Unveiling the cosmic cradle: clustering and massive star formation in the enigmatic Bubble N59

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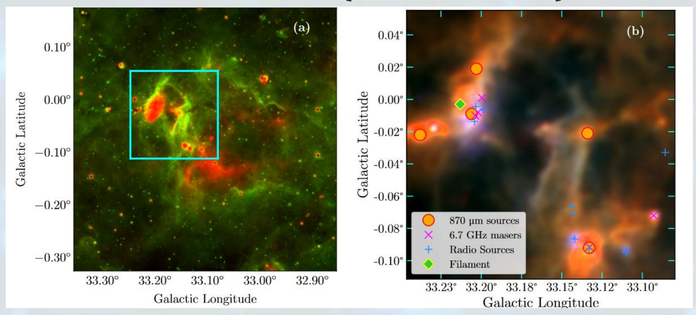
Massive stars play a key role in the evolution of our Universe and have a profound impact on their local environment through massive outflows, strong stellar winds, ultraviolet radiation, and supernovae explosions. Despite their profound influence on the Universe, many aspects of massive star formation still remain elusive. This can be mainly attributed to rapid formation, which takes place while they are deeply embedded in dense clumps. Methanol masers at 6.7 GHz are used as an ideal tool to probe the early phases of massive star formation as they are almost exclusively fond towards massive star forming regions. Here, we focus our attention on the specific star-forming region known as MIR bubble N59. This region stands out for hosting approximately eight 6.7 GHz methanol masers, alongside numerous compact H II regions, massive clumps, filaments, and prominent bright rims. Analyzing the characteristics of this region, therefore, allows us to glean valuable insights into the interplay between the processes involved in the early phase of high-mass star formation.

Clustering and massive star formation in the enigmatic Galactic bubble N59

Background

- 6.7 GHz methanol masers – tool to study the HMSF at large scales.
- Many found towards the edges of expanding bubble.
- The expanding nature of these bubbles possibly plays a role in the formation of interstellar filaments.
- It is thought that star formation occurs preferentially along the filaments.
- Regions where filaments, Masers and Bubble coexist → ideal location to study HMSF

Bubble N59 (G33.071-0.075)



Eight 6.7 GHz methanol maser detections | Two filaments at the edge of bubble (Li et al. 2016) | Abundance of HII regions & ATLASGAL clumps

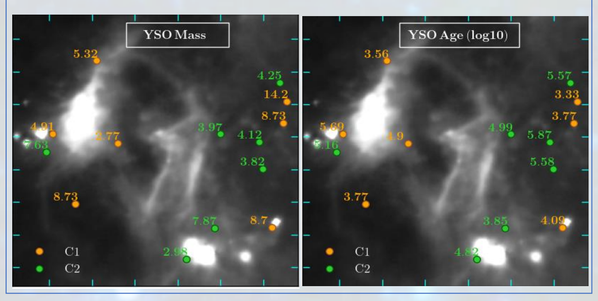
Performed Multiwavelength Analysis of Region R1 of Bubble N59

DATA SAMPLE

- The UKIRT IR Deep Sky Survey – UKIDSS
- IRAC – Infrared Array Camera, Spitzer Space Telescope
- Herschel – Exploring the Cold Universe
- Atacama Pathfinder Experiment – APEX
- CORNISH – Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation
- The NRAO VLA Sky Survey
- MAGPIS: The Multi-Array Galactic Plane Imaging Survey
- CHIMPS2 – The CO Heterodyne Inner Milky Way Plane Survey

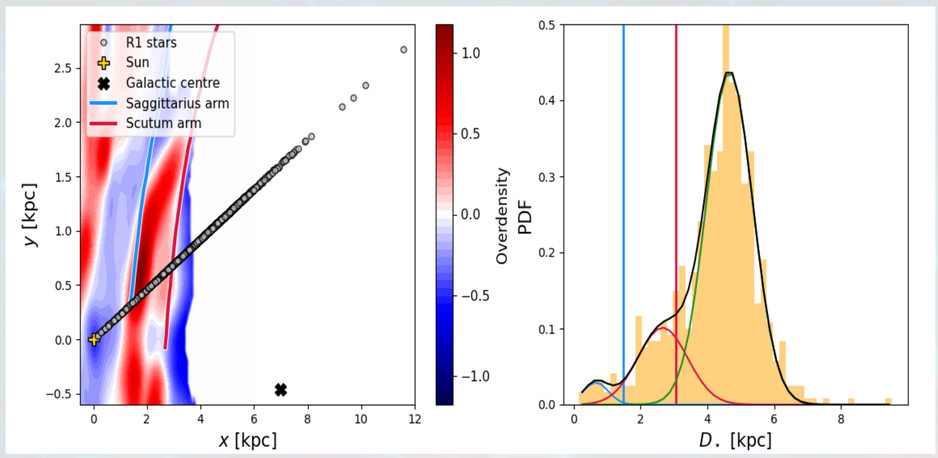
Results from YSO analysis

- 12 Class I & 8 Class II YSOs
- 4 Class I YSOs with mass > 8 $M_{\odot}$
- Most of the YSOs are young (< 1Myr)
- Average Dust Temperatures ~ 22 K



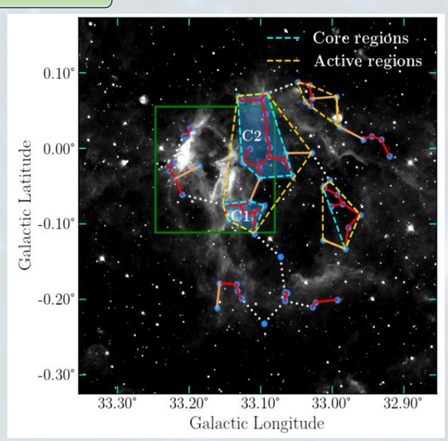
Notes on Distances

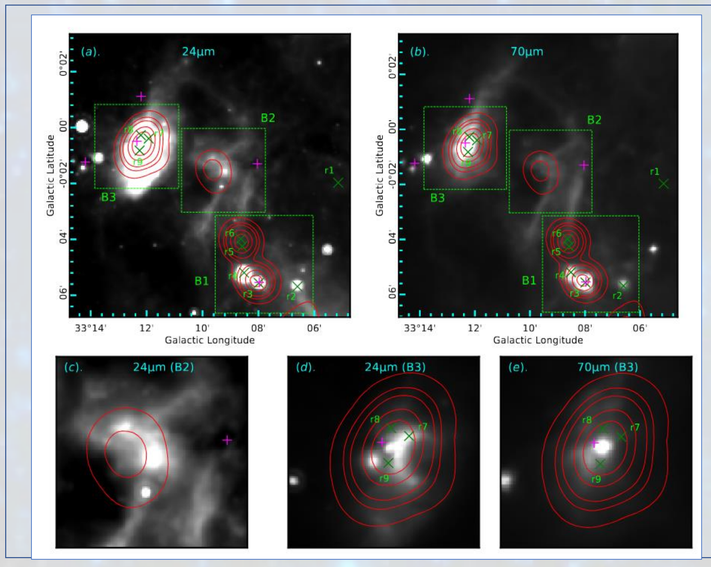
- Bailer-Jones et al. (2021) used parallax for distance likelihoods -- smaller uncertainties than kinematic distances.
- Bailer-Jones' distances used for R1 distance calculation.
- Stars in R1 with < 10% parallax uncertainty considered.
- PyUPMASK algorithm determined membership probabilities for stars in R1.
- Stars with >80% probability used to estimate mean R1 distance of 4.66 ± 0.70 kpc.

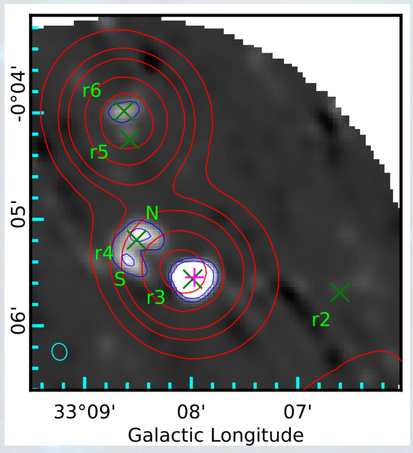


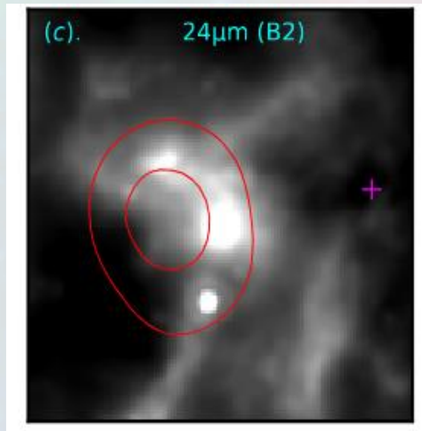
Clustering of YSOs

- Employed the Minimum Spanning Tree method.
- Applied initially to bubble N59's sample of 59 YSOs, then focused on R1.
- Branch cut-off set $lc = 114''$, equivalent to 2.59 pc at 4.66 kpc.
- Identified core regions C1 and C2 within R1.
- Core C1 features a 6.7 GHz methanol maser and an ATLASGAL clump.









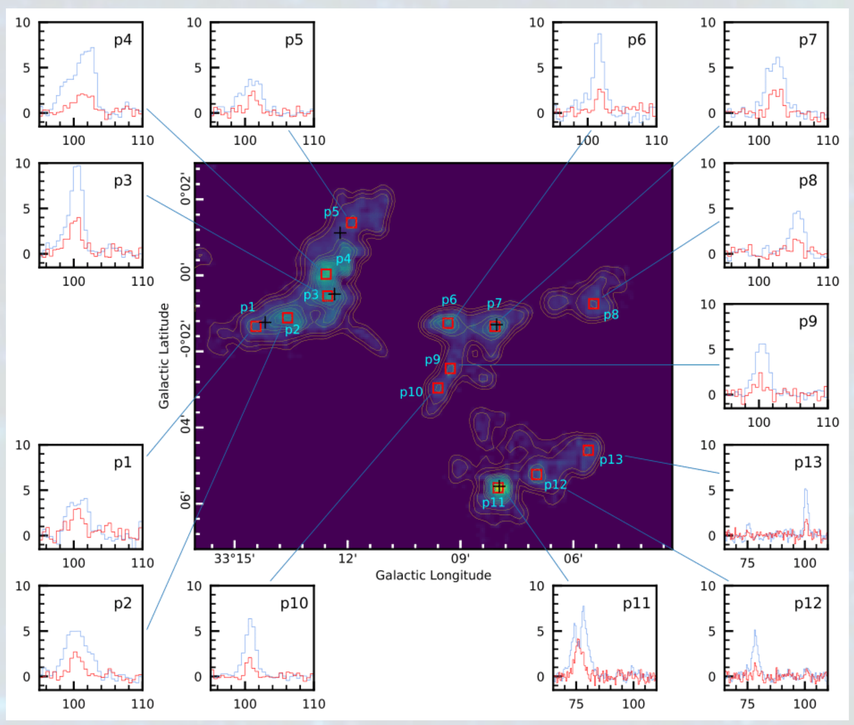
Results from Radio Analysis

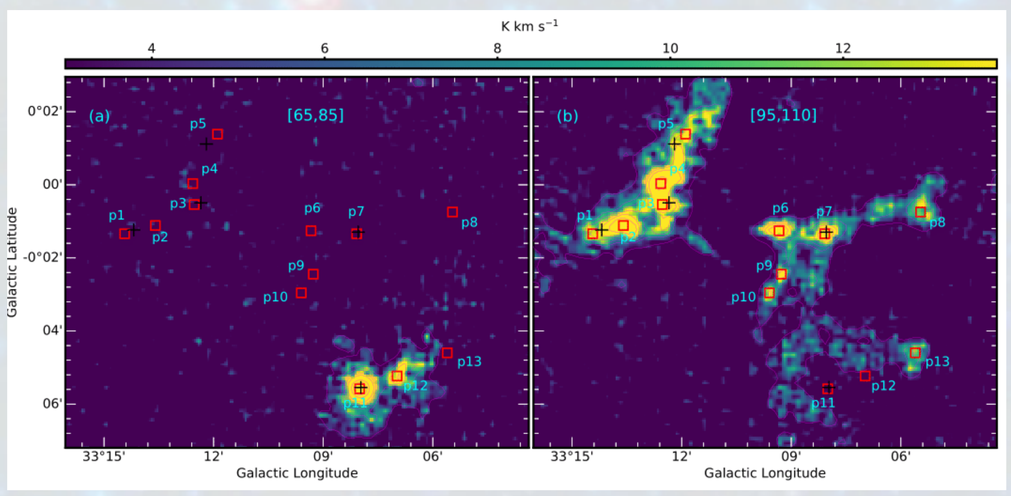
- Cluster of O and B type stars

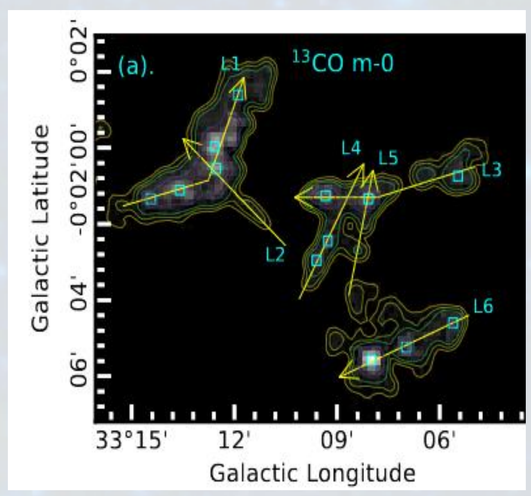
r2	r3	r4-N	r4-S	NVSS (B2)	NVSS (B2)
B1	O9.5	B0.5	B0.5	B0.5	B0

- High-resolution 8.49 GHz image from VLA shows r3 and r4 as distinct H II regions unlike what showed by NVSS emission
- No YSOs detected in B2, but NVSS emission suggests young embedded star formation.
- Feedback by the bright H II region possibly resulted in the formation of Bright Rimmed Cloud in B2

Results from Molecular Analysis







- Two different molecular clouds in the region, which spatially might appear as part of the same complex, but are differentiated in velocity space.
- Possible hub-filament system in area surrounding B2 with p6 and p7 as central "hubs."

Summary

- The clustering analysis reveals two prominent core regions with multiple H II regions and massive YSOs.
- We find a O-type star coexisting with five B-type stars, numerous low-mass stars, and at least four high-mass YSOs.
- The bright-rimmed cloud has likely formed as a result of feedback from the intense H II region. The NVSS emissions from the cloud indicate ongoing massive star formation, hinting at radiation-driven implosion.
- The area around B2 aligns with hub-filament scenario. We observe velocity gradients towards the CO(3-2) peaks (p6 and p7) along three filaments. Moreover, p7 is associated with an ATLASGAL clump with a column density similar to that of the hub.
- We also find two co-spatial molecular clouds with velocities of 70-80 km/s and 100 km/s. Source p11 has a 6.7 GHz methanol maser separated by less than 14''; high-resolution studies are warranted for further investigation.

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