Galaxies/Cosmology HEAC II
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Lecture 2

Contents:
- Stars, building blocks of galaxies
- Photometry and magnitudes
- The cosmological framework
Stellar evolution

Any star spend most of its life on the so called main sequence fusing hydrogen to helium. 0.7% goes to E=mc²

L \propto M^\alpha , \alpha = 2.2 \text{ to } 5 \text{ on main sequence}

⇒ Massive stars run out of fuel faster! (metallicity effect)

After hydrogen is exhausted the core of the star contracts and its outer parts expand => red luminous giant

If the temperature gets high enough in the core, then He Can be fused into Oxygen, etc. This depends on the mass Of the star, but there is a limit…

AGB stars (pulsating) give WD, massive stars give SN
Luminosity of black body

\[ L = 4\pi R^2 \sigma_{SB} T^4 \]

Stellar spectra are black bodies modified by absorption in stellar atmospheres

Defines effective temperature: \( T_{\text{eff}} \)
Herzsprung-Russel / Colour-Magnitude Diagram
HR diagram / CMD

Luminosity ↑

blue ← Temperature ← red
Iso-chrones / *Stellar populations*

Positions of stars of given age

RGB more sensitive to metallicity than age
Stellar evolutionary tracks in the HR diagram

C. Charbonnel et al.

![Diagram showing stellar evolutionary tracks with metallicity effect highlighted.](image)

**Metallicity effect**

\[ Y = 0.252 \]
\[ Z = 0.004 \]

**Fig. 2.** Influence of the metallicity on the evolutionary tracks of a $2 M_\odot$ in the HR diagram
Stellar evolution time scale is set by Mass

$Z = \text{metallicity}$ (mass fraction of elements heavier than He)

Not to be confused with redshift: $z$
observed CMDs for two "simple/single stellar populations"
End points of stellar evolution:
Planetary nebulae → white dwarf
End points of stellar evolution: (core collapse) supernova → neutron star or black hole

A supernova may outshine an entire galaxy

SN1987A
Galaxy spectra:

composite of all stars present, weighted by their luminosity

+ gas (cold, warm, hot)
  + dust (BB)

• Massive stars are rare but blue and luminous, die young, produce and return lots of "metals"

• Low mass stars are numerous red and faint, live long but don’t return much - Mass sink
Galaxy Spectra

- Si iv $\lambda$1400
- C iv $\lambda$1549
- [O iii] $\lambda$4959, 5007
- [O ii] $\lambda$3727
- $\lambda$4861
- H$\gamma$ $\lambda$4340
- H$\delta$ $\lambda$4101
- [S ii] $\lambda$6716, 6731
- [S iii] $\lambda$9068
- [S iii] $\lambda$9532
- starburst

- flux $F_{\lambda}$ (arbitrary units)

- Sc
- Sb
- S0

- Mg ii $\lambda$2800
- Na d $\lambda$5892
- Ti o $\lambda$6180, 7150
- Ca ii $\lambda$8489, 8542, 8662

- 4000Å break
Edwin Hubble's Classification Scheme

Ellipticals
- E0
- E3
- E5
- E7
- S0

Spirals
- Sa
- Sb
- Sc
- SBa
- SBB
- SBc
Figure 1.7 Above, atmospheric transmission in the optical and near-infrared. Below, flux $F_\lambda$ of a model A0 star, with transmission curves $T(\lambda)$ for standard filters from Bessell, PASP 102, 1181; 1990. $UX$ is a version of the $U$ filter that takes account of atmospheric absorption. For $JHKK'LL'$, $T(\lambda)$ is for transmission through the atmosphere and subsequently through the filter.
Magnitudes and Colours

- “Magnitudes” are a logarithmic relative flux unit:
  - \( m_1 - m_2 = -2.5 \log_{10}(s_1/s_2) \)
  - smaller magnitude means brighter
  - 1 mag difference means a factor 2.5 in flux.
  - need for a zero-point. Vega has \( m=0 \) in all bands.

- A “Colour” is the difference of magnitudes between two bands.
  - e.g. B-V=1 means 2.5x more flux in V than in B (as compared to Vega, not absolute)
  - higher value in a colour means “redder”.
Observing at different redshifts

- Same filter observes different wavelengths at different $z$.
- K-correction possible if spectrum known or assumed.
- Can be used for drop-out technique
- Problems for classification.
Same galaxy (M81) at different wavelengths
Stars: Summary

- Mass - luminosity colour relation
- Mass vs lifetime
- Stellar death and ISM enrichment
- IMF and stellar populations
- Photometry: the magnitude system
- Galaxy spectra: a time integral of IMF, stellar evolution and birthrate

- Stars: main generator of electro-magnetic radiation (reradiated by dust and ionised gas)
The cosmological framework

Redshift: \[ 1 + z \equiv \frac{\lambda_{obs}}{\lambda_{em}} = 1 + \frac{v_r}{c} \]

Hubbles law: \[ v = H d \]

Robertson-Walker line element (GRT + cosm principle)

\[ ds^2 = c^2 dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2(\theta)d\phi^2) \right] \]

\[ 1 + z = \frac{R(t_o)}{R(t_e)} \]

\[ H = \frac{\dot{R}(t)}{R(t)} \]

\[ q = \frac{\ddot{R} R}{\dot{R}^2} \]
Hubbles law

1929 data fits in here →

Z=0.1
Z=0.066
Z=0.033
Large scale distribution of galaxies
FRW-models, summary

\[ \dot{R}^2 = \frac{8\pi G \epsilon R^2}{3c^2} - kc^2 + \frac{1}{3}\Lambda R^2 \]

\[ \ddot{R} = - \frac{4\pi G R (3p + \epsilon)}{3c^2} + \frac{1}{3}\Lambda R \]

Energy density:

- Matter: \[ \epsilon = \rho c^2 \propto \rho_0/R^3 \]
- Radiation: \[ \epsilon \propto \epsilon_0/R^4 \]
Critical density

Assume matter with $p=0$ and $\Lambda=0$

Use:

$$H_0 = \frac{\dot{R}_0}{R_0}$$

That is, if:

$$\rho_0 = \frac{3H_0^2}{8\pi G} \equiv \rho_{0,\text{crit}}$$

Then $k=0$

About 5 protons/m$^3$
Cosmic epochs
Matter-domination ends and dark energy-domination begins

$\dot{R}^2 = \frac{8\pi G\epsilon R^2}{3c^2} - k c^2 + \frac{1}{3} \Lambda R^2$

$t_{DE} \sim 10$ Gyr

Density

Matter

Radiation

Dark energy

Dark energy dominates
The early universe

Gamov criterium: A reaction may be important as long as its interaction time scale is shorter than the expansion time scale of the universe

Pair production. e.g. \[ \gamma + \gamma \rightleftharpoons e^- + e^+ \]

reaction balance set by temperature, e.g: \[ \nu_e + n \rightleftharpoons e^- + p \]

As long as \( m_A c^2 < kT \) a particle ’A’ may be kept in equilibrium, then ”freeze out”
The early universe...

Baryogenesis: matter-antimatter equality broken, Possibly by the decay of a so called X-boson
⇒ Net amount of matter
⇒ Photon to baryon ratio $\eta = 10^9$

Neutrino freeze out (decoupling) at $t=0.7s$
Electron-positron pair production ceased and the Annihilation of existing pairs heated up radiation and Matter but not the neutrinos that had already decoupled
Primordial nucleosynthesis

All fusion of hydrogen to heavier elements go through the stage of deuterium. $p + n \rightarrow D + \gamma$

However, D can be dissociated by photons more energetic than 2.2 Mev

Since there are many more photons than baryons
This will occur frequently enough also at much lower Temperatures than $kT=2.2$ Mev $\sim 10^{10}$ K

$\Rightarrow$ Nucleosynthesis inhibited until the D production rate was higher than the distruction rate ($10^9$K, t=200s)

DEUTERIUM BOTTLENECK
Primordial nucleosynthesis...

However, neutron to proton ratio was fixed earlier (t=1s) when the neutrinos froze out: \[ \frac{N(n)}{N(p)}=0.22 \]

Since then until t=200s, some neutrons have decayed so \[ \frac{N(n)}{N(p)}=0.16 \]

Basically all leftover n ends up in D and almost all of that becomes He. Nothing heavier than Li is made.

The He abundance is therefore determined by \( \eta \) (since we know the current CMBR photon density this gives us \( \Omega_{\text{bar}} \))

Other trace elements: D, \(^3\)He, \(^7\)Li depend more strongly…
Primordial nucleosynthesis...

Only a small Fraction of all Matter may be Baryonic

Still larger than The luminous Matter density

Galaxies could be baryonic?
(re)combination

Similarly to above, the vast amount of photons can keep hydrogen ionised to temperatures well below 13.6 eV. But when \( T < 4500 \text{ K} \) the number of energetic enough photons is too small and protons and electrons can combine to form neutral hydrogen.

Matter and radiation decouples.

Last scattering surface at \( z = 1100 \) (\( T = 3000 \text{ K} \)) leads to a dramatic drop in pressure for the matter.

Observable as \( 3000/1100 = 3 \text{ K} \) CMBR, no lines since \( \eta >> 1 \) and \( \Delta z >> 1 \).
Cosmic microwave Background

Early universe
Hot & Dense

Penzias & Wilson

CMBR according to COBE
Figure 1.20 Extragalactic background radiation: vertical logarithmic scale shows energy density per decade in frequency or wavelength. Arrows show upper and lower limits. The curve peaking at $\lambda \sim 1$ mm is the cosmic microwave background; the far-infrared background is the light of stars and active galactic nuclei, re-radiated by dust – T. Ressell, D. Scott.