Low- and intermediate-mass star formation

Part I

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Outline:

Part I

- What tracers for star formation?
- Context: A simple picture of star formation
- Structure of low-mass star-forming regions

Part II

- Kinematics of low- and intermediate-mass star-forming regions
- Galactic plane survey of Infrared Dark Clouds
Tracers to study the early stages of star formation

**Interstellar dust:**

- Mostly amorphous silicates
- Distribution in size (from nm to micron) and composition (mostly amorphous silicate and carbonaceous grains) - See Draine 2003, ARA&A, 41, 241

Bradley et al. 2005
Tracers to study the early stages of star formation

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Dust plays a crucial role in cooling down interstellar material and is at the center of molecule formation process (grain surface chemistry)
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Dust forms mostly in the winds of AGB stars and supernova
- In dense interstellar medium dust/gas ratio is about 1% in mass
Tracers to study the early stages of star formation

absorption

observer

fore

$\tau$: opacity

$I_{bg}$
Tracers to study the early stages of star formation

\[
I_{\text{obs},\nu} = I_{\text{bg},\nu} \times \exp^{-\tau_{\nu}} + I_{\text{fore},\nu}
\]

\[
\tau_{\nu} = N_{\text{H}_2} \times \kappa_{\nu}
\]
Tracers to study the early stages of star formation

B68: NTT near infrared composite image

IRDC: Spitzer mid-infrared composite image

Credit: ESO

Peretto & Fuller 2010
Tracers to study the early stages of star formation

B68: NTT near infrared composite image

IRDC: Spitzer mid-infrared composite image

Can be used to get the column density and therefore mass (if distance known), not a function of dust temperature, but need a background emission, need to know the foreground
Tracers to study the early stages of star formation

emission

stars

Radiation short wavelength

Absorbing dust

Radiation long wavelength
Tracers to study the early stages of star formation

emission

stars

Radiation short wavelength

Absorbing/emitting dust

Radiation long wavelength

 Emitting dust is similar to the one of a black body times an opacity term: greybody
Tracers to study the early stages of star formation

Optically thin dust emission up to $\sim 10^{24} \text{ cm}^{-2}$

In (sub-)millimeter dust continuum emission:

$$I_v = B_v(T) (1 - e^{-\tau_v})$$

$$I_v \approx B_v(T) \tau_v$$

$$N_{\text{H}_2} = 2.02 \times 10^{20} \text{ cm}^{-2} \left( e^{1.439(\lambda/\text{mm})^{-1}(T/10 \text{ K})^{-1}} - 1 \right) \left( \frac{\lambda}{\text{mm}} \right)^3 \cdot \left( \frac{\kappa_v}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \left( \frac{F_v^{\text{beam}}}{\text{mJy beam}^{-1}} \right) \left( \frac{\theta_{\text{HPBW}}}{10 \text{ arcsec}} \right)^{-2} \; (\text{A})$$

Kauffmann et al. 2008

IC5146: Herschel far infrared composite image

Arzoumanian et al. 2011
Tracers to study the early stages of star formation

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Used to get the column density (mass if we know the distance) and the temperature (if enough wavelength) of the cold interstellar dust
Tracers to study the early stages of star formation

Optically thin dust emission up to $\sim 10^{24} \text{ cm}^{-2}$

In (sub-)millimeter dust continuum emission:

$$I_\nu = B_\nu(T) \left( \frac{1}{0.01} \right)$$

$$N_{\text{H}_2} = 2.02 \times 10^{22} \text{ cm}^{-2}$$

Kauffmann et al. 2008

IC5146: Herschel far infrared composite image

Used to get the column density (mass if we know the distance) and the temperature (if enough wavelength) of the cold interstellar dust
Tracers to study the early stages of star formation

**Molecules:**

Molecular clouds are cold (~10 K) and dense (10³ cm⁻³)

> rotational transitions are the most easily excited ones

H₂, CO (~10⁻⁴) and then many others: HCN, HNC, NH₃, CS, HCO⁺ (~10⁻⁸), N₂H⁺ (~10⁻⁹)

(Onishi et al. 1991)
Tracers to study the early stages of star formation

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H₂ most abundant but no permanent electric dipole moment, so no H₂ rotational lines
CO is the second most abundant molecule, has a permanent dipole moment and its first rotational level above ground is at 5K
- easily excited
Tracers to study the early stages of star formation

First $^{12}$CO spectrum in Orion

Wilson, Jefferts, Penzias, 1970
Tracers to study the early stages of star formation

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What can we learn from molecular lines?

Integrated intensity:
- opacity, column density
- compared to col. dens. of H$_2$ gives you abundances
Tracers to study the early stages of star formation

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**Optically thin line:**
- peak velocity $\rightarrow$ systemic velocity of the source
- linewidth $\rightarrow$ velocity dispersion of the gas:

$$\Delta V^2_{\text{obs}} = \Delta V^2_{\text{Th}} + \Delta V^2_{\text{N.Th.}}$$

**Optically thick line:**
- outflow wings
- infall motions (cf later)

Wilson, Jefferts, Penzias, 1970
Tracers to study the early stages of star formation

Different molecules trace different part of the clouds

**Critical density:**

\[ n_{\text{crit}} = \frac{A_{ul}}{q_{ul}} \]

- \( A_{ul} \): spontaneous deexcitation coefficient
- \( q_{ul} \): collisional de-excitation rate

- \( n > n_{\text{crit}} \): collisional excitation
- \( n < n_{\text{crit}} \): radiative excitation

**Abundance variations:**

Chemistry and evolution (molecule formation, destruction, depletion)
Tracers to study the early stages of star formation

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Abundance variations:
Chemistry and evolution (molecule formation, destruction)

Zhang et al. 2009
Initial Mass Function and star formation

Trapezium d’Orion - VLT/ISAAC

ESO/M.McCaughrean et al. (AIP)
Initial Mass Function and star formation

Luminosity function

ESO/M.McCaughrean et al. (AIP)
Initial Mass Function and star formation

Luminosity function

Trapezium (Muench et al. 2002)

IMF

Salpeter
Initial Mass Function and star formation

Luminosity function

Is there a physical reason to separate stars in 3 mass ranges?
Do all stars form in the same way?

low-mass stars < $1 \, M_{\text{sun}}$

$1 \, M_{\text{sun}} < $ Intermediate mass stars < $8 \, M_{\text{sun}}$

Massive stars > $8 \, M_{\text{sun}}$ (Friedrich’s lectures)
Where do stars form?

- M51: sun et al. 2006
- Perseus: CO(1-0)
- Serpens: CO(2-1)
- Serpens: Spitzer 4/8/24μm

Zoom in
Where do stars form?

- M51
  - 12CO(2-1) 10 kpc, n=1cm⁻³
  - Shuster et al. 2007

- Perseus
  - 13CO(1-0) 20 pc, n=100cm⁻³
  - Sun et al. 2006

- Serpens
  - 850μm
  - Spitzer 4/8/24μm
  - Davis et al. 1999

- Serpens
  - Spitzer 4/8/24μm

Zoom in

Galaxie

Clouds

Cores

Stars

Planets
Does global gravitational collapse of molecular clouds can explain star formation rate in the Galaxy?

Total mass of observable molecular gas in the Galaxy ~ $5 \times 10^8 \, M_{\odot}$ (Dame et al. 2001)
Does global gravitational collapse of molecular clouds can explain star formation rate in the Galaxy?

Image of the galactic plane in $^{12}$CO

Dame et al 2001

Total mass of observable molecular gas in the Galaxy $\sim 5 \times 10^8$ M$_{\text{sun}}$ (Dame et al. 2001)

Average volume density of molecular clouds $\sim 100$ cm$^{-3}$
We would need $\sim 4$ Myr (freefall time) to collapse $5 \times 10^8$ M$_{\text{sun}} \rightarrow 100$ M$_{\text{sun}}$ yr$^{-1}$
Does global gravitational collapse of molecular clouds can explain star formation rate in the Galaxy?

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Observed star formation rate in the Galaxy \( \sim 1-4 \) M\(_{\text{sun}}\) yr\(^{-1}\)

(Robitaille et al. 2011 and ref therein)
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Observed star formation rate in the Galaxy \( \sim 1-4 \text{ M}_{\odot} \text{ yr}^{-1} \)

(Robitaille et al. 2011 and ref therein)

Stars do not generally form from the global collapse of molecular clouds (Zuckerman & Evans 1974)
Molecular clouds are “turbulent” structures

Larson’s relations: $\Delta V \propto L^{0.38}$ (Larson 1981) - $\Delta V \propto L^{0.5}$ (Heyer et al. 2009)

Thermal dispersion at 20K

Larson 1981
Molecular clouds are “turbulent” structures

Larson’s relations: $\Delta V \propto L^{0.38}$ (Larson 1981) - $\Delta V \propto L^{0.5}$ (Heyer et al. 2009)

Incompressible Kolmogorov turbulence: $\Delta V \propto L^{0.33}$
Virial equilibrium: $\Delta V \propto L^{0.5}$ when $n \propto r^{-1}$
A simple picture for the formation of a single star

Star formation efficiency

\[ \varepsilon = \frac{M_{\text{star}}}{M_{\text{star}} + M_{\text{core}}} \]
A simple picture for the formation of a stellar cluster

\[ \subseteq = \text{cst} \rightarrow \text{Core mass function must be similar to the IMF shifted by a factor } \subseteq \rightarrow \text{Mapping the CMF (Motte et al. 1998; Johnstone et al. 2000; Enoch et al. 2008; etc..)} \]
A simple picture for the formation of a stellar cluster

Aquilla cloud: Herschel image (70/250/500 micron)

\[ \langle \ell = \text{cst} \rightarrow \rangle \text{Core mass function must be similar to the IMF shifted by a factor} \quad \langle \ell \rightarrow \rangle \]

Mapping the CMF (Motte et al. 1998; Johnstone et al. 2000; Enoch et al. 2008; etc.)

CMF provides the IMF with a star formation efficiency \( \langle \ell = 30\% \)
Is stellar cluster formation that simple?

**Assumptions:**
1. Core as the mass reservoir for the proto-star
2. Constant ∈

**Implications:**
- No accretion onto the core, No core merging
- Same accretion history for all protostars, No enhancement or early termination of protostellar accretion
- Massive stars form in the exact same way as low-mass stars

-> Kinematics and feedback cannot be important
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→ Kinematics and feedback cannot be important

And then even if everything was true... well we just shift the problem one step upward
How do we know that a prestellar core is a prestellar core?

Virial equilibrium: \( \partial^2_t I = 0 \)

See Spitzer 1978

Without magnetic field

\[
0 = \frac{3}{2} M \sigma^2 - 4\pi R^3 P_s - a \frac{GM^2}{R}
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**Virial equilibrium**

- \( M = 1 \, M_{\text{sun}} \)
- \( T = 10 \text{K} \)
- Uniform density

![Graph showing pressure vs. radius for prestellar core](image-url)
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Critical Bonnor Ebert Sphere: solutions of hydrostatic equilibrium

\[
M_{BE} \approx 1.18 \frac{\sigma^4}{G^{3/2} P_s^{1/2}} = 0.47 M_\odot \left( \frac{\sigma}{0.2 \text{ km s}^{-1}} \right)^4 \left( \frac{P_s/k_B}{10^6 \text{ K cm}^{-3}} \right)^{-1/2}
\]

\( M, R, \sigma \)

Virial equilibrium

\( \text{Radius, } R \text{ (pc)} \)

\( \text{Pressure, } P_s \text{ (K/cm}^3) \)
How do we know that a prestellar core is a prestellar core?

On core size (< 0.1pc) the linewidths (kinetic support) are sub-sonic (e.g. Myers & Benson 1983, Jijina et al. 1999, Hacar & Tafalla 2011)

Prestellar cores are gravitationally bound structures
How do we know that a prestellar core is a prestellar core?

Blue-shifted self-absorbed optically thick spectra + optically thin line probing the systemic velocity near the dip of the self-absorbed signature

Belloche et al. 2002
How do we know that a prestellar core is a prestellar core?

Use of self-absorbed lines to probe collapse in cores
(Tafalla et al. 1999; Mardones et al. 1999; Fuller et al. 2005)

Statistical surveys of velocity shifts: \((V_{\text{thick}} - V_{\text{thin}})/\Delta V_{\text{thin}}\)

Most bound starless cores are slowly collapsing:
They are true prestellar cores

Lee & Myers 2011
Prestellar cores as finite reservoirs for star formation?

Density profiles of isolated cores seem to show core edges

- **L1544**: 1.2mm dust continuum emission
- **Oph D**: ISO 7micron extinction

Ward-Thompson et al. 1999
Bacmann et al. 2000
Tafalla et al. 2002
Bergin & Tafalla, 2007
Most stars form in clusters (e.g. Lada & Lada 2003)

Prestellar cores as finite reservoirs for star formation?

Ophiuchus: Vista image ESO credit
Prestellar cores as finite reservoirs for star formation?

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MAMBO 1.2mm dust continuum

Motte et al. 1998
Most stars form in clusters (e.g. Lada & Lada 2003)

MAMBO 1.2mm dust continuum

Sources are more compact in proto-clusters and evidence for edges are unclear, PdBI and ALMA can definitely help in that respect

Motte et al. 1998