# Dynamics of Ultracompact H II Regions: Confronting Theory with Observations

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# Introduction

## Ultracompact H II Regions

- have diameters less than 0.1 pc and densities larger than $10^4\,\mathrm{cm}^{-3}$
- start expanding when the protostar reaches $\sim$10 $M_\odot$
- are forming while the massive star is still accreting
- are closely connected to high-mass star formation

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First 3D collapse simulations of massive star formation including ionizing radiation!

## Comparison with observations

H II regions around massive protostars can be observed!
$\rightarrow$ direct comparison with observations possible

# Link to Observations

Simulations show two distinctive differences to simple analytical models of H II regions:

- H II regions fluctuate ("flicker") on short timescales as long as powering star is accreting.
- Ionizing radiation drives molecular fountains ("outflows") perpendicular to accretion disk.

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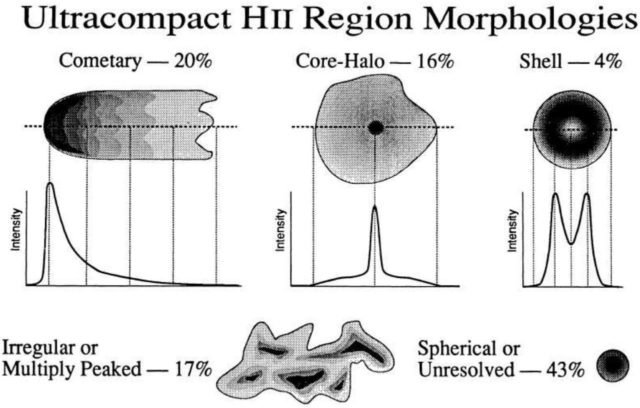
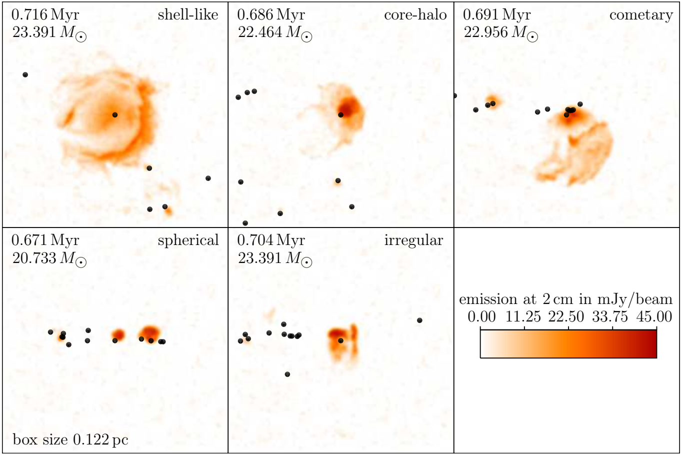
These effects can in principle be observed!
Post-process simulations to create mock observations to make observational predictions.

# Classification of UC H II Regions



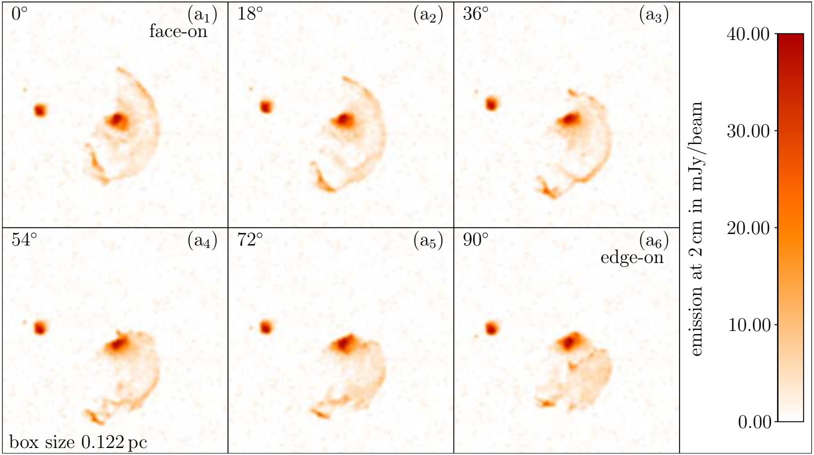

- Wood & Churchwell 1989 classification of UC H II regions
- Question: What is the origin of these morphologies?
- UC H II region lifetime problem: average sizes of regions inconsistent with Spitzer evolution, they are too small!

# H II Region Morphologies




- synthetic VLA observations at $2\,\mathrm{cm}$ of simulation data
- find all morphologies from surveys in single simulation
- morphology depends on snapshot and viewing angle

# H II Region Morphologies




- morphologies depend a lot on viewing angle
- example: shell morphology face-on turns into cometary morphology edge-on
- different behavior in each particular case

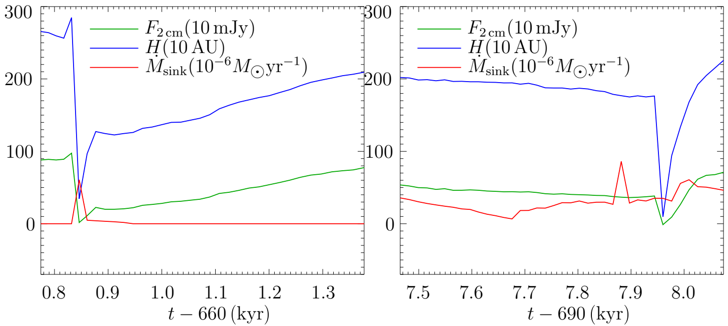
# H II Region Morphologies

| Type | WC89 | K94 | Run B |
|---|---|---|---|
| Spherical/Unresolved | 43 | 55 | $60 \pm 5$ |
| Cometary | 20 | 16 | $10 \pm 5$ |
| Core-halo | 16 | 9 | $4 \pm 2$ |
| Shell-like | 4 | 1 | $5 \pm 1$ |
| Irregular | 17 | 19 | $21 \pm 5$ |

WC89: Wood & Churchwell 1989, K94: Kurtz et al. 1994

- statistics over 25 simulation snapshots and 20 viewing angles
- quantitatively reproduce high fraction of spherical regions
- non-monotonic expansion of H II region during accretion phase
- flickering resolves the lifetime problem!

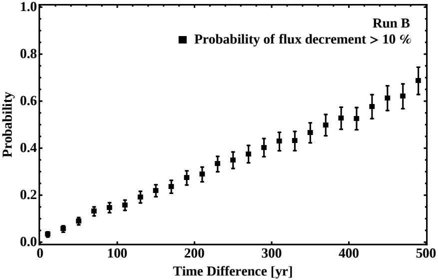
# Time Variability

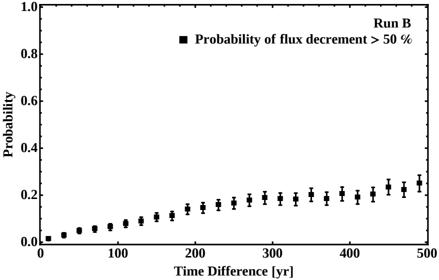



- correlation between accretion events and H II region changes
- time variations in size and flux have been observed
- changes of size and flux of $5$–$7\%\mathrm{yr}^{-1}$ match observations
  Hughes 1988, Franco-Hernández et al. 2004, Rodríguez et al. 2007, Galván-Madrid et al. 2008, Gómez et al. 2008
- flickering due to protostellar evolution too slow

  Klassen, TP and Pudritz, ApJ 758, 137 (2012)

# Short Term Variations




- re-run four time intervals at time resolution of $\approx 10$ yr with pair of negative/positive flux changes
- small decrements much more likely than large decrements
- for 20 years: 5% probability for 10% flux decrement
- this should make detection with repeated observations possible!

# Variability Test with Sgr B2

Sgr B2 is excellent candidate to test this prediction:

- 49 H II regions, 41 ultracompact
- VLA observations exist from 1989
- expect ∼1–4 shrinking regions and ∼4–7 growing regions

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Re-observation with EVLA in 2012 (23 years baseline) at 1.3 cm:

- 4 sources deviate by more than 10 times the RMS noise
- 3 sources (F10.303, F1 and F3) increase by 18, 5 and 6%
- 1 source (K3) decreases by 20%
- almost perfect agreement with predictions!

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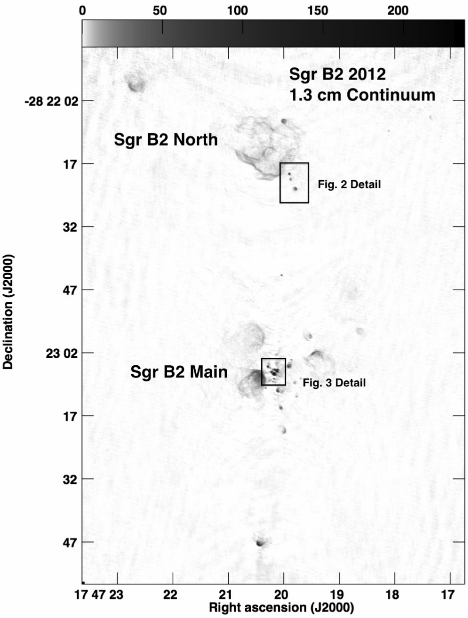


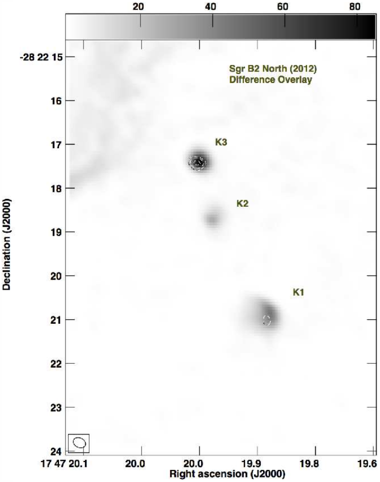


contours show difference between 1989 and 2012 data at $(1,1.4,2)\times 10\sigma$ level

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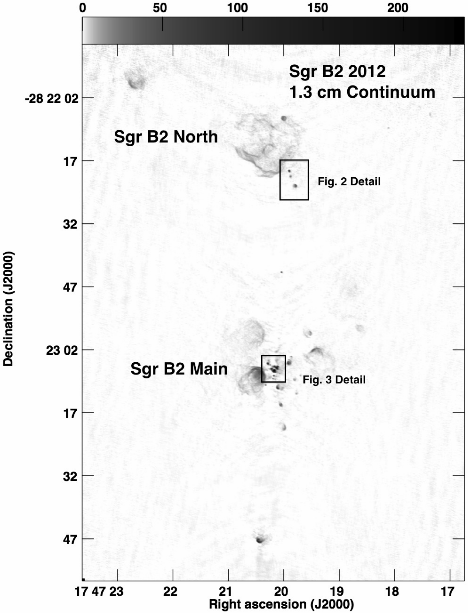


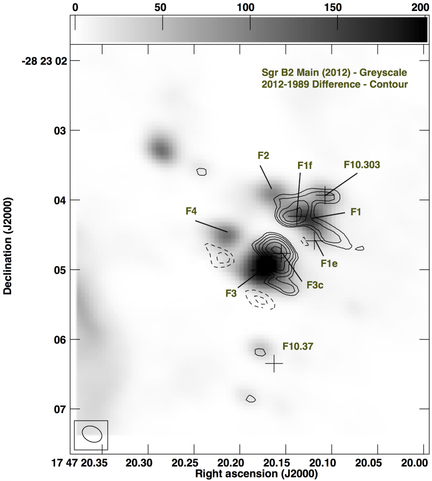


contours show difference between 1989 and 2012 data at (1,1.4,2,2.8,4,5.6)$\times 10\sigma$ level

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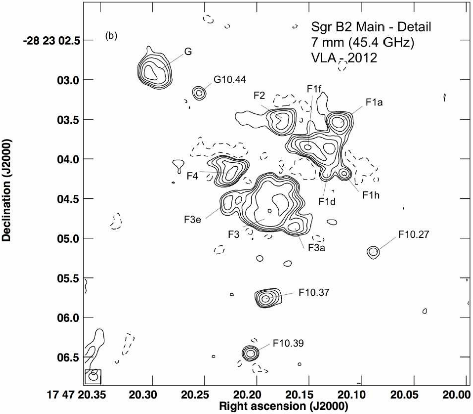


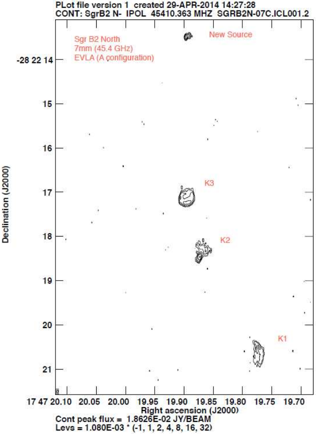


2012 EVLA observations at 7 mm can resolve H II region morphologies

# Variability Test with Sgr B2

- comparison with previous VLA observations of Sgr B2 Main (1997,2002) and Sgr B2 North (2001)
- new source detected in Sgr B2 North (K7)
- one source in Sgr B2 North (K2) drops between 2001 and 2012 by 40%
- one source in Sgr B2 Main (F3) steadily drops between 1997 and 2012 by 30%
- other sources constant at 10% errors
- reminder: K3 decreased by 20% and F3 increased by 6% between 1989 and 2012 at 1.3 cm!

# Variability Test with Sgr B2

Possible explanations:

- optical depth effects (?)
- variability at timescales of years (!)

K3 decreased from 1989 to 2001, remained constant until 2012
K2 increased from 1989 to 2001, decreased until 2012
F3 increased from 1989 to 1997, decreased until 2012

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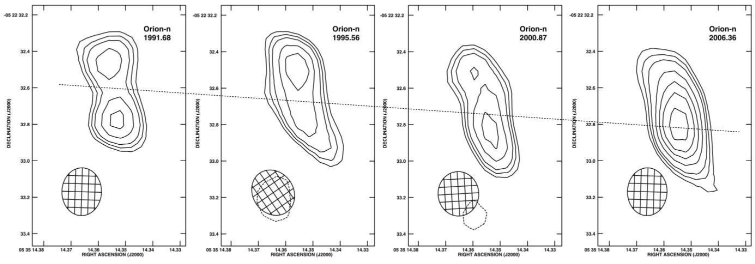
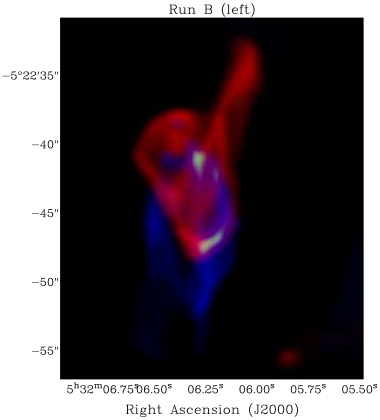
### Gómez et al. 2008: Orion-n



# Ionization-driven Molecular Outflows




- synthetic CO emission line ALMA maps
- mass, momentum and kinetic energy are relatively weak
- kinematic age of outflow is extremely young

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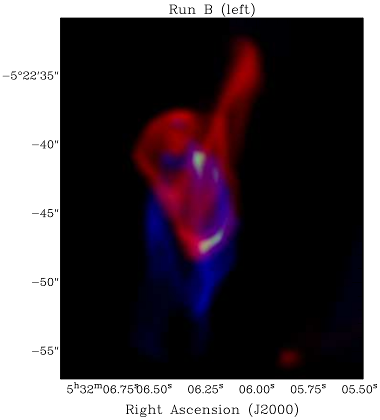


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If we want to see this effect, we have to scale up our region!

# Ionization-driven Molecular Outflow in K3-50A

K3-50A provides ideal conditions to look for ionization-driven molecular outflows:

- Driven by three $\sim 20\ M_{\odot}$ stars (Okamoto et al. 2003).
- Has 8 $M_{\odot}$ of ionized gas (13 times the simulation)!
- Envelope mass of 2200 $M_{\odot}$.
- More centrally condensed, stronger infall.
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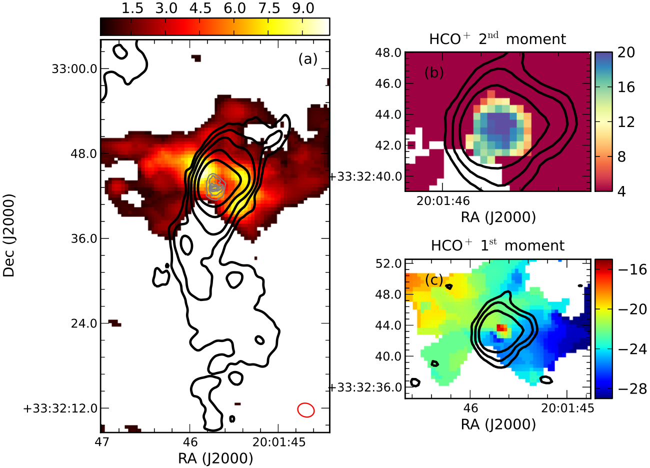
Observations:

- CARMA: 90GHz continuum, $HCO^+$ ($J = 1 - 0$, 89.19 GHz), H41$\alpha$ (92.03 GHz)
- VLA: 23 GHz and 14.7 GHz continuum

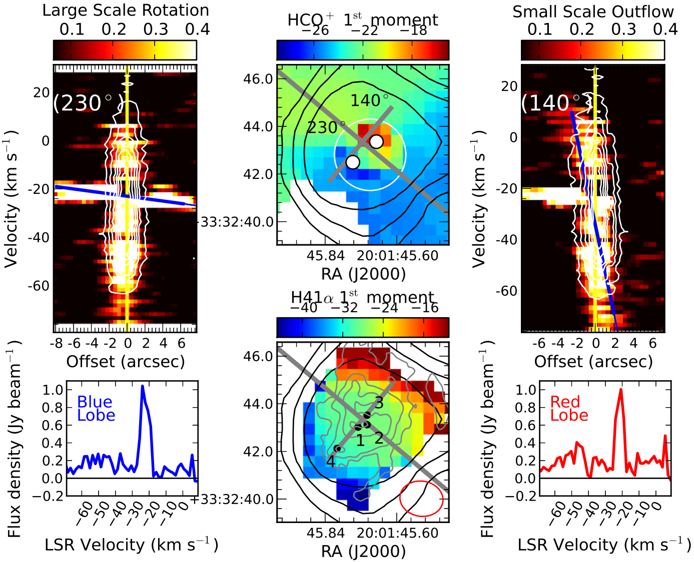
HCO$^+$ integrated intensity and moment maps




black/gray contours:
14.7/23 GHz continuum

black contours:
90 GHz continuum

# Zoom-in on H II Region




molecular: colorscale, ionized: contours

# K3-50A outflow properties compared to other sources

| Source | $L_{Bol}$ | SiO | Molecular Outflow Properties | | |
|---|---|---|---|---|---|
| | | detection | Mass | Momentum | Energy |
| | ($10^6$ $L_\odot$) | (Y/N) | ($M_\odot$) | ($M_\odot$ km $s^{-1}$) | ($10^{45}$ erg) |
| K3-50A | 2 | $Y^{a,b,d}$ | 4.6 | 28 | 1.65 |
| G10.60−0.40 | $1.1^c$ | $Y^d$ | $90^c$ | $670^c$ | $50^c$ |
| G10.47+0.03 | $1.4^c$ | $Y^{a,d}$ | $150^c$ | $1110^c$ | $81^c$ |
| G48.61+0.02 | $1.3^c$ | $Y^e$ | $590^c$ | $2550^c$ | $118^c$ |
| G19.61−0.23 | $1.7^c$ | $Y^d$ | $200^c$ | $1740^c$ | $150^c$ |

[a] Klaassen & Wilson 2007, [b] Howard et al. 1997, [c] López-Sepulcre et al. 2009, [d] Klaassen & Wilson 2008, [e] Klaassen et al. 2012

Outflow in K3-50A tiny compared to other sources of similar $L_{Bol}$!

# Conclusions

- Simulations reproduce H II region morphologies and number statistics.
- H II regions highly variable in time.
- Flickering resolves the lifetime problem.
- Time dependence caused by accretion process.
- This explains time variability of individual sources.
- Statistical predictions verified in Sgr B2.
- Ionization-driven molecular outflow found in K3-50A.