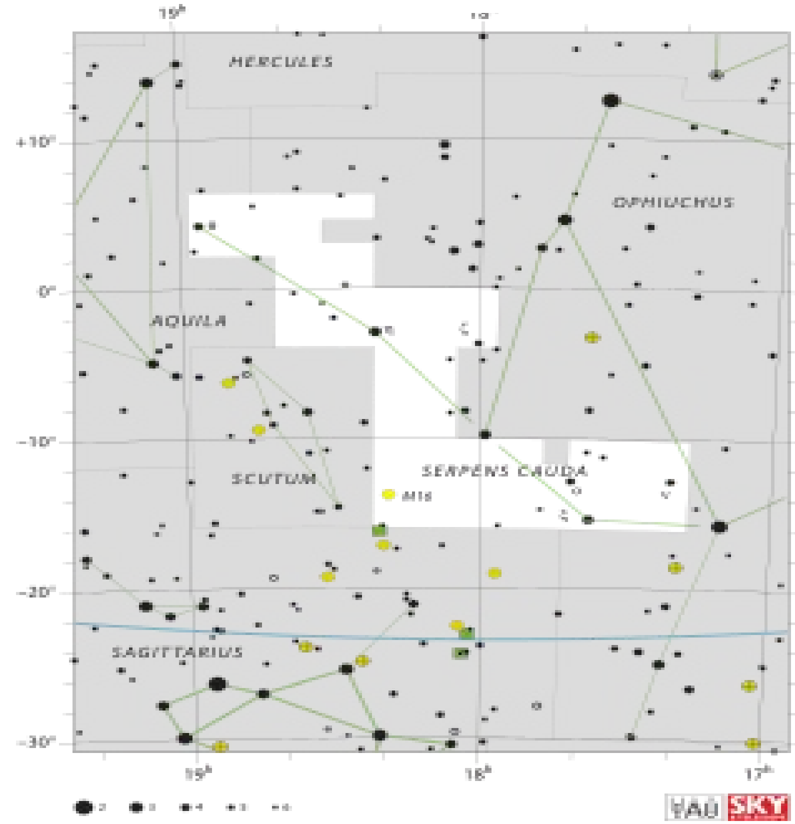
Star Formation and its Progress in Serpens

2017 APRIM
2017 Asia-Pacific Regional IAU Meeting



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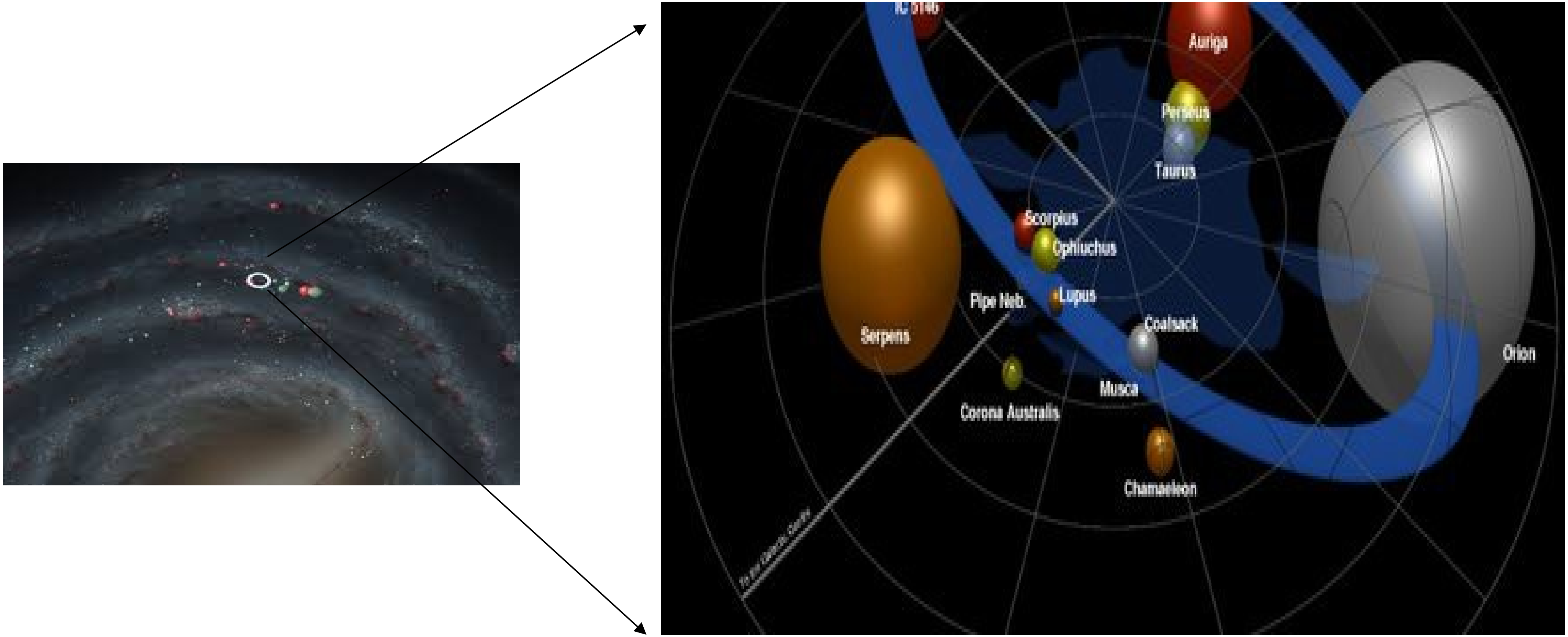
Motivation

- How do clusters form and evolve?
- What effect does environment have?
- How does star formation progress through a molecular cloud?

Solar Neighbourhood: The Gould Belt



Fragmented ring of of star-forming clouds, young stars and nebulae, containing young O- and B-type stars, tilted toward the galactic plane by about 16^0 to 20^0

Includes: the Orion Nebula and the Orion molecular clouds, the Scorpius-Centaurus OB Association, Cepheus OB2, Perseus OB2, and the Taurus-Auriga Molecular Clouds. The Serpens Molecular Cloud containing star-forming regions W40 and Serpens south is often included in Gould Belt surveys, but is not formally part of the Gould Belt due to its greater distance.

Where the story starts....

Giant Molecular Clouds

- Sizes 20-100 pc, Mass 10^4 -10^6 $M_\odot$, n~50-100 $cm^{-3,}$ T~10K
- Heavily obscured in the optical by gas and dust (confined to the Galactic plane, coincides with the spiral arms, ring 3.5-7.5 kpc in diameter)

- Star Counts
A_V = [0.5, 3], Wolf (1923), Bok (1937, 1956)
- radio observations of molecular tracers
(e.g., CO, CS, NH_3)
- Extinction (assuming constant gas to dust ratio)
- House young embedded clusters
- Critical step is to identify its young population.

BVI Barnard 68

Embedded Clusters

- Size 0.3-1 pc, Mass 20-1000 $M_\odot$, n~10-1000 $M_\odot$ pc^{-3}
- SFE 10-30%

Gas provides the gravitational glue that binds the cluster

- Birthrate ~ 10 X Birthrate for open clusters
- Extreme high rate of "infant mortality"
- Only 4 % survive beyond 100 Myr, evaporation?
- Tidal Encounters (Spitzer, 1958) will disrupt clusters with densities < 1 $M_\odot$ pc^{-3} within 200 Myr ?
- Critical to the understanding of the origin of IMF, stellar, planetary companions, etc

What is a cluster?

A group of 35 or more physically related stars whose stellar mass density exceeds 1 M_sun /pc^3

If in a state of virial equilibrium:

$\rho_* > 0.1$ M_sun/pc^3 Galactic tidal forces (Bok, 1934)

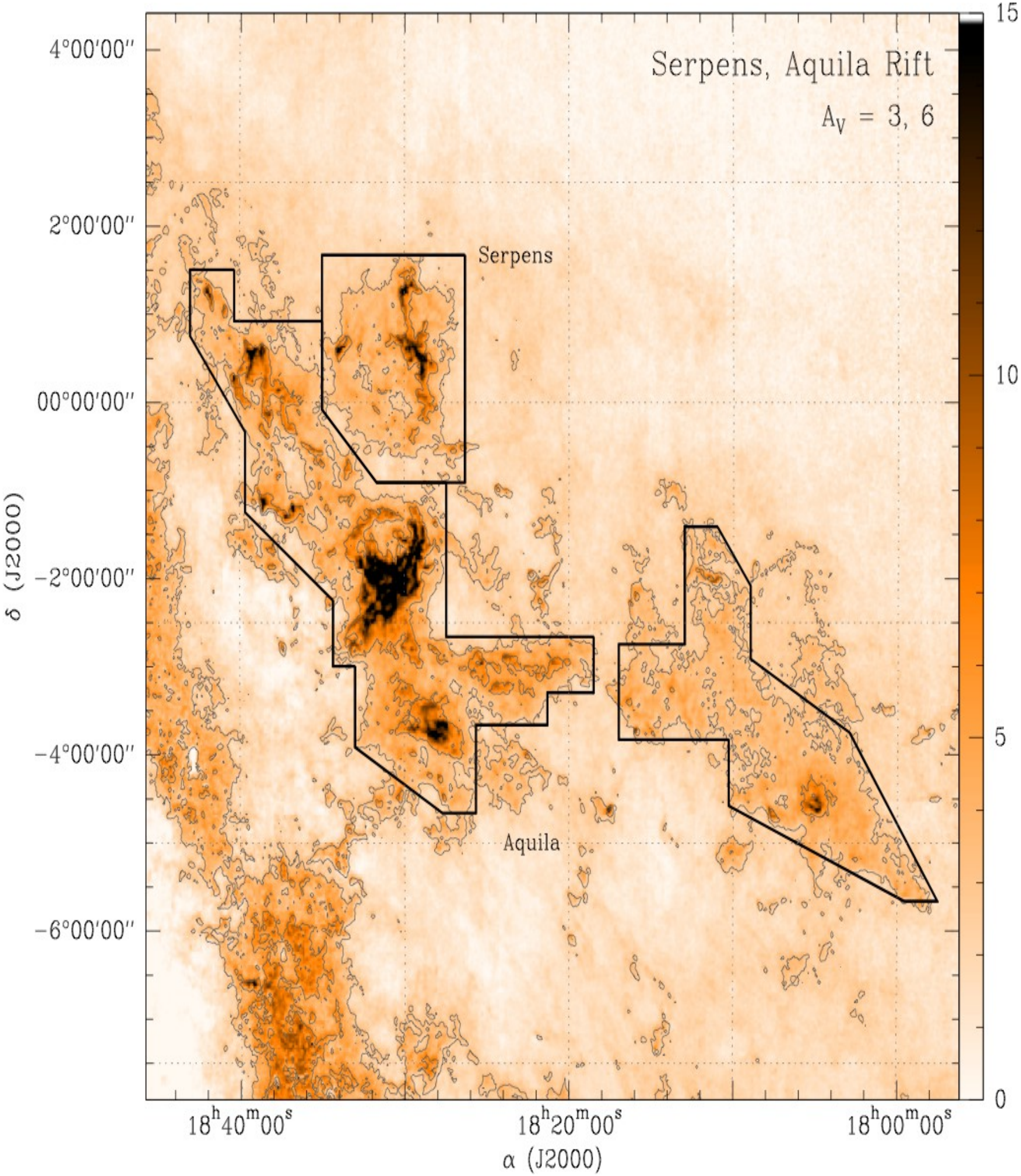
$\rho_* > 1$ M_sun/pc^3 Interaction with molecular clouds (Spitzer 1958)

Age >= 100 Myr (Adam and Myers, 2001)

t_evap=10^2*t_relax , t_relax= 0.1N t_cross/(ln N) , t_cross=10^6 yr (Binney and Tremaine 1987)

N=35, for an age of 100 Myr

Review by Lada & Lada, ARAA, vol. 41, pp.57-115



Serpens is an example of a nearby (<0.5 kpc) cluster with low mass regions Serpens is deeply embedded with extinctions exceeding 40 magnitudes in the visual.

C2D: Cores to Disks

Spitzer Legacy Survey "Molecular Cores to Planet Forming Disks" (c2d; Evans et al. 2003)

Five large clouds were selected for the c2d project: Serpens, Perseus , Ophiuchus , Lupus , and Chamaeleon

These were chosen to lie within about 300 pc of the Sun, to span a range of previously-known star formation activity, and to complement observations of smaller regions in these clouds obtained by Guaranteed Time Observers (GTOs).

Serpens: Area: 0.89 deg^2

Serpens: A Rich, but Contaminated, Sample

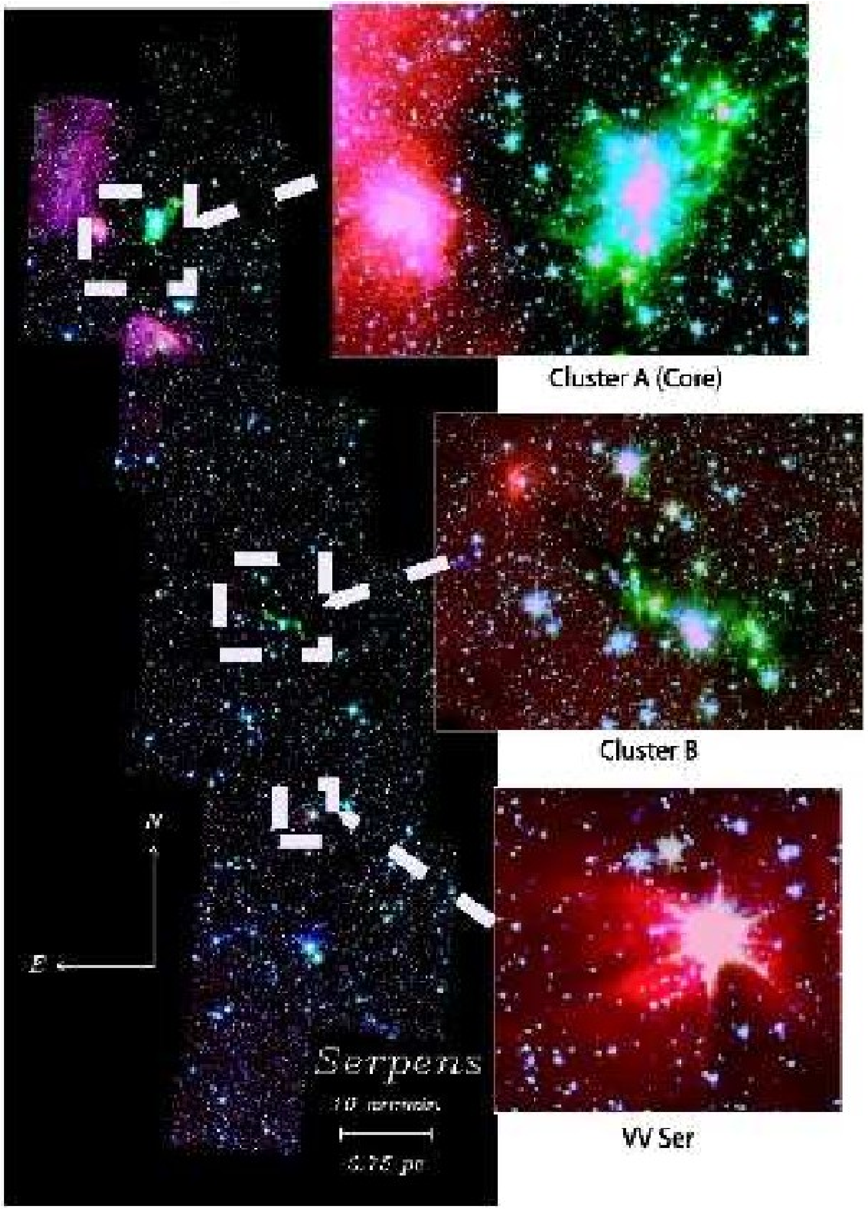
Serpens (0.85 sq deg)
377,456 total sources

104,099 in High Reliability Catalog

91,555 with at least 3 bands (2MASS-MIPS)

- 57,784 stars
- 208 candidate star forming galaxies
- 262 candidate YSOs (0.3%)
- 235 (90%) certified YSOs by human examination

Serpens Cloud



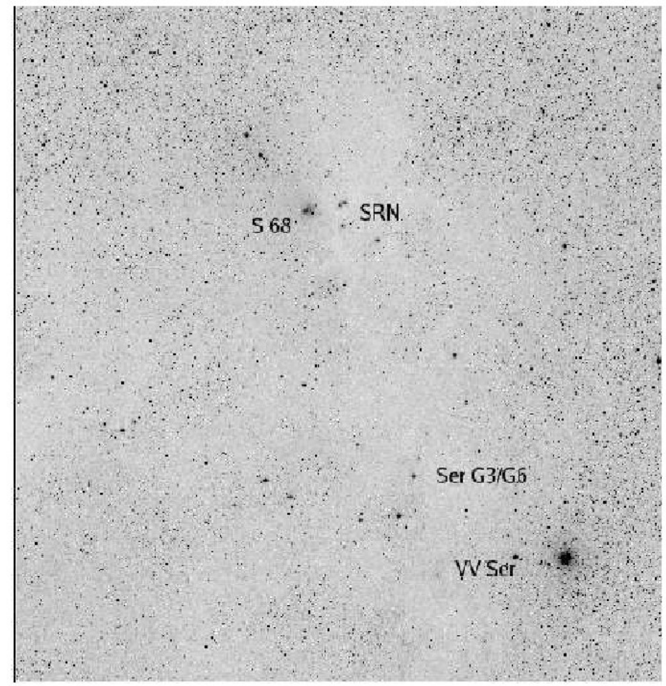
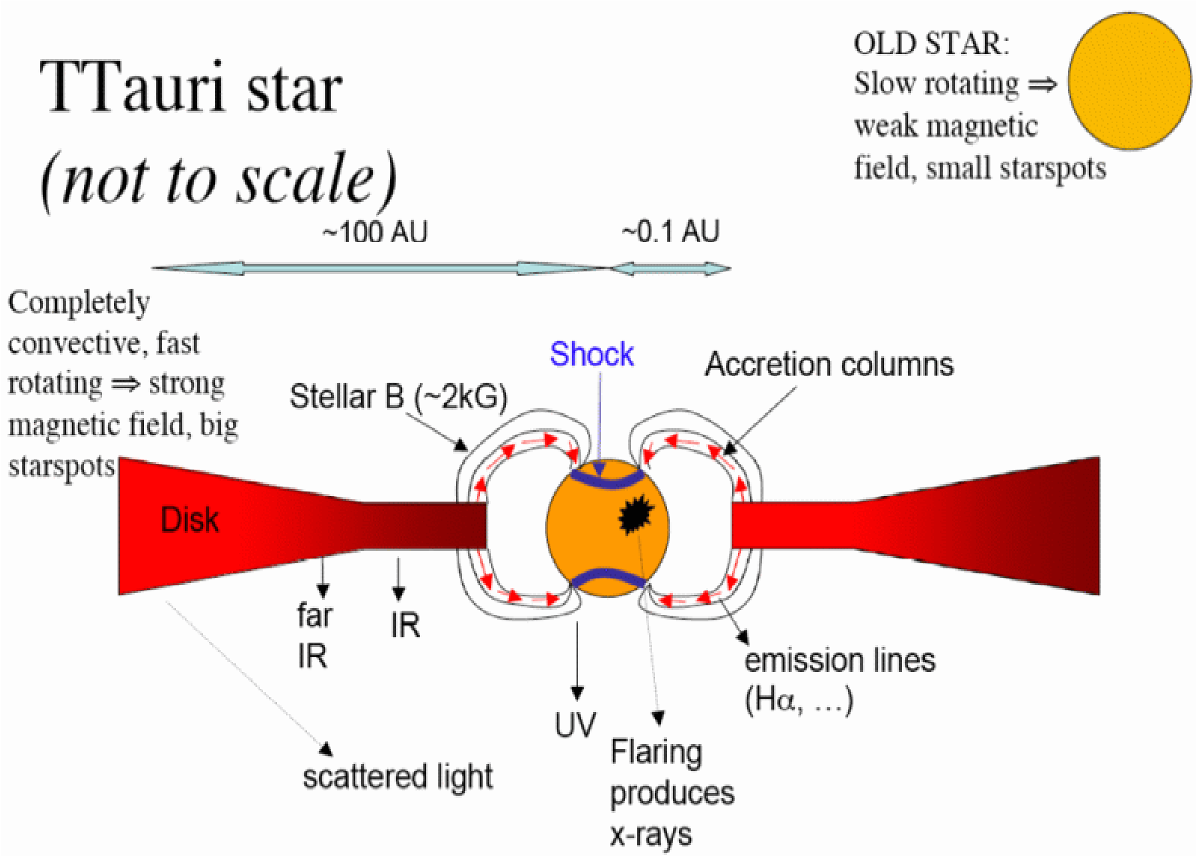


Figure 1. The Serpens molecular cloud as seen on the DSS R-band plates. Large scale irregular dark structures are clearly seen. The reflection nebulosities S 68 and SRN are indicated, as well as the position of VV Ser and of the Hα emission line stars Ser G3/G6. Field size is $2° \times 2°$. Field centre: $\alpha_{2000} = 18^h\ 30^m$, $\delta_{2000} = 0°\ 50'$. North to the top, East to the left. The image has been downloaded from the Canadian Astronomy Data Center (http://cadcwww.dao.nrc.ca/dss).

VV Serp:Herbig Ae/Be star (A_V = 3.0m , M ~ 3$M_\odot$, d ~400pc), 1 deg south of core

Colour image from Spitzer IRAC1 (blue), IRAC2 (green), and IRAC4 (red) (Harvey et al. ,2006)

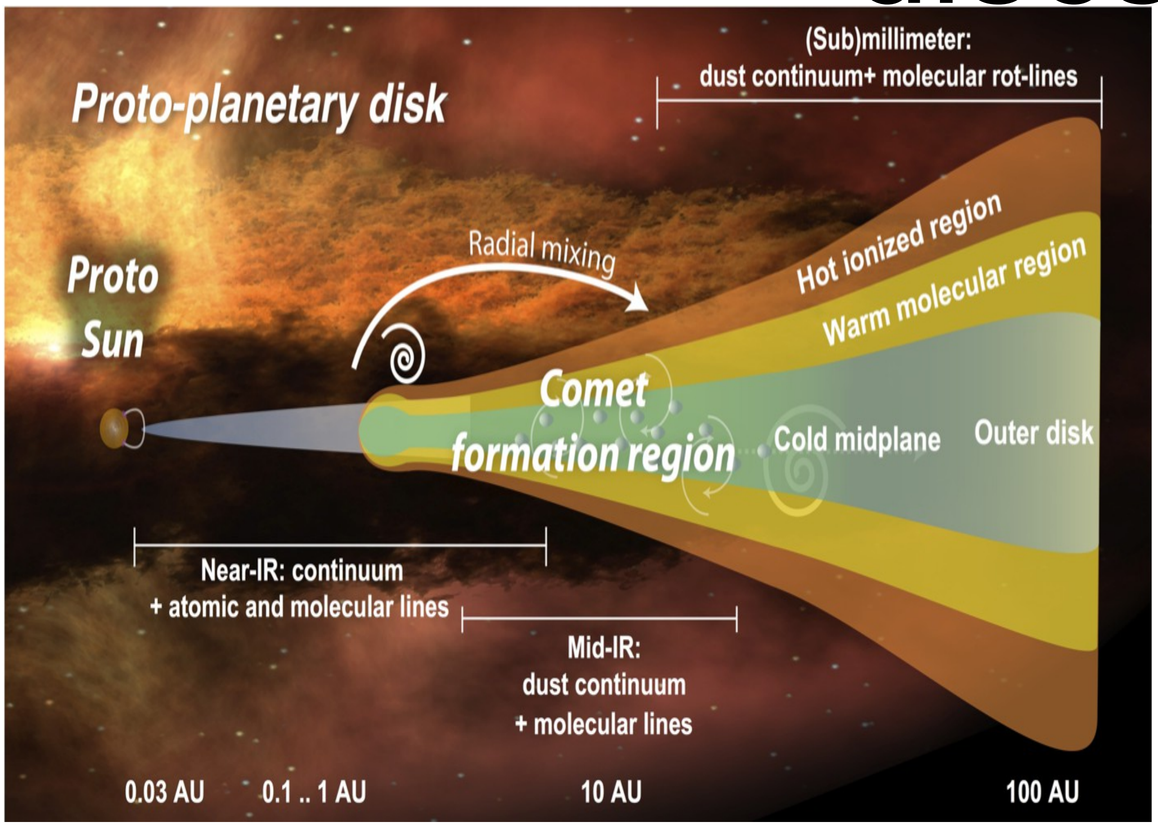
YSO Detection

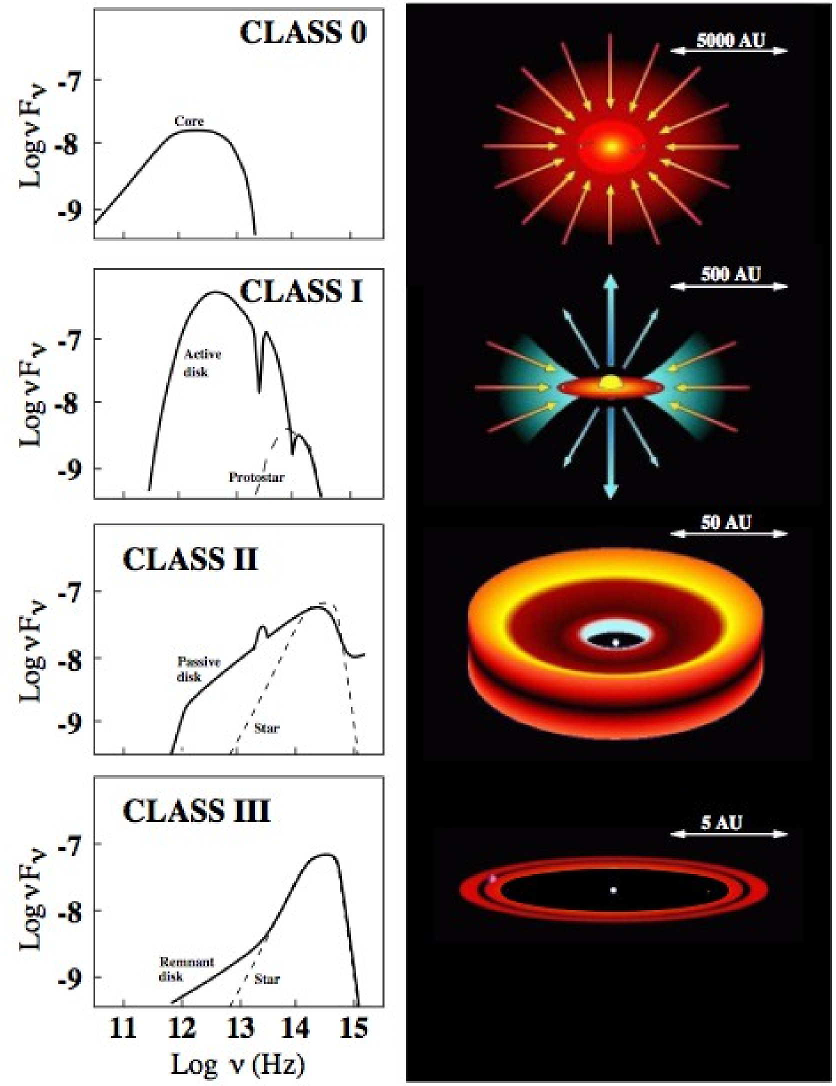


IR excess method, misses YSOs that have already dispersed their circumstellar material.

To obtain a total count of the cloud population, complementary methods such as association with nebulosities, X-rays, Radio, Imaging in H alpha, etc, and variability surveys that detect YSOs by the elevated magnetic activity

YSO detection: Circumstellar discs





Isella'(2006)

IR Data

All three major IR space observatories: IRAS (Zhang et al. 1988a,b), ISO (Kaas et al. 2004; Djupvik et al. 2006), and Spitzer.

Legacy project: From Molecular Cores to Planet-Forming Disks (c2d) (Evans et al. 2003), 0.9 deg^2 area in Serpens, has been surveyed with IRAC (3.6, 4.5, 5.8, and 8.0 μm) 2^0 in DEC and 40” MIPS bands (24, 70 and 160 μm)~ 20% > IRAC, area chosen to follow the A_V = 6 mag contour in the extinction map of Cambresy (1999).

Spitzer Gould Belt Legacy Survey: Gutermuth et al. (2008):, found a new young embedded cluster associated with a filamentary dark cloud, located 3◦ to the South of the Serpens cloud core

Xray Data

XMM-Newton: Preibisch (2004), 30' area, for a total exposure time of 52 ks
Chandra: Giardino et al. (2007), 17' with for 90 ks
Winston et al. (2007) found 95% agreement between their and Giardino's
Limitations to X-ray surveys:
smaller FOV that only covers the Main Core area
lower yield of detections for embedded objects, Sensitivity
Preibisch et al. (2005) report >97% detection rate for optically-visible T Tauri members of the ONC
Winston et al. (2007) only ~50% for classes 0/I-II in Serpens, and no confirmed detections of class 0 is reported anywhere (either due to high extinction, a flaring pattern of their X-rays, or be cause X-rays are simply not emitted)
The X-ray detected YSO sample can be still contaminated by the foreground active binaries and M dwarfs

Florida Multi-Object Imaging Near-Infrared Grism Observational Spectrometer (FLAMINGOS)

NOAO survey program Toward a Complete Near-Infrared Spectroscopic and Imaging Survey of Giant Molecular Clouds.

To study the global properties of star formation in GMCs

Observe GMCs one at a time, detect low mass stars

Cover max area to identify low density populations, if any

Obtain unbiased statistics of the embedded stellar populations

2K HgCdTe "HAWAII-2" imaging array

2.1m Kitt Peak telescope, 20.5' X 20.5' FOV, plate scale 0.608'/ pixel for imaging and spectroscopy on the 4 m

DATA

Imaging Data of the Serpens molecular cloud in JHK bands with FLAMINGOS instrument in October 2003.

Seventeen 20'X20' fields tiled in the NESW direction

October 2003 (in the J, H and K filters). In the J and H filters 9 dithered exposures were taken 35 sec each, in K 25 exposures 15 sec each, for a total time of 5-6 min per filter.

Plate scale: 0.6" pixel , Seeing: 1.5" - 2.15", Airmass: 1.2 – 2, 1.7^{0} sq deg

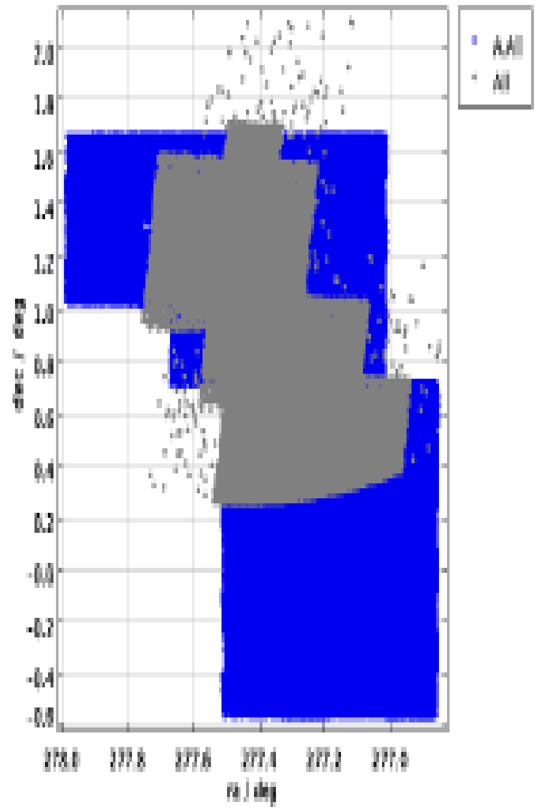
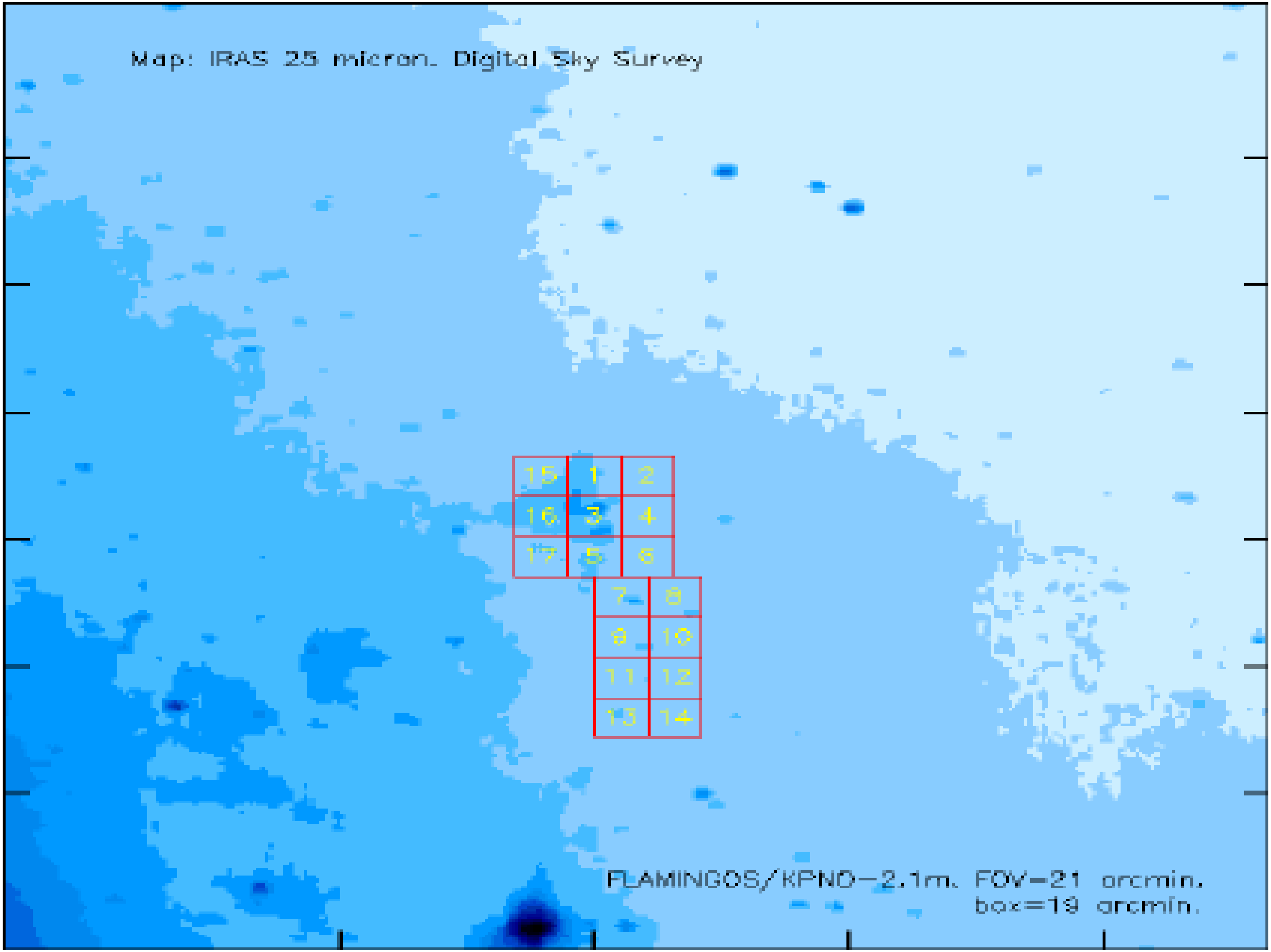
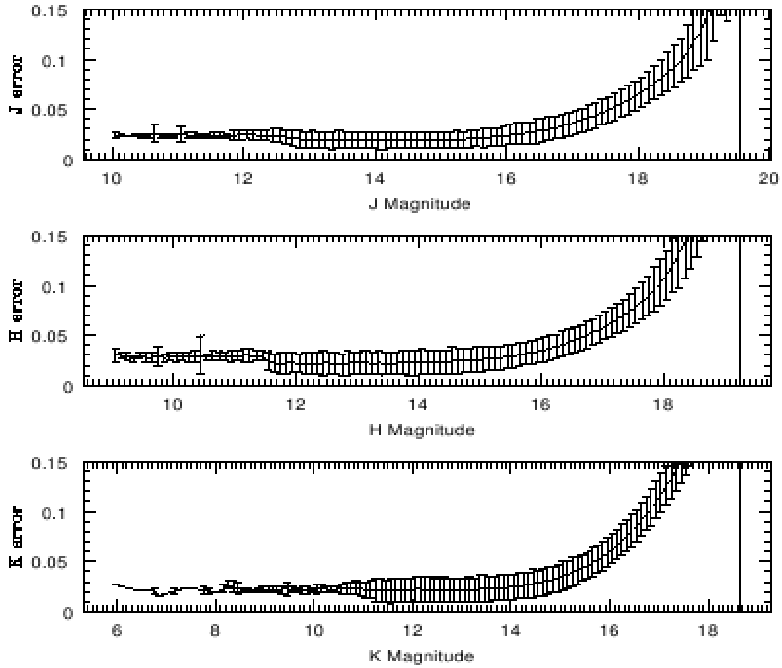


Figure 2: The footprint of the C2D survey (grey) on the FLAMINGOS (blue) Serpens field.


Map: IRAS 25 micron. Digital Sky Survey
15
1
2
16
3
4
17
5
6
7
8
9
10
11
12
13
14
FLAMINGOS/KPNO-2.1m. FOV=21 arcmin.
box=19 arcmin.

Data reduction



Saturated sources H < 11.5, replaced by 2MASS (1861)

Detection limits: ~ 18, 18, & 17 mag at J, H, & K,

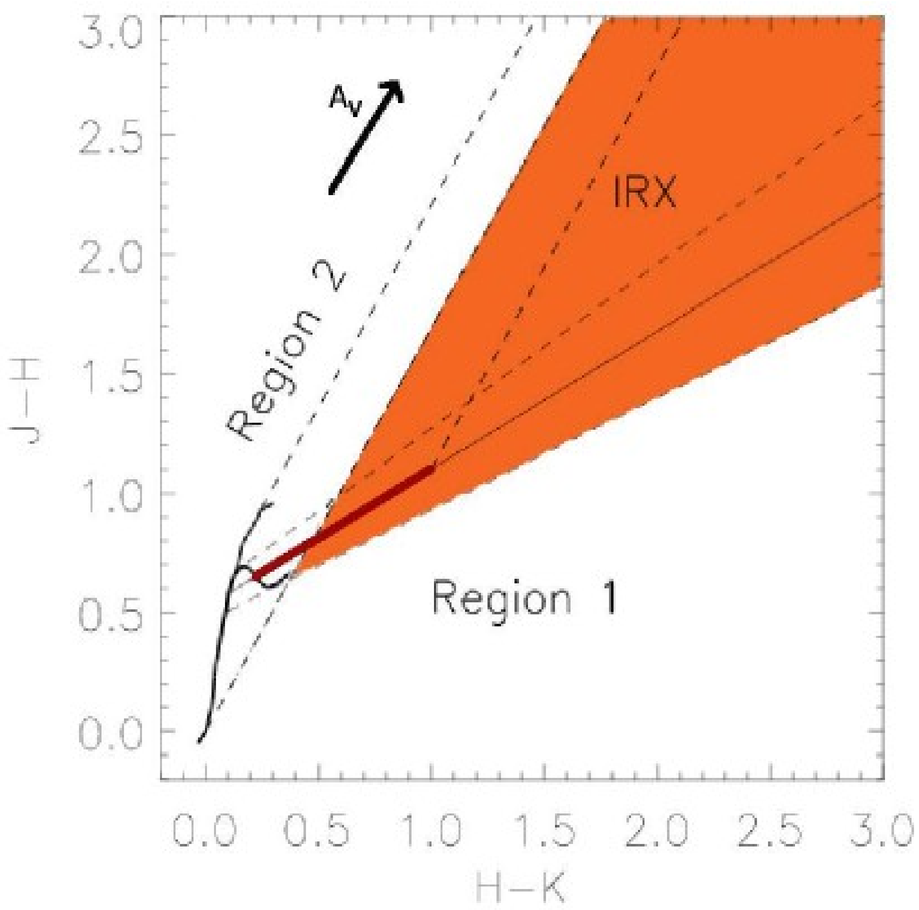
The no of sources is 71,257.

Detection of clusters

Problems in using traditional star counts:
Background contamination:highly non-uniform extinction and proximity to the galactic plane ($b = 5^\circ$).
Other Contaminants:brown dwarfs, a variety of evolved stars, galaxies, and AGNs
Ideal: Spectroscopy

Optimization:
(1) selecting them from a sample of NIRX stars and
(2) analyzing their distribution of surface densities using a method of nearest neighbors.

NIR Color-Color Space



Thick dark solid lines: loci of the zero age main sequence and the giant branch (Bessell & Brett, 1988).

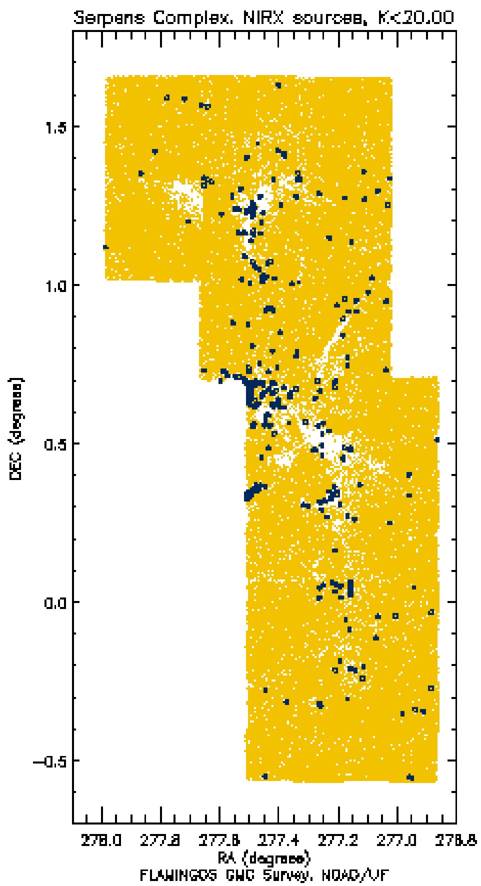
Thick colored line is the Classic T-Tauri locus (Meyer et al., 1997) extended to large H − K values and above and below by its observational error.

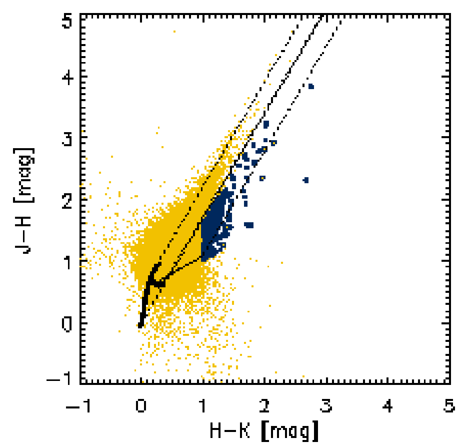
Dashed lines represent extinction along the direction of the reddening vector indicated by the arrow on the left.

Shadow region: IRX

Regions 1 and 2: spurious detections and high photometric color scatter.

IRX sources





Magnitude: 5 < K < 20 mag
Errors: error(J-H)<0.2 and error(H-K)<0.2 K<16.0
error(J-H)<0.1 and error(H-K)<0.1 IF K>16.0
= yellow points
IRXsources (blue dots):
J-H < 1.692(H-K) - 0.1
AND
J-H >= 0.470(H-K)+0.46+0.1
AND
H-K >= 1.0

345 stars!!!
To be used only to identify clusters.....

Color-color plots

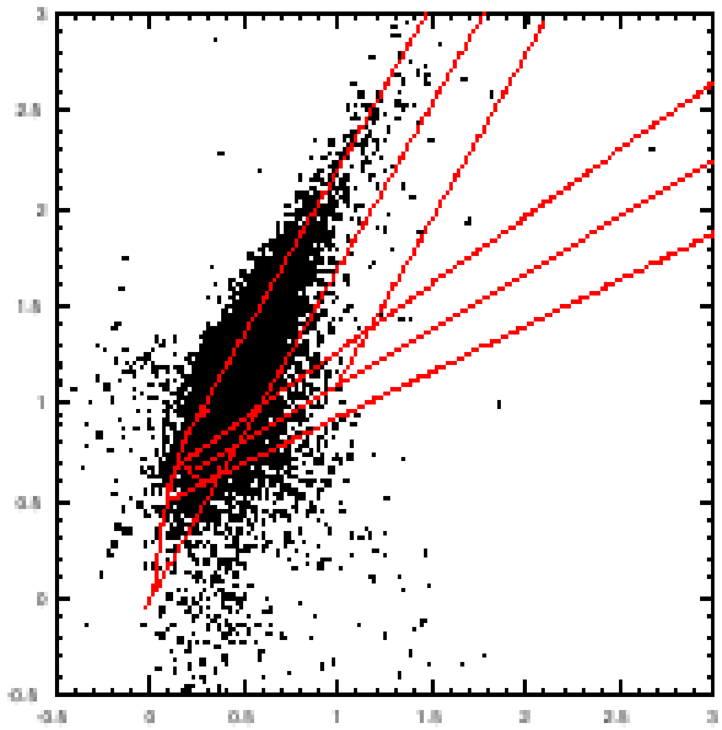


Figure 8: Color-color plots for stars brighter than 15.75m

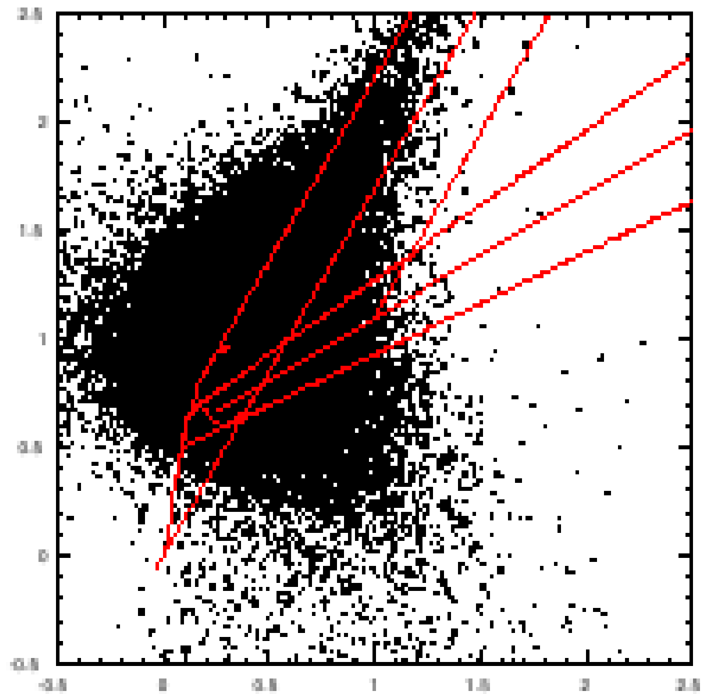
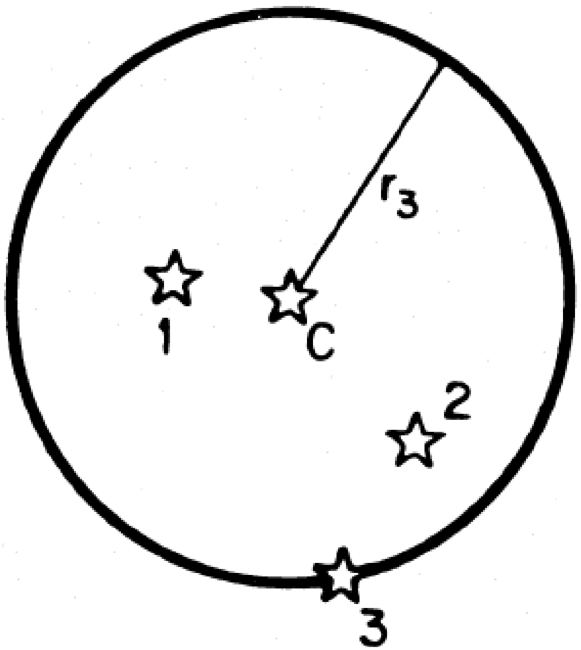


Figure 9: Color-color plots for stars fainter than 15.75m

Nearest Neighbour Method

$$\mu_j = \frac{j-1}{\pi D_j^2}$$



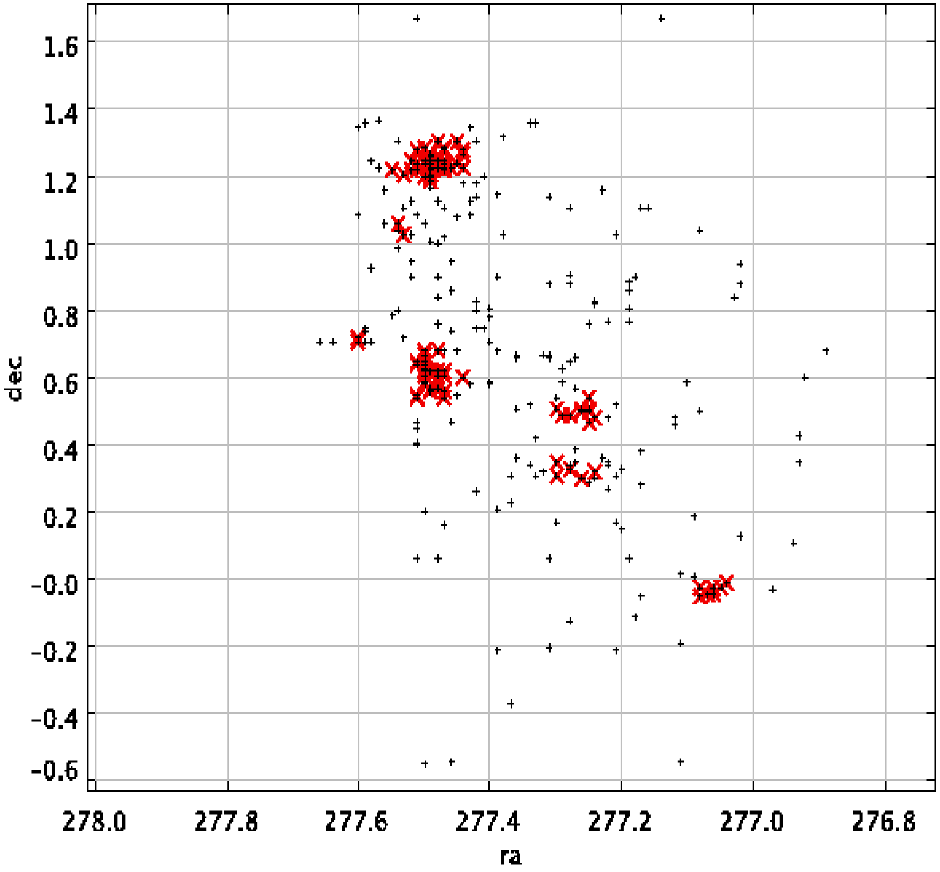
The j^th NN surface density estimator for a star

D_j is the distance from any given star to its j^th neighbor

Casertano & Hut, ApJ,1985, 298, 85

(Nakajima et al.1998; Gutermuth et al. 2005)

NNN on Spitzer sources



$$\mu_j = \frac{j-1}{\pi D_j^2}$$

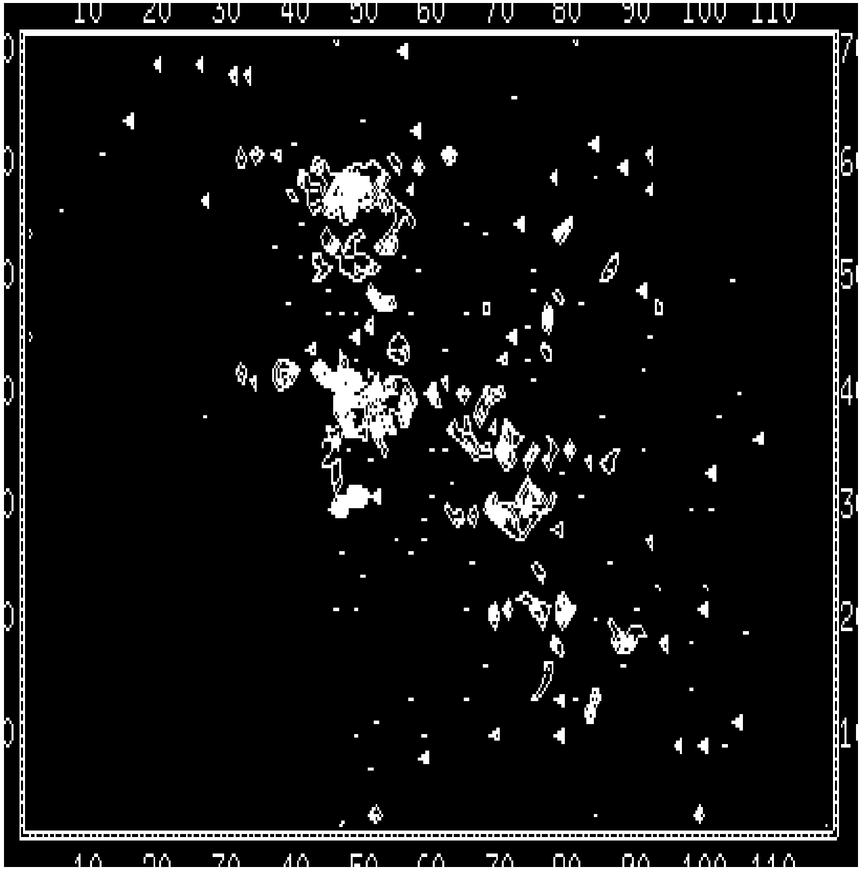
Choice of j:

If j is much larger than the minimum number of stars that define a group or cluster, then small structures could be overlooked

If j is small: we detect those smaller stellar groups

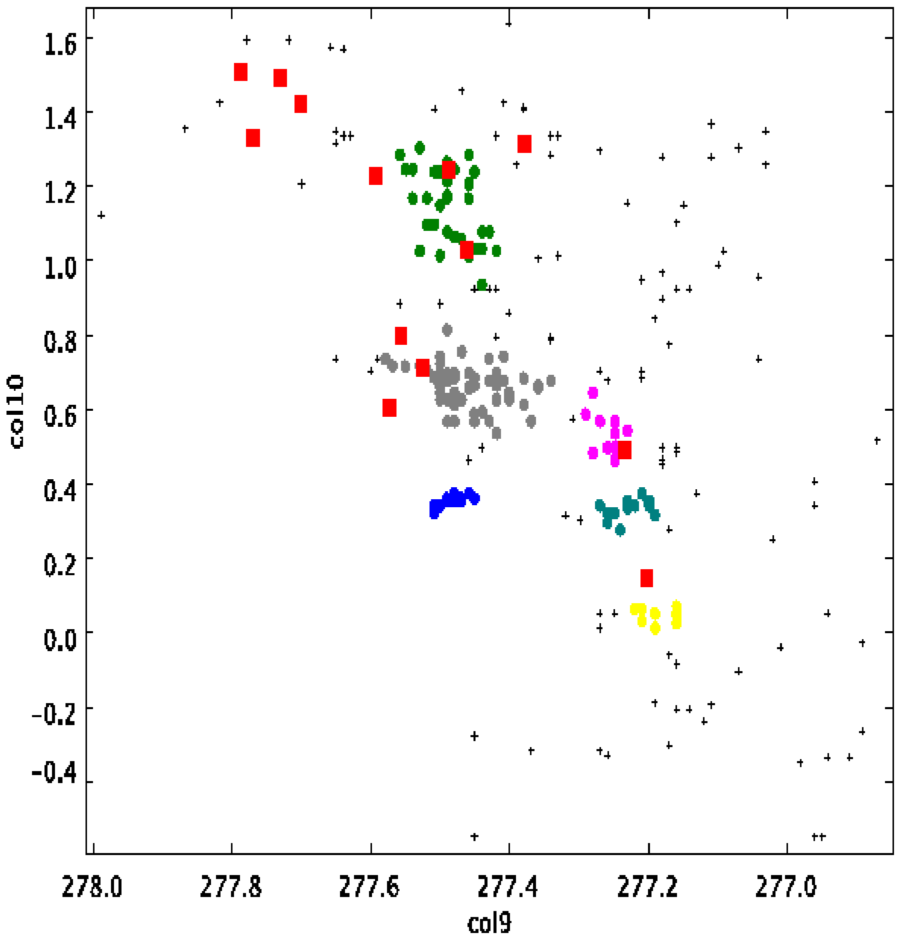
Clusters > Mean dens 0.30 stars/arc min^2, 5 clusters (2 new)!

Young Clusters in Serpens



- Using NIR, Spitzer data....
- 5 clusters...3 new!
- False clusters? (extinction check)

NNN on IRX sources

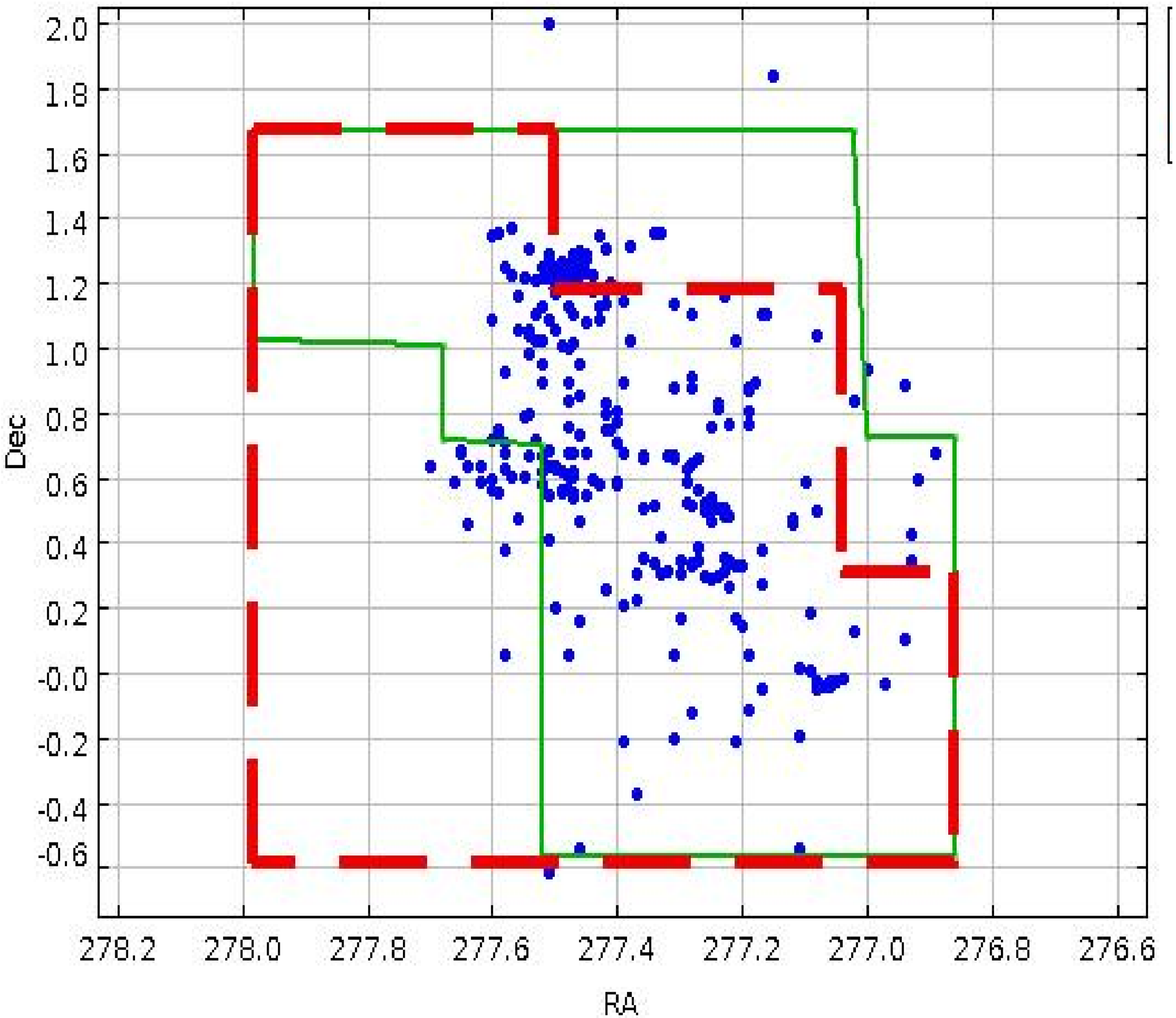


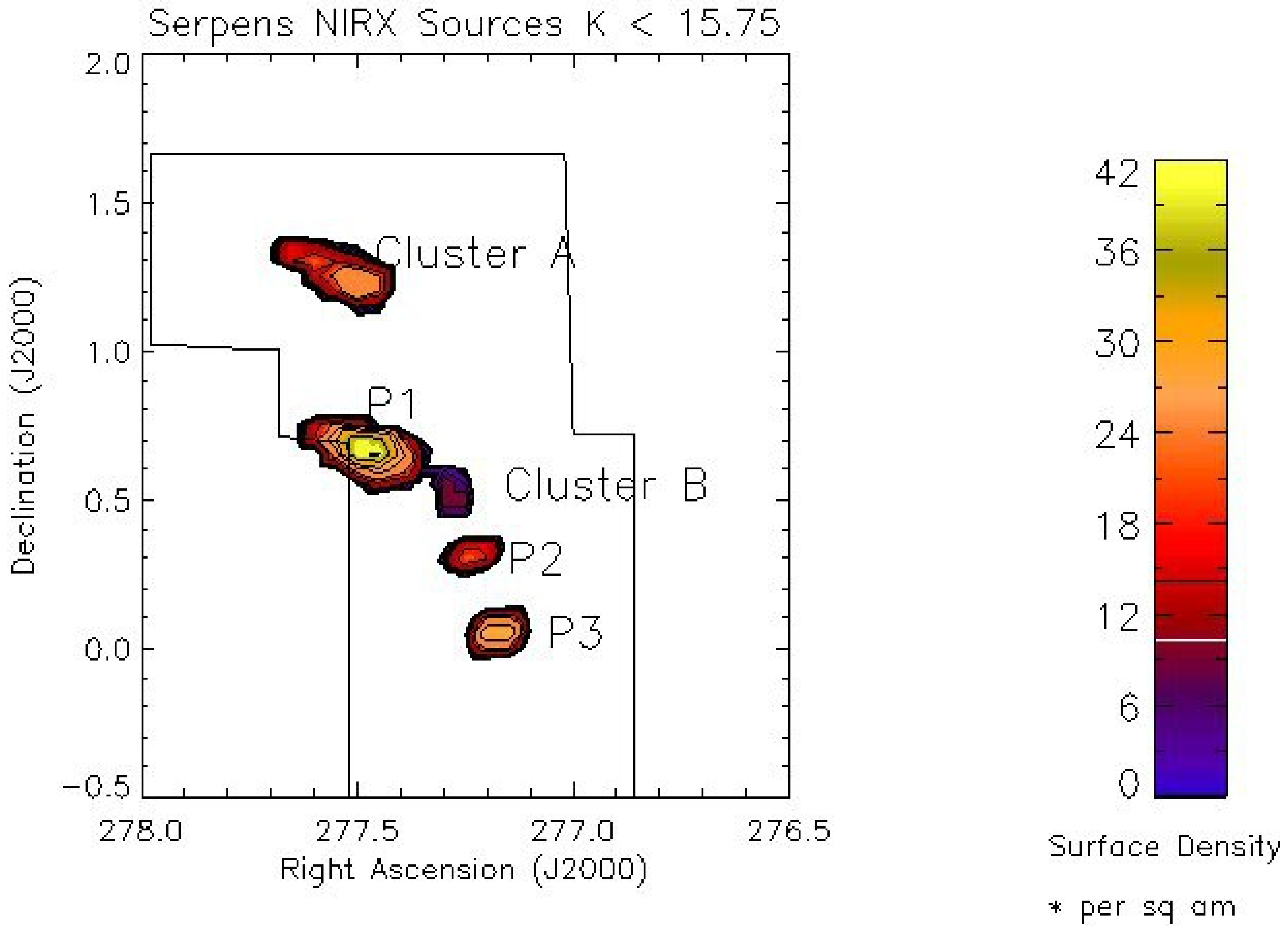
Density Center, Core Radius:

$$X_d = \frac{\sum_i X(i)\mu_j(i)}{\sum_i \mu_j(i)}$$

$$R_{core} = \frac{\sum_i |X(i) - X_{d,j}|\mu_j(i)}{\sum_i \mu_j(i)}$$

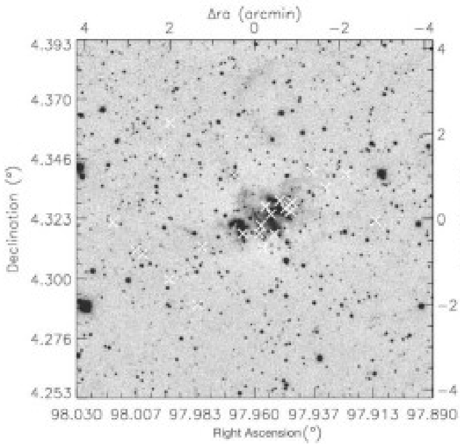
FLAMINGOS-UKIDSS fields

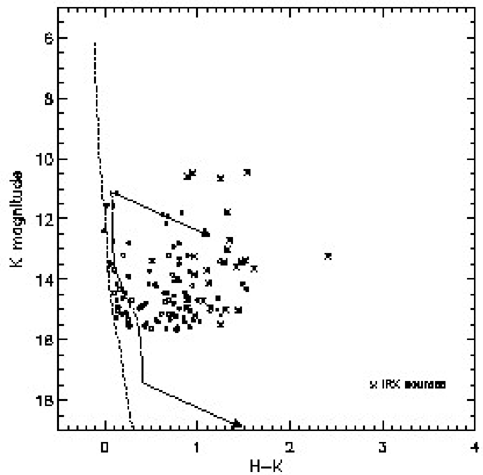


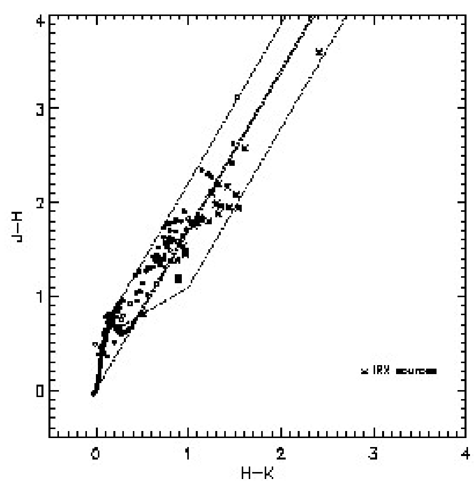


Serpens NIRX Sources K < 15.75
2.0
1.5
1.0
0.5
0.0
−0.5
Declination (J2000)
278.0
277.5
277.0
276.5
Right Ascension (J2000)
Cluster A
P1
Cluster B
P2
P3
42
36
30
24
18
12
6
0
Surface Density
* per sq am

Individual Clusters







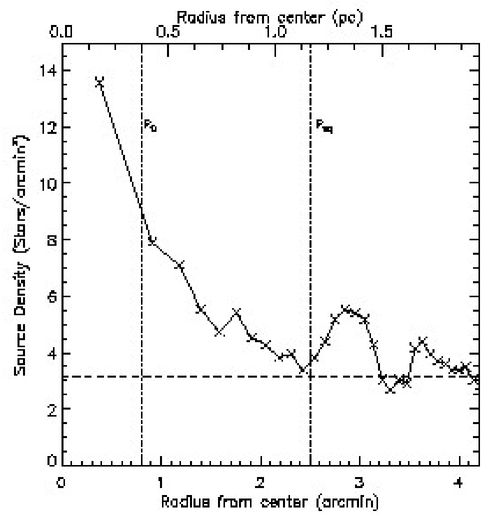


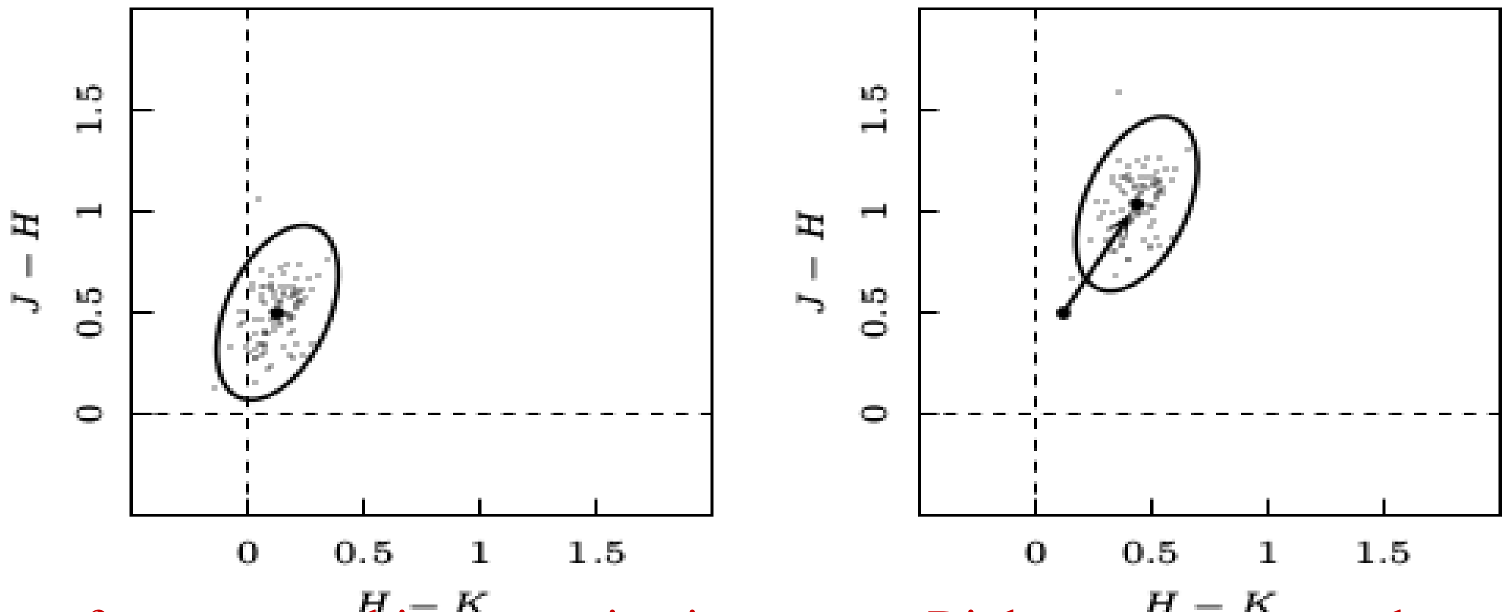
Table 1. Cluster parameters

Cluster	RA deg	Dec deg	R_C (pc)	R_E (pc)	N_{NIRX}	A_V
A	277.53	1.26	0.31	0.87	37	9.8±3.88
P1	277.48	0.67	0.13	0.73	78	8.36±1.7
P2	277.24	0.32	0.17	0.52	14	10.42±4.1
B	277.30	0.58	0.35	0.73	21	9.07±2.7
P3	277.16	0.05	0.05	0.28	24	7.65 ±1.7

Extinction Maps: NICE-NICER-NICEST

To measure and map the distribution of dust through a molecular cloud

NICE: Near-Infrared Color Excess: Lada et al. (1994)

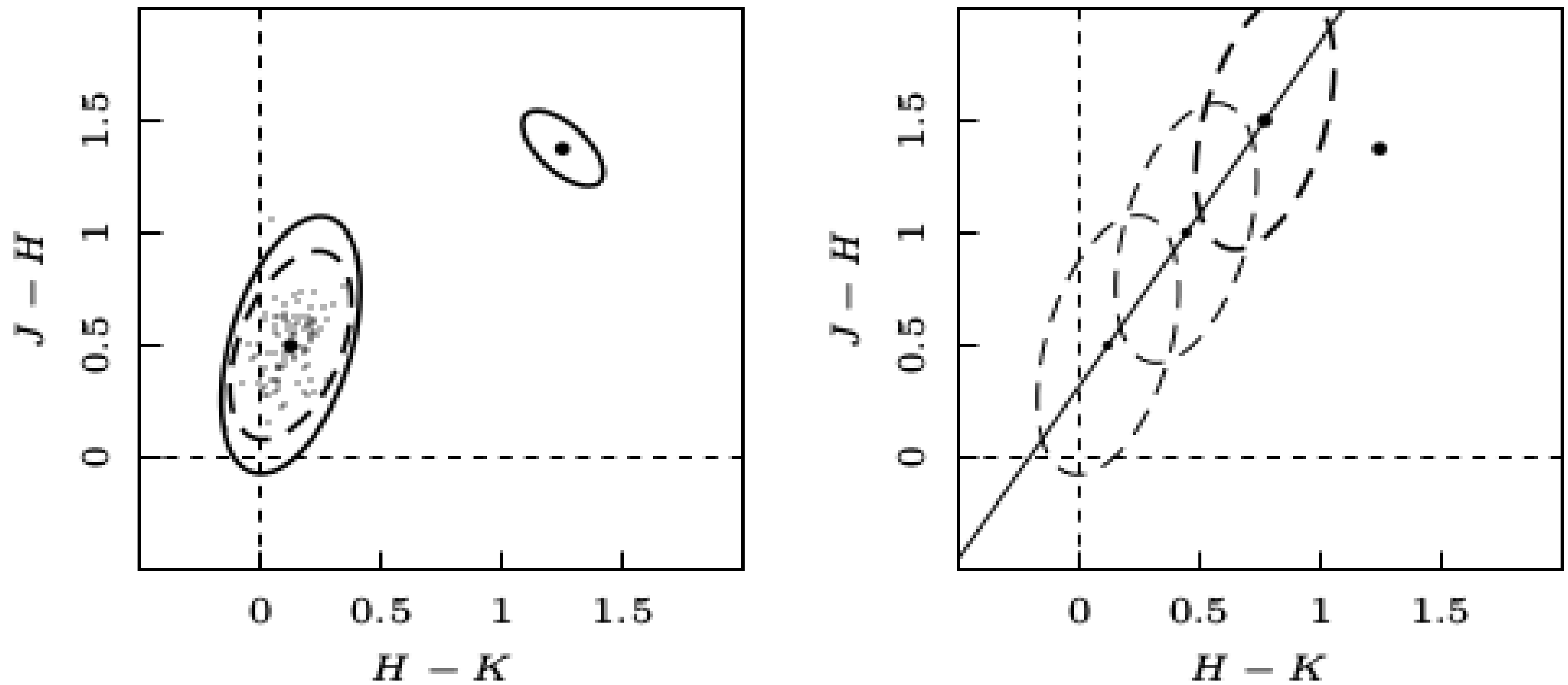


Left: Colors of stars not subject to extinction. Right: same stars as observedwith $A_V = 5$

The ellipse encloses a 3σ confidence region, (a normal reddening law is assumed).

$$\hat{A}_V = 15.87 \left[\frac{1}{N} \sum_{n=1}^{N} (H-K)_i^{\text{obs}} - \langle (H-K)^{\text{tr}} \rangle \right],$$

NICER: Near-Infrared Color Excess method Revisited (Lombardi & Alves 2001)

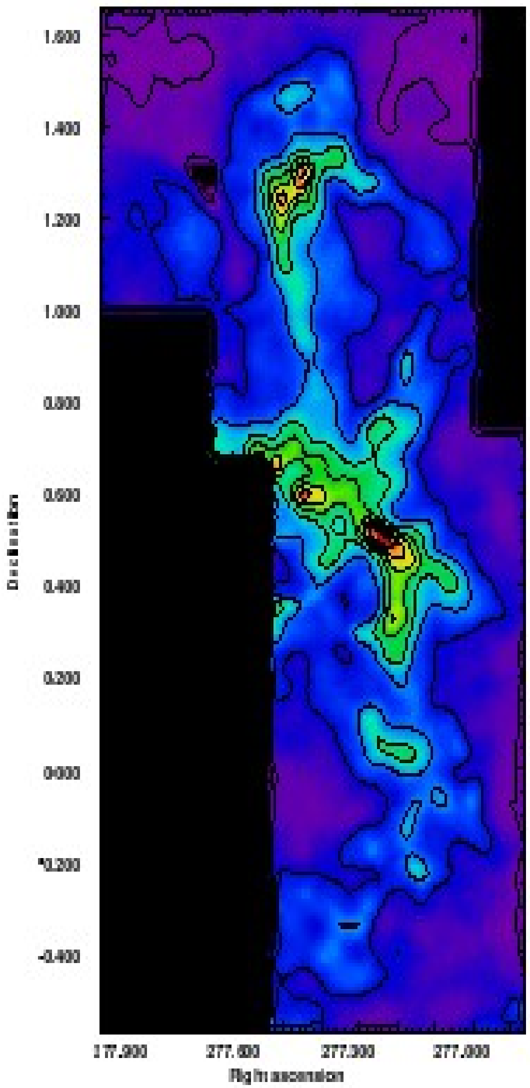


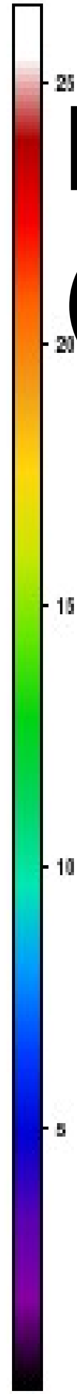
For each star, Nicer obtains A_V using a maximum-likelihood technique.

Relative covariance (small ellipse to the top right) causes widening (solid ellipse) of the intrinsic color scatter.
NICER finds the ellipse center along the reddening line closer to the observed colors of the star

Adv: Uses all JHK, and works in the absence of one too....

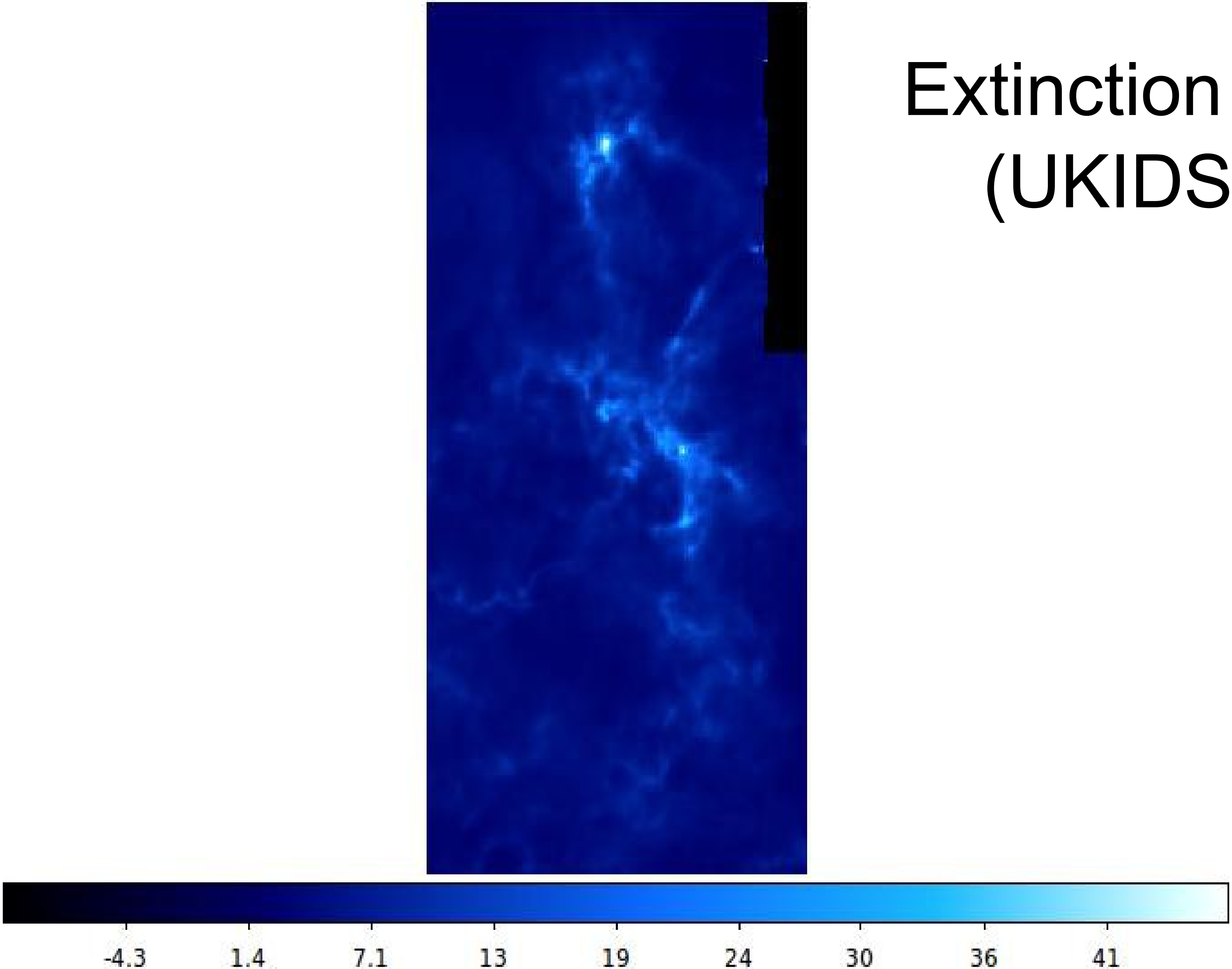
Extinction Map (FLAMINGOS)

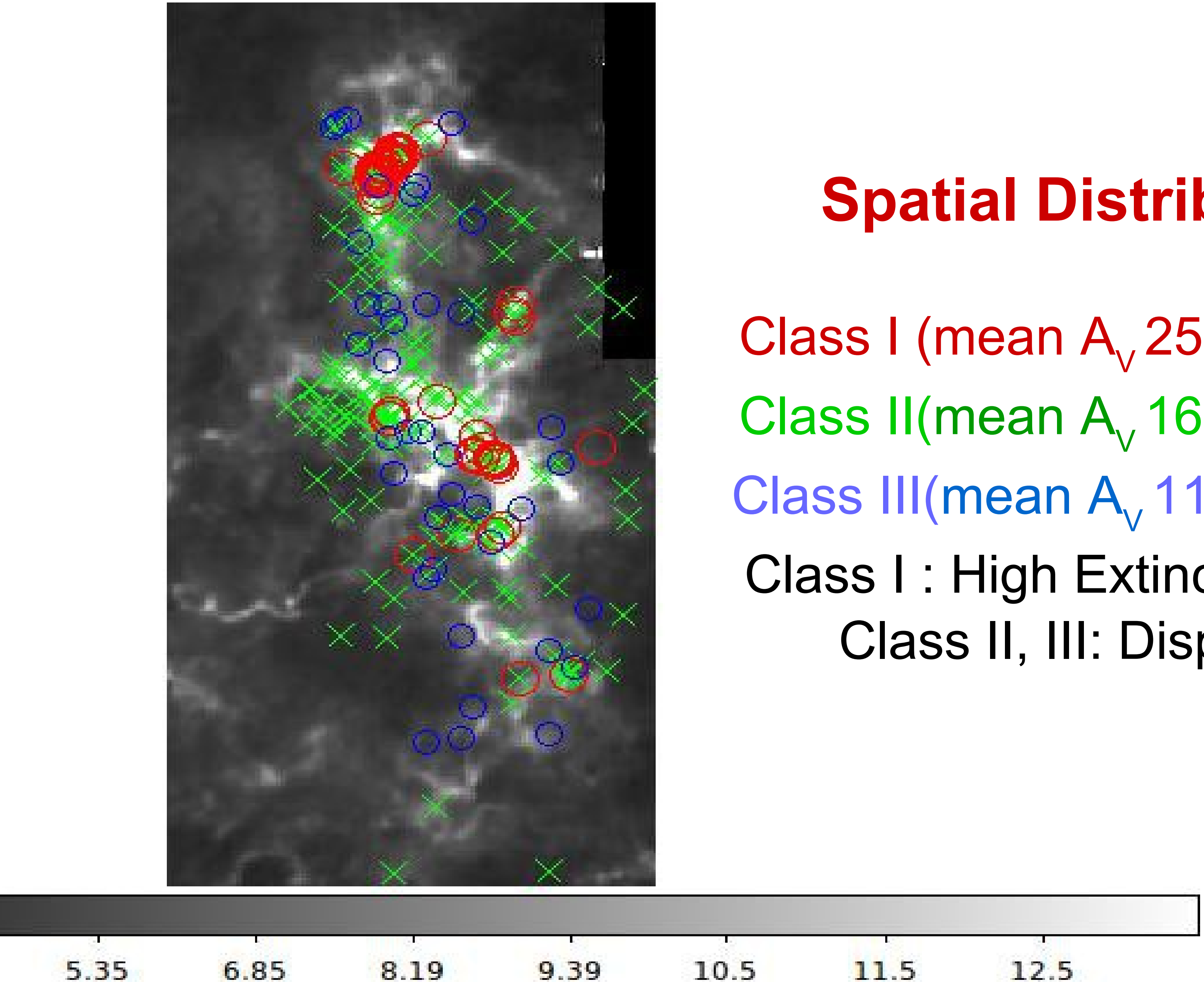




NICER extinction map at 90" resolution

Extinction Map (UKIDSS)





Spatial Distribution

Class I (mean A_V 25 /pm 3.32),

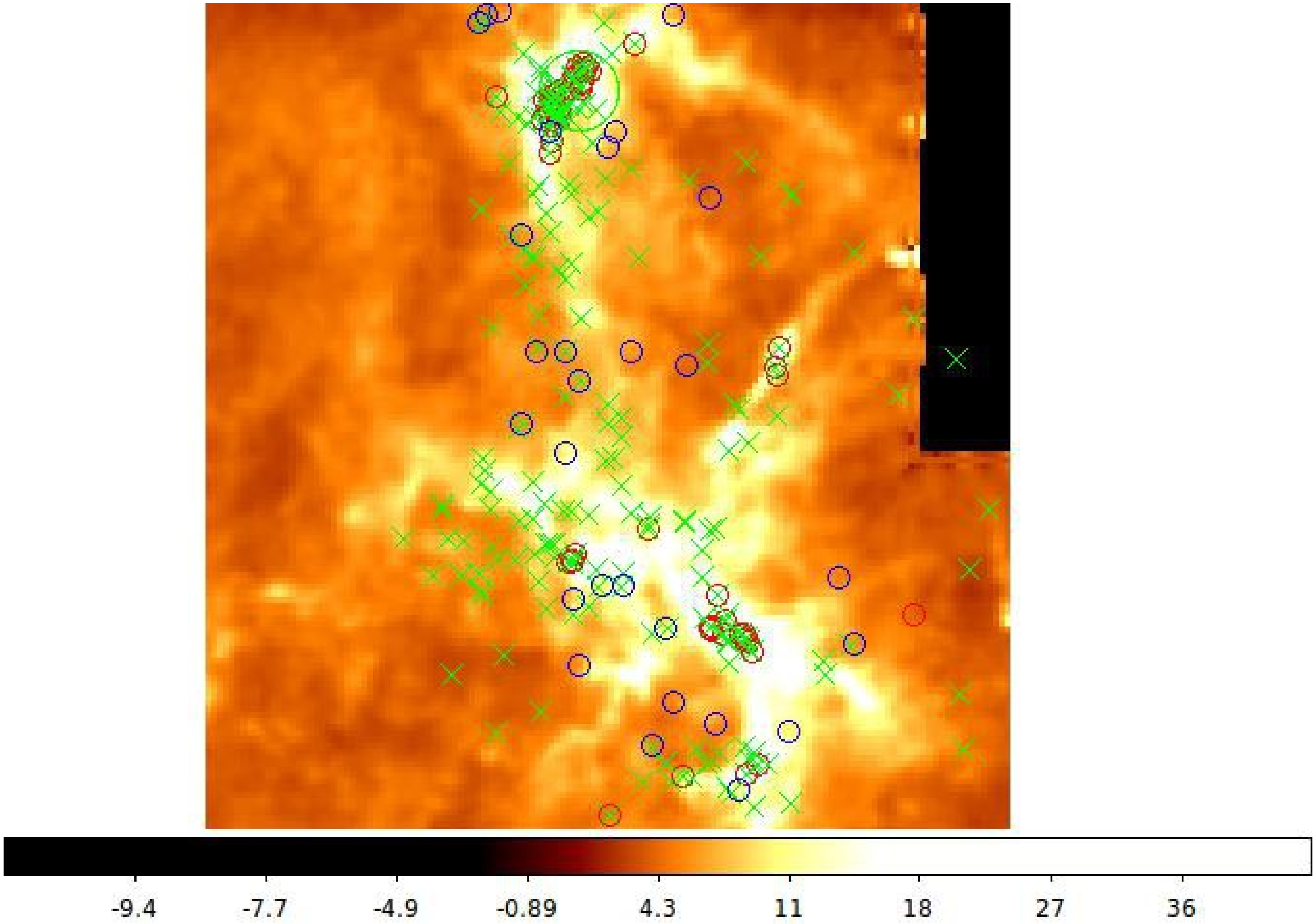
Class II(mean A_V 16 /pm 1.77),

Class III(mean A_V 11.2 /pm 1.8)

Class I : High Extinction areas

Class II, III: Dispersed

Cluster B+P1: Two components?



Star Formation in Filaments

Stars clusters are found where filaments overlap, this suggests that the collision between the filaments might create the necessary conditions for a star cluster to form. The question is whether the filament collision occurs before, after, or even during the star formation process.

Clustered star formation or in-situ cluster formation: If the filament collision occurs before star formation then the collision is effectively bringing together large volumes of dense gas into a small space. This would allow star formation to proceed very rapidly in a very dense cluster of gas, leading to the formation of stars in a highly clustered distribution.

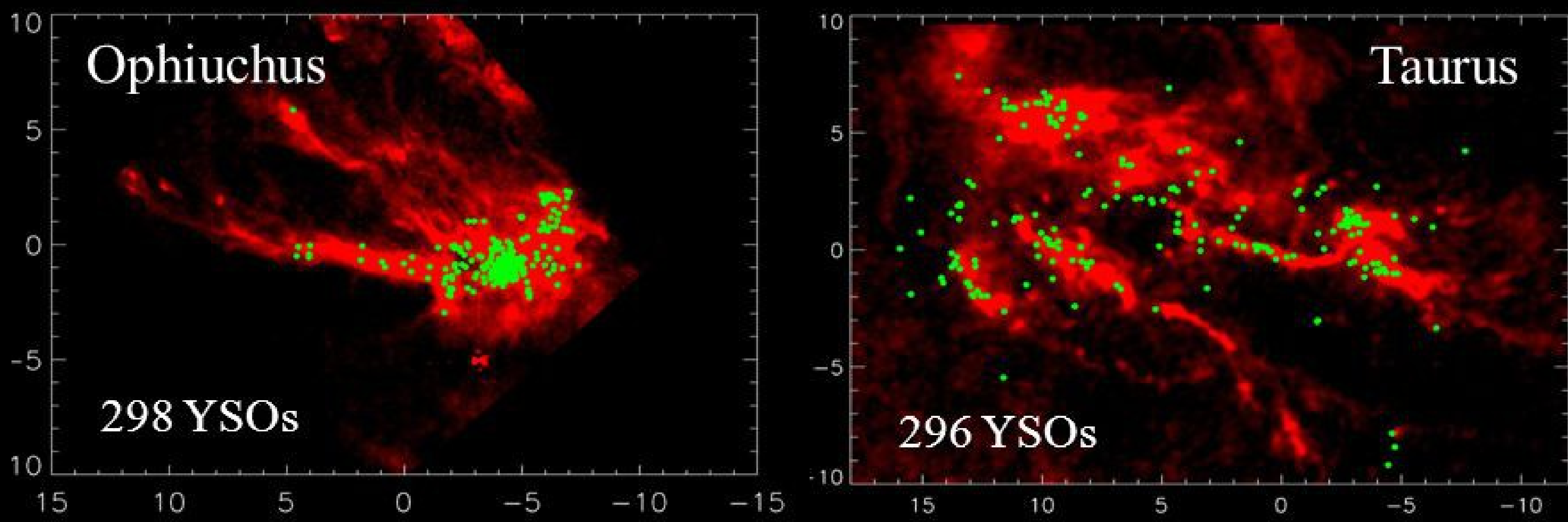
Comparing Clustered and Distributed Modes

Relative importance of clustered and distributed stars appears to be linked to the organization of gas in the clouds.

Taurus – spaghetti like filaments, no major clumps with large column densities.

Ophiuchus – star formation found in one large clump, perhaps the result of compression by Upper Scorpius association.

Does compression from external stars play role? Do magnetic fields inhibit the formation of clumps?



Results

Cluster B: A particularly rich area of star (and substellar) formation southwest of the well-studied Serpens core. This region is much larger than earlier and structured

The core of the cluster is on average younger than the rest of the cluster. The core is richer in Class I stars, while the outskirts are dominated by a much larger scattered population of Class II or later type stars

Average Extinction Av =10, max 40

The young cluster population accounts for 262/345~ 76% of the YSOs are in clusters. This implies that the majority of stars in Serpens form in embedded clusters

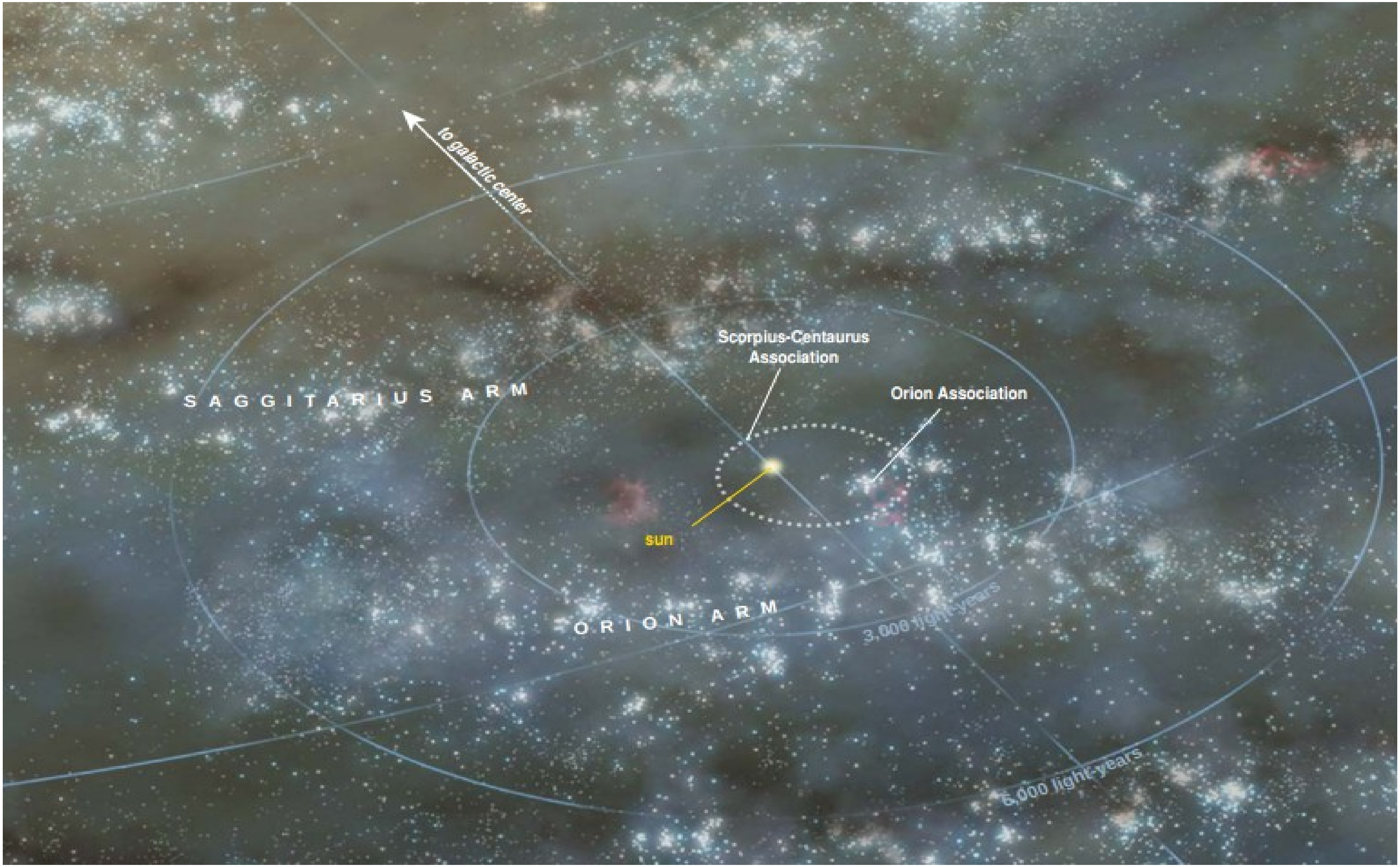
The sizes of clusters appear to be anticorrelated with their mean extinctions and infrared excess fractions, suggesting that clusters form as compact units then expand shortly after formation

Star formation in the cloud occurs preferentially in high extinction regions. Class I stars are at highest extinction areas

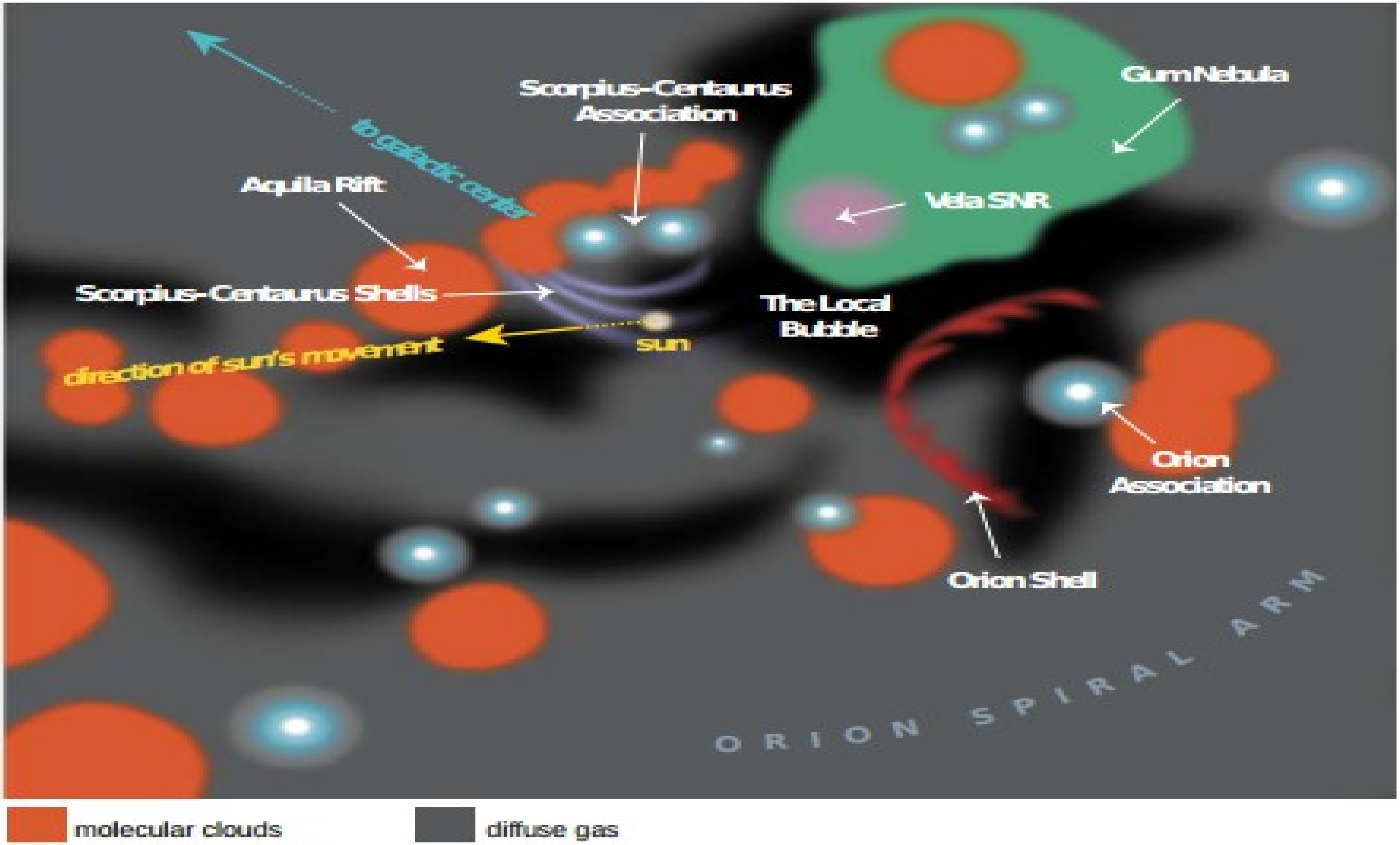
Thank You!

Observational approach

- Case studies of SF regions: NGC 2282,   NGC 281
- Surveys of signposts of SF: outflows, luminous IRAS sources, Herbig AeBe stars, etc
- Systematic surveys of Molecular cloud complexes
- young stars emit X-rays at levels 10^2–10^4 times that of normal stars, particularly during the first 10 Myr of their lives
- Surveys using all sky data of 2MASS, DENIS, WISE
- Spitzer, Herschel



Solar "neighborhood" in the Milky Way lies just inside one of the galaxy's great spiral arms, the Orion Arm. The majority of the brightest stars are distributed along a section of sky known as Gould's Belt (dashed ellipse), which also marks the distribution of the nearby star-forming regions in the Orion spiral arm. The sun is on the edge of the Local Bubble, a great void in the distribution of interstellar gas in the nearby galactic neighborhood.



Galactic environment within 1,500 light-years of the sun contains gas clouds of various densities and temperatures. The sun has been passing through a hot, very low-density region—the Local Bubble (black)—for several million years, and it is now embedded in a shell of warm, partly ionized material (violet) flowing from the Scorpius-Centaurus star-forming region. Cold, dense molecular clouds (orange), such as the Aquila Rift, can inhibit the flow of these shells, but the low density bubble around the sun readily allows such interstellar material to sweep over the solar system. The Vela supernova remnant (SNR, pink) should ultimately cool and expand to form shells of material similar to that surrounding the sun. The Gum Nebula (green) is a complex region of ionized hydrogen

Serpens molecular cloud

Well-suited for studies of very young low-mass stars and sub-stellar objects because of proximity (260 pc; and young age (2-6 Myr)

Surface density of young stars in this region is much higher, by a factor of 10-100, than that of the other star-forming regions mapped by the c2d team (Evans et al. 2009)

includes 22% of the c2d sources classified as “transitional” disks.

Ideal region to build a “template” sample for the study of disk evolution up to a few Myr within a single, small, well defined region by obtaining a complete, well-defined sample of multi-wavelength observations of young stars and sub-stellar objects

Complementary Data: X-ray to millimeter wavelengths, and spectroscopic follow-ups of the newly discovered population of young stars in Serpens

The third star-forming region after Taurus and IC 348 for which such an unbiased dataset exists (Goodman 2004; Harvey et al. 2007; Enoch et al. 2007; Oliveira et al. 2009, 2010).

Serpens Main Cluster

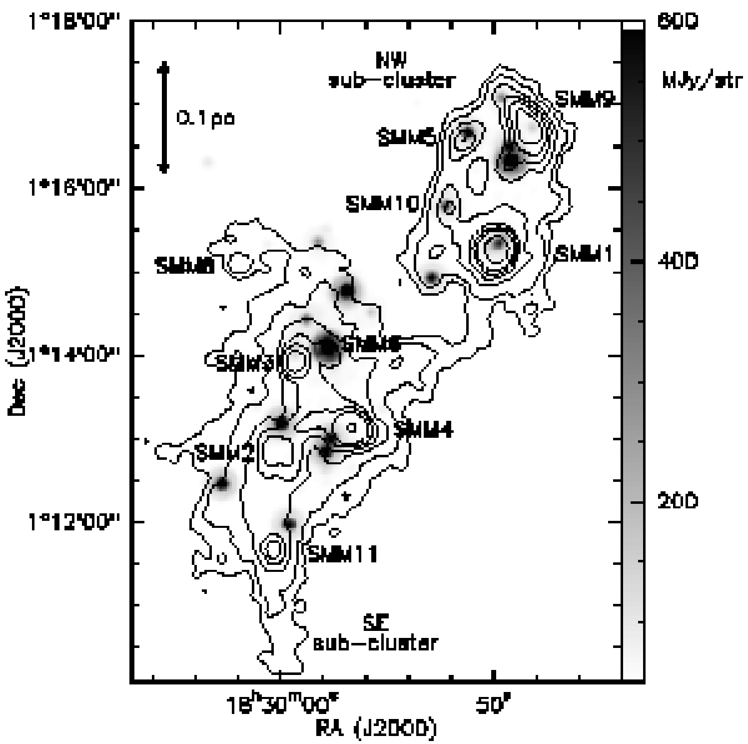


Fig. 1. Serpens region as seen in 850 μm dust continuum emission with SCUBA (Davis et al. 1999) in contours, at 0.4, 0.6, 1, 1.4, 1.8, 2.4 and 5 Jy beam^{-1}. In grey scale is the 24 μm from Spitzer MIPS (Harvey et al. 2007). All the sources seen in this image, both 24 μm and 850 μm sources, are Class 0 and I, with only a few flat-spectrum sources. The 850 μm sources are labeled.

Known since mid 70s, two compact protoclusters, lying in a 0.6pc long filamentary structure, along NW-SE

Similar masses within similar sized regions: ~ 30 $M_\odot$ in 0.025 pc^2 each, average age of 10^5 yr

velocity structure, molecular emission from each sub-cluster differ. NW is devoid of bright NIR sources, has outflows powered by deeply embedded class 0 and I protostars

Probably triggered by the collision of two filament-like clouds .The SE sub-cluster is at the interface of a cloud-cloud collision, as opposed to the quiescent NW sub-cluster.