# Class 10: Galactic-scale star formation rates: observations ASTR 4008 / 8008, Semester 2, 2020

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## Outine

- Prelude: history of the field and the technology
- Whole-galaxy star formation rates 0
  - Local galaxies
  - High-redshift galaxies
  - Low surface-brightness galaxies
- Spatially-resolved star formation rates
  - Local depletion times and efficiencies
  - Phase- and metallicity-dependence
  - Pressure- and stellar mass-dependence
  - Small-scale decorrelation
- Correlations with tracers of dense gas

## (Highly condensed) prelude on history First generation (1970s - 1990s)

- Key technologies:
  - Discovery of interstellar CO 1-0 line at 2.6 mm (Wilson 1970), leading to first generation of mm telescopes (e.g., FCRAO in 1976, IRAM 30m in 1984, **BIMA** in 1986)
  - Space-based IR detector technology (largely borrowed from the military), leading to first IR astronomy satellites (IRAS, launched 1983)
- Combination of these two lead to first systematic exploration of relationship between gas (traced by CO and earlier 21 cm data) and star formation (traced by IR + ground-based H $\alpha$ )
- Culminates in discovery of "Kennicutt-Schmidt relation"

#### Prelude on history Second generation (2000s)

- Key technologies:
  - PdBI 1990s 2000s)
  - makes it possible to observe beyond  $z \sim 0$  in IR for first time

  - Efficient selection of z > 0 objects using HST + ground-based colours
- Main outcomes:

  - First reliable studies of star formation in dwarf galaxies
  - First studies of KS relation beyond local universe

 Interferometry at mm wavelengths makes it possible to map gas in nearby galaxies, and start to detect CO beyond z = 0 (SMA in 2003, CARMA in 2004,

• Spitzer telescope in IR (launched 2003) — much higher resolution than IRAS, • GALEX telescope in UV (launched 2003) — mapping nearby galaxies in FUV

Exploration of the KS relation on sub-galactic (~1 kpc) scales in local galaxies

#### Prelude on history Third generation (2010s - today)

- Key technologies:
  - Atacama Large Millimeter Array (ALMA; science begins 2011) can map nearby galaxies at < 100 pc resolution, fairly easily detect CO at high z, do surveys of dense gas tracers like HCN
  - IFUs on 4m- and 8m-class ground-based telescopes (CALIFA at Calar Alto, MaNGA at Kitt Peak, SAMI at AAO, MUSE on VLT) — spectroscopic mapping of ionised gas across at < 100 pc resolution in nearby galaxies
- Major discoveries:
  - KS relation for normal (non-starburst) galaxies at high-z; "main sequence" of star-forming galaxies
  - Small-scale breakdown of KS relations in local galaxies
  - "Dense gas" KS relations



#### Whole-galaxy star formation scalings **The Kennicutt-Schmidt relation**

- Schmidt (1959) first proposed ansatz where SFR scales as density to a power
- Kennicutt (1998) showed strong scaling between SFR / area and neutral (HI + H<sub>2</sub>) gas mass / area:  $\Sigma_{SFR} \sim \Sigma_{g}^{1.4}$ 
  - One of the 20 most highly cited papers of all time in astronomy
- Exact index depends on assumed  $\alpha_{CO}$  1.4 is for constant  $\alpha_{CO}$ , but could be as low as  $\sim 1.1$ , or as high as  $\sim 1.7$

of the gas, within way 1.5 expected for a constant mean sc height, a reasonable approximation for the galaxies a starbursts considered here. Although this is hardly a rob devivation, it does show that a global Second law w  $N^{\geq}$  1.5 is physically plausible.  $\Rightarrow$ 

In a variant of this argument, Silk (1997) and Elmegre (1997) have suggested a generic form of the star formation law, in which the SFR surface density scales with the ra of the gas density to the food dynamical timescale:

$$\frac{1}{2} \frac{1}{2} \frac{1}$$

where  $\tau_{d,n}$  refers in this case to the local orbital timescale the disk, and  $\Omega$  is the angular rotation speed. Models of t general class have been studied previously by Wyse (19 and Wyse & Silk (1989), though with different scalings

Kennicutt & Evans 2012



#### KS relation Orbital period form

- Same galaxies also consistent with a relationship  $\Sigma_{\rm SFR} \sim \Sigma_{\rm g}$  /  $t_{\rm orb}$
- This relationship is linear
- Constant of proportionality is ~0.1, i.e., galaxies convert ~10% of their gas to stars per orbit
- Star formation fuelling problem: MW is ~50 orbits old, so why isn't it out of gas?



#### KS relation at high z How the two forms hold up

- KS relation in terms of  $\Sigma_{g}$  alone seems to break down at high-z: local merging galaxies and high-z "normal" galaxies have similar  $\Sigma_q$ , but starbursts have higher SFR
- Second form of KS relation seems to apply equally well at low- and high-z
- However, conclusions highly-dependent on  $\alpha_{CO}$ ; breakdown in first form of KS relation much less apparent if one assumes constant (or continuously: varying) rather than bimodal  $\alpha_{CO}$



Figure 2. SFR density as a function of the gas (atomic and molecular) surface density. Red filled circles and triangles are the BzKs (D10; finded) and  $z \sim 0.5$ disks (F. \$almi et al. 2010, in preparation). Frown crosses are z = 1-2.3 normal gataxies (Tacconi et al. 2010). The enorty squares are SMGs: Bouché et al (2007; Bute) and Bothwell et al. (2009, Ifght green). Crosses and filled triangles are (U)LIRGs and spiral galaxies from the sample of K98. The shaded regions are THINGS spirals from Bigiel (2008). The lower solid line is a fit to local spirals and z = 1.5 Bzk genaxies (Equation (2), slope of 1.42), and the upper dotted line is the same relation shifted up by 0.9 dex to fit local (U)LIRG and SMGs. SFRs are derived from IR luminosities for the case of a Chabrie

measured at a higher signal to - mais Matro. Again, we find that the populations are split in this diagram and are not well fit by a single sequence. Our fit to the local spirals and the BzK galaxies is virtually identical to the original K98 relation:

(A color version of this figure is available in the online journal.)

$$\log \Sigma_{\rm SFR} / [M_{\odot} \, {\rm yr}^{-1} \, {\rm kpc}^{-2}] = 1.42 \times \log \Sigma_{\rm gas} / [M_{\odot} \, {\rm pc}^{-2}] - 3.83.$$

The slope of 1.42 is slightly larger than that of Equation ( $\overline{1}$ with an uncertainty of 0.05. The scatter along the relation is 0.330 det. Local (U)LIRG and SMGs/QSOs are consistent with a relation having a similar slope and normalization higher by 0.9 dex and a scatter of  $0.39 \text{ dex}_{GS}$ 

Despite their high SFR  $\gtrsim 100 M_{\odot} \text{yr}^{-1}$  and  $\Sigma_{\text{SFR}} \gtrsim 1 M_{\odot}$ yr  $^{-1}$  kpc  $^{-2}$ , BzK galaxies are not starburst, as their SFR can be sustained over timescales company to those of local spiral disks. On the other hand, M82 and the nucleus zyfs NGG 253 are prototypical starbursts, although they only reach an SFR of a few  $M_{\odot}$  for  $M_{\odot}$  for displacement of the disk and starburst sequences, a starburst may be quantitatively distinct as a galaxy with  $L_{\text{tR}}$  (or  $\Sigma_{\text{SFR}}$ ) exceeding the value derived from Equation (2) for Equation (2) by more than 0.5 dex. The stuation changes substantially when introducing the dy

namical timescale ( $\tau_{dyn}$ ) into the picture (Silk 1997; Elmegreen 2(3)2; Krumolz et al. 2009; Kennicutt 1998). In Figure 3, we compare  $\Sigma_{gas}/\tau_{dyn}$  to  $\Sigma_{SFR}$ . Measurements for spirals and (U)LIRGs are from K90; where  $\tau_{dyn}$  is cleaned to be the rota-RzKs/norma





## KS relation in dwarfs and LSBs

- Dwarf galaxies fall substantially below the KS scaling for local spirals
- Major data issues: molecular gas very hard to observe due to low metallicity, total mass assumed dominated by HI
- If one uses only H<sub>2</sub>, results depend entirely on choice of  $\alpha_{CO}$
- H $\alpha$  very faint, hard to see against sky background – reliable measurement requires UV from space



Wyder+ 2009



### The spatially-resolved KS relation Measured at ~1 kpc resolution

- Molecular gas in nearby galaxies shows a nearly universal t<sub>dep</sub> ~ 1 - 4 Gyr
- No major variation with galactocentric radius, except possibly at very centre
- Conclusion only applies to nearby spirals based on integrated measurements, t<sub>dep</sub> ~ must be smaller in starburst and high-z systems
- Also holds in dwarfs, as long as one measures H<sub>2</sub> using something other than CO as a proxy



Utomo+ 2017

#### SF efficiency The ε<sub>ff</sub> parameter

- To include starbursts, it is helpful to normalise to free-fall time
- Estimate by assuming disc in hydrostatic equilibrium, or by using typical GMC surface densities (whichever gives higher density)
- Result: a universal efficiency  $\varepsilon_{\rm ff} \approx$ 1 - 2%, factor of ~3 scatter



Krumholz 2014

## SF in atomic gas

- Outer galaxies and dwarfs dominated by HI rather than H<sub>2</sub>
- In inner galaxies, basically no correlation between SFR and amount of HI.
- Instead HI has a maximum surface density of ~10  $M_{\odot}$  pc<sup>-2</sup> independent of SFR
- In outer galaxies there is a correlation, but with very large scatter, and very large depletion time - t<sub>dep</sub> ~ 100 Gyr
- Ratio of H<sub>2</sub> and HI depletion times implies a minimum H2 fraction ~2%







## Metallicity-dependence

- HI/H<sub>2</sub> transition depends on metallicity — both theoretically predicted and observed
- Stars seem to form only in H<sub>2</sub>, which suggests total gas KS relation should vary depending on metallicity
- This appears to be the case: SMC (Z ~ 0.2 Z<sub> $\odot$ </sub>) has lower SFR at same total surface density than LMC (Z ~ 0.5 Z<sub> $\odot$ </sub>) or spirals (Z ~ Z<sub> $\odot$ </sub>)

Wong+ 2013



#### Jameson+ 2016



C3147 C6951 C5371 C40772 C4654 C1637 C4254 C3486 C2976 C3486 C2976 C3198 C4536 C3198 C4536 C3198 C4536 C2782 C2782 C4151 C4605 C1156

## Pressure dependence

- In local discs, SFR and molecular fraction also correlate with ISM pressure
- Pressure depends on both gas and stellar surface density, and on ratio of stellar to gas velocity dispersion
- Degeneracy between metallicity and pressure dependence: pressure is higher in high metallicity regions (inner discs, spirals) and lower in lower metallicity regions (dwarfs, outer discs), so it is unclear which is primary variable





Sun+ 2020

### Going to smaller scale

- Tracers of gas and star formation de-correlate on scales ≤ few hundred pc
- In grand-design spiral galaxies, CO is often on leading edge of spiral, Hα on trailing edge
- Suggested interpretation (discussed last time): result of rapid cloud destruction



Kreckel+ 2018



#### **Dense gas KS relations** Basic considerations

- CO has a critical density ~1000 cm<sup>-3</sup>, so it traces most of the molecular gas
- It is interesting to look at denser gas, e.g., HCN traces gas at  $\sim 10^4$  cm<sup>-3</sup>
- This is hard due to brightness: HCN is ~10x dimmer than CO in a typical spiral galaxy, so ~100x the telescope time is needed to reach equal SNR
- Everything else even fainter, too dim to use
- Whole-galaxy HCN measurements starting appearing in 2000s, focusing mostly on bright targets (starbursts)
- First spiral galaxy HCN maps only made ~2016 today

## All the HCN data in one place



Jiménez-Donaire+ 2019

## **HCN-IR correlation**

- To zeroth order, there is near-linear correlation between HCN (~dense gas mass) and IR luminosity ( $\sim$ SFR)  $\rightarrow$  about constant SFR / dense gas mass
- First order: IR / HCN lower in galaxies with higher density / pressure / total SFR
- Suggested explanation:
  - Near-linear because SFR =  $\varepsilon_{\rm ff} M / t_{\rm ff}$ ;  $\varepsilon_{\rm ff}$ universal and  $t_{\rm ff}$  fixed by critical density
  - Deviation from linearity because shape of PDF causes mean *t*<sub>ff</sub> of HCN-emitting gas to go up when mean density does



## HCN star formation efficiency



Onus+ 2018