The Impact of Massive Star Formation on Their Environments

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Star Formation Then and Now

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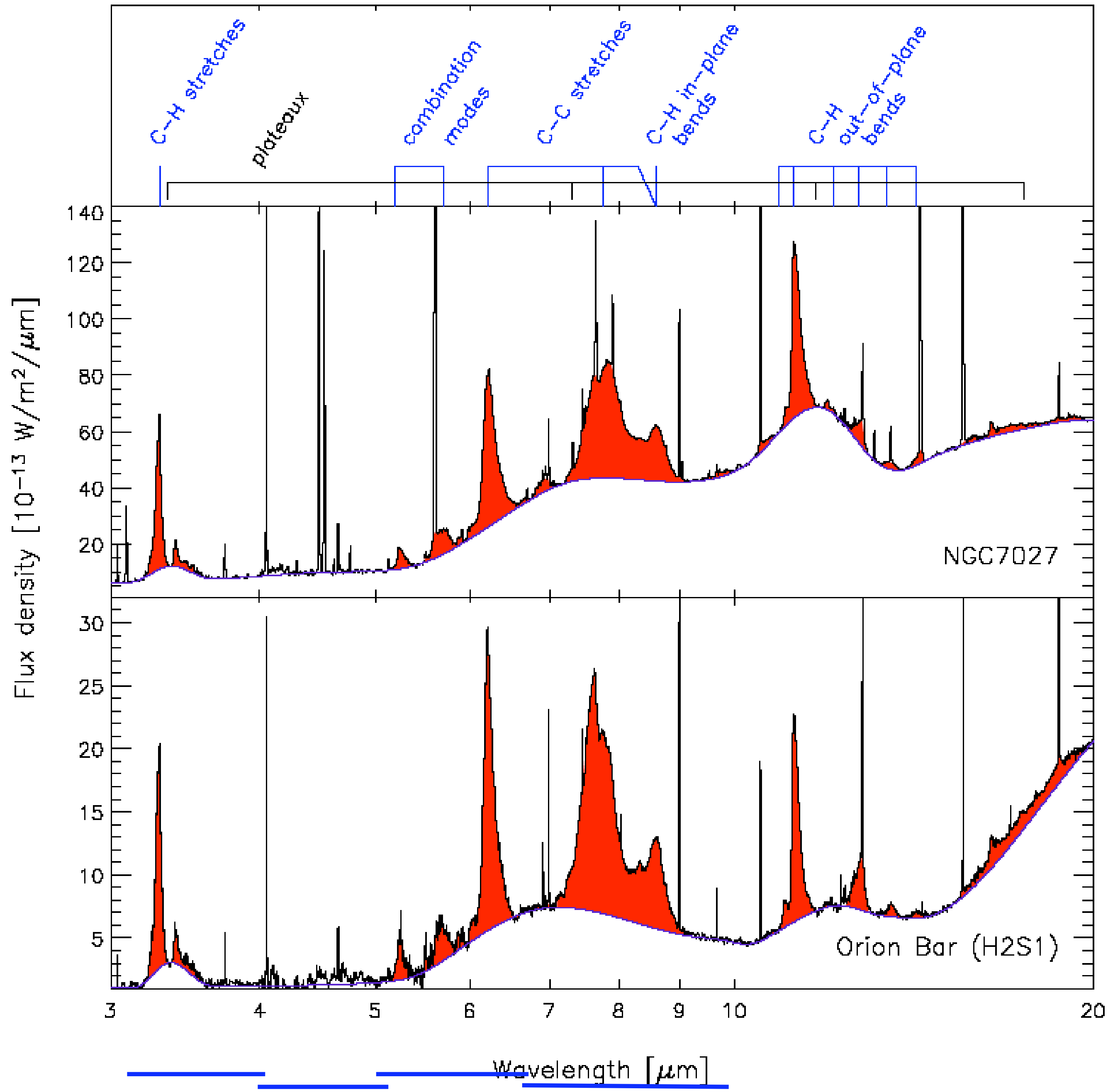


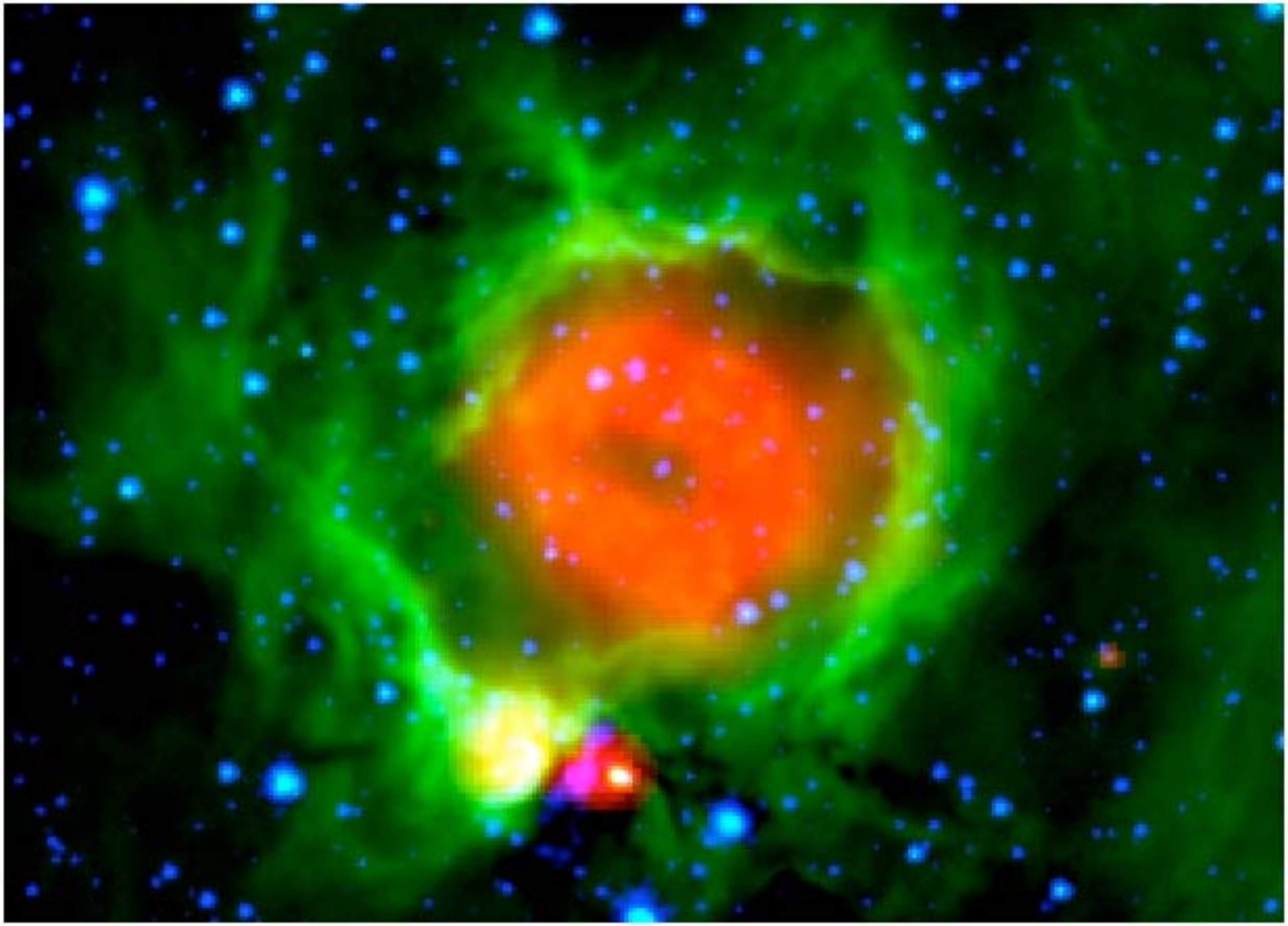
Peeters et al. (2003)

Properties of Bubble N49

- Distance: 5.7±0.6 kpc (Churchwell et al. 2006)
- 20cm continuum flux density: 2.8 Jy (Helfand et al. 2006)
- Radio morphology: approximately a spherical shell
- Ionizing photon flux required to maintain ionization of the associated HII region: 7.8×10^{48} photons s^{-1} => an equivalent O6V star or hotter
- Angular diameter of the HII region: 3.0' (5 pc)

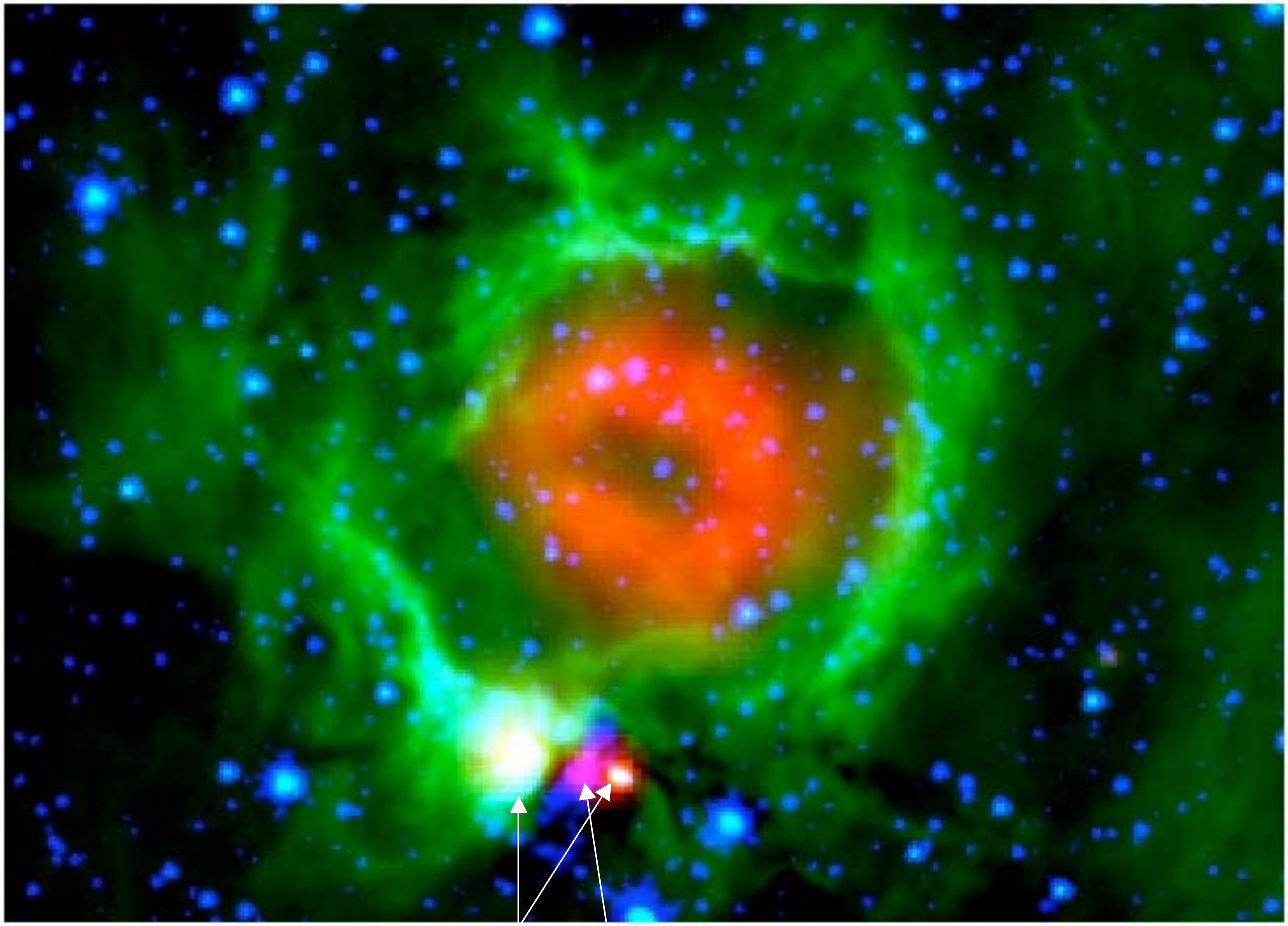
Protostellar Jet: G28.83-0.25 (N49)
8(R), 4.5(G), 3.6(B) μm

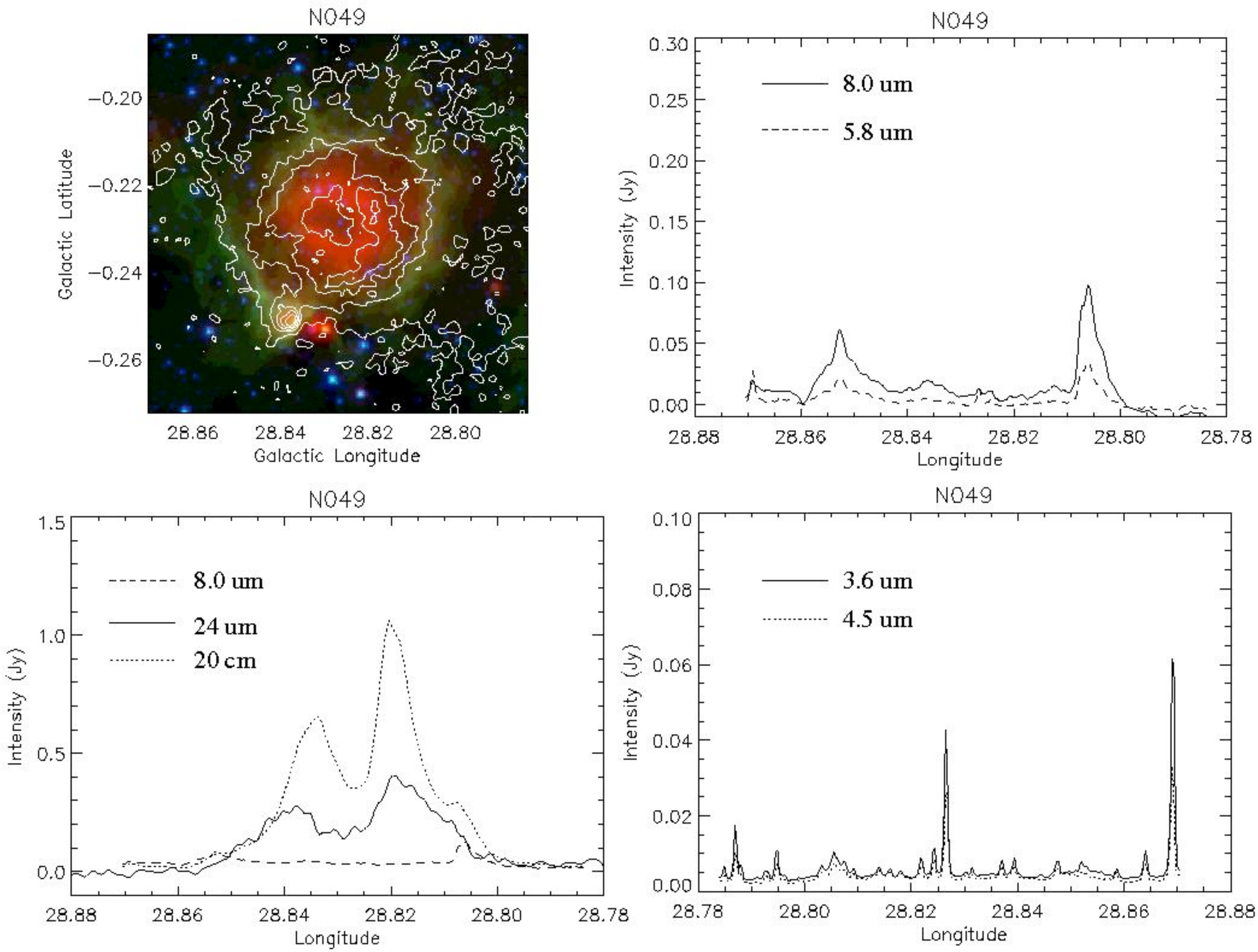
N49 (4.5, 8.0, 24μm)



N49a (4.5, 8.0, 24μm)

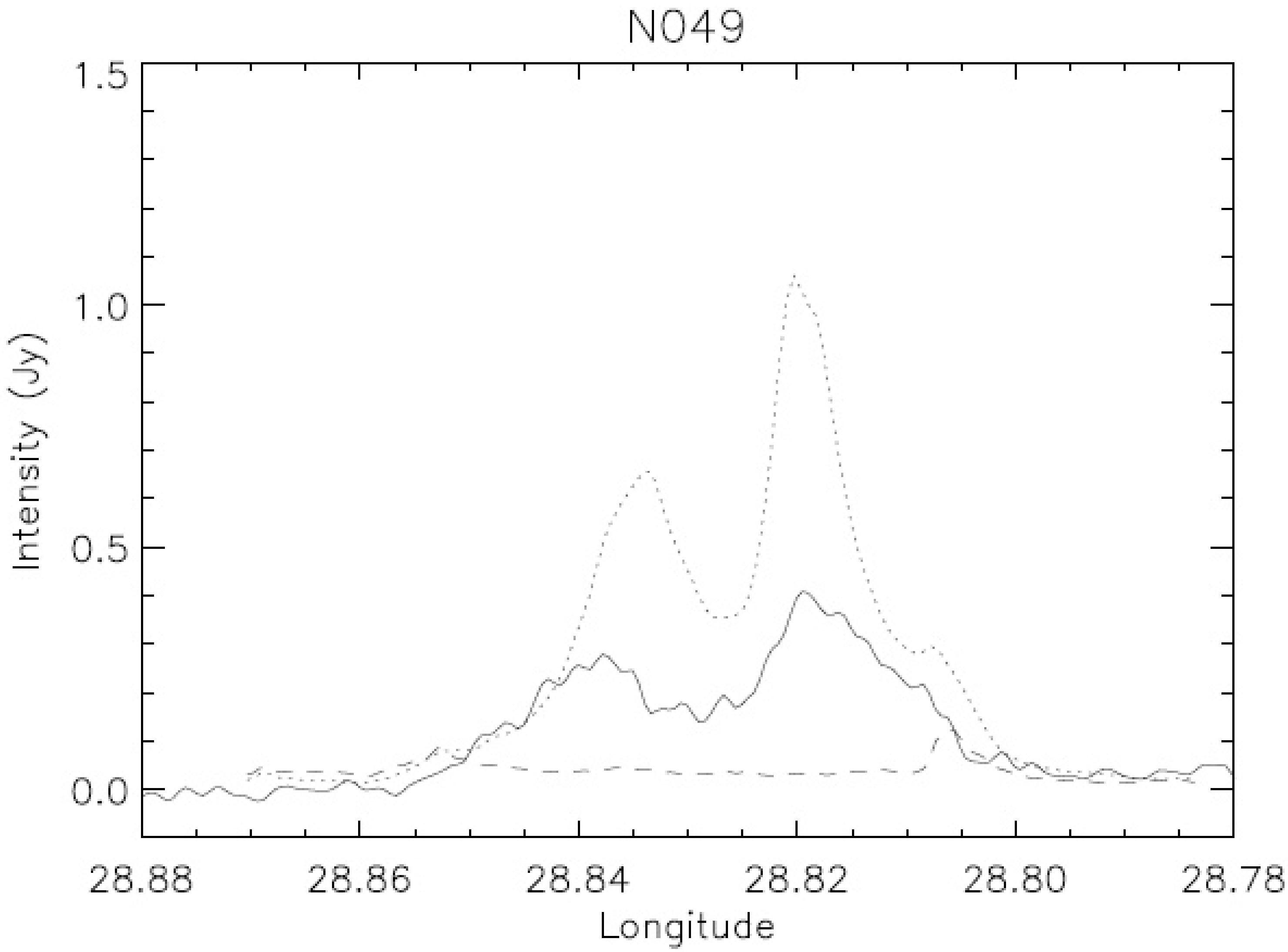
Enhanced 4.5μm to show outflow more clearly



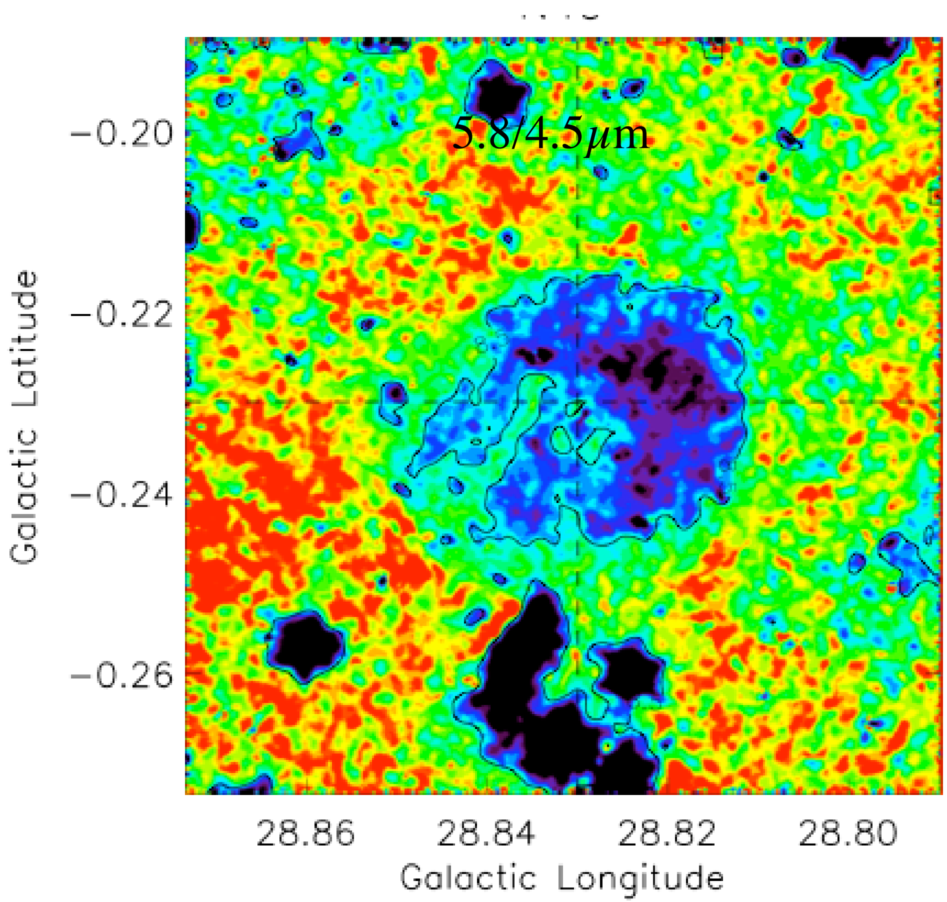


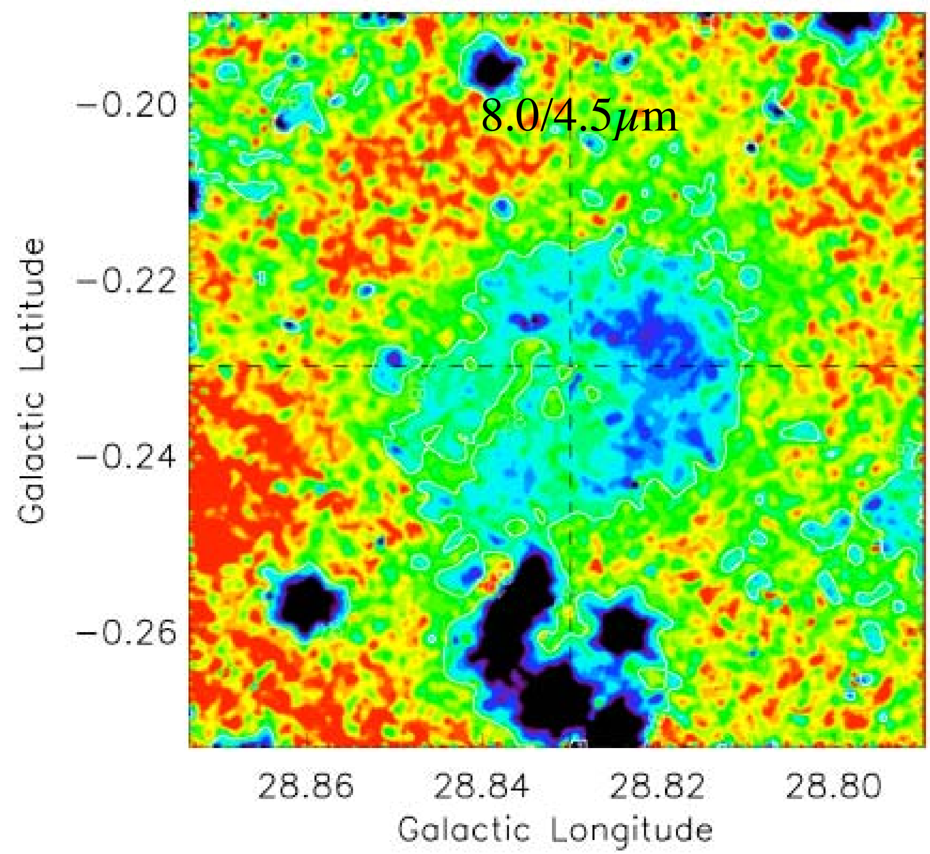
N049
Galactic Latitude
-0.20
-0.22
-0.24
-0.26
28.86
28.84
28.82
28.80
Galactic Longitude
N049
Intensity (Jy)
8.0 um
5.8 um
0.30
0.25
0.20
0.15
0.10
0.05
0.00
28.88
28.86
28.84
28.82
28.80
28.78
Longitude
N049
Intensity (Jy)
8.0 um
24 um
20 cm
1.5
1.0
0.5
0.0
28.88
28.86
28.84
28.82
28.80
28.78
Longitude
N049
Intensity (Jy)
3.6 um
4.5 um
0.10
0.08
0.06
0.04
0.02
0.00
28.78
28.80
28.82
28.84
28.86
28.88
Longitude

N49 8μm(dashed), 24μm(dotted), 20cm(solid x100)



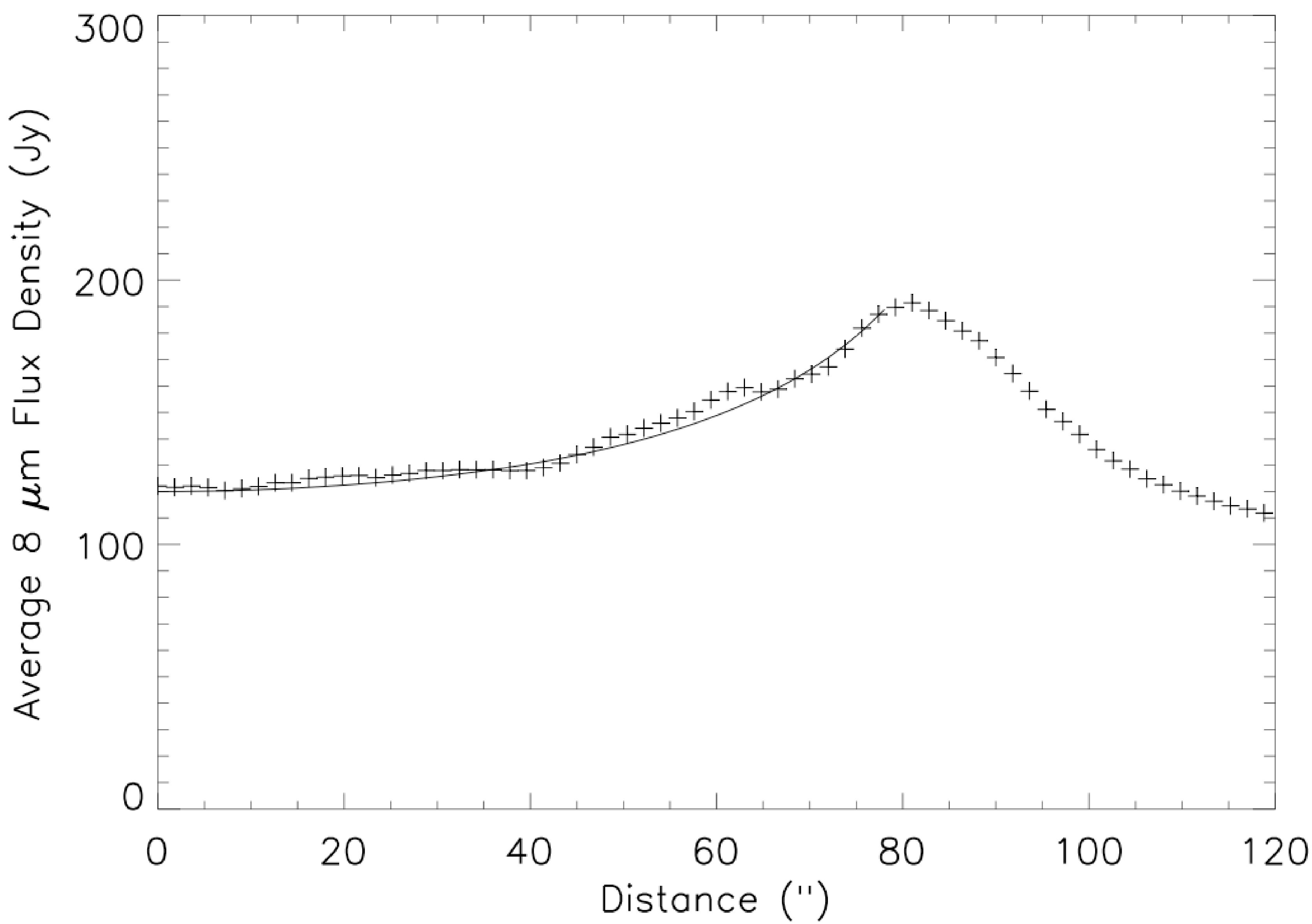
N49: PAH Destruction Radius





Ang. Diameter ~0.03^0 @ 5.7 kpc => R~1.5 pc

N49: 8μm Observations Azimuthally averaged (+);
Model of 8μm Shell Emission (solid curve)



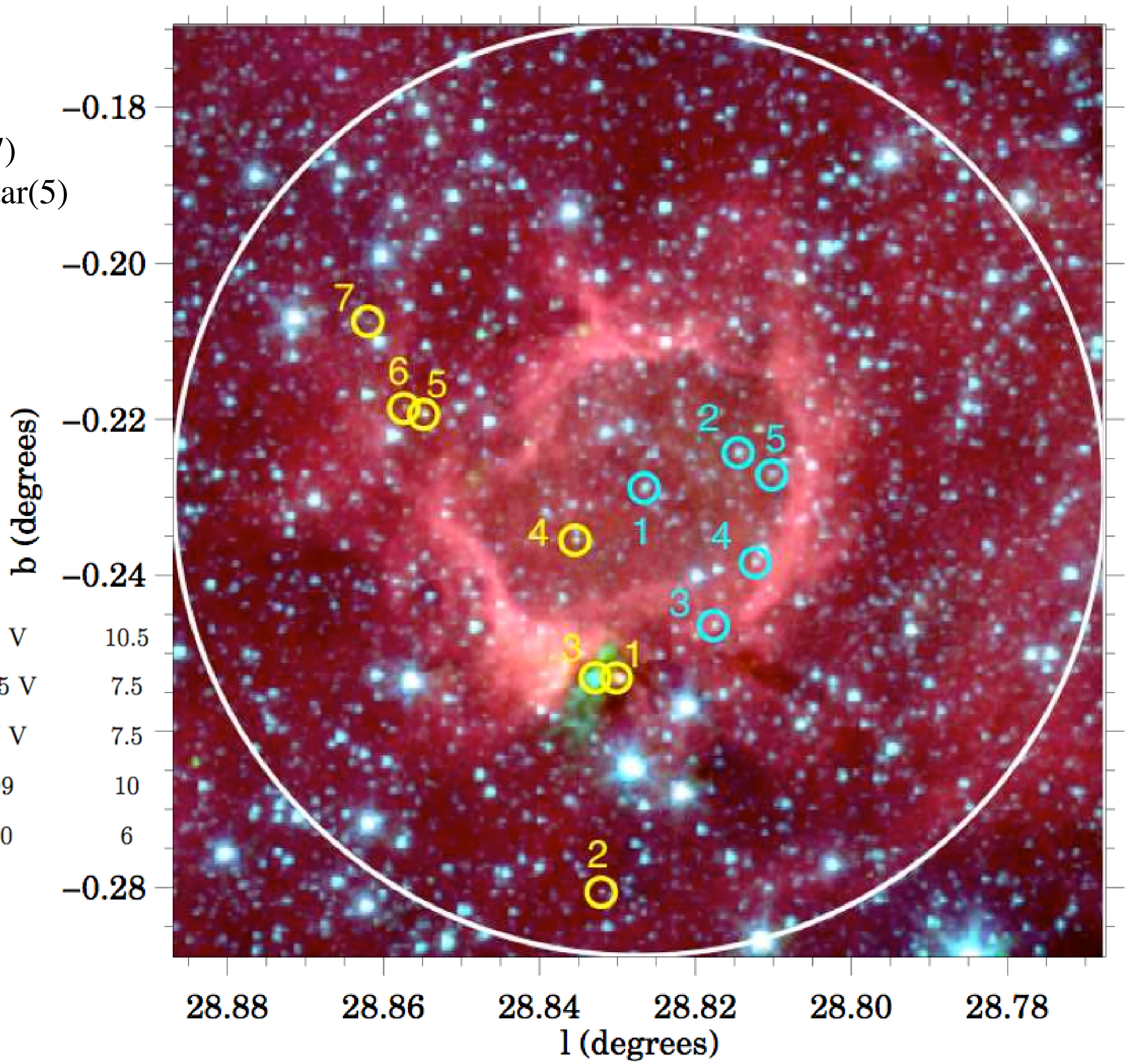
N49: Candidate YSOs & Ionizing Stars

Yellow: candidate YSOs (7)
Cyan: candidate ionizing star(5)

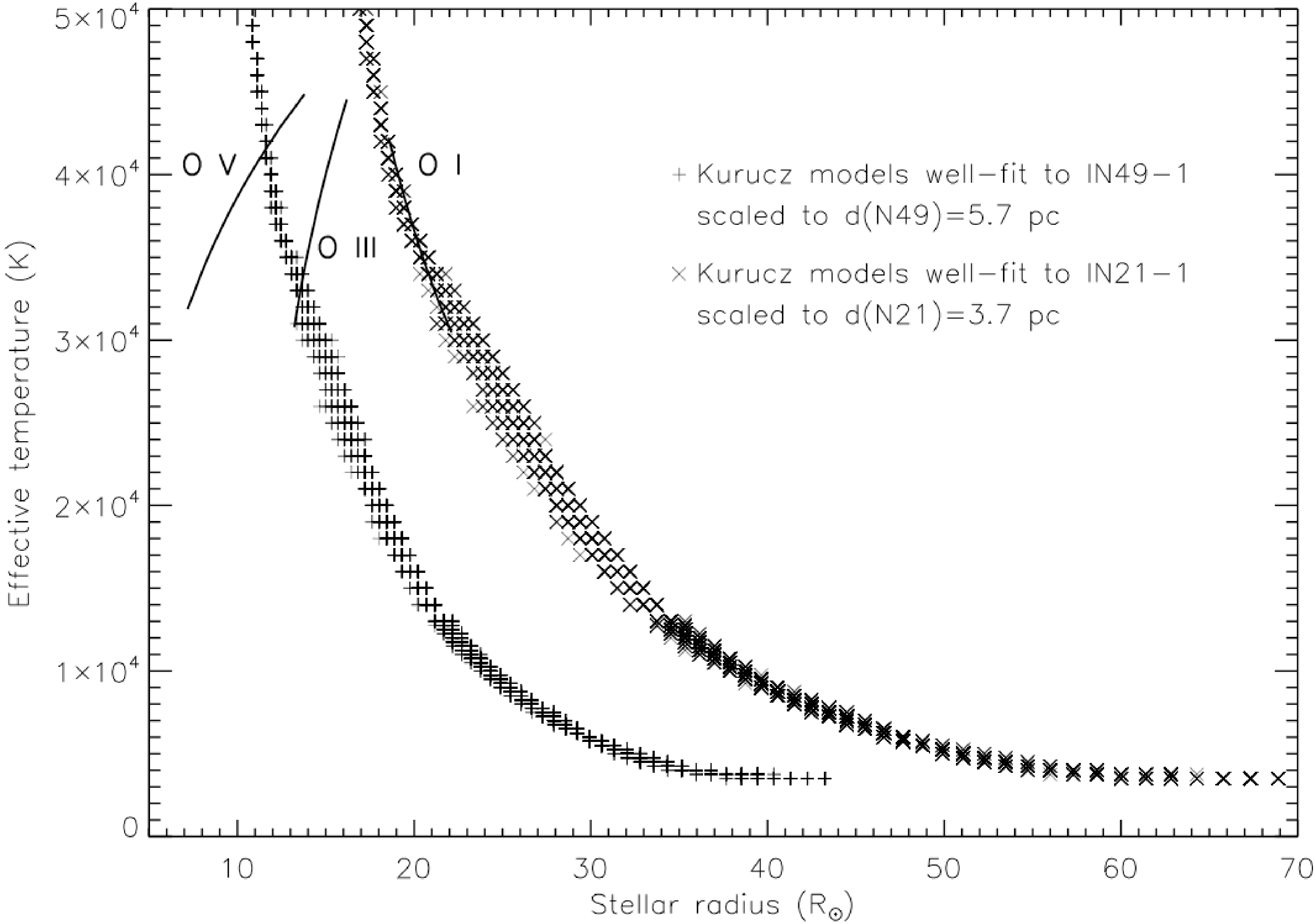
Within circle (R=6pc)
722 stars analyzed

IR Model Predictions

IN49-1	28.8263-00.2287	O5 V	10.5
IN49-2	28.8142-00.2241	O5.5 V	7.5
IN49-3	28.8174-00.2464	O7 V	7.5
IN49-4	28.8119-00.2383	O9	10
IN49-5	28.8098-00.2270	B0	6

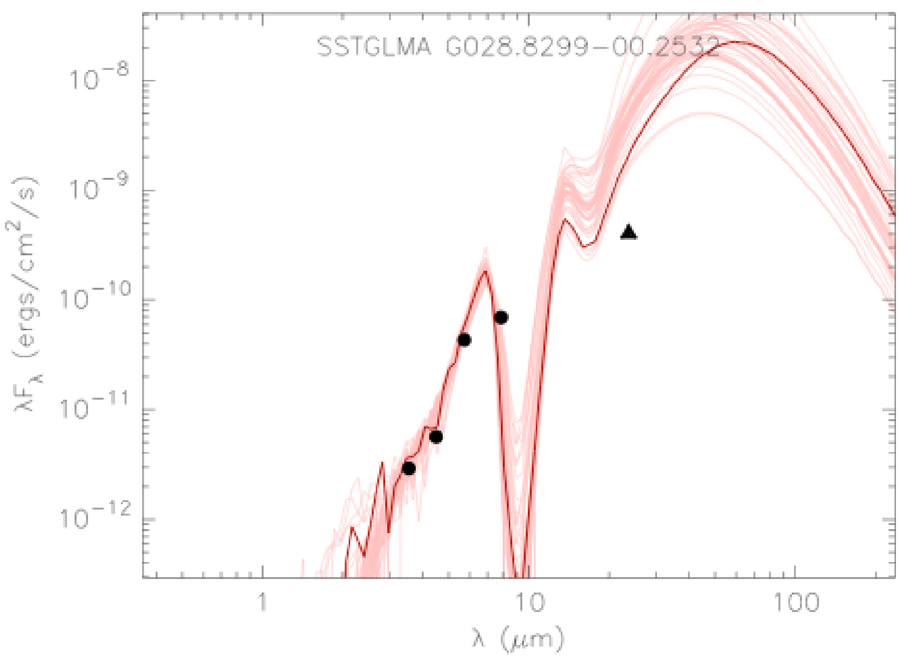


Ionizing Stars: N49 & N21

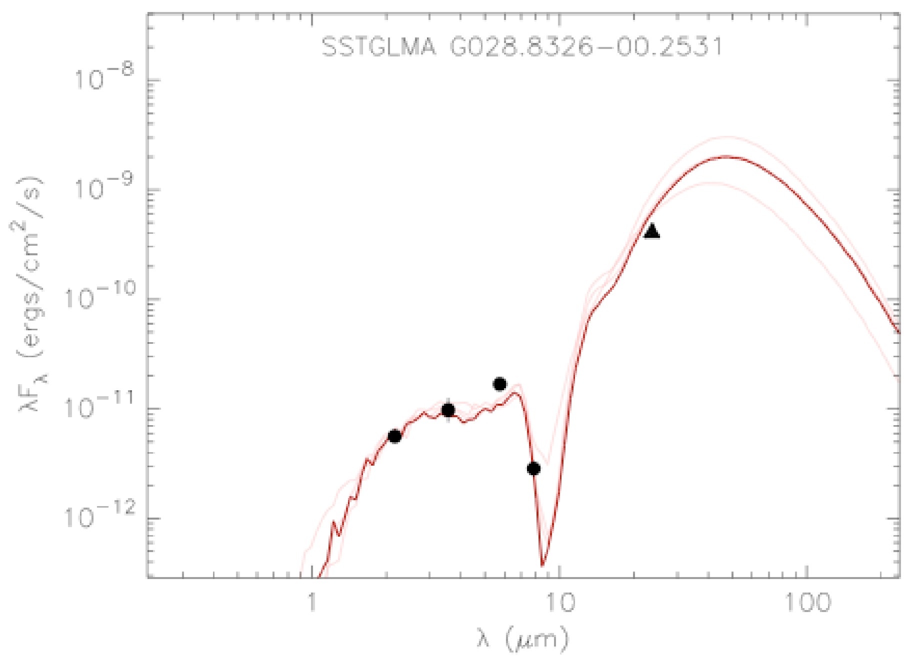


Model fits to N49-1&3

N49-1

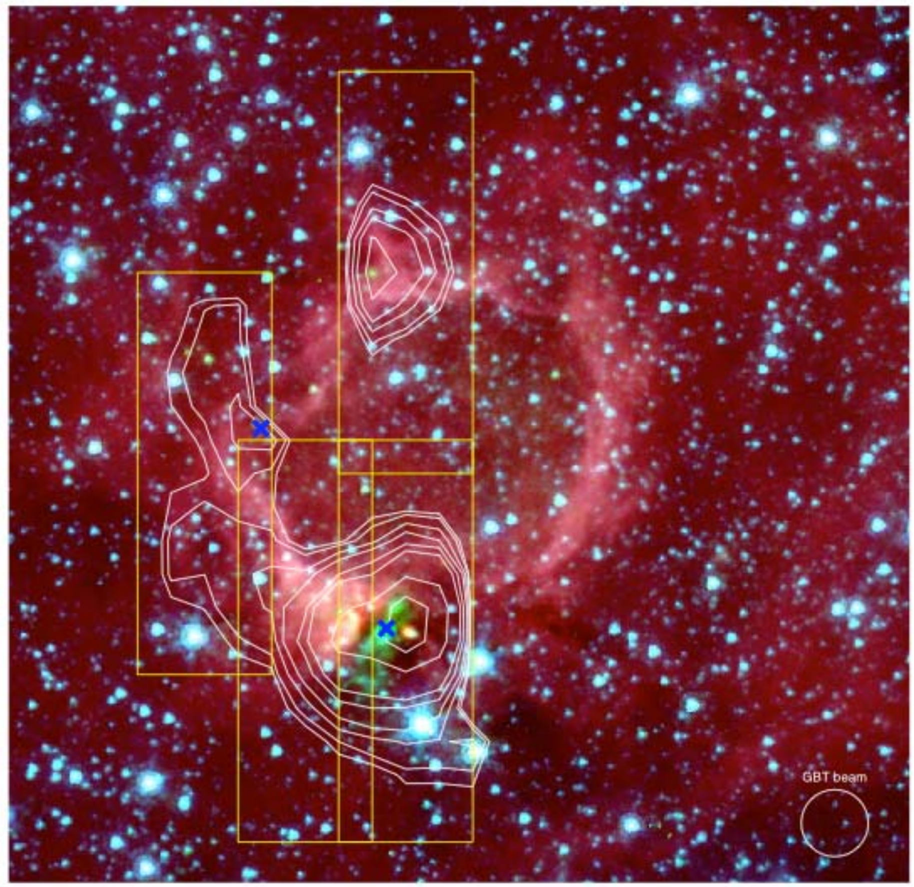


N49-3



A Partial Image of NH_3(1,1) Distribution Around N49

In all regions where NH_3 has been searched, dense molecular gas has been detected around the periphery of N49.



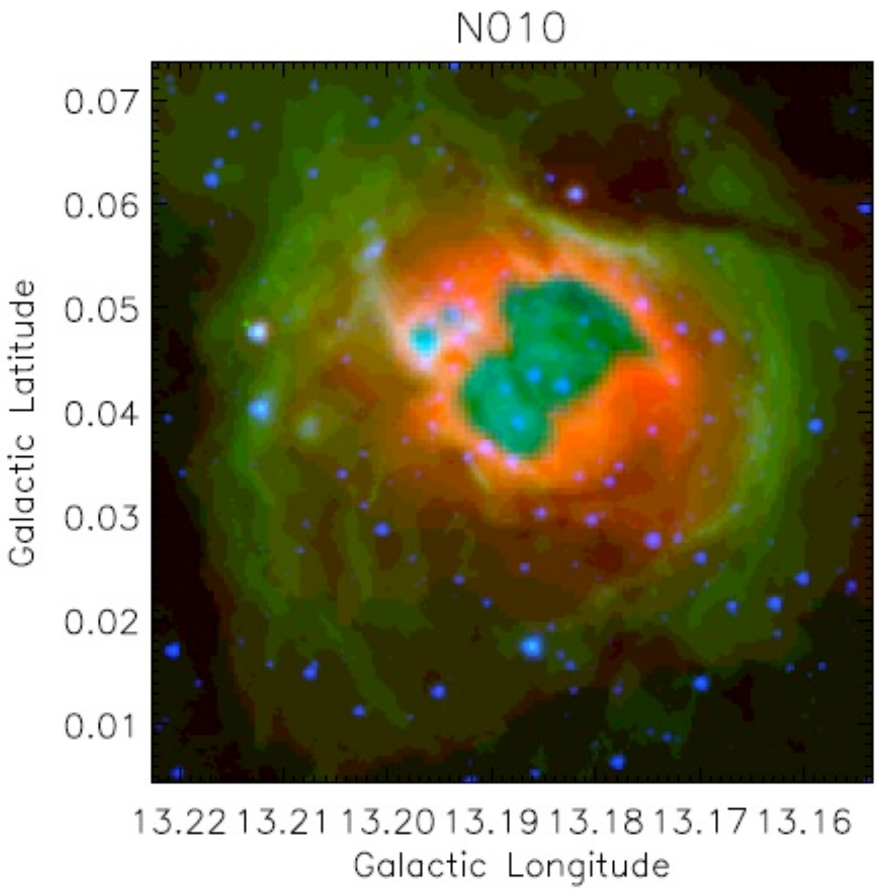
Age constraints on N49

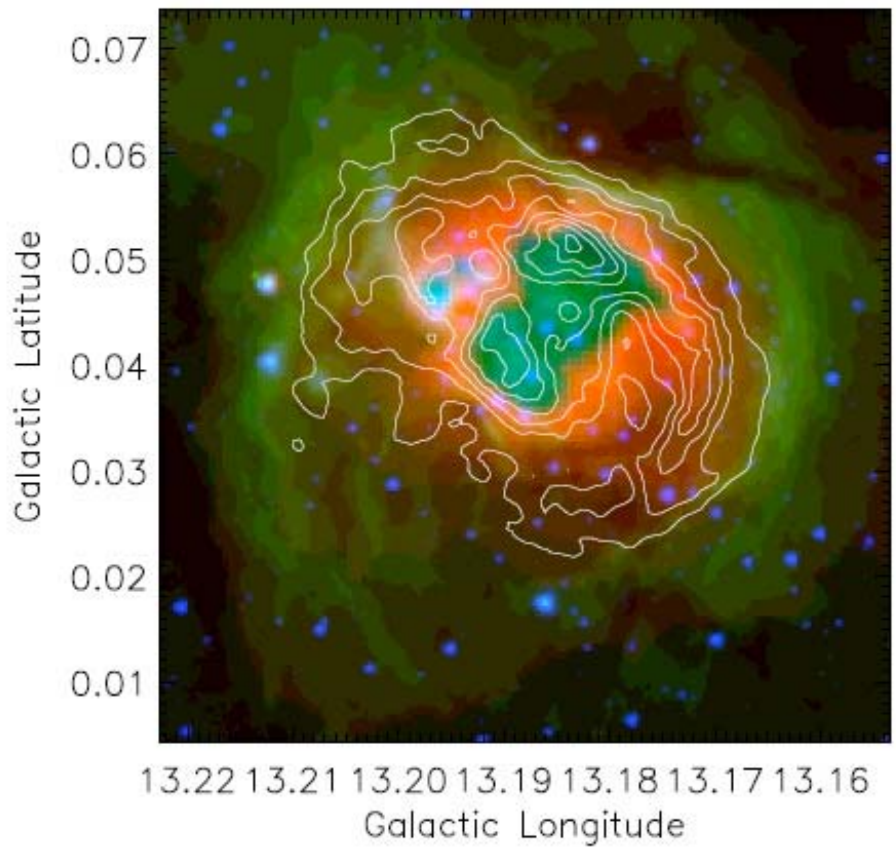
- $R(t) \alpha n_0^{-1/5} L_w^{1/5} t^{3/5}$ => age $\alpha R(t)^{5/3} n_o^{1/3} L_w^{-1/3}$ => can infer age as a function of ambient density if the radius is measured and the star responsible for producing the bubble is known (i.e. L_w is known). N49 at a distance of 5.7 kpc, SpT~O5V star (L_w~$4x10^{36}$ erg s^{-1}) reaches a radius of 2.5pc at $5.5x10^5$ yr if n_0~10^5 cm^{-3} or $1.2x10^6$ yr if n_0~10^6 cm^{-3}.
- If N49-1&3 were triggered by N49 expansion, then the minimum age of N49 is set by the time required to produce a massive YSO (a few $x10^5$ yr). A maximum age is set by the ambient density becoming unreasonably high (≤10^6 cm^{-3} as implied by NH_3 observations).
- Conclusion: the N49 bubble is quite young (>a few x 10^5 yr and ≤10^6 yr)!

N10 Properties

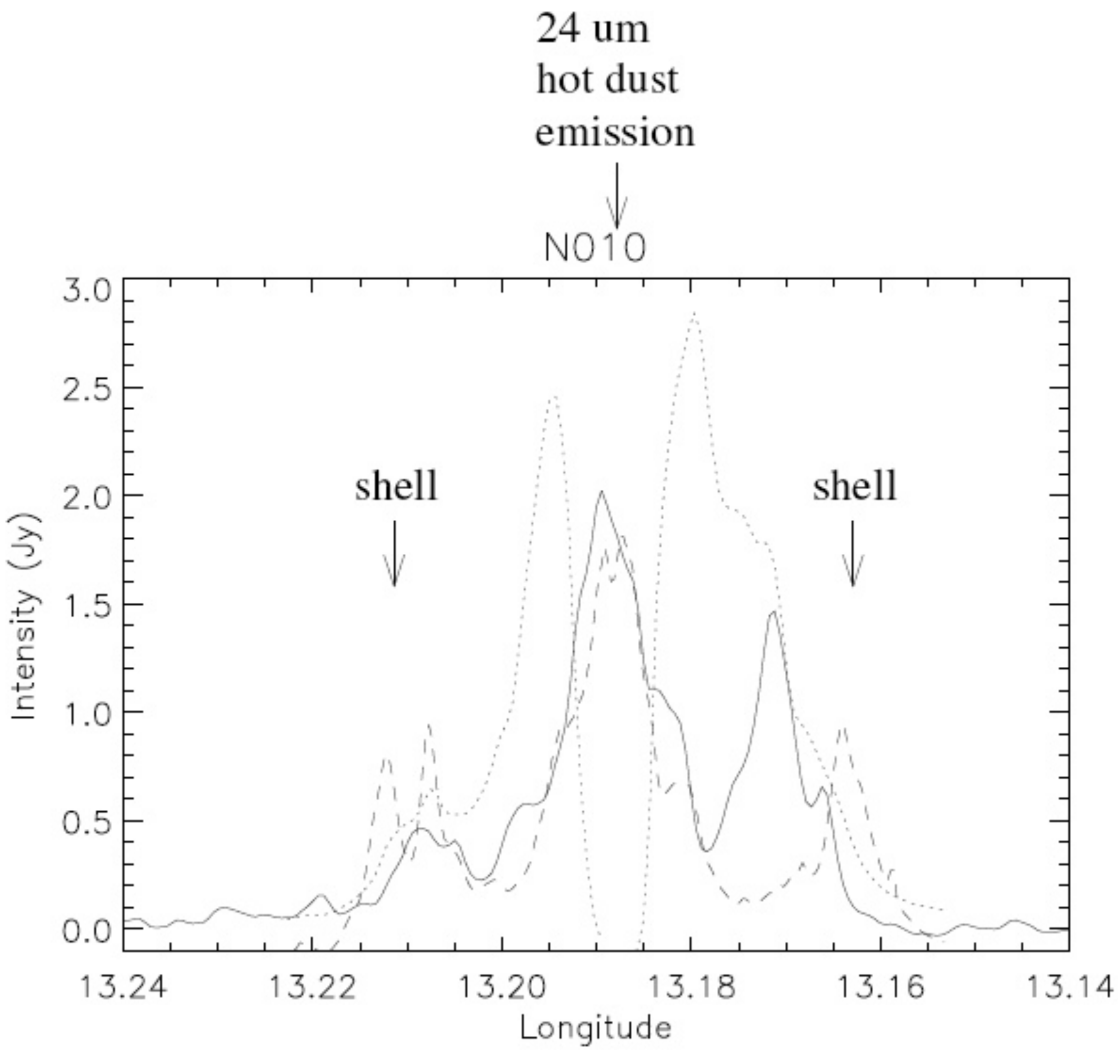
- Distance: 4.9±0.5 kpc (Churchwell et al. 2006)
- 20 cm flux density: 7.58 Jy (Helfand et al. 2006)
- Radio morphology: Elliptical symmetry
- Angular diameter of HII region: 2.52' (~3.6 pc)
- UV photon flux necessary to maintain ionization of the HII region: 1.6×10^{49} photons s^{-1} (equivalent to a single O5V star)

N10 (color [4.5, 8.0, 24μm]; contours 20cm)

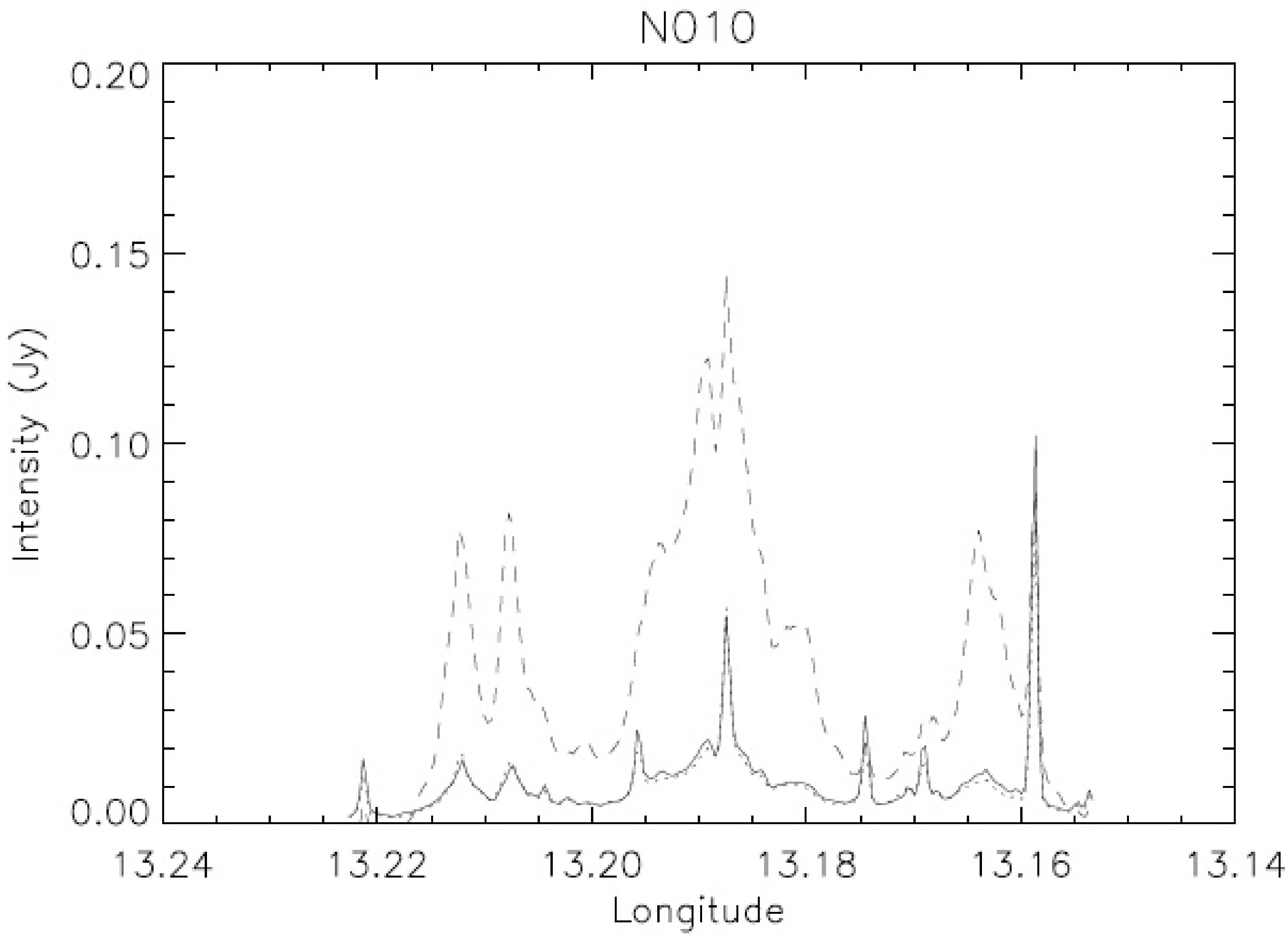




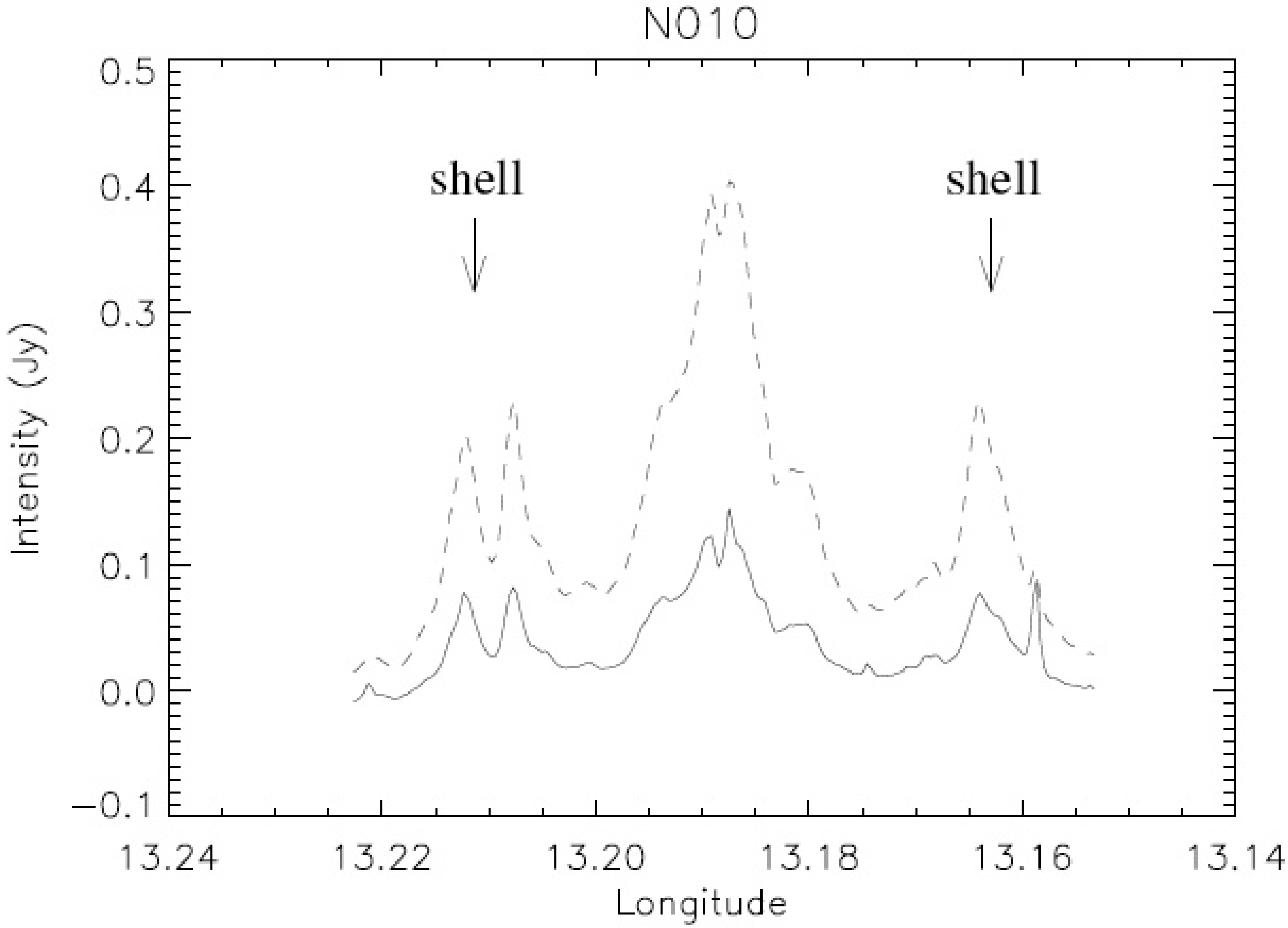
N10: Comparison of 8, 24μm, 20cm Emission



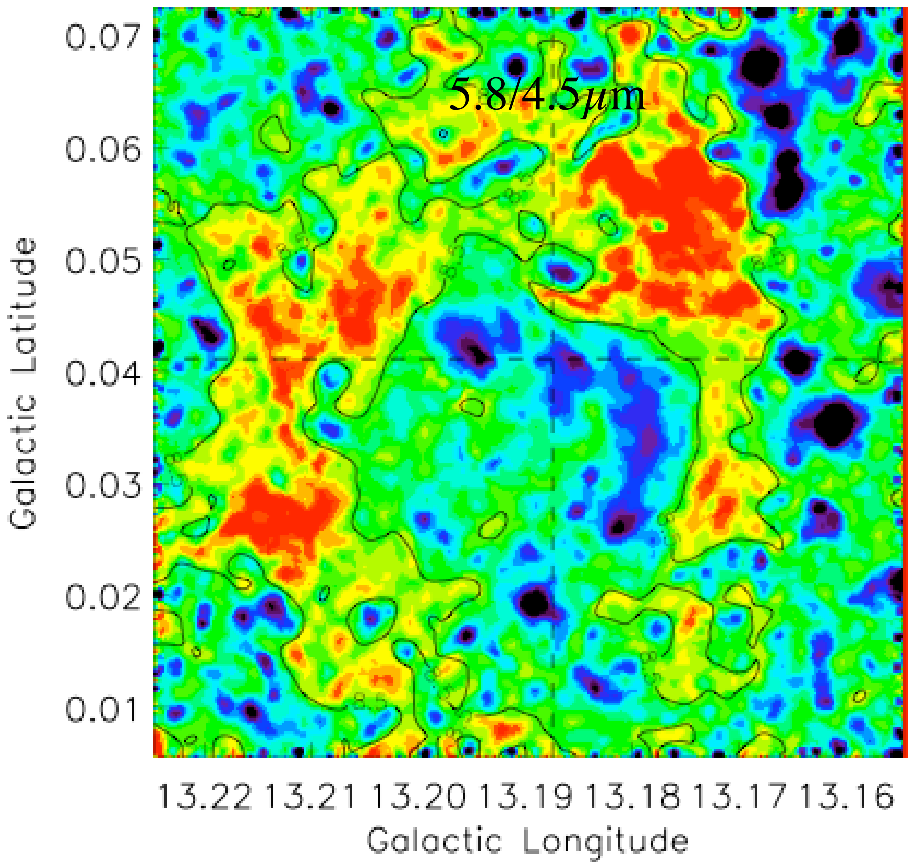
N10 3.6(solid), 4.5(dotted), 5.8(dashed)

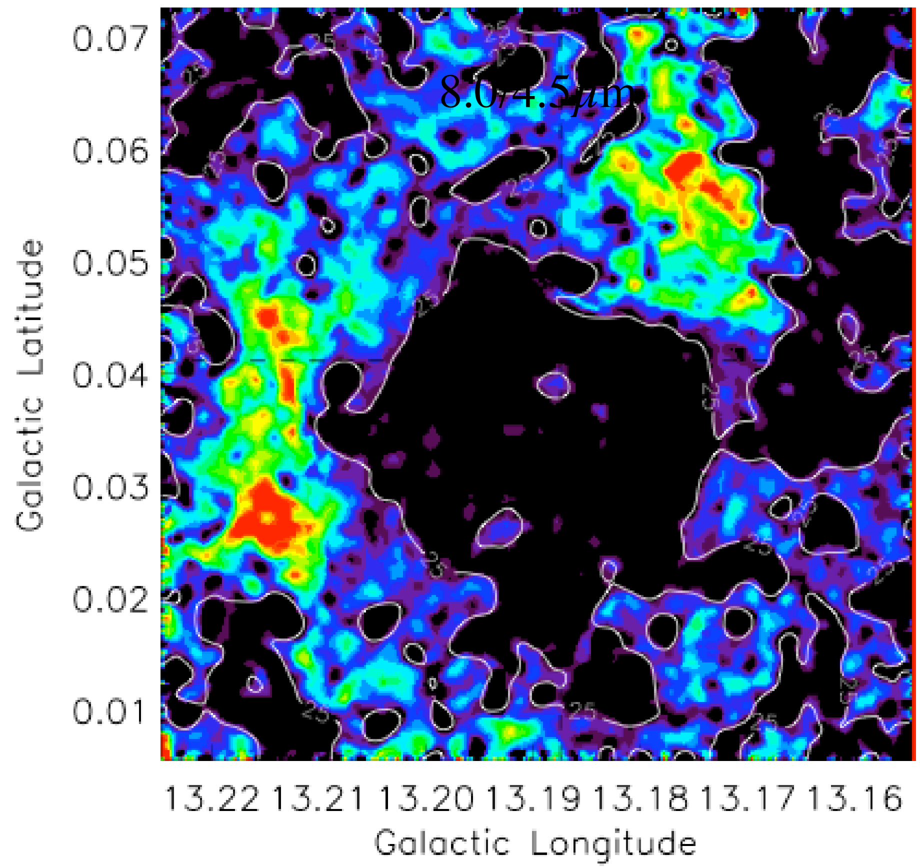


N10 5.8(solid), 8.0μm(dashed)



N10: PAH Destruction Radius



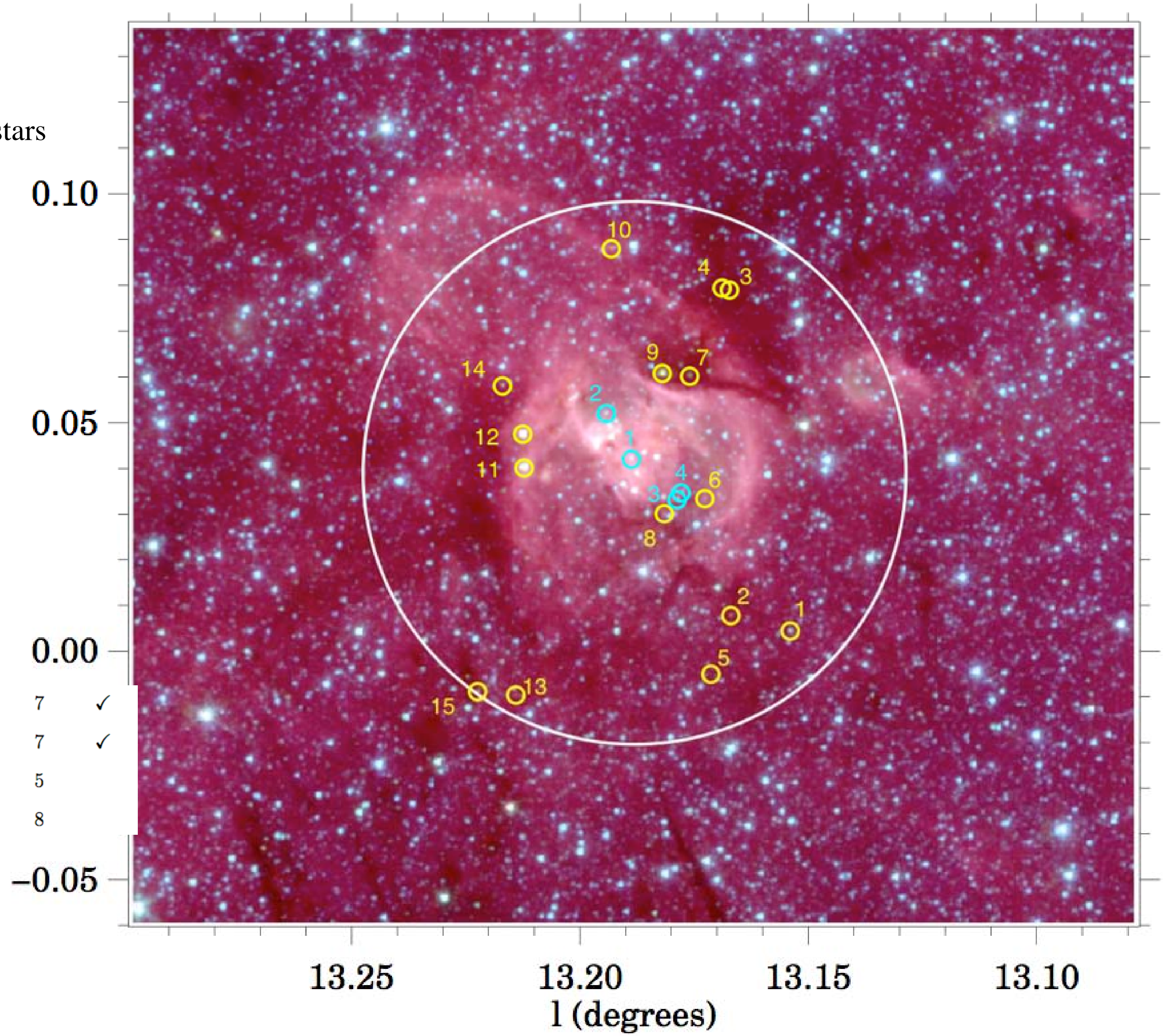


Ang. Diameter ~0.03^0 @ 4.9 kpc => R~1.3 pc

N10: Candidate YSOs and Ionizing Stars

Yellow: candidate YSOs
Cyan: candidate ionizing stars

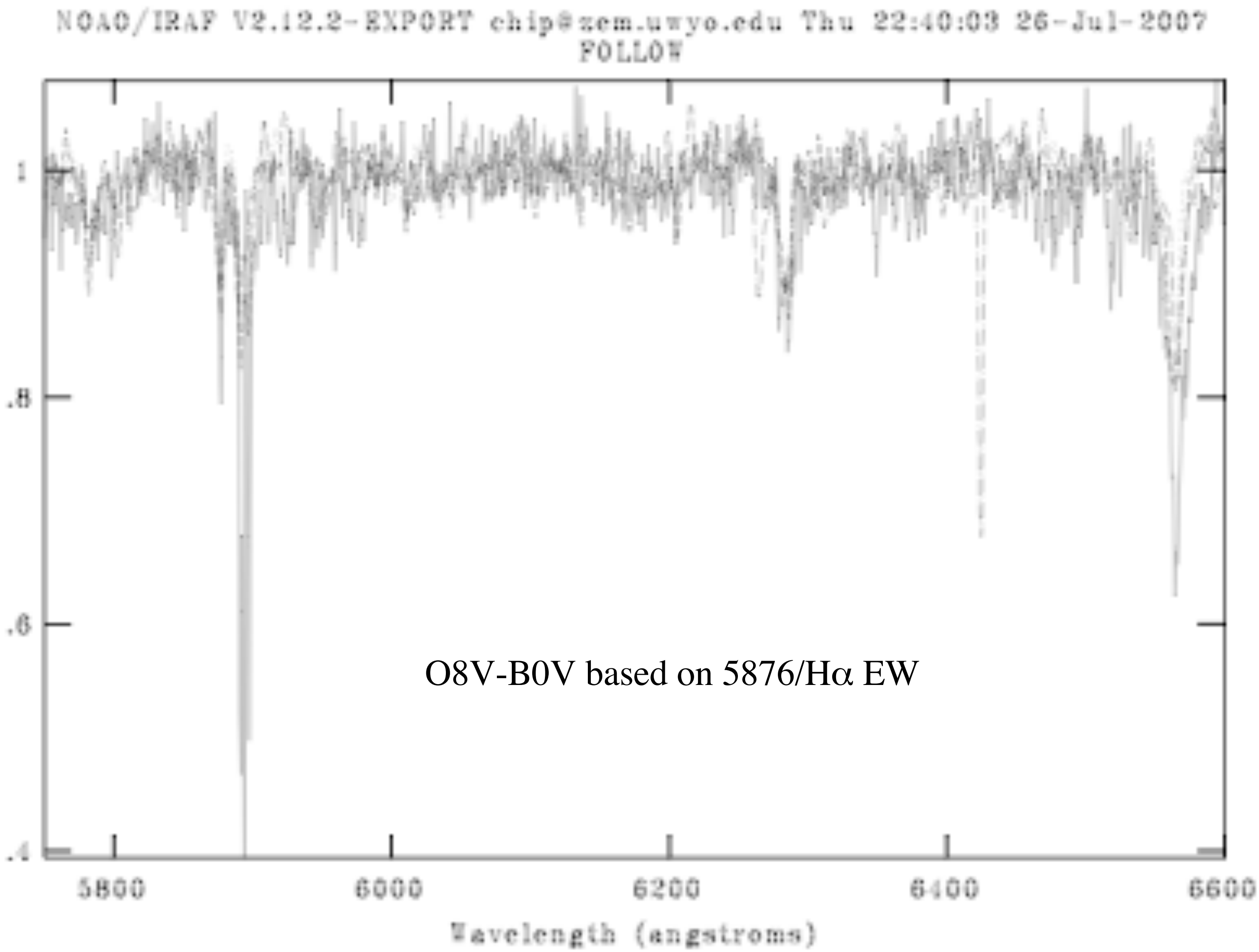
Circel R=5.2 pc
687 stars analyzed



IR Model Predictions

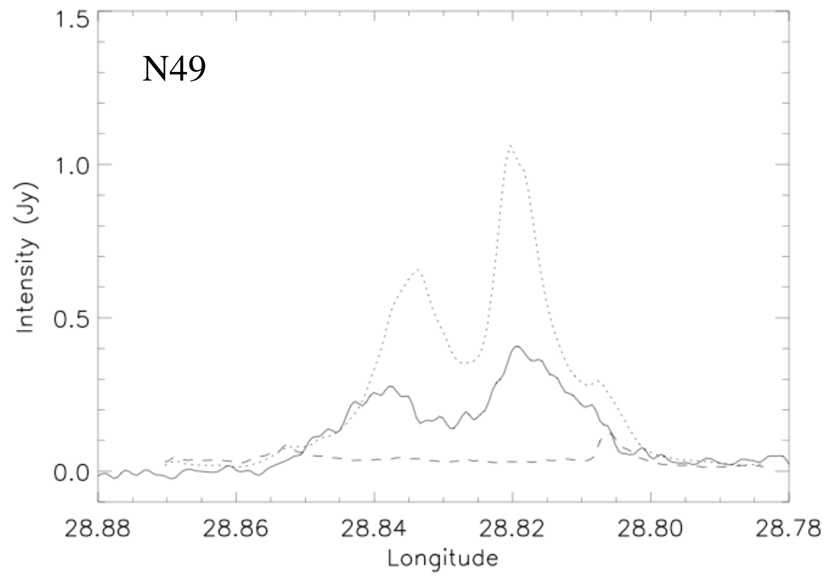
IN10-1	13.1887+00.0421	O7.5 V	7	✓
IN10-2	13.1942+00.0521	O6.5 V	7	✓
IN10-3	13.1786+00.0331	O6 V	5	
IN10-4	13.1777+00.0346	O7 V	8	

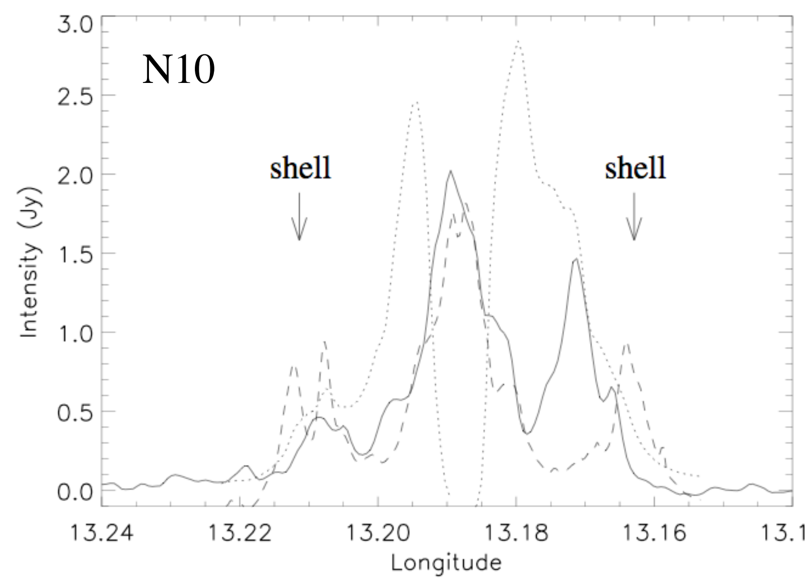
Optical Spectrum of N10_3 (WIRO)



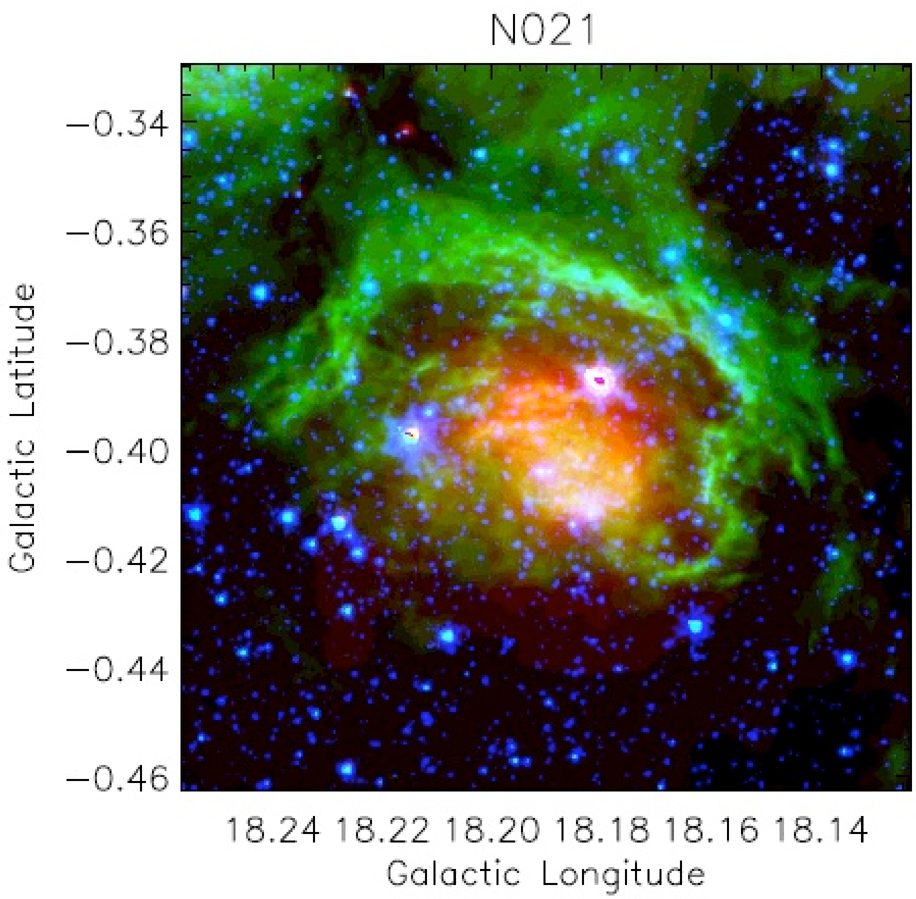
Comparison of N49 and N10

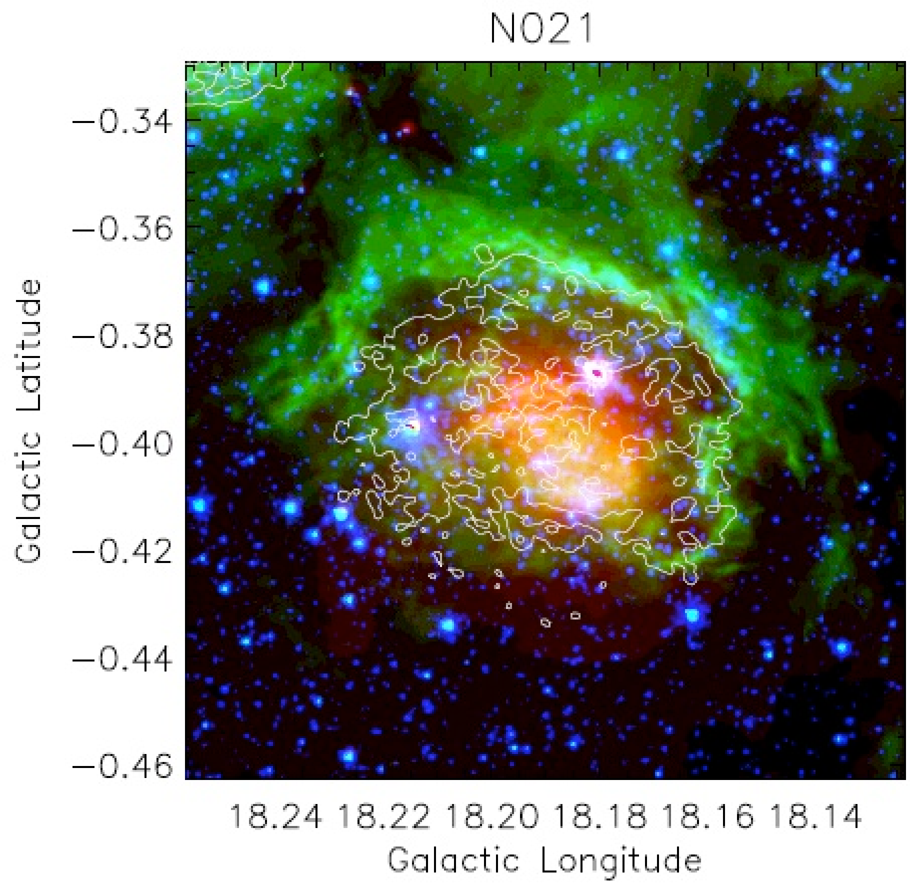
- 8μm emission peaks at the center of N10 and follows the 24μm thermal dust emission at the center of N10. The 8μm emission does not peak nor follow the thermal 24μm dust emission at the center of N49.
- Reason: N49 has a central evacuated cavity with no dust and N10 does not. So in N10 one sees hot dust heated mostly by direct stellar radiation and secondarily by trapped Lα photons, and stochastically heated small grains out to about 0.85pc, beyond which geometrical dilution limits dust heating.
- Both have YSOs along their rims suggesting that both have triggered star formation implying minimum ages of a few x10^5 yr for both bubbles. Upper limits of ~10^6 yr are set by interstellar densities $\leq 10^6$ cm^{-3}. Both bubbles seem to be $\leq 10^6$ yr!
- Open questions: Why does dust exist at the center of N10? Why isn't the dust within N10 and N49 HII regions not blown out by the stellar wind? N10 has ~ a factor of 4 weaker wind than N49, so maybe there is a threshold for dust clearing? Maybe dust is continuously replenished by embedded neutral globules that was overrun by the I-front?



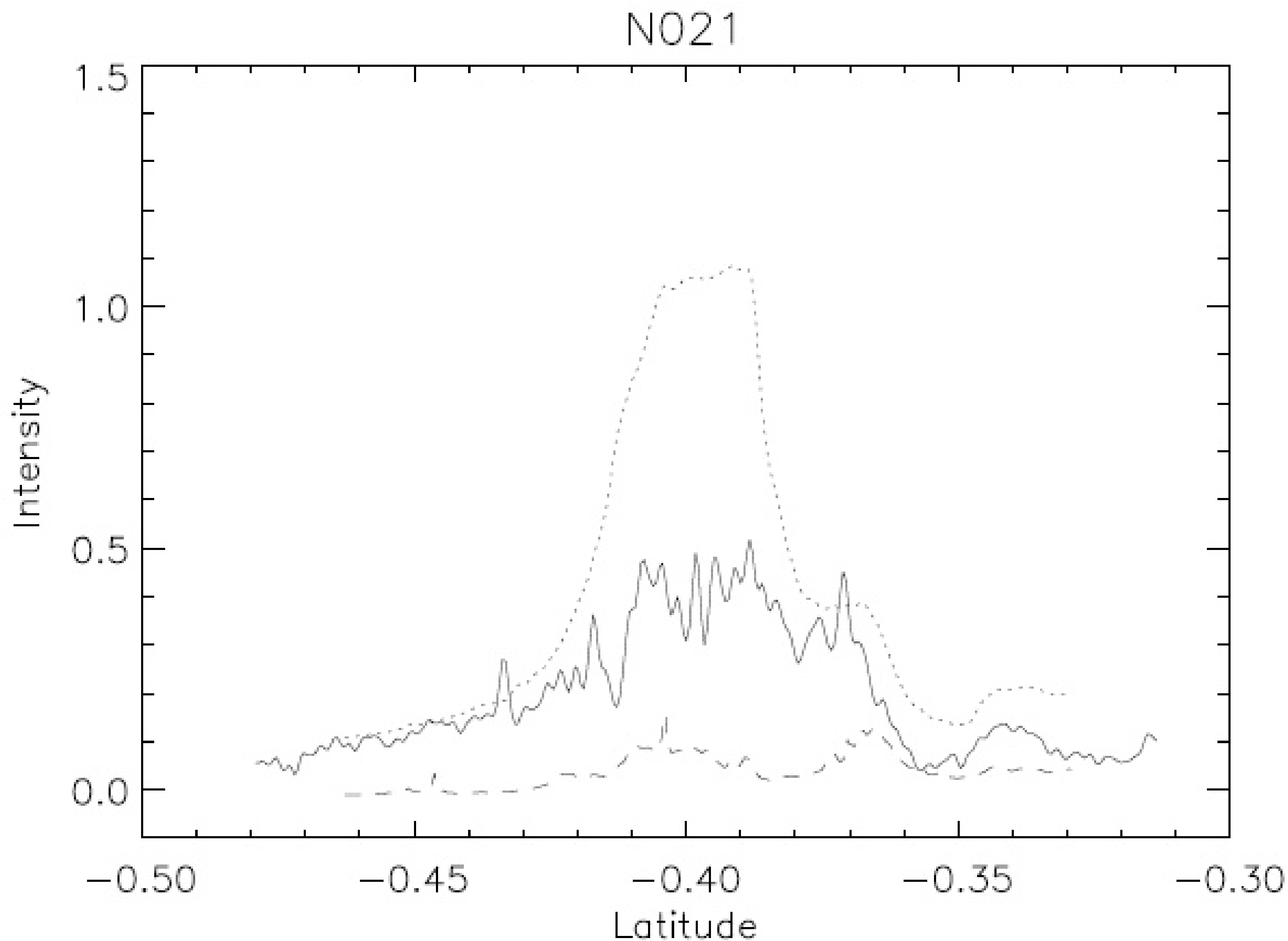


N21 4.5μm(blue), 8.0μm(green), 24μm(red)

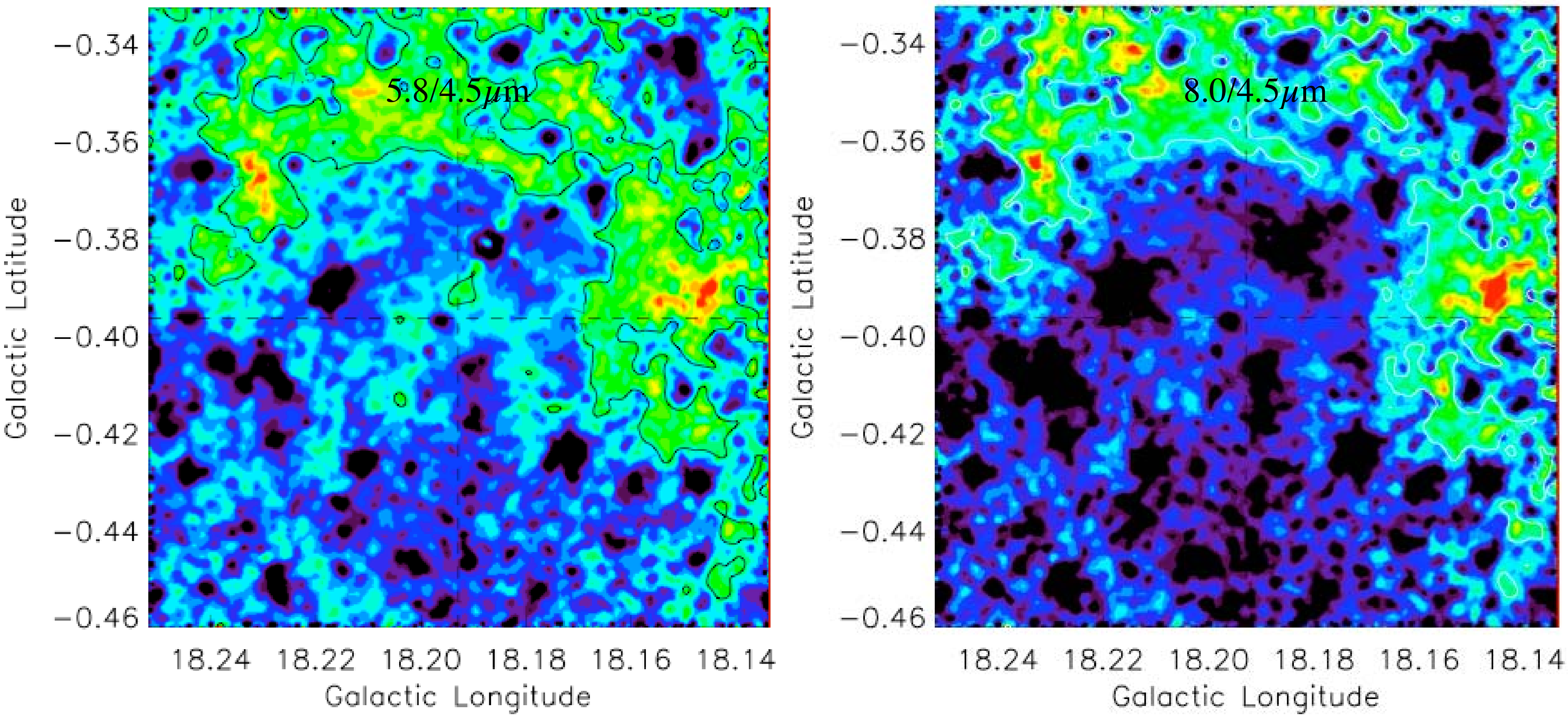




N21 8μm(dashed), 24μm(dot), 20cm(x100, solid)



N21: PAH Destruction Radius

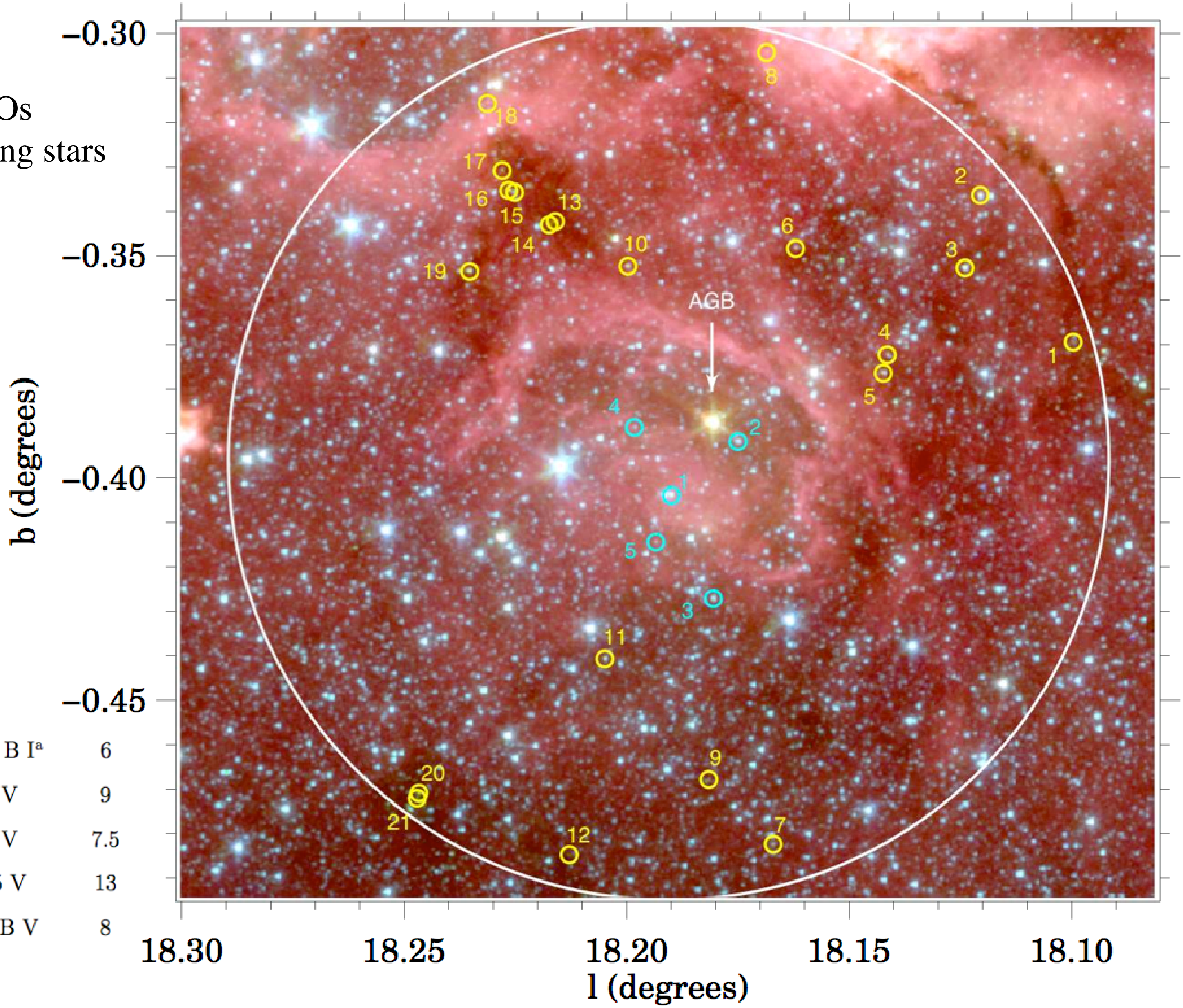


Ang. Diameter ~0.06^0 @ 3.7 kpc => R~1.9 pc

N21: Candidate YSOs & Ionizing Stars

Yellow: candidate YSOs
Cyan: candidate ionizing stars

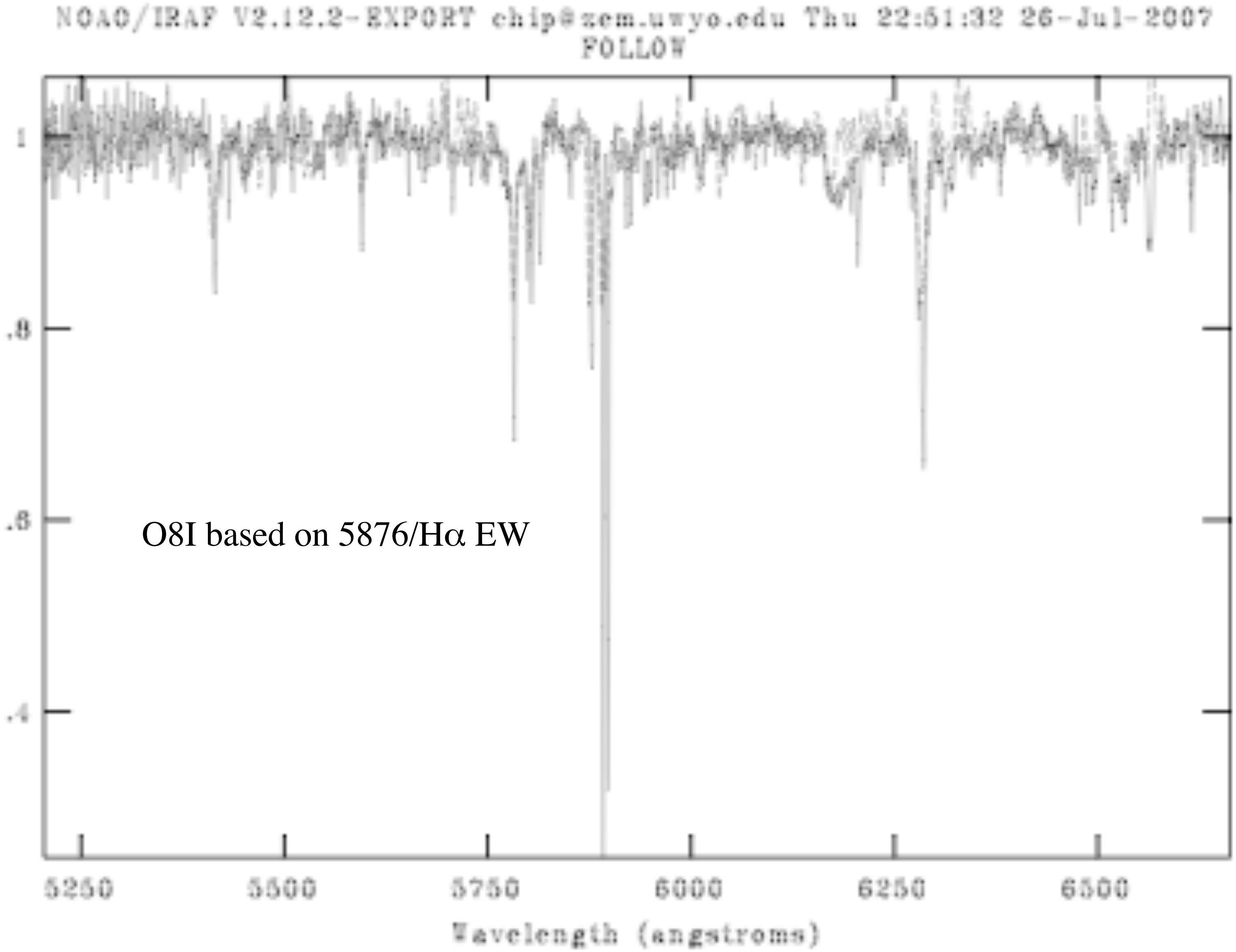
Circle R=6.5pc
2333 stars analyzed



IR Model Predictions

IN21-1	18.1893-00.4041	early B I[a]	6
IN21-2	18.1742-00.3918	O6 V	9
IN21-3	18.1798-00.4275	O8 V	7.5
IN21-4	18.1977-00.3886	O8.5 V	13
IN21-5	19.1928-00.4147	early B V	8

N21-1 Optical Spectrum (WIRO)



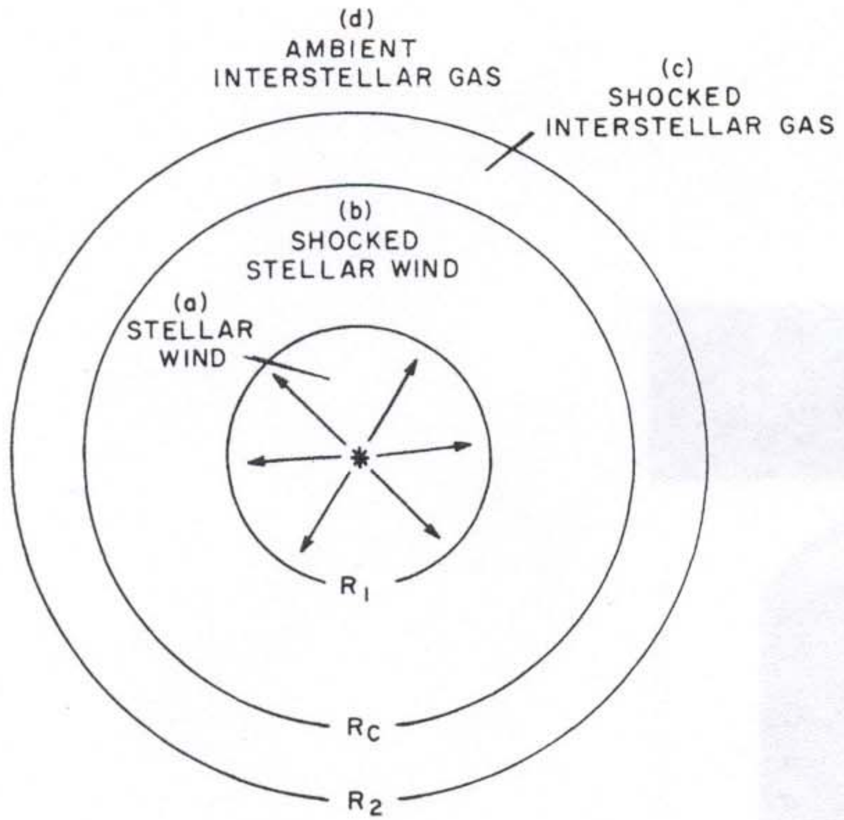
Summary: N21

- This cometary bubble is located near two other star forming regions. Although there are several YSOs in the neighborhood of N21, it is not clear that any of them are associated with, or triggered by, N21. We therefore cannot assign a minimum age to this bubble. Also, since it is open on one side (which drains off internal pressure), its size cannot easily be related to its age even when we know the stellar types responsible for producing the partial bubble.

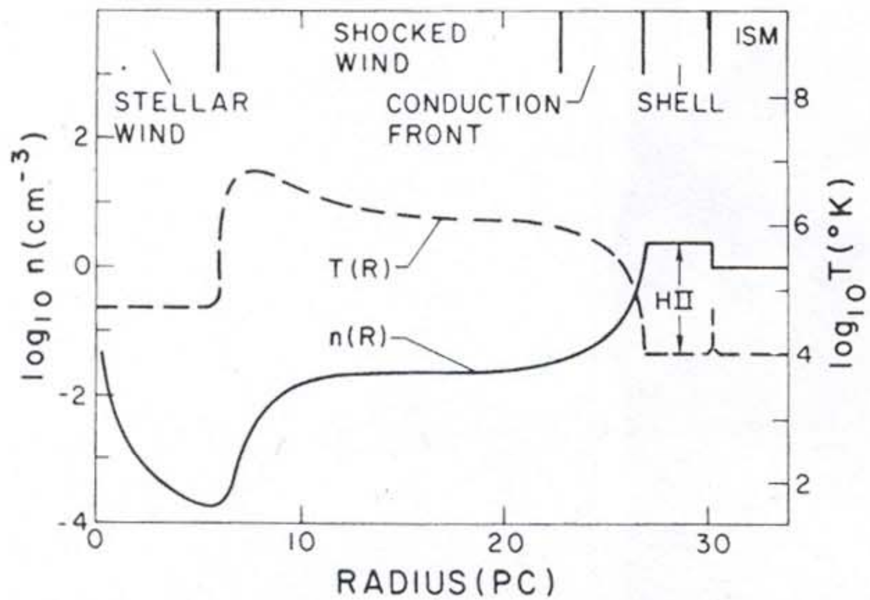
Table 2. Candidate Ionizing Stars

ID	Name ($Gl+b$)	Spectral Type	A_V	Best?
IN10-1	13.1887+00.0421	O7.5 V	7	✓
IN10-2	13.1942+00.0521	O6.5 V	7	✓
IN10-3	13.1786+00.0331	O6 V	5	
IN10-4	13.1777+00.0346	O7 V	8	
IN21-1	18.1893-00.4041	early B I[a]	6	✓
IN21-2	18.1742-00.3918	O6 V	9	
IN21-3	18.1798-00.4275	O8 V	7.5	
IN21-4	18.1977-00.3886	O8.5 V	13	
IN21-5	19.1928-00.4147	early B V	8	
IN49-1	28.8263-00.2287	O5 V	10.5	✓
IN49-2	28.8142-00.2241	O5.5 V	7.5	
IN49-3	28.8174-00.2464	O7 V	7.5	
IN49-4	28.8119-00.2383	O9	10	
IN49-5	28.8098-00.2270	B0	6	

Weaver et al. (1977)

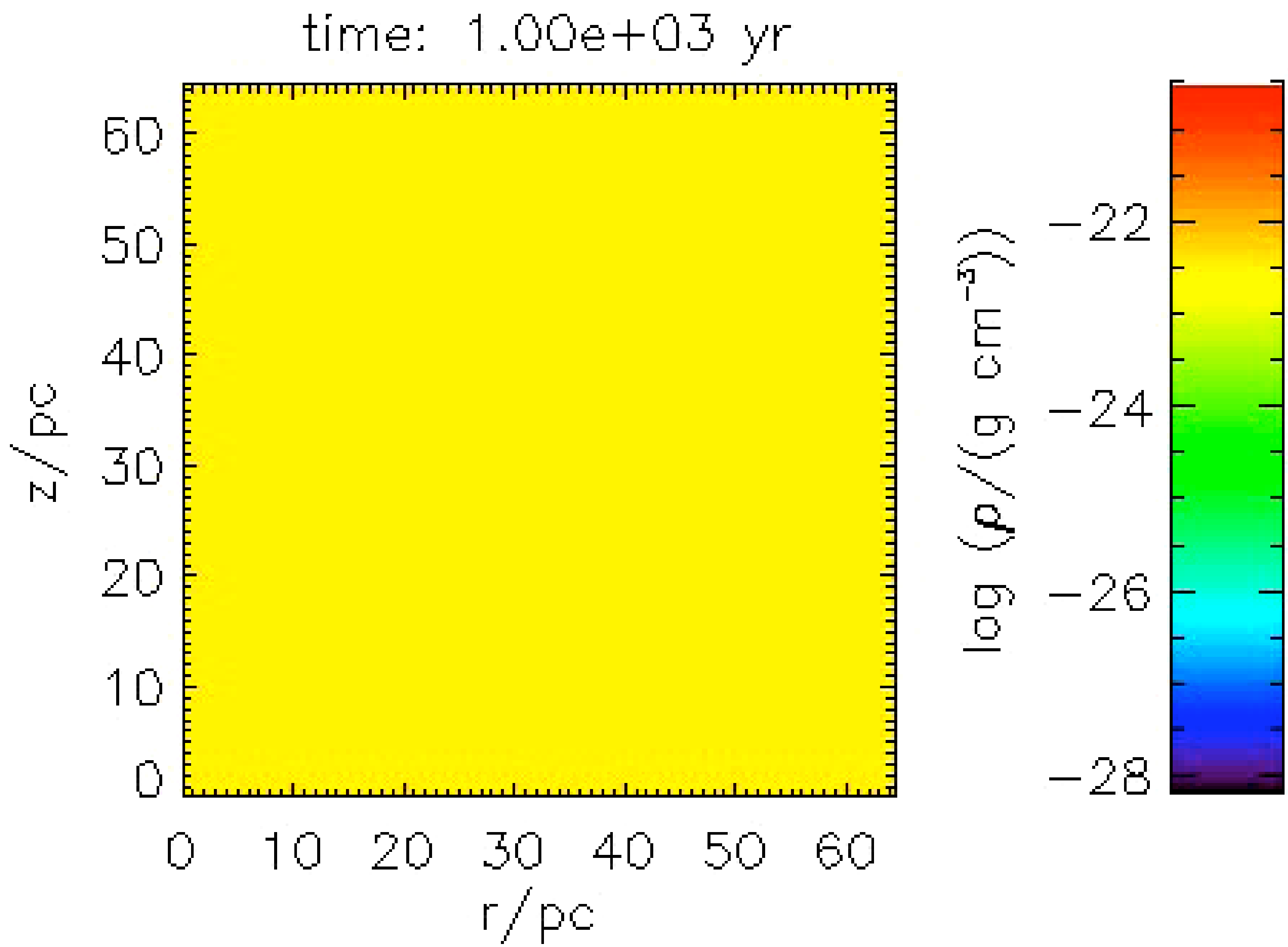


—Schematic sketch indicating the regions and boundaries of the flow.

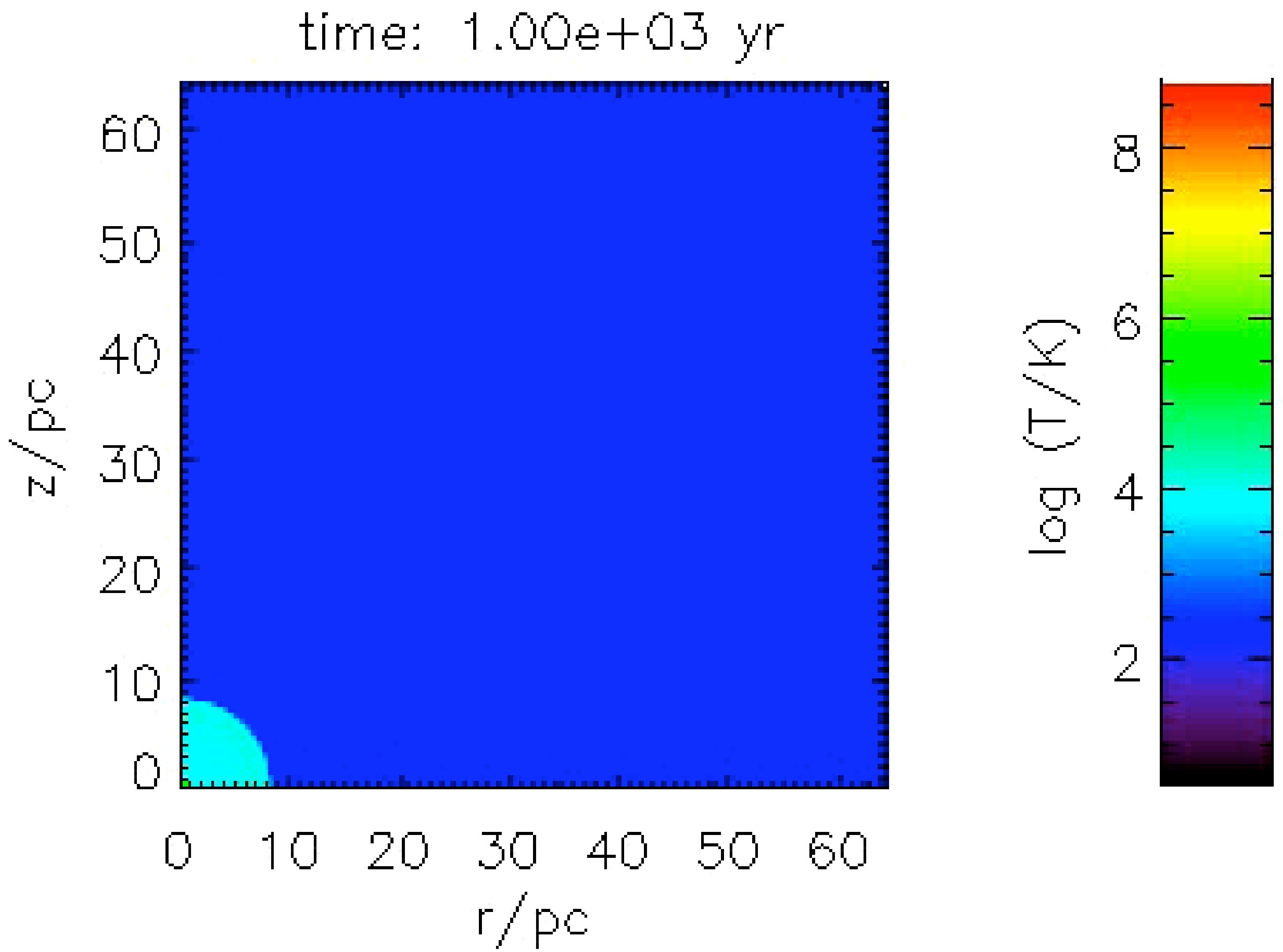


—The large-scale features of the temperature and density structure of an interstellar bubble for which $L_w = 1.27 \times 10^{36}$ ergs s^{-1}, $n_0 = 1$ cm^{-3}, and $t = 10^6$ yr. ISM means ambient interstellar medium. For a typical O7 I star, the H II region would extend to $\sim 3\ R_2$.

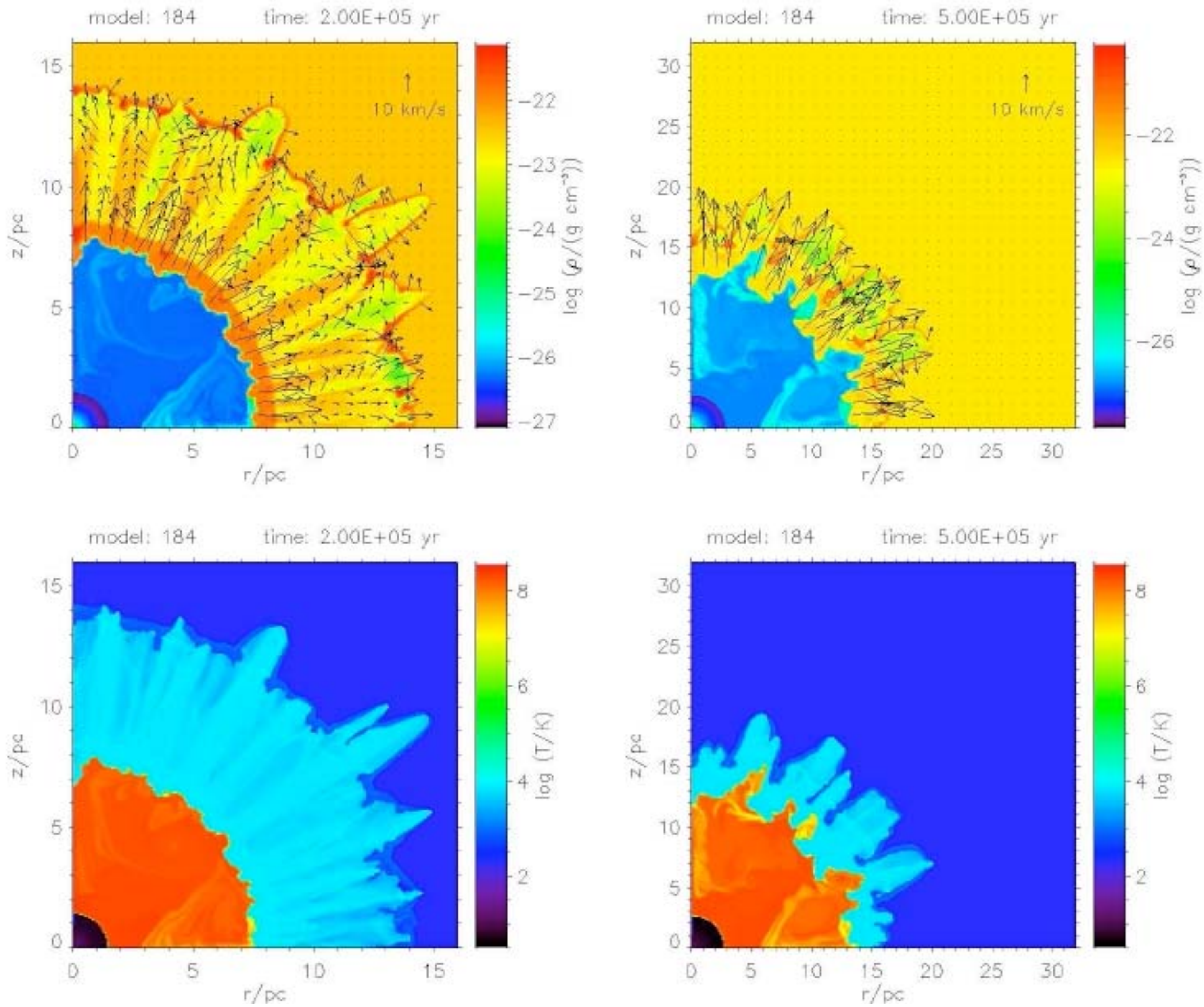
Density Evolution of a 60 Solar Mass Star
Freyer, Hensler, & Yorke 2003, A&A, 594, 888



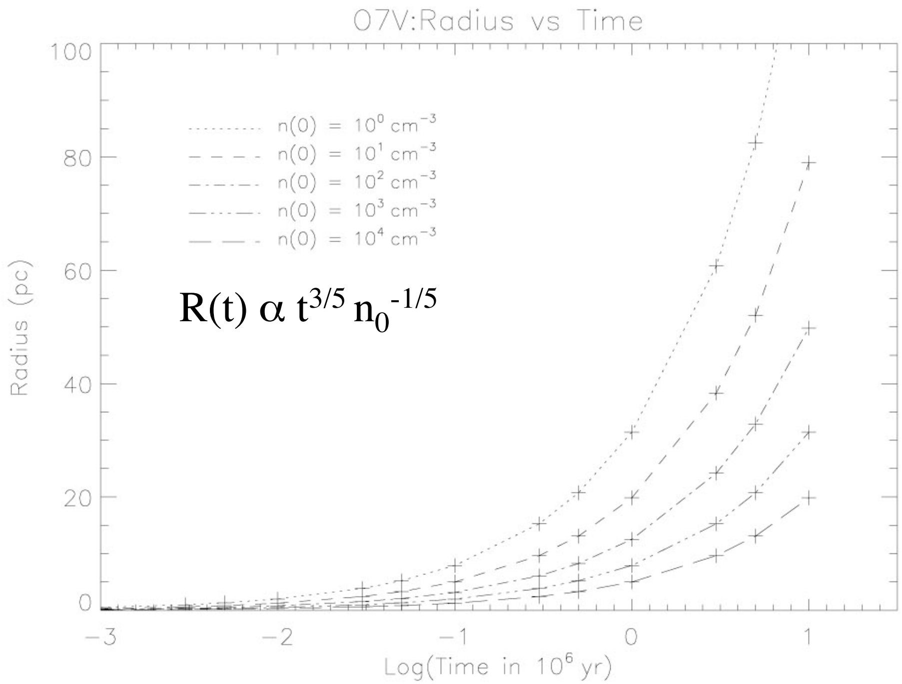
Temperature Evolution of a 60 M_0 Star

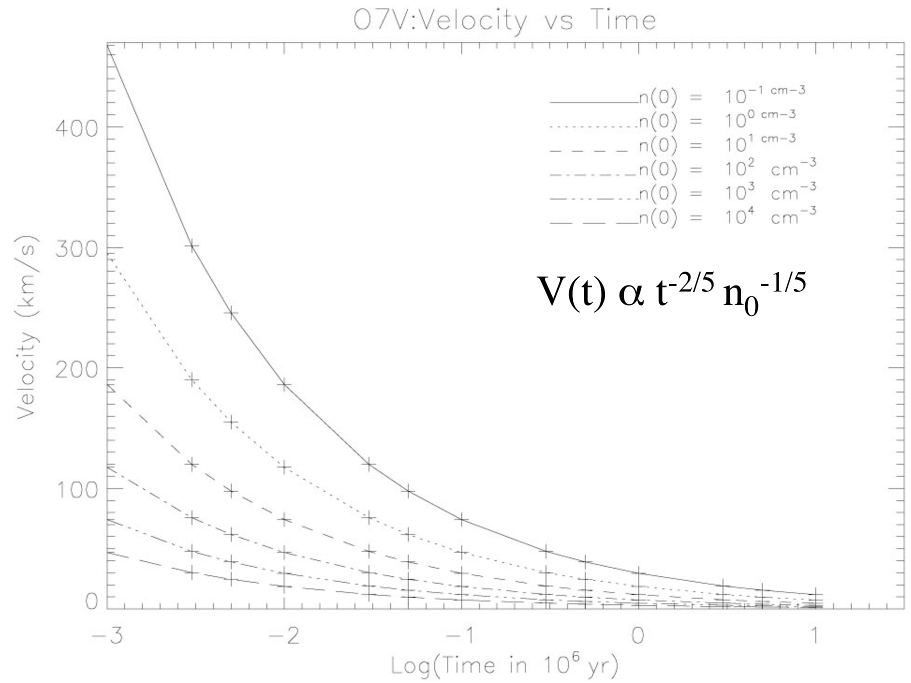


60 M_0 Density and Temp Dist. at $2x10^5$ yr

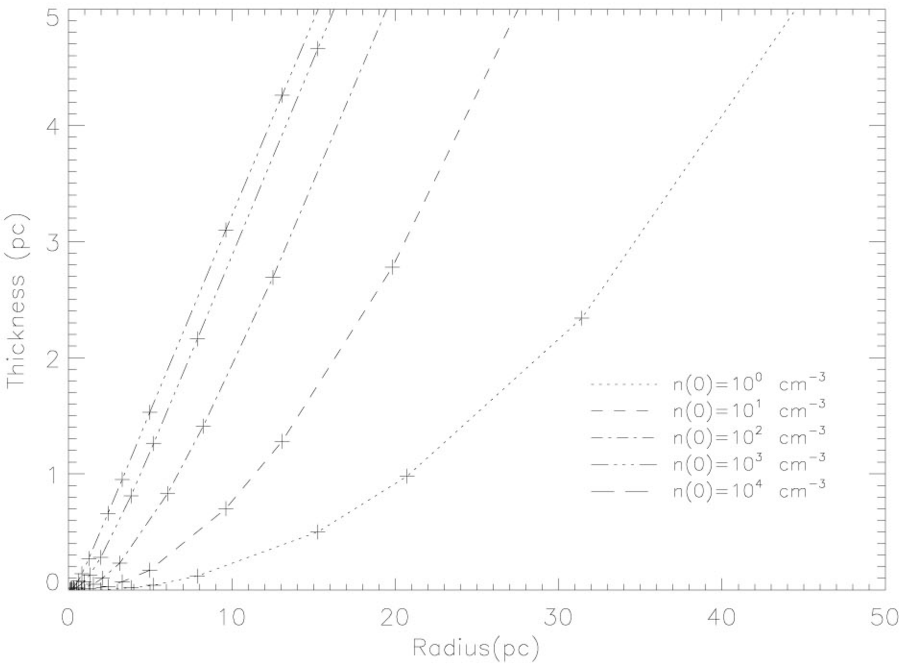


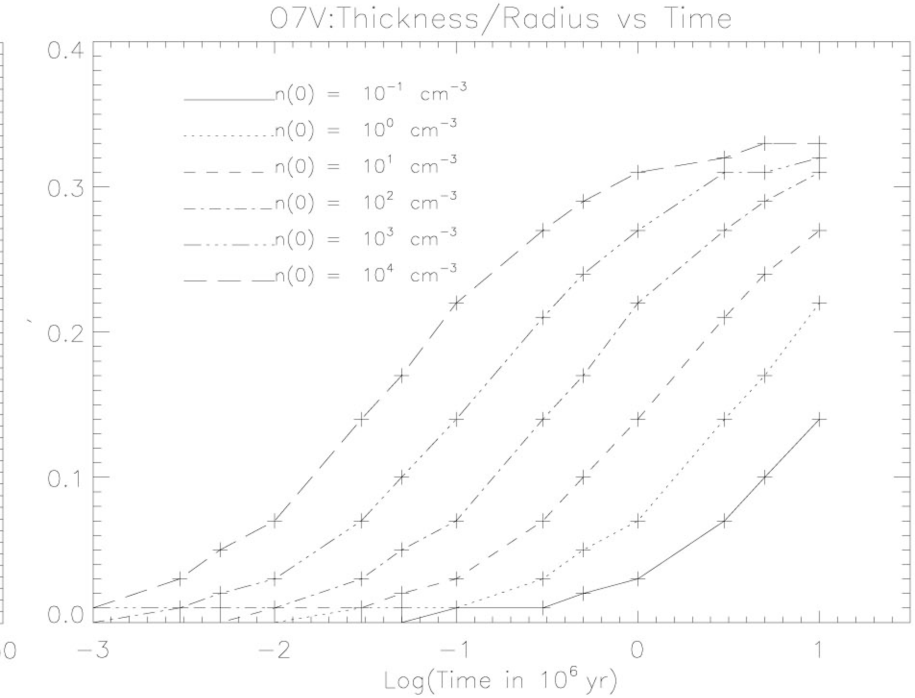
Evolution of an O7V Stellar Bubble





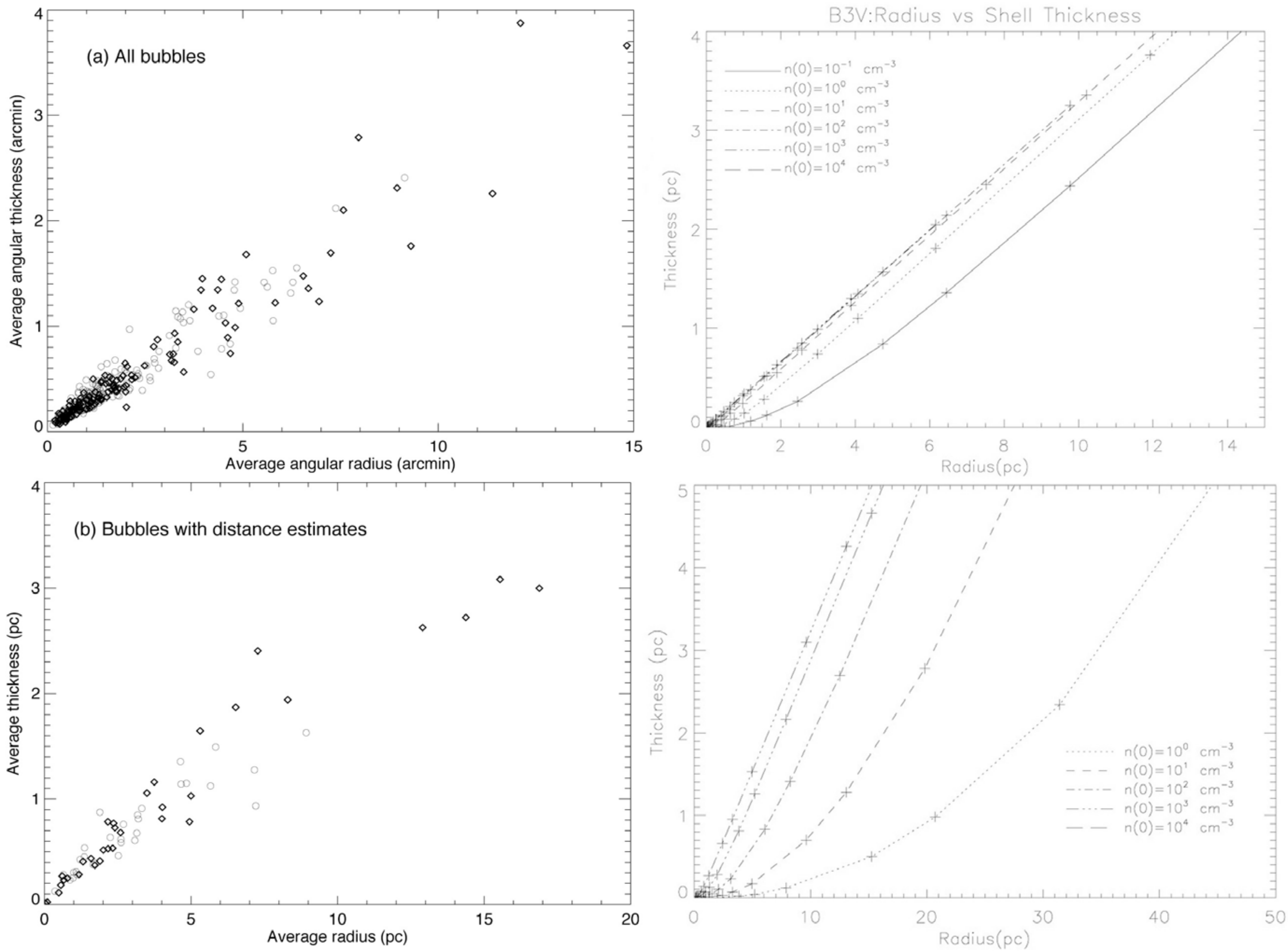
Bubble Evolution:O7V Star





Asymptotic T/R ~ 0.32

Comparison of Observed ΔR/R vs Theory



Main Conclusions

- Expanding bubbles around OB stars appear to trigger new generations of star formation
  - This does not appear to be a primary mechanism of star formation (≥10%)
  - Further observations are required to establish that the bubbles are dynamic and that relative stellar ages are consistent with triggering
- PAHs are destroyed in HII regions but define the PDR areas around the bubbles =>
- PAHs are excited by soft UV radiation (non H-ionizing photons).
- Dust exists in HII regions
  - Bright 24 μm emission (thermal + transiently heated small grains)
  - Generally confined within the radio continuum emission (i.e. inside the I-front)
  - Why is the dust not blown out by stellar winds or destroyed by radiation?
    - Possibly continuously replenished by dense neutral globules that were over-run by the I-front?
    - Wind luminosity threshold? (L_w(O5V) in N49~4 x L_w(O7V) in N10
- Stellar winds fundamentally alter the structure of HII regions
  - Ionization, temperature, and density structures are very different from classical picture of 10^4 K gas filled HII regions.
  - Around O stars with strong winds most of the bubble volume is filled with very hot (several x 10^7 K), low density, X-ray emitting gas.
- Some bubbles show evidence of evacuation of both gas and dust around the central star(s)--N049, others not--N10 and N21
- Indirect evidence that the bubbles are dynamic
- Open questions: Why does dust exist at the center of N10? Why isn't the dust in N10 and the N49 HII region not blown out by the stellar wind? N10 has a factor ≤ 4 weaker wind than N49, so maybe there is a threshold for dust clearing? Maybe dust is continuously replenished by embedded neutral globules that was overrun by the I-front?