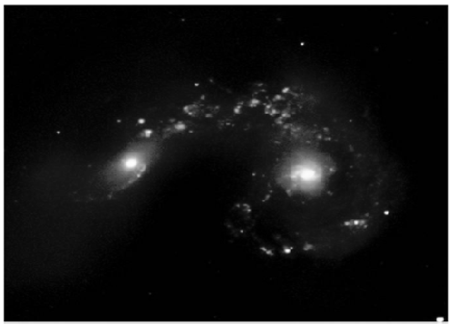
Galaxies AS7007, 2012
Lecture 5: Dwarf galaxies & starbursts



Outline

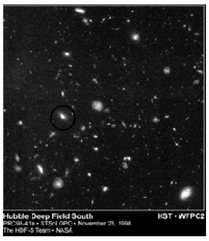
- Important concepts:
  - Stellar LF, galaxy LF
  - Initial mass function
  - Surface brightness
- Dwarf galaxies
  - Dwarf Spheroidals
  - Dwarf Ellipticals & Compact Ellipticals
  - Dwarf irregulars

Recap - stellar Populations

Resolved

- Individual stars can be analyzed
- Applicable for Milky Way star clusters and the most nearby galaxies

Unresolved



- Integrated spectroscopy / photometry only
- The most common case in extragalactic astronomy

Stellar Evolution

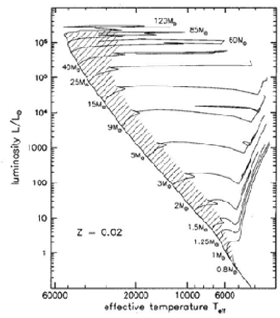


Figure 1.4 Luminosity and effective temperature during the main-sequence and later lives of stars with solar composition: hatched region shows where the star burns hydrogen in its core. Only the main-sequence track is shown for the $0.8\mathcal{M}_\odot$ star – Geneva Observatory tracks.

The Stellar Luminosity Function

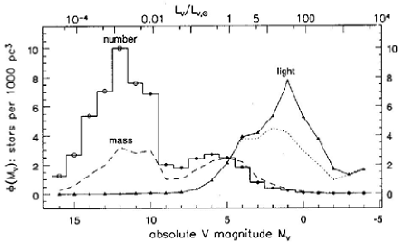


Figure 2.3 Luminosity function $\Phi(M_V)$ for nearby stars: solid dots are from the stars of Figure 2.2; open circles are from *photometric parallax*. The solid line and triangles show $L_V\Phi(M_V)$, light from stars in each magnitude bin; the dotted curve shows the light of main-sequence stars alone. The dashed curve gives $\mathcal{M}\Phi_{MS}(M_V)$, the mass in main-sequence stars: units are $L_\odot$ or $\mathcal{M}_\odot$ per 10 pc cube.

The Initial Mass Function (IMF)

Knowing the lifetimes of stars of different masses, the IMF may be deduced from the observed stellar luminosity function. The IMF may be written:

$$dN \propto M^{-\alpha} dM$$

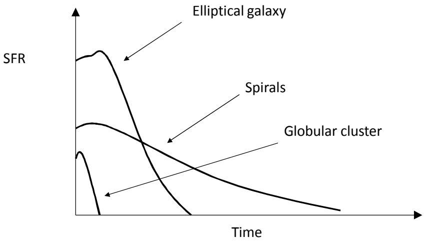
dN is the number of stars per mass interval dM.

$\alpha = 2.35$ represents the Salpeter IMF.

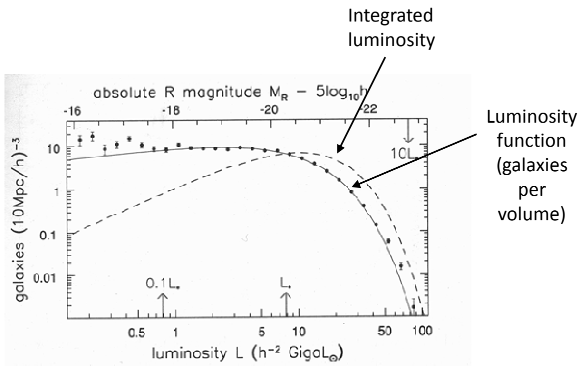
The mass interval is normally assumed to be 0.1—120 or 0.08—120 solar masses.

Star Formation Rate (SFR)

- SFR: M_{solar}/yr
- Star formation history: SFR(t)



The Galaxy Luminosity Function



The Galaxy Luminosity Function

Schechter function (galaxies / Mpc^3)

$$\phi(L)\Delta L = n_*\left(\frac{L}{L_*}\right)^{\alpha}\exp\left(-\frac{L}{L_*}\right)\frac{\Delta L}{L_*}$$

Total Luminosity Density

$$\int_{L_{min}}^{L_{max}} \phi(L)L\, dL$$

Surface Brightness

$$\alpha = \frac{D}{d}$$

Size of object (D)

Distance to object (d)

$$I(x) = \frac{F}{\alpha^2} = \frac{L/4\pi d^2}{D^2/d^2} = \frac{L}{4\pi D^2}$$

- I(x) in mag arcsec^{-2} or L_{solar} kpc^{-2}
- Determines observability of extended objects (e.g. galaxies)
- I(x) independent of distance(!) in local universe…
- … but subject to factor $(1+z)^{-4}$ of redshift dimming $\rightarrow$ One reason why high-redshift objects are extremely difficult to detect

Dwarf Galaxies

- "Dwarf" typically implies small size, small mass, low luminosity and low central surface brightness
- Common, but sloppy definition:

  $M_B > -18$ or -17
- In general: Higher total M/L than in normal galaxies $\rightarrow$ Extremely dark-matter dominated

Dwarf Galaxies

- Often difficult to distinguish from normal galaxies, without measuring luminosity
- Tell-tale sign: when you see right through them

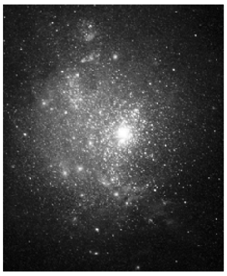
Dwarf Spheroidals (dSph)

- Almost no gas
- Very diffuse (can often see right through them)
- Old; no stars younger than 1—2 Gyr
- Metal-poor ($Z<10\% Z_{solar}$)
- Random motion dominates: $v_{rot}/\sigma_v<1$
- Probably triaxial
- May have luminosities as low as globular clusters, but are bigger and have globular clusters of their own

Dwarf Ellipticals (dE) & Compact Ellipticals

- Dwarf Ellipticals:
  - Similar to dSph, but more luminous
  - Distinction somewhat unclear, many people write dE/dSph
- Compact Ellipticals:
  - Rare (example: M32 in Local Group)
  - High density
  - More rotationally supported than dE/dSph: $v_{rot}/\sigma_v\geq1$

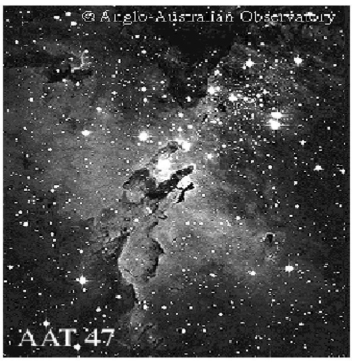
Dwarf Irregulars



Dwarf Irregulars

- Contain gas and young stars
- Metal-poor: ($Z<10\% Z_{solar}$)
- Some rotationally supported, some not:
  - Low L-systems: $v_{rot}/\sigma_v<1$
  - High L-systems: $v_{rot}/\sigma_v\approx4—5$

Star formation

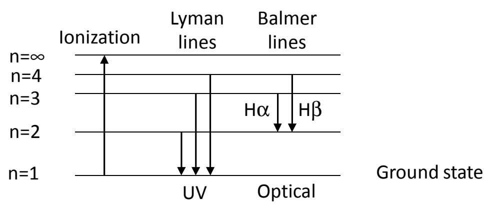


Indications of star formation I

- Recombination emission lines
- UV continuum
- IR thermal emission
- Radio continuum emission
- CO from molecular clouds

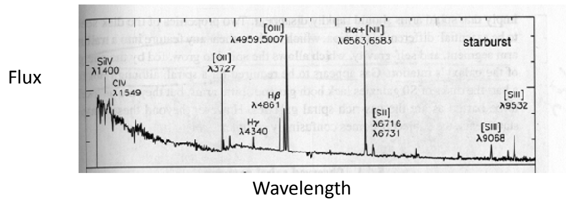
Recombination emission lines

- Radiation with λ< 912 Å (Lyman break) from hot stars ionize hydrogen
- When proton and electron recombine → cascade towards ground state → Recombination emission lines



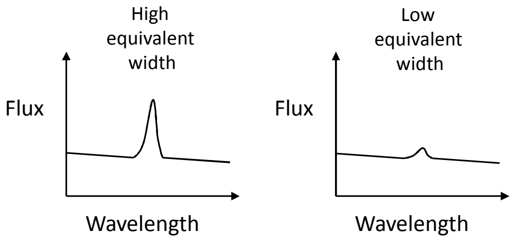
Recombination emission lines

- In star-forming regions, Hα & Hβ are very prominent in the optical region
  - Hα: 6563 Å
  - Hβ: 4861 Å



Emission-line equivalent width

How strong are the lines relative to the continuum?



High equivalent width indicates high star formation activity

Recombination emission lines

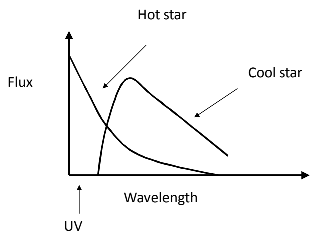
- Hα luminosity can be used to estimate the SFR:

$$SFR(M_{\text{solar}}/\text{yr}) = 7.9 \times 10^{-42} L_{\text{H}\alpha}(\text{erg/s})$$

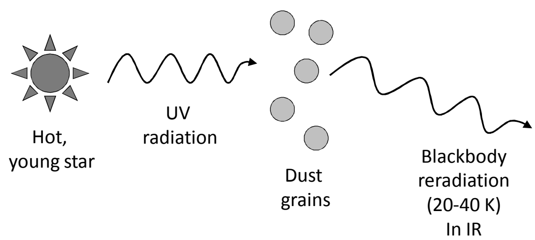
- Measurements of Hα & Hβ luminosities can constrain the amount of dust reddening

UV continuum

- Young, massive stars are hot → High UV-luminosity
- L_{UV} can (in analogy with $L_{H\alpha}$) be related to SFR



IR Thermal Continuum



High L_{IR}/L_B indicates high star formation

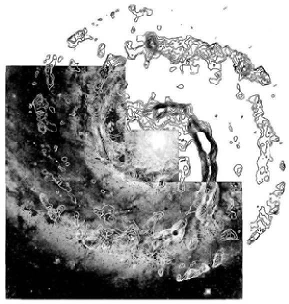
Radio continuum emission

- Star-forming galaxies emit a lot of cm-wavelength radio emission
- Posssible origin: synchrotron radiation from particles accelerated in supernova remnants
- Supernovas trace SFR → cm-wavelength radiation trace SFR

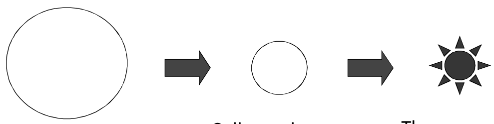
Remember: Dust extinction is not an issue in radio observations

CO from Molecular Clouds

- Star formation starts in giant molecular clouds → Molecules (like CO) trace star formation



Star Formation Made Simple

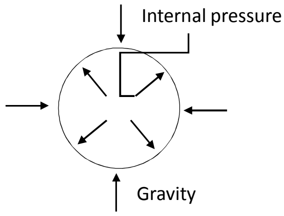


Gas cloud

Collapse due to self-gravity→ Temperature rises

Thermonuclear reactions kick in → A star is born

When Does Star Formation Occur?



Gravity wins when Length > Jeans length, λ_J:

$$\lambda > \lambda_J = \frac{\sigma_v}{\sqrt{G\rho}}$$

Or equivalently, when mass > Jeans mass, M_J:

$$M > M_J = \frac{\pi}{6}\lambda_j^3 \rho_m$$

When Does Star Formation Occur?

$M<M_J$ ensures stability on small scales

On larger scales, regions of size D are prevented from collapse by disk rotation if:

$$D > D_{\text{critical}} = \frac{2G\Sigma}{3\Omega^2}$$

Surface Density (Σ)

Angular velocity (Ω)

Low-surface brightness disks fulfil this criterion!

Star formation triggers

- Gravitational instabilities
  - $M>M_J$
  - $D<D_{critical}$
- Density waves
  - Compression in spiral arms
- Direct collisions

Feedback from Star Formation

- Gas ionized by massive stars
  - Gas must be cool to collapse
- Winds from Supernovae
  - Loosen up compressed regions
  - Removes gas from low-mass galaxies (blow-out)

Star Formation Efficiency

Typically less than 10% of the available gas is converted into stars before feedback prevents further star formation

Star formation efficiency

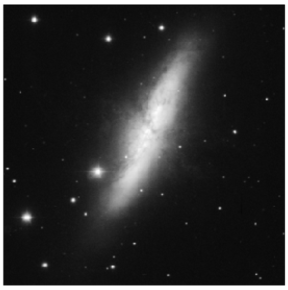
Star formation rate (assumed constant during star formation episode)

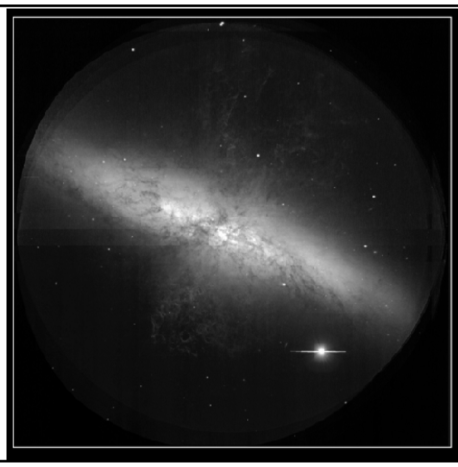
Duration of star formation episode

$$\varepsilon = \frac{\mathrm{SFR}\,\tau}{M_{\mathrm{H_2}}} \leq 0.1$$

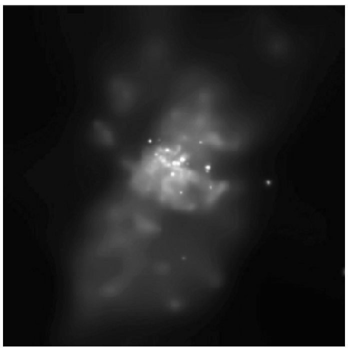
Starburst Galaxies


M81 & M82


Starburst Galaxy M82



Starburst Galaxies


M82 in X-rays

Recommended Definitions of Starbursts

- Global starburst:
  - SFR high enough to consume the gas in less than one Hubble time over a size larger than a single HII-region
- Local starburst:
  - SFR increases by factor of 10 or more across an HII-region

Starbursts are transient phenomena unless new gas is added

Starburst galaxies

- Gas-consumption timescale:

$$t_{gas} = \frac{M_{gas}}{SFR}$$

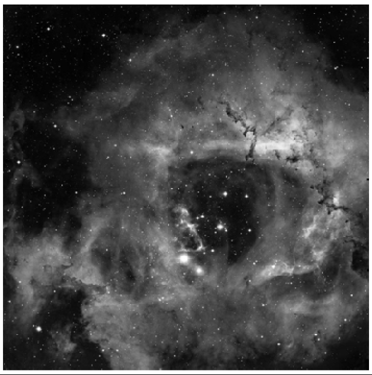
- Typical galaxy: SFR~0.1 M_{solar}/yr
- Common, but dangerous starburst definition:

SFR > 50 M_{solar}/yr

Starburst Galaxies

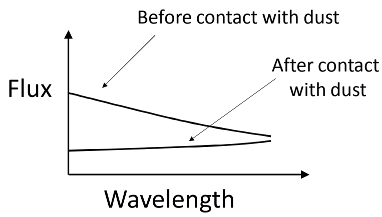
- Possible triggers:
  - Mergers/collisions
  - Interactions (controversial)
  - Large intergalactic gas clouds falling into a galaxy

The Interstellar medium



Dust extinction

- Dust absorbs light in UV/optical
- Dust opacitiy is wavelength-dependent: Blue light is absorbed more efficiently than red light → Reddening of the spectrum



Dust extinction II

- The Balmer decrement Hα/Hβ, can be estimate the amount of dust reddening in galaxies with emission lines
- Theory predicts $L_{H\alpha}/L_{H\beta}\approx 2.85$ from gas ionized by stars (Note: $L_{H\alpha}/L_{H\beta}$ is often written Hα/Hβ)
- Dust reddening → $L_{H\alpha}/L_{H\beta}>2.85$
- Knowing $L_{H\alpha}/L_{H\beta}$ and using an extinction curve (extinction as function of wavelength), dust reddening can be corrected for

Metallicity

- Metallicity, Z: Mass fraction of elements other than H and He
  - $Z_{solar} \approx$ 0.013-0.016 (depending on who you belive)
- Abundance ratio:

$$[A/B] = \log_{10}\left(\frac{(\text{number of A atoms / number of B atoms})_{\text{object}}}{(\text{number of A atoms / number of B atoms})_{\text{sun}}}\right)$$

- Often [Fe/H] or [O/H] is also referred to as "metallicity"

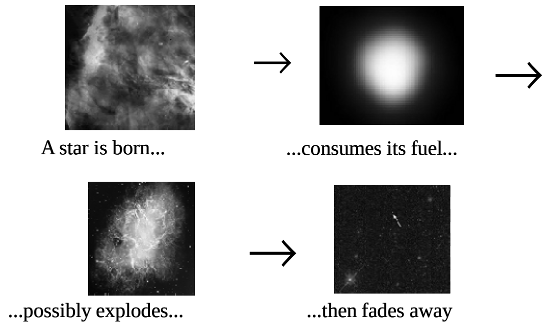
Metallicity

- The metallicity of the gas can be measured using emission-line ratios
- E.g. a measurement of:
  - OII at 3727 Å
  - OIII at 4959 and 5007 Å
  - Hβ at 4861 Å

gives R_{23} , which can be converted into [O/H]

$$\log R_{23} = \log\left(\frac{L_{[\mathrm{OII}]\lambda 3727} + L_{[\mathrm{OIII}]\lambda\lambda 4959,5007}}{\mathrm{L}_{\mathrm{H}\beta}}\right)$$

Chemical evolution



Stellar evolution made simple

The Closed-Box Model

- No gas added or lost from the system
- Yield, p:
  - Determines return of heavy elements to interstellar medium
  - Often defined as mass fraction of heavy elements returned per mass locked up in stellar remnants (black holes, neutron star, white dwarfs) and long-lived, very low-mass stars

The Closed-Box Model

$$Z(t) = Z(0) + p \ln\left(\frac{M_{\mathrm{gas}}(0)}{M_{\mathrm{gas}}(t)}\right)$$

Prediction:

Gas-rich systems are metal-poor (e.g. dI)

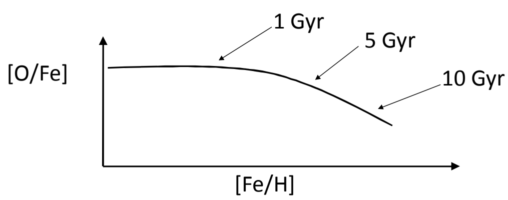
Gas-poor systems are metal-rich (e.g. E)

However, dSph are gas-poor and metal-poor…

Relaxation of the Closed-Box Assumption

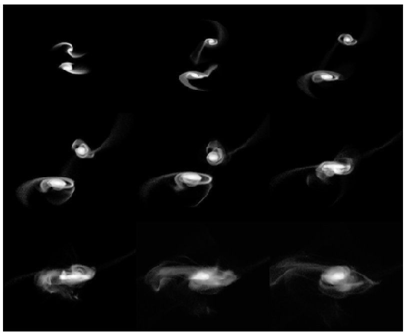
- Blow-out of gas by stellar winds
  - Mainly in low-mass systems (dwarf galaxies, globular clusters, first galaxies)
- Infalling gas
  - Intergalactic gas clouds (primordial metallicity)
  - Merger with gas-rich galaxy

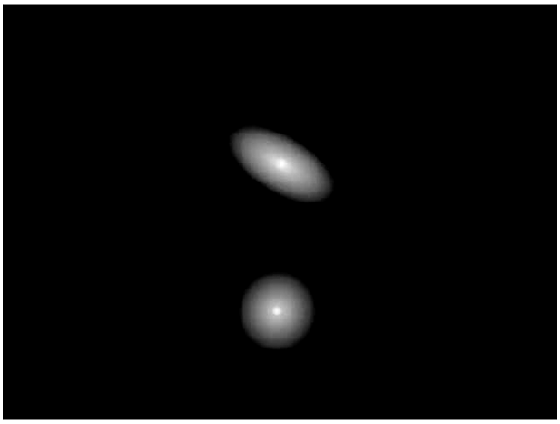
Chemical Evolution of Individual Elements



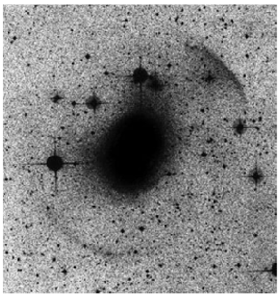
- Type II supernovae: O (quick)
- Type Ia supernovae: Fe (prolonged)

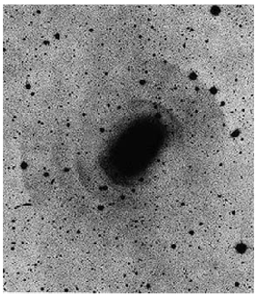
Galaxy Interactions & Mergers





Signs of interaction: Shells





Signs of Interactions: Warps

Signs of interaction: Tidal Tails & Filaments