Overview of how we measure Star Formation Rates

The solid line shows the stellar Initial Mass Function (IMF) from Kroupa (1993). If we know the IMF, we can infer the star formation rate (SFR) from the massive SFR.
3 important features of high mass stars

1. emit more ultraviolet light (750-3500 A or 75 to 350 nm) than low mass stars
2. emit Lyman continuum photons at $\lambda \leq 912$ A or 91.2 nm that ionize hydrogen
3. are short-lived (lifetime < $10^7$ yr for $M \geq 10 M_\odot$ star vs $10^{10}$ yr for $1 M_\odot$ star)

Methods for estimating the Massive Star Formation Rate (MSFR)

- MSFR from the UV continuum (750-3500 A)
- MSFR from Ly continuum photons & Hydrogen Recombination Lines (Ly-alpha, H-alpha, Pa-alpha, Br-gamma)
- MSFR from Thermal Radio continuum
- MSFR from Non-Thermal Radio Continuum
- MSFR from Far-IR continuum
- MSFR from Mid-IR emission

1. Most of the UV light is absorbed by dust in the external galaxy, and re-radiated by warm dust at far-infrared (4x10^5 - 1x10^6 A or 40-120 micron) wavelengths.

2. The UV light, which is not absorbed by dust, is hard to observe
   - at $\lambda \leq 2800$ A, the Earth's atmosphere blocks UV light (top figure);
   - need space satellites like ASTRO-1 or GALEX
   - Over a narrow window ($\lambda \sim 2800-3500$ A), UV light can reach Earth telescopes
3/29/12

1) Top panel shows SFR_UV, the SFR derived from UV light. This is calculated from ground-based images at 2800 Å after doing extrapolations to cover the light emitted at $\lambda = 1216-3000$ Å, as well as at $\lambda < 1216$ and $\lambda > 3000$ Å. A Kroupa (2001) IMF is assumed.

$$SFR_{UV} = 9.8 \times 10^{-11} \times 2.2 \times L_{UV}$$

$$SFR_{total} = SFR_{UV} + SFR_{IR}$$


Ionization of H atom requires that it absorbs a Lyman continuum photon of $\lambda = 912$ Å or Energy $= 13.6$ eV

Ly cont photons disappear a few $10^7$ yrs after the episode of SF

Right: For an episode of star formation that happened less than 0.01 Gyr or $10^7$ yrs ago, high $M > 10^5$ Mo stars are still alive and produce Lyman continuum photons at $\lambda = 912$ Å that ionize Hydrogen. As the stellar population ages beyond a few $10^7$ yrs, the high-mass stars die, and there are no Ly continuum photons.
Recombination lines of hydrogen

Emission lines from electronic transitions from higher to lower levels:
Lyman series; UV
Balmer series; optical e.g. H\(\alpha\)
Paschen series; NIR
Brackett series; MIR

MSFR from Ly\(\alpha\) cont photons and Hydrogen Recombination lines

Purple = H\(\alpha\) emission line

Archetypal starburst galaxy M82. It shows the horizontal stellar disk of the galaxy, which harbors its active star formation, + a perpendicular supagalactic wind of ionized gas powered by the energy released in the starburst.

Credit: Mark Westmoquette (University College London), Jay Gallagher (University of Wisconsin-Madison), Linda Smith (Un. College London), WIYN/NSF, NASA/ESA

MSFR from Hydrogen H\(\alpha\) Recombination lines

Tracing MSFR from UV and mid-infrared emission in M81

UV/ASTR0-1 UV continuum from high mass stars
Mid-IR/Spitzer at 24\(\mu m\) = hot dust heated by massive young stars
Visible light
NIR/Spitzer at 3\(\mu m\) = Underlying low mass stars

Tracing MSFR from mid to far-infrared emission

Movie: From optical to IR view of M81 (Courtesy: NASA/Spitzer)
Near-IR at 1-3\(\mu m\) penetrates dust & shows low mass stars
Mid and far-IR from 10 to 100\(\mu m\) shows dust heated by massive young stars
Star formation is obscured at optical wavelengths by dust in gas-rich region, but revealed in mid-infrared images that trace hot dust.

**Tracing MSFR from mid-infrared emission**

**Ultra Luminous Infrared Galaxies (ULIRGs)**

![Image](image1.png)

![Image](image2.png)

Star formation is obscured at optical wavelengths by dust in gas-rich region, but revealed in mid-infrared images that trace hot dust.

![Image](image3.png)

![Image](image4.png)

**MSFR from thermal + non-thermal radio continuum**

Condon (1992)

![Image](image5.png)

**Far-IR and radio spectrum of galaxies**

The solid line is the total light and the 3 dashed lines show the contribution from 3 components:

- At short FIR wavelengths (0.01 cm or 100 microns) emission from warm 40 K dust dominate the spectrum
- Thermal free-free radio emission dominates only over a narrow range of intermediate wavelengths
- At long wavelengths (20 cm) non-thermal radio continuum emission (i.e., synchrotron emission) dominate spectrum

**SFR from thermal + non-thermal radio continuum**

SFR estimates based on UV continuum or optical Hα recombination line are affected by dust and can underestimate the SFR.

SFR estimates from longer wavelength tracers (Far-IR or radio continuum) which are less affected by dust.
**Conditions for the Onset of Star Formation**

The simulation shows the collapse and fragmentation of a molecular cloud of mass 50 $M_\odot$, with initial diameter of ~0.4 pc, and temperature of 10 K.

→ Jean mass $M_J = 1 M_\odot$ for $T=10$ K, $n=10^{5}$ atoms cm$^{-3}$

High density regions within the cloud gravitationally collapse and fragment to form stars.

Surrounding some of these stars are swirling discs of gas which may go on later to form planetary systems like our own Solar System.

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**Collapse of a molecular cloud to form stars**

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**Evidence for suppression of SF at large radii in disk of spirals**

Kennicutt 1989

SFR traced by H$\alpha$ appears suppressed at large radii although atomic hydrogen (HI) is present.

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**Evidence of a threshold gas density for SF in disk of spirals**

Kennicutt 1989

SFR traced by H$\alpha$ appears suppressed at large radii although atomic hydrogen (HI) is present.
Using the gravitational instability model to account for the threshold gas density for SF disk of spirals

\[ \Sigma_{\text{crit}} = \alpha \left( \frac{\kappa \sigma}{3.36 \, \text{G} \, \Sigma} \right) = \alpha \Sigma_c \]

- At each radius R calculate \( \Sigma \) and measure total gas density \( \Sigma_g \).
- Plot \( \left( \Sigma / \Sigma_g \right) \) vs radius R: its value at the threshold radius \( R = R_{\text{HII}} \) for star formation gives \( \alpha \).

\( \Sigma_{\text{crit}} = \alpha \left( \frac{\kappa \sigma}{3.36 \, \text{G} \, \Sigma} \right) = \alpha \Sigma_c \)

\( \alpha \approx 0.7 \) for all galaxies !

**Schmidt Law relating \( \Sigma_{\text{gas}} \) and \( \Sigma_{\text{sfr}} \)**

\[ \Sigma_{\text{sfr}} \propto (\Sigma_{\text{gas}})^p \]

Composite star formation law for the normal disk (filled circles) and starburst (squares) samples.

Open circles show the SFRs and gas densities for the centers of the normal disk galaxies.

The line is a least-squares fit with index \( N = 1.40 \). The short diagonal line shows the effect of changing the scaling radius by a factor of 2.

SF in the central kpc

In the central kpc of NGC 4314, the Toomre Q parameter is a minimum (~1-2) in regions of SF and rises sharply inside the ring of SF.

Is there a critical density for SF in the inner kpc controlled by gravitational instabilities?
In the central kpc of both NGC 4314 and NGC 4102 the Toomre Q parameter is a minimum (~1-2) in regions of SF.

(Jogee, Scoville & Kenney 2005)

**Feedback on Star Formation**

(stellar and AGN)

**Stellar Feedback on Star Formation**

Massive stars formed in a recent star formation episode can exert “feedback” to suppress the very star-formation process that produced them (no good deed goes unpunished!)

The feedback happens via supernovae and winds associated with the massive stars in different ways, e.g.,

1) Energy or momentum from supernovae and winds can be transferred to the ambient gas, which is blown out to large scale heights in a starburst wind. (The ejected gas can escape if its speed $> \text{escape speed at relevant radii}$ or later rain back on the galaxy)

2) Cold atomic (and molecular) gas fueling star formation can be heated by shocks, plus it can be dynamically heated (its velocity dispersion rises). This makes the gas less susceptible to gravitational instabilities, such as those believed to convert atomic gas into molecular hydrogen.

**Feedback on SF from SNe driven winds**

Purple = Ha emission line

Starburst galaxy M82.

Note perpendicular starburst wind of ionized gas powered by the energy released in the starburst.

Credit: Mark Westmoquette (University College London), Jay Gallagher (University of Wisconsin-Madison), Linda Smith (Un. College London), WIYN/NSF, NASA/ESA
Feedback from Active Black holes

Di Matteo et al 2005
This computer animation visualizes the time evolution of a merger simulation of two spiral galaxies that host supermassive black holes at their centres. Only the gas distribution is shown. Brightness represents gas density, whereas the colour hue indicates gas temperature.

Outstanding Questions

- Decline in frequency of galaxy mergers and interactions
- Decline in cold gas content due to gas consumption/removal by SF/AGN
- Decline in accretion rate from filaments
- Transition of SF to lower mass

What drives decline in cosmic SFR density over z =1 to 0
Example of interacting/merging galaxies at lookback =3 to 8 Gyr

Example of interacting/merging galaxies at lookback =3 to 8 Gyr

SFR density from mergers over last 7 Gyr

For \( M^* \geq 1 \times 10^{10} \) and \( M^* \geq 2.5 \times 10^{10} \), visible mergers account for less than 30% of the SFR density over the last 7 Gyr. Most (above 70%) of the SFR density comes from normal non-interacting systems.

Implications

1) The behavior of the SFR density over the last 7 Gyr is shaped by non-interacting galaxies rather than mergers,
2) At half of its present age, the Universe had already transitioned from a violent to a fairly quiescent phase and the evolution of massive galaxies was no longer dominated by mergers.