1. HISTORY & PRELIMINARIES

(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.

(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

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Key Events</th>
</tr>
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<tbody>
<tr>
<td>1750 - 1900</td>
<td>[figure]</td>
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<td>1900 - 1950</td>
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<td>1950 - present</td>
<td>[figure]</td>
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<td>all combined:</td>
<td>[figure]</td>
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### (b) Before 1850: Search & Discovery

- **1610**: Galileo Galilei (Italian) uses early telescopes  
  He realizes the Milky Way is composed of many stars [image]

- **1750**: Thomas Wright (English): [image]  
  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): [image]  
  writes: "General Natural History & Theory of the Heavens"  
  (1) rejects spherical shell  
  (2) MW like huge solar system, rotating; origin from rotating cloud.  
  (3) stars far from plane on different orbits  
  (4) disks (like MW) project to ellipses  
  (5) oval nebulae (seen by de Maupertius) = "Island Universe"  
  → remarkably precient, but not widely accepted through 1800s

- **1780s**: William Herschel (English): [image]  
  star counts → MW = flat disk with sun @ center  
  no size estimate  
  ultimately recognizes wrong assumptions & retracts

- **1781**: Charles Messier (French): [image]  
  completes first catalog of nebulae (109)

- **1770 - 1810**: William & Caroline & John Herschel (English): [image]  
  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 dont (gas?)  
  speculation: uniform distribution of stars will gravitationally cluster

- **1845**: William Parsons (3rd Earl of Rosse): [image]  
  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) [image]
telescopic visual spectra of nebulae
1/3 emission lines (gaseous); 2/3 continuous (stellar)

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: [image]
estimates ~120,000 nebulae accessible; ~50% are spiral

1906-22: Jacobus Kapteyn (Dutch): detailed study of MW: [image]
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

Period-Luminosity relation for Cepheids in Magellanic Clouds
tool for measuring distances

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

1918: Harlow Shapley (USA, Princeton/Harvard): [image]
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" [image]
finds Cepheids in M31 → 300 kpc (now, 770 kpc) → external galaxy
(cenntennial review of Hubble's career by Sandage: [ o-link ])

(d) 1925 - 1950: Expanding Horizons

1927: Bertil Lindblad (Sweedish) and Jan Oort (Dutch): [image]
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

1929: Edwin Hubble and Milton Humason (USA, Mt Wilson) [image]
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 ~ 530 km/s/Mpc → 2 Gyr age (less than earth !?)
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

1936: Hubble: publishes galaxy classification (tuning fork) [image]
uses names (early, late) influenced by Jean's theory of gravitational collapse
e.g. E's = large gas cloud, evolves into spiral

1936: Fritz Zwicky (Swiss/USA, Cal Tech): [image]
measures galaxy velocities in Coma;
infers dark matter needed if clusters are bound
no one believes him

1944: Walter Baade (German/USA, Mt Wilson): [image]
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

(e) 1950 - Present: Modern Developments

1952: Baade: uses 200" to recalculate 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 (!)

1962: Eggen, Lynden-Bell & Sandage (ELS): [image]
Collapsing 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): [image]
Discovers Quasars (identifies redshift of 3C 273).

1965: Arno Penzias & Robert Wilson (USA, Bell Labs): [image]
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): [image]
infers dark matter from spiral rotation curves
inspires Cold Dark Matter (CDM) models of 80s-90s

1978: Len Searle & Robert Zinn (USA, Cal Tech):
Abundance analysis of MW Globular Clusters: infer range of ages
Suggest MW halo built up by accretion of fragments after main formation

1980: Alan Guth & Alexei Starobinski (USA; USSR): [image]
Independently conceive of early period of extremely rapid, accelerated expansion.
Guth calls this "inflation": solves several deep problems.
Provides natural explanation for creation of everything, and launching the expansion.

measures stunningly accurate black body spectrum
finds slight \(10^{-5}\) anisotropies in CMB → pregalactic structure
1996: HST's HDF (NASA): [image]
galaxies down to 29<sup>m</sup>; out to z~3; total ~10<sup>10</sup>
young galaxies visibly different
early star formation rate is high ("Madau" plot)

Two groups use Type Ia SN as standard candles out to z ~ 1
Both find evidence for non-zero cosmological constant (universe accelerating)

2003: 2dF (& SDSS) Galaxy Surveys (UK/Australia & USA): [image]
The first of the large scale galaxy redshift surveys is completed (2dF)
250,000 galaxy redshifts out to z-0.1 allow detailed analysis of large scale structure.
SDSS completed later (800,000 galaxy redshifts) but with more detailed information.

2003: WMAP (NASA): [image]
CMB power spectrum measured; includes acoustic peaks 1.2, (~3)
inspires concordance model with "high" accuracy (few %)
combines: WMAP, SN-1a, 2dFGRS, HST-H<sub>-o</sub>, BBNS; to find: [image]

- 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)

(3) Preliminaries

Before delving into the subject proper, there are a few preliminaries worth introducing.

(a) Basic Scales

The following ASTRO-101 type diagrams remind us of the relative size of galaxies and our visible horizon

- Remind yourself, using simple scale models, just how BIG the Universe is: [image].

(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 [image].

  - 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;

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

(c) Colors and Spectra
A montage of SDSS galaxies shows a limited range of colors: blue -- red [image]. Statistical analysis suggests the color distribution is roughly bimodal [image]. Crudely speaking:
- blue = younger population
- red = older population (actually, more like yellow/orange)

This can be understood in terms of stellar evolution:
Following an episode of star formation, the main sequence "erodes" downwards. [image].
- Young population: light is dominated by higher mass main sequence stars.
- Older population: light is dominated by red giants.
  (In both cases these are a minor but luminous sub-population.)

Spectra show in more detail these population differences
- Star spectra primarily follow the spectral type [image].
- Galaxy spectra show mixed populations [image].

Analysis of these spectra can reveal many properties:
- population mix of stars
- current star formation (e.g. emission lines)
- metallicity (fraction of heavy elements, i.e. beyond He)
- kinematics of gas and stars: rotation and dispersion.

(d) 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:

```plaintext
"psm": parsec, solar mass, Megayear : pc, M☉, 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: \( (\text{pc}^3/\text{M}☉) \text{ Myr}^{-2} = \rho^1 \text{ Myr}^{-2} \approx (\text{km/s})^2 \text{ pc} \text{ M}☉^{-1} \)
- (3) Equations, such as \( M = R V^2 / G \), directly accept and yield observational values
- (4) Densities, \( \rho \text{psm} \), are in \( \text{M}☉/\text{pc}^3 = 6.76 \times 10^{23} \text{ gm cm}^{-3} = 40.4 \text{ m}_p \text{ cm}^{-3} = 3.60 \times 10^6 \text{ h}_2 \text{ crit} \)
- (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~8kpc; V~220 km/s)
  use (3): \( M \sim RV^2 / G \rightarrow 8000 \times 220^2 / 4.5 \times 10^{-3} \sim 8.6 \times 10^{10} \text{ M}☉ \)

- What's the density at the galactic center, where \( V \sim 100 \text{ km/s} @ R \sim 1\text{pc}? \)
  use (6): \( R^2/V^2 = 1 / (G \rho) \)
  \( \rightarrow \rho = V^2/(G R^2) = 100^2 / (4.5 \times 10^{-3} \times 1^2) = 2.2 \times 10^6 \text{ M}☉/\text{pc}^3 \)

- What's the Schwarzschild radius of a \( 10^8 \text{ M}☉ \) black hole ?
  use \( R_s = 2GM/c^2 = 2 \times 4.5 \times 10^{-3} \times 10^9 / (3 \times 10^5)^2 = 1.0 \times 10^{-5} \text{ pc} = 2 \text{ AU} \)

- 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:

- psm energy units: \( \text{peu}(\text{M}☉/\text{pc}^2\text{Myr}^{-2}) = 1.89 \times 10^{36} \text{ Joules} \)
A few more examples help illustrate:

- What's the gravitational luminosity of a galaxy merger (M \sim 10^{11} \, M_\odot \text{ in } R \sim 10 \, \text{kpc})
  - Use (6) for collapse time \sim (G M)^{-\frac{1}{2}} \sim 4.5 \times 10^{15} \, \text{peu}
  - Energy of collapse \sim GM^2/R \sim 4.5 \times 10^{15} \, \text{peu}
  - Gravitational luminosity \sim 3.5 \times 10^{13} \, \text{plu} = 5.4 \times 10^9 \, L_\odot
    (much less than \sim 10^{11} \, L_\odot \text{ from typical star formation}).

- What's the ejection velocity of a 10 \, M_\odot \text{ supernova envelope of energy } 10^{46} \, \text{J}?
  - Energy is \sim 5 \times 10^9 \, \text{peu} \sim \frac{1}{2} MV^2 \rightarrow V \sim 32,000 \, \text{km/s}

- What's the mechanical luminosity and force of a 1000 \, \text{km/s AGN jet carrying } 10^7 \, \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{pfu} = 5.9 \times 10^{34} \, \text{dyne}

### (e) 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:

\[
m = \text{const} - 2.5 \log_{10}[\text{flux}] = -2.5 \log_{10}[\text{flux} / \text{flux}_0]
\]

where \text{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).
Apparent magnitudes, m, include information on both intrinsic luminosity and distance.

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

\[
m = \text{const} - 2.5 \log f_{d_{\text{pc}}}
M = \text{const} - 2.5 \log f_{10_{\text{pc}}}
\]

but from the inverse square law:

\[
f_{10_{\text{pc}}} = f_{d_{\text{pc}}} \times (d_{\text{pc}} / 10)^2
\]

so, substituting:

\[
M = \text{const} - 2.5 \log [f_{d_{\text{pc}}} \times (d_{\text{pc}} / 10)^2]
M = \text{const} - 2.5 \log f_{d_{\text{pc}}} - 2.5 \log d_{\text{pc}}^2 - 2.5 \log (1/100)
\]

Giving the well-known relation:

\[
M = m - 5 \log d_{\text{pc}} + 5
\]

By placing everything at 10pc, absolute magnitudes are related to an object's **luminosity**
M \sim -10 to -17 (dwarfs);
M ~ -18 to -21 (normal galaxies);
M ~ -22 to -24 (giant galaxies & QSOs).

**Solar magnitudes and fluxes:**
Often, we express luminosities relative to the sun (e.g. $3 \times 10^8 \, L_{\odot}$)
The sun's absolute magnitude in band $X = U, B, V, R, I$ is $M_{\odot} = 5.66, 5.47, 4.82, 4.28, 3.94$.
Hence, an object with absolute magnitude $M_X$, has luminosity:

$$L_X = \text{dex}[ -0.4(M_X - M_{\odot}) ] \cdot L_{\odot}$$  \hspace{1cm} (1.3)

**Surface Brightness:**
Extended objects have **surface brightness**, $\mu$ in mag arcsec$^{-2}$ (mag/ss; sometimes written $\Sigma$).
Since $\mu$ is **independent of distance**, it immediately gives the **surface luminosity density**, $I \, L_{\odot} \, \text{pc}^{-2}$
e.g. using $M_{\odot}$ from above, we find (see homework):

$$\mu_B = 27.04 - 2.5 \log(I_B)$$  \hspace{1cm} (1.4)

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 $\mu_V = 17$ mag/ss.

$\rightarrow$ the core has projected luminosity density: $I_V = \text{dex}[ -0.4(17 - 26.39) ] = 5.700 \, L_{\odot} \, \text{pc}^{-2}$.
if the core radius is 10 arcsec, what's the core's apparent magnitude?

$\rightarrow$ $m_{\text{core}} \sim 17 - 2.5 \log(10^2) = 10.75$
for a distance of 15 Mpc, what's the total core luminosity?

$\rightarrow$ $M = m - 5 \log d_{\text{pc}} + 5 = -20.13$, giving $L = \text{dex}[0.4(-20.13 - 4.82)] = 9.55 \times 10^9 \, L_{\odot}$
Using 10 arcsec $= 10 \times 15 \times 10^6 / 206265 = 730 \, \text{pc}$, we find a luminosity density:

$\rightarrow$ $I_{\text{core}} \sim I_{\text{core}} / 2 \, r_{\text{core}} \sim 3.9 \, L_{\odot} \, \text{pc}^{-3}$.
to find the mass density requires a mass-to-light ratio, which is our next topic:

**(f) 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 $\lambda$).
e.g. for waveband "$X"$, using absolute magnitudes:

$$\frac{(M/L)_X}{(M/L)_\odot} = \frac{M/M_\odot}{L_X/L_{\odot,X}} = \frac{M/M_\odot}{\text{dex}[ -0.4(M_X - M_{\odot,X}) ]}$$  \hspace{1cm} (1.5)

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 $X = U, B, V, R, I, K, \text{bol}$ 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, bol} = 3.84 \times 10^{33} \text{ erg s}^{-1} \quad \text{and} \quad M_{\odot, bol} = -2.5 \log(L_{\odot, bol}) + 4.74

- For **main sequence** stars, we have \( L \propto M^{3.5} \), giving \( (M/L) \propto M^{-2.5} \propto L^{0.71} \)
  - Later spectral types have higher \( M/L \).
  - For K stars: \( M \sim 0.5 M_{\odot} \), \( M/L \sim 10 \);
  - For A stars: \( M \sim 2.0 M_{\odot} \), \( M/L \sim 0.1 \).

- 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 \( V \):

<table>
<thead>
<tr>
<th>Type</th>
<th>( M / M_{\odot} )</th>
<th>( M_V )</th>
<th>( L_V / L_{\odot, V} )</th>
<th>( (M/L)_V )</th>
<th>System</th>
<th>( (M/L)_V )</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>O5</td>
<td>60</td>
<td>-5.7</td>
<td>16,140</td>
<td>0.0037</td>
<td>HII region</td>
<td>0.3 - 1</td>
<td>Pop I only</td>
</tr>
<tr>
<td>B5</td>
<td>5.9</td>
<td>-1.2</td>
<td>255</td>
<td>0.023</td>
<td>Spiral Disk</td>
<td>2 - 5</td>
<td>Pop I + II</td>
</tr>
<tr>
<td>A5</td>
<td>2.0</td>
<td>+1.95</td>
<td>14</td>
<td>0.14</td>
<td>Bulges / Ellipticals</td>
<td>8 - 15</td>
<td>Pop II</td>
</tr>
<tr>
<td>F5</td>
<td>1.4</td>
<td>+3.5</td>
<td>3.4</td>
<td>0.41</td>
<td>Nucleus (no AGN)</td>
<td>10 - 50</td>
<td>BH present</td>
</tr>
<tr>
<td>G5</td>
<td>0.92</td>
<td>+5.1</td>
<td>0.77</td>
<td>1.19</td>
<td>Galaxy + halo</td>
<td>20 - 50</td>
<td>DM important</td>
</tr>
<tr>
<td>K5</td>
<td>0.67</td>
<td>+6.4</td>
<td>0.23</td>
<td>2.87</td>
<td>Clusters</td>
<td>100 - 500</td>
<td>DM dominates</td>
</tr>
<tr>
<td>M5</td>
<td>0.21</td>
<td>+12.3</td>
<td>0.001</td>
<td>206</td>
<td>Universe</td>
<td>~1000</td>
<td>DM dominates</td>
</tr>
</tbody>
</table>

(g) **Cosmology 101**

- **The Hubble Law**
  The most basic piece of cosmology is the Hubble Law, which arises from Cosmic expansion.
  \[ v = H_0 \times d \]
  where \( v \) is recession velocity, \( d \) is distance, and \( H_0 \) is Hubble's constant \( \sim 72 \text{ kms/s/Mpc} \)
  - Example: what's the distance to a galaxy with \( z = 0.02 \)?
    \[ v \sim cz = 6000 \text{ km/s}, \]
    \[ d = v / H_0 = 6000 / 72 = 83.3 \text{ Mpc} = 272 \text{ Mly} \]
  - This now allows you to calculate luminosities & linear sizes from fluxes & angular sizes.

Note: at higher \( z \) (e.g. \( > 0.3 \)), this equation won't work, and one needs a more sophisticated approach. Also, at very low \( z \), peculiar velocities can be significant introduce errors to distances.

- **Use of Scaled Hubble Constant: \( h \)**
  For decades, \( H_0 \) was uncertain to \( \sim 50\% \)
  It was/is useful, therefore, to set \( H_0 \) to \( 100 \text{ km/s/Mpc} \) with \( h \) kept explicit
  \( h \) appears once for each redshift-distance, with a power of opposite sign: e.g.
  - 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 \( 2 \times 10^{10}h^{-1} \text{ M}_\odot \) [\( M \sim RV^2/G, \text{ & } R \propto d \)]
  - Its luminosity density is \( 1.6h L_{\odot} \text{ pc}^{-3} \) [\( h^2 / h^3 \)]
  - Its M/L ratio is \( 10h \text{ solar units} \) [\( h^2 / h^2 \)]

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.
Concordance Model Parameters

After WMAP, the various cosmological datasets have yielded a robust cosmological model. The total density is equal to the critical density ($\Omega_{\text{tot}} = 1.00$) so the spatial geometry is Euclidean. The breakdown of today's densities is: $\Omega_b = 0.04, \Omega_{\text{dm}} = 0.23, \Omega_{\text{de}} = 0.73, \Omega = 8.4 \times 10^{-5}$.

These are routinely used to define the relation between redshift and other important parameters, including cosmic time.

Intermediate & High Redshift

It is now routine to ask how any properties change with redshift (i.e. cosmic epoch). It is therefore useful to have a basic feel for the link between $z$ and lookback time.

- $z \sim 1$ is $\sim$60% lookback time (LBT), with cosmic age $\sim$6 Gyr
- coasting (changeover 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 $\sim$1Gyr
- recombination is at $z=1100$, $T$=3300K, age=380 kyr, $\rho \sim 10^3$ cm$^{-3}$
- at recombination, 10kpc subtends $\sim$2.8 arcmin, or 1 deg $\sim$170 kpc
- matter/energy equality occurs at $z\sim3300$, $T$=10,000K, age=50 kyr.

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