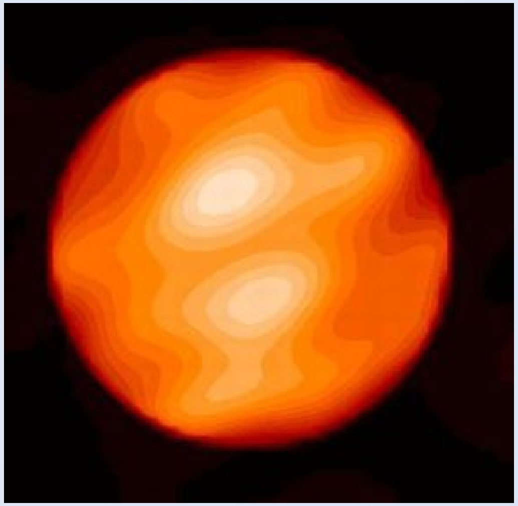
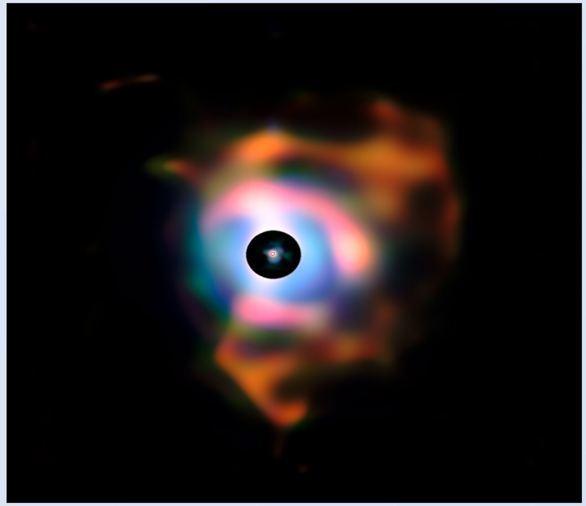


Credit: Haubois/Perrin



Credit: ESO

Credit: CARMA

CO in the Circumstellar Envelope of Betelgeuse with CARMA

Eamon O’Gorman
Trinity College Dublin

YERAC
University of Manchester, July 18th 2011

Overview

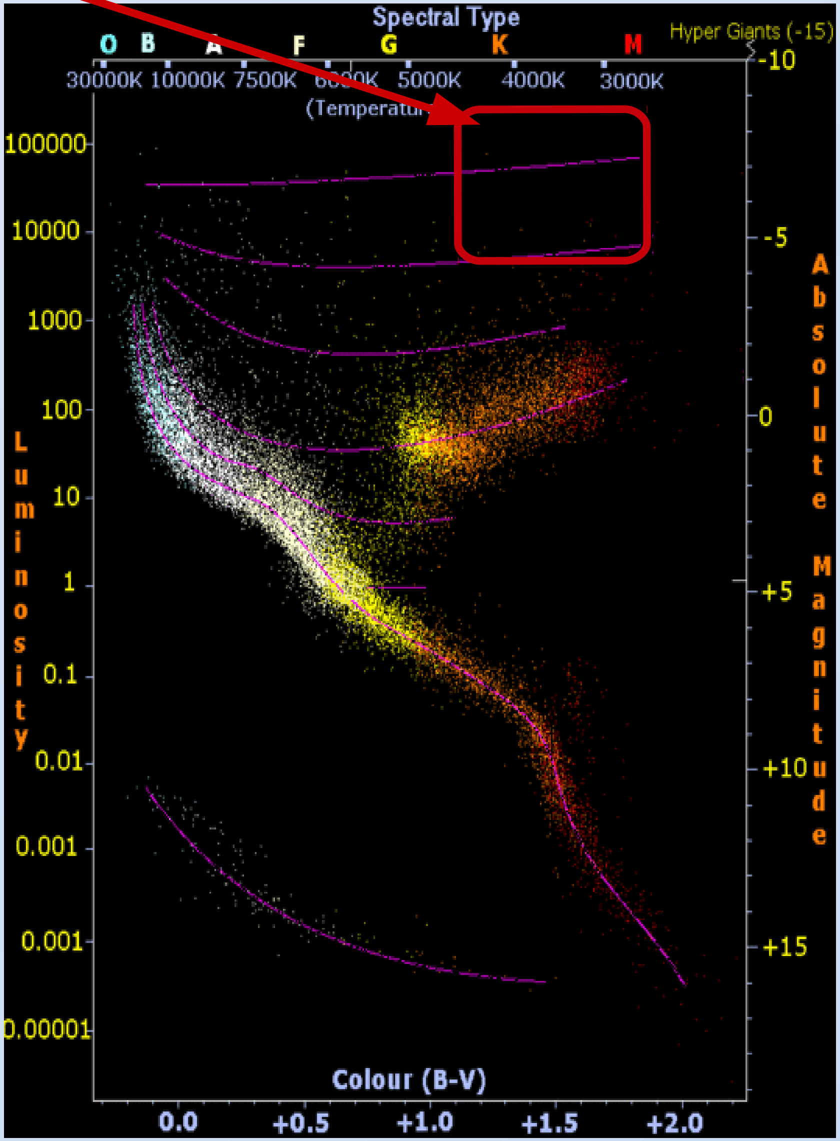
- Red Supergiants & Betelgeuse
- The Circumstellar Environment (CSE) of Betelgeuse
- CARMA & Observations
- Results
- Summary

Red Supergiants (RSGs)

- Supergiant stars (luminosity class I) of spectral type K or M.

- Evolved stars with (Levesque et al. 2005):
  - $10\ M_{\odot} \leq M \leq 40\ M_{\odot}$.
  - $3{,}450\ K \leq T_e \leq 4{,}100\ K$ (i.e. M5 -> K1)
  - $2{,}000\ L_{\odot} \leq L \leq 300{,}000\ L_{\odot}$
  - Radii up to $1500\ R_{\odot}$!

- Mass loss occurs via a slow stellar wind and rates are substantial ($10^{-4} – 10^{-6}\ M_{\odot}\ yr^{-1}$).



Credit: Richard Powell based on data Hipparcos Catalog and Gliese Catalog

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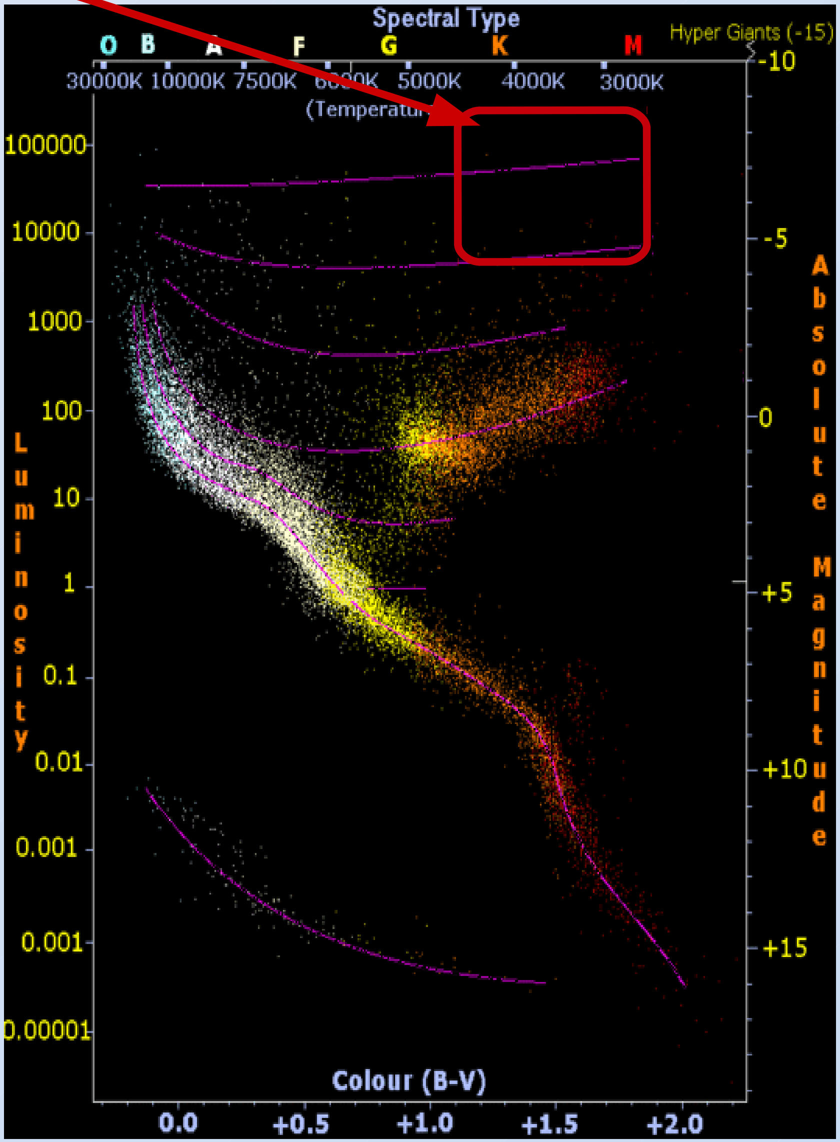
  - Radii up to 1500 $R_\odot$!

- Mass loss occurs via a slow stellar wind and rates are substantial ($10^{-4} – 10^{-6}\ M_\odot\ yr^{-1}$).

- **Importance:**
  (a) Enrich the interstellar medium with material for the next generation of stars and planets.

  (b) Mass loss can alter the evolutionary fate of a star.

- Mass loss mechanism for AGB stars (pulsation + radiation pressure on dust grains) is **unlikely** to be applicable for RSGs.



Credit: Richard Powell based on data Hipparcos Catalog and Gliese Catalog

Betelgeuse: Quick Facts

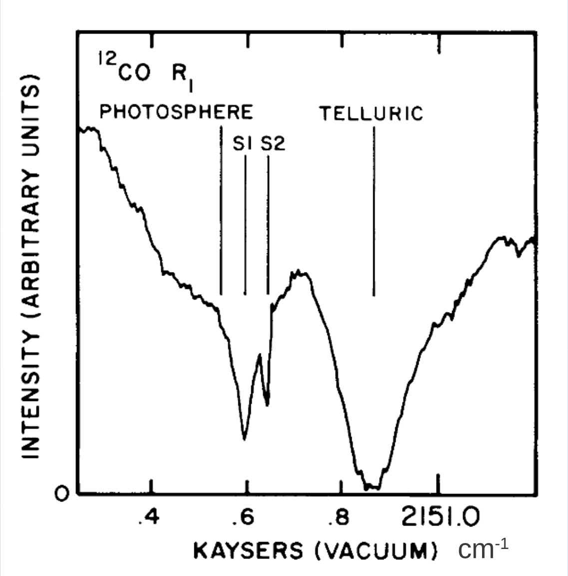
Credit: STScI, NASA

Spectral Type	M2 Iab
Radial Velocity	20.7 km s^{-1}
$Log(L/L_{\odot})$	5.12
Distance	197 ± 45 parsec
Mass (birth)	~20 $M_{\odot}$
Mass (current)	~18 $M_{\odot}$
Mass loss rate	3×10^{-6} $M_{\odot}$ yr^{-1}
Period	17 years
Photospheric Radius	22.5 mas (645 $R_{\odot}$)
Photospheric Temperature	3,600 K (cool star)
Origin	O-type main sequence
Fate	Supernova Type II

The CSE of Betelgeuse

- At least two different mass loss phase in the last 300 yr.

- Two distinct shells spectrally resolved in 4.6 μm $^{12}C^{16}O$ absorption spectra (Bernat et al., 1979):
  - A fast, low column outer shell, S2, moving at 17 km s^{-1}
  - A slower, high column inner shell, S1, moving at 10 km s^{-1}
  - Spatial extent not directly determined



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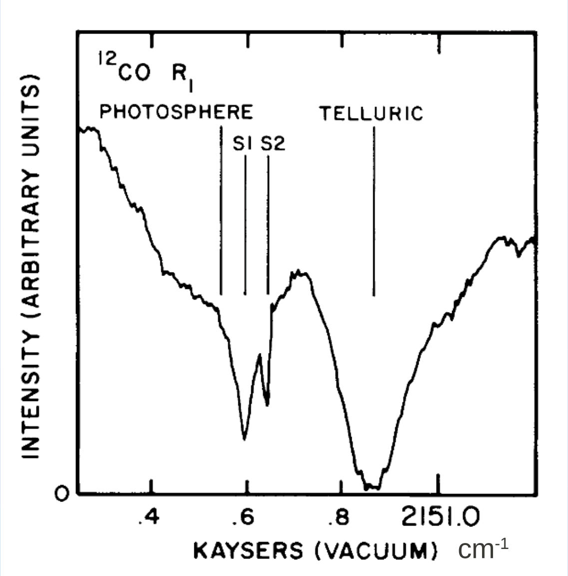

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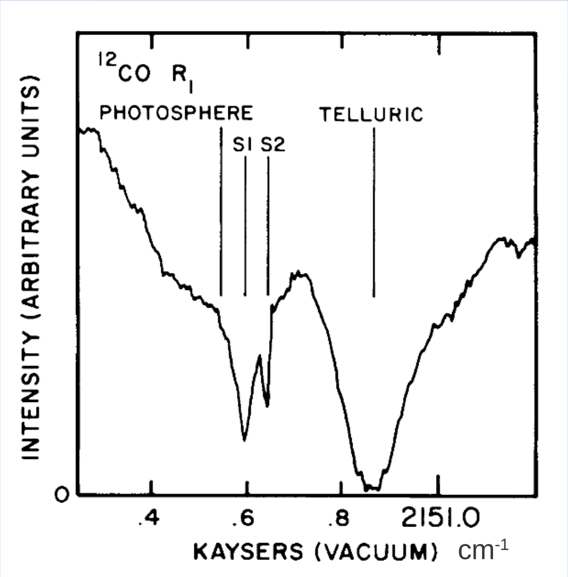
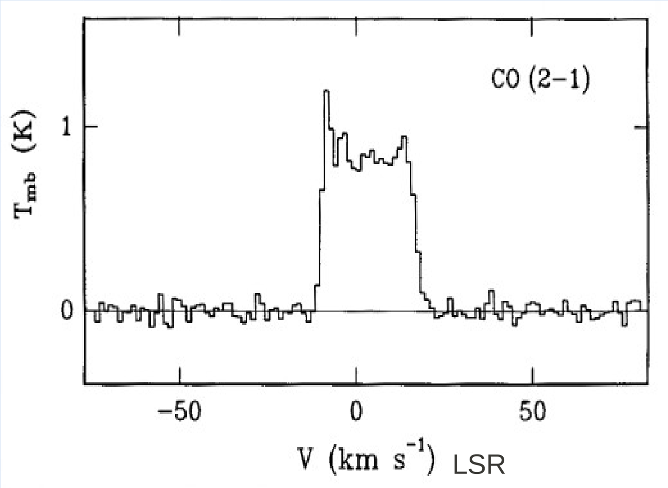
- IRAM 30 m telescope (beam size ~12") fails to resolve S2 shell (Cernicharo & Bachiller, 1993) at 1.3 mm (i.e. $^{12}C^{16}O$).

- Single dish $^{12}C^{16}O$ mm-observations reveal only high velocity S2 shell.

- Signature of S1 shell not obvious at millimeter wavelengths.





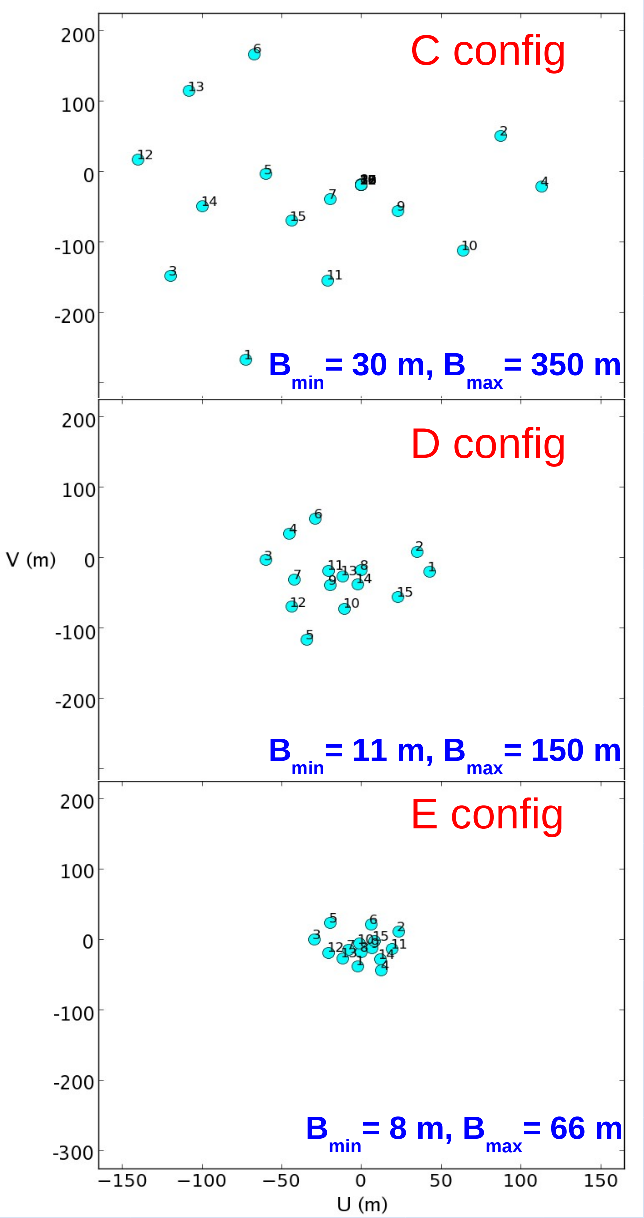
Goal: *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

CARMA

- **C**ombined **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy
- 15 element interferometer (9 x 6.1 m + 6 x 10.4 m antennas)
- Cedar Flat, eastern California (~ 2,200 m)
- Merger of two independent arrays: BIMA + OVRO (2007)
- 105 baselines (n(n-1)/2) with 5 configurations (B_{min} = 8 m and B_{max} = 2 km)
- Three bands: 7 mm, 3 mm and 1.3 mm

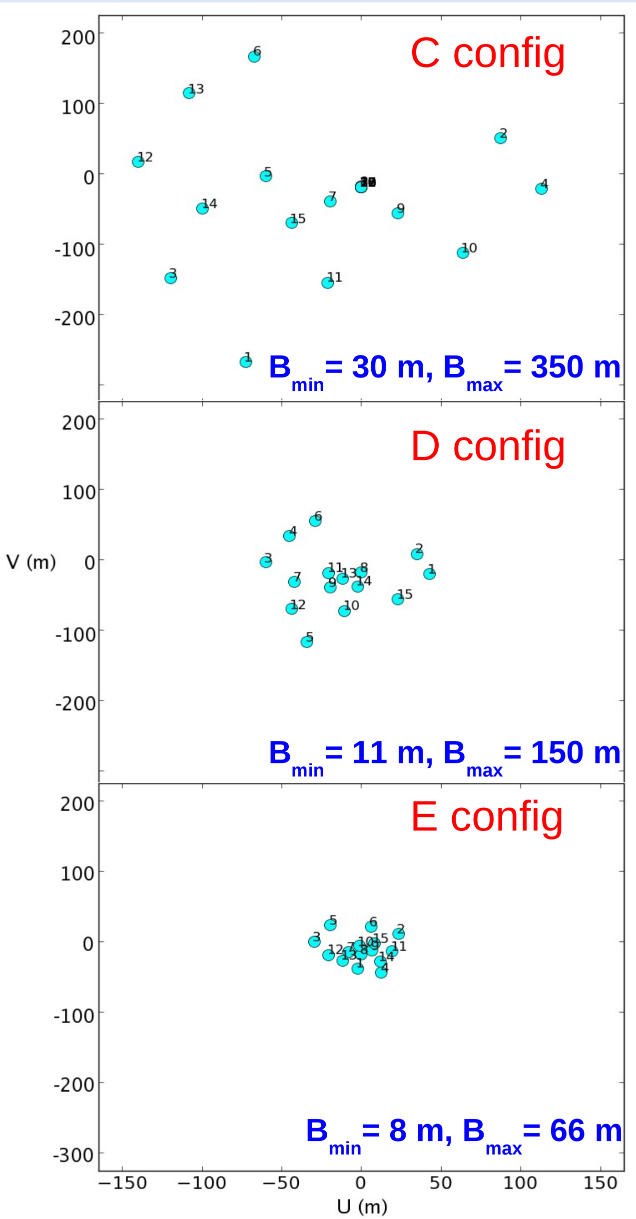
Credit: 2009 John Carlstrom

CARMA Observations



Date	Config	Tracks	Time (hr)	Resolution ('')	Max Scale ('')
Jun 07	D	5	9.5	1.8	24.4
Jul 09	E	1	3.25	4.0	33.5
Nov 09	C	5	8.75	0.8	8.9

CARMA Observations



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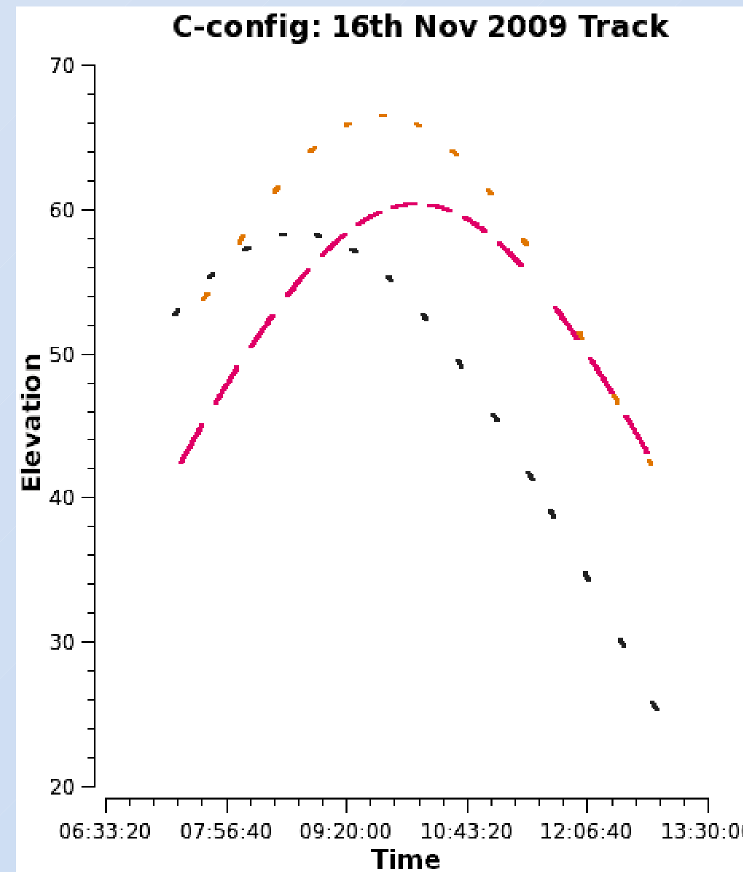
3 separate bands: All centered on line

(1) Maximum bandwidth of 468 MHz (15 channels)

(2) 62 MHz of bandwidth across 63 channels (1 MHz or 1.3 km s^{-1} resolution)

(3) 31 MHz of bandwidth across 63 channels (0.5 MHz or 0.65 km s^{-1} resolution)



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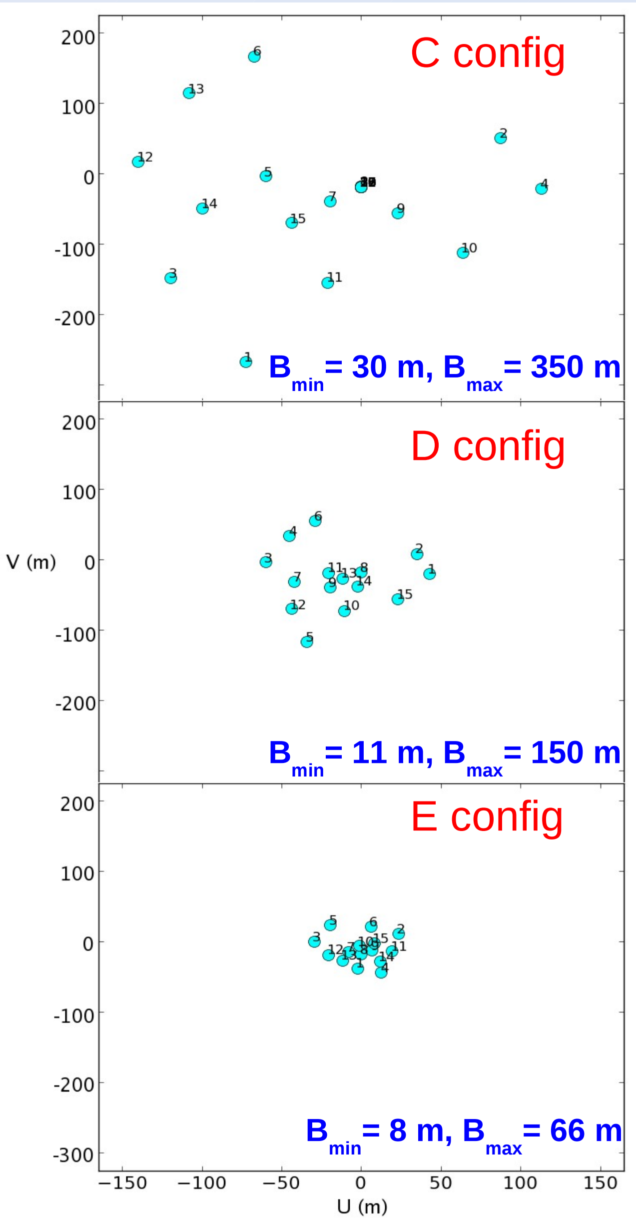

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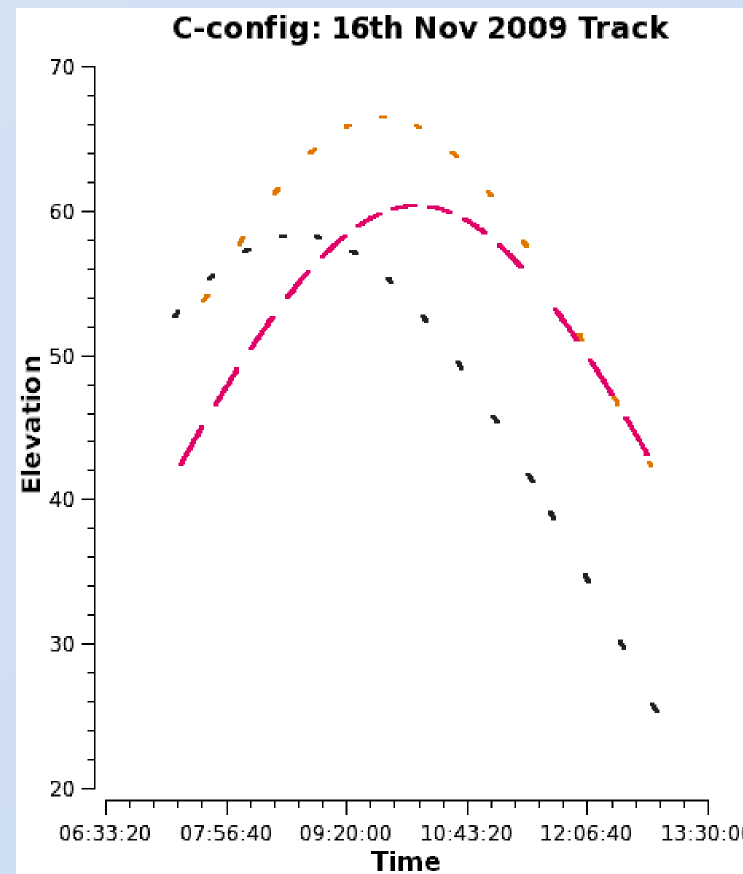
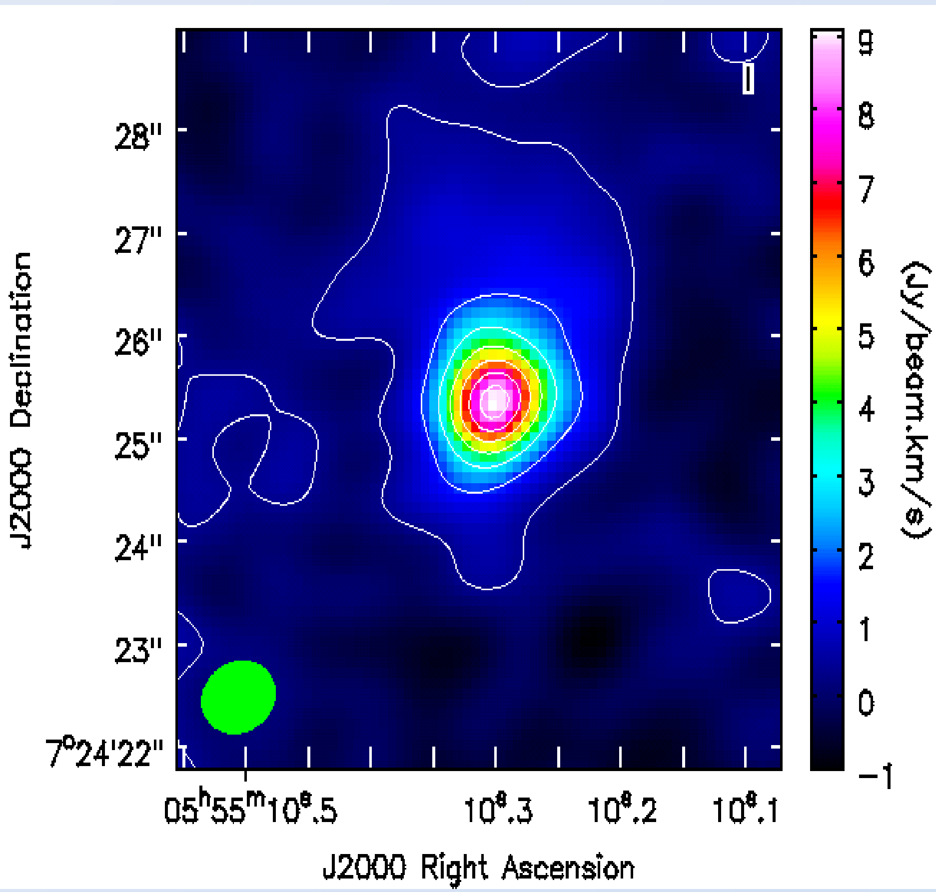
Calibration and imaging done using the CASA data reduction package.



Results: Individual Configurations

C Configuration (i.e. most extended)



Integrated intensity map

Full width ~ 22 km s^{-1}

3 seperate features

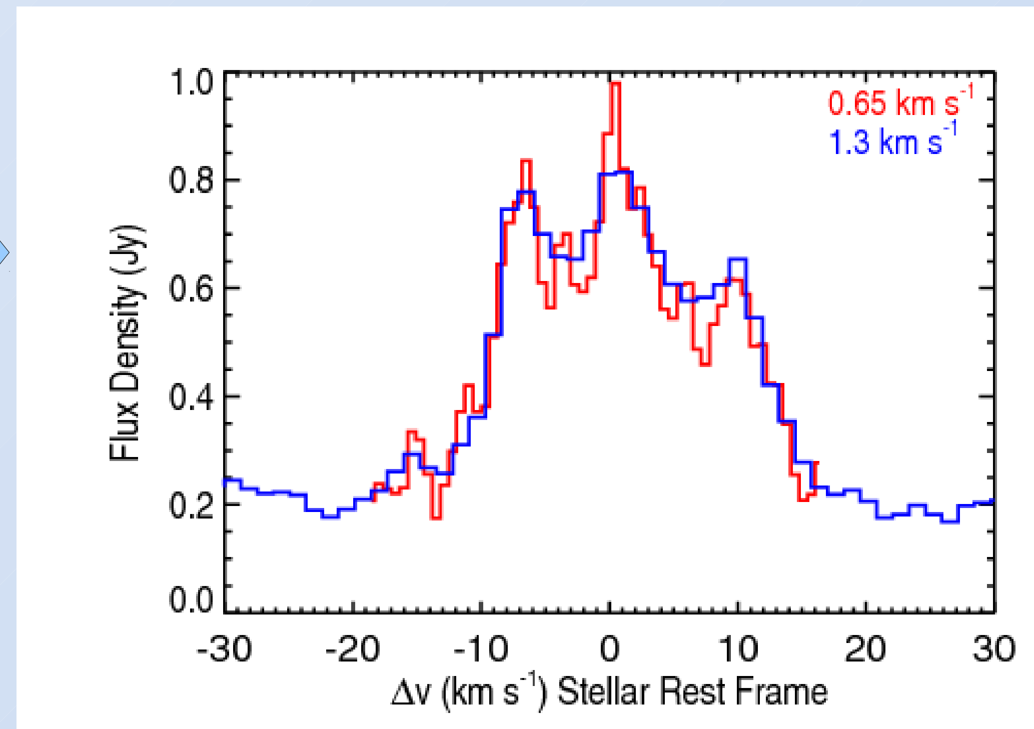
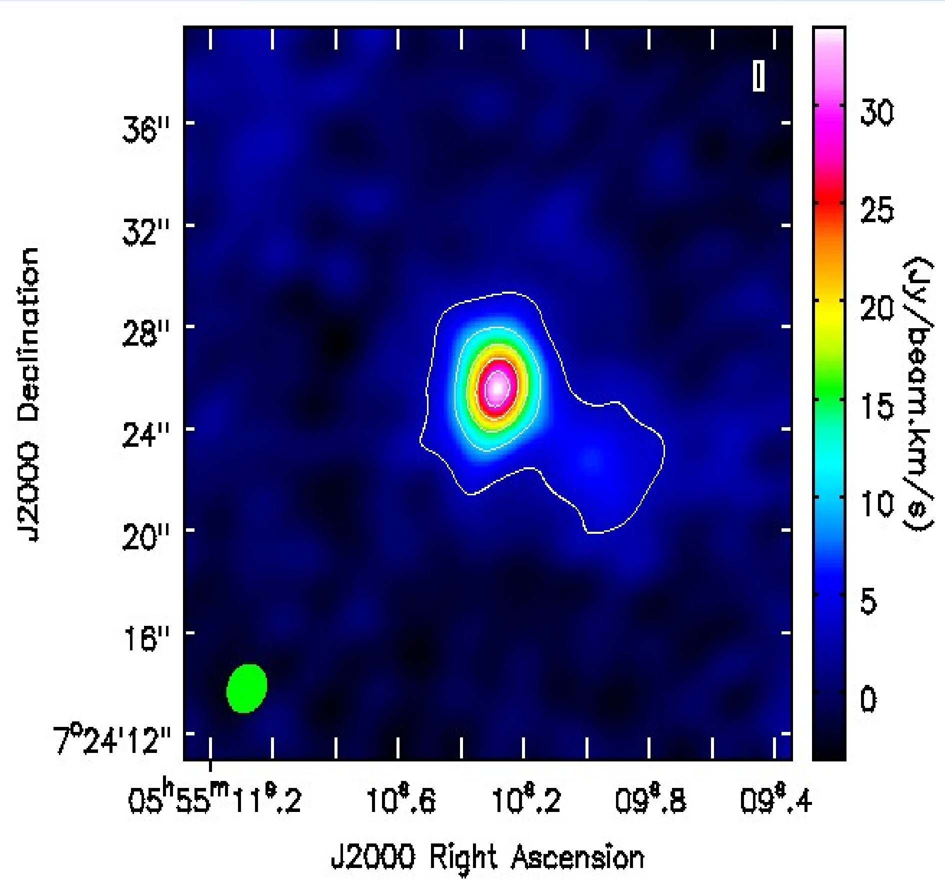


Image Cube Spectrum

Results: Individual Configurations

D Configuration (i.e. middle)



Integrated intensity map

4 seperate features

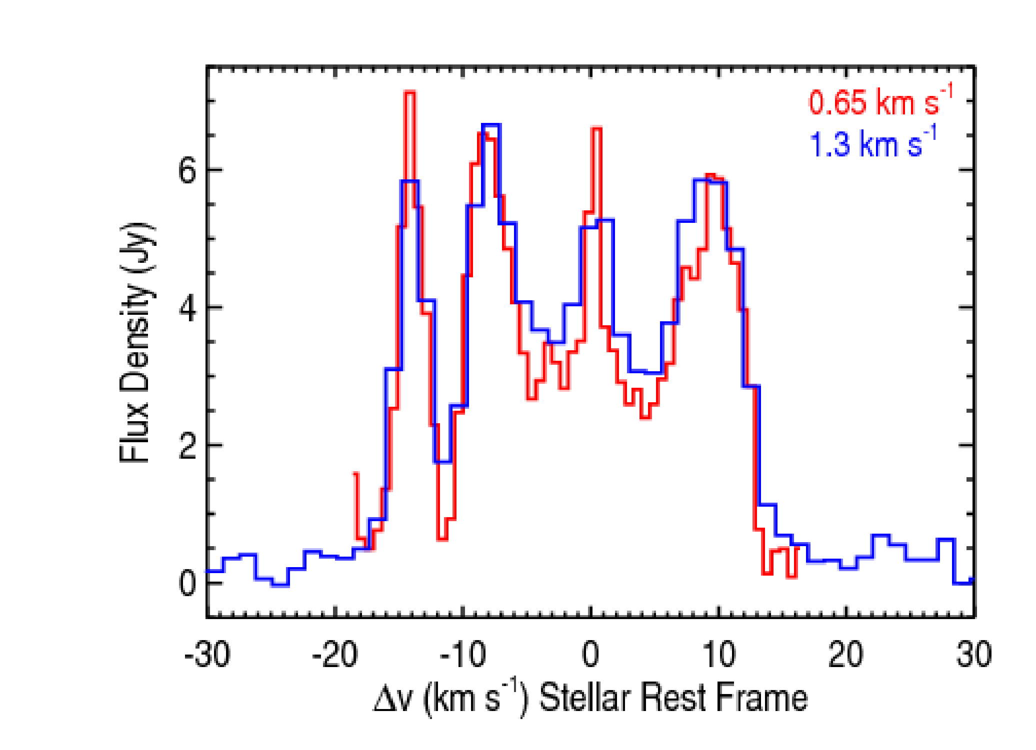
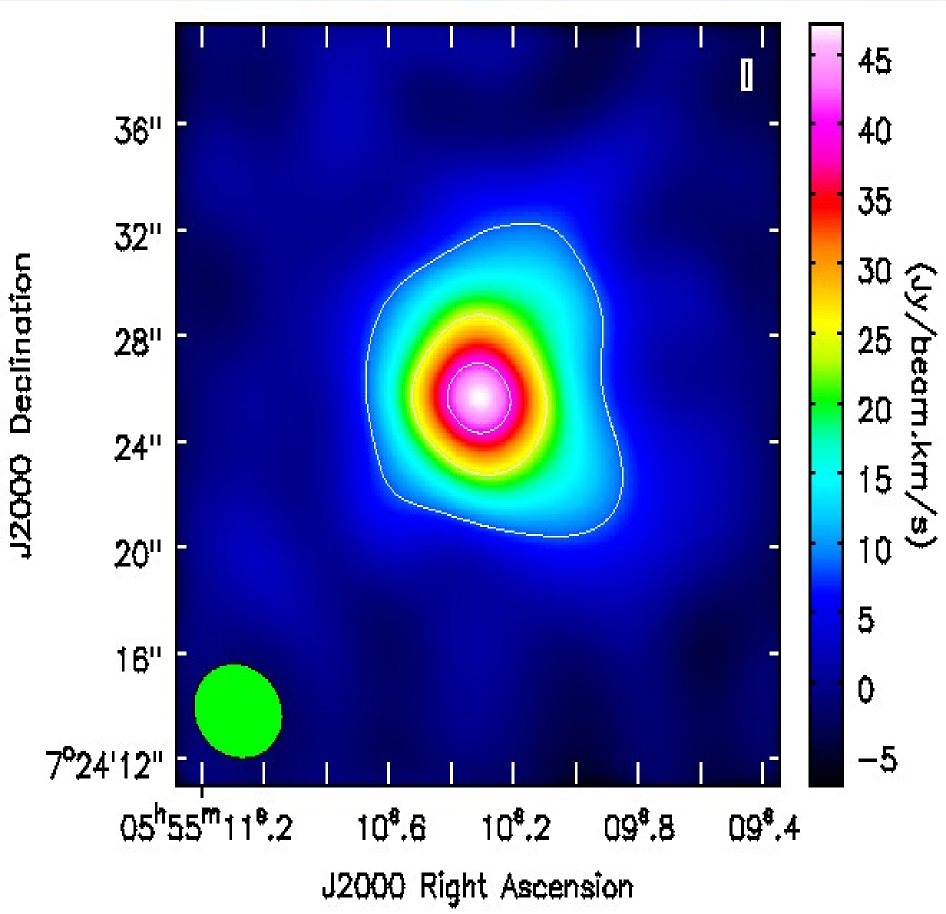


Image Cube Spectrum

Results: Individual Configurations

E Configuration (i.e. most compact)



Integrated intensity map

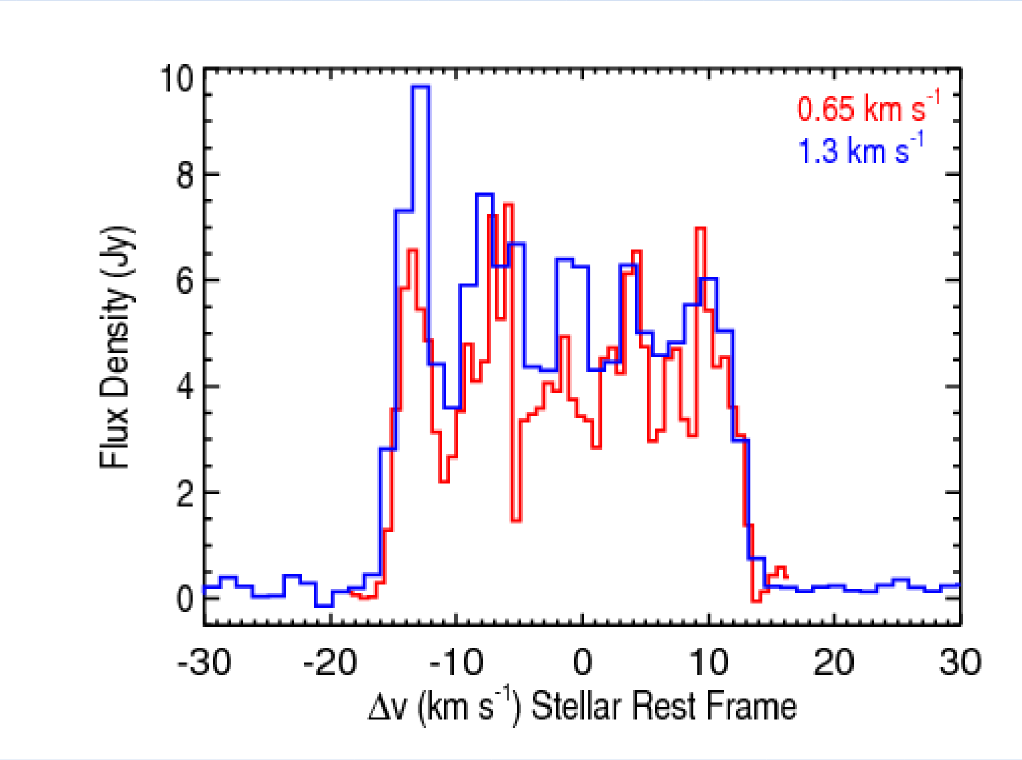
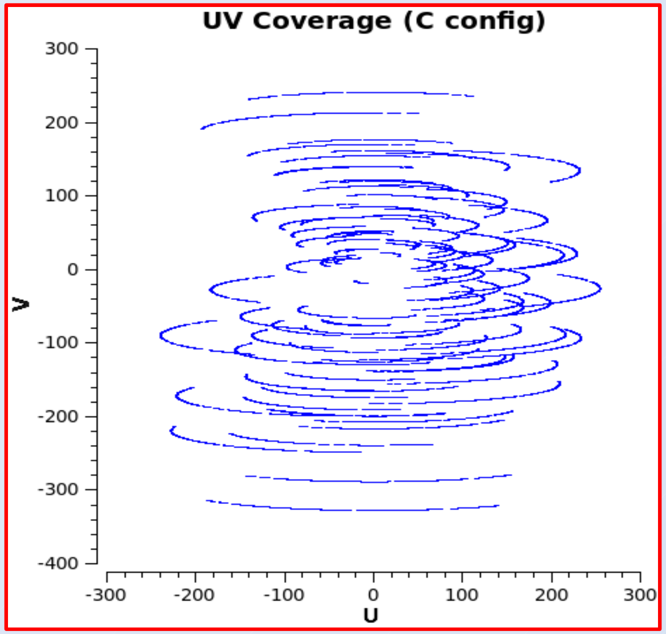
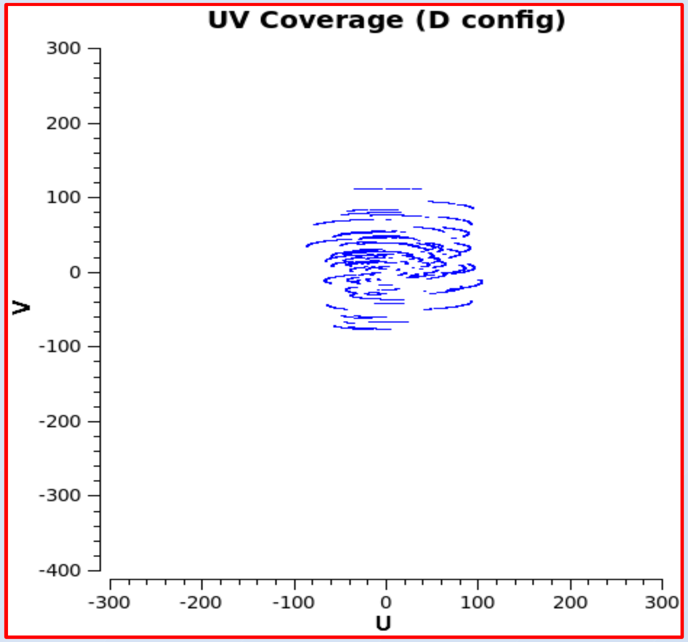
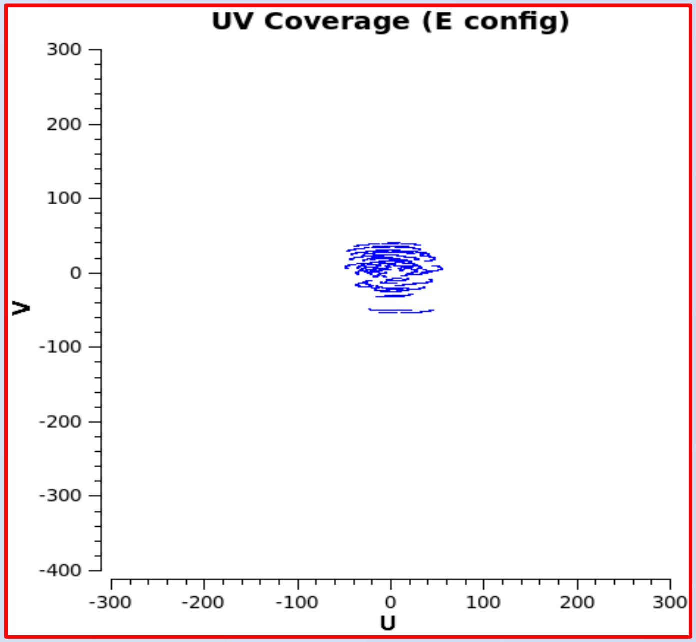


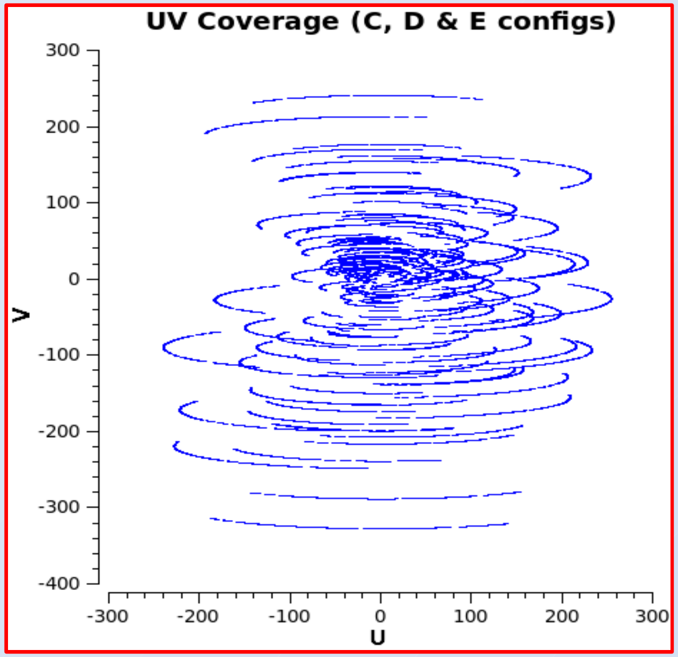
Image Cube Spectrum

Combining Configurations



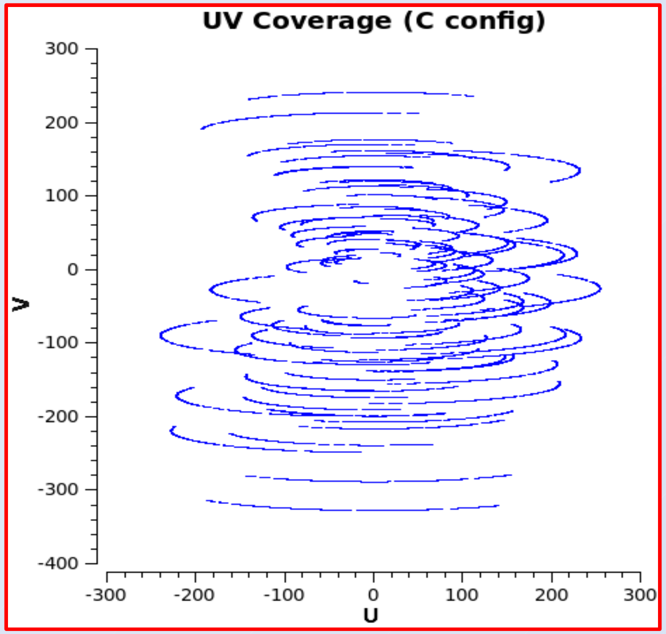


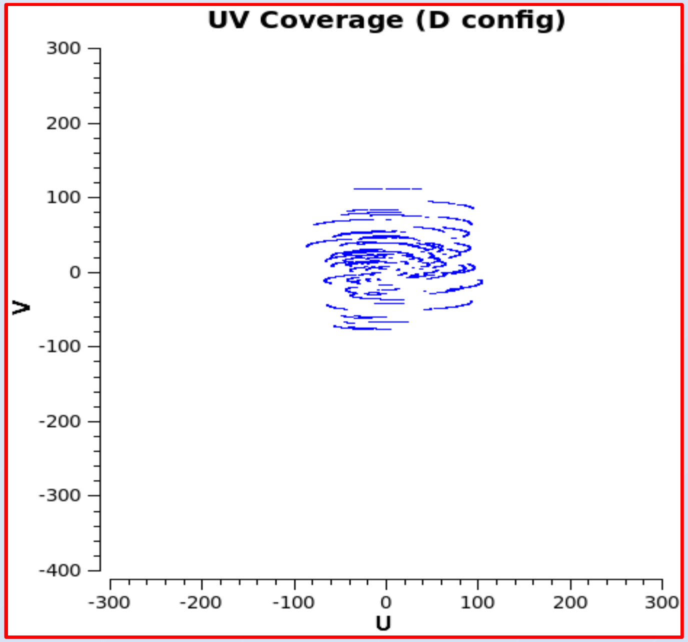


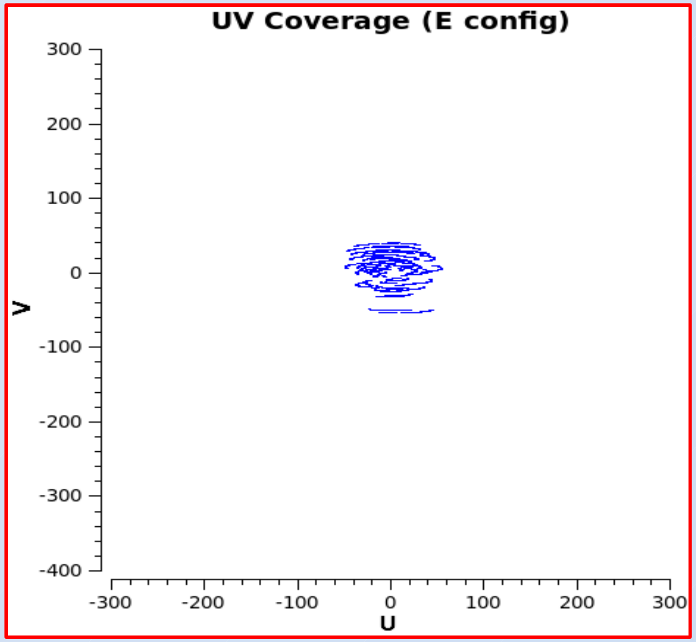


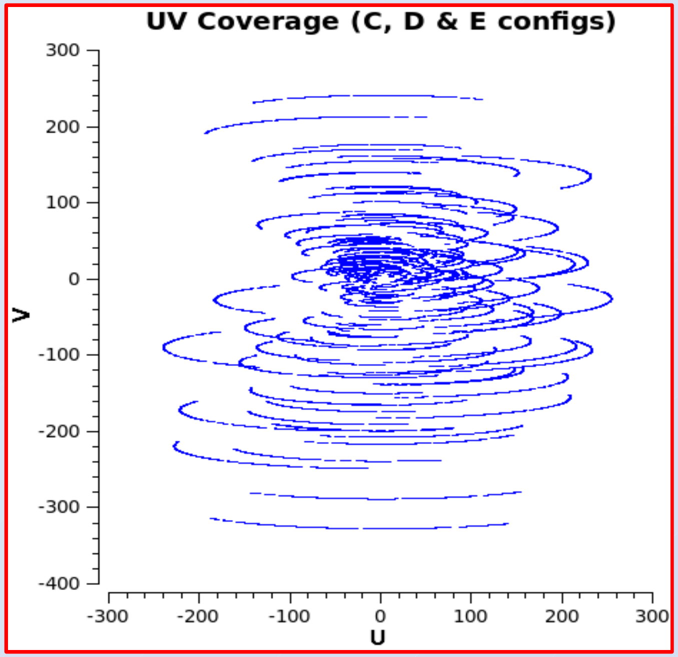
Increase uv-coverage

Combining Configurations





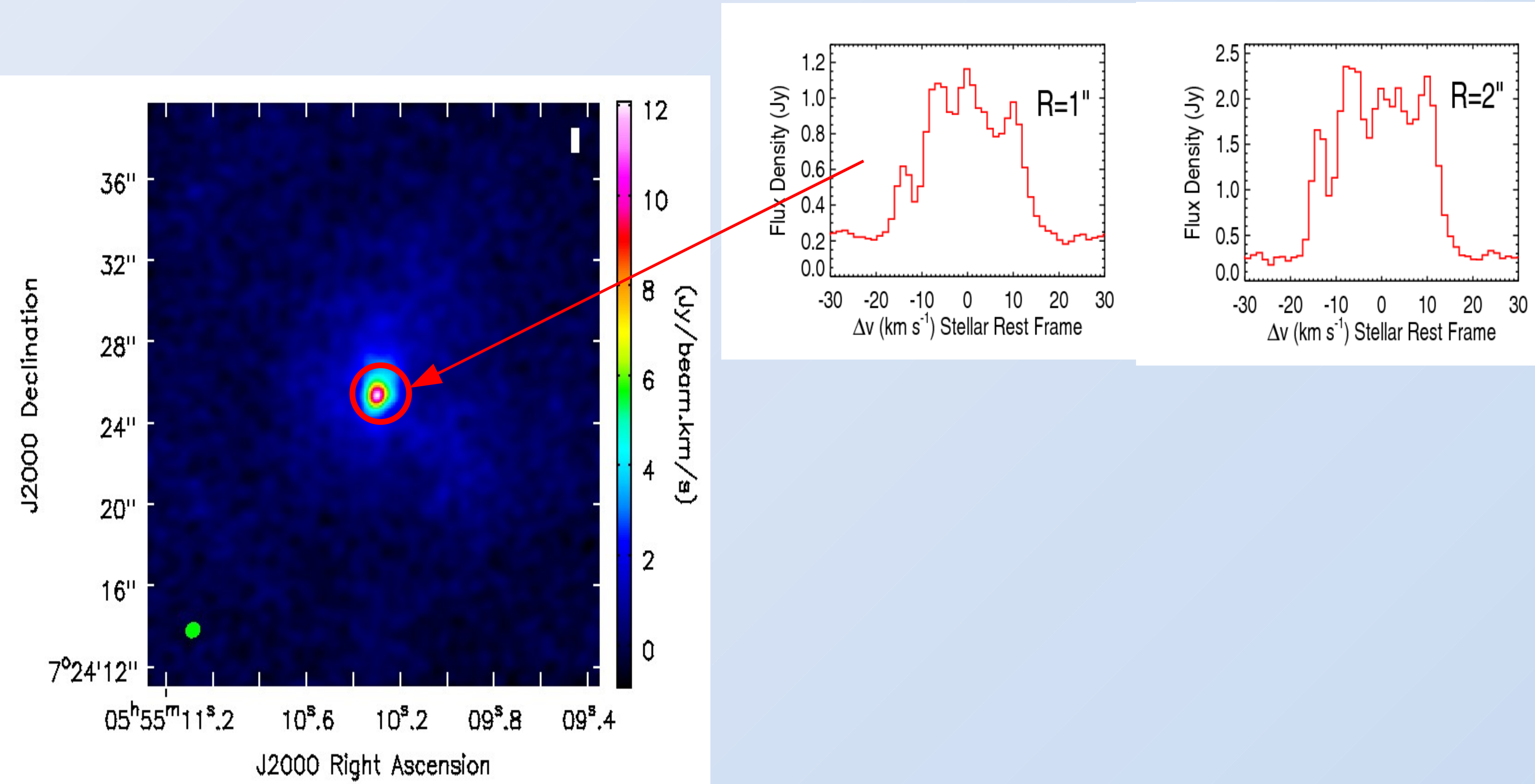




Increase uv-coverage and S/N

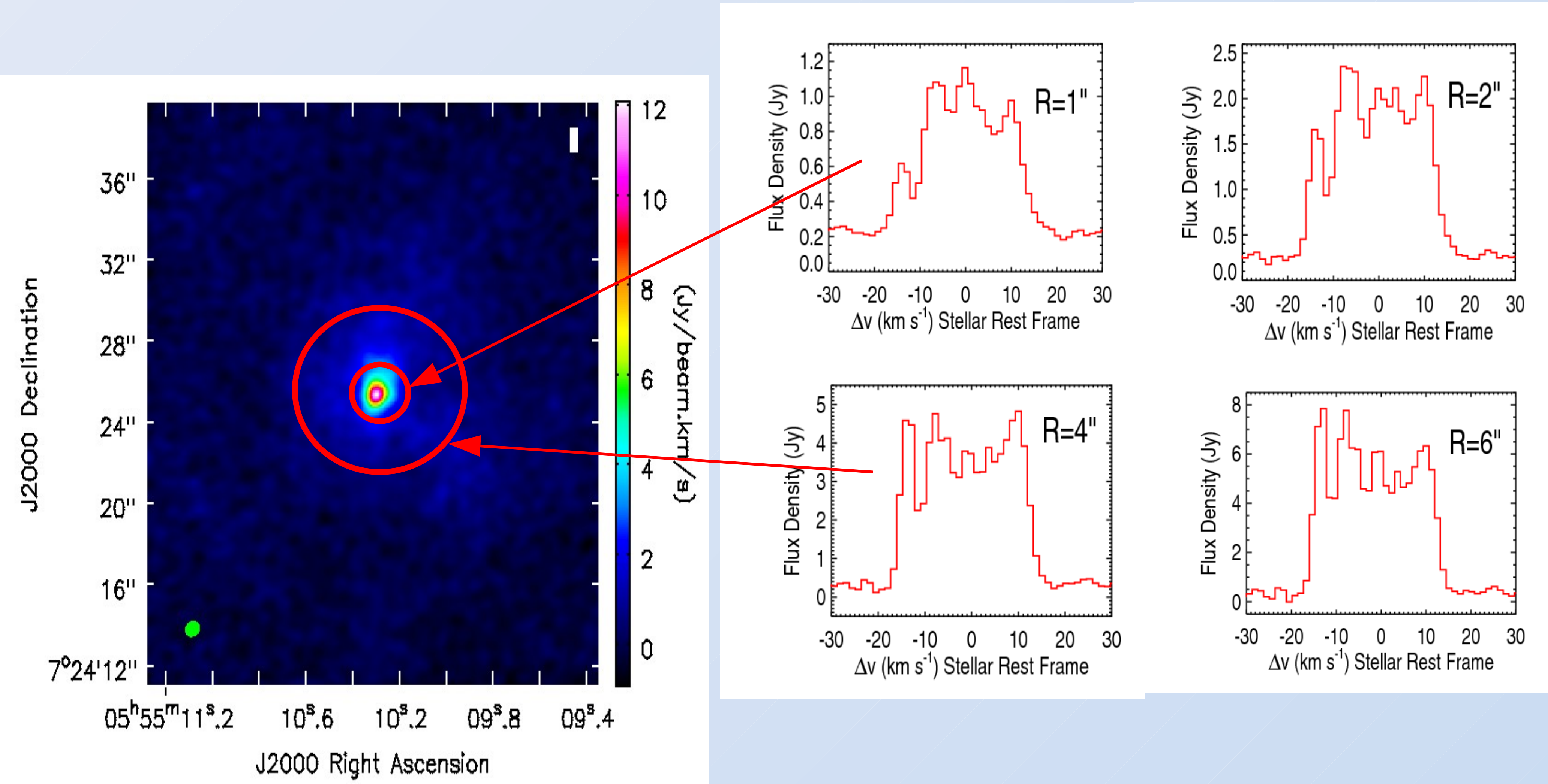
Config	S/N (1.3 km s^{-1})	S/N (0.65 km s^{-1})
C	24	18
D	23.5	21.5
E	21.5	13.5
Combined	33	24

Results: Combined Configurations



Integrated intensity map

Results: Combined Configurations



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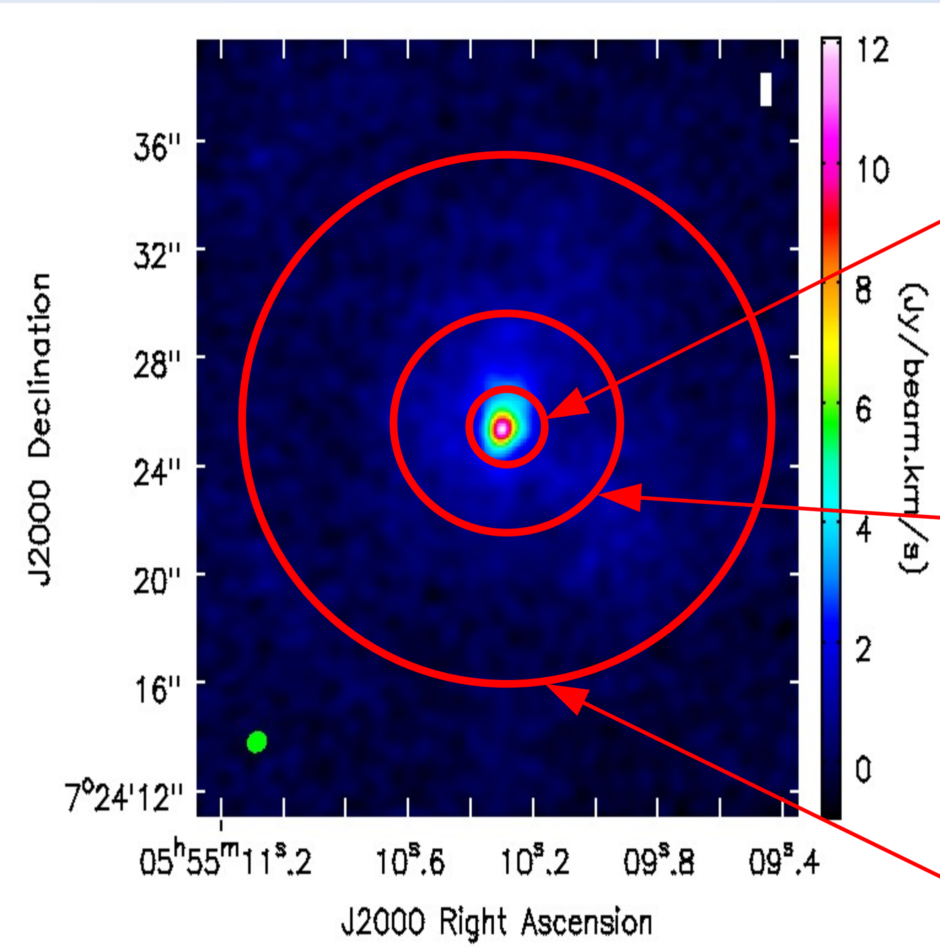


Integrated intensity map

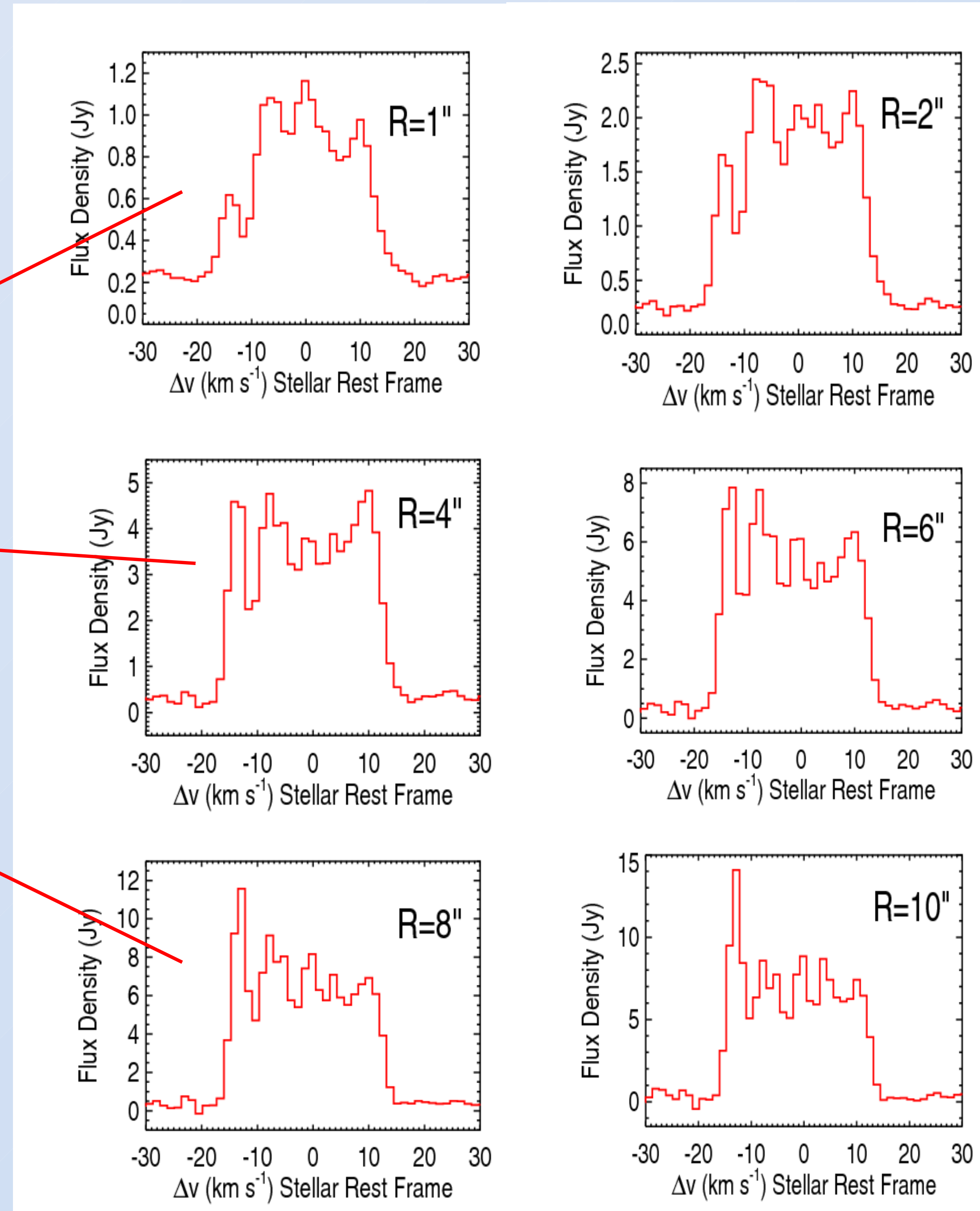
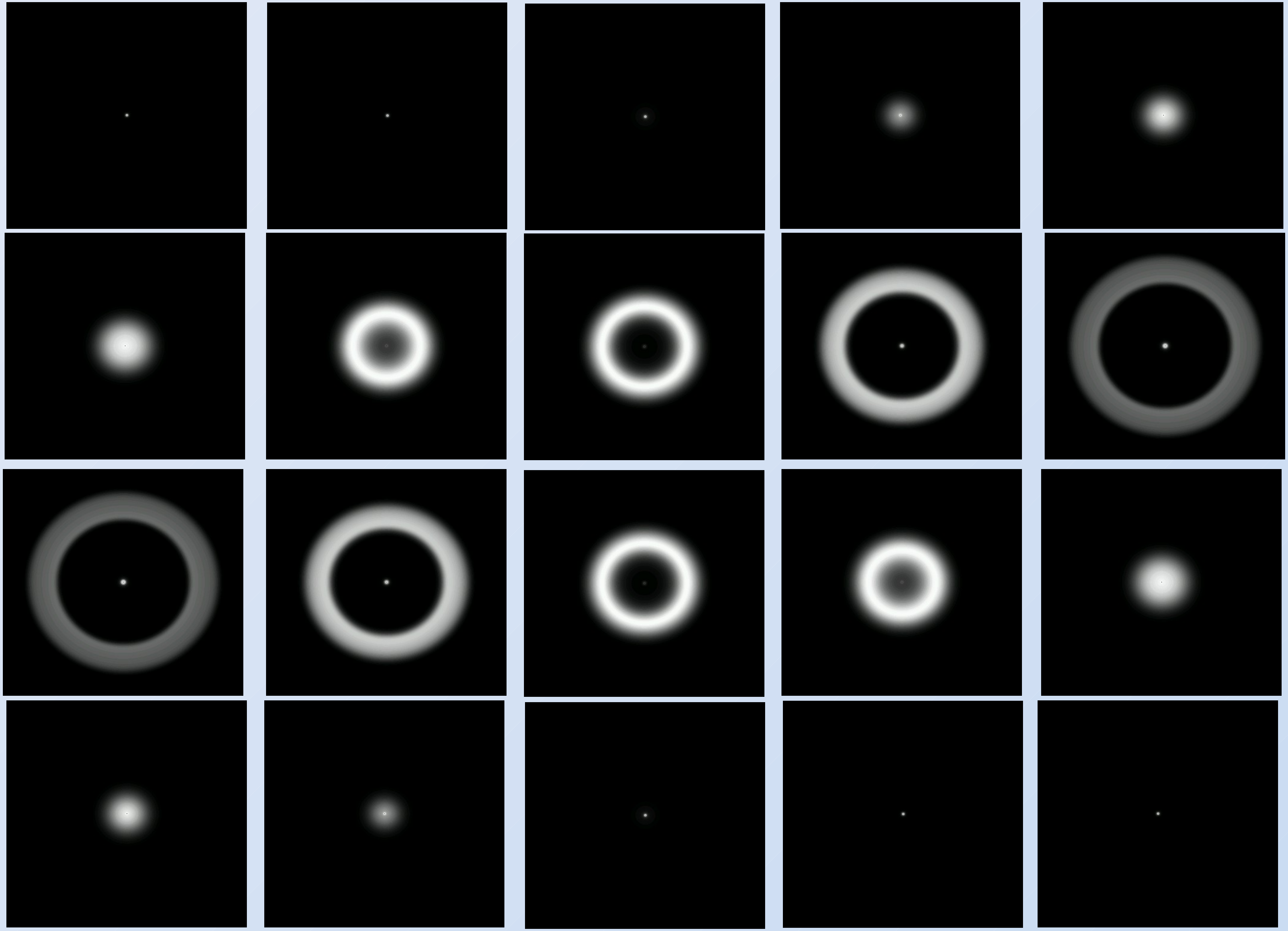


Image Cube Simulation



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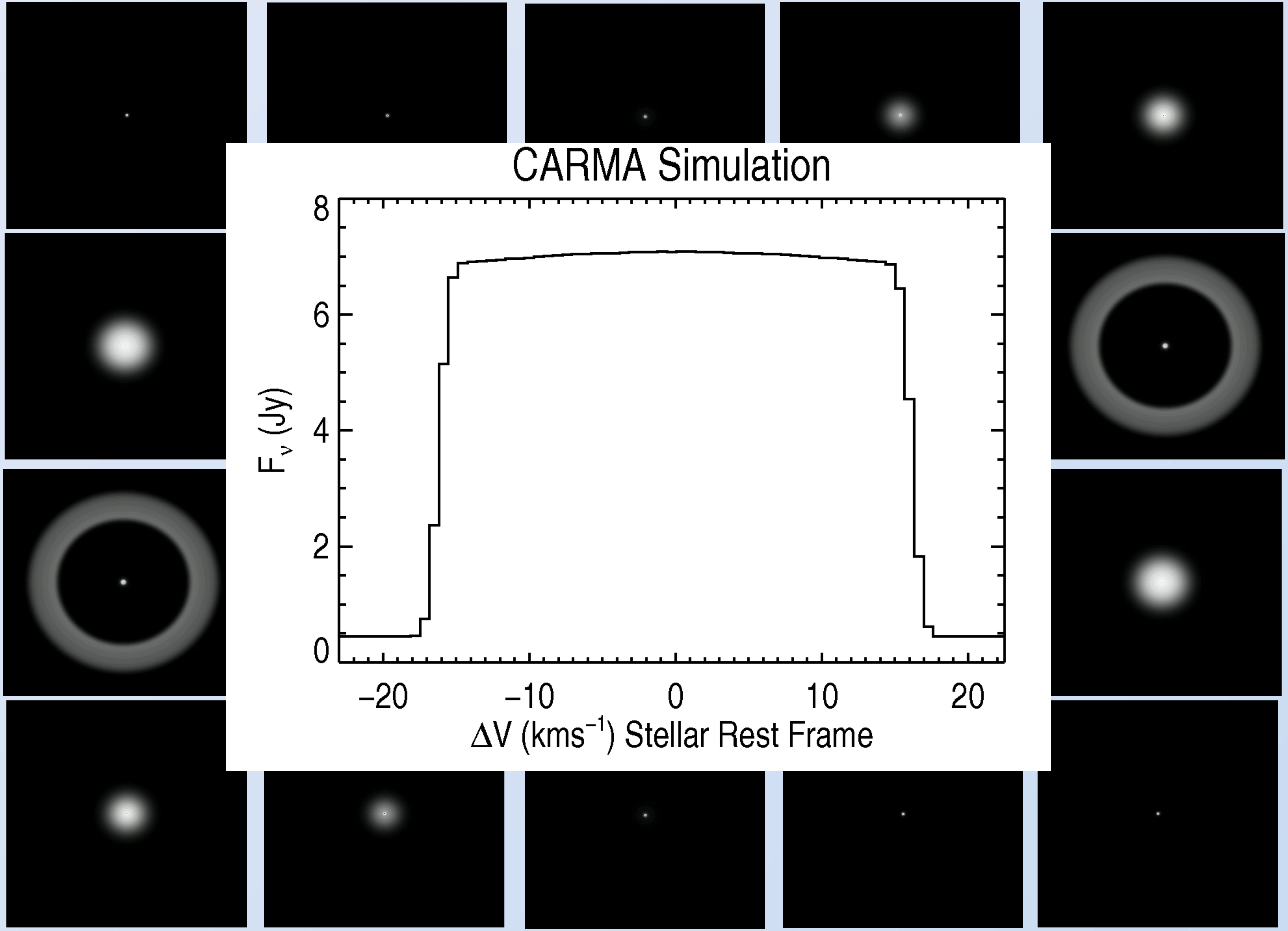

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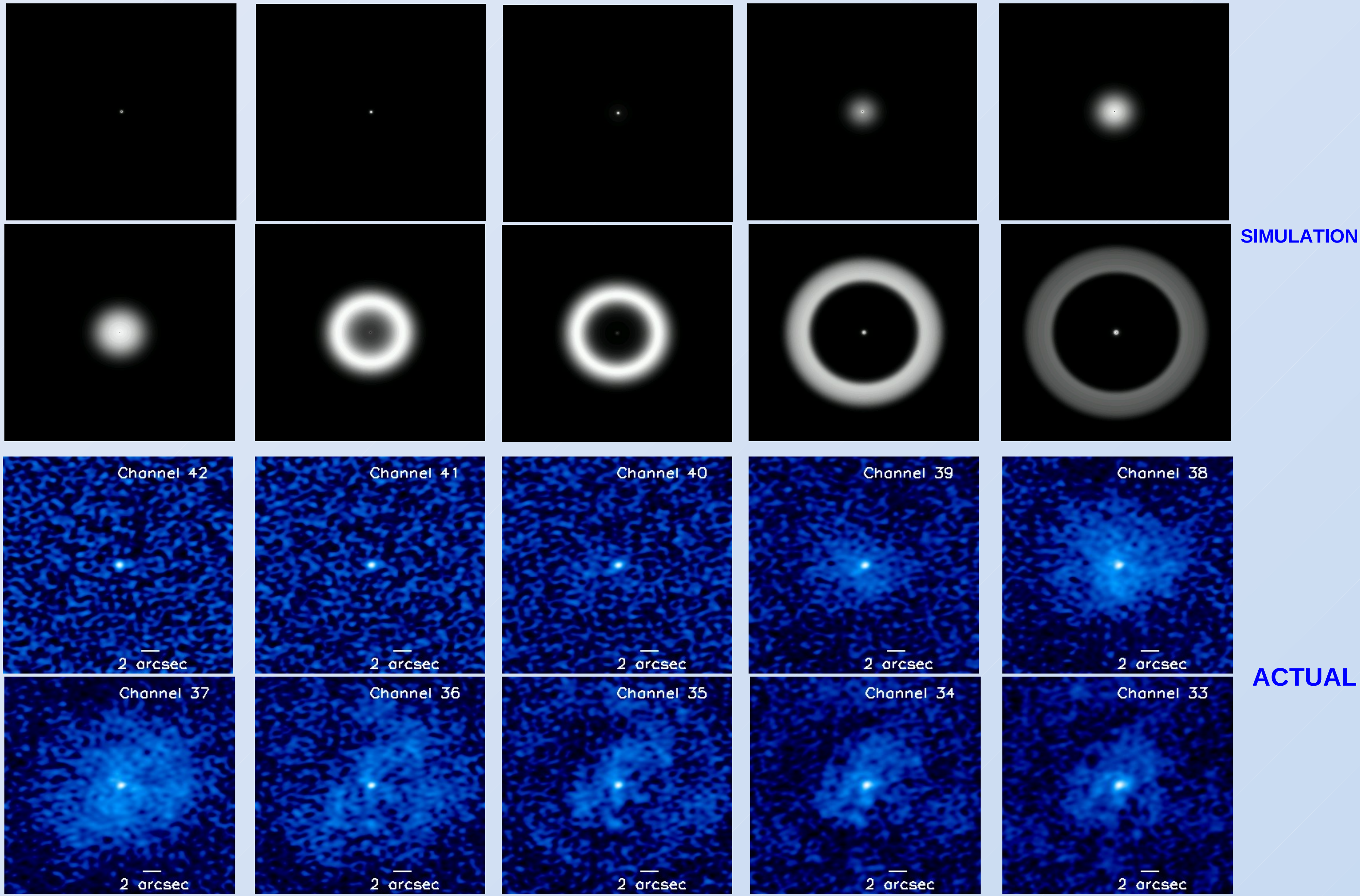

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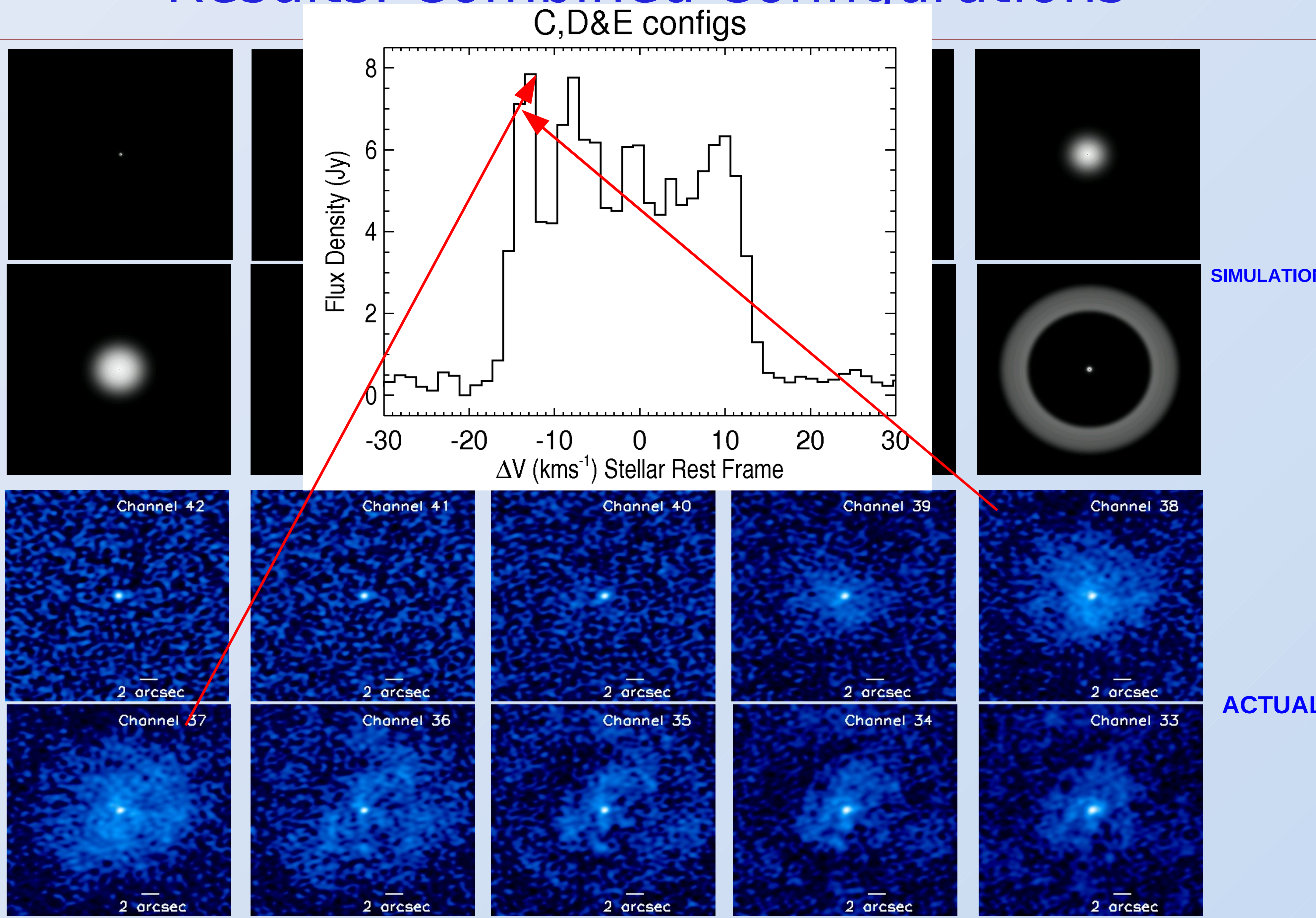

Summary

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6) Final Image Cube suggests:

$R_{s1\ out}$ ~ 5 arcsec

$R_{s2\ in}$ ~ 8 arcsec

$R_{s2\ out}$ ~ 10 arcsec

Credit: ESO

Questions?

Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the James S. McDonnell Foundation, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the University of Chicago, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

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2) Levesque, E. M., Massey, P., Olsen, K. A. G., et al. 2005, ApJ, 628, 973

3) Bernat, A. P., Hall, D. N. B., Hinkle, K. H., & Ridgway, S. T. 1979, ApJ, 233, L135

4) Plez, B., & Lambert, D. L. 2002, A&A, 386, 1009

5) Cernicharo, J., & Bachiller, R. 1993, private communication

6) Rodgers, B. & Glassgold, A. E. 1991, ApJ, 382, 606

7) Knapp, G. R., Morris, M., 1985, ApJ, 292, 640

8) Lamers H. J. G. L. M., Cassinelli J. P., 1999, Introduction to Stellar Winds. Cambridge University Press

ALMA

$J_{mp} = (T_{ex}/5.53)^{1/2}$ (Rodgers & Glassgold, 1991):

S1 @ 200 K J_{mp} = 6 (i.e. J=6->5 691 Ghz ALMA band 9)

S2 @ 70 K J_{mp} = 3 (i.e. J=3->2 245 Ghz ALMA band 6)

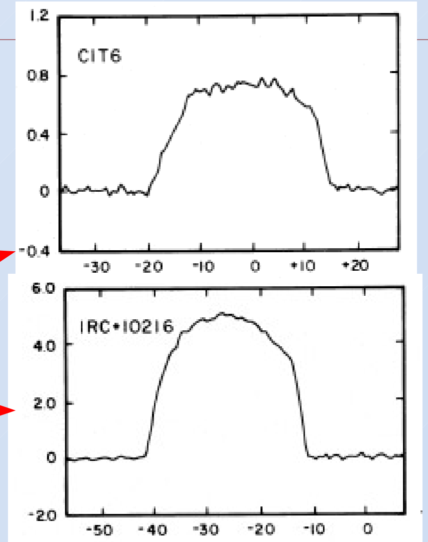
AND....

66 antennas
5,000 m site
B_{max} = 16 km

Credit: ESO

Molecular emission lines from Cool Star Winds

Can form over a region with a radius of the order of 10^4 stellar radii:
High mass loss rates + low outflow velocities = relatively high density



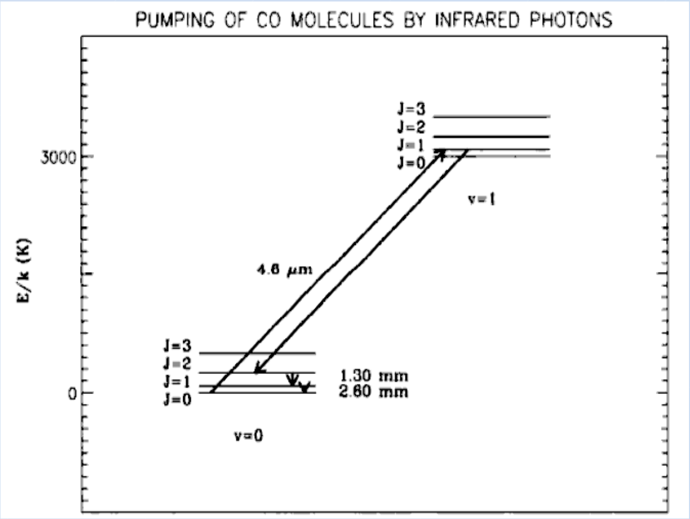
Knapp & Morris, 1985

Line profiles are either flat-topped (if line is optically thin)
or parabolic (if line is optically thick)

Line full widths typically between 20 and 50 km s^{-1}
=> outflow velocities between 10 and 25 km s^{-1}
Usually smaller than v_{esc} at stellar surface but molecular lines form at large distances from star where local escape velocity << v_{esc}

CO, most important molecule for studying mass loss from cool evolved stars:
- Observed in winds of both O-rich and C-rich stars
- Very stable

2 important excitation processes for CO:
1) excitation of rotational levels by H2 collisions
2) photo-excitation of vibrational levels by IR photons



Lamers & Cassinelli, 1999