Formation of Molecular Clouds and Global Conditions for Star Formation

Clare Dobbs, U. Exeter
Mark Krumholz, UC Santa Cruz
Javier Ballesteros-Paredes, UNAM
Alberto Bolatto, U. Maryland
Yasuo Fukui, Nagoya U.
Mark Heyer, U. Massachusetts
Mordecai Mac Low, AMNH
Eve Ostriker, Princeton U.
Enrique Vázquez-Semadeni, UNAM
The Four Questions

• What do observations tell us?

• How do molecular clouds form?

• What processes control molecular cloud structure, evolution, and dissolution?

• What regulates star formation in molecular clouds?
Question 1:

WHAT DO OBSERVATIONS TELL US?
In the beginning...

- **1930s**: molecules in optical absorption
- **1960s**: molecules in radio emission
- **1970**: $\text{H}_2$ (Carruthers 1970), CO (Wilson+ 1970)
- **1980s**: all-Galaxy CO maps (Dame 1987), cloud catalogs (Solomon+ 1987, Scoville+ 1987), high density tracers: NH$_3$, HCN, CS (Myers 1983; Snell+ 1984)
- **1990s**: extragalactic GMCs, interferometer maps, sub-mm dust

Stars form in molecular clouds

Leroy et al., 2008, AJ, 136, 2782
Quantitative correlations

- SFR-HI correlation poor
- SFR-H$_2$ correlated, index $\sim 1$, $\tau_{\text{dep}}(H_2) = M_{H_2}/\text{SFR} \sim 2$ Gyr
- Caveats: CO-H$_2$ and light-SFR conversion; correlation fails on small scales

Bigiel et al., 2008, AJ, 136, 2846
MC masses

- Mass range $\sim 10^2 - 10^7 \, M_\odot$
- Mass spectrum is a powerlaw $dN / dM \sim M^\gamma$, possibly with an upper cutoff
  - $\gamma \sim -2$ to $-1.5$ in $H_2$-rich regions (inner MW and M33)
  - $\gamma \sim -2.5$ to $-2$ in $H_2$-poor regions (outer MW and M33, LMC, SMC)
- NB: $\gamma > -2$ means most gas in big clouds

MC surface densities

- MC surface densities $\sim 100 \, M_{\odot} \, \text{pc}^{-2}$, no systematic variation with mass or Milky Way galactocentric radius.
- Possible weak dependence on environment in other galaxies: lower in low $\Sigma$ regions, higher in high $\Sigma$ regions.
- PDF of $\Sigma$ within GMCs roughly lognormal w/powerlaw tail.
- Caveat: sensitivity bias.

MC velocity dispersions

- Velocity dispersion obeys
  \[ \sigma_v = (\alpha_G \pi G \Sigma R/5)^{1/2} \]
  with \( \alpha_G \approx 1 \) (Heyer+ 2009)
- Could be virialization, pressure confinement, free-fall collapse
- Most power on large scales

Virial balance:
Heyer+ 2009

Pressure confinement:
Field+ 2011

Collapse: Ballesteros-Paredes+ 2011

Complex internal structure!

Narayanan et al., 2008, ApJS, 177, 341
Dimensionless numbers!

- Virial theorem describes large-scale dynamics of GMCs; ratio of terms says what forces are important
  - $\alpha_G = -2 \frac{T}{W} \approx 1$: gravity and large-scale motions comparable
  - $\frac{M}{M_{\text{crit}}} = \frac{M}{[\Phi/(4\pi G)^{1/2}]} \approx 2$: magnetic fields not negligible, but not strong enough to offset gravity

GMC lifetimes

M51: lots of inter-arm clouds, lifetime $\sim 100$ Myr (Koda+ 2009)

LMC: lifetime from number counts + cluster ages $\sim 30$ Myr (Kawamura+ 2009)

- For comparison, free-fall time $t_{ff} = (3\pi/32G\rho)^{1/2} \approx 1 - 5$ Myr
- Local vs. M51, LMC lifetime difference may be selection effect

Solar neighborhood: no post-T Tauri stars in nearby clouds, $\sim 3$ Myr (Hartmann+ 2001)

Star formation: low efficiency

- SFR per free-fall time $\epsilon_{ff} = \frac{\text{SFR}}{M_{\text{gas}}/t_{ff}} \sim 0.01$ (factor of $\sim 3$ spread) over broad range of densities, environments
- $t_{\text{life}} < 100 \ t_{ff}$, so GMCs disrupted at low overall SFE

GMCs in extreme environments

Physical and star formation properties vary near galactic centers, in starburst galaxies, and at low metallicity

Bottom left: Bigiel et al., 2008, AJ, 136, 2846
Question 2:

HOW DO MOLECULAR CLOUDS FORM?
Local converging flows

Local converging flows II

• Local turbulence or feedback (e.g. SN blast wave) triggers collision of warm HI streams
• Density rise triggers transition to cold HI, then $\text{H}_2$ once column exceeds $\sim 10^{21} \text{ cm}^{-2}$; $\text{H}_2$ formation and star formation simultaneous
• Maximum mass $\sim$ mean ISM surface density $\times$ $\text{H}_2 \sim 10^4 \text{ M}_\odot$; can’t produce the big GMCs that contain most of the mass
Cloud collisions in spiral arms I

Dobbs & Pringle 2013

Dobbs+ 2012

Cloud collisions in spiral arms II

- Collisions slow except in spiral arms, where rate is enhanced by orbit crowding
- Can build $> 10^6 \, M_\odot$ clouds in such regions
- Explains why many GMCs are counter-rotating relative to galaxy
- Produces right cloud mass spectrum
- Operation unclear in flocculent galaxies without big stellar spiral potential
Gravitational and magneto-Jeans instability I


GI and MJI II

• Non-axisymmetric instability occurs when $Q = \frac{\kappa c_{\text{eff}}}{\pi G \Sigma} < \sim 1.5$
• GI makes $\sim 10^{7-8} \, M_\odot$ clouds without spiral structure; smaller clouds from fragmentation
• MJI: works in arms w/low shear, B fields counter Coriolis; high $\Sigma$ allows $\sim 10^6 \, M_\odot$ clouds
• Naturally explains spurs, “beads on a string” HII regions, low GMC spins (magnetic braking)
• Full cloud mass spectrum not yet determined
Parker + thermal instability

- Buoyancy makes B field lines rise out of plane, gas collects in valleys
- For isothermal medium density enhancement only factor of a few
- TI allows runaway cooling (cf. colliding flows)
- Makes $\sim 10^5 M_\odot$ clouds
- May not work in turbulent or multiphase medium

Forming \( \text{H}_2 \) and CO

- \( \text{H}_2 \) forms on dust grains, dissociated by FUV; dominates only in dense, shielded regions
- CO forms in gas, requires \( \text{H}_2 \), also FUV dissociated
- Layered structure: \( \text{HI} + \text{CII} \) with column \( \Sigma \sim 10/Z \, \text{M}_\odot \, \text{pc}^{-2} \), then \( \text{H}_2 + \text{CII} \), then \( \text{H}_2 + \text{CO} \)
- Dust abundance matters a lot
- Unclear whether / when non-equilibrium chemistry important

Do H$_2$, CO matter for SF?

- **CO**: no! CO-SF correlation fails at low Z, CO forms rapidly, not needed for cooling
- **H$_2$**: H$_2$-SF still correlated at low Z, but probably because shielding matters for both H$_2$ and SF

---


Question 3:

WHAT PROCESSES CONTROL GMC STRUCTURE, EVOLUTION, AND DISSOLUTION?
Morphological evidence

- Filaments with converging flows toward / along them
- Offset maxima of velocity, col. density
- Origin unclear: HD turbulence w / no self-gravity and free-fall magnetized collapse both fit!
- Need statistical measures

All figures: Schneider et al., 2010, A&A, 520, A49
Non-thermal motions

- $\sigma \sim 1 - 10 \text{ km s}^{-1}$ on $L \sim 10 \text{ pc}$ scales
- Viscosity $\nu \sim 10^{16} \text{ cm}^2 \text{ s}^{-1}$, so $Re \sim LV/\nu \sim 10^9$: flow inevitably turbulent
- Turbulence decays, so why is $\sigma$ so large?
- Possibilities:
  - Global gravitational collapse
  - External driving (e.g., accretion, collisions)
  - Internal energy injection from SF feedback
Global collapse

- Colliding flows of warm gas drive turbulence via NLTSI
- Gravity takes over, chaotic collapse follows
- Linewidths reflect collapse
- Easily explains linewidths
- Getting right $\epsilon_{\text{ff}}$ depends on details of feedback

External driving

- Accretion onto cloud as it forms drives turbulence
- For big clouds, large-scale shear flows and turbulent cascade from rest of galaxy
- Seems able to explain both linewidths and lifetimes
- Needs feedback to get right $\epsilon_{ff}$

Internal driving

- Protostellar jets too weak on GMC scales
- Radiation pressure, main sequence winds: couple too weakly
- HII regions may work
- Gets $\varepsilon_{\text{ff}}$ right
- Challenge: drive without disruption
- B fields may be important

GMC disruption

- Except perhaps in M51, $\tau_{\text{life}} \ll \tau_{\text{dep}}$, so disruption mechanism required
- In global collapse, need disruption time $< \sim \tau_{\text{ff}}$; can be $1 - 10 \tau_{\text{ff}}$ for external or internal driving
- Same candidate mechanisms as for internal driving: HII regions, Sne
- FEW FIRST-PRINCIPLES SIMULATIONS, mostly simulations with subgrid feedback recipes, and (semi-)analytic models
Question 4:

WHAT REGULATES STAR FORMATION IN GMCS?
The problem in a nutshell

- For uninhibited collapse, $\varepsilon_{\text{ff}} \sim 1$, but observed value is $\varepsilon_{\text{ff}} \ll 1$
- In MW, $\varepsilon_{\text{ff}} \sim 1$ gives $\text{SFR} \sim 100 \ M_\odot \ \text{yr}^{-1}$; observed $\text{SFR} \sim 1 \ M_\odot \ \text{yr}^{-1}$
- Classical explanation is B fields, but observed field strengths too small
- Remaining contenders: collapse + rapid disruption by feedback, and turbulence
Collapse + disruption

- Can keep $\varepsilon_{ff}$ low if clouds disrupted by feedback in $\lesssim 1 \, t_{ff}$, before much SF
- Disruption by ionization possible up to $\sim 10^5 \, M_\odot$ clouds, but depends on subgrid model
- Not clear if large clouds can be disrupted rapidly

Turbulence-regulated SF

- Turbulence supports against collapse on large scales, allows it on small scales
- Many models for $\varepsilon_{\text{ff}}$ ($\alpha_G$, $M$, $\beta$); all give $\varepsilon_{\text{ff}} \sim 0.01 - 0.1$ for GMCs
- Turbulence must be maintained by external driving and/or feedback
Combination models

Reality likely between pure collapse and turbulence models: SF regulated by turbulence, but cloud properties evolve with time

Connection to galactic scale

- What sets $\Sigma_{\text{SFR}}$ at galactic scales?
- $\Sigma \sim 10 - 100 \, M_\odot \, pc^{-2}$: $\Sigma_{\text{SFR}} \sim \Sigma_g^N$ with $N \sim 1$: probably just cloud-counting, all clouds are (on average) the same
- $\Sigma > 100 \, M_\odot \, pc^{-2}$: $N > 1$, probably because GMCs are getting denser
- $\Sigma < 10 \, M_\odot \, pc^{-2}$: $N > 1$, and third parameters (e.g. metallicity, mass of old stellar population) seem to matter
Three possibilities

- GI dies out at low $\Sigma_g$, so $\Sigma_{SFR}$ declines non-linearly
- ISM at low $\Sigma_g$ is HI-dominated, only $H_2$ phase forms stars; metallicity matters for this reason
Three possibilities ctd.

- Balance between feedback-driven turbulence and gravity is key, with vertical $g_z$ dominated by stars at large radii

Things will be better in...

THE FUTURE
Observations

- ALMA and NOEMA: sensitivity to measure internal GMC structure in extragalactic sources
- IRAM 30m, NRO 45m, LMT 50m, NANTEN2, CCAT: large-area mapping
- CARMA, SMA: big surveys of GMCs in MW
Theory

- Combine galactic-scale codes w/small-scale ones
- Idea: get both environment and feedback right – needs physics beyond hydro + gravity