STAR FORMATION IN GALAXIES:
1. INTRODUCTION TO GALAXIES

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Nordic-Baltic Optical/NIR and Radio Astronomy Summer School:
Star Formation in the Milky Way and Nearby Galaxies
Tuorla Observatory, 11.6.2009

1. Introduction to galaxies
2. How to measure star formation?
3. Where is star formation located?
4. Why is star formation triggered?
5. Starbursts and galaxy mergers

The Hubble Morphological Sequence of Galaxies
Galaxies at different wavelengths

Multi-wavelength imaging of M81

Ultraviolet (GALEX)
Bimodal Galaxy Distribution in:

- **Colours**
- **Morphologies**
High mass galaxies passive red spheroids dominated by old stars
Low mass galaxies star-forming, blue disk galaxies
What produces this bimodality? (c.f. Hierarchical models)
Why are there few low-mass passive galaxies?
STAR FORMATION IN GALAXIES

2. HOW TO MEASURE STAR FORMATION?

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What do we need to measure SF?

- Millimeter
  - Atomic Gas
- Mid-IR
  - Molecular Gas
  - Embedded SFR
- Near-IR
  - Stellar Mass
  - New Stars

- Emission lines
- Young stars
- Gas
- Dust
- IR
Characteristics of Extragalactic SF:

SFR - SF Rate (per year; per area)
SFH - SF History (Continuous, Instantaneous)
SFE - SF Efficiency (Gas Conversion)

\[
SFE = \frac{S_{SFR}}{S_{Gas}}
\]

Star formation rate normalized by gas.

How effective is ISM in turning itself into stars?

*Integrated Flux, Not Individual (Young) Stars*

*Synthesis Models (IMF, Metallicity, SFH, Age)*
Diagnostic Methods of Star Formation in Galaxies

1. Integrated Colors and Spectra + Synthesis Modeling
2. UV / Lyman Continuum (most direct, but $A_v$)
3. Recombination Lines (e.g. $H\alpha$, Case B, $A_v$)
4. Forbidden Lines (e.g. [OIII]) (Physical State of Gas)
5. Far-Infrared (FIR) Continuum
6. Radio Continuum (Contribution from Old Stars)

All Measures affected by Age, Metallicity, Dust

=> Can Trace Different SF Populations
1. Integrated spectra of elliptical, spiral, and irregular galaxies.
Several changes along this sequence:
  - rise in the blue continuum,
  - change in the stellar absorption spectrum from K-giant to A-star,
  - dramatic increase in the nebular emission lines, especially Hα.
Dominant contributors at visible wavelengths are intermediate main sequence stars (A to early F) and G-K giants.
The spectrum of any given object dictated by the ratio of early-type (< 1 Gyr) to late-type (> 3 Gyr) stars.
The contributions to the spectrum by young and old stars need to be discriminate using evolutionary synthesis models to infer the evolution and SF history of the galaxy.
Evolutionary Synthesis Models:

Ingredients:
- Stellar Evolutionary Tracks
  + Geneva & Padua Tracks
  + Metallicity dependency
  + Uncertainties: BSGs; AGB Stars
- Shape of IMF
  + Salpeter, Kroupa,...
  + Truncated, Top-Heavy,...
- Star Formation History
  + Instantaneous (Decay Time: 1-30 Myr)
  + continuous

![EvolutionarySynthesisModels.png](image-url)
**Initial Mass Function (IMF)**

IMF = number of stars of a mass range created per unit volume

**Form of IMF**: crucial in converting observations into stellar mass. Simple power law; different indices depending on mass
High mass stars most luminous → distribution best understood

**Salpeter** (1955): canonical
IMF: $\alpha = 2.35$

**Scalo** (1986): flattened IMF,
$\alpha \sim 0$ at low-mass

**Kroupa** (1997): accounts for underabundance of low-mass stars
Synthesis Models:
Single Population

Composite Populations

Synthetic spectra of galaxies as a function of age
Elliptical galaxies

• The easiest galaxies to model by single age, metallicity, using high-resolution stellar spectra

Formed most of their stars at least ~10 billion years ago
Metallicities solar or sub-solar
Spiral galaxies

- Stars with a wide range of ages and metallicities
  - Usually modeled with continuous SF (SFR changes with time)
  - Bulge, disk, and halo have different stellar populations.

Spectral fit of a dusty starburst
2) SFR from Ultraviolet Continuum

SFR is more reliably measured at UV wavelengths (~1250 – 2500 A) where the spectrum is dominated by young stars => SFR scales linearly with luminosity.

99.5% of stars formed 10 Gyrs ago (old)
0.5% of stars formed 0.1 Gyrs ago (young)

Optically indistinguishable from old stellar population BUT strong UV signal
Conversion between UV flux and SFR using synthesis models.

Usually assume that SFR has remained constant over timescales longer than the lifetimes of the dominant UV population (<$10^8$ yr), i.e. continuous star formation.

Assuming a Salpeter IMF between 0.1 and 100 $M_\odot$ yields:

$$\text{SFR} \ (M_{\text{sun} \ \text{yr}^{-1}}) = 1.4 \ 10^{-28} \ L_{\text{UV}} (\text{erg s}^{-1} \ \text{Hz}^{-1})$$

N.B. SFR/L ratio is significantly lower in younger populations (e.g. starburst galaxies).

**Advantage:** directly tied to the photospheric emission of the young stellar population.

**Drawbacks:** (a) sensitivity to extinction which is very patchy, with UV emission dominated by regions of low obscuration.

(b) sensitivity to the assumed form of IMF. The integrated UV spectrum is dominated by stars with $M > \sim 5 \ M_\odot$, => a large extrapolation to lower masses.
The UV continuum

Very good SF tracer...

BUT….very sensitive to dust attenuation

Starburst99, continuous SF

\[
\text{log (Luminosity [erg s^{-1}])}
\]

\[
\text{log (Wavelength [Å])}
\]

\[
\nu_f \quad (\text{scaled at } 2.2\mu\text{m})
\]

Wavelength (μm)

Dale et al. 07
3) SFR from Recombination Lines

- Nebular lines re-emit the integrated stellar luminosity shortward of the Lyman limit (912 Å) => direct probe of young massive stars. Only stars with $M > 10 \, M_{\odot}$ and $t < 20$ Myr contribute significantly to the ionizing flux, so emission lines provide a nearly instantaneous measure of SFR, independent of previous SF history.

For solar abundance and Salpeter IMF (0.1–100 $M_{\odot}$):

SFR ($M_{\text{sun}} \, \text{yr}^{-1}$) = $7.9 \times 10^{-42} \, L(H\alpha)$ (erg s$^{-1}$)

SFR ($M_{\text{sun}} \, \text{yr}^{-1}$) = $8.2 \times 10^{-40} \, L(B\gamma)$ (erg s$^{-1}$)

Salim et al. 07
Advantages: (a) sensitivity, (b) direct coupling between nebular emission and massive SF.

Limitations: (a) extinction, IMF and metallicity; (b) uncertainty whether all massive SF is traced by the ionized gas.

a steeper IMF for faint galaxies

SFR/L(H$_\alpha$) varies with galaxy mass.

=> SFR underestimated for faint (dwarf) galaxies.

Pflamm-Altenburg et al. 07
Brinchmann et al. 04
Kennicutt 1998
Higher order Balmer lines are poorer SFR diagnostics than H\(\alpha\) (weak, affected by stellar absorption). These lines in fact are rarely seen in emission in the spectra of early-type galaxies.

The luminosities of forbidden lines are not directly coupled to the ionizing luminosity, and their excitation is sensitive to abundance and ionization state of gas. However, [OII]3727 can be calibrated (through H\(\alpha\)) as a SFR tracer (but less accurate than H\(\alpha\)). For the same Salpeter IMF as for H\(\alpha\): 

\[
\text{SFR (}\text{M}_{\odot}\text{ yr}^{-1}) = 1.4 \times 10^{-41} \text{ L([OII]) (erg s}^{-1})
\]
The calibration of the \([\text{OII}]\) emission line

**Moustakas et al. 07**

**Kewley et al. 04**

Calibration derived from comparison with \(\text{SFR}(\text{H} \alpha)\)

Sensitive to

- Dust reddening
- Metallicity
- Ionization state of the gas
5. SFR from Far-Infrared Continuum

A significant fraction of the luminosity of a galaxy is absorbed by dust and re-emitted in IR. Dust absorption most efficient in UV => FIR luminosity can be a sensitive tracer of SFR. This depends on the contribution of young stars to heating of the dust, and on the optical depth of the dust.

When young stars dominate UV–optical radiation, and dust opacity is high everywhere, FIR luminosity truly measures bolometric luminosity. Such conditions hold in dense circumnuclear starbursts in IR-luminous galaxies.
In late-type galaxies, where dust heating from young stars dominates (warm component $\lambda \sim 60\mu m$), FIR luminosity correlates with other SFR tracers (UV, H$\alpha$). However, early-type galaxies often exhibit FIR from cooler, IR cirrus component ($\lambda \geq 100\mu m$) from more extended dust heated by interstellar radiation field.

The SFR vs L(FIR) conversion is derived using synthesis models for the bolometric luminosity of the stellar population. For continuous SF and Salpeter IMF:

\[
\text{SFR (M}_{\sun}\text{ yr}^{-1}) = 4.5 \times 10^{-44} L(\text{FIR}) (\text{erg s}^{-1}) \text{ (starbursts)}
\]

where $L_{\text{FIR}}$ refers to the TOTAL 5–1000 $\mu$m IR luminosity (which can be difficult to estimate...).
How to Measure SF in the Mid-IR: 24 and 8 µm luminosities as SFR estimators

$L_{24\mu m}$ is a reliable SF tracer, more difficult for $L_{8\mu m}$

SFR($M_{sun}$ yr$^{-1}$) = $1.27 \times 10^{-38} \ (L_{24\mu m} \ (erg \ s^{-1}))^{-0.8850}$

Calzetti et al. 07
The 8 $\mu$m emission comes from diffuse regions ⇒ not directly related to SF

The 24$\mu$m emission peaks in point-like regions ⇒ closely related to SF
SFR\((M_{\text{sun}} \text{ yr}^{-1}) = 5.3 \times 10^{-42} (L(H\alpha_{\text{obs}}) + 0.031 L_{24\mu m}) \text{ (erg s}^{-1})\)
6) SFR from Radio Continuum

Very tight correlation between SFRs from FIR and radio.

Same massive young stars produce synchrotron emission (e.g. supernovae) and FIR emission. SFR can also be estimated from the number of O stars required to produce thermal free-free continuum emission.

No dust extinction, but can be difficult to separate thermal and non-thermal components.

**Infra-red continuum**

\[
SFR_{\text{FIR}} \left( M \geq 5M_\odot \right) = \frac{L_{60\,\mu m}}{5.1 \times 10^{23} \, W H z^{-1}} \, M_\odot \, yr^{-1}
\]

**Total Radio Continuum**

\[
SFR_{1.4} \left( M \geq 5M_\odot \right) = \frac{L_{1.4}}{4.0 \times 10^{21} \, W H z^{-1}} \, M_\odot \, yr^{-1}
\]
The Dual Effects of Dust:

Changes Morphology     Causes extinction

![M31 in the visible.](image1)
![ISO map of M31. (wavelength of 175 microns) North is up, east is left.](image2)

Interstellar extinction curve
2175 Å bump
Steep rise in far-UV

Graph showing the interstellar extinction curve with various extinction coefficients for different regions.
Correction for dust attenuation:

Star forming galaxies and various geometries/dust properties (Gordon et al. 2000)

Balmer Decrement: \( \frac{H\alpha}{H\beta} \) (or \( \frac{H\alpha}{Pa\alpha} \)) (theoretical ratio = 2.86)

\( \frac{F_{\text{dust}}}{F_{\text{UV}}} \) ratio:

Cortese et al. 08

Calibration depends on SF history
Selection effects: Different behavior for FIR- and UV-selected galaxies
Summary

How to measure SF?
- all SF measures affected by Age, Dust, Metallicity
- always integrated Light from Many (Young) Stars
- synthesis Models for Single & Multiple Populations