Dense cores. Recent work

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Evolution of core studies

• "Classical" period: global properties

- angular resolution > arcminute (unresolved)
- mass, size, shape, mean density, mean linewidth
- Benson & Myers (1989), Jijina, Myers, Adams (1999)
- "Modern" period: internal structure
 - observations resolve cores
 - combination of tracers (esp. gas + dust)
 - emphasis on starless cores (initial conditions of SF)

• This talk:

- internal structure: density, velocity, chemical composition, temperature
- new surveys of full core populations in clouds

Density structure

Deviation from single power law

- Ward-Thompson et al. (1994)
- single-pixel mm/submm bolometer observations
- central flattening of density profile

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A submillimetre continuum survey of pre-protostellar cores

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ABSTRACT

Results are presented of a submillimetre continuum survey of 21 Myers cores that have no known infrared (near-IR or *IRAS*) associations – the so-called 'starless cores'. ¹³CO maps show that 17 of the cores have structure in the form of one or more clumps, with significant departures from spherical symmetry. The clumps were surveyed in the submillimetre continuum, but only 12 were detected. In all cases no more than one clump in each of the Myers cores was detected in the continuum, no matter how many ¹³CO clumps it contained. Five of the clumps were mapped in the continuum to demonstrate.

Density structure: central flattening



Fig. from Bergin & Tafalla (2007) ARAA

- Let's start by studing the density structure of cores.
- This is one of the most important observables, and there is a number of ways to study it.
- The most reliable ones are based on the use of dust measurements, which do not suffer from the depletion problem that affects molecules and which we study later
- The dust traces column density, so all these models require some deprojection to convert this parameter into a volume density.
- Spherical symmetry is usually assumed.
- 1. The first method measures the redening of background stars to produce a distribution of visual of IR extiction, which is converted into a colum density assuming some dust properties
- 2. The second method uses the mm or submm emission from the dust to derive a radial profile of flux as a function of radius. Assuming some emissivity for the dust and a dust temperature, the flux profile can be converted into a column density profile
- 3. The third method illustratd here uses extiction againist the diffuse MIR background. Asumming dust propeties in the MIR, we can again convert the measured distribution of extinction into column density
- All these models depend on different assumptions but tend to given consistent results, in particular, they show that the density profile flattens towards the core center
- Explain in some detail.

Ambipolar diffusion fits



Fig. 9. Comparison of the magnetically supported core model B_{UV} (at time t_2) from CM95 with the column density profiles of L1544 and Oph D (see Table 6 for model parameters).

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Source	Model	Inclination angle i	Scaling factor γ	$n_{c,0} ({\rm cm}^{-3})$	B_{ref} (μ G)	reduced χ^2
L1544	model B_{UV} of CM95 at t_2	75 °	1	2.6×10 ³	35	5.2
Oph D	model B_{UV} of CM95 at t_2	75 °	1	2.6×10^{3}	35	1.3
L1709A	model 7 of BM95 at t ₂	70 °	1.5	4.5×10^{3}	150	3
L1689B	model 7 of BM95 at t ₂	65 °	1.7	5.1×10^{3}	170	~ 2
L328	model B_{UV} of CM95 at t_2	0 °	1.4	3.6×10 ³	50	6.8
L429	model 7 of BM95 at t ₃	65 °	1	3×10^3	100	5.7
GF5	model 7 of BM95 at t_2	60 °	1	3×10^3	100	3.3

- Isothermal spheres are not the only models that produce central flattening.
- In this example, Bacmann et al fitted a series of density profiles with models of ambipolar diffusion from Mouschovias and collaborators.
- As can be seen, the fits are relatively good, but the implied magnetic fields seem in some cases higher than expected

Bonnor-Ebert sphere fits



Problem with isothermal sphere fits

- required T_K often too high (factor 2)
- too many unstable cores (Kandori et al. 2005)
- cores are not spherical (Myers et al. 1991)

- The most elegant example of a core determination is that of B68 done by Alves et al.
- It isllustrates clearly how the density profile does not follow a power law at the center but flattens in
- The central 5,000 AU or so.
- The exact shape of the curve is nicely fitted with an isothermal sphere very close to the point of gravitational instability

"Alternative" fits

- Simple analytic 3-parameter fit
 - Tafalla et al. (2002), Dapp & Basu (2009)
 - but von Neumann could fit an elephant with 4 param. (Fermi)

Dynamical cores formed in turbulence simulations

- Ballesteros-Paredes et al. (2003)
- non equilibrium strutures
- Collapsing Bonnor-Ebert spheres
 - Myers (2005), Kandori et al. (2005)

Density profile is not a good constraint on core equilibrium state



$$n(r) = \frac{n_0}{1 + (r/r_0)^{\alpha}},$$

Velocity field



- Core linewidth-size relation flatter than in cloud
 - break down from Larson's (1981) law
 - cores are velocity coherent (Goodman et al. 1998)

- The analysis we have seen before was based on measuremens towards the core centers
- Maps of the spatial distribution of linewidths allow us to study its dependence as a function of distance to the core center.
- In their 1998 study, Goodman et al found that the linewidth-size relation seen in cores as a whole, and often referred to as Larson's law, breaks down inside cores.
- They coined the term velocity coherence to descrie this effect
- Higher S/N data from more recent observations illustrates the extreme coherence of some cores, like L1498, and the very small level of NT motions compared with the sound speed.

Non-zero non-thermal component



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Velocity centroid variations (pos)



- Caselli et al. (2002)
 - no solid body rotation but more complex internal motions
 - possible correlation with linewidth
 - order of 0.1 km/s
- Unclear origin
 - residual turbulence?
 - time scale ~ 0.1 pc/0.1 km/s = 1 Myr. Related to core formation?

Line of sight inward motions



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- The final element of kinematics that I'll discuss is the presence of _ inward motions in cores
- These motions are inferred from studying the shape of the line profiles of optically thick lines
- This profile often presents a self absorption dip, which results from the presence of low-excitation material in the fron part of the cloud. The velocity of the absorption informs us of the velocity of the material in the front of the cloud, and comparing this velocity with that of the back, we can infer inwards or outward motions along the los
- Evidence for infall known towards protostars (esp. Class 0) and usually interpreted as star-forming gravitational infall.
- More surprising was the find of infall profiles towards starless cores

Chemical structure

- Molecular line emission needed for tracing gas component and kinematics
- Previous evidence for discrepancies between line tracers: CS vs NH₃



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Molecular differentiation in L1498

- Kuiper, Langer & Velusamy (1996)
 - L1498: onion-shell structure
 - CS and CCS ring + NH₃ central peak
- Interpreted as selective depletion/freeze out
 - Bergin & Langer (1997)
 - CO and N₂ have different binding energies onto grains
 - (but Bischopp et al. 2006)



CO freeze out



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Molecular freeze out

Gas-grain equilibrium (sticking vs evaporation) is almost step function

- if T_{grain} > T_{freezeout}, most molecules in gas phase
- if T_{grain} < T_{freezeout}, most molecules on grains
- T_{freezeout} ~ 16 K for CO

Time scale: gas-grain collision (~ 5 10⁹/n(H₂) yr)



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- The presence of molecules in the gas phase is controlled by the equilibrium between sticking and evaporation.
- The process is like a phase transition, in the sense that there is a critical temperature set by the temperature of the dust grains. If Tgrain...
- This plot shows the effect for a simple case with only thermal evaporation. As can be seen, below about 15 K, molecules are not expected to be present in the gas phase.



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- To reach the above situation of freeze out, molecules have to collide with grains, and this sets the time scale of the problem.
- As can be seen, the time scale depends inversely proportional to density, and can become very short
- In a core center with 1e5 cm-3, it becomes if the order of 5e4 yr, which is much shorter than the freefall time

Molecular differentiation in B68



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 Evidence for freeze out appear as emission holes in the maps of some molecules

Bergin et al. (2002)

Molecular differentiation



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- By modeling the physical structure of the cloud, we can determine the abundance variation of a number of molecules

L1517B

NH₃ and N₂H⁺ are truly unique

MOLECU	$\mathbf{LE} = \mathbf{X}_0$	R _{hole} (cm)	
\mathbf{NH}_3	$2.8 imes10^{-8}$	_	
$\mathbf{N}_{2}\mathbf{H}^{+}$	$1.7 imes \mathbf{10^{-10}}$	_	
\mathbf{DCO}^+	$5.0 imes10^{-11}$	0.65×10^{17}	
HCN	$\textbf{7.0}\times\textbf{10^{-9}}$	$0.8 imes10^{17}$	
$\mathbf{HC}_{3}\mathbf{N}$	$5.0 imes \mathbf{10^{-10}}$	$0.8 imes10^{17}$	
\mathbf{CS}	$\textbf{3.0}\times\textbf{10^{-9}}$	$1.0 imes10^{17}$	

NO/INNER DEPLETION

MOLECULE	$\mathbf{Z} = \mathbf{X}_0$	R _{hole} (cm)	
$\mathbf{C}_3\mathbf{H}_2$	1.6×10^{-9}	$1.1 imes10^{17}$	
\mathbf{HCO}^+	3.0×10^{-9}	1.15×10^{17}	
CH_3OH	$6.0 imes10^{-10}$	$1.2 imes10^{17}$	
H_2CO	$1.3 imes10^{-9}$	$1.3 imes 10^{17}$	
CCS	$4.0 imes10^{-10}$	1.25×10^{17}	
SO	1.25×10^{-9}	$1.5 imes10^{17}$	
CO	2.5×10^{5}	$1.5 imes10^{17}$	

Some exceptions

- very young cores with no CO freeze out (e.g., L1521E): Hirota et al. (2002), Tafalla & Santiago (2004)

- "anomalous" cores (Friessen et al. 2009 in Oph, Olmi et al. 2005 in Perseus)

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OUTER DEPLETION

Deuteration

 Deuterium fractionation as a consequence of CO depletion in low temperature gas

 $H_3^+ + HD \iff H_2D^+ + H_2 + 230 \text{ K}$

- If no CO depletion
 - H₂D⁺ abundance is limited by CO destruction (+e)
 - D enrichment of order of 1-10 %
- If CO depletion (and low e)
 - H₂D⁺ is further enhanced, which further enhances N₂D⁺, NH₂D, etc.
 - even D₂H⁺ and D₃⁺ are produced: multiply deuterated species



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Further evidence for enhanced deuteration



- Recent detections od deuterated versions of H₃⁺
 - H₂D⁺ in L1544 (Caselli et al. 2003)
 - D₂H⁺ in IRAS 16293E (Vastel et al. 2004)

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!""

Gas and dust temperature

Dust and gas temperature set by heating = cooling
If n(H₂) > 10⁵ cm⁻³, dust and gas are coupled thermally



- Another important parameter of a core is the temperature of the core.
- When talking about temperature, we need to distinguish between the temperature of the dust and the gas components.
- Each of them is set by the balance between heating and cooling processes.
- They can differ because both components do not become coupled thermally up to densities of about 1e5 cm-3
- The general behavior is shown here in a model by Galli et al.
- The left panel represents a model for a typical los mass core in Taurus with a central density of a few 1e5
- Both the dust and gas temperature decrease outward and are similar but exactly equal. The dust is colder than the gas.
- The right panel presentes a model for a denser core showing how dust and gas temperatures equalize in the interior. The temperature of this model is higher because the model assumes a more intense external radiation field

T_d drops towards UV-extincted core center



- The large scale temperature gradient seems to continue inside the core (not resolved in previous data)
- This is shown by the plot from Kramers et al, who have combined NIR dust extiction observations with mm dust emission data. As can be seen, the temperature drops below 10K in the most opaque region of the core.
- A similar behavior was found by Pagani et al in the very opaque cloud L183, where the central temperaure
- Is estimated in about 7K.
- In addition to the temperature drop, the data show a systematic change in the optical properties of the dust grains in the form of a variable ratio between opacities. This is consistent with the result from grain growth due to coagulation, that makes the population of small grains dissapear and be replaced by a population of fluffy grains
- A more extreme example of grain growth is illustrated by the ISDP captured in the Earth's upper atmosfere
- Show where core center is!

Gas temperature. Radial profiles



- Using higher angular resolution, we can determine the radial profile of gas temperature in a core
- Moderately dense cores show an almost flat distribution, again centered around 10 K, when observed with 40 arcsec resolution
- Interferometric observations can penetrate deeper, and for the case of the denser L1544, Crapsi et al. finds a central temperature drop consistent with the expectations of gas-dust thermal coupling
- Similar drops have been found in a few other cores, again indicating the possible onset of thermal coupling.
- If this is so, we may be witnessing a change in the gas EOS, and this may have consequences for stability, as suggested by Larson, Withworth and others.

Sampling the entire core population in clouds

- Complementary approach to detailed studies of individual cores. It provides
 - statistics on core parameters (mass, size, density)
 - dependence on environment
- Initial (bolometer) studies: CMF mimics IMF
 - Motte et al. (1998), Johnstone et al. (2000)



Sampling the entire core population in Perseus

• Perseus

- c2d (Evans et al. 2003) and COMPLETE (Ridge et al. 2006)
- Bolometer: Hatchell et al. (2005), Enoch et al. (2006)
- NH₃ (+CCS): Rosolowski et al. (2008), Foster et al. (2009), Schnee et al. (2009)
- further obs/analysis: Joergensen et al. (2006), Kirk et al. (2007), Hatchell & Fuller (2008), Enoch et al. (2008), Johnstone et al. (2009)



Sampling the entire core population in the Pipe Nebula

• Pipe Nebula

- extinction: Lombardi et al. (2006), Alves et al. (2007)

- C¹⁸O: Muench et al. (2007)

-NH₃: Rathborne et al. (2008)

- analysis: Lada et al. (2008)



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Conclusions

• Enormous progress in determining internal structure of cores during last decade

- flattened density distributions
- coherent velocity field (+infall, etc.)
- chemical differentiation
- central temperature drop ?
- First fruits from studies of full populations in cores
 - role of fragmentation/core formation in IMF
 - environmental effects on core properties

• Future surveys

- Herschel Space Observatory, SCUBA 2

It's never been a better time to study Dense Cores in Dark Clouds[™] !