Understanding Ultracompact H II Regions

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Abstract

H II regions are important signatures of star formation both in the Milky Way and in external galaxies, play an important role in destroying the parental molecular clouds in which stars form, and, while still in the ultracompact phase, give insight into the process of high-mass star formation. We present simulations that consistently follow the gravitational collapse of a massive molecular cloud, the subsequent build-up and fragmentation of the accretion disk surrounding the nascent massive star, and, for the first time, the interaction between its intense UV radiation field and the infalling material. We show how these simulations help explain the origin of ultracompact H II region morphologies, their number statistics, their time variability, and the long-standing lifetime problem.

Scientific Questions

- What is physical origin of ultracompact H II region shapes?
- Why do observed H II regions remain small far longer than expected for uniform expansion (lifetime problem, see [1])?
- What causes observed time variability of ultracompact and hypercompact H II regions?
- What determines slope of H II region spectral energy distributions (SEDs)?

Simulation Method

- FLASH code models of high-mass star formation including self-gravity, ionization [2].
- Protostar is represented by a sink particle; emits ionizing and non-ionizing radiation dependent on mass, accretion rate.
- Radiation propagated on adaptive mesh using the hybrid characteristics ray tracing.

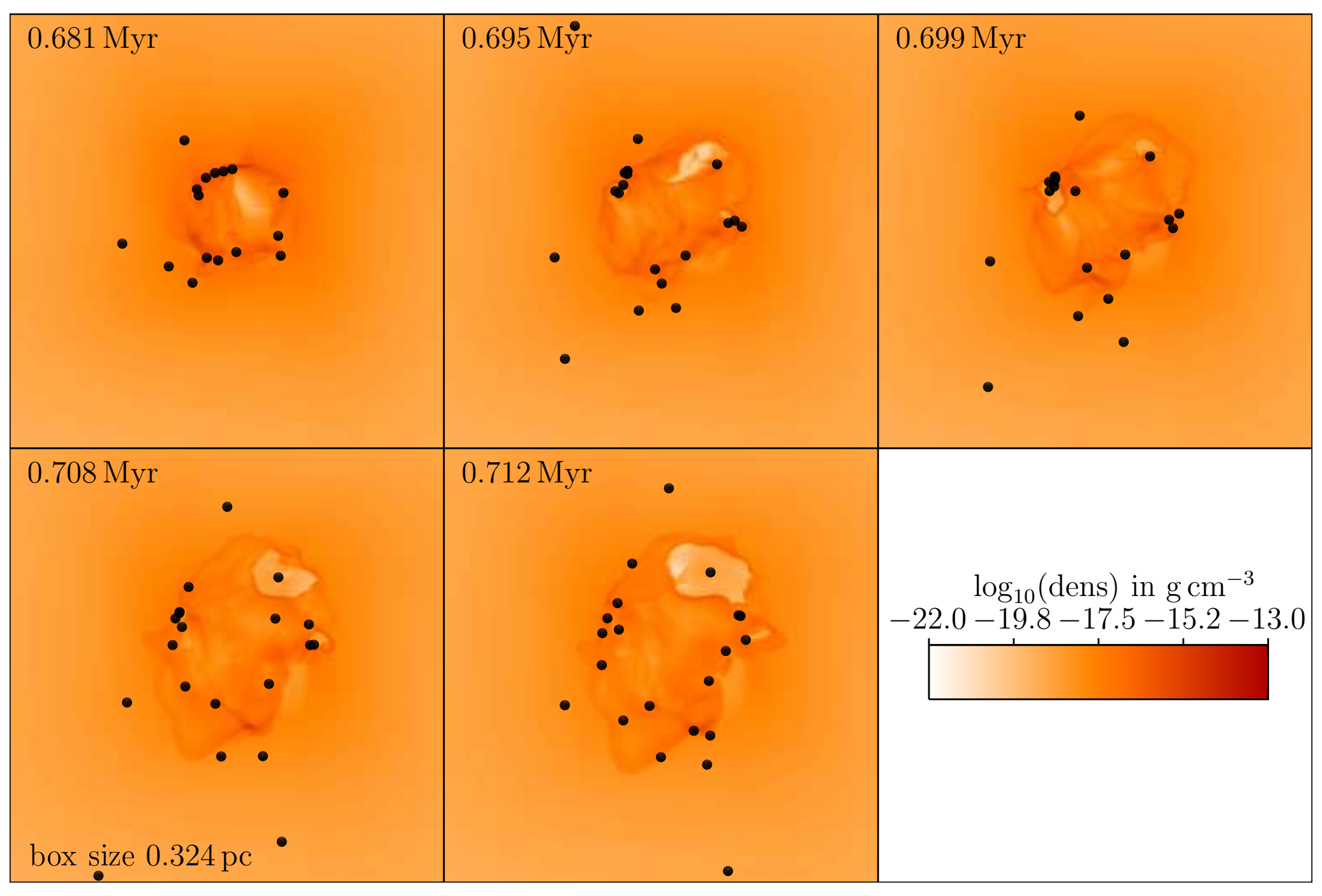
Initial Conditions

- $M = 1000\,M_\odot$ molecular cloud with $T_0 = 30\,\mathrm{K}$.
- Spherical cloud, with $\rho(r) \sim r^{-3/2}$ outside $r = 0.5\,\mathrm{pc}$, constant density $\rho = 1.3 \times 10^{-20}\,\mathrm{g\,cm^{-3}}$ within.
- Solid body rotation with ratio of rotational to gravitational energy $\beta = 0.05$. No turbulent velocity fluctuations.
- Eleven refinement levels, with maximum spatial resolution 98 AU.

Post-processing

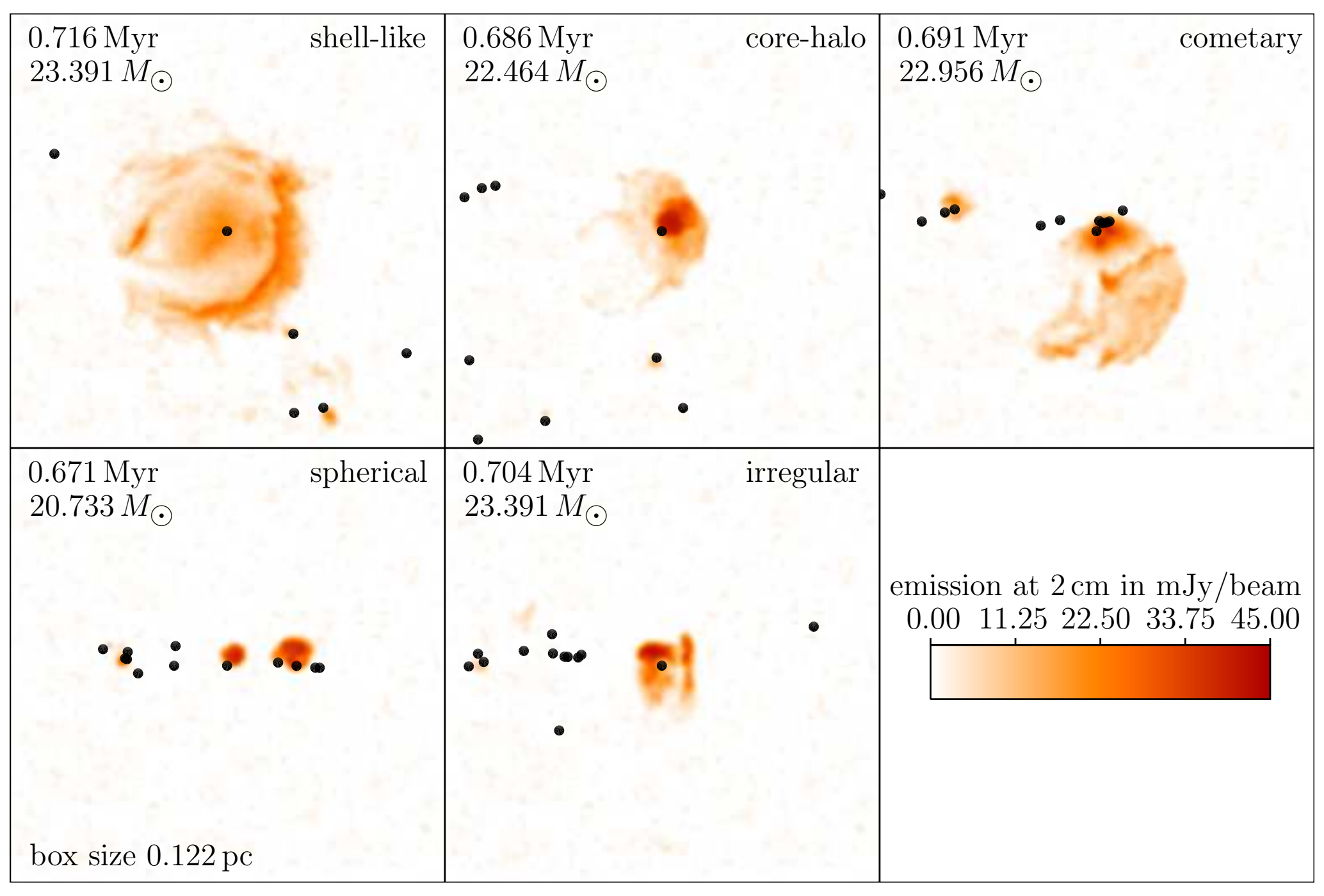
- Compare synthetic VLA observations of free-free continuum emission to observed ultracompact H II regions [3].
- Use RADMC-3D to compute thermal dust emission with a Monte Carlo calculation of dust temperature.
- Include effective telescope beam and receiver noise.

H II Region Evolution

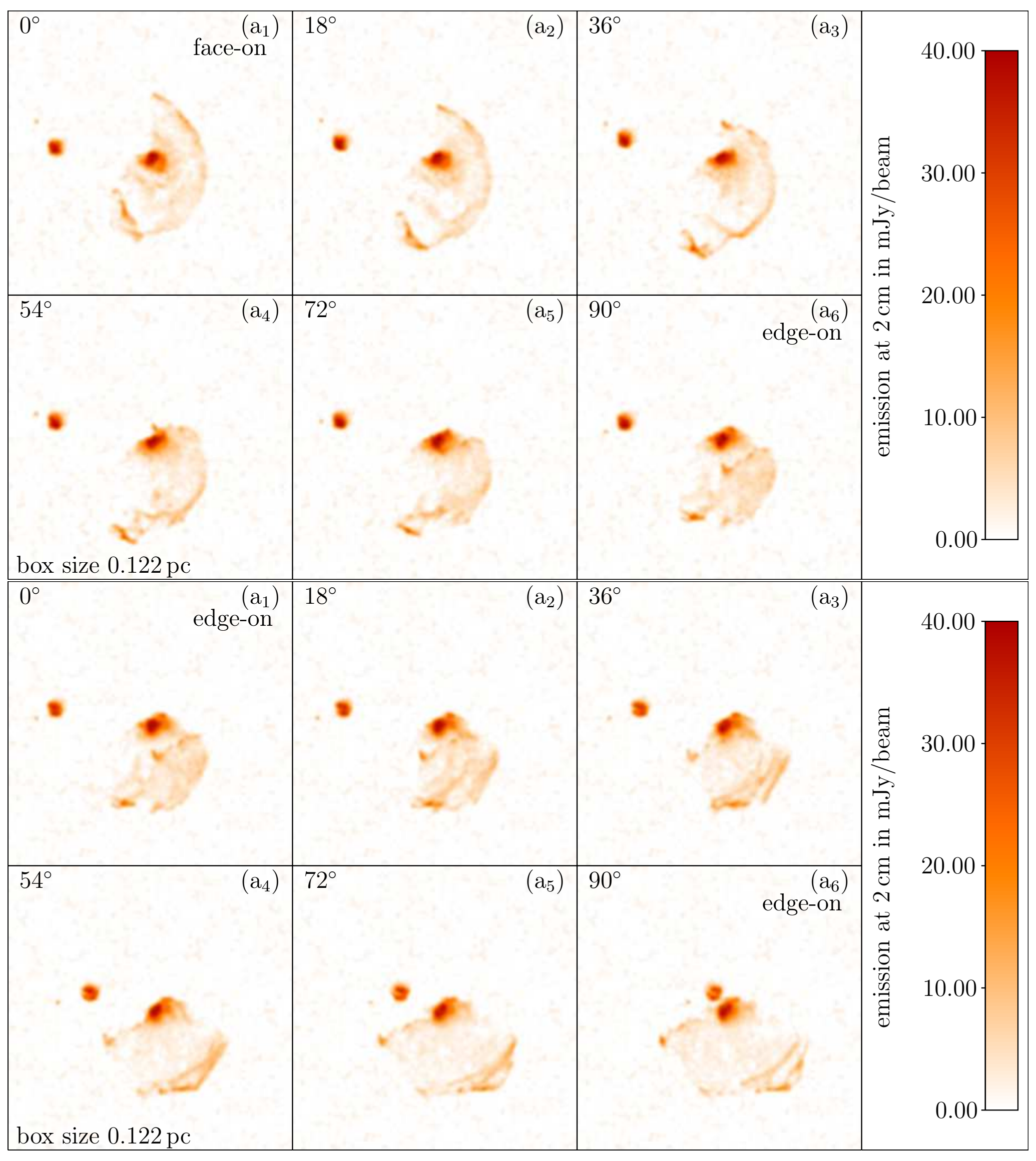


- Figure above shows density slices through cluster, black dots are sink particles.
- When massive star starts ionizing surroundings, gas near the star starts expanding. If density increases, H II region collapses back onto star. This happens repeatedly over 30–50 kyr.
- Only when accretion flow gets weak enough, does H II region bubble systematically expand.

H II Region Morphologies



- Figure above shows that we can reproduce all ultracompact H II region morphologies found in surveys.
- Figure below shows that time and viewing angle determine morphologies.
- Different morphologies come from same process: interaction between ionizing radiation and clumpy, irregular accretion flow onto massive star.
- Magnetic fields only influence H II region morphology weakly [4].



- Example shows region that is shell-like from one angle, cometary after 90° rotation, and shell-like again after further rotation by 90° around different axis.

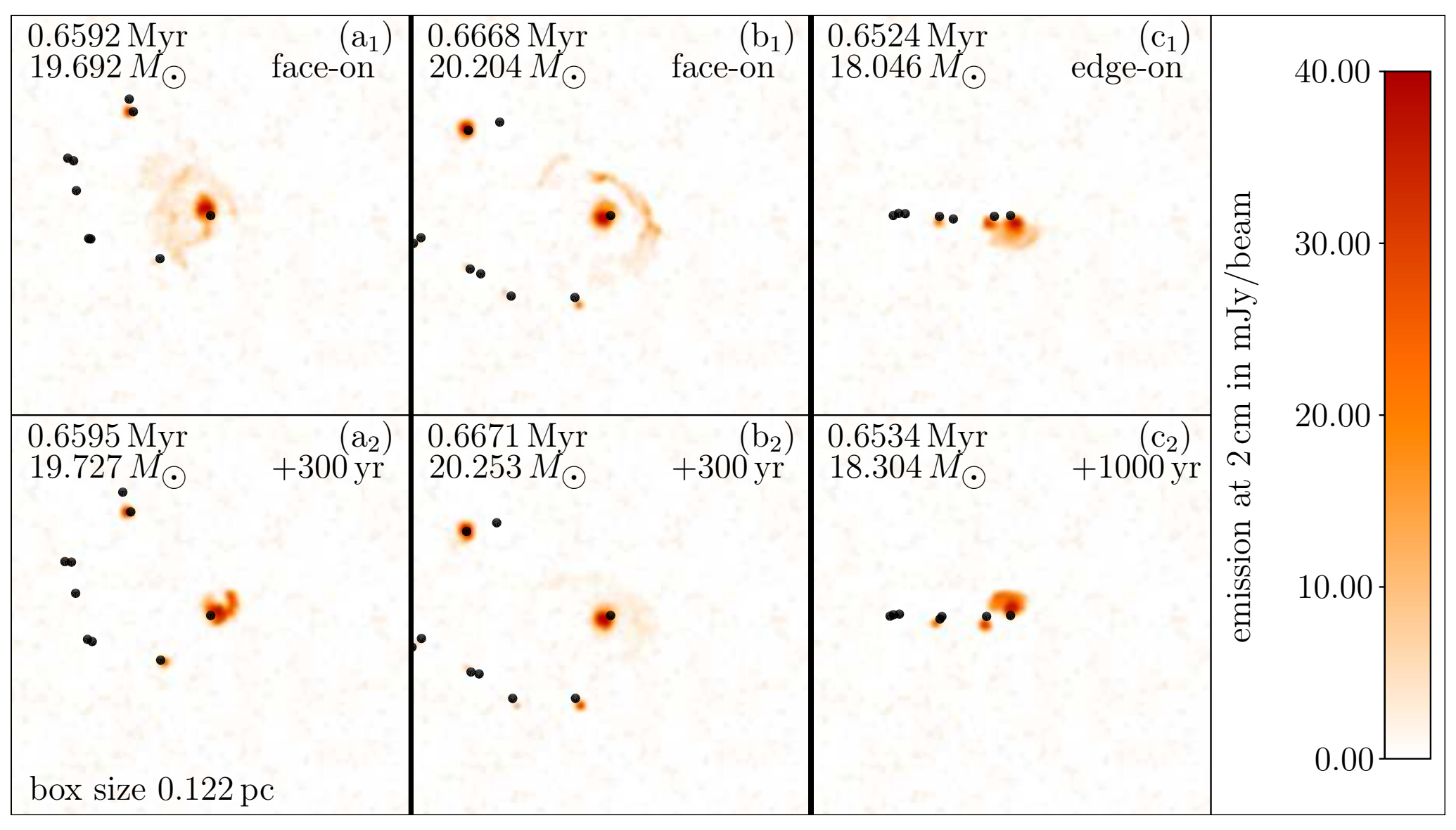
Morphology Statistics

- We compared morphology statistics of our simulations quantitatively to surveys by Wood & Churchwell (WC89, [1]) and Kurtz et al. (K94, [5]).
- 25 simulation times viewed from 20 different angles.
- H II region morphologies classified in these 500 images.
- Table gives relative frequencies for two runs and two surveys.

Type	WC89	K94	Run A	Run B
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

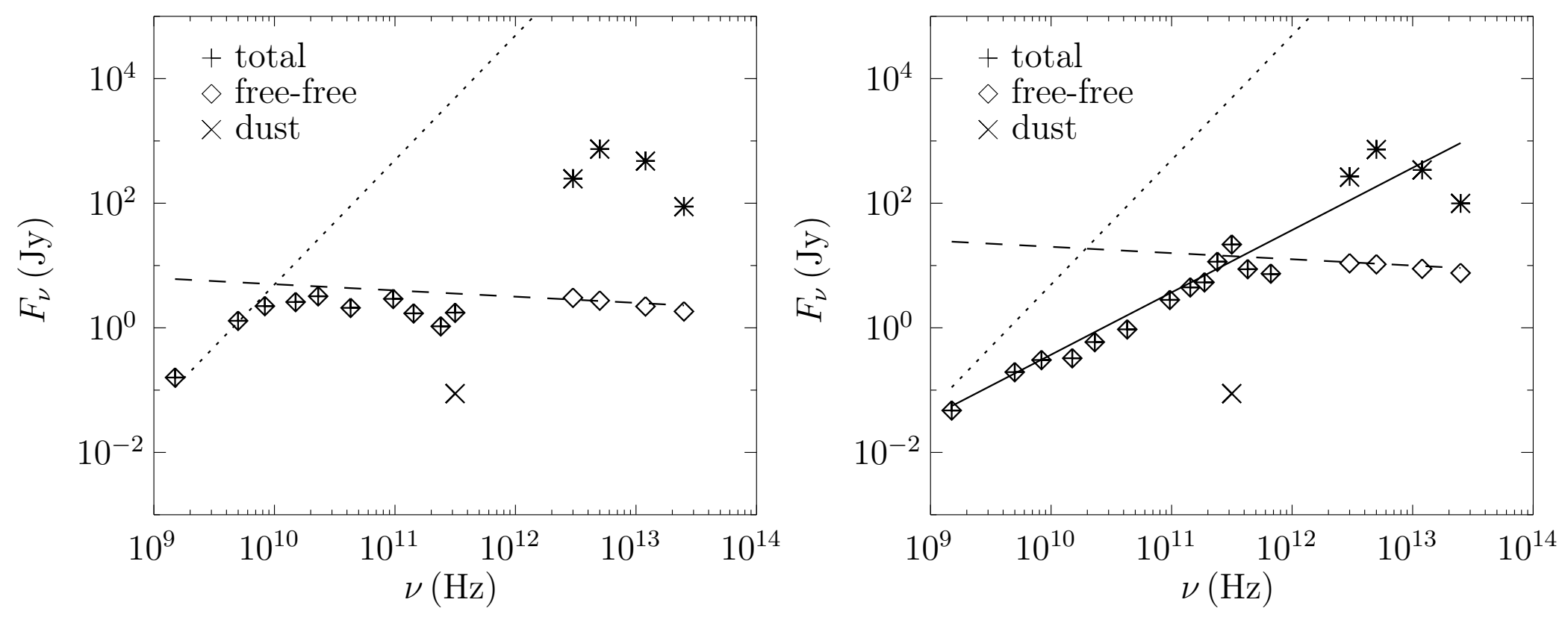
- Run B is a simulation in which a full stellar cluster forms, with three massive stars around $20\,M_\odot$.
- Only one sink particle allowed to form in Run A, so it just contains a single ionizing source of $70\,M_\odot$ star.
- Errors for Run B based on independent classifications by first four co-authors.
- Run B consistently exhibits high fraction (≈ 50%) of spherical and unresolved morphologies, reproducing the observations.
- Run A, a model of isolated high-mass star formation, fails because its massive star grows quickly, forming a compact H II region early.
- Morphology statistics sensitive to the clustered nature of massive star formation, whose importance is discussed by Ref. [6].

Time Variability



- Massive star formation requires strong accretion flows.
- Gravitational instability causes clumping.
- While clumps accrete, they trap stellar ionizing radiation, and surrounding H II region recombines.
- Thus ultracompact H II regions flicker rather than growing steadily.
- H II regions remain ultracompact for entire accretion phase, far longer than predicted by steady growth, giving a solution to lifetime problem.
- Radio continuum morphology can change on recombination timescale ~ 10 yr (see Figure).
- Shrinking H II regions have been observed, with timescales in agreement with our prediction [2].
- Our models predict a 3.3% chance of a 10% flux decrement in 10 years, and a 1.5% chance of a 50% decrement [7].
- JVLA observations underway to confirm this prediction (De Pree et al. in prep.).

Spectral Energy Distributions



- Our H II region SEDs show both the expected slopes ($\alpha = 2$ in the optically thick and $\alpha = -0.1$ in the optically thin regime, left) as well as anomalous SEDs with a spectral slope $\alpha \approx 1$ over a wide range of frequencies (right). These anomalous SEDs are caused by density inhomogeneities (gradients and clumpiness) and not by additional dust emission.

Conclusions

Our simulations reproduce many of the observed features of ultracompact H II regions, including their morphologies, number statistics, time variability and spectral energy distributions. Most importantly, our simulations show that H II regions flicker during the accretion process, resolving the lifetime problem.

More information:

References

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