Whittle : EXTRAGALACTIC ASTRONOMY

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11. STAR FORMATION & STARBURST GALAXIES

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(1) Introduction

First some preliminaries :

- Star Formation is an **important** and **widespread** phenomenon in the universe
  in Bill Keel's words, it is "**galaxy evolution caught in the act**"
  With this evolutionary perspective, one should distinguish between
  current star formation -- HII regions, OB associations, starbursts, etc
  past star formation -- which gave rise to the present day stellar population
  → the current stellar mix is defined by the **history of star formation**

- There is an enormous (10^7) **range** in galaxy star formation rates : 10^{-4} - 10^{3} $M_\odot$ yr^{-1}
  Loosely, we divide this range into two regimes :
  (i) **normal galaxies** (≈75% of local SF) have SFRs : 0 - few $M_\odot$ yr^{-1} [fig 1 from K98]
  note: integrated galaxy spectra ≈varying mix of A-F V (<1 Gyr) and G-K III (3 - 15 Gyr)
  (ii) **starburst galaxies** (≈25% of local SF) range from :
  few $M_\odot$ yr^{-1} (SB) → ≈50 $M_\odot$ yr^{-1}(LIGs) → 10^{2-3} $M_\odot$ yr^{-1} (ULIGs)

- We must also distinguish between two rather different **locations** for SF :
  (i) **galaxy disks** -- predominantly **normal** SF
  (ii) **near galaxy nuclei** (circumnuclear, C-Nuc) -- both normal and starburst SF
  Note : high luminosity C-Nuc SF is qualitatively different from Disk SF.

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(2) Definitions and Abbreviations

SF	Star Formation
SFR	Star Formation Rate, in $M_\odot$ yr^{-1}
Σ_{SFR}	surface SFR rate, in $M_\odot$ yr^{-1}kpc^{-2}
Σ_{gas}	surface density of gas, in $M_\odot$ pc^{-2}
SF-History	time dependence of SFR (eg declining exponential; burst; constant; etc)

C-Nuc	Circumnuclear $\lesssim$100 - 1000 pc
IRAS	Infrared Astronomical Satellite (1983): S_{12} etc = fluxes at 12; 25; 60; 100 μ (in Jy)
PSC & FSC	Point (& Faint) Source Catalogs from IRAS all sky survey
FIR	Far-Infrared : $\approx$40 - 500 microns, depends on usage
NIR & Mid-IR	Near-IR (1-5μ) & Mid-IR (5-20μ)
FUV & NUV	Far (ionizing) UV & Near (1500-2800) UV
F_{FIR}	FIR flux (40 - 500μ) = $1.26\times10^{-14}(2.58S_{60} + S_{100})$ W m^{-2}
F_{IR}	IR flux (8 - 1000μ) = $1.8\times10^{-14}(13.5S_{12} + 5.2S_{25} + 2.58S_{60} + S_{100})$ W m^{-2}
L_{FIR} & L_{IR}	Luminosities corresponding to F_{FIR} & F_{IR}
L_{cm}	Radio luminosity at cm wavelengths (eg 5 GHz), mostly synchrotron
CR	Cosmic Rays associated with synchrotron radio emission
SN & SNR	Supernova & Supernova Remnant
SB	Starburst
LIG	Luminous Infrared Galaxy ($L_{FIR} > 10^{11}L_{\odot}$)
ULIG	Ultra-Luminous Infrared Galaxy ($L_{FIR} > 10^{12}L_{\odot}$)
LINER	Low Ionization Nuclear Emission Line Region (low luminosity AGN)
EW(Ha)	Equivalent width of Ha = f(Ha) / f_{λ}(cont) Angstroms
IMF	Initial Mass Function, usually PL : $N(M) \propto M^{-x}$ (eg x = 2.35 = Salpeter IMF)
M_{low} & M_{up}	lower and upper mass cut-off for the IMF

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(3) Emission From Star Formation Regions

(a) Relevant Observables

Star formation yields an IMF with high mass stars dominating the luminosity
These yield, directly or indirectly, to a wide range of emission [image]

- **UV flux** : high mass stars dominate UV luminosity → visible if non-dusty
- **Hα flux** : B0 and hotter create ionizing flux <912 A → 1 ionizing photon = 1 ionized H atom
  Photoionization rate ($Q_H = dN_{ion}$ / dt s^{-1}) balances recombination rate ($3\times10^{-13}n_e^2V$ s^{-1})
  (n_e = electron density; V = total volume; 3×10^{-13} = recombination coeff at T = 10^4K)
  1 in 4 recombinations yield an Hα photon → $L_{H\alpha} = 1.3\times10^{-12}Q_H$ erg/s
- **Radio free-free flux** : ionized gas also radiates free-free (Bremmstrahlung) at $\approx$ 5 GHz
  L_{ν} (erg/s/Hz) = $7.3\times10^{-39}n_e^2V = 2.4\times10^{-26}Q_H$ (at 10^4K)
- **FIR flux** : dust absorbs UV very efficiently, reradiates in FIR (20-200μ; T_D = 15-30K)
  hence, IRAS selected galaxies often have high star formation rates
  L_{FIR} is acting like a **bolometer**

  Only the most massive stars are relevant and, for single stars, we have :

Star	Mass	Log Q_H	Log $L_{\nu ff}$	Log $L_{H\alpha}$	Log L_{bol}
O5	40	50.0	24.4	38.1	39.0
B0	16	48.7	23.1	36.8	38.0
A0	4	42.7	17.1	30.8	35.5

- **Radio Synchrotron flux** : most radio emission is from diffuse cosmic rays
  (MW CRs are detected striking our upper atmosphere)
  the CRs are generated in SNR shocks; they diffuse out into the galaxy (which holds 99%)
  Despite rather indirect link to SFR -- L_{cm} is well correlated with other SFR diagnostics (viewgraphs)

- **CO and HI flux** : molecular and atomic emission (CO acting for H_2; 21cm from HI) traces the gas component immediately prior to SF

(b) Empirical Relations

Many correlations of various strengths support the above picture :

Good correlations include : $L_{H\alpha}$ vs L_{FIR} vs L_{cm} (viewgraphs)
Less good correlations include : $L_{H\alpha}$ vs colors vs L_{CO} (viewgraphs)

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(4) Measurements of Current SFR

- Almost **all** the above observables depend on **high mass stars**
  these are a **transient** population, and so track **current** SFR

- Lower mass stars contribute essentially **nothing** to these observables
  however, these low mass stars **dominate** the mass and should not be forgotten!

(a) Synthesis Models to Calibrate SFR Relations

To calibrate the SFR (in $M_\odot\ yr^{-1}$) we need **synthesis models** (eg refs) :

- evaluate evolutionary tracks → L_{bol} & T_e & R_* as functions of Mass and Age
- add stellar atmospheres (T_e & g) → spectra (or UBV etc)
- Sum over an IMF → isochrone spectrum (or UBV)
- Sum over a chosen star formation history → current spectrum

Free parameters : SF-History; IMF; Metallicity.
in practice, main parameters are : burst age and/or e-folding decay; plus fraction of old pop

(b) Conversion Relations to find SFR

(i) Near-UV (1500 - 2800) Luminosity

hot high mass young stars dominate the NUV emission, yielding :

$$\mathrm{SFR}\ \ (M_\odot\ yr^{-1}) \ = \ 1.4\times10^{-28}\, L_{NUV}\ \ (erg\ s^{-1} Hz^{-1})$$

strengths : for moderate-strong SFR, very little contamination from non-SB stars;

useful for high-z galaxies (where UV is redshifted into optical)
weaknesses : sensitive to IMF and to dust

(ii) Hα Luminosity

In principle this applies to other recombination lines : eg Brγ & Paα & H109 etc
Significant ionizing radiation only comes from stars with $M > 10M_\odot$
lifetime of these stars is < 20 Myr → Hα measures **current** SFR

$$\begin{aligned}\mathrm{SFR}\ \ (M_\odot\ yr^{-1}) \ &= \ 7.9\times10^{-42}\, L_{H\alpha}\ \ (erg\ s^{-1})\\ &= \ 8.2\times10^{-40}\, L_{Br\gamma}\ \ (erg\ s^{-1})\end{aligned}$$

$$= 1.1\times10^{-53}\,Q_H \quad (s^{-1})$$

<u>strengths</u> : sensitive; direct; high spatial resolution; useful out to $z \lesssim 2$

<u>weaknesses</u> : sensitive to reddening (typical $A_{H\alpha} \approx 0.5 - 1.5$ mags), IMF slope and M_{up}

5 - 50% of the ionizing radiation **escapes** the HII regions
→ must include Hα from the **diffuse ionized medium** (DIM) emission
(only ≈3% ionizing flux escapes the **galaxy**)

at higher z (when Hα too redshifted), a less precise relation is :

$$\mathrm{SFR}\quad (M_\odot\,yr^{-1}) \;=\; 1.4\pm0.4\times10^{-41} L_{[OII]\lambda3727} \quad (erg\ s^{-1})$$

(iii) Equivalent Width : EW(Hα)

Recall EW(Hα) measures the **relative** strength of Hα to the continuum under the line
It therefore acts like a long baseline color index UV(Hα) ↔ λ6550 A
Although it cannot be converted to a current SFR, it has another important use :
It measures the ratio of the current SFR (from Hα) to the integrated past SF (from the continuum)
Using synthesis models, this relation can be **quantified**, to give :
EW(Hα) → (current SFR) / (mean past SFR) ; written SFR/<SFR> or "b"

(iv) FIR Luminosity

For Starbursts, where SF dominates the FIR emission, we have :

$$\mathrm{SFR}\quad (M_\odot\,yr^{-1}) \;=\; 4.5\times10^{-44}\,L_{IR}\,(8 - 1000\mu) \quad (erg\ s^{-1})$$

Unfortunately, FIR can contain **two other** components :

- **cirrus** : diffuse emission @ ≈100μ from dust warmed by **normal optical starlight**
  this may dominate in E, S0, Sa, Sab → so FIR is **not** good SFR measure for these early types
  However, for Sb and later, we have a rough relation :

  $$\mathrm{SFR}\quad (M_\odot\,yr^{-1}) \;=\; 8(+8/-3)\times10^{-44}\,L_{IR}\,(8 - 1000\mu) \quad (erg\ s^{-1})$$

- **AGN** : important in Seyferts & many ULIGS
  AGN generates hotter dust, so spectrum is "warmer" (eg fig 2 SM 96)
  eg $S_{25}/S_{60} > 3$ &/or $S_{60}/S_{100} > ??$

(v) Radio Free-Free Luminosity

$$\mathrm{SFR}\quad (M_\odot\,yr^{-1}) \;=\; 4.3\times10^{-28}\,L_{\nu ff} \quad (erg\ s^{-1}Hz^{-1}\ @\ 5\ GHz)$$

<u>strengths</u> : direct link to HII regions (like Hα); zero reddening

<u>weaknesses</u> : usually weak w.r.t. synchrotron; requires separation using spectral indices.

(vi) Radio Synchrotron Luminosity

This **cannot** be calibrated **directly** because of the uncertainties of SNR & CR production
not to mention the synchrotron efficiencies
One could use the L_{cm} vs $L_{H\alpha}$ or L_{cm} vs L_{FIR} correlations to derive an SFR vs L_{cm} relation
but it would not be an independent relation.

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(5) Factors Affecting the SFR

(a) Preliminaries

It is clearly important to understand the origin of the enormous spread in SFRs found amongst galaxies.

Before considering the various factors, there are a few preliminaries :

- Recall, there are **two significantly different** regions to consider
  Both/either/neither can be significant
  - Galaxy Disks
  - Galaxy Circum-Nuclear Regions (C-Nuc)
    (the latter includes both "normal" and "starburst" phenomena)

  To a large extent, star formation is **decoupled** between these two regions

- Depending on the type of observations, measurements may refer to disk; C-Nuc; or both
  eg :
  - IRAS fluxes are usually integrated, except for the nearest galaxies
    (eg BGS; FPSC...)
  - small aperture spectoscopy yields C-Nuc fluxes
    (eg Stauffer '82; Keel '83; Ho et al '87)
  - wide aperture spectrophotometry yields integrated fluxes
    (eg Hα measurements of Kennicutt & Kent '83; Romanishin '94)

- Several measures of SFR are useful :
  - direct SFR, in $M_{\odot}$ yr^{-1}
  - surface density of SFR : Σ_{SFR}, measured in $M_{\odot}$ yr^{-1} kpc^{-2}
  - relative SFR = (current SFR)/(mean SFR in past); where a continuum flux measures <SFR>
    eg EW(Hα) = f(Hα) / f$_{\lambda}$(cont) Angstroms; or L_{FIR} / $L_{1\mu m}$
    Synthesis models convert these to a quantitative measure : b = SFR/<SFR>

- Results can depend on the sample selection method, eg :
  - Optical selection usually includes low to moderate SFRs (eg NGC galaxies)
  - UV selection usually includes moderate SFRs (eg Markarian galaxies)
  - FIR selection usually includes moderate to high SFRs (eg IRAS galaxies)

(b) Hubble Type

(i) Integrated SF

- Loosely speaking, there is a strong dependency of SFR on Hubble type, with significant scatter :
  eg $\lesssim 10^{-2}$ $M_{\odot}$ yr^{-1} for S0; up to 20 $_{\odot}$ yr^{-1} for gas rich spirals
  (on up to 1000 $_{\odot}$ yr^{-1} for merging starbursts with Hubble type "pec")

  Eg Fig 4 from K98 shows the FIR / H band luminosity for nearby galaxies
  (note: cirrus contributes to the early types, **reducing** the apparent trend with SFR)

(ii) Disk SF

- A purer measure of relative SFR is EW(Ha), shown in Fig 3 from K98 for nearby galaxies
  (while EW(Ha) is integrated, in this sample, disk emission dominates)
- There is a strong trend with considerable scatter : SFR/<SFR> increases by ×10 from Sa to Sc
  (<EW> = 3 - 30A or SFR = 0.2 - 2 $M_{\odot}$ yr^{-1} for an L^* galaxy)
- This increase is due to two factors :
  - more HII region complexes
  - more luminous HII region complexes
    for Sa : HII cluster has a few OB stars
    for Sc : HII cluster has few **hundred** OB stars (see figure of NGC 604 in M33)
- Now consider the **quantitative** values of b = SFR / <SFR> (RHS of figure) :
  for Sa : <b> $\approx$ 0.1 while for Sc : <b> $\approx$ 1
  $\rightarrow$ SFRs in Sa disks were significantly **higher** in the past
  $\rightarrow$ SFRs in Sc disks have been roughly **constant** over cosmic history
- Although the **actual** SFR-Histories may be complex, figure 8 from K98 shows simple exponentials consistent with these numbers
  (in the heirarchical merger picture, these smooth trends would be punctuated by merger induced spikes)

As a function of redshift, we expect :
z = 0 (locally) : most SF is in late type disks
z = 1 : SF is equally spread along the Hubble sequence Sa - Sb - Sc
z > 1 : present day Sa galaxies increasingly **dominate** the SFRs
Note, however, the Madau peak at $z \approx 1$-2 is **not** represented here (mergers probably important)

(iii) C-Nuc SF

- As for disk emission, there is a **wide range** $\approx 10^{-4}$- 10^{2} $M_{\odot}$ yr^{-1} (mean 0.1; median 0.02)
- Detection/classification of C-Nuc HII emission **increases** along the Hubble sequence :
  0% E; 8% S0; 22% Sa; 51% Sb; 80% Sc-Im (viewgraph from Ho et al 97)
  (but overestimates trend since LINER/AGN emission may mask HII emission in eary types)
- However, C-Nuc SFRs **decrease** down the Hubble sequence :
  most **nuclear** SF comes from early types (despite lower frequency)
  in early types, C-Nuc SFR often similar/surpasses disk emission
- Overall, **not** a clear Type dependence of C-Nuc SFR
- C-Nuc $\langle EW(H\alpha) \rangle \approx 3$ - 30 A $\approx \langle EW(H\alpha) \rangle$ for Sc disks
  → SFR/<SFR> ≈ 1 → SF-History ≈ constant interspersed by bursts (see below)

(c) Arm Structure

Dividing galaxies into Grand Design and Flocculant :

- **No difference**, statistically, in SFRs, for either Disk or C-Nuc
  → density waves are not themselves responsible for variation in SFR
- However, Grand Design Arms have higher **SFR contrast** than Arms in flocculants

(d) Bars

(i) Disk SF

There is **little/no dependence** of disk SFR on presence/absense of bar (Fig 3 in K98)

(ii) C-Nuc SF

- HII detection/classification is **independent** of Bar
- However, **mean** SFR is significantly **higher** in barred galaxies
  tail in SFR distribution out to 0.2 - 8 $M_{\odot}$ yr^{-1} (absent in unbarred galaxies)
  especially true in **early types**, eg ≈30% of SB0/a - SBb galaxies are in this tail.
- Bars are effective at transporting gas to the nuclear regions
  especially in large bars, as found typically in early types

(e) Interactions

Overall, interactions have a **dramatic impact** on star formation rates

(i) Disk SF

- On average, interacting galaxies have disk SFRs ×2-3 higher than isolated galaxies
- However, the effect is very variable :
  gas poor galaxies show ≈no enhancement
  in extreme cases the SFR is ×10-100 higher

(ii) C-Nuc SF

- even stronger effect than disks : mean enhancement ×3-4 in interacting galaxies
- at higher luminosities (LIGs & ULIGs) interactions are clearly important :
  $L_{IR} < 10^{10} L_{\odot}$ (<1 $M_{\odot}$ yr^{-1}) 20 - 30% are interacting (75% of remainder have strong bars)
  $L_{IR} > 10^{12} L_{\odot}$ (>100 $M_{\odot}$ yr^{-1}) 70 - 95% are interacting/merging

(iii) Physical Effects of Tidal Interaction

- At low level of tidal interaction, we may have :
  -- induced density wave
  -- induced bar which removes AM from gas
  -- orbit crossing → cloud-cloud collisions
  -- modified rotation curve → drops Q → disk unstable
- For stronger interactions and mergers :
  -- star distributions drain AM from gas (Topic 12)
  -- cloud collisions due to interpenetrating galaxies
  -- gas falls into E-S0 galaxies → nuclear gas disk → SF

(f) Gas Surface Density

It is useful to consider properties expressed **per unit area**
eg Σ_{SFR} in $M_\odot\,yr^{-1}kpc^{-2}$ and Σ_{gas} in $M_\odot\,pc^{-2}$.

(i) Disk SF

- Fig 5 from K98 shows Σ_{SFR} vs Σ_{gas} for **normal galaxy disks**
  There is a clear trend for SFR to **increase** with surface gas density
- The trend holds **within a given Hubble type** (symbols divide sample by type)
  this accounts for some of the scatter in the EW(Hα) vs Type plot
- Expressed as an efficiency, ϵ in % per 10^8yr, there is a **large range**
  → 1-30% per 10^8yr
- Roughly, for disks with gas mass fraction 20%, $<\epsilon>$ 5% per 10^8yr
  → 1% stellar disk added per 10^8 → stellar disk constructed in a Hubble time

(ii) C-Nuc SF

C-Nuc SF often occurs within dense gas disks, 100-1000pc in size
In these disks, $\Sigma_{gas} \approx 10^2\text{-}10^4\ M_\odot pc^{-2}$, comparable to the cores of disk DMCs (eg 30 Doradus <10pc) but extended over 1 kpc
These gas densities are **much** higher than in normal disks (by factors $10\text{-}10^3$)

- Fig 7 from K98 shows Σ_{SFR} vs Σ_{gas} for C-Nuc **starbursts**
  the correlations persists even at these higher rates
- In fact, not only is there more SF because there is more gas,
  but the **efficiency** is higher than in disks by factors 2-30

(iii) Schmidt Law

A relationship between surface density and star formation rate was postulated by Schmidt (1959)

- Fig 9 from K98 (LHS) shows the combined sample of galaxy disks and C-Nuc disks
  There is a single Schmidt law spanning 6 decades :
  $\Sigma_{SFR}\ (M_\odot\,yr^{-1}kpc^{-2}) = 2.5\pm0.7\times10^{-7}\ \Sigma_{gas}^{1.4\pm0.15}\ (M_\odot\,pc^{-2})$
- We naively expect a PL index of 1.5 :
  SFR $\propto$ (gas density)/(free fall time) $\propto \rho/\rho^{-1/2} \propto \rho^{1.5}$
- We can consider the SFR **per orbit** ($\Sigma_{SFR}\times P_{rot}$) by plotting Σ_{SFR} vs Σ_{gas}/P_{rot}
  where P_{rot} is the orbital period at ½ R_{outer} (see RHS of Fig 9 from K98)
- Remarkably, we obtain a graph of gradient unity
  → for all systems, ≈10% gas is converted to stars per orbit
  $\Sigma_{SFR} = 0.017\ \Sigma_{gas}\,\Omega_{gas}$
- This allows two alternative view of why LIGs and ULIGs are so **efficient** :
  - due to higher densities :
    efficiency $\propto \Sigma_{SFR}/\Sigma_{gas} \propto \Sigma_{gas}^{0.4}$
    since Σ_{gas} is $10^2\text{-}10^3$ higher than disks → efficiency is ≈5-50 times higher
  - due to shorter timescales :
    efficiency = $\Sigma_{SFR}/\Sigma_{gas} = 0.017\ \Omega_{gas}$ which is independent of Σ_{gas}
    since ≈10% gas goes into SF per orbit, the higher efficiencies simply reflect shorter orbital times for the ULIG gas

- The Schmidt law fails at low SFRs, below a critical threshold (see 11.6 below)

(iv) Consumption Timescales

- Returning to Fig 5 and Fig 7 from K98, we can reinterpret the three efficiency lines in terms of **gas depletion times**
  100%   10%   1%   SFR efficiencies per 10^8yr correspond to
  10^8yr 10^9yr 10^{10}yr   depletion timescales
  for the mean of ≈5%, the mean depletion timescale is ≈2Gyr
- For the longer times, these are **underestimates** because gas can be **replenished** from stellar has loss and from infall
- The starburst LIG and ULIGs have **much shorter** depletion timescales : 1-10×10^8yr
  The maximum SFR arises from 100% conversion in a dynamical time ($P_{rot} = P_{free\ fall}$) :
  $SFR_{max} \approx 100\ M_\odot\ yr^{-1}\ M_{gas,10}\ P_{rot,8}^{-1}$ with corresponding :
  $L_{max} \approx 7\times10^{11}\ L_\odot M_{gas,10}\ P_{rot,8}^{-1}$
- Fig 6 from K98 shows L_{FIR} vs H_2 mass for LIGs (open circles) and ULIGs (filled circles)
  the points lie between the solid line for normal MW galaxies, and the dashed line for SFR_{max} for $P_{free\ fall} = 10^8$yr.
  → the most powerful ULIGs are converting $10^{10}\ M_\odot$ gas into stars on a dynamical timescale
  This can only occur during :
  - violent interaction/mergers
    eg entire ISM of galaxy driven into nucleus & converted into stars over 10^8yrs
  - initial collapse of protogalaxy
    hence ULIGs may be thought of as local analogs to high z young forming galaxies

(g) Summary of Star Formation in Disks and Nuclei

Here is Table 1 from Kennicutt 1998 ARAA **36** 189 :

Property	Spiral disks	Circumnuclear regions (including starbursts)
Radius	1–30 kpc	0.2–2 kpc
Star formation rate (SFR)	0–20 $M_\odot yr^{-1}$	0–1000 $M_\odot\ yr^{-1}$
Bolometric luminosity	10^6–10^{11} $M_\odot$	10^6–10^{13} $M_\odot$
Gas mass	10^8–10^{11} $M_\odot$	10^6–10^{11} $M_\odot$
Star formation time scale	1–50 Gyr	0.1–1 Gyr
Gas density	1–100 $M_\odot\ pc^{-2}$	10^2–10^5 $M_\odot\ pc^{-2}$
Optical depth (0.5 μm)	0–2	1–1000
SFR density	0–0.1 $M_\odot yr^{-1}\ kpc^{-2}$	1–1000 $M_\odot\ yr^{-1}\ kpc^{-2}$
Dominant mode	steady state	steady state + burst
Type dependence	strong	weak/none
Bar dependence	weak/none	strong
Spiral structure dependence	weak/none	weak/none
Interactions dependence	moderate	strong
Cluster dependence	moderate/weak	moderate
Redshift dependence	strong	?

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(6) SF Threshold & Toomre's Q Parameter

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(7) Starburst Galaxies

(a) Overview

- Three examples with decreasing luminosity:
  Arp 220 is the nearest ULIRG.
  The Antennae an interacting luminous starburst.
  M 82 is a nearby lower luminosity Starburst.
  Henize 2-10 is a nearby dwarf starburst galaxy.

- Although there is no formal definition of Starbursts, two aspects are key :
  -- **intense** SF which dominates the integrated luminosity
  -- **short burst** → gas depletion $\lesssim 10^8$yrs << age of galaxy

- other characteristics include :
  -- often nuclear location $\lesssim$100-1000pc
  -- fueled by central accumulation of dense molecular gas
  -- SFR significantly higher than in galaxy disks (by $\approx 10^3$)
  MW : SFR $\approx 1\ M_\odot\ yr^{-1}$ over entire disk → $\Sigma_{SFR} \approx 0.01\ M_\odot\ yr^{-1} kpc^{-2}$
  SB : SFR $\approx 10\ M_\odot\ yr^{-1}$ within 500pc → $\Sigma_{SFR} \approx 10\ M_\odot\ yr^{-1} kpc^{-2}$
  -- Locally, 25% SF occurs in SBs (75% occurs in spiral disks)
  -- at higher z this fraction increases

(b) Samples of SB galaxies

- Several methods have generated samples of SB galaxies
  - UV continuum (objective prism) surveys, eg Markarian
    these SBs tend to be low-moderate luminosity, less dusty galaxies
  - Emission line surveys (objective prism, or aperture), eg SBS, many redshift surveys
    again, these tend to find low-moderate luminosity, less dusty galaxies
    note : spectroscopy of magnitude limited sample gives a low yield of SBs
  - FIR (IRAS) survey yield many samples
    eg BGS (Bright Galaxy Sample, Soifer et al 89),
    1Jy ULIGs (Ultra Luminous Infrared Galaxy, Kim 95)
    These tend to have high luminosity and be quite dusty.

- Dust relates to metallicity :
  larger galaxies tend to be more metal rich, more dusty, more prone to FIR detection
  dwarf galaxies tend to be metal poor, less dusty, often detected by UV or emission lines
  Fig 4 from SM96 shows 10 ULIRGs from the BGS
  Fig 8 from SM96 shows 4 (U)LIRGs mergers with HI and CO contours superposed

(c) Luminosity Function

Fig 1 from SM96 shows the LF for starburst galaxies

- the overall form is **not** like the Schechter function
  it can be characterised by a double power law, slope $\lesssim$-1 below $10^{10.3} L_\odot$ and -2.35 above
- at low luminosities, SBs are much less common than normal galaxies
  (eg only a small fraction of RSA or RC3 galaxies are SBs)
- at higher luminosities (eg $L > 10^{11} L_\odot$) LIGs dominate over all other galaxy types
- at the highest luminosities (eg $L > 10^{12} L_\odot$) ULIGs are 2× more numerous than QSOs
  these are, of course, still quite rare : expect 1 within cz$\approx 10^4$km/s (find 1 : Arp 220 at cz=6000)
- Emission from LIGs and ULIGs makes up $\approx$6% of the FIR in the local universe.

(d) Spectral Energy Distributions (SEDs)

Fig 2 from SM96 shows 0.1-1000μ spectra for galaxies spanning a wide range in IR luminosity

- while IR fluxes go up by ×10^3, the optical fluxes only increase by ×3-4
  → ULIGs are not particularly luminous **optically**
- IR colors change as L_{IR} increases : S_{60}/S_{100} increases, S_{12}/S_{25} decreases
  overall, the emission is becoming dominated by a 60μ component at high L_{IR}
- **Different components** dominate at different luminosities :
  - Normal Galaxies
    100-200μ ($T_D \approx$20K) emission from cirrus heated by old population starlight
    10μ ($T_D \approx$200K) peak from small hot dust grains near hot stars
    (note these high temps are **non-eqlm** since grain thermal capacity < UV photon energy)
  - Seyferts
    include a "warm" component @ ≈25μ ($T_D \approx$150-200K) heated by the AGN
  - LIGs
    the starburst component at 60μ ($T_D \approx$30-60K) becomes increasingly strong
    some ULIGs also have an AGN which adds a 25μ component making the spectrum "warmer"
    (see inset in fig 2)

- Optical spectra allow classification by emission lines (see Topic 14)
  Fig 5 from SM96 shows the changing classifications at higher IR luminosities :
  the fraction of HII nuclei gradually drops as the fraction of Seyferts spectra increases
  the high nuclear gas content is either creating or feeding a nuclear black hole
  the fraction of LINERs is approximately constant

(e) Cause of Starbursts

- Without a doubt, interactions & mergers play a crucial role in triggering luminous SBs
  A nice example : M81/M82/NGC3077, (cf interaction more evident in HI)
  (the M82 starburst was triggered 600 Myr ago near closest approach)
- furthermore, the most strongly interacting tend also to be the most luminous
  Table 3 from Sanders & Mirabel 1996 ARAA **34** 749 shows these trends nicely :

		Luminosity Ranges : Log $L_{IR}/L_\odot$			
		10.5–10.99	11.0–11.49	11.5–11.99	12.0–12.50
No. of objects[a]		50	50	30	40
Morphology	merger	12%	32%	66%	95%
	close pair	21%	36%	14%	0%
	single (?)	67%	32%	20%	5%
Separation[b]	[kpc]	36.	27.	6.4	1.2
Opt Spectra	Seyfert 1 or 2	7%	10%	17%	34%
	LINER	28%	32%	34%	38%
	H II	65%	58%	49%	28%
L_{IR}/L_B[c]		1	5	13	25
L_{IR}/L_{CO}[c]	[$L_\odot$ (K km $s^{-1}pc^2)^{-1}$]	37	78	122	230

[a] Objects in the *IRAS* BGS plus additional ULIGs from Kim & Sanders (1996)
[b] Mean projected separation of nuclei for mergers and close pairs only.
[c] Mean values.

  - Less Luminous SBs :
    often milder interactions; pairs at larger separation;
    lower fraction interacting, although remainder have strong bars
  - ULIGs :
    high fraction of strong mergers; close double nuclei; progenitors probably gas rich spirals
    (See fig 8 from SM96 for examples)
    $\approx 10^{10} M_\odot$ gas (eg MW ISM) goes to center $\approx 10^{2\text{-}3}$pc → SF (+AGN) yields $\approx 10^{12} L_\odot$
- In all these cases, the interactions (and bars) result in the loss of AM from the gas
  (see Topic 12 for a more complete discussion of this process)
- **Dwarf** starbursts (eg BCDs) do **not** seem to involve interactions
  it is currently unclear what the trigger mechanisms are in these cases :
  possibilities include :
    self-propagating star formation
    widespread instability (many BCDs hardly rotate, hence Q is very low)

(f) Compact Super-Star Clusters

Star formation is **not** uniform in starburst galaxies: It occurs in **compact star clusters**
consider M82 as example:

- HST sees ≈100 clusters (maybe ×20-40 more hidden)
  They reside in the central few 100 pc, each of size ≈3pc & luminosity $\approx 10^6 L_\odot$
  They have a power law luminosity distribution, and ages ≈600 Myr (matching time since last encounter)
  This HST image shows some of the clusters (in V and NIR)

- Similar young blue super star clusters are ofen seen in merging galaxies
  Examples : Antennae fig A, fig B, NGC 5253, NGC 1569

- They are **larger** than any MW star formation region (eg 30 Doradus) with M_V = -8 to -14

- These clusters are therefore similar to **forming globular clusters**
  → maybe MW globulars were formed this way during early galaxy assembly
  → lower mass clusters are destroyed by evaporation/disruption to leave the present (Log Gauss) distribution

(g) Galactic Scale Superwinds

What is the effect of all this energy release on the ISM of the starburst galaxy ?

(i) Sketch of Physical Mechanisms

- The principle **energy source** entering the ISM is from winds and supernovae
  Their relative contributions are 1:3, so SNe dominate
  Typical rates in SB galaxies are ≈1 per 10-20 yrs (few million per burst)
  The average KE input rate is ≈1% L_{bol}

- This energy dumped goes through a number of transformations :
  KE from SN explosion → thermalised in shocks → hot gas expanding
  SNRs overlap → superbubble which expands at ≈100 km/s

- This expanding shock/shell initially decelerates and is Rayleigh-Taylor (RT) stable
  The superbubble tends to expand perpendicular to the disk (lowest pressure gradient)
  When the bubble reaches a few scale heights, it accelerates and becomes RT unstable

- The shell breaks up into a poorly collimated bipolar flow, or **superwind**
  The wind has terminal velocity ≈1-few 1000 km/s
  It also incorporates colder ISM gas by turbulent entrainment &/or conductive evaporation

- Thus, hot, warm, cold (and relativistic) components are **advected** up into the galaxy halo
  in a loosely biconical outflowing wind.

See Images from Simulations.

(ii) Observational Signatures

The most well studies examples include: M82, NGC 253; NGC 3079; NGC 1482

- Hα images show bi-conical filaments
- Long slit spectroscopy shows line-splitting indicating an expanding shell
  Velocities for this warm (10^4K) component are $\approx 10^2$-10^3 km/s

- Significant quantities of neutral gas (eg NaI D, OI, CII lines) can be seen in absorption
  Blueshifts unambiguously indicate outflow

- Hot (3-10×10^6K) X-ray emission is seen $\approx$10-30 kpc along the minor axis

- Low surface brightness radio synchrotron is seen above and below the disk

- FUSE has detected $\approx 10^{5\text{-}6}$K gas via absorption of the OVIλ1035 doublet
  This (and the X-ray luminosities) show the superwind does not suffer significant radiative losses

(iii) Global Characteristics

- The above observations have yielded estimates of the total rates of mass and energy loss carried out by the superwind
  They **match the SFR conversion and energy deposition rates of the nuclear starburst**
  The wind is clearly driven by the nuclear starburst

- The threshold SFR which can drive a superwind is **not very high**
  approximately, $\Sigma_{SFR} \gtrsim 0.1\ M_\odot\ yr^{-1} kpc^{-2}$ seems to be the threshold (less for dwarf galaxies)
  This is only about 10× that of the MW disk
  (cf galactic fountains are, of course, related lower power phenomena --- see Topic 9)

- Similar phenomena have been seen in high-z galaxies
  UV absorption line blueshifts indicate outflowing superwinds

(h) Cosmological Implications of Starbursts

- Although starbursts only account for 25% of current star formation, in the past this fraction was probably much higher
  → most current epoch stars may have formed in starbursts
  for this (and other reasons, see below) starbursts are **cosmologically very important**

(i) Possible Importance of Superwinds

- Superwinds carry enriched gas into the galaxy halo and possibly beyond
  This has several consequences :
  - Narrow metal line absorption systems in QSO spectra originate in the halos of young(ish) galaxies [image]
    This halo gas is clearly quite metal rich --- how come?
    Starburst driven winds are likely the main pollutant

  - Galaxy clusters contain a massive metal rich ICM
    The ICM contains as many metals as all the stars in all the cluster galaxies
    Abundance analysis suggests the metals were generated by Type II (core collapse) SN
    → the ICM and its metals probably originated from starburst driven superwinds.

  - The metallicity vs mass relation in spheroidal galaxies seems ubiquitous and fundamental
    again, enriched SB driven winds can explain this relation
    gas is lost more easily from lower mass galaxies
    recall (Topic 7) that the correlation can be recast as metallicity vs escape velocity
- at temperatures of 1-10×10^6K, the ICM contains a huge quantity of thermal energy
  there has been some discussion as to where this energy originated
  clearly, superwinds may be the answer --- the energy budget works out fine

- superwinds may also clear out a path for UV ionizing radiation to escape from the center
  this UV flux may contribute to the UV background, especially at high-z
  obviously, QSOs also contribute, but SBs may also be important
  the UV background is important since it is responsible for ionizing the IGM

(ii) Starbursts at low and high z

- Starbursts provide 25% of the local star formation (75% in spiral disks)
  they also provide ≈10% L_{bol} in the local universe
- these fractions are probably simliar out to $z \approx 1$
- at higher z, it seems **many galaxies** resemble SBs (see MDS galaxies)
  at z>2, UV, V, FIR are redshifted to V, K, sub-mm and are now observationally accessible
  the "UV" selected galaxies at high z resemble local UV SBs :
  - same Σ_{SFR}; same colors; same spectra
  - however, SF regions are **larger** → few $\times 10^2\ M_{\odot}\ yr^{-1}$ over a few kpc
- clearly, local SBs seem to provide close analogs to many high-z galaxies

(i) Starburst Relics

- Since starbursts are, by definition, short lived, we expect to find evidence of "past starburst" relics
  What might they look like ?
- E+A galaxies are in the post-starburst phase, with A stars still present but no current SF.
- As the A-type spectra fades, the last Balmer line to disappear is $H\delta\ \lambda 4101$
  → strong $H\delta$ may signify a slightly older SB relic
- Kinematically decoupled cores (KDCs -- Topic 7) are often found in E and S0 galaxies
  Rotation suggests they formed from a nuclear gas disk → a starburst
  Since KDCs usually have old population colors, the SB event was probably $\gtrsim 5$ Gyr ago

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