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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 existance
- ~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 hightlights.

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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

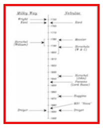
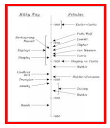
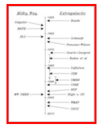
    - What are the **Nebulae** (Latin : clouds)
        - initially : use "large" telescopes to find, catalog, and describe them
        - later : are they unresolved star groups, or genuinely nebulous (gaseous)
        - finally : are they internal to the MW, or external "island universes"

- 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.

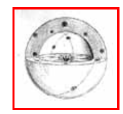
- Here are some simple time-line sketches identifying the key people/work

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

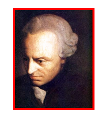




(b) Before 1850 : Search & Discovery

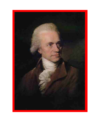
- **1610** : **Galileo** Galilei (Italian) uses early telescopes
  He realizes the Milky Way is composed of many stars [image]



- **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

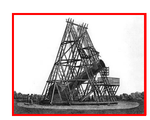


- **1755** : Immanuel **Kant** (German) : [image]
  writes : "General Natural History & Theory of the Heavens"
  (1) rejects spherical shell
  (2) MW like huge solar system, rotating; origin from rotating cloud.
  (3) stars far from plane on different orbits
  (4) disks (like MW) project to ellipses
  (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)

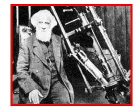


- **1770 - 1810** : William & Caroline & John **Herschel** (English) : [image]
  all-sky survey → 2500 nebulae
  used 18" (20 foot) reflecting telescope, diurnal sweeps
  extended to southern skies by son John at Cape of Good Hope (1834-9)
  some resolve into stars (clusters) others dont (gas?)
  speculation : uniform distribution of stars will gravitationally cluster


- **1845** : William **Parsons** (3^{rd} 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

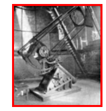
(c) 1850 - 1925 : The Great Debates

- **1864-68** : William **Huggins** (English) : [image]
  telescopic visual spectra of nebulae
  1/3 emission lines (gaseous); 2/3 continuous (stellar)

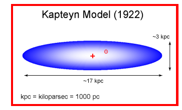


- **1888** : John **Dreyer** (Danish) [image] working at Birr Castle, compiles
  New General Catalog (NGC) : 7840 nebulae
  Index Catalog (IC) : 5086 more

- **1900s** : James **Keeler** and Herber **Curtis** (USA, Lick) use **photography**
  36" Crossley reflector @ Lick : [image]
  estimates ~120,000 nebulae accessible; ~50% are spiral



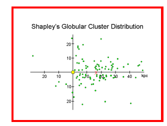
- **1906-22** : Jacobus **Kapteyn** (Dutch) : detailed study of MW : [image]
  surveys 200 areas : star counts, proper motions, radial velocities
  concludes : MW = thick disk, 5kpc radius, sun @ center
  considers absorption and finds some reddening, but
  assumes Rayleigh scattering so infers (wrongly) absorption unimportant



- **1912** : Henrietta **Leavitt** (USA, Harvard) : [image]
  Period-Lumimosity 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

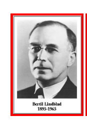
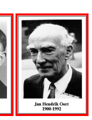


- **1920** : **Shapley (no) - Curtis (yes) Debate** : "Are Spiral Nebulae Island Universes" [image]
  public debate @ National Acadamy of Science, Washington DC.
  Short (30min) presentations, but summary articles published 1921
  surprisingly, Shapley "won" the debate, though Curtis was right.
  Shapley :
    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**
  (centennial review of Hubble's career by Sandage : [o-link])

(d) 1925 - 1950 : Expanding Horizons

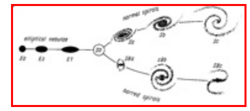
- **1927** : Bertil **Lindblad** (Sweedish) and Jan **Oort** (Dutch) : [image]
  Lindblad predicts differential rotation near sun; Oort find it
  supports Shapley's MW with sun off-center (against Kapteyn's MW)
  however, derives smaller size than Shapley

- **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
  eg E's = large gas cloud, evolves into spiral



- **1930s** : 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

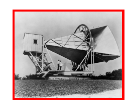
(e) 1950 - Present : Modern Developments

- **1952** : **Baade** : uses 200" to 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 (!)

- **1962** : **Eggen, Lynden-Bell & Sandage** (ELS) : [image]
  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) : [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

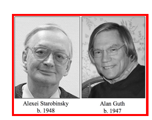


- **1972** : Leonard **Searle** & Wal **Sargent** (USA, Cal Tech) :
  measure 24% He basiline in low metallicity Dwarfs
  consistent with Big Bang nucleosynthesis

- **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

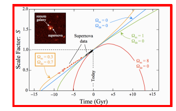
- **1980** : Alan **Guth** & Alexei **Starobinski** (USA; USSR) : [image]
  Independently conceive of early period of extremely rapid, **accelerated expansion**.
  Guth calls this **"inflation"**: solves several deep problems.
  Provides natural explanation for **creation** of everything, and **launching**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



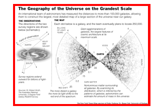
- **1992** : **COBE** (NASA): [image]
  measures stunningly accurate black body spectrum
  finds slight (10^{-5}) anisotropies in CMB → pregalactic structure

- **1996** : **HST's HDF** (NASA): [image]
  galaxies down to 29^m; out to z~3; total $\sim 10^{10}$
  young galaxies visibly different
  early star formation rate is high ("Madau" plot)

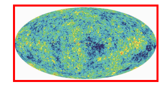
- **1998** : **High-z SN Projects** (USA, Berkeley & Harvard): [image]
  Two groups use Type Ia SN as standard candles out to z ~ 1
  Both find evidence for non-zero **cosmological constant** (universe accelerating)

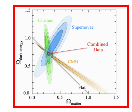


- **2003** : **2dF (& SDSS) Galaxy Surveys** (UK/Australia & USA): [image]
  The first of the large scale galaxy redshift surveys is completed (2dF)
  250,000 galaxy redshifts out to z~0.1 allow detailed analysis of large scale structure.
  SDSS completed later (800,000 galaxy redshifts) but with more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



- **2003** : **WMAP** (NASA) : [image]
  CMB power spectrum measured; includes accoustic peaks 1,2,(~3)
  inspires **concordance model** with "high" accuracy (few %)
  combines : WMAP; SN-1a; 2dFGRS; HST-H_o; 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)





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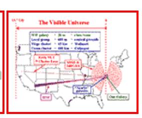
(3) Preliminaries

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

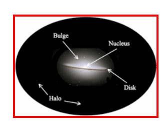
- Three **constituents**, with rough mass ratio 1/10/100 : **Gas / Stars / Dark Matter**

  The first two have complex identity :
  - **Gas**: different phases; dynamics; composition; (like "weather")
  - **Stars**: different ages; locations; kinematics; metallicities; (like "cars")

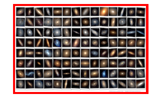
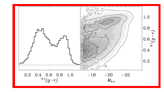
  The third is simpler but more enigmatic:
  - **DM**: collisionless "gas" (of WIMPs?); huge; ~smooth; centrally concentrated

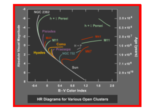
- Several **components**, with varying prominence depending on galaxy type [image].
  - **Nucleus**: dense; star formation; supermassive black hole
  - **Bulge**: spheroidal; mixed ages; kinematically "hot" & little rotation
  - **Disk**: gas & stars; younger; star formation; spiral arms; kinematically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

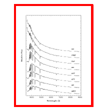
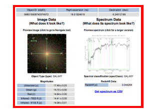
  Note : Dark Matter dominates on **large scales only**
  bulge & disk dynamics determined by **stars & gas alone**



(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 <u>minor</u> but <u>luminous</u> 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:

"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 pnemonic: "a kilometer per second is a parsec in a million years ")
- (2) Newton's constant: $\mathbf{G = 4.50 \times 10^{-3}}$ (4.49846×10^{-3})
  its units are: $(pc^3/M_\odot)\ Myr^{-2} \equiv \rho^{-1}\ Myr^{-2} \approx (km/s)^2\ pc\ M_\odot^{-1}$
- (3) Equations, such as $M = R\,V^2 / G$, directly accept and yield **observational values**
- (4) Densities, ρ_{psm}, are in $\mathbf{M_\odot/pc^{-3}}$ $= 6.76 \times 10^{-23}$ gm cm^{-3} = 40.4 m_p cm^{-3} = $3.60 \times 10^6\ h^2 \rho_{crit}$
- (5) **Frequencies**, Myr^{-1}, are also **velocity gradients: km/s/pc**
- (6) **Crossing/collapse times**: R(pc) / V(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): $M \sim RV^2 / G \rightarrow 8000 \times 220^2 / 4.5 \times 10^{-3} \sim 8.6 \times 10^{10}\ M_\odot$

- Whats the density at the galactic center, where V ~100 km/s @ R ~1pc?
  use (6) : $R^2/V^2 = 1 / (G\rho)$
  $\rightarrow \rho = V^2/(G R^2) = 100^2 / (4.5\times10^{-3} \times 1^2) = 2.2 \times 10^6\ M_\odot/pc^{-3}$

- What's the Schwarzchild radius of a $10^8\ M_\odot$ black hole ?
  use $R_s = 2GM/c^2 = 2 \times 4.5 \times 10^{-3} \times 10^8 / (3 \times 10^5)^2 = 1.0 \times 10^{-5}$ pc = 2 AU

- What's the Hubble time for H_o = 75 km/s/Mpc ?
  use (5) : t_H(Myr) = 1 / (75 km/s/Mpc) = 1 Mpc / (75 km/s)
  = $10^6 / 75 = 1.33 \times 10^4$ Myr = 13.3 Gyr

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

- psm energy units: peu ($M_\odot pc^2 Myr^{-2}$) = 1.89×10^{36} Joules

- psm luminosity units: plu (peu/Myr) = 5.97×10^{22} Watt = 1.56×10^{-4} $L_\odot$
- mass/luminosity units: $M_\odot$/plu = 3.33×10^7 kg/Watt = 6400 ($M_\odot/L_\odot$)
- linear momentum: pmu ($M_\odot$pc/Myr $\approx M_\odot$km/s) = 1.85×10^{33} kg m s^{-1}
- angular momentum: pamu ($M_\odot$pc^{2}Myr^{-1} $\approx M_\odot$ km/s pc) = 5.71×10^{49} kg m^2 s^{-1}
- force (momentum flux): pfu ($M_\odot$pc/Myr^2 $\approx M_\odot$km/s/Myr) = 5.86×10^{19} N
- acceleration: pau (pc/Myr^2 $\approx$ km/s Myr^{-1}) = 3.09×10^{-11} m s^{-2}

A few more examples help illustrate:

- What's the *gravitational* luminosity of a galaxy merger ($M \sim 10^{11} M_\odot$ in R ~ 10 kpc)
  Use (6) for collapse time ~ $(G\rho)^{-½}$ ~ $(4.5 \times 10^{-3} \times 10^{11}/20000^3)^{-½}$ ~ 130 Myr
  Energy of collapse ~ GM^2/R ~ 4.5×10^{15} peu
  Gravitational luminosity = 3.5×10^{13} plu = 5.4×10^9 $L_\odot$
  (much less than ~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 ~5×10^9 peu ~ ½MV^2 → V ~ 32,000 km/s

- What's the mechanical luminosity and force of a 1000 km/s AGN jet carrying 10 $M_\odot$ yr^{-1} ?
  L = ½ Mdot V^2 = ½ × 10^7 × 10^6 = 5×10^{12} plu = 3×10^{42} erg s^{-1}
  F = Mdot V = $10^7 \times 10^3 = 10^{10}$ pfu = 5.9×10^{34} 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:

$$m = \text{const} - 2.5 \log_{10}[\text{flux}] = -2.5 \log_{10}[\text{flux / flux\_0}] \quad 1.1$$

where flux_0 is a reference flux for a star with m = 0.0 (usually Vega), and is filter-specific.
Typically, m ~ 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.:

$$m = \text{const} - 2.5 \log f_{d\,pc}$$
$$M = \text{const} - 2.5 \log f_{10pc}$$

but from the inverse square law:

$$f_{10pc} = f_{d\,pc} \times (d_{pc} / 10)^2$$

so, substituting:

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

Giving the well-known relation:

$$M = m - 5 \log d_{pc} + 5 \quad 1.2$$

By placing everything at 10pc, absolute magnitudes are related to an object's **luminosity**
M ~ -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. $3 \times 10^8\ L_{V,\odot}$)
  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:

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

- **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 $L_\odot$ pc^{-2}
  e.g. using $M_{\odot,B}$ from above, we find (see homework) :

$$\mu_B = 27.04 - 2.5 \log(I_B) \qquad 1.4$$

  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 μ_V = 17 mag/ss.
  → the core has projected luminosity density: $I_V = \text{dex}[\,-0.4(17 - 26.39)] = 5{,}700\ L_{V,\odot}\ \text{pc}^{-2}$.
  if the core radius is 10 arcsec, what's the core's apparent magnitude?
  → $m_{core} \sim 17 - 2.5 \log[\pi \times 10^2] = 10.75$
  for a distance of 15 Mpc, what's the total core luminosity?
  → $M = m - 5\log d_{pc} + 5 = -20.13$, giving $L = \text{dex}[-0.4(-20.13 - 4.82)] = 9.55 \times 10^9\ L_{V,\odot}$
  Using 10 arcsec = $10 \times 15 \times 10^6/206265$ = 730 pc, we find a luminosity density:
  → $j_{core} \sim I_{core} / 2\, r_{core} \sim 3.9\ L_{V,\odot}\ \text{pc}^{-3}$.
  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: $(M/L)_{\odot,bol}$ = 5173 kg/Watt = 0.5173 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 :

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

  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,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)

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

- For **main sequence** stars, we have $L \propto M^{3.5}$, giving : $(M/L) \propto M^{-2.5} \propto L^{-0.71}$
  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	$L_V / L_{\odot,V}$	$(M/L)_V$
O5	60	-5.7	16,140	0.0037
B5	5.9	-1.2	255	0.023
A5	2.0	+1.95	14	0.14
F5	1.4	+3.5	3.4	0.41
G5	0.92	+5.1	0.77	1.19
K5	0.67	+6.4	0.23	2.87
M5	0.21	+12.3	0.001	206

System	$(M/L)_V$	Reason
HII region	0.3 - 1	Pop I only
Spiral Disk	2 - 5	Pop I + II
Bulges / Ellipticals	8 - 15	Pop II
Nucleus (no AGN)	10 - 50	BH present
Galaxy + halo	20 - 50	DM important
Clusters	100 - 500	DM dominates
Universe	~1000	DM dominates

(g) Cosmology 101

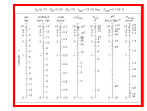
- **The Hubble Law**
  The most basic piece of cosmology is the Hubble Law, which arises from Cosmic expansion.
  $\mathbf{v = H_0 \times d}$
  where v is recession velocity, d is distance, and H_0 is Hubble's constant ~ 72 kms/s/Mpc
  Example: what's the distance to a galaxy with z = 0.02?
  $v \approx cz = 6000$ km/s,
  so $d = v / H_0 = 6000 / 72 = 83.3$ Mpc = 272 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_o was uncertain to ~50%
  It was/is useful, therefore, to set H_o to 100h 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 ~ 6000 km/s, is $60h^{-1}$ Mpc
  The luminosity of 3C 123 is $3\times10^{44}h^{-2}$ erg/s
  3C 123 has $M_B \sim -24.5 + 5\log(h)$ [recall m - M = 5log(d) - 5]
  The jet in 3C 123 has length $150h^{-1}$ kpc [length = angle x distance]
  The core mass of NGC 1234 is $2\times10^{10}h^{-1}$ $M_\odot$ [$M \sim RV^2/G$, & $R \propto d$]
  Its luminosity density is 1.6h $L_\odot$ 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 ~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 (Ω_{tot} = 1.00) so the spatial geometry is Euclidean.
  The breakdown of today's densities is: $\Omega_b = 0.04$, $\Omega_{dm} = 0.23$, $\Omega_{de} = 0.73$, $\Omega_r = 8.4 \times 10^{-5}$.
  These are routinely used to define the relation between redshift and other important parameters, including cosmic time [image]



- **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 ~ 1 is ~60% lookback time (LBT), with cosmic age ~6 Gyr
  - coasting (changover from de to ac-celeration) occurs at z~0.65 or ~45% LBT
  - high-z galaxies and QSOs at z~4-6 are at ~90% LBT, age ~1Gyr
  - recombination is at z=1100, T=3300K, age=380 kyr, $\rho \sim 10^3$ cm^{-3}
  - at recombination, 10kpc subtends ~2.8 arcmin, or 1 deg ~170 kpc
  - matter/energy equality occurs at z~3300, 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.