Star Formation in Galaxies & its Relationship with the Gas Supply
make-up class:
tomorrow Thurs 10:30am in Watson B51
Sampling star formation history over different timescales

1. Present or “instantaneous” SFR (over last $\sim 10^7$-$10^8$ yrs)

2. Past-average SFR (over galaxy lifetime of $\sim 10^{10}$ yrs)

3. Intermediate-scale SFRs (over timescales of $10^7$-$10^{10}$ yrs, depending on type of data)

4. Future star formation lifetime (for $t > t_{\text{now}}$)
Sampling star formation history over different timescales

1. present “instantaneous” SFR (over last $\sim 10^7$-10$^8$ yrs)

-> measure luminosity of massive stars from e.g., UV, H$\alpha$, FIR, radio continuum
Sampling star formation history over different timescales

2. Past-average SFR (over galaxy lifetime of $\sim10^{10}$ yrs)

$$\text{PASFR} = \frac{M_{\text{star}}}{T_{\text{gal}}(1-R)}$$

$M_{\text{star}} = \text{mass in stars in galaxy}$
$T_{\text{gal}} = \text{age of galaxy}$
$R = \text{return fraction}$

$R = \text{fraction of mass in stellar generation (batch with given IMF)}$
$\text{that is returned to ISM by SN and stellar mass loss, over its lifetime}$
$R \sim 0.25-0.5$ (depends on IMF)
Sampling star formation history over different timescales

1. present “instantaneous” SFR (over last $\sim 10^7$-$10^8$ yrs)
2. Past-average SFR (over galaxy lifetime of $\sim 10^{10}$ yrs)

Simple comparisons of present to past SF activity:

$$\frac{\text{Present SFR}}{\text{Past SFR}} = b = \frac{\text{SFR}}{\text{M}_{\text{star}}} \frac{T_{\text{gal}} (1-R)}{\text{M}_{\text{star}}} \quad \text{(dimensionless)}$$

Related quantity:

Specific star formation rate (sSFR) = $\frac{\text{SFR}}{\text{M}_{\text{star}}}$ \text{ (has units of yr}^{-1})

sSFR gives rough measure of ‘timescale’ of SF activity, BUT doesn’t include the important recycling factor
most actively star-forming galaxies lie in part of SFR-M_{star} diagram called “main sequence of SF galaxies”

for typical ‘main sequence’ galaxy
\[ sSFR = \frac{\text{SFR}}{M_{\text{star}}} \approx 3 \times 10^{-11} \text{ yr}^{-1} \]

i.e. SF timescale \( \approx (1-R)^{-1}(sSFR)^{-1} \)
\[ \approx 6 \times 10^{10} \text{ yr} \] (if R=0.5)
i.e. much longer than age of universe
so most galaxies forming stars now at rate much less than in past

Chang+2015
Sampling star formation history over different timescales

1. present “instantaneous” SFR (over last $\sim 10^7$-$10^8$ yrs)
2. Past-average SFR (over galaxy lifetime of $\sim 10^{10}$ yrs)

A simple comparison of present to past SF activity:

$$\frac{\text{Present SFR}}{\text{Past SFR}} = b = \frac{\text{SFR} \times T_{\text{gal}} \times (1-R)}{M_{\text{star}}}$$

$\text{EW}(H\alpha)$ is a good rough measure of $b$:

$$\text{EW}(H\alpha) = \frac{\text{flux}(H\alpha)}{\text{flux density (continuum starlight)}}$$

measure of SFR \hspace{1cm} \text{rough measure of } M_{\text{star}}
Star formation (from Hα) in nearby galaxies

if b=1 then past-average SFR ~ present SFR
median of b=1 for nearby Sc galaxies (Type= 5)
but ~order of magnitude variation in each type (SF is bursty)
Average Star formation histories of galaxies
if you fit exponential SFR profile to b value (real SFHs are not so smooth)

b<<1 for E’s, Sa’s : most of gas->star conversion happened in past
b~1 for typical Sc:
b>1 for some dwarfs: current SFR> past average (not shown)
Starbursts

- Large range in $b$ values for galaxies of given mass & type
- Interpretation: SFR(t) is episodic, at least some galaxies form significant fraction of their stars in short-lived, intense episodes of SF
- Starbursts triggered in some cases by mergers or accretion or galaxy-galaxy interactions
possible SFHs with bursty behavior
Sampling Star Formation History (SFH) over different timescales

3. Intermediate-scale SFRs (over timescales of $10^7$-$10^{10}$ yrs, depending on type of data)
   a. In nearby galaxies, measure luminosities and colors of individual stars and make HR diagram
   b. For any galaxy, measure spectrum of integrated light, compare with stellar population models
      i. High resolution spectrum, showing absorption lines and continuum shape (some use only absorption lines)
      ii. Medium resolution “spectrum” = Spectral Energy Distribution (SED) (some measure only “color”)

The more detail in the data, the more accurate is the estimate of star formation history
deriving SFH by observing & modelling color-magnitude diagram for stars in galaxy

this is powerful technique but works only for nearby “sparse” galaxies where individual stars can be detected

nearby dwarf galaxies ANGST Weisz+2011
CMD analysis to learn SFH

Two sample isochrones plotted with occupation probability represented by point size.

Harris & Zaritsky 2001
CMD analysis to learn SFH

Two sample isochrones plotted with occupation probability represented by point size.

Observations usually don’t see much of main sequence, most sensitive to giant stars – but if lot of main sequence can be observed gives info on IMF – unlike other techniques!

Harris & Zaritsky 2001
deriving SFH by observing & modelling color-magnitude diagram for stars in galaxy

NOTE: finer time sampling in most recent ~ 2 Gyr
NOTE: range of SFHs for dwarfs

nearby dwarf galaxies
ANGST Weisz+2011
constraining Star Formation Histories (SFHs) by fitting models to Spectral Energy Distributions (SEDs)

MAGPHYS model package (daCunha+2008)  
NGC 4808, a low-mass Sc spiral

points: data  
black line: best-fit model  
blue line: stellar light, after correction for dust extinction

stellar photosphere emission  
dust emission

program derives SFH by detailed fit to UV-OPT-NIR starlight spectrum
how does this work? by adding linear combinations of SSPs

“single stellar population” (SSP): bunch of stars formed at the same time with a given IMF & metallicity

Ages of stellar population in Gyr given on plot

Note huge change in UV light with age $> 1$ Gyr

UV-NIR Spectrum of SSP

Bruzual & Charlot 2003

GALEX FUV 1344-1786 Å
GALEX NUV 1771-2831 Å
constraining Star Formation Histories (SFHs) by fitting models to Spectral Energy Distributions (SEDs)

MAGPHYS model package (daCunha+2008)  
NGC 4808, a low-mass Sc spiral

points: data  
black line: best-fit model  
blue line: stellar light, after correction for dust extinction

note that this galaxy has similar luminosities in UV-OPT-NIR (stars) and MIR-FIR-Submm (dust)  
i.e., \( \frac{L_{\text{opt}}}{L_{\text{FIR}}} \sim 1 \) so dust captures \( \sim \) half the starlight energy.  
\( \frac{L_{\text{opt}}}{L_{\text{FIR}}} \) varies a lot among galaxies, can be 0.01 - 100
Sampling star formation history over different timescales

4. Future star formation lifetime (for $t > t_{\text{now}}$) (also Gas Depletion Timescale; Gas Consumption Timescale)

$$\tau_{\text{gas}} = M_{\text{gas}} f_r / \text{SFR}$$

$f_r =$ recycling factor
$f_r >\sim 1 / (1-R)$

For $R=0.4$, $f_r \sim 1.7 - 4$ (1.7: no delay; 4: reasonable guess for delay)

Can be larger than $1/(1-R)$ due to delayed return of gas mass from older stars
Gas depletion timescales

• In typical nearby galaxies \( \tau_{\text{gas}} \sim 2 \text{ Gyr} \) (if \( f_r = 2 \))
  
  -> Star formation activity in galaxies cannot last much longer unless they are resupplied with gas
  
  -> Suggestive evidence for ongoing gas accretion

• In starbursts, \( \tau_{\text{gas}} < 1 \text{ Gyr} \)
  
  -> present level of activity can’t continue for long (hence *starBURST*)
relationship between gas supply & SFR
introductory thoughts

• suppose

\[ \rho_{SFR} = \frac{SFR}{Volume} \sim \rho_{gas}^n \]
\[ \Sigma_{SFR} = \frac{SFR}{Area} \sim \Sigma_{gas}^N \]  

(Schmidt 1959)

expect SFR to depend on volume density – but hard to observe so express also in terms of surface density, since this is observable.
Global Relation between gas surface density $\Sigma_{\text{gas}}$ and star formation rate per area $\Sigma_{\text{SFR}}$

What is shown: Disk-averaged surface densities (total SFR and $M_{\text{gas}}$ averaged over area of main star-forming disk)

Non-linear Schmidt law:
$\Sigma_{\text{SFR}}$ vs. $\Sigma_{\text{HI+H2}}^{1.4}$ fits much of data although data falls below this simple trend at low surface densities

Implication: star formation timescale (or gas depletion timescale) is shortest (or star formation is more “efficient”) if gas densities are higher

This helps explain why galaxies grow from the inside-out

Kennicutt & Evans 2012
Local Relation between gas surface density $\Sigma_{\text{gas}}$ and star formation rate per area $\Sigma_{\text{SFR}}$

Radial variation in $\Sigma_{\text{SFR}}$ is similar to $\Sigma_{\text{H}_2}$ and less similar to $\Sigma_{\text{HI}}$ or $\Sigma_{\text{HI+H}_2}$
Local Relation between gas surface density $\Sigma_{\text{gas}}$ and star formation rate per area $\Sigma_{\text{SFR}}$

$\Sigma_{\text{SFR}}$ vs. $\Sigma_{\text{H}_2}$ relation is $\sim$linear

$\Sigma_{\text{SFR}}$ vs. $\Sigma_{\text{HI}}$ and

$\Sigma_{\text{SFR}}$ vs. $\Sigma_{\text{HI}+\text{H}_2}$ relations are non-linear

Star formation more closely tied to molecular gas, star formation from HI is inefficient

$\sim$500 pc apertures in 18 nearby spirals & late type dwarfs (no starbursts)

Bigiel et al. 2008
Local Relation between gas surface density $\Sigma_{\text{gas}}$ and star formation rate per area $\Sigma_{\text{SFR}}$

Schmidt law with total ($\Sigma_{\text{HI}} + \Sigma_{\text{H}_2}$) gas:
3 regimes
1. Starburst -- efficient SF
2. Normal
3. Outer disk/LSB/dwarf – inefficient SF

lines for gas depletion timescales labeled

Bigiel et al. 2008
Kennicutt & Evans 2012
relationship between gas supply & SFR

• suppose

$$\rho_{SFR} = \frac{SFR}{Volume} \sim \rho_{gas}^n$$ or

$$\Sigma_{SFR} = \frac{SFR}{Area} \sim \Sigma_{gas}^N$$ (Schmidt 1959)

-> predict SFR(t) which decreases strongly with time for $n,N>1$

if $n,N=1$, SFR$\sim M_{gas}$, predict SFR with exponential decrease over time

if galaxy is closed box
relationship between gas supply & SFR

• suppose

\[ \rho_{SFR} = \frac{SFR}{\text{Volume}} \sim \rho_{gas}^n \quad \text{or} \]
\[ \Sigma_{SFR} = \frac{SFR}{\text{Area}} \sim \Sigma_{gas}^N \quad (\text{Schmidt 1959}) \]

\[ \rightarrow \text{predict SFR}(t) \text{ which decreases strongly with time for } n,N\geq 1 \]
if \( n,N=1 \), \( SFR \sim M_{gas} \), predict SFR with exponential decrease over time
if galaxy is closed box

• Sc galaxies on average have \( b \sim 1 \), i.e. \( \sim \text{constant} \)
SFR over lifetime yet \( M_{gas}/M_{\text{star}} \sim 0.1 \)

\[ \rightarrow \text{not consistent with simplest idea of galaxy as} \]
\text{closed box with } SFR \sim \text{amount of gas} \]
with closed box model expect \( b \sim 1 \) and \( M_{\text{gas}}/M_{\text{star}} \sim 1 \) or \( b<<1 \) and \( M_{\text{gas}}/M_{\text{star}} \sim 0.1 \)
simple model inadequate

3 basic ideas proposed to modify SFR laws

1. **gas accretion/inflow** (probably episodic supply)
   (suggested by chemical evolution studies & cosmological simulations)
   (only idea which can explain both $b \sim 1$ and $M_{\text{gas}}/M_{\text{star}} \sim 0.1$ for spirals)

2. **SF thresholds** – SF does not occur unless gas density is higher than some critical value – something prevents gravitational collapse of gas clouds

3. **SF regulation** – something limits SFR or $t_{\text{SFR}}$ -- could be self-regulated – energy dumped into newly formed stars & SNe disrupt ISM and prevents further SF – or regulated by shear
Theoretical relationship between $\Sigma_{\text{gas}}$ and $\Sigma_{\text{SFR}}$

Some properties of star formation in galaxy disks can be understood by:

Large-scale gravitational instabilities in gas disks:

*If a thin gas disk with uniform density is perturbed slightly (so as to produce a slight overdensity in one region), will perturbation damp out (stable) or grow (unstable)?*

Answer depends on fight of gas self-gravity, which acts to make gas collapse, versus pressure and centrifugal & coriolis forces, which act to prevent gravitational collapse
Is disk dynamically cold enough for structure to form?

Toomre Q: Fight of gravity vs. pressure and centrifugal forces from rotation

\[ Q_{\text{star}} \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma} \]

- \( \sigma_R \): radial velocity dispersion
- \( \kappa \): epicyclic frequency
- \( \Sigma \): mass surface density

If \( Q \lesssim 1 \) gravity wins, structure can form
- Spiral arms
- Dense (star-forming?) gas clouds

\[ Q_{\text{gas}} \equiv \frac{c_s \Omega}{\pi G \Sigma} \]

- \( c_s \): sound speed \( \sim \sigma = \) velocity dispersion
- \( \Omega \): angular frequency
- \( \Sigma \): mass surface density
\[
Q_{\text{gas}} \equiv \frac{c_s \Omega}{\pi G \Sigma_{\text{gas}}} = \Sigma_{\text{crit}} / \Sigma_{\text{gas}}
\]

- If \( \Sigma_{\text{gas}} > \Sigma_{\text{crit}} \) (Q<1) then gravity wins! gas disk is unstable to perturbation, gas clouds start to collapse, SF may occur.

SFR depends on local value of Q:
- If \( \Sigma_{\text{gas}} > \Sigma_{\text{crit}} \) (Q<1) SF occurs and \( \Sigma_{\text{SFR}} \sim \Sigma_{\text{gas}}^N \); N=1-1.5
- If \( \Sigma_{\text{gas}} < \Sigma_{\text{crit}} \) (Q>1) large scale gravitational instabilities are suppressed although SF may occur by other mechanisms (with lower efficiency)
$\Sigma_{\text{gas}}, \Sigma_{\text{crit}}$, and $Q$ versus radius in disk of spiral NGC 6946

$Q^{-1} = \frac{\Sigma_g}{\Sigma_c}$

$Q$ becomes larger than $\sim 1$ at radius $R_{\text{HII}}$ where star formation starts becoming much less intense.

$Q \sim 1$ over most of star-forming disk, suggesting that gravitational instabilities are of fundamental importance in governing star formation in galaxy disks.
Q helps regulate SF in disks

\[ \Sigma_{\text{gas}} \text{ is close to } \Sigma_{\text{crit}} \text{ (i.e., } Q \sim 1) \text{ over much of the disk in many galaxies} \]

\[ \rightarrow \text{This indicates that large-scale gravitational instabilities are important in governing star formation in galaxy disks} \]

How this works:

- Gas becomes unstable \((Q < 1)\) so star formation starts
- Energy from massive stars (feedback) increases velocity dispersion (and therefore \(Q\)) of gas until star formation nearly stops
- If SF stops, velocity dispersion of gas may decreases until \(Q\) reaches \(\sim 1\) again
- \(Q \sim 1\) is balance point between ongoing gravitational collapse and energetic feedback (which increases velocity dispersion)
Does star formation occur in the extended HI disks of galaxies?

HI-rich outer disk of spiral M83

Park et al. 2002 -- HI Rogues Gallery
UV from recent star formation in outer disk of M83

Hα seems to show cutoff, but no cutoff in UV!
Although SF occurring, UV drops off with radius much more rapidly than $\Sigma_{\text{gas}}$
Extended UV disks of spirals

~30% of nearby spirals have extended UV disks (XUVs)

If episodic, fraction of galaxies that experience this could be larger

Natural part of inside-out galaxy growth, possibly due to accretion

Thilker et al. 2007
Why is $\text{H}\alpha$/FUV sometimes low in regions of low SFR and low SFR-density?

RED: $\text{H}\alpha$  BLUE: FUV
Goddard et al. 2010
Why is Hα/FUV sometimes low in regions of low SFR and low SFR-density?

Not well understood, but some possibilities:

- **IGIMF (integrated galactic IMF)** – IMF is different -- deficit of massive stars in star-forming gas clouds of lower mass -- not enough mass available in gas cloud to make largest stars)(Hα traces higher stellar masses than FUV)

- **Temporal variations in SFRs** -- Hα traces SFR over shorter time (10⁷ yr) than FUV (10⁸ yr)

RED: Hα  BLUE: FUV
Goddard et al 2010
Lyman continuum photon rate

\[ N_{\text{Ly}}(\text{tot}) = \dot{N}(>10 \ M_{\odot}) \int_{10}^{M_u} \frac{\Psi(M) \ N_{\text{Ly}}(M) \ \tau_{\text{MS}}(M) \ dM}{\int_{10}^{M_u} \Psi(M) \ dM} \]

where:

- \( N_{\text{Ly}}(\text{tot}) \) = total # Lyman continuum photons from galaxy
- \( \dot{N}(>10 \ M_{\odot}) \) = stellar birthrate (stars born per year) for stars with \( M>10 \ M_{\odot} \) (only ones that emit LyC photons)
- \( N(M) = \int_{M_1}^{M_2} \Psi(M) \ dM \) #stars formed with masses between \( M_1 \) and \( M_2 \)
- \( \Psi(M) = dN/dM = \text{IMF} = \text{initial mass function} \)
- \( \Psi(M) = \text{# stars formed per unit mass interval} \)
- \( N_{\text{Ly}}(M) \) = Lyman continuum photon rate for star of mass \( M \)
- \( \tau_{\text{MS}}(M) \) = main sequence lifetime of star
- \( M_u \) = upper mass “cutoff” (most massive stars which form)
UV continuum (~125nm<\(\lambda\)<~280nm)

Advantages:

- Measures all MSF, including those which have escaped any surrounding gas & therefore don’t have HII regions (naked O stars)
- **Flux at 125-280nm sensitive to wider range of stellar masses than flux at \(\lambda<91.2\text{nm}\), therefore probes SF on longer timescale than LyC/H\(\alpha\) – 10^8 yr (UV) vs. 10^7 yr (H\(\alpha\))

Disadvantages:

- Dust extinction
- Must be done from space (for nearby galaxies)
outer disk FUV profiles generally steeper than HI profiles

Outer disks show range of HI + FUV radial profiles but FUV generally much steeper than HI profile \(\rightarrow\) outer disk star formation is inefficient
Inefficient star formation in outer disks

Gas depletion time is \(~2\) Gyr in main H\(_2\)-dominated part of spiral & dwarf disks, but is much longer (\(~20\)-100 Gyr) in outer disks where gas surface densities are low.
Inefficient star formation in outer disks: related to $Q>1$

$Q>1$ in outer disks where star formation is inefficient. Suggests a different mode of star formation from inner disk.

Bigiel et al 2010
Large-scale gravitational instabilities important but not decisive for presence of star formation

Many outer disks have $Q>1$ yet have some (inefficient) star formation

Things may happen *locally* to cause local gas overdensities resulting in collapse, e.g.,

- Gas compression by turbulence
- Gas compression by supernovae
- Extragalactic cloud impacts

So some star formation happens, but with lower efficiency (longer timescale) than in disk regions which are gravitationally unstable on large scales