Cores, Stars, and Clusters

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## Summary

**isolated cores**... form 0-few low-mass stars

<table>
<thead>
<tr>
<th>geometry</th>
<th>centrally condensed, aspherical, embedded in filaments</th>
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<tr>
<td>physics</td>
<td>sparse, cold, thermal &gt; turbulent, <strong>contracting</strong>, ~ magnetic</td>
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<td>cold: freeze-out (CO), neutral (N$_2$H$^+$), enhanced (DX)</td>
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<td>models</td>
<td>expanding, self-gravitating, condensing, <strong>collapsing</strong></td>
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<td>evolution</td>
<td><strong>prestellar cores seem evolved, cores with VLM stars don’t</strong></td>
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**cluster-forming cores**... form more stars, more massive stars

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<td>physics</td>
<td><strong>numerous</strong>, hot, thermal &gt; turbulent, <strong>contracting</strong></td>
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<td>chemistry</td>
<td>hot: <strong>diversity of species</strong>, liberation, shocks</td>
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<td>models</td>
<td>collapse and accretion in a centrally condensed layer</td>
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Cores are Centrally Condensed

B68 optical, NIR absorption
Alves, Lada & Lada 01

L1498, L1517B millimeter emission
Tafalla et al 04
Many Models Fit Flat-Top Profile

magnetic contraction
Ciolek & Basu 00

spherical isothermal eq.
Lada, Alves & Lada 01

turbulent fragmentation
Ballesteros-Paredes et al 03

early spherical collapse
Whitworth & Ward-Thompson 01

top for many shapes, collapse ages

need more information to choose among models
Infall Asymmetry Probes Inward Motion

- Red-shifted self-absorption, increases with $\tau$, $v_{in}/\sigma_v$
- To create: $\tau>1$, grad $T_{ex}<0$
- To detect: $\Delta v/\delta v>>1$, S/N>>1
- To understand: multi-lines, maps, and models

Hummer & Rybicki 68
Bourke et al 05
Freeze-out Selects Dense Gas

- CO freeze-out expected in dense gas (Leger 1983).

- CO and CS should deplete more than N₂H⁺, NH₃ where n ~ 10⁴ cm⁻³ (Bergin & Langer 1997).

- N₂H⁺ and NH₃ follow dust; other species have “depletion holes” r ~ 0.05 pc (Caselli et al 99, Tafalla et al 2002).

- Choose proper lines to probe inner and outer core regions.

Tafalla et al 2004
Contraction is More Common than Expansion

• CS 3-2 and 2-1 line shifts are correlated
• \( \delta V = (V_{\text{thick}} - V_{\text{thin}}) / \Delta V_{\text{thin}} \)
• 14 cores with \( \delta V < -0.5 \) (22% - common)
• 3 cores with \( \delta V > +0.5 \) (5% - rare)
Infall Asymmetry in Many Cores and Stars

Table criteria:

Starless cores with infall asymmetry in at least two of four mapped lines (Lee et al 04, Bourke et al 05)

<table>
<thead>
<tr>
<th>CORE</th>
<th>CS 2-1</th>
<th>CS 3-2</th>
<th>DCO$^+$ 21</th>
<th>N$_2$H$^+$ 1-0</th>
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<tbody>
<tr>
<td>L1544</td>
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<td>L694-2</td>
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<td>L234E-S</td>
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Colors of 15 Infall Candidates

-----outer-----  -----inner-----
CS Infall Asymmetry from “Outer Core”

- $N_2H^+$ 1-0 (gray) traces dense core, extends over ~0.1 pc
- CS 2-1 spectra with infall asymmetry extend over ~0.2 pc, typical of 18 maps (Lee et al. 2001)
Deep N$_2$H$^+$ Spectra Trace Inner Core Motions

infall asymmetry but no infall “wings”

Bourke et al 05
Inner and Outer Core Motions

Outer core -
$n_{\text{cr}} \sim 10^4 \text{ cm}^{-3}$, $\tau > 1$,
freeze-out species
(CS, H$_2$CO)

Inner core -
$n_{\text{cr}} \sim 10^5 \text{ cm}^{-3}$, $\tau > 1$,
“anti-freeze” species
(N$_2$H$^+$, H$_2$CO)

$V_{\text{in}}(\text{inner}) > V_{\text{in}}(\text{outer})$
for L1544 and L694

$V_{\text{in}}$ (km s$^{-1}$)

0.1
0.1
0.04
0.02

Bourke et al. 05
Velocities Increase Inward in Maps

From $x \approx 0.05$ to $0.01$ pc...
DCO$^+$ and N$_2$H$^+$ lines get brighter, broader, and bluer
model infall speed $v_{\text{in}}$ increases from 0.01 to 0.1 km s$^{-1}$
Static and Collapsing B-E Profiles

density and velocity profiles together: L1544 and L694 may be in early stages of collapse from centrally condensed initial state
Prestellar cores seem more “evolved” than other starless cores in column density, deuteration, CO depletion, dust density, line width, infall asymmetry.

Does every low-mass star form from such a prestellar core? (No...)
A Spitzer Source in a “Starless” Core

L1014

DSS R-band

Spitzer blue=3.6 \( \mu \text{m} \), green=8.0\( \mu \text{m} \), red=24\( \mu \text{m} \)
Spitzer Source is Probably A Protostar

L1014

L1014 Source and Core Properties

Source:
model bb+disk+envelope
M* << 0.1 M_O --a very young protostar or proto-BD
(D=200 pc) No CO outflow

Core:
weaker than typical "prestellar" core by factors 2-5 in 1.2 mm dust emission, N, n, ΔT_B(N_2H^+)
--Crapsi et al 05

--a very low-mass "star" in a low-mass core

L1148B - Another Spitzer Surprise

0.1 $L_\odot$ source near peak of mm emission from an ordinary “starless” core

SED similar to that of L1014, but with less emission in mid-IR

Preliminary result, less well studied than L1014

L1014 and L1148B protostars did not form in prestellar cores like L1544

*Not all differences among cores are due to evolution*

---

Kauffmann & Bertoldi 05
Where Clusters Form: “Blobs,” not “Filaments”

Cluster-forming geometry: blobs are dense, low-aspect-ratio “hubs” for filaments with low density, high aspect ratio, and low star formation efficiency. 

Speculation: blobs are “layers” whose geometry promotes star formation
Embedded Cluster NGC 1333

Spitzer IRAC 1,2,3 Porras et al 05

JHK Lada & Lada 2003
93 $N_2H^+$ Clumps in NGC1333

big clump
M = 1.6 $M_\odot$
R = 0.03 pc
$\Delta v = 0.5$ km s$^{-1}$

BIMA + FCRAO

small clump
M = 0.05 $M_\odot$
R < 0.01 pc
$\Delta v < 0.2$ km s$^{-1}$

Walsh et al 05

~100 dense clumps in 1 pc$^2$ - more than in isolated regions
Inward Motions on Many Scales

Localized \( \sim 0.01 \) pc

Extended \( 0.1 - 0.3 \) pc

\[ V_{\text{peak}, N_2H^+} \approx V_{\text{dip}, HCO^+} \Rightarrow 2 \text{ peaks due to self-absorption, not 2 unrelated layers} \]

Walsh et al (2004b)

Di Francesco et al (2001)
“Infall asymmetry” in HCO$^+$ 3-2 and 1-0 extends over $>0.2$ pc, includes three protostellar groups, red asymmetry localized to protostars (Walsh et al 2004b)
Inward Motions Around Complex

Blue asymmetry in HCO$^+$ 1-0 extends over ~0.6 pc (also some red near protostars)

Similar to HCO$^+$ 3-2 but at lower density, larger scale

Effective inward speed few 0.1 km s$^{-1}$ --> sonic flows

Similar to Serpens (CS 2-1, Williams & Myers 1999)

Walsh et al 05
# Multiscale Inward Motions

<table>
<thead>
<tr>
<th>Radius (pc)</th>
<th>Density (cm(^{-3}))</th>
<th>(V_{\text{in}}) (km s(^{-1}))</th>
<th>(\frac{\text{d}M}{\text{d}t}) (10(^{-5}) M(_{\odot}) yr(^{-1}))</th>
</tr>
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<tbody>
<tr>
<td>0.01</td>
<td>3 (10^5)</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>3 (10^4)</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>0.3</td>
<td>2 (10^3)</td>
<td>0.2</td>
<td>3</td>
</tr>
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\(\frac{\text{d}M}{\text{d}t}\) is “star-forming” on small scale but too small to be “cluster-forming” on large scale (late-stage accretion?)
Chemical Diversity in Hot Cores

SMA submillimeter observations of Orion KL - Beuther et al 04
Diverse Species Reveal Hot Chemistry

4 GHz SMA bandwidth harbors >50 lines from dozens of species - liberation from grain mantles, shock-enhanced chemistry
Resolving Abundance Structure

S and Si-bearing molecules

O-bearing molecules

N-bearing molecules
Hot Chemistry in Low Mass Envelopes

Complex species found in low mass protostar envelopes I16293 and NGC1333 IRAS4A at high resolution (IRAM 30-m)

Complex species are no longer limited to hot cores like Orion KL

Molecular composition of ice mantles, liberation by photoheating, gas phase processing may be similar between cold and hot cores
Modelling Star Formation in Clusters

| Importance: | most stars form in clusters (Lada & Lada 03) |
| Constraints: | high number density of cores |
| | >100 stars in ~1 pc³ in ~ 1 Myr |
| | massive stars |
| | MF of clumps (Motte, André, & Neri 98) |
| | MF of stars (Salpeter 54) |

| Key model: | turbulent fragmentation (Elmegreen 93, Padoan 95, Ballesteros-Paredes et al 99, Klessen et al 00, MacLow & Klessen 04) |

| Today: | collapse and accretion in a centrally condensed layer |
A self-gravitating isothermal layer has more than half its mass in gas denser than $0.75 \, n_{\text{max}} \Rightarrow$ more dense cores, more accretion than in spheres or cylinders
Layer Accretion Can Make Massive Stars

Steady flow onto stationary point source (Bondi 52) has solution for layer flow (2D) but not filament flow (1D).

2D flow is like large-scale disk accretion with no rotation.

\[
\frac{dm}{dt} \propto m \Rightarrow \text{exponential growth with time scale } \tau_{\text{acc}} \sim (G \rho_{0,\text{layer}})^{-1/2}
\]

toy model - critical isothermal sphere embedded in layer collapses, then layer accretes.
Matching the IMF

Assume densest gas is in isothermal spheres which model ‘prestellar cores’ (Ward-Thompson, Motte & André 94).

spheres are either isolated or ‘embedded’ in filaments or layers (Curry 00).

collapsing spheres accrete layer gas.

outflows, turbulence, ejection, and competition stop collapse and accretion with equal likelihood in each ∆t - ‘random stopping’ (Myers 00, Basu & Jones 04)

cf. Muench et al 02, Lada & Lada 03
spherical collapse + random stopping...

matches low-mass slope (=2/3, property of isothermal sphere)

gives peak mass 0.2 M$_\odot$
for T=10 K, n$_0$=3-10$\times$10$^5$ cm$^{-3}$

cannot match high-mass IMF slope (Salpeter 55).

accretion + random stopping can match high-mass IMF slope.

high-mass slopes match if mean stopping time=(3/4) $\tau_{acc}$
Summary

isolated cores... form 0-few low-mass stars

- **geometry**: centrally condensed, aspherical, embedded in filaments
- **physics**: sparse, cold, thermal > turbulent, **contracting**, ~ magnetic
- **chemistry**: cold: freeze-out (CO), neutral (N$_2$H$^+$), enhanced (DX)
- **models**: expanding, self-gravitating, condensing, **collapsing**
- **evolution**: prestellar cores seem evolved, cores with VLM stars don’t

cluster-forming cores... form more stars, more massive stars

- **geometry**: centrally condensed, aspherical, **embedded in “blobs”**
- **physics**: numerous, hot, thermal > turbulent, **contracting**
- **chemistry**: hot: diversity of species, liberation, shocks
- **models**: collapse and accretion in a centrally condensed layer