Star Formation from Nearby Clouds to Distant Galaxies: Common Features and Common Myths

Neal J. Evans II
University of Texas at Austin
KASI
The Basic Problem of Star Formation

- It is slower and less efficient than expected
- For Milky Way, $M_{\text{mol}} = 1 \times 10^9 \, M_{\odot}$
- Typical $t_{\text{ff}} = 3 \times 10^6 \, \text{yr}$
- Simple estimate: $\text{SFR} = 300 \, M_{\odot}/\text{yr}$
- 100 times higher than average over last Gyr
  - Zuckerman & Palmer 1974, ARAA, 12, 279
- Roughly applies to other galaxies, Universe as a whole
Only a few percent of the baryons are in the form of stars. Simulations predict most (e.g., Hopkins et al., 2014, MNRAS, 445, 581).

Madau & Dickinson 2014 ARAA
Galaxy Scale: Extreme Diversity

![Graph showing log \( \Sigma(SFR) \) vs log [SFR (\( M_\odot \) year\(^{-1}\))] with various galaxy types indicated.

- **Galaxy type**
  - Normal/irregular
  - Infrared-selected
  - Blue compact
  - Circumnuclear

**(MW)**

\( R = 13.5 \) kpc

Kennicutt & Evans 2012
Collapses to KS Relation

Solid circles are disk-averaged normal spirals
Open circles are central regions of normal disks
Squares are circumnuclear starbursts

\[ \Sigma_{SFR} = A \Sigma_{gas}^N \]

\[ N = 1.4 \pm 0.15 \]

Kennicutt 1998, ARAA 36, 189
SFR Linear above Threshold $\Sigma_{\text{gas}}$

Study of 18 nearby galaxies with sub-kpc resolution in HI, CO.
SFR from UV+24 micron
Color code is location in galaxy.
Threshold around 10 $M_{\odot}\text{pc}^{-2}$ in total gas:
transition from HI to $H_2$
Linear above threshold
Typical depletion time 1-2 Gyr

Bigiel et al. 2008
SFR in Starburst Galaxies

- $L_{IR}$ correlates better with $L$(HCN)
- Smaller scatter
- Higher SFR/Gas
- SFR rate linearly proportional to amount of dense gas
- “Efficiency” for dense gas constant and high

Extends Across Many Scales

From talk by Yu Gao on Tuesday

Extends from MW dense clumps to high-z starbursts: Linear with standard deviation about half that for CO
Testing Star Formation Prescriptions

- Use Star Formation “Efficiency”
  - SFE = SFR/X
  - Units of 1/Myr, inverse of depletion time
  - A linear SFR “law” becomes flat with SFE
  - Better measure of scatter
- What is the best predictor?
  - Mass of molecular gas
  - Mass of molecular gas divided by free-fall time
  - Mass of dense gas
Use the Milky Way to Study
Star Formation in Nearby, “Large” (3-10pc) Clouds

- c2d+GB Survey
  - Survey 29 large clouds with Spitzer (if split into individual regions)
- Where do stars form?
- Which SFE predictor works best?
SFE for Dense Gas

\[
\log \left( \frac{SFR}{M_{\text{dense}}} \right) (\text{Myr}^{-1}) \quad \log M_{\text{dense}} (M_{\odot})
\]

\(M_{\text{dense}}\) predicts SFR to within uncertainty (factor of 2)

Clouds, \(A_V\) above 8 mag

Mean Value
SFE for Cloud Mass

Dispersion is 3.6 x bigger

Clouds, $A_V$ above 2 mag
What About Massive Stars?

- Need to study more distant clouds
- Can’t get SFR by counting YSOs (yet!)
- Use tracers of massive stars (MIR, free-free, RRL)
Mass of Molecular Cloud

GP clouds systematically less efficient by nearly factor of 10
Dispersion is large (recall Onodera talk)

N. Vutisalchavakul et al.
Does $t_{\text{ff}}$ decrease dispersion?

No, dispersion about the same

Nearby Clouds, $A_v > 2$ mag

Galactic Plane Clouds

No, dispersion about the same

N. Vutisalchavakul et al.
Mass of Dense Gas

Nearby, GP agree
Dispersion smaller
but still large
What about other galaxies?

- Big picture
  - Take mean and std deviation (in log) of all the nearby clouds and all the GP clouds
  - Do the same for exgal samples
  - Leroy (30 galaxies, CO) (~1 kpc res)
  - Chen (M51, CO, HCN) (~1 kpc res)
  - Liu (115 spirals, 66 (U)LIRGS, CO, HCN)
Star Formation Efficiency

Nearby GP Resolved galaxies

Efficiency per molecular gas varies by a lot.
$\langle \text{Log}[\varepsilon_{\text{ff}}]\rangle = -1.80 \pm 0.50$
Note: plotted on the same scale. Scatter is much less.
SFE for dense gas is remarkably constant from scales of pc to 10 kpc.
What is the Best Predictor?

- Grand average of log(SFE)
  - For $M_{\text{cloud}}$, std dev = 0.42
    - 0.59 if use (U)LIRG $\alpha$(CO)
  - Total range, factor of 40
- For $M_{\text{dense}}$, std dev = 0.19
  - Total range, factor of 4
- Including center of M51
Similar effect seen in central molecular zone of MW. Kruijssen et al. (2014) suggest that threshold density there is $>10^7\, \text{cm}^{-3}$, rather than about $10^4\, \text{cm}^{-3}$, as in other regions.
What do we mean by “dense”?

- $A_V > 8$ mag (nearby clouds)
- Clumps defined by mm/smm continuum emission (Galactic Plane)
- Regions emitting HCN J = 1-0 line (exgal)
- Need cross-calibration!
- Look for second parameters
HCN as a Probe

- $M_{\text{dense}} = (20+/–5) \ L(\text{HCN} \ 1-0)$ Wu+ 2010
- $M_{\text{dense}} = 10 \ L(\text{HCN} \ 1-0)$ Liu+ 2015
- Pety et al. (2016) map of Orion B
  - 38% of HCN 1-0 from $A_V < 6$ mag.
  - Conversion to mass depends on $G_0$
- Higher J transitions will work better
- Ongoing studies at TRAO
Preliminary result: HCN, HCO$^+$ agree with dust continuum, but are somewhat more extended. Significant line luminosity from less dense regions.
Recall point by Jens on Tuesday; much of L(HCN) arises from lower density part of cloud. But still biased toward dense.
Summary So Far

- Among empirical relations, $\text{SFR-M}_{\text{dense}}$ works best
- Centers of galaxies, other special regions need more parameters
- Probably gas has to be still denser in regions of high turbulence
- Need to calibrate tracers of dense gas
Common Features, Common Myths

- Common feature is star formation in dense gas
- Now let’s examine some common myths
- Recall the basic problem of star formation
The Basic Problem of Star Formation

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Reconsidering Some Myths

- Two definitions of “Myth”:
  - an unfounded or false notion
  - a popular belief or tradition that has grown up around something

- By myth, I mean the second definition
  - Things we tend to believe because they are constantly repeated
  - May or may not be true
  - As scientists, we should re-examine them critically
Myth 1

- Molecular clouds are gravitationally bound
- What is the actual evidence?
Virial Ratio for Molecular Clouds

Dotted lines are $\alpha_v = 3$ and 10, solid line $\alpha_v \sim 1$

Heyer and Dame 2015 ARAA, 53, 583
Heyer and Dame comment: “Clouds within the Galactic disk have virial ratios between 1 and 3 that are consistent with being gravitationally bound, given the systematic errors of recovering cloud properties.”
An Equally (or more?) True Statement

With my slight edit:
“Clouds within the Galactic disk have virial ratios between 1 and 3 that are consistent with NOT being gravitationally bound, given the systematic errors of recovering cloud properties.”.
Or, from Talk by Quang

Almost all are nominally unbound. Many by large margins; note log scale.
Does this look bound?

The Taurus Cloud R. Snell: three colors for velocity components
More like which of these?

Cirrus
No precip.

Cumulonimbus
Precipitates
A Proposal

Molecular “clouds” are unbound structures.
Heresy!
“Low SFE requires initially unbound clouds even with radiative feedback.”
(emphasis added)
Myth 2

- The free-fall time is the characteristic timescale for molecular cloud evolution
  - If clouds are not bound, this is clearly not true
- What is the actual evidence?
  - If true, $M_{\text{cloud}}/t_{\text{ff}}$ should predict SFR
  - Requires factor of 50-100 fudge factor ($\varepsilon_{\text{ff}}$)
  - Does not decrease dispersion
Theorists LOVE $t_{ff}$

- For example, Krumholz, Dekel, McKee (2012)
- Many talks at this meeting
- Observers generally skeptical
Is $t_{\text{ff}}$ Predictive at cloud level?

- Does SFR of a cloud depend on free-fall time of the cloud ($t_{\text{ff}}$ based on mean $\rho$)?

No, correlation is not statistically significant ($r = 0.34$)
Myth 3: Feedback Solves Everything!

- The current favorite of theorists
- No doubt it is important for starbursts, high mass star forming regions
- But invoking feedback by SNe, HII regions cannot explain low SFE in nearby clouds
- Why is the SFE (or the $\varepsilon_{ff}$) for dense gas about the same from nearby clouds to starburst galaxies?
Remember this one

N. Vutisalchavakul et al.
A Modest Suggestion

- Suppose molecular clouds are not bound
  - Just part of the mostly atomic flow that becomes molecular for a while
  - Collisions, turbulence causes a small fraction (few percent) to become bound dense clumps
  - The rest of the molecular gas rejoins the atomic flow
  - Galactic feedback keeps ISM stirred up, unbound
- The basic problem of slow star formation goes away
- Consistent with talks by Federrath, Padoan?
Best Correlation is with “boundedness”

Leroy et al. 2017
Analysis of M51
No good correlations with any model predictions.
Only good correlation was $t_{\text{dep}}$ with “boundedness” = $\Sigma_{\text{gas}}/\sigma^2$
Upside down and backwards: $\text{SFE} \sim 1/\alpha$
These are measured as 40 pc averages. None are remotely close to bound. Better to think of $b \sim U_g/E_k \ll 1$
Summary

- Dense gas best predicts SFE
- We need to improve understanding of tracers
- The concept of “clouds” may be misleading
- Free-fall time is meaningless when nothing is falling
Back-up slides
Surveys of the Galactic Plane

- **Galactic Ring Survey** (Jackson et al. 2006) - 13CO1-0
  A peak in molecular gas column density around 5kpc.
  Observed the galactic plane at \( L = 18 \pm 55 \) degree.

-Bolocam Galactic Plane Survey (BGPS)
(PI: John Bally)
1.1 mm continuum survey of the Northern Galactic Plane
-10.5 < \( l \) < 90.5
with follow up observations in CS 5-4, HCO\(^+\) 3-2, and N\(_2\)H\(^+\) 3-2 transitions
Selection

- Need “high” SFR, velocity information
- Use radio recombination line (RRL) survey
  - Anderson et al. 2011, 2014
  - Several lines around $n = 90$ (H90$\alpha$)
  - Essentially equivalent to H$\alpha$, but no extinction
  - Pick regions with RRL, radio continuum, covered by other surveys
  - This is a SFR-selected sample
- SFR from radio and mid-infrared agree
Associating Clouds and Clumps

- With HII region position and velocity
  - Search $^{13}$CO survey for matches
  - Require $|v_{CO} - v_{RRL}| < 10$ km s$^{-1}$
  - Careful examination to avoid contamination
Associating Clumps

- Use mm-wave dust continuum
  - Bolocam Galactic Plane Survey (BGPS)
  - Follow-up survey in dense gas tracers for v
- Associated with molecular cloud
  - In space and velocity
  - Add up if more than one to get $M_{\text{dense}}$
SFR(radio)

- NOT the exgal relation!
  - For other galaxies, radio beam dominated by extended synchrotron emission
  - SFR(radio) reflects past star formation (maybe 100 Myr averaging time)
- In MW, free-free dominates
  - SFR(radio) averages over about 3-10 Myr
  - Will underestimate SFR unless IMF well sampled up to O stars
SFR(MIR)

- Use exgal relation
- Known to fail below about $5 \, M_{\text{sun}} \, \text{Myr}^{-1}$
- Limit sample to sources above that rate
- Leaves 51 regions
Do IR and Radio Agree?

Generally yes…
Black line is 1:1
Blue line is fit
Red line is fit from previous, smaller sample

Fitted slope is 0.85 +/- 0.02
Points higher at low SFR(radio)
MIR less sensitive to IMF
Use SFR(MIR) but only include if SFR > 5 M_{sun}yr^{-1}

N. Vutisalchavakul et al.
Murray (2011) selected most radio-luminous sources from WMAP; connection to cloud mass not so clear. Including them increases the SFE and the scatter (std dev. (Log SFE) = 0.72)
E. Lee et al. find similar result for inner Galaxy. Std dev. of Log(SFE) is ~ 1, or about factor of 10 in SFE.

No theories of steady state SFR predict this.

They argue that SFE is function of time.
Supported by Cloud Type

- Red points: HII regions
- Blue points: HII regions and stellar clusters
- Blue more evolved

Ochsendorf et al. 2017