given waveband, most commonly B,V,I,K, or bolometric (all λ).
e.g. for waveband "X", using absolute magnitudes :

$$(M/L)_X = M/M_{\odot} / L_X/L_{\odot, X} = M/M_{\odot} / \text{dex}[-0.4(M_X - M_{\odot, X})] \quad (1.3g - 1)$$

where M_X & $M_{\odot, X}$ are X-band absolute magnitudes of the object & sun;
and L_X & $L_{\odot, X}$ are X-band luminosities of the object & sun
and X = U,B,V,R,I,K,bol and $M_{\odot, X} = 5.66, 5.47, 4.82, 4.28, 3.94, 3.33, 4.74$
note : $(M/L)_X$ is the same for all X only if the object and sun have the **same colors**
(careful : M used for both mass and absolute magnitude here - sorry)

One can also use luminosities (usually only bolometric)

$$L_{\odot, \text{bol}} = 3.84 \times 10^{33} \text{ erg s}^{-1} \quad \text{and} \quad M_{\text{bol}} = -2.5 \log(L_{\text{bol}} / L_{\odot, \text{bol}}) + 4.74$$

- For **main sequence** stars, we have $L \propto M^{3.5}$, giving : $(M/L) \propto M^{-2.5} \propto L^{-0.71}$
showing, as one expects, **later** spectral types have **higher** M/L.
eg K stars : $M \sim 0.5M_{\odot} \rightarrow M/L \sim 10$; A stars : $M \sim 2.0M_{\odot} \rightarrow M/L \sim 0.1$
- For **composite** systems, M/L reflects the average M/L over the population
 - Pop I (young) : massive stars dominate light; low mass stars dominate mass
 - Pop II (old) : giants dominate light; M.S. stars dominate mass
 → Typical galaxy (& solar neighborhood) has $M/L_V \sim 6$, $M/L_B \sim 10$
 → In general : M/L increases with age and metallicity
 → Maximum range : $2 < M/L_B < 20$.

Dark components further increase these values, eg

- SMBH in galaxy nuclei
- Dark Matter in galaxy halos

More specifically, for main sequence stars and composite systems in V :

| Type | M / M_{\odot} | M_V | $L_V / L_{\odot, V}$ | $(M/L)_V$ | System | $(M/L)_V$ | Reason |
|------|-----------------|-------|----------------------|-----------|----------------------|-----------|------------|
| O5 | 60 | -5.7 | 16,140 | 0.0037 | HII region | 0.3 - 1 | Pop I only |
| B5 | 5.9 | -1.2 | 255 | 0.023 | Spiral Disk | 2 - 5 | Pop I + II |
| A5 | 2.0 | +1.95 | 14 | 0.14 | Bulges / Ellipticals | 8 - 15 | Pop II |

| | | | | | | | |
|----|------|-------|-------|------|------------------|-----------|--------------|
| F5 | 1.4 | +3.5 | 3.4 | 0.41 | Nucleus (no AGN) | 10 - 50 | BH present |
| G5 | 0.92 | +5.1 | 0.77 | 1.19 | Galaxy + halo | 20 - 50 | DM important |
| K5 | 0.67 | +6.4 | 0.23 | 2.87 | Clusters | 100 - 500 | DM dominates |
| M5 | 0.21 | +12.3 | 0.001 | 206 | Universe | ~1000 | DM dominates |

- Surface brightness to surface mass density:

From 3f above, surface brightness μ mag/arcsec yields surface luminosity density, $I L_{\odot} / \text{pc}^2$.
 adopting a value for (M/L) now gives the **surface mass density** Σ_M , in $M_{\odot} \text{pc}^{-2}$
 Combining M/L and the relation between μ and I , we have (for the B band):

$$\Sigma_M = (M/L)_B \times \text{dex}[-0.4 \times (\mu_B - 27.05)] \quad M_{\odot} \text{pc}^{-2} \quad (1.3g - 2)$$

e.g. the cores of giant E's have $\mu_B \sim 18$ mag arcsec⁻², $(M/L)_B \sim 10$, $R_c \sim 1$ kpc,
 $\rightarrow \Sigma_M \sim 4 \times 10^4 M_{\odot} \text{pc}^{-2}$ & $\rho \sim 20 M_{\odot} \text{pc}^{-3}$ (taking depth $\sim 2R_c$)

Note that nowhere did we need distance to obtain this important parameter.
 Another example : M32 & M87 have cores with $\mu_V \sim 11$ & ~ 17 V mag/arcsec (Topic 7.4cii)
 \rightarrow M32 is a much denser system : $\Sigma_M \sim 250$ × higher (in fact, $\rho \sim 10^5$ × higher)

(h) Gas in and Between Galaxies

Despite its small total mass, diffuse gas is an important component of galaxies.

- Gas (and dust) comes in a wide range of **phases** :

Within galaxies :

- **Molecular** cold "dense" clouds (DMCs) : (eg CO 2.6mm); (pre)-star formation regions
- **Dust** ($\sim 1\mu$ graphite/silicates): (IR); DMCs; diffuse ISM; old star winds.
- **Atomic** warm neutral gas : (eg HI 21 cm); disk ISM; outer disk
- **Ionized** gas @ 10^4 K : (eg H α); HII star formation regions; diffuse ISM; cooled SNRs
- **Ionized** gas @ 10^6 K : (eg X ray); SNRs; diffuse ISM
- **Relativistic** magnetoionic plasma : (eg synchrotron); SNRs; widespread; AGN-jets.

Between galaxies :

- Almost **no** neutral atomic or molecular gas
- **Superwinds** : energetic multiphase global outflow, driven by a starburst (or AGN);
- **Intracluster** gas (ICM) : (X-ray); $M \sim 1-5x M(\text{gals})$; $Z \sim 1/3$ solar; primordial + superwinds
- **Intergalactic** gas (IGM) : v. low density; UV (AGN+SF) ionized; Ly α clouds ($X_e \sim 10^{-5}$)

- Gas cooling enables the formation of dense systems (see 3l below)
stars & DM undergo dissipationless collapse \rightarrow **low density** endpoint
gas, however, can radiate energy during collapse \rightarrow **high density** endpoint
 \rightarrow gas plays a **fundamental role** in giving galaxies their present day form

The **efficiency** of gas cooling depends on **three** factors :

- **density** : almost all radiation mechanisms are **collisional**, hence $\propto \rho \times \rho$
- **temperature** : this defines the **state** of the gas (molecular / atomic / ionized),
 which in turn determines the particular radiation processes which can operate

- **metallicity** : since most radiation comes from elements other than H or He.

Some examples :

ICM gas cannot cool easily : ρ too low

DMC gas cools efficiently : ρ high; molecular lines; dust IR

10^5K gas is rare : strong resonance line cooling in, eg, OV & OVI

primordial star formation unusual : no metals, just H and H_2 cooling

All complexities are absorbed in **cooling curves** : efficiency as $f(T,Z)$

- Two kinds of ionization :
 - **photoionization** : photon energy > electron binding energy (UV - Xray).
typically found near OB stars (thermal UV) or AGN (non-thermal UV)
ionization degree depends mainly on ratio (ionizing flux / gas density)
typically, $T(e) \ll T(\text{ionization degree}) \rightarrow$ ions and electrons **not** in LTE
 - **collisional ionization** : thermal energy > electron binding energy ($T > 10,000\text{K}$).
typically found in shocks; accretion disks; ICM;
usually, $T(e) = T(\text{ions}) = T(\text{ionization degree})$

Note: in most circumstances, ISM/IGM gas is **optically thin**.

Inside stars, of course, the high density makes the gas **optically thick**,
and we have full LTE : $T(e) = T(\text{ions}) = T(\text{ionization degree}) = T(\text{photons})$

- Gas provides access to chemical evolution
emission **and** absorption produced by diffuse gas can yield abundances, eg
within galaxies : ISM gas participates in the star/gas evolutionary cycle
 \rightarrow abundance gradients; comparisons between galaxies; low Z (\sim primordial) galaxies.
outside galaxies : gas is sensitive to superwind pollution history
 \rightarrow high-z QSO metal absorption gives halo abundances in young galaxies.
 \rightarrow primordial D/H & He^3 abundances \rightarrow BBNS constraint on Ω_b

(i) Collisionless Components

Stars fill galaxies **very sparsely**

They never collide and rarely experience large deflections. Here's why :

Consider the solar neighborhood. A typical star size/separation is:

- size $\sim D(\text{sun}) \sim 1/100 \text{ AU}$ (sun $\frac{1}{2}$ deg); sep $\sim 1\text{pc} \sim 10^5\text{AU}$
 \rightarrow size/sep $\sim 10^{-7} \rightarrow$ filling factor $\sim 10^{-21}$ (note, for air : $10^{-1.5}$ & $10^{-4.5}$)
Illustration : star=sand grain ($\sim 0.1\text{mm}$) \rightarrow typical galaxy $\sim 10^{11}$ = cubic yard of sand
but, each separated by $\sim 1\text{km}$ (10m in nucleus) \rightarrow fills Earth \rightarrow **very empty**.
[amusingly, since dynamical time $t \sim 1 / (G \rho)^{1/2}$ & $\rho_{\text{sand}} \sim \rho_{\text{star}}$, then
the sparse sand model & MW galaxy have the **same** gravitational timescale : $\sim 100 \text{ Myr}$]
- Pathlength : $1/n\sigma = \text{sep}^3/\text{size}^2 = (\text{sep}/\text{size})^2 \times \text{sep} = 10^{14}\text{pc} \sim 10^9 \text{ orbits} !$
Collision time : $\sim 10^{17}\text{yrs}$ @ 200 km/s ($\sim 10^{18}\text{yrs}$ @ disk dispersion).
Hence the famous statement : when two galaxies collide, no stars collide.
- Alternate perspective : typical star-star encounter deflection $\sim \frac{1}{2}$ arcsec
hence, **star orbits follow smooth potential**
 \rightarrow long range forces dominate, and physics tends to be **global**
since potential determined by distribution of all stars, behaviour can be complex.
- Dark Matter (elementary particles) **also** behaves in a collisionless manner.
strange : usually view particles as bouncing around, but these move on smooth orbits
 \rightarrow to first order, DM particles and stars share similar dynamics.

however, DM currently more extended, so how did this arise ?

→ **gas** behaves **differently** (see 3g below) → **settles** before forming stars.

(j) Thermal & Fluid Character of Stellar Dynamics

It may be useful at this time to plant some seed thoughts about Stellar Dynamics, let them germinate before starting the subject proper in Topic 8.

- Consider a gas of atoms :
 - unlike** stars in a galaxy, the atoms collide **frequently**, having small free path quickly, an **isotropic** Maxwell-Boltzmann velocity distribution is established if there is bulk flow, a mean velocity is added to the random thermal motions. Thus, much physics is **local**, and most memory of initial conditions is **lost** if the gas is bound by its own gravity (eg a star), thermal motions "match" the potential
- Now consider our galaxy of collisionless stars :
 - in each region (dx,dy,dz at x,y,z) we have stars with a range of velocities ie a **distribution function** : $DF(V_x, V_y, V_z, x, y, z) dV_x dV_y dV_z dx dy dz$
 - this is analogous to the Maxwell-Boltzmann DF, but it usually has different form typically, there is a **mean velocity** and a **random dispersion**
 - these are analogous to the **bulk flow** and **thermal motion** for atoms in a gas eg if dispersion velocity is ~same everywhere, one speaks of an **isothermal system**
- There are further similarities with fluids :
 - stars & atoms are neither created nor destroyed → their DF's obey **continuity equations**
 - star & atom ensembles obey energy and momentum **conservation equations**
 - star & atom movement is affected/defined by the total gravitational field

these similarities are sufficient that :

 - the equations governing the stellar DF look like fluid equations
 - hence, we speak of the "equations of stellar hydrodynamics"
- Stellar dynamics can be more complicated/interesting for several reasons :
 - Because no strong collisions, the **memory** of former conditions can persist, eg
 - the MW has tidal streams from cannibalized infalling dwarfs
 - many galaxies have counter rotating cores, formed from an accreted companion (note that smooth looking galaxies can hide structured velocity distributions)

Dispersion velocities can be **anisotropic** (and non-Gaussian), eg

 - can have mainly radial dispersion, with little azimuthal or polar dispersion
 - since dispersion defines scale height, then anisotropy can cause non-spherical shape
 - the analogous thermal property is anisotropic pressure (impossible for gas)

Stellar systems are gravitationally bound → they have **negative specific heat**

 - **remove** energy → system contracts → star velocities **increase** = **hotter**
 - note, same for single stars → when cores contract(expand) they heat(cool)

(k) Support: Rotation vs Dispersion

Since galaxies are empty and gravity attracts, why don't they just collapse: what "supports" them? There are two extreme situations, and everything in between :

- Pure rotation :
 - like the solar system, **circular** orbits hold stars "up" very effectively
 - in a pure **rotationally supported** disk, all stars follow circular orbits.
 - at each radius $V_{rot} = V_{circ}$ (the "circular velocity" which balances gravity).
 - note, there is **zero** velocity dispersion → the system is kinematically **"cold"**

- Pure dispersion :
because stars never collide, their orbits are free to intersect one another a "swarm" of **random** orbits could have **only** dispersion and **zero** net rotation with no collisions, stars continue on their orbits, and the galaxy "stays up" we say the system is **dispersion supported** → it is kinematically "**hot**" in this case, velocity dispersion acts like a **pressure**, giving **hydrostatic support** since the orbits follow gravity, then $V_{\text{disp}} \sim V_{\text{circ}}$, as one might expect
- Intermediate cases :
not surprisingly, one can have intermediate cases, for example :
 - The MW disk near the sun has $\langle V_{\text{rot}} \rangle \sim 220$ km/s, and $V_{\text{disp}} \sim 40$ km/s it is mainly rotationally supported, but has a small dispersion component note that $\langle V_{\text{rot}} \rangle$ is **slower** than V_{circ} (an effect called asymmetric drift)
 - The MW bulge rotates slowly it is mainly dispersion supported, with a small rotational component
 - As expected, rotation and dispersion combine to provide the full support needed :

$$V_{\text{circ}}^2 \approx V_{\text{rot}}^2 + V_{\text{disp}}^2 \quad (1.3k - 1)$$

- Rotational flattening :
if a galaxy of stars behaves like a fluid, then a rotating galaxy should flatten conversely, flattened galaxies should rotate accordingly it came as a great surprise in 1977 when this was found **not** to be the case → flat-ish (luminous) ellipticals do not rotate so, what flattens them ?

Unlike atoms in fluids, stars can have **anisotropic** velocity dispersions since dispersion acts like "pressure", it sets the **scale height** against gravity thus, one can have different scale heights in different directions → non-rotating Ellipticals can be oblate, prolate, or even triaxial

(I) Dissipationless vs Dissipational Collapse

Before galaxies formed, the Universe had roughly uniform **low** density somehow, parts of it collapsed to form much denser systems (galaxies, bulges, stars). It is not immediately obvious how this can happen :

- Consider first the collapse of a **collisionless** system (stars or dark matter) :
it starts large and motionless, falls radially, at the bottom of the hill **nothing collides** so, out it goes again, getting larger and slower, back to its starting point.

In practice, small irregularities grow, causing "orbit scrambling" (**violent relaxation**) we say the system "**virializes**" → it settles down, relaxed and unchanging the final system is **~half** the original size & supported by random motions it therefore has low-ish density → still not dense enough to be a galaxy.

We need to **remove energy** from the system to allow further collapse. In a **smooth** collisionless system this **cannot happen**. The only "cooling" possible is ejection of "hot" stars (or DM) by **scattering**. However, 2-body scattering never occurs & large scale scattering needs inhomogeneities hence the collapse is termed **dissipationless** : no energy is dissipated.

- Consider now the collapse of **gas** :
 - this proceeds quite differently : atoms collide, so free fall is halted by **pressure** as before, the binding and kinetic (thermal) energies are equal ("virial theorem")
 - but there is a crucial new aspect : the gas can lose energy by **radiation** (photons)
 - this allows the gas to cool, lose pressure, and **contract**
 - this is **dissipational** collapse (energy is dissipated), and creates **much denser** systems
 - an obvious example: stars form from collapsing gas clouds.
 - if the compact gaseous region *then* forms stars, we finally achieve high **stellar** densities.
- Rotation complicates **both** types of collapse :
 - the previous discussion ignored angular momentum (AM)
 - conservation of AM ($V \times R$) prevents efficient collapse ("AM barrier")
 - for efficient collapse, one needs efficient AM **transfer/loss mechanisms** to operate
 - two such mechanisms have recently been identified :
 - MHD torques operating in gas (accretion) disks
 - gravitational torques operating between stars and gas during galaxy mergers
 - these allow dissipational collapse to proceed and build the dense systems we find.

(m) Concordance Cosmology

- Our subject is explicitly and implicitly **cosmological**
 - We will need to frame questions within a chosen "World Model"
 - Contemporary models (GR + FRW + more) involve several important parameters :
 - Ω_{tot} = the total density, determining global geometry (1.0=flat) : $\Omega_{\text{tot}} = \Omega_{\text{m}} + \Omega_{\lambda}$
 - Ω_{m} = total **matter** density, including dark matter and baryons : $\Omega_{\text{m}} = \Omega_{\text{DM}} + \Omega_{\text{b}}$
 - Ω_{λ} = density of dark energy (cosmological constant). Exerts "pressure".
 - H_0 = **current** rate of expansion (sets basic age, modulo de(ac)celeration)
 - Primordial perturbation spectrum : creates **structure** (Pow Law : index & amp)
- We approach this subject at an ideal time
 - Before ~1995 : fundamental ambiguity in parameter values
 - eg uncertainty in H_0 (50 - 100); Omega (~0.3 & 1.000); the age problem ($t_U < t_{\text{GCs}}$); etc..
 - Since ~1995 : astounding progress, culminating with WMAP in Feb 2003.
- Cosmologists now combine about 5 datasets to constrain all the parameters :
 - WMAP : power spectrum of CMB fluctuations [Ω_{tot} ; Ω_{b} ; index & amp]
 - HST- H_0 : local Cepheid distances and radial velocities [H_0]
 - High-z SN Ia : Hubble diagram using bright standard candles [$H(t)$; Ω_{λ}]
 - BBNS : Helium and light element abundances [Ω_{b}]
 - 2dFGRS/SDSS : large scale structure [Ω_{m} ; index & amp]

These yield a single self-consistent framework : **the concordance model**
- Parameter values are now known (reliably?) to a few %
 - $\Omega_{\text{tot}} = 1.0$ $\Omega_{\lambda} = 0.7$ $\Omega_{\text{m}} = 0.3$ $\Omega_{\text{DM}} = 0.26$ $\Omega_{\text{b}} = 0.04$
 - $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ $t_{\text{age}} = 13.7 \text{ Gyr}$ $t_{\text{CMB}} = 380 \text{ kyr}$
 - $Z_{\text{reion}} \sim 20$ index ~ -1.0 (consistent with inflation)
- Here are some useful time-line diagrams for the concordance world model.

- Full history : **Parameters** and **Events**
- The first Gyr : **Parameters** and **Events**
- The first 500 kyr : **Parameters** and **Events**



etc....

- A few key facts :
 - $z \sim 1$ is $\sim 60\%$ lookback time (LBT), with cosmic age ~ 6 Gyr
 - coasting (changover from de to ac-celeration) occurs at $z \sim 0.65$ or $\sim 45\%$ LBT
 - high- z galaxies and QSOs at $z \sim 4-6$ are at $\sim 90\%$ LBT, age ~ 1 Gyr
 - recombination is at $z \sim 1100$, $T \sim 3300\text{K}$, age ~ 380 kyr, $\rho \sim 10^3 \text{ cm}^{-3}$
 - at recombination, 10kpc subtends ~ 2.8 arcmin, or 1 deg ~ 170 kpc
 - matter/energy equality occurs at $z \sim 3300$, $T \sim 10,000\text{K}$, age ~ 50 kyr, $\rho \sim 10^5 \text{ cm}^{-3}$
- Using a normalized Hubble constant : "h"

For decades, H_0 was uncertain to $\sim 50\%$
 it was/is useful, therefore, to set H_0 to $100h \text{ km/s/Mpc}$ with h kept explicit
 h appears once for each redshift-distance, with a power of opposite sign : eg

The distance to Coma, $cz \sim 6000 \text{ km/s}$, is $60h^{-1} \text{ Mpc}$
 The luminosity of 3C 123 is $3 \times 10^{44} h^{-2} \text{ erg/s}$
 3C 123 has $M_B \sim -24.5 + 5 \log(h)$ [recall $m - M = 5 \log(d) - 5$]
 The jet in 3C 123 has length $150h^{-1} \text{ kpc}$ [length = angle x distance]
 The core mass of NGC 1234 is $2 \times 10^{10} h^{-1} M_\odot$ [$M \sim RV^2/G$, & $R \propto d$]
 Its luminosity density is $1.6h L_\odot \text{ pc}^{-3}$ [h^{-2} / h^{-3}]
 Its M/L ratio is $10h$ solar units [h^{-1} / h^{-2}]

Note that h does **not** appear for non-redshift distances (eg Cepheid distances).
 Although we now know $h=0.72$ (with $\sim 5\%$ uncertainty), its good to keep using it.

This concludes our introduction to the subject of Extragalactic Astronomy
 We are now ready to start, relatively gently, with **Topic 2 : Galaxy Morphology**.

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