Observations of high-order multiplicity in a high-mass stellar protocluster

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High-mass stars ($\geq 8\ M_\odot$) in the Milky Way are overwhelmingly (>80%) found in binaries or higher-order multiplicity systems that play a key role in governing cluster dynamics and stellar evolution. However, the dominant mechanism forming multiple stellar systems in the high-mass regime remained unknown because direct imaging of multiple protostellar systems at early phases of high-mass star formation is very challenging. High-mass stars are expected to form in clustered environments containing binaries and higher-order multiplicity systems. So far only a few high-mass protobinary systems, and no definitive higher-order multiples, have been detected. ***Here we report the discovery of 1 quintuple, 1 quadruple, 1 triple, and 4 binary protostellar systems simultaneously forming in a single high-mass protocluster, G333.23–0.06, using ALMA high-resolution observations.***

G333.23–0.06 is a typical high-mass star-forming region at a distance of 5.2 kpc associated with Class II CH_3OH maser emission. It has a mass reservoir of ~3000 $M_\odot$ with a mean column density of 1.6×10^{23} cm^{-2} within a 1.2 pc radius.

Hierarchical fragmentation

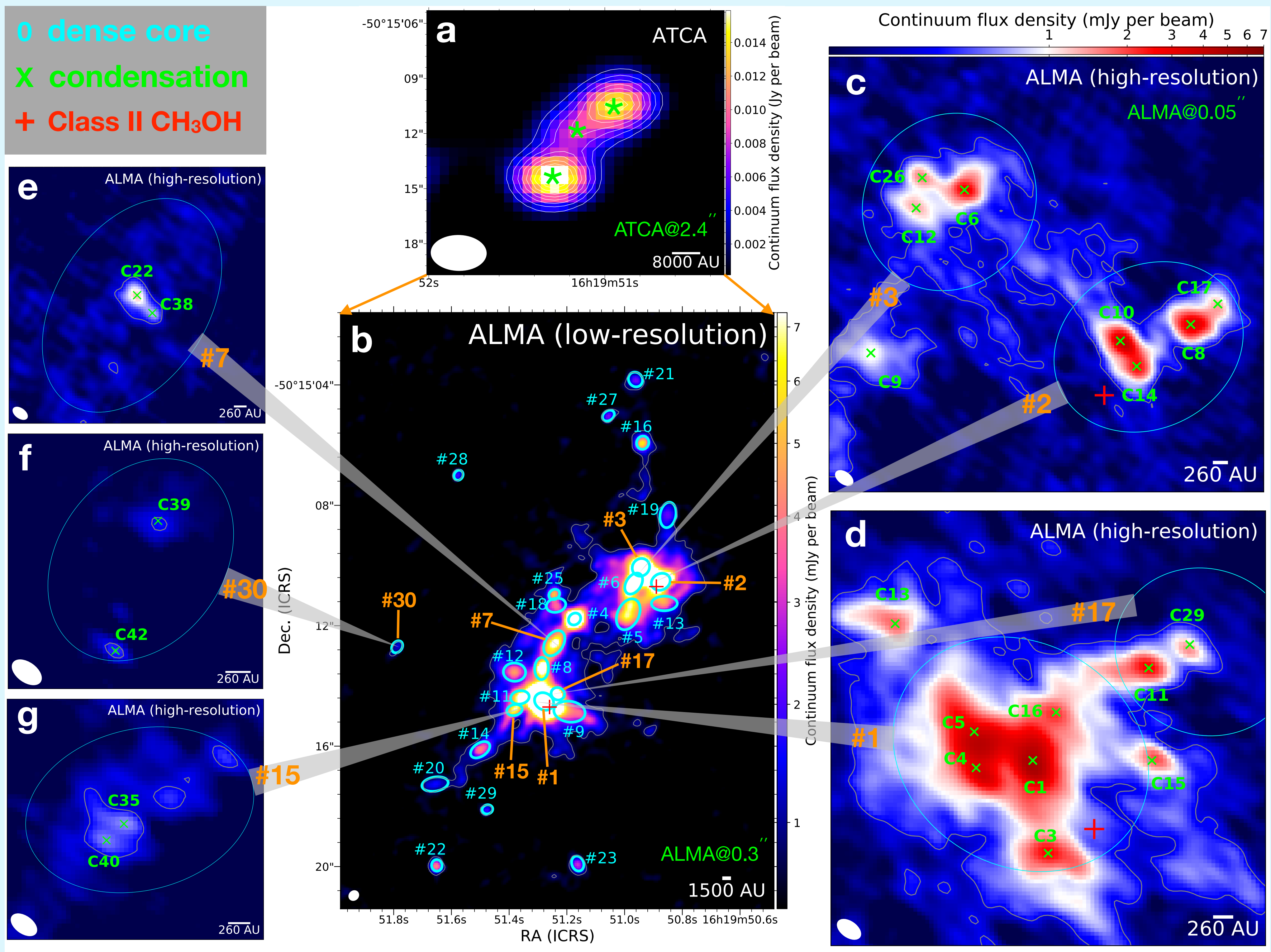
Multi-scale observations:
from 10^4 au scale down to 10^2 au scale.
ATCA@2.4″(12500 au): 3 sub-clumps.
ALMA@0.3″(1560 au): 30 dense cores.
ALMA@0.05″(260 au): 44 condensations.

- **Multiplicity:**

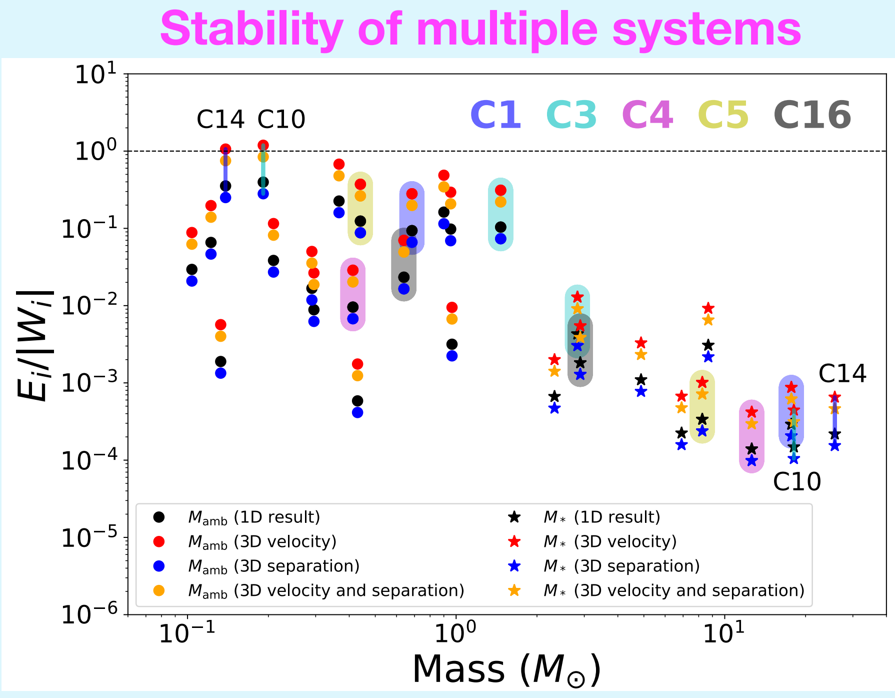
1 quintuple (C1/C3/C4/C5/C16)
1 quadruple (C10/C14/C8/C17)
1 triple (C6/C12/C26)
4 binary (C11/C29, C22/C38, C39/C42, and C35/C40)

Multiplicity fraction (MF) is 20/44 ≈ 45%.
Companion frequency (CF) is 46/44 ≈ 1.
The derived MF and CF are higher than those measured in low-mass star-forming regions for a similar separation range of 300–1400 au, indicating that the multiplicity could be higher in denser cluster-forming environments.

Hight-mass protostars:
There are at least one high-mass protostar in both quintuple and quadruple systems as suggested by the presence of Class II CH_3OH maser, which are excited in high-density regions by strong radiation fields and exclusively tracing high-mass star-forming regions.

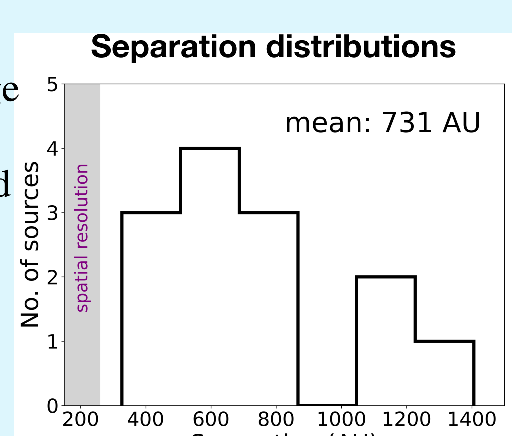


Stability of multiple systems



The kinetic-to-gravitational energy ratio as a function of mass for the multiple system. _The detected multiple systems are kinematical confirmed to be gravitationally bound ($E_i/|W_i|<1$)_. The circles and stars symbols are the results derived from ambient mass (M_{amb}) and protostellar mass (M_*), respectively. $E_i/|W_i|$ has been estimated with four different methods: (1) line-of-sight velocity difference and on-sky separation (1D), (2) three-dimensional (3D) velocity difference and on-sky separation, (3) line-of-sight velocity difference and 3D separation (3) 3D velocity difference and 3D separation.

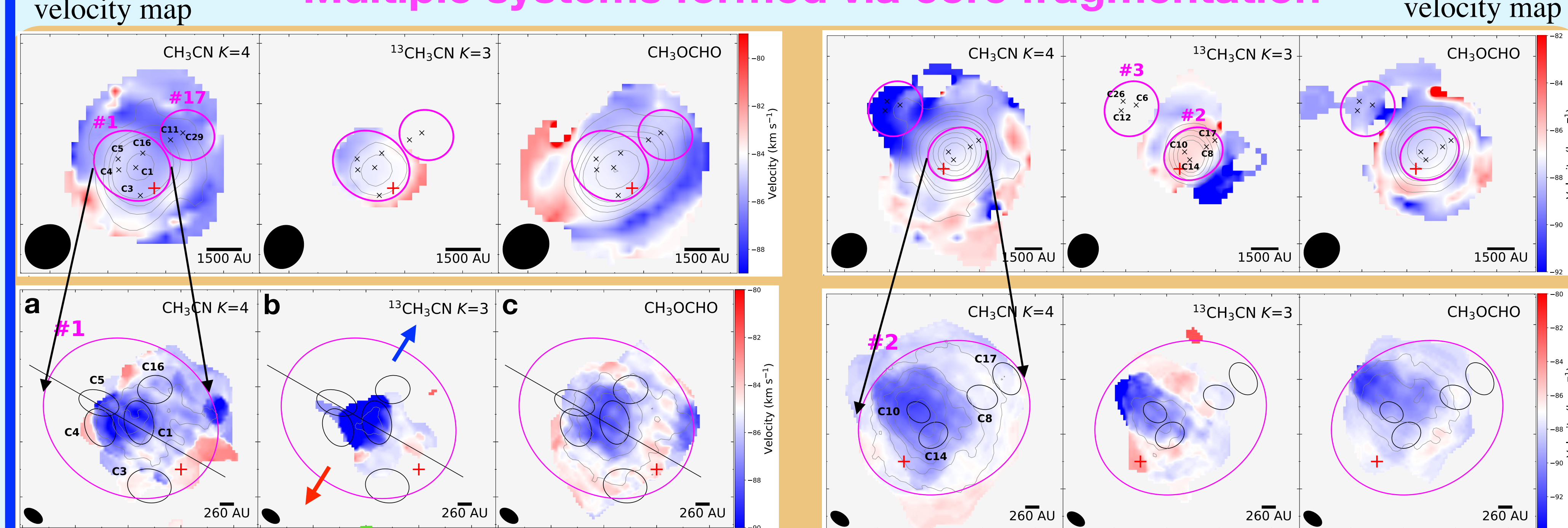
The projected separations range from **327 to 1406 au, with a mean value of 731 au**, in good agreement with the typical projected separation of 700 au in the simulation of multiple star formation via core fragmentation (Kuruwita+2023).



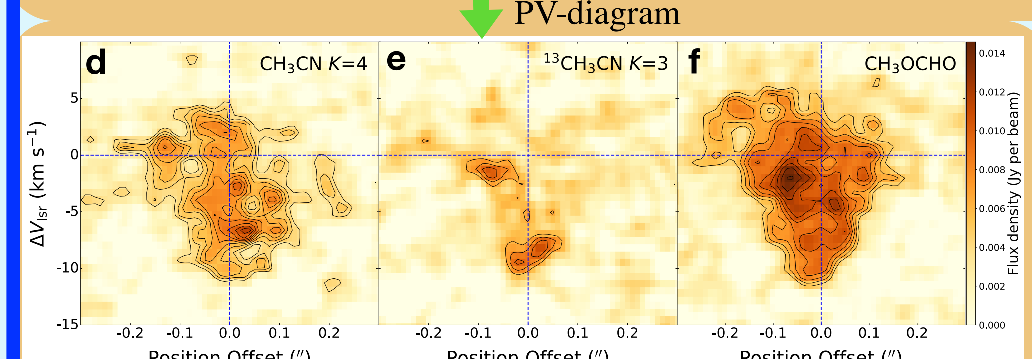
Multiple systems formed via core fragmentation

velocity map

velocity map

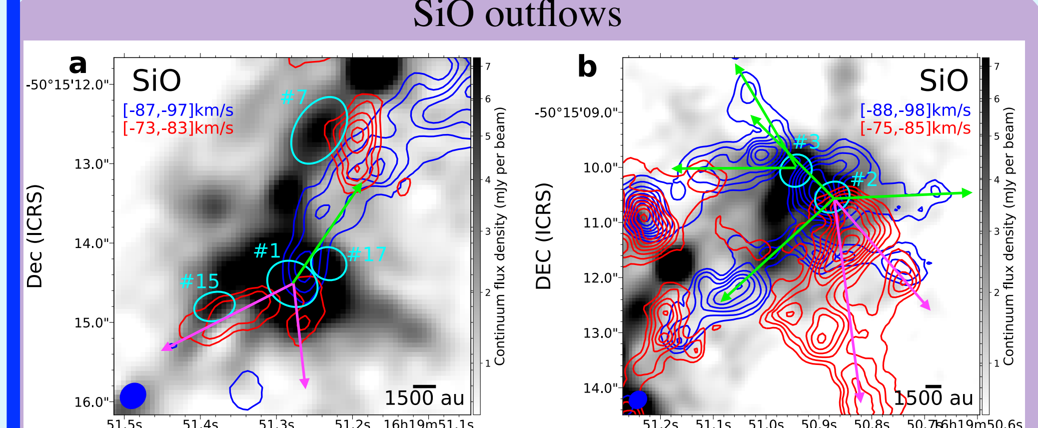


PV-diagram



There are no obvious sign of disk kinematic structures toward the multiple systems and their parent cores in any of detected lines based on short-baseline (@0.3″) and combined (@0.05″) data; e.g., CH_3CN, $^{13}CH_3CN$, CH_3OCHO, CH_3OH, $^{13}CH_3OH$, SO_2, SO, HC_3N, HNCO, NH_2CHO, H_2CO, $H^{13}CO$, etc.

SiO outflows



The detected misaligned outflows indicate that the embedded driven sources do not come from the same co-rotating structures. This suggests that the quintuple, quadruple, and triple systems are formed from core fragmentation (Offner+2016).

1. The observed fragmentation into binary and higher-order multiple systems can be explained by core fragmentation, indicating **core fragmentation play a crucial role in establishing the multiplicity** during high-mass star cluster formation. Disk fragmentation may still occur on smaller scales than those we can resolve with the current spatial resolution.
2. The results indicates that the **multiplicity in clusters is established in the protostellar phase**.
3. High- and low-mass multiple protostellar systems are simultaneously forming within G333.23–0.06

Offner, Stella S. R., et al. et al. 2016 , ApJ 827, L11; Kuruwita, R. L., et al. et al. 2023, A&A, 674, A196

Li et al 2024, Nature Astronomy
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