STAR FORMATION RATES
observational overview
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Remember, remember..

Simplified Illustration
Outline

- measurements of SFRs:
  - techniques to see what the SF rate is
  - importance of massive stars and HII regions
  - the IMF and population synthesis

- theories vs. observations for SFR
  - physical mechanisms and uncertainties in theories

- observed SF in the galaxies
  - UV star formation rates in the local universe,
    SFR-mass relation (Salim)
1. Measurements of SFRs

Massive Stars

- continuous formation of stars
- equilibrium radius, luminosity and surface temperature depends on star’s mass
- very bright: increase in luminosity the more massive a star is
- very hot
- very ionizing: strong ionization field
- very short-lived
Massive Stars and the SFR

- Short lifetime $\rightarrow$ number of massive stars is proportional to instantaneous SFR (SFR is fairly constant)

- number of massive stars $\rightarrow$ measure SFR; made easier by their characteristics: luminosity, ionization

- 2 step-problem:

$\rightarrow$ To get the SFR, one can **measure the massive stars** and convert that to the SFR.

HII regions, spectral features

HII region line emission

NGC 2237, NOAO press release 04-03

Spectra of Virgo Intracluster HII Region
From Massive Stars to SFR

- ionization rate = recombination rate
- Measure the recombination rate (flux of line photons) -> convert line luminosity to ionization rate:

  e.g. luminosity of H α, Kennicutt et al. 1998:

  \[ L_{H\alpha} \left[ \text{ergs}^{-1} \right] = 1.36 \times 10^{-12} S \left[ \text{s}^{-1} \right] \]

  also: free-free emission technique (e.g. Murray & Rahman 2010)

- from ionizing photon emission rate, get the SFR with population synthesis technique:

  - Stars forming at rate \( \dot{M}_* = \text{const} \)
  - IMF, known empirically \( \xi(m) = \frac{dn}{dm} \)
  - Total ionizing luminosity:
    \[ S = \dot{M}_* \int \xi(m)Q(m)t_{\text{life}}(m)dm \]
  - Uncertainties in the IMF, dust absorption and form of the ionizing luminosity
Population Synthesis Results, Initial mass function (IMF)

IMF determined for the Orion Nebula Cluster (black), the Pleiades (green), the cluster M35 (blue) and Kroupa IMF for field stars (red hatched region).

\[ \dot{M}_* \left[ \frac{M_{\text{sol}} \text{yr}^{-1}}{} \right] = \frac{S}{2.4 \times 10^{53} \text{s}^{-1}} \]

Kroupa, P. 2002

→ Evaluate integral → conversion between SFR and the rate of ionizing photon emission

Result (Murray & Rahman 2010): \[ SFR(MW) \approx 1.3 M_{\text{sol}} \text{yr}^{-1} \]

Result (Williams & McKee 1997): \[ SFR(MW) \approx 3 M_{\text{sol}} \text{yr}^{-1} \]
2. Theories (vs. Observations) and their Embarrassments

- observed SFR is too slow (Zuckermann & Evans 1974, Wong & Blitz, 2002) and too low by a factor of 100

- MW disc contains $10^9 M_{\text{sol}}$, molecular clouds

- need dense gas $\rightarrow$ giant molecular clouds $n_H \approx 100 \text{cm}^{-3}$, $t_{ff} \approx 4 \text{Myr}$

  if GMCs collapse, the SFR would be $10^9 M_{\text{sol}} / 4 \text{Myr} = 250 M_{\text{sol}} \text{yr}^{-1}$

  but measured to be $\sim 2 M_{\text{sol}} / \text{yr}$

  even in Starburst Galaxies: 5000 vs. 50

- slow SF everywhere (Tan, Krumholz & McKee 2006): $\epsilon_{ff} = \text{const} = 1\%$

- haven’t found dense enough gas
Where in a galaxy do stars form

- Stars only form in molecular gas H$_2$: GMC
- turbulence in GMC: supersonic isothermal turbulences
- most form in the center of the galaxy
- form in H$_2$ regions, but universe mostly made out of HI
  - more dissociation than ionization
  - dissociation balance in atomic-molecular complexes (GMC): (Krumholz, McKee & Tumlinson 2008a)
- supply of gas into the galaxy from the IGM $\Rightarrow$ suppression of accretion of gas? Fading star formation in massive galaxies due to AGNs? Responsible for quenching of SF?
Star Formation Law

\[
\dot{\Sigma}_* = f_{H_2}(\Sigma_{gal}, Z) \frac{\Sigma_{gal}}{2.6 \text{Gyr}} \times \begin{cases} 
\left( \frac{\Sigma_{gal}}{85 M_{\odot} \text{pc}^{-2}} \right)^{-0.33}, & \Sigma_{gal} < 85 M_{\odot} \text{pc}^{-2} \\
\left( \frac{\Sigma_{gal}}{85 M_{\odot} \text{pc}^{-2}} \right)^{0.33}, & \Sigma_{gal} > 85 M_{\odot} \text{pc}^{-2}
\end{cases}
\]

Krumholz, McKee & Tumlinson, 2009

Figure 2: Star formation rate surface density \( \Sigma_* \) as a function of total gas surface density \( \Sigma_{gal} \). Lines and contours are the same as in Figure 2. Other points are a compilation of literature data from H08. We show individual spotter in M31 (black dot), Kennicutt et al. (2007), azimuthal averages (blue circles) in NGC 4736 and NGC 5055 (Wang & Blitz (2004), NGC 6946 (Coyle et al. (2007), and M31 (Schuster et al. (2007)), and global averages for starburts (open green triangles, Kennicutt (1998)), normal spirals (filled green triangles, Kennicutt (1998), and low surface brightness galaxies (yellow diamonds, Wyder et al. (2009)). The gray arrows and labels indicate schematically the dominant physical process responsible for setting the slope in each region.
Summing up I

- We can measure SFR reasonably well
  - Physics of hydrogen atom
  - stellar structure
  - IMF (weak link)

- Understanding of SF: turbulence and H$_2$ formation
  - low SFR observed
3. Observed SFR

- SF observable in present epoch, importance of OB associations
- “direct” optical observations limited due to formation in obscuring clouds
- observations with various SF indicators:
  - UV continuum, nebular recombination lines (H $\alpha$, [OII], FIR dust emission, synchrotron radio continuum at 21cm)
  - “UV” star formation rates in the local universe
  - NIR photometry method (see also Jaron Kurk’s talk)
Salim et al. 2007; “UV” SFRs

- multiwavelength approach: GALEX (Galaxy Evolution Explorer) in 2 UV bands and SDSS optical photometry

- SDSS-measured emission lines (Hα) compared to UV based SFRs derived from SED fitting

- role of AGNs

- statistical sample of 50,000 optically selected galaxies with GALEX and SDSS photometry and SDSS redshifts

- SED fitting with population model library → dust-corrected SFRs (“UV” SFRs)
- BPT diagram adopted for classification
- “UV” SFR can be used for galaxies where emission lines are too weak (red sequence galaxies) or contaminated by narrow line AGNs
- Agrees well with dust-corrected SFRs from Halpha lines

Notice blue and red sequence of UV to optical CMD. Blue: SF, red: no Halpha, between: AGNs or composites
The main sequence of star forming galaxies

Dependence of the sSFR on stellar mass; narrow sequence for SF galaxies visible

Figure 1. The distribution of the galaxies in our sample in the BPT line-ratio diagram. The two lines show the division of our sample into the three subsamples discussed in the text. An unweighted version of this diagram can be seen in Figure 2. The galaxies plotted here have S/N > 3 in all four lines.

Brinchmann et al., 2004
Fig. 17. — Dependence of the specific SFR on the stellar mass for different classes of galaxies. Star forming (left panels); galaxies with AGN (middle panels); and galaxies without Hα detection (right panels) all occupy distinct regions of the parameter space, indicating different SF histories. SF galaxies form a narrow sequence. AGN have intermediate specific SFRs, and are predominantly high mass. Galaxies without Hα, mostly red-sequence galaxies, have low specific SFRs. The dashed lines shows the reference SFR of $1 M_\odot$ yr$^{-1}$. The lower panel shows values weighted by $V_{\text{max}}$. Uneven behavior at low masses is because of small number of galaxies (or no galaxies) in those mass bins.
Summing up II

• Candidate or gas accretion stop: AGN
• Gas supply stops → dead, red
• Quenched from main sequence → AGN → No H α

Fig. 18.— Specific SFR and mass of star forming, and of galaxies hosting AGN. We plot density contours for normal SF galaxies having no AGN (thin solid contours), of SF/AGN composites (bold solid contours), and of “pure” AGN (dashed contours). The SF/AGN composite class (lower part of the AGN branch in BPT diagram) bridges normal SF galaxies and the AGN lying on the upper part of the AGN branch. Contours of unweighted distribution encompass 10, 30, 50, and 70% of objects, i.e., their composite PDF densities.

Logarithm of the column density, $\Sigma$, for one projection of the decaying (left) and driven (right) simulations at $1t_{\text{ff}}$. 