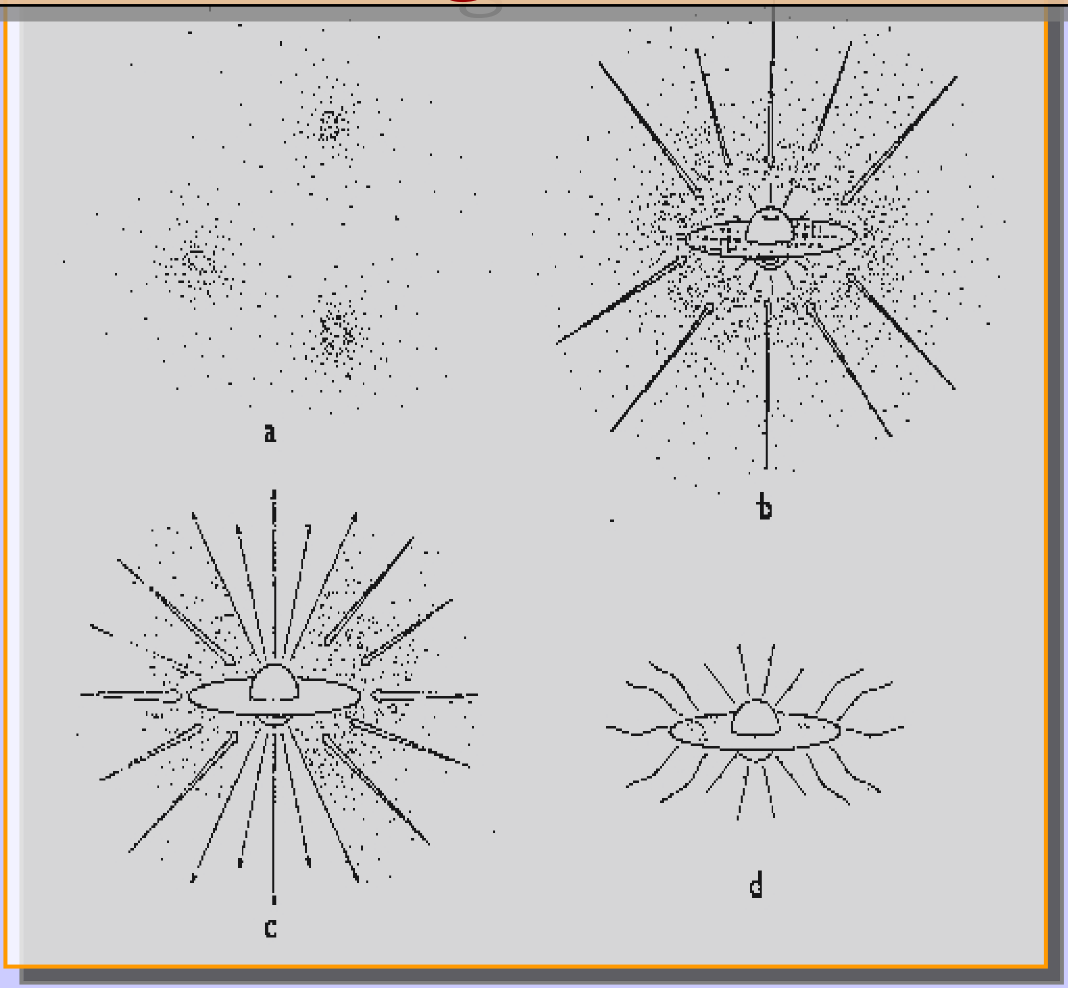
Revisiting Two Old Issues:

The Characteristic Mass of the IMF and the Formation of Clusters

Leo Blitz
UC Berkeley

Is the problem of the formation of low-mass single stars solved?

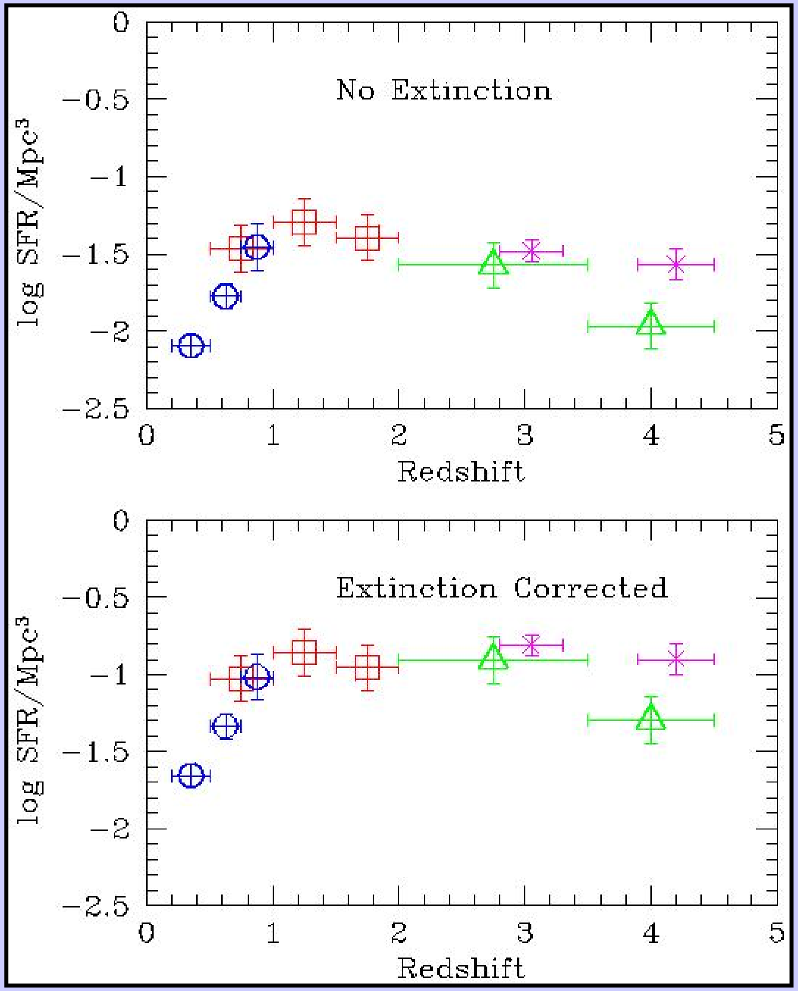


Shu, Adams and Lizano 1987

What’s Left to Be Done

- Universality of the IMF??
- Formation of Clusters
- Initial Conditions
- Formation of Planets from Disks

How can we understand the star formation history of a hierarchical Universe?



Steidel et al. 1999

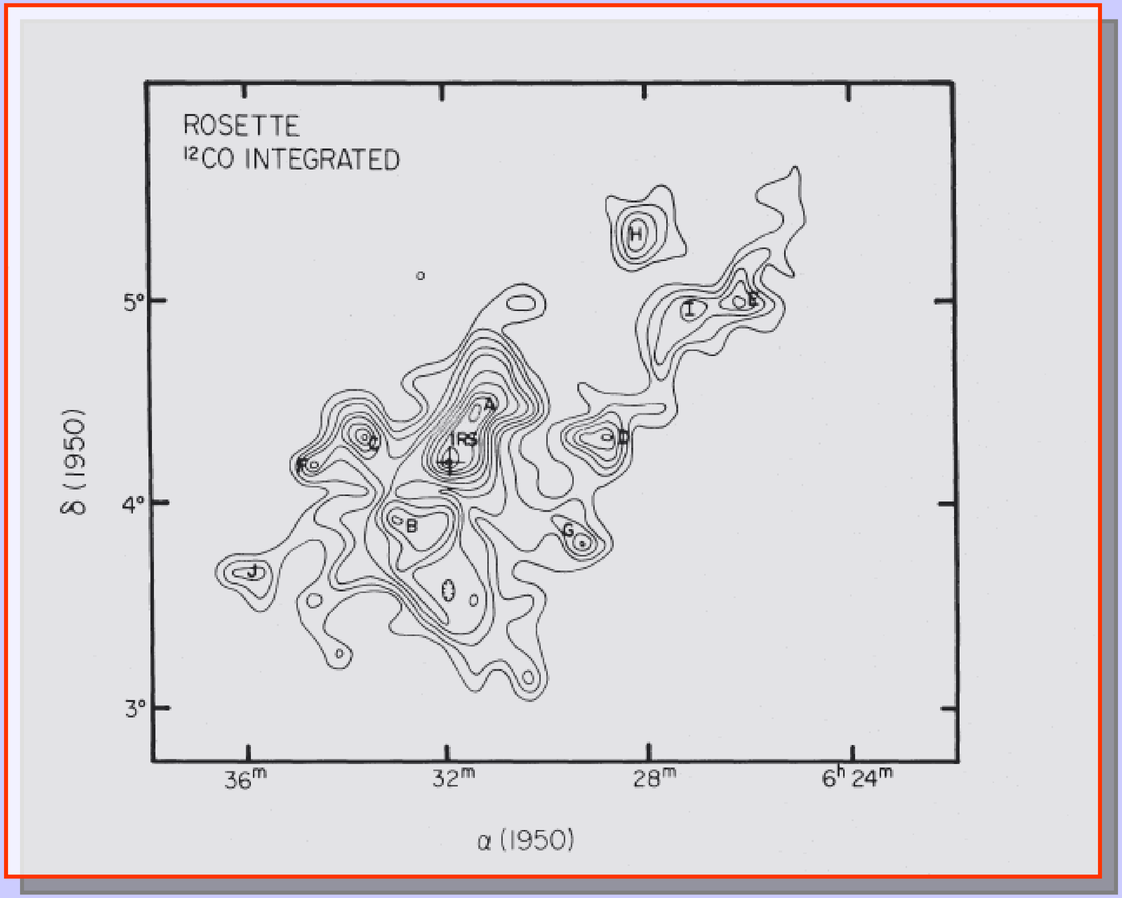
Universal Star Formation Rate is declining linearly with z at about 10% per 10^9 y; more slowly with time.

But the depletion rate of SF gas is much faster than this at $z = 0$.

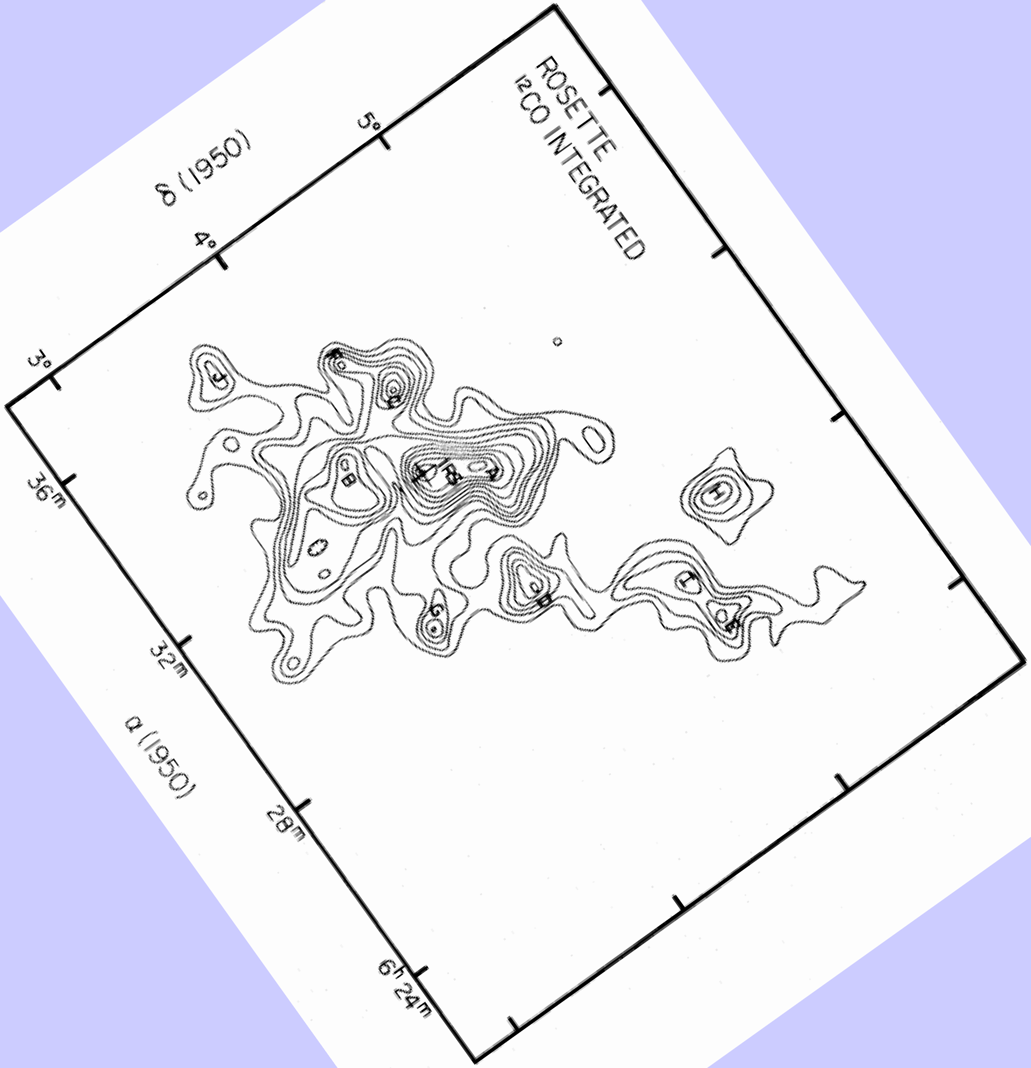
How is this possible??

Rosette Nebula

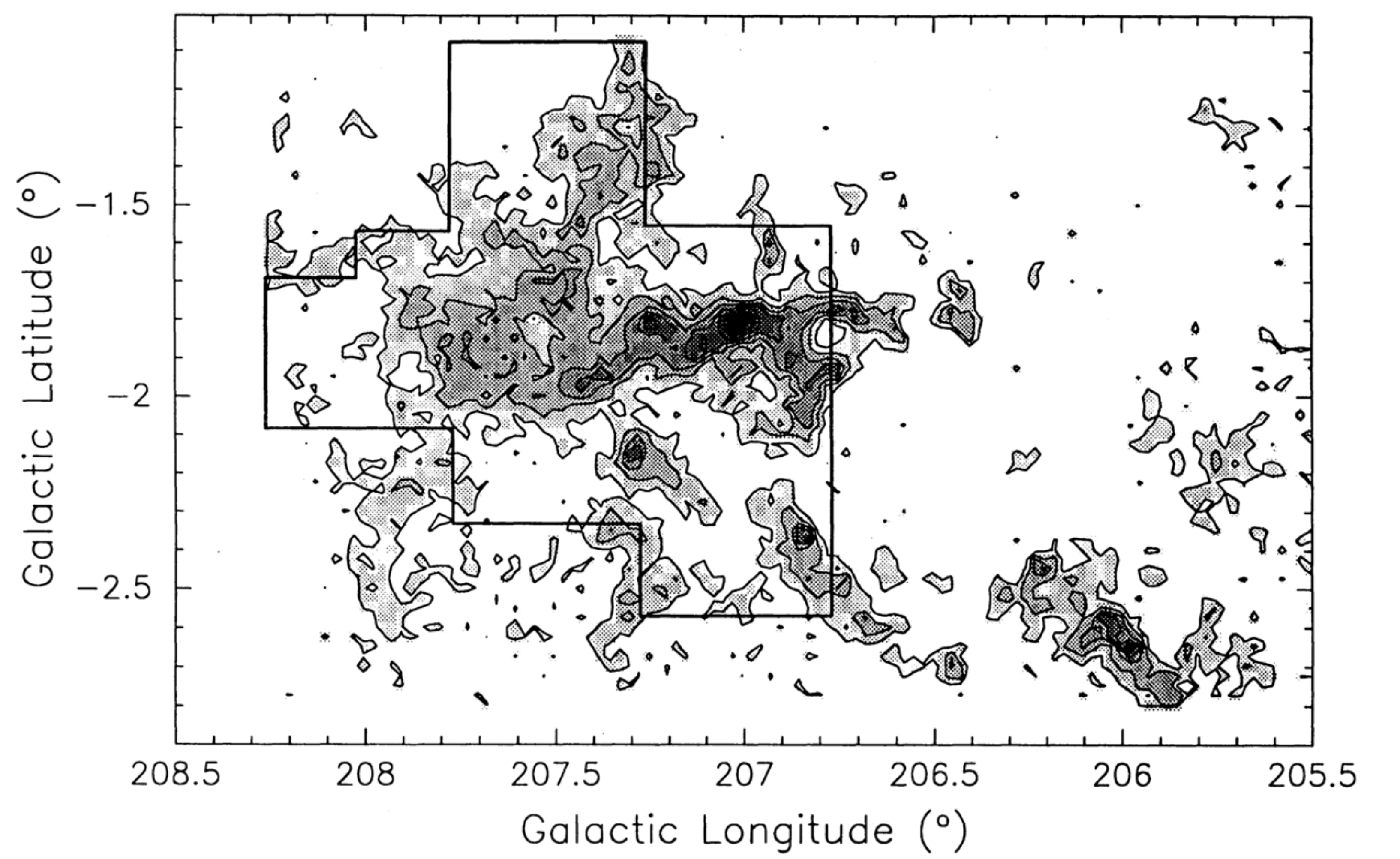
Rosette Molecular Cloud



Clumps are roundish?

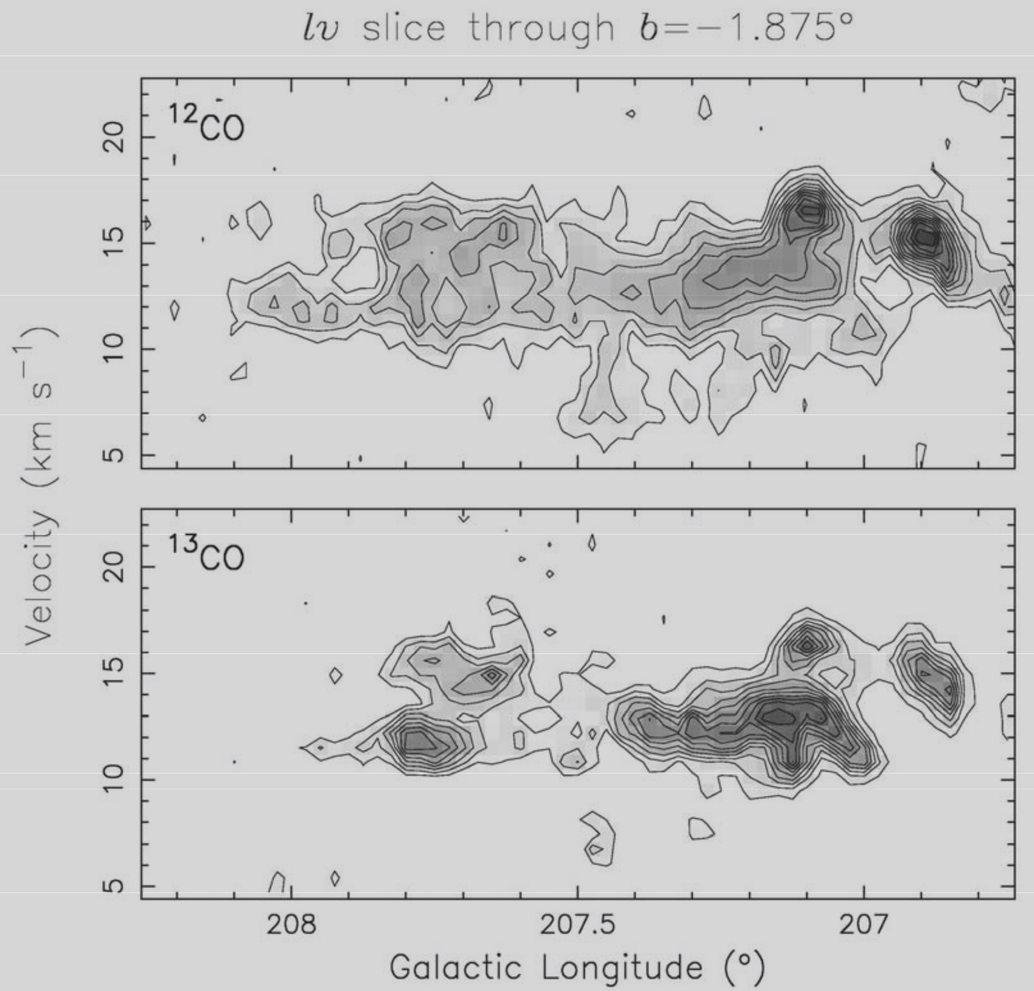

ROSETTE
^{12}CO INTEGRATED
δ (1950)
3°
4°
5°
α (1950)
36m
32m
28m
6h 24m
A
B
C
D
E
F
G
H
I
J
K

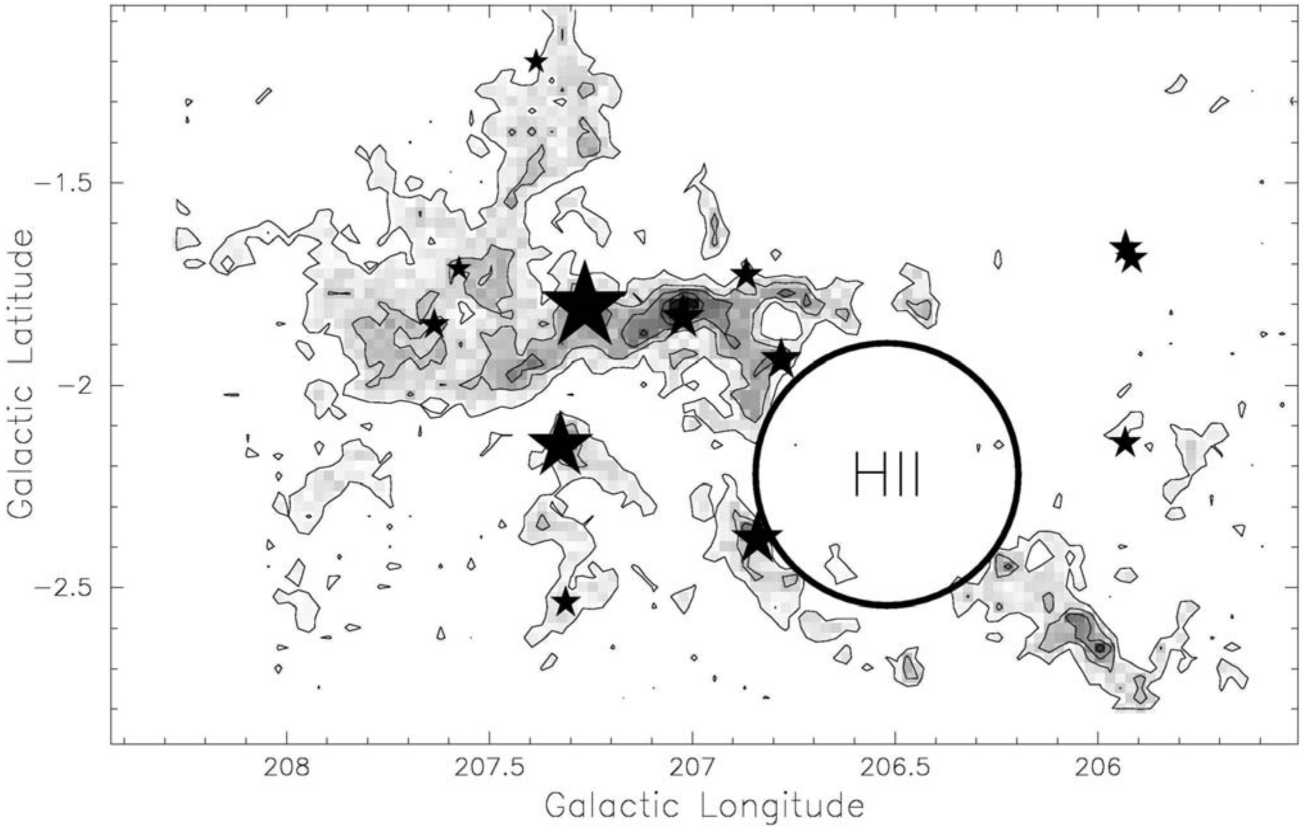
Rosette MC ^{12}CO

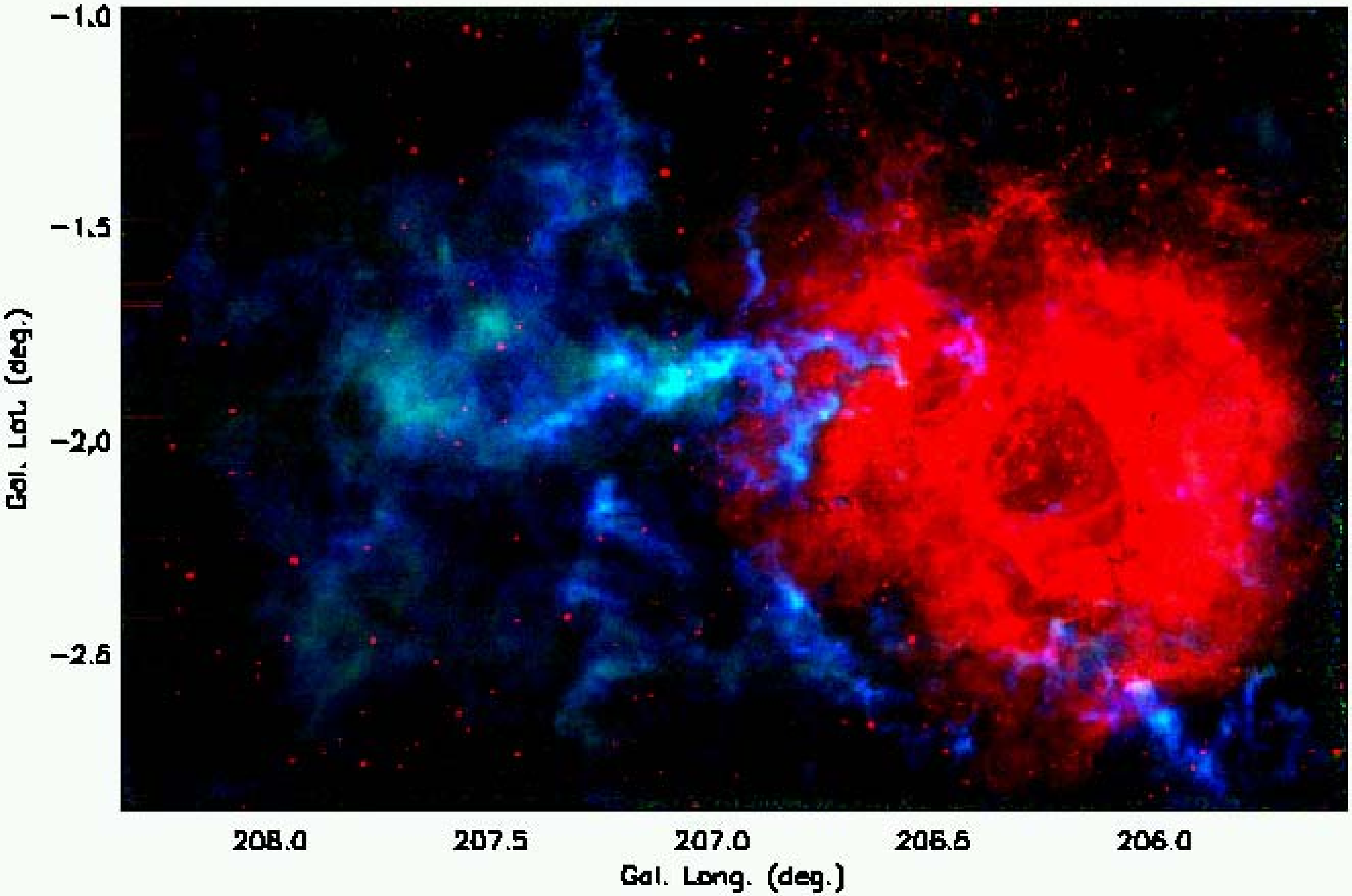


Clumps are roundish?

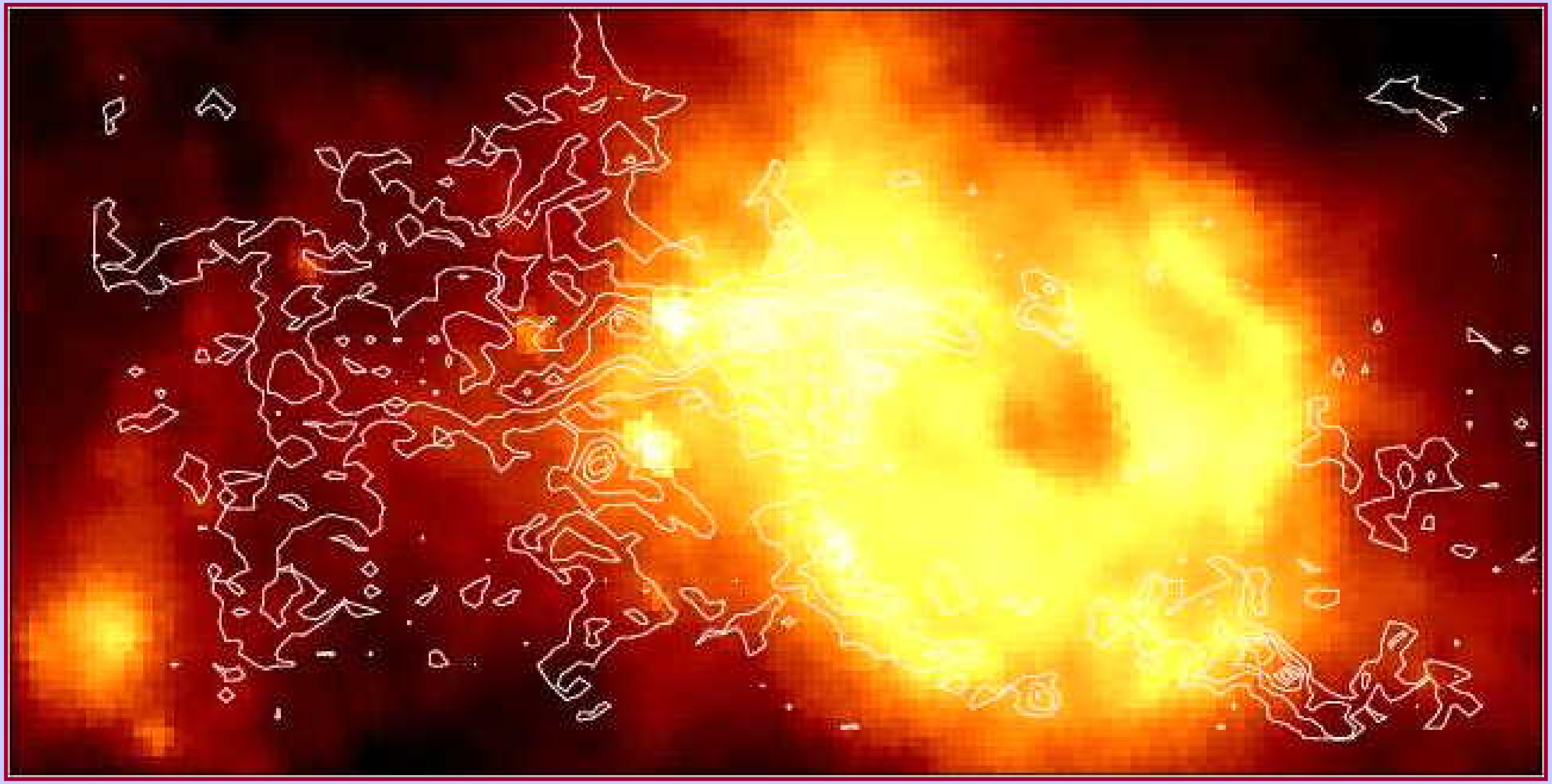
Clumps in the Rosette MC




HII
Galactic Latitude
−1.5
−2
−2.5
208
207.5
207
206.5
206
Galactic Longitude

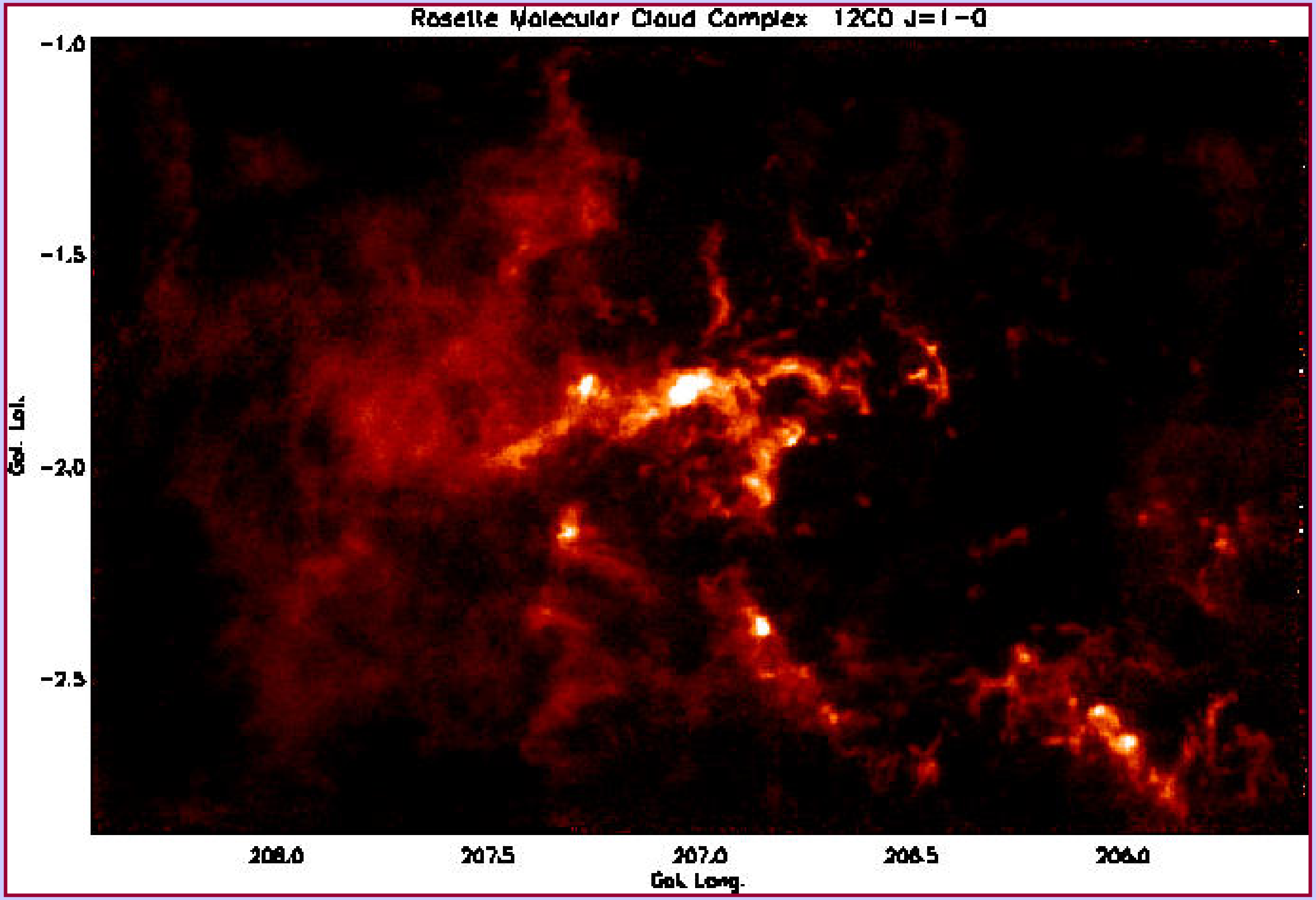

−1.0
−1.5
−2.0
−2.5
Gal. Lat. (deg.)
208.0
207.5
207.0
206.5
206.0
Gal. Long. (deg.)

Rosette ^{12}CO + Dust Temperature



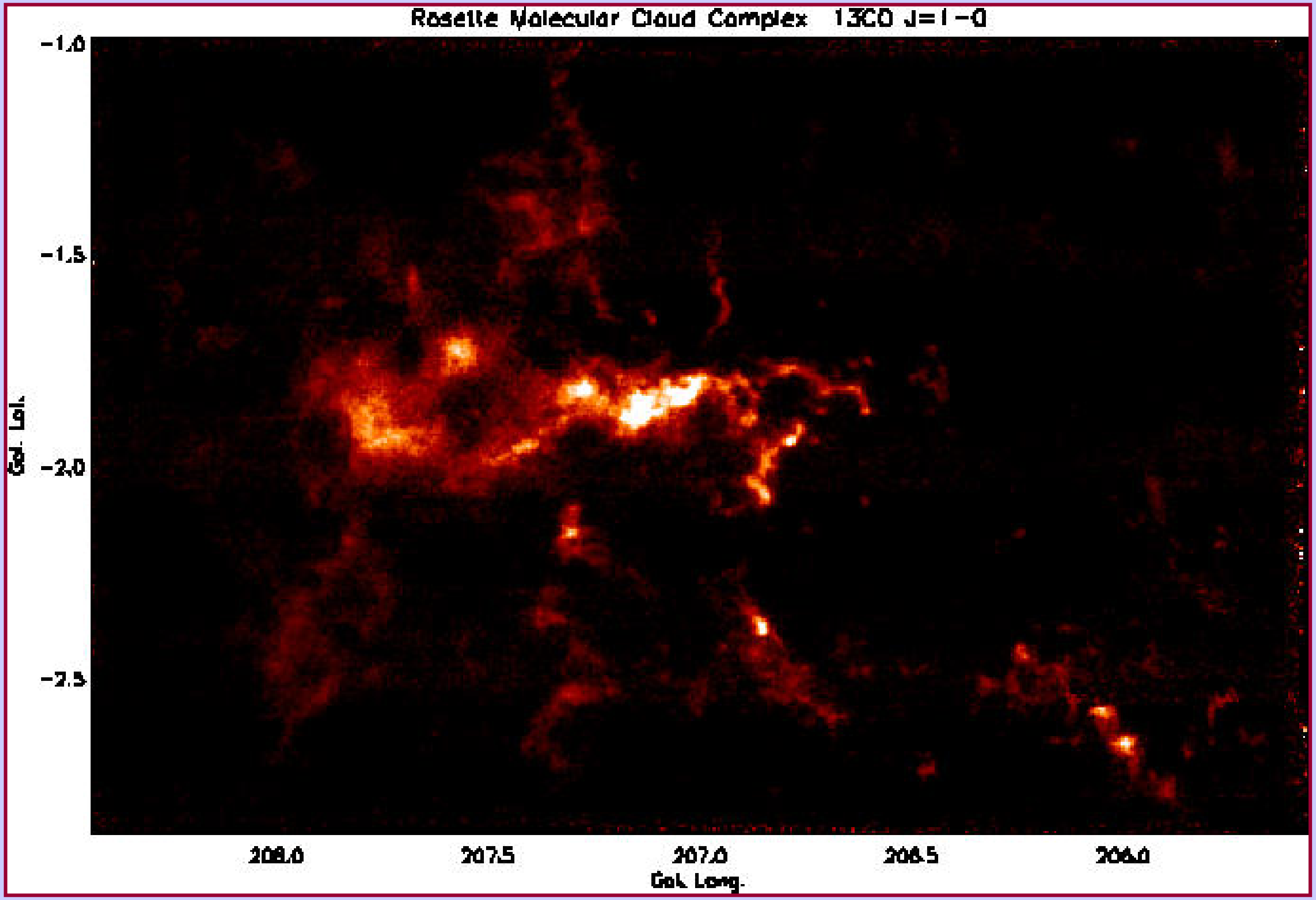
Williams, Blitz & Stark 1995

Rosette ^{12}CO



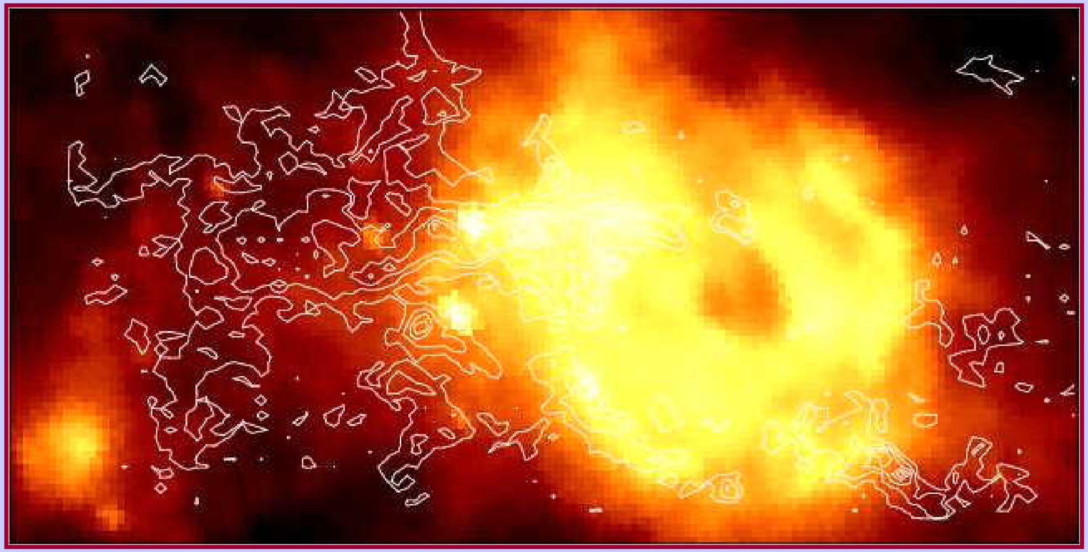
Williams, Heyer, and Brunt 2006

Rosette ^{13}CO

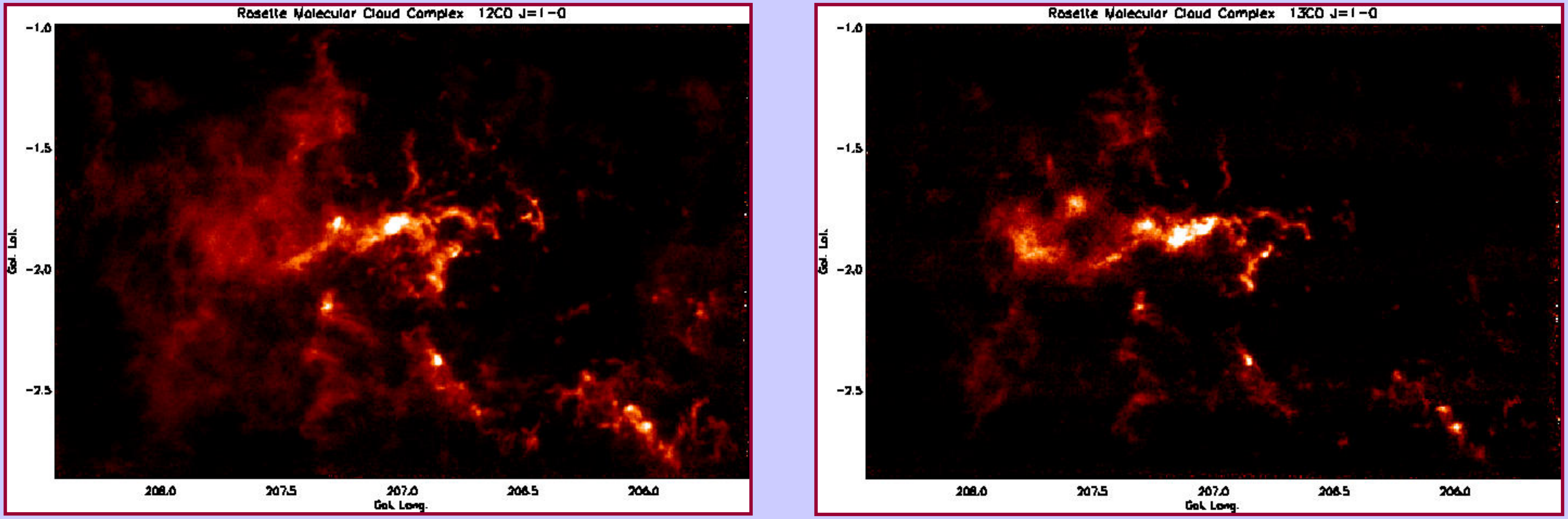


Williams, Heyer, and Brunt 2006

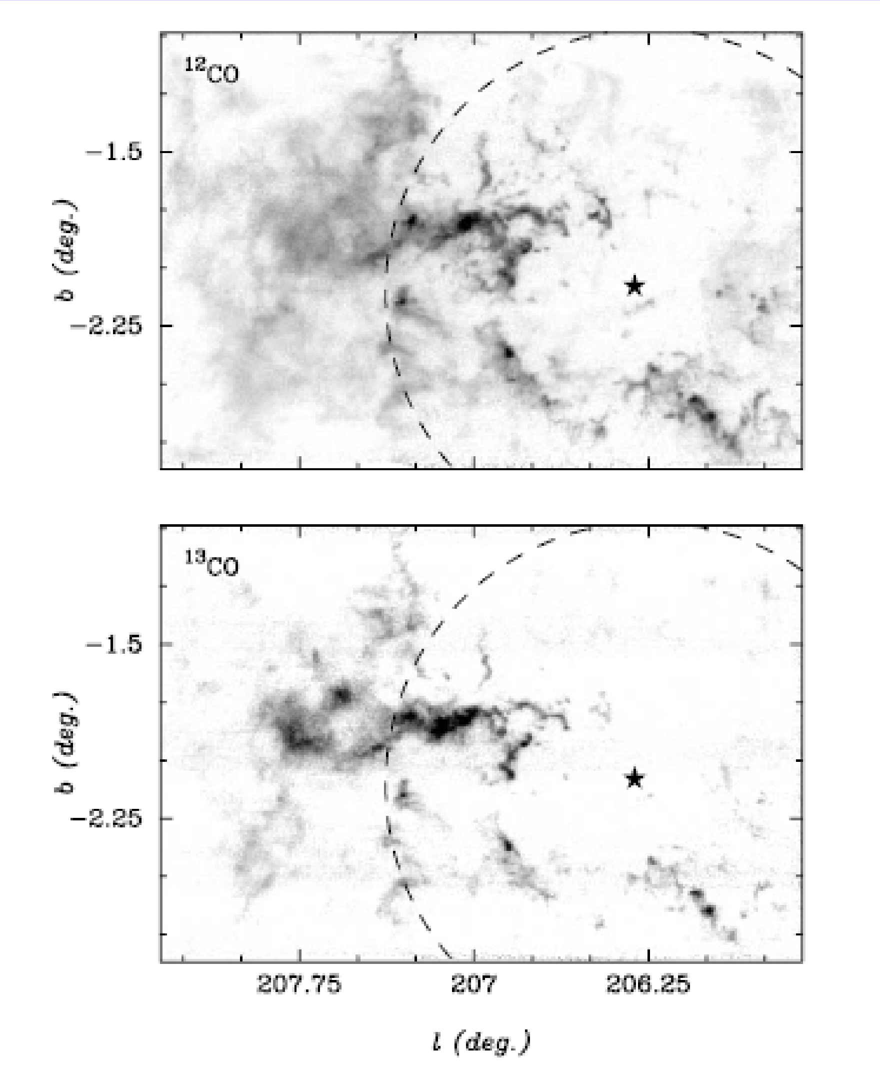
The Rosette Molecular Cloud



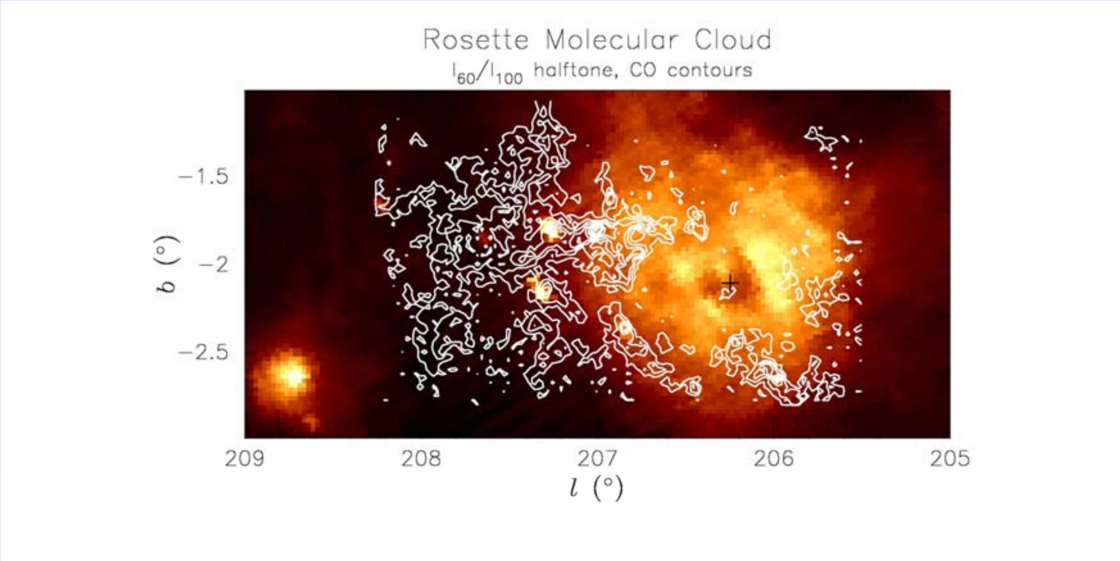
Williams, Blitz & Stark 1995

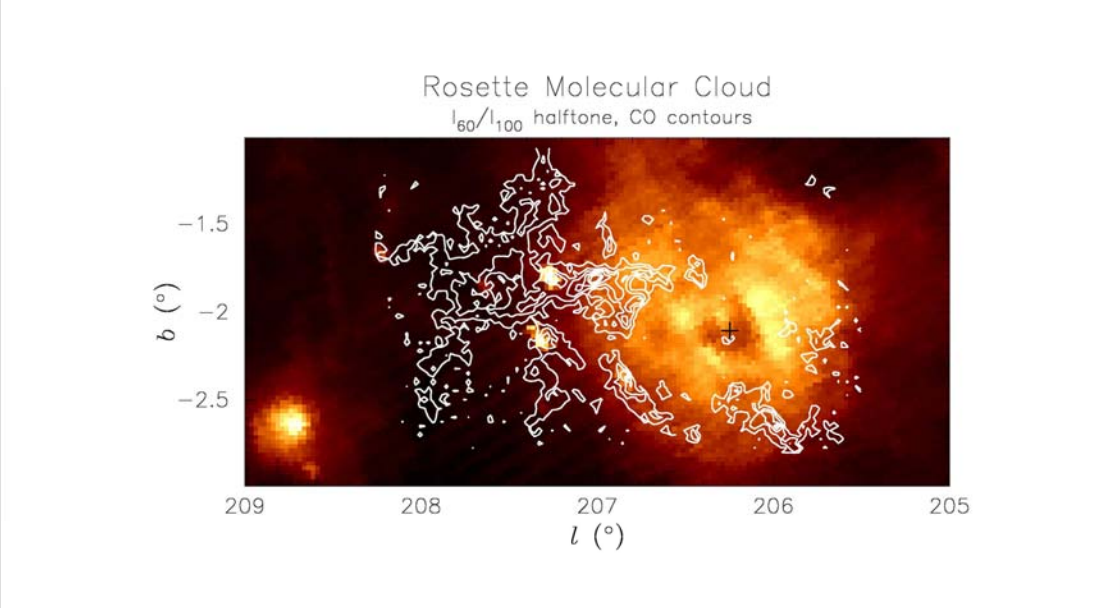


Williams, Heyer and Brunt 2006



Williams, Heyer and Brunt 2006


Rosette Molecular Cloud
I_{60}/I_{100} halftone, CO contours
−1.5
−2
−2.5
b (°)
209
208
207
206
205
l (°)


Rosette Molecular Cloud
I_{60}/I_{100} halftone, CO contours
−1.5
−2
−2.5
b (°)
209
208
207
206
205
l (°)

Clump ID from CLUMPFIND

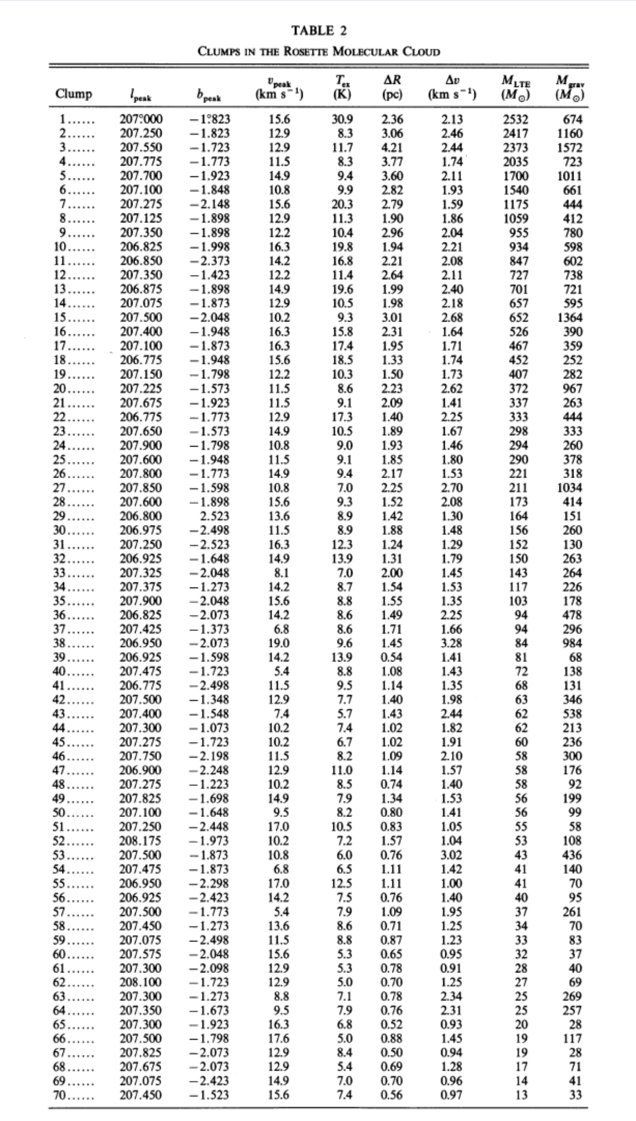
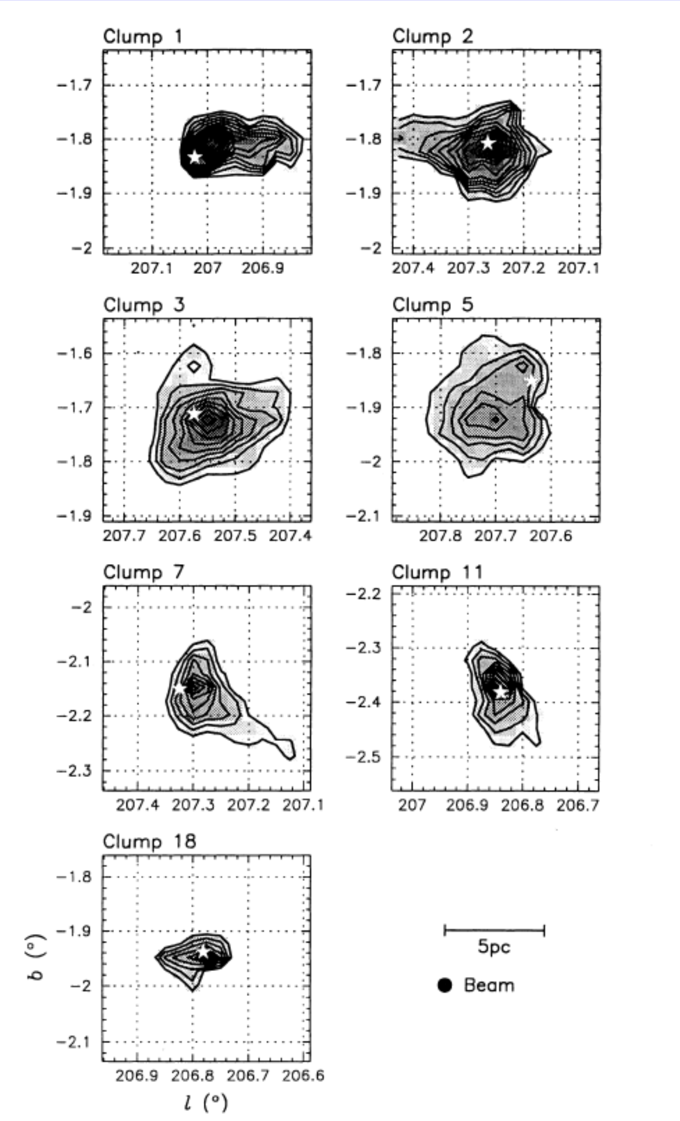


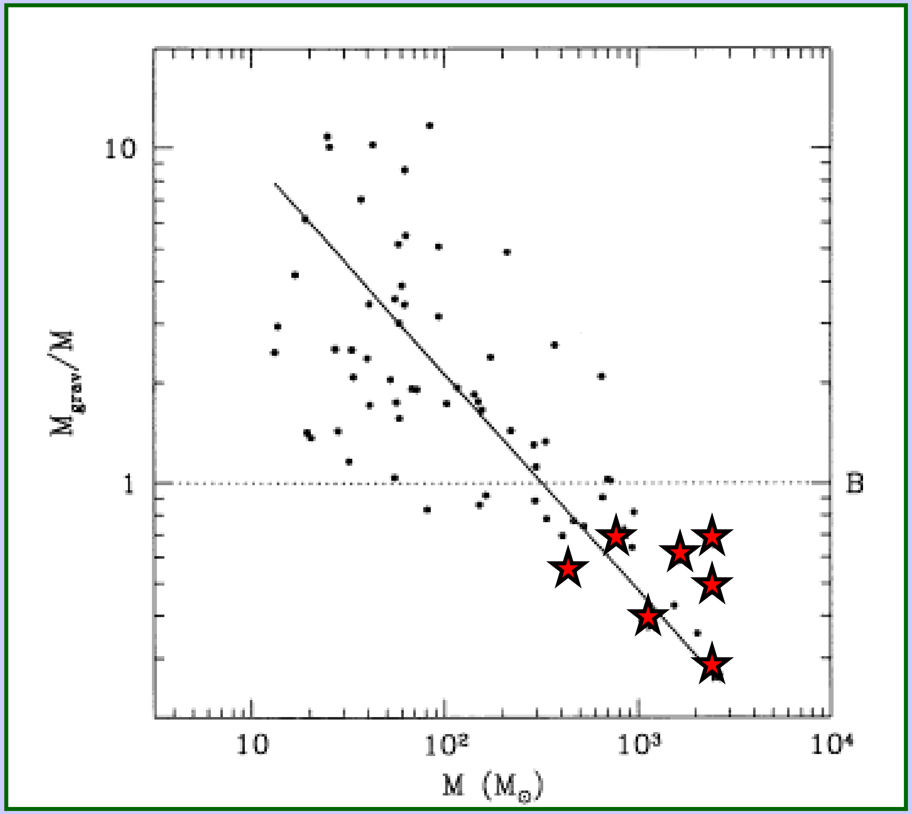
TABLE 2

Clumps in the Rosette Molecular Cloud

Clump	l_{peak}	b_{peak}	v_{peak} (km s^{-1})	T_{ex} (K)	ΔR (pc)	Δv (km s^{-1})	M_{LTE} ($M_{\odot}$)	M_{grav} ($M_{\odot}$)
1......	207°000	−1°823	15.6	30.9	2.36	2.13	2532	674
2......	207.250	−1.823	12.9	8.3	3.06	2.46	2417	1160
3......	207.550	−1.723	12.9	11.7	4.21	2.44	2373	1572
4......	207.775	−1.773	11.5	8.3	3.77	1.74	2035	723
5......	207.700	−1.923	14.9	9.4	3.60	2.11	1700	1011
6......	207.100	−1.848	10.8	9.9	2.82	1.93	1540	661
7......	207.275	−2.148	15.6	20.3	2.79	1.59	1175	444
8......	207.125	−1.898	12.9	11.3	1.90	1.86	1059	412
9......	207.350	−1.898	12.2	10.4	2.96	2.04	955	780
10......	206.825	−1.998	16.3	19.8	1.94	2.21	934	598
11......	206.850	−2.373	14.2	16.8	2.21	2.08	847	602
12......	207.350	−1.423	12.2	11.4	2.64	2.11	727	738
13......	206.875	−1.898	14.9	19.6	1.99	2.40	701	721
14......	207.075	−1.873	12.9	10.5	1.98	2.18	657	595
15......	207.500	−2.048	10.2	9.3	3.01	2.68	652	1364
16......	207.400	−1.948	16.3	15.8	2.31	1.64	526	390
17......	207.100	−1.873	16.3	17.4	1.95	1.71	467	359
18......	206.775	−1.948	15.6	18.5	1.33	1.74	452	252
19......	207.150	−1.798	12.2	10.3	1.50	1.73	407	282
20......	207.225	−1.573	11.5	8.6	2.23	2.62	372	967
21......	207.675	−1.923	11.5	9.1	2.09	1.41	337	263
22......	206.775	−1.773	12.9	17.3	1.40	2.25	333	444
23......	207.650	−1.573	14.9	10.5	1.89	1.67	298	333
24......	207.900	−1.798	10.8	9.0	1.93	1.46	294	260
25......	207.600	−1.948	11.5	9.1	1.85	1.80	290	378
26......	207.800	−1.773	14.9	9.4	2.17	1.53	221	318
27......	207.850	−1.598	10.8	7.0	2.25	2.70	211	1034
28......	207.600	−1.898	15.6	9.3	1.52	2.08	173	414
29......	206.800	2.523	13.6	8.9	1.42	1.30	164	151
30......	206.975	−2.498	11.5	8.9	1.88	1.48	156	260
31......	207.250	−2.523	16.3	12.3	1.24	1.29	152	130
32......	206.925	−1.648	14.9	13.9	1.31	1.79	150	263
33......	207.325	−2.048	8.1	7.0	2.00	1.45	143	264
34......	207.375	−1.273	14.2	8.7	1.54	1.53	117	226
35......	207.900	−2.048	15.6	8.8	1.55	1.35	103	178
36......	206.825	−2.073	14.2	8.6	1.49	2.25	94	478
37......	207.425	−1.373	6.8	8.6	1.71	1.66	94	296
38......	206.950	−2.073	19.0	9.6	1.45	3.28	84	984
39......	206.925	−1.598	14.2	13.9	0.54	1.41	81	68
40......	207.475	−1.723	5.4	8.8	1.08	1.43	72	138
41......	206.775	−2.498	11.5	9.5	1.14	1.35	68	131
42......	207.500	−1.348	12.9	7.7	1.40	1.98	63	346
43......	207.400	−1.548	7.4	5.7	1.43	2.44	62	538
44......	207.300	−1.073	10.2	7.4	1.02	1.82	62	213
45......	207.275	−1.723	10.2	6.7	1.02	1.91	60	236
46......	207.750	−2.198	11.5	8.2	1.09	2.10	58	300
47......	206.900	−2.248	12.9	11.0	1.14	1.57	58	176
48......	207.275	−1.223	10.2	8.5	0.74	1.40	58	92
49......	207.825	−1.698	14.9	7.9	1.34	1.53	56	199
50......	207.100	−1.648	9.5	8.2	0.80	1.41	56	99
51......	207.250	−2.448	17.0	10.5	0.83	1.05	55	58
52......	208.175	−1.973	10.2	7.2	1.57	1.04	53	108
53......	207.500	−1.873	10.8	6.0	0.76	3.02	43	436
54......	207.475	−1.873	6.8	6.5	1.11	1.42	41	140
55......	206.950	−2.298	17.0	12.5	1.11	1.00	41	70
56......	206.925	−2.423	14.2	7.5	0.76	1.40	40	95
57......	207.500	−1.773	5.4	7.9	1.09	1.95	37	261
58......	207.450	−1.273	13.6	8.6	0.71	1.25	34	70
59......	207.075	−2.498	11.5	8.8	0.87	1.23	33	83
60......	207.575	−2.048	15.6	5.3	0.65	0.95	32	37
61......	207.300	−2.098	12.9	5.3	0.78	0.91	28	40
62......	208.100	−1.723	12.9	5.0	0.70	1.25	27	69
63......	207.300	−1.273	8.8	7.1	0.78	2.34	25	269
64......	207.350	−1.673	9.5	7.9	0.76	2.31	25	257
65......	207.300	−1.923	16.3	6.8	0.52	0.93	20	28
66......	207.500	−1.798	17.6	5.0	0.88	1.45	19	117
67......	207.825	−2.073	12.9	8.4	0.50	0.94	19	28
68......	207.675	−2.073	12.9	5.4	0.69	1.28	17	71
69......	207.075	−2.423	14.9	7.0	0.70	0.96	14	41
70......	207.450	−1.523	15.6	7.4	0.56	0.97	13	33



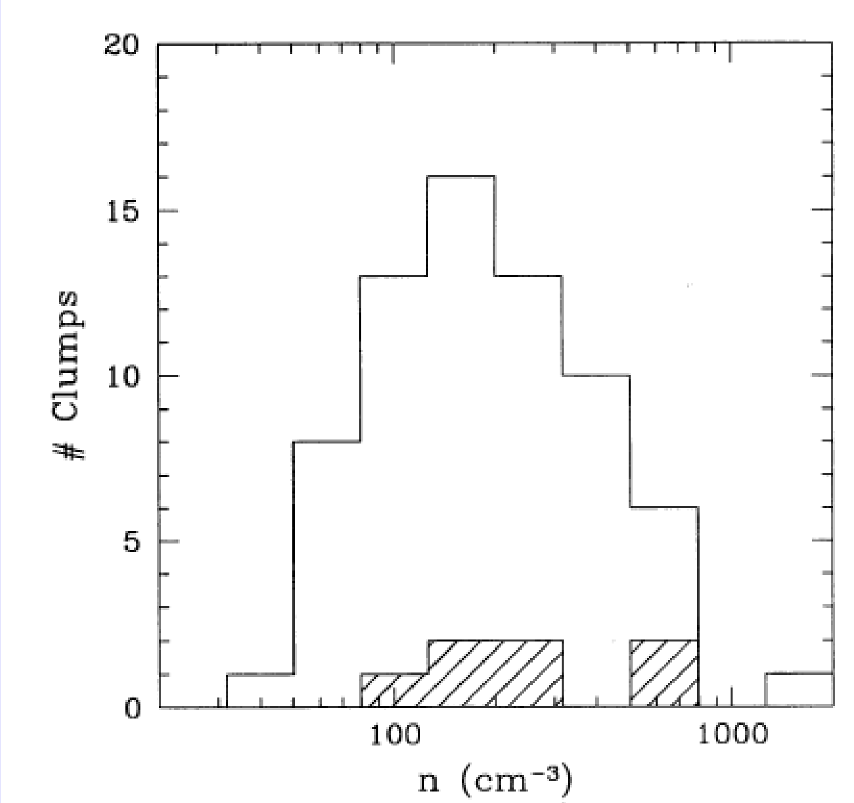
Stars form from clumps, not filaments



$3R\sigma_v^2/2GM_{lum}$

Williams, Blitz & Stark 1995

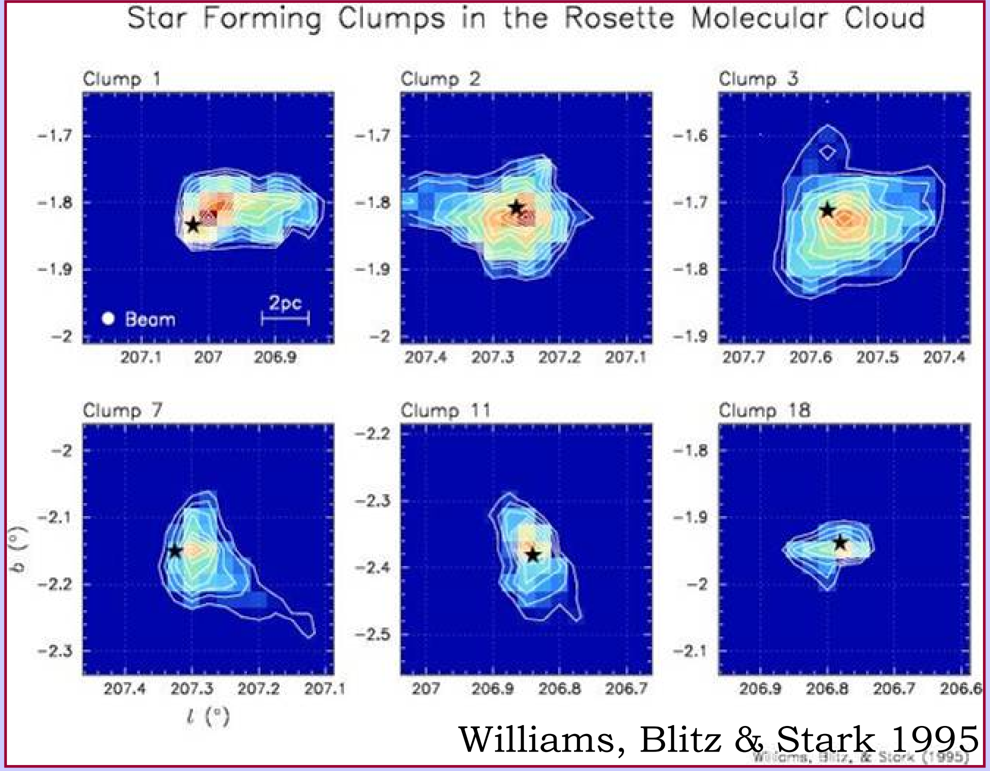
All of the star forming clumps are the most tightly bound.



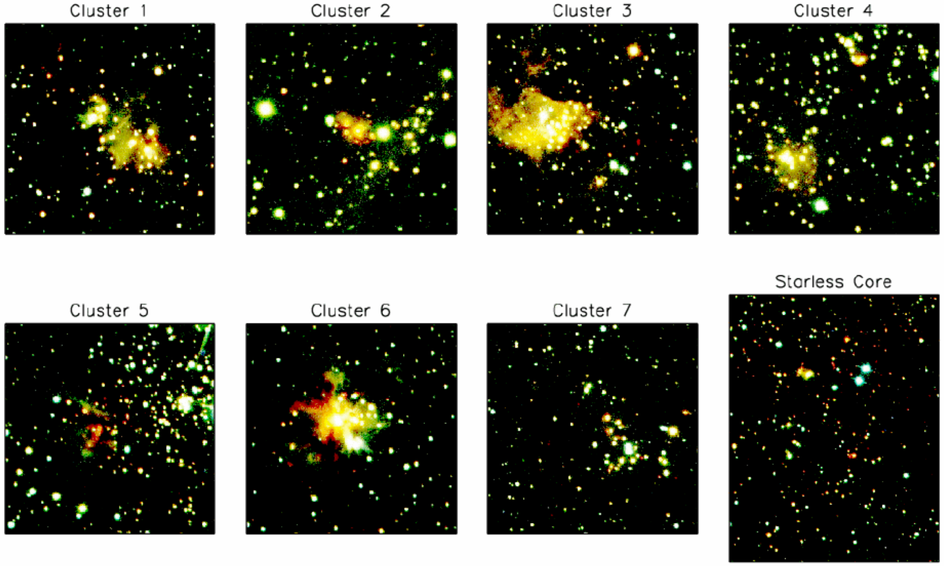
Williams, Blitz & Stark 1995

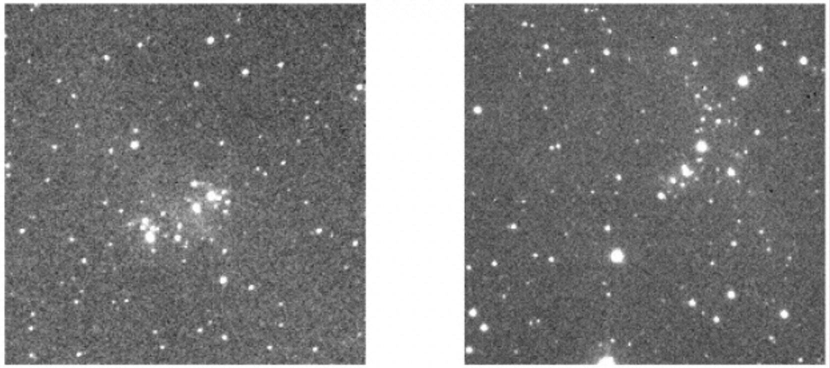
It is apparently not a matter of mean density in a clump that initiates star formation.

All of the star forming clumps are the most tightly bound.



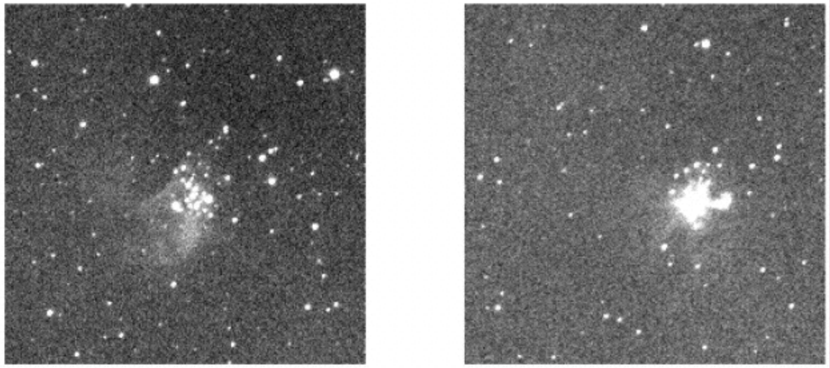
Williams, Blitz & Stark 1995





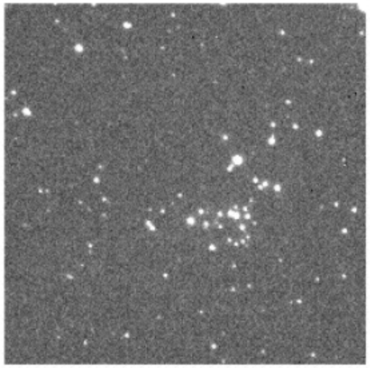
(a) Cluster 1

(b) Cluster 2



(c) Cluster 3

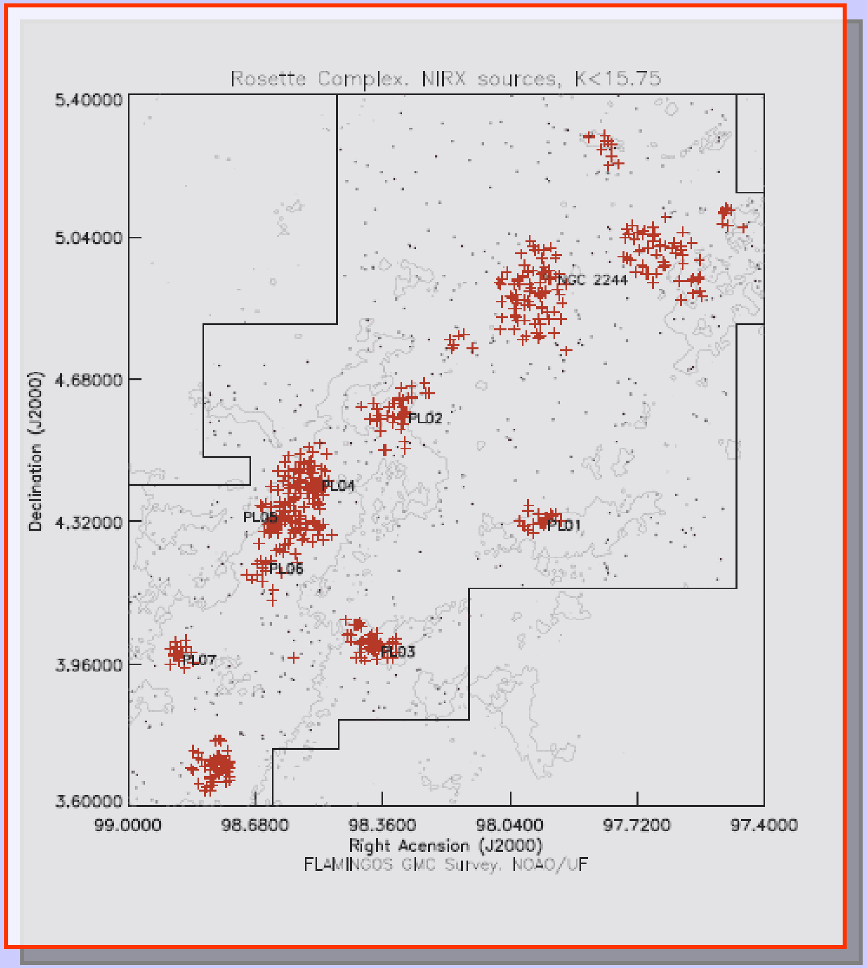
(d) Cluster 6



(e) Cluster 7

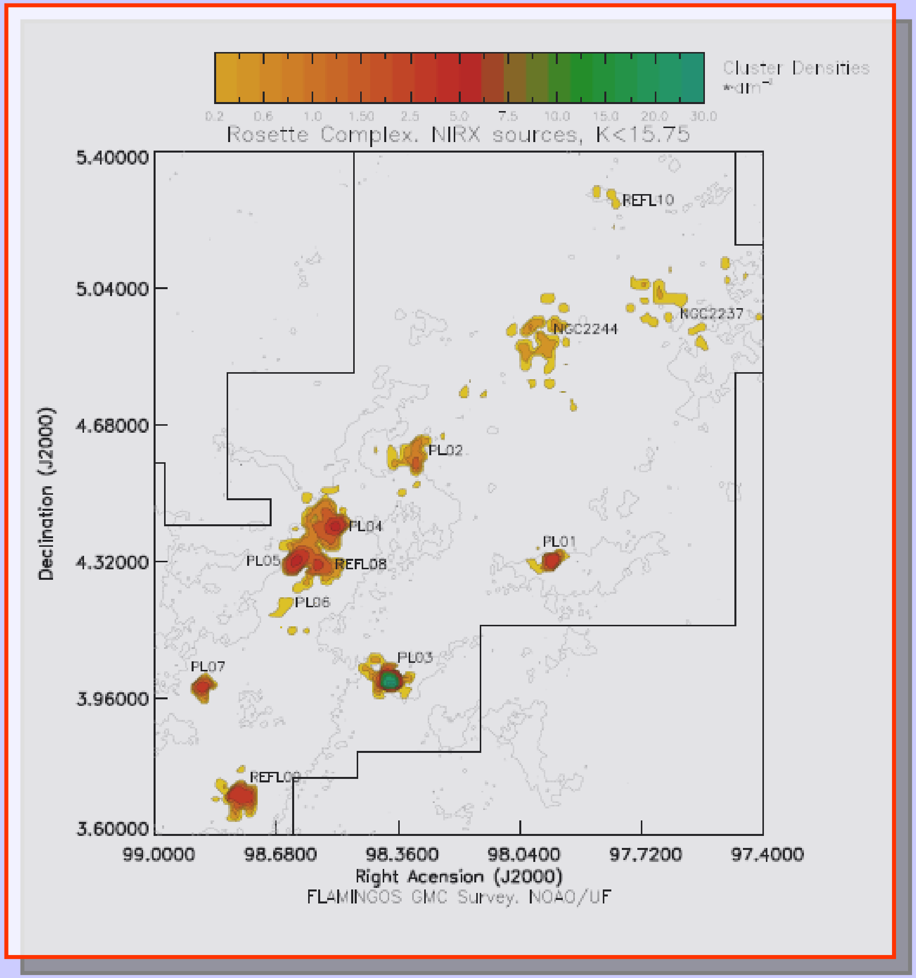
Phelps & Lada 1997

Star Clusters in the Rosette



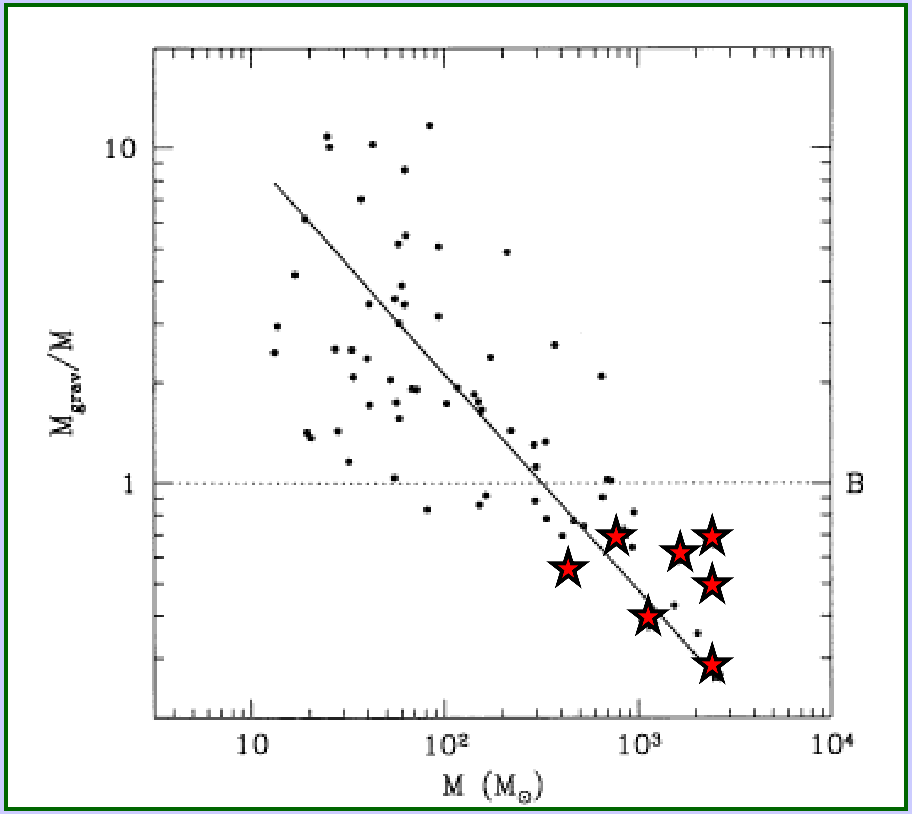
Roman-Zuniga et al. 2007

Star Clusters in the Rosette



Roman-Zuniga et al. 2007

Free-fall time for clumps is 1 x 10^6 y. If star formation time is short, what synchronizes individual centers of star formation? Why are they all initiated within 10^6 y.



$3R\sigma_v^2/2GM_{lum}$

Williams, Blitz & Stark 1995

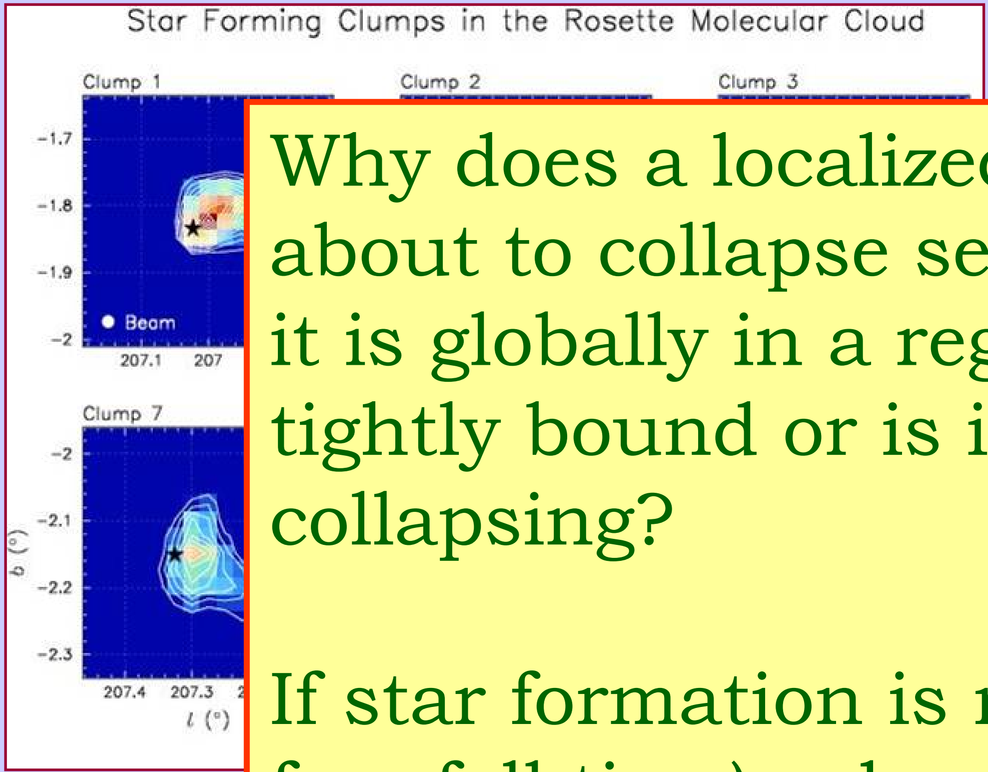
All of the most star forming clumps are the most self-gravitating.

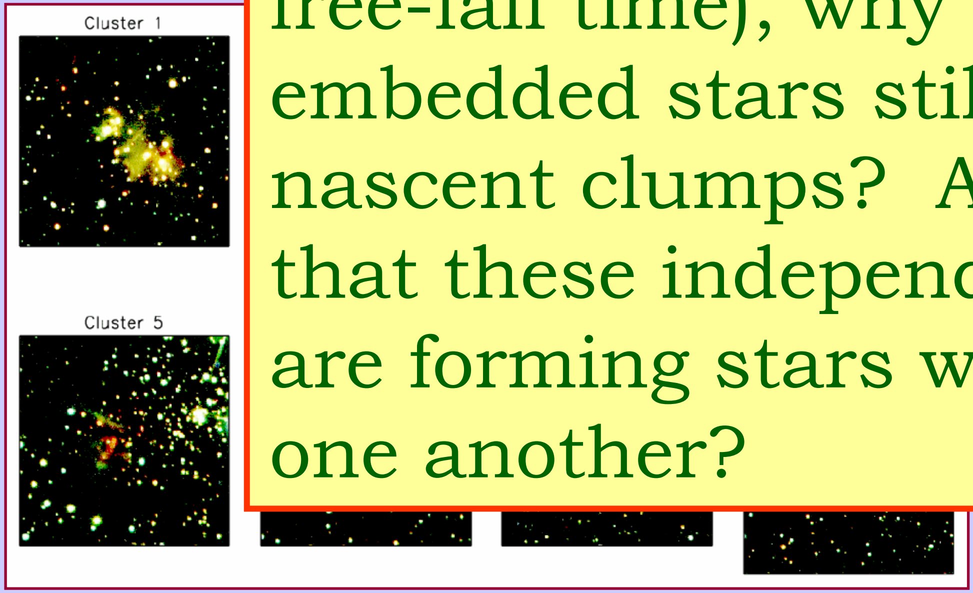
Apparently, star formation is not an entirely local process.

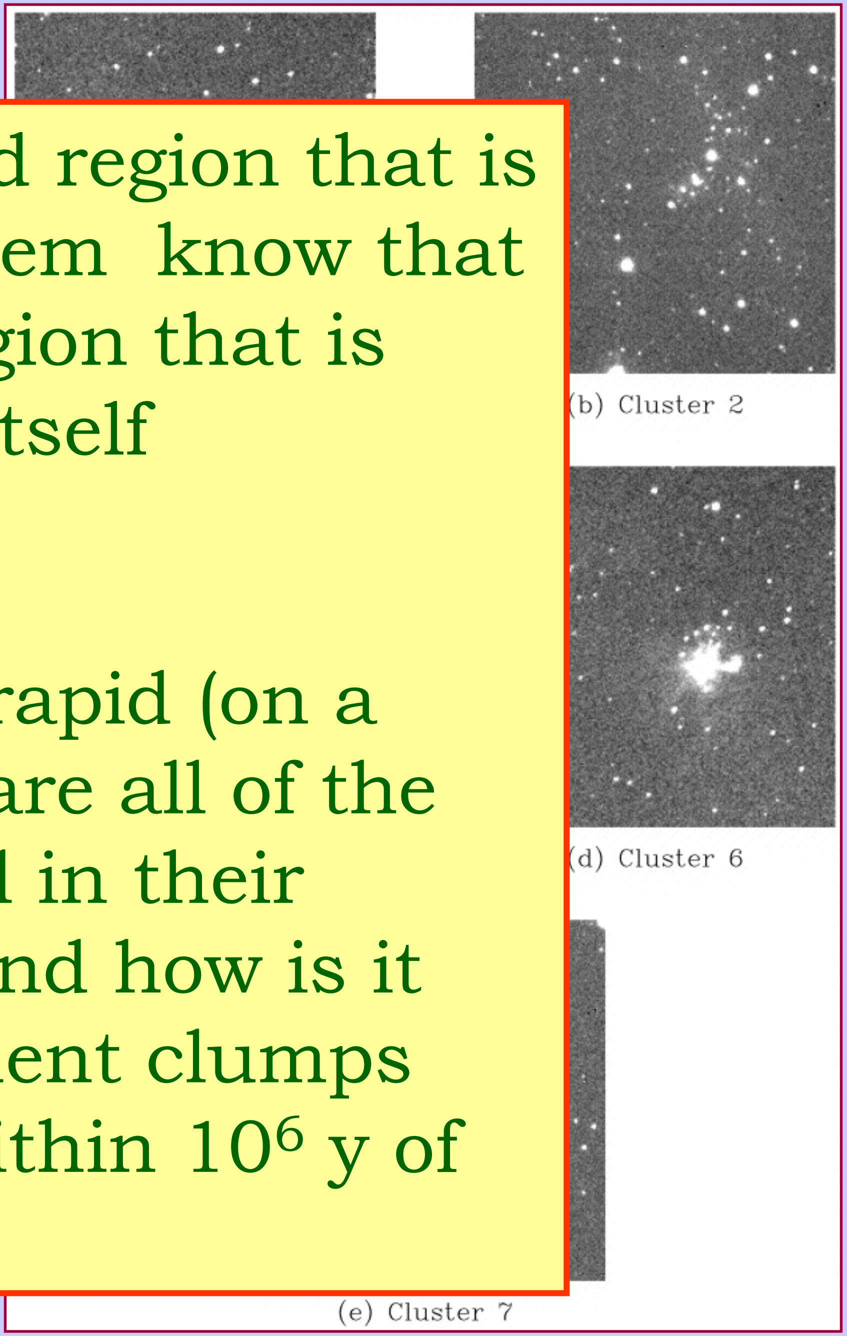
Each of the star-forming clumps is forming a cluster, and the stars in each cluster seem to know that it it’s time to collapse.

Why??

What are the initial conditions that make local and global star formation simultaneous?





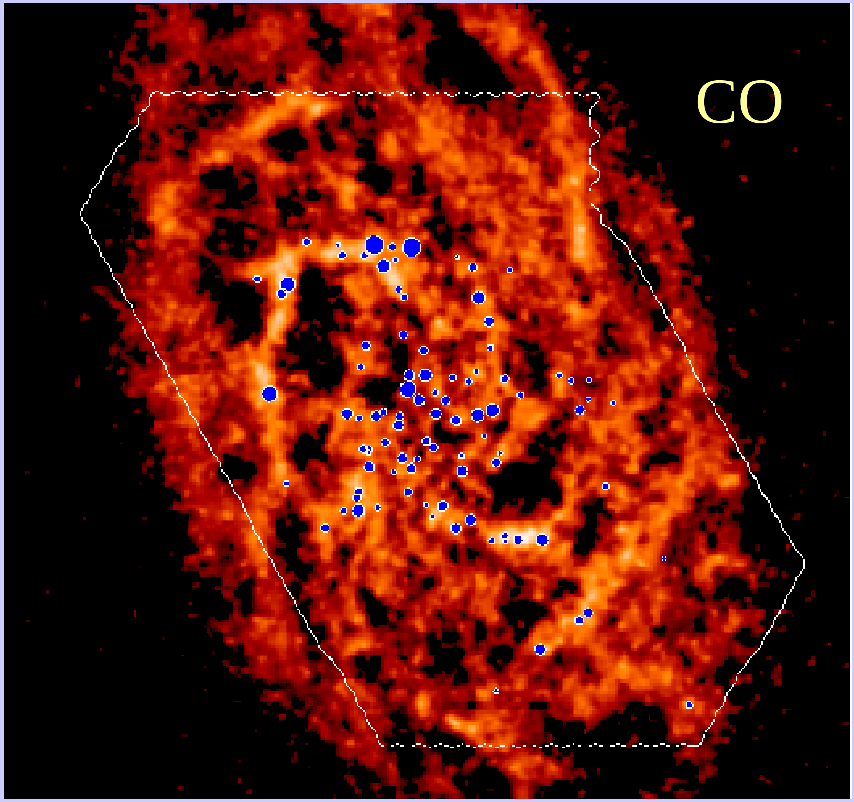


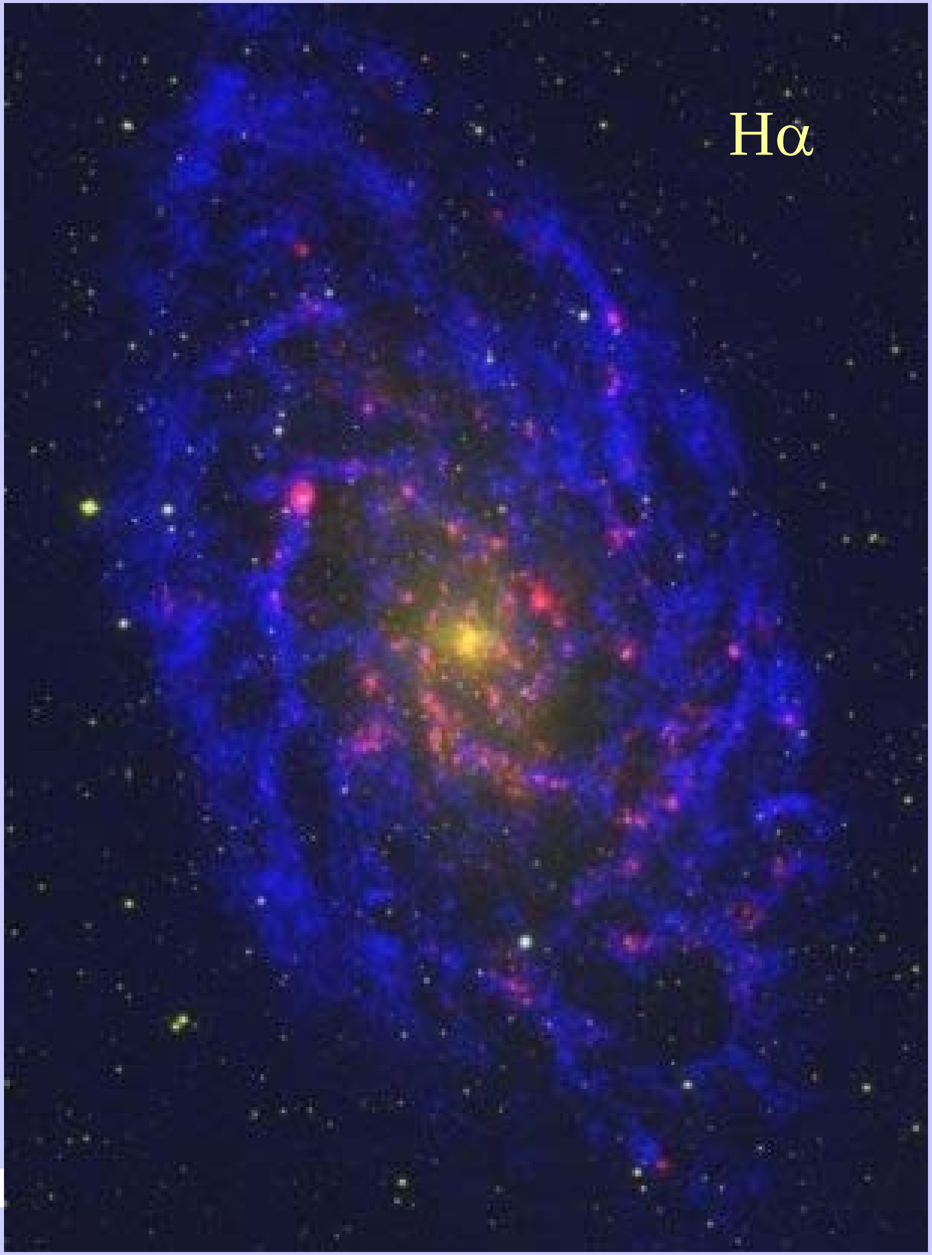
Why does a localized region that is about to collapse seem know that it is globally in a region that is tightly bound or is itself collapsing?

If star formation is rapid (on a free-fall time), why are all of the embedded stars still in their nascent clumps? And how is it that these independent clumps are forming stars within 10^6 y of one another?

Phelps & Lada 1997

CO, Hα on HI in M33





What determines the turnover in the IMF?

or: Why does nature abhor Brown Dwarfs?

Jeans Density

$$\rho_0 = \left(\frac{kT}{\mu m_H G}\right)^3 \frac{\pi^5}{(6M_J)^2}$$

$$\rho_0 = \frac{\pi^5 {v_s}^6}{(6M_J)^2 G^3}$$

$$\rho_0 = \left\{\frac{\pi^5 P^3}{(6M_J)^2 G^3}\right\}^{1/4}$$

To be able to get solar mass stars requires densities and temperatures found only in molecular clouds. *Observationally, one does find such conditions.*

For $T = 10$ K; $M_J = 1\ M_\odot$

$\rho_O = 1.5 \times 10^{-18}$ g cm^{-3}

$n_H = 9 \times 10^5$ cm^{-3}

Jeans Density for Brown Dwarfs

$$\rho_0 = (\frac{kT}{\mu m_H G})^3 \frac{\pi^5}{(6M_J)^2}$$

$$\rho_0 = \frac{\pi^5 {v_s}^6}{(6M_J)^2 G^3}$$

$$\rho_0 = \{\frac{\pi^5 P^3}{(6M_J)^2 G^3}\}^{1/4}$$

To be able to get brown dwarfs, with masses of ~0.1 $M_\odot$ requires densities two orders of magnitude higher.

For T = 10 K; $M_J = 0.1\ M_\odot$

$\rho_O = 1.5 \times 10^{-16}$ g cm^{-3}

$n_H \sim 10^8$ cm^{-3}

Are such conditions found in GMCs?

Global Properties of Solar Neighborhood GMCs

Mass	1-2 x 10^5 $M_\odot$
Mean diameter	45 pc
Projected Surface Area	2.1 x 10^3 pc^2
Mean Surface Density	~ 100 $M_\odot$ pc^{-2}
Mean Volume Density	~ 50 cm^{-3}
Mean Clump Volume Density	~ 2 x 10^3 cm^{-3}

Blitz 1993

$\Sigma(H_2)$ in solar vicinity ~1.8 $M_\odot$ pc^{-2}

Dame 1993

In galactic centers (and the inner regions of H_2 – rich disks) do GMCs exist at all?

Q. What is the best evidence that GMCs as a whole are self-gravitating?

A. Their internal pressures exceed that of the ambient ISM by at least an order of magnitude.

$$P_{ext} = 2\pi G \Sigma_g \rho_* h_g$$

$$P_{int} = {}^{\pi}\!/_{2} G \Sigma^2 (H_2)$$

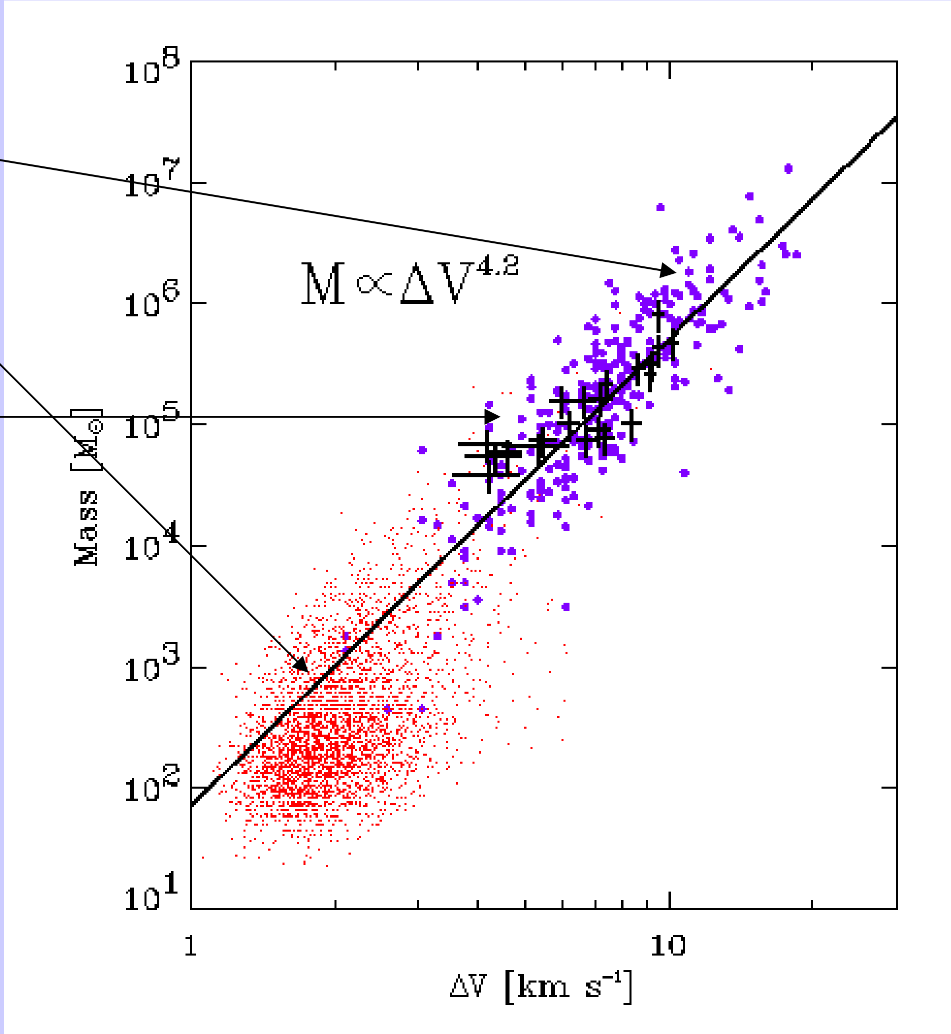
$$P_{ext} << P_{int}$$

In Solar Vicinity: $P_{ext}/k \sim 3 \times 10^4$ K cm^{-3}

$P_{int}/k \sim 3 \times 10^5$ K cm^{-3}

Inner Galaxy: $P_{int}/k \sim 5 \times 10^5$ K cm-3

Linewidth-Size Relation for M33



Inner Milky Way

Outer Milky Way

M33

Constant surface density implies $M \sim R^2$

Thus $R \sim \Delta V^2$

$$P_{ext} = 2\pi G \Sigma_g \rho_* h_g$$

$$P_{int} = {}^{\pi}\!/_{2}\, G \Sigma^2 (H_2)$$

$$V^2 = \frac{GM(H_2)}{R}$$ (self-gravity)

$$V^2 = const\ R$$ (linewidth-size relation)

$$const = \frac{GM(H_2)}{R^2} = G\Sigma(H_2)$$

GMCs have constant surface density from cloud-to-cloud as long as obey linewidth-size relation. This implies that the internal pressures do not significantly vary from cloud-to-cloud.

$$P_{ext} = 2\pi G \Sigma_g \rho_* h_g$$

$$P_{int} = \pi/_2 G \Sigma^2 (H_2)$$

$$V^2 = \frac{GM(H_2)}{R}$$ (self-gravity)

$$V^2 = const\ R$$ (linewidth-size relation)

$$const = \frac{GM(H_2)}{R^2} = G\Sigma(H_2)$$

In Solar Vicinity: P_{ext} /k ~ 3 x 10^4 K cm^{-3}

P_{int} /k ~ 3 x 10^5 K cm^{-3}

Inner Galaxy: P_{int} /k ~ 5 x 10^5 K cm-3

But to form a brown dwarf, one needs a density of 10^8 cm^{-3} at a temperature of 10 K. How is this possible?

Now, consider a solar mass core. Here one needs Jeans densities of 10^6 cm^{-3}. This is not difficult, because if the clump is a Bonnor-Ebert Sphere, one can get a density contrast within the clump of 14 (say 7 times the mean density) or several times what's needed to form a solar mass clump.

So, if the stellar IMF is determined by the clump IMF (see Alves, et al.) then solar mass stars can form readily, but stars of somewhat lower mass cannot. Is this the reason for the turnover in the IMF?

In Solar Vicinity: $P_{ext}/k \sim 3 \times 10^4$ K cm^{-3}

$P_{int}/k \sim 3 \times 10^5$ K cm^{-3}

Inner Galaxy: $P_{int}/k \sim 5 \times 10^5$ K cm-3

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On the other hand, conditions CAN favor the formation of brown dwarfs if there are pressure fluctuations to bring the density up to the Jeans density. But these are probably rare.

A good project for turbulent simulations?

In Solar Vicinity: $P_{ext}/k \sim 3 \times 10^4$ K cm^{-3}

$P_{int}/k \sim 3 \times 10^5$ K cm^{-3}

Inner Galaxy: $P_{int}/k \sim 5 \times 10^5$ K cm-3

Bottom Line

- *Is it the large scale pressure and structure of GMCs that determines the downturn of the IMF? If so, then we have good reason for thinking that the IMF is universal for galactic disks.*
- *This also suggests that we rarely see densities in excess of a few x 10^6 cm^{-3} except if a core is in a state of collapse. Seems to be verified by observation.*

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$$V^2 = const\ R$$ (linewidth-size relation)

$$const = \frac{GM(H_2)}{R^2} = G\Sigma(H_2)$$

But ρ_* increases exponentially with decreasing distance from the center(as does Σ_{gas}.

$$P_{ext} << P_{int} ??$$