Initial Conditions for Star Formation

Neal J. Evans II

Why Initial Conditions?

- Many calculations of collapse
  - Depend on initial conditions
- Relevant Initial Conditions
  - Density distribution: n(r)
  - Velocity
    - turbulence
    - rotation
  - Magnetic field (subcritical or not?)
  - Ionization (if subcritical, $t_{AD} \sim x_e$)

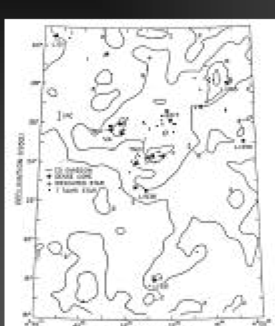
Focus on Density

- Larson-Penston
  - Uniform density
    - fast collapse, high accretion rate
- Shu
  - Singular isothermal sphere $n(r) \sim r^{-2}$
    - slow infall, low, constant accretion rate
- Foster and Chevalier
  - Bonner-Ebert sphere
    - initial fast collapse (LP), relaxes toward Shu

Low Mass vs. High Mass

- Low Mass star formation
  - “Isolated” (time to form < time to interact)
  - Low turbulence (less than thermal support)
  - Nearby (~ 100 pc)
- High Mass star formation
  - “Clustered” (time to form > time to interact)
  - Turbulence >> thermal
  - More distant (>400 pc)

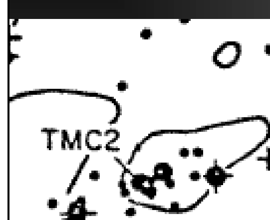
Even “Isolated” SF Clusters

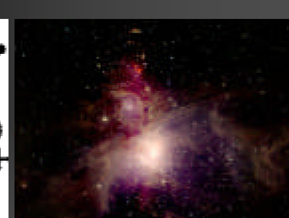


Taurus Molecular Cloud
Prototypical region of
“Isolated” star formation

Myers 1987

But Not Nearly as Much





Taurus Cloud at same scale
4 dense cores, 4 obscured stars
~15 T Tauri stars

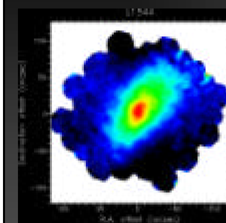
1 pc

Orion Nebula Cluster
>1000 stars
2MASS image

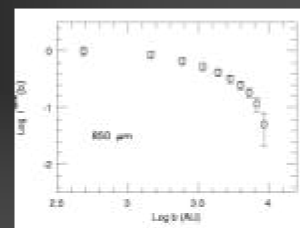
Low Mass Initial Conditions

- Molecular line maps: denser cores
  - $n > 10^4$ cm^{-3}
- IRAS: some not seen (starless cores)
- Submm dust emission from some starless
  - Pre-protostellar cores (PPCs)
- ISO: detected FIR, but not point like
  - Consistent with heating by ISRF
- SCUBA: submm maps made "easy"
  - Study n(r)

SCUBA Map of PPC

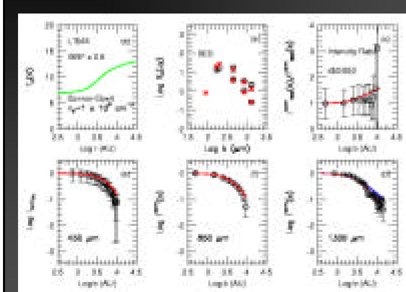


850 micron map of L1544
A PPC in Taurus
Shirley et al. 2000



Radial Profile, from azimuthal average

Results of Modeling



Density:
Bonnor-Ebert
$n_c = 10^6$ cm^{-3}

Dust temp.
Calculated for n(r)
Heated by ISRF
Drops to 7K inside

Fits radial profiles
and SED well.

Evans 2001

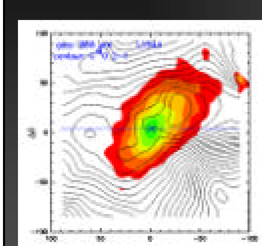
Results of Dust Modeling

- Centrally peaked density
  - Bonnor-Ebert sphere is a good model
  - Central density reaches 10^6 cm^{-3}
  - May approach singular isothermal sphere
- Dust temperature very low toward center
  - Down to about 7 K
  - Affects emission
- Some cores denser than others
  - Evolutionary sequence of PPCs?

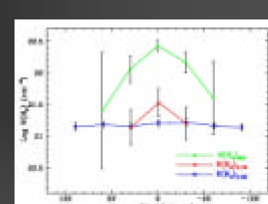
Molecular Line Studies

- Study of PPCs with dust emission models
- Maps of species to probe specific things
  - $C^{18}O$, $C^{17}O$, HCO^+, $H^{13}CO^+$, DCO^+, N_2H^+, CCS

The PPC is Invisible to Some

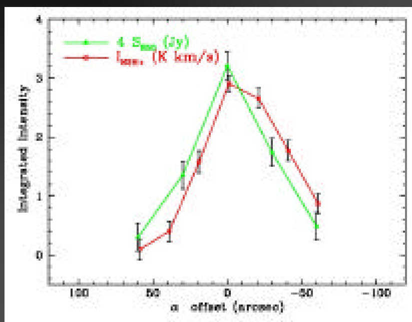


Color: 850 micron dust continuum
Contours: $C^{18}O$ emission



Cut in RA: Convert to $N(H_2)$ with standard assumptions
$C^{18}O$ does not peak
$C^{17}O$ slight peak
Optical Depth plus depletion

Others See It



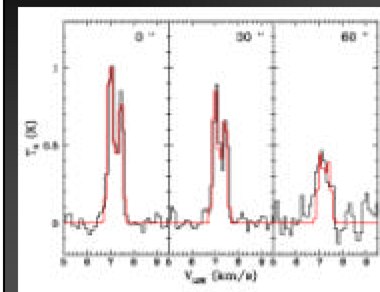
Green: 850 mic.
Red: N_2H^+ traces PPC

Agrees with predictions of chemical models

Nitrogen based and ions less depleted.

Lee et al. 2002

Evidence for Infall Motions



Line profiles of HCO^+
Double peaked,
Blue peak stronger
Signature of inward motion.

Red: Model with simple dynamics, depletion model fits the data.

Lee et al. 2002

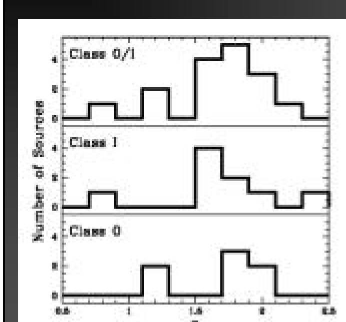
Results for Low Mass

- Dust traces density
  - Must account for temperature
- Bonnor-Ebert spheres fit well
  - High central densities imply unstable
- Cold, dense interior causes heavy depletion
- Molecular emission affected by
  - Opacity, depletion, low temperature
- Evidence of inward motions
  - Before central source forms

Not Quite Initial…

- Once central source forms, self-luminous
  - Class 0 evolving to Class I
- Similar studies of dust emission show
  - Power laws fit well: $n(r) = n_f(r)\ (r/r_f)^{-p}$
  - Aspherical sources have lower p
  - Most rather spherical
    - For those, <p> ~1.8

Distributions of p



Cores with p<1.5 are quite aspherical

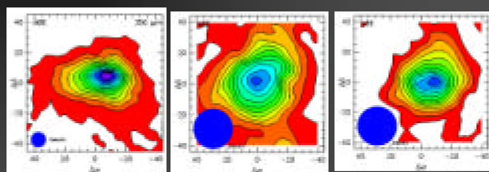
Spherical cores have p in narrow range.
<p> = 1.8 +/–0.2

Shirley et al. 2002
Young et al. 2002

Studies of High Mass Regions

- Survey of water masers for CS
  - Early, but not initial
  - Plume et al. (1991, 1997)
  - Dense: <log n> = 5.9
- Maps of 51 at 350 micron dust emission
  - Mueller et al. 2002, Poster 71.02
- Maps of 63 in CS J = 5–4 emission
  - Shirley et al. 2002
- Maps of 24 in CS J=7–6 emission
  - Knez et al. 2002

Example of Maps



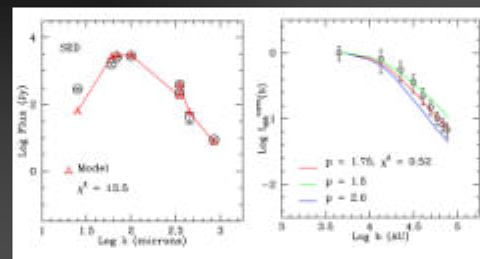
350 micron Dust
4 sigma contours

CS J=5–4
Int. Intensity
4 sigma contours

CS J=7–6
Int. Intensity
4 sigma contours

M8E

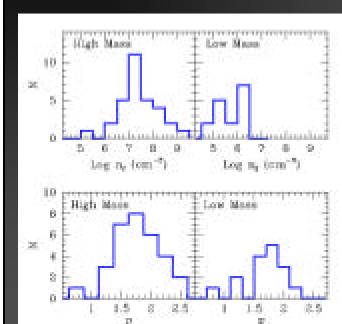
Modeling the Dust Emission



M8E Model: Best fit to SED, radial profile

Mueller et al. 2002

Distribution of p, n_f



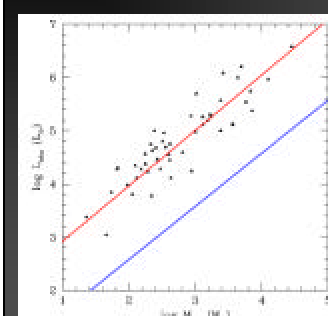
Distributions of p
(Shape of density dist.)
are similar

Fiducial density is
higher by 70–230 for
massive regions.

n_f is density at 1000 AU

Mueller et al. (2002)

Luminosity versus Mass



Log Luminosity vs. Log M

red line: masses of dense
cores from dust
Log L = 1.9 + log M

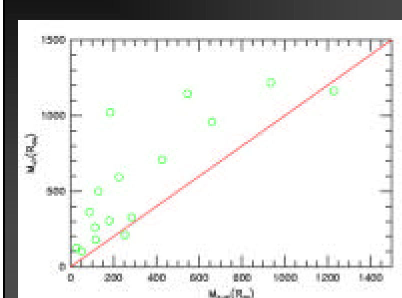
blue line: masses of GMCs
from CO
Log L = 0.6 + log M

Mueller et al. (2002)

Results from Dust Models

- Power laws fit well
  - <p> ~ 1.8 (~ same as for low mass)
  - Denser (n_f 1–2 orders of magnitude higher)
- Luminosity correlates well with core mass
  - Less scatter than for GMCs as a whole
  - L/M much higher than for GMCs as a whole
- Using DUST mass (as in some high-z work)
  - L/M_{dust} ~ 1.4 x 10^4 L_{sun}/M_{sun} ~ high-z starbursts
  - Starburst: all gas like dense cores?

Virial Mass vs. Mass from Dust



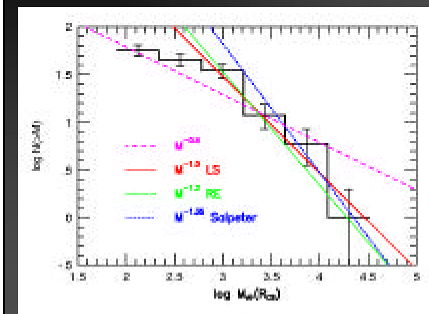
Virial Mass from CS
vs. Mass from Dust

Correlate well

Good agreement
$\langle M_v/M_d \rangle$ = 2.4+/–1.4
Dust opacities
about right
(to factor of 2)

Shirley et al. 2002

Cumulative Mass Function

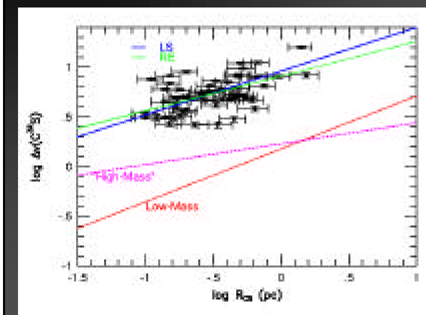


For logM>2.5
Power law
Slope ~ 1.1
(Lower masses incomplete)

Clouds: 0.5
Stars: ~1.35

Shirley et al. 2002

Linewidth versus Size



Shirley et al. 2002

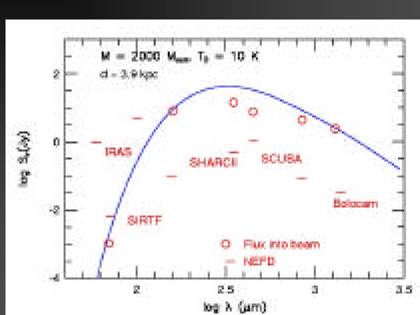
Results from Molecular Studies

- Virial mass correlates with mass from dust
- Mass distribution closer to stars than GMCs
- Much more turbulent
  - than low mass cores
  - than usual relations would predict

INITIAL Conditions: Speculation

- Based on sample from maser study
  - Massive: <M> ~ 2000 M_{sun} from dust
  - Dense
  - Tending toward power law density, p ~ 1.8
  - Turbulent? (assume virial)
- But COLD (heated only by ISRF)
- No clear examples known

Predicted SED



High vs. Low Initial Conditions

Condition	Low	High
Observed?	yes	no
n(r)	Bonnor-Ebert	??

High vs. Low Early Conditions

Property	Low	High
p	~1.8	~1.8
n_f (median)	2 x 10^5	1.5 x 10^7
Linewidth	0.37	5.8

Summary of Results

- Low mass stars form in
  - Cold regions (T<10 K)
  - Low turbulence
  - Bonnor-Ebert spheres good models
  - Power laws after central source forms
- High Mass stars
  - Much more massive, turbulent
  - Power law envelopes, similar p to low mass
  - But much denser

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  - Chad Young (11.04)
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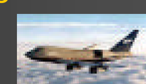
  - Yancy Shirley
  - Claudia Knez

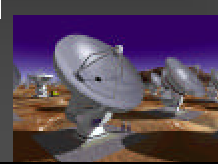
The Future is Bright

SIRTF

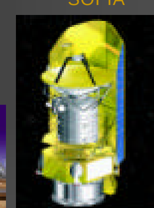
Plus,
NGST,
SMA,
CARMA,
eVLA,
SKA,
…



SOFIA



ALMA



Herschel