Radio Interferometric Studies of Cool Evolved Stellar Winds

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November 15, 2013

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Mass-loss Across the H-R Diagram

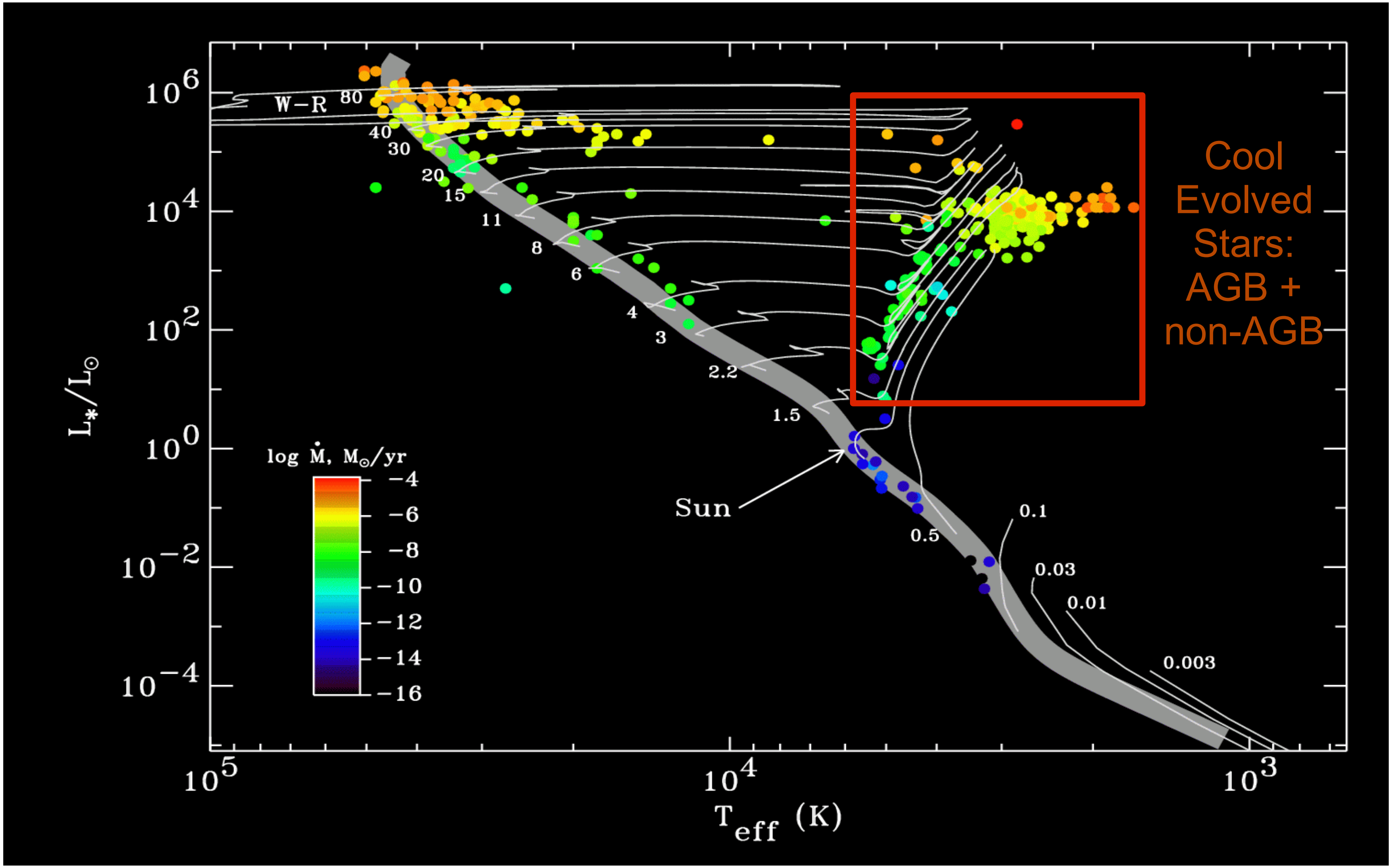


Image Credit: S. R. Cranmer

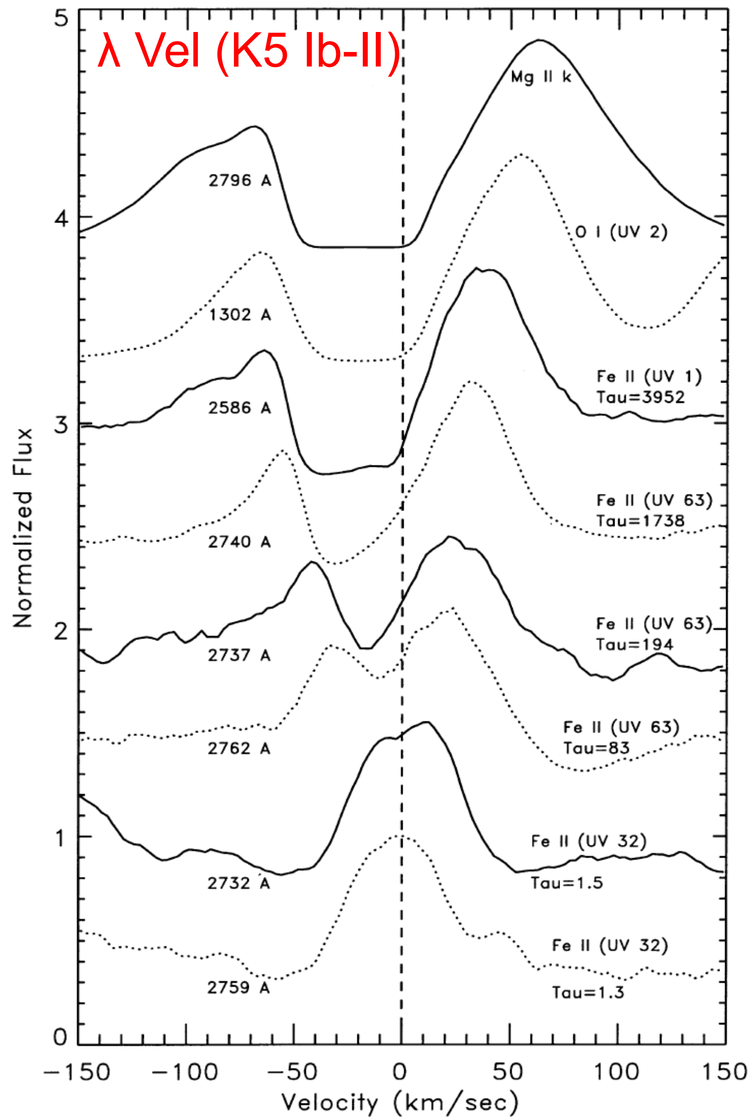
Traditional Diagnostics of Mass Loss

- Optical and UV spectroscopy:
  Full "P Cygni" profiles or blueshifted absorption

- IR continuum:
  SED excess

- Molecular lines:
  mm, sub-mm (disk averaged)

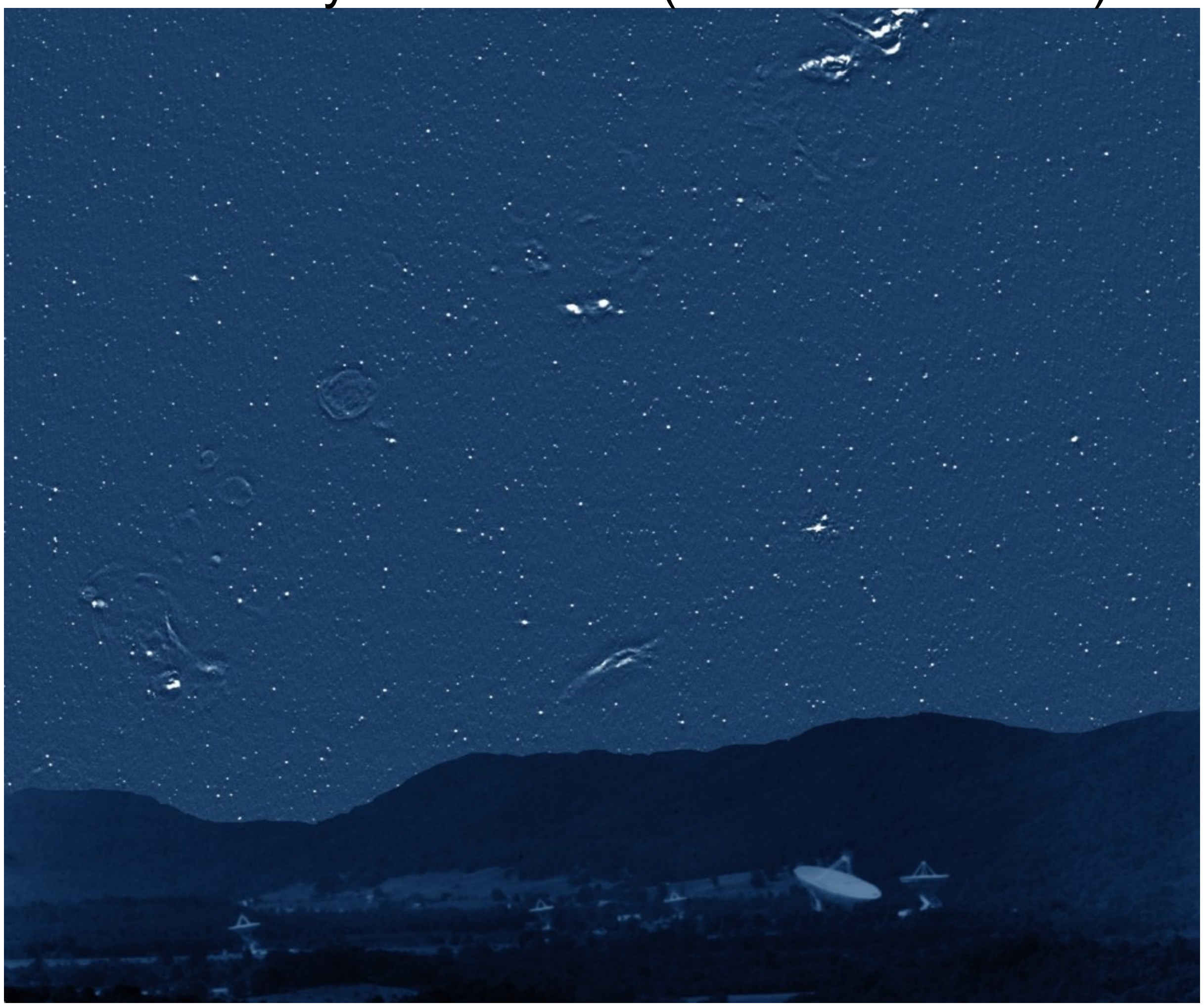
- Centimeter continuum:
  If $v_{terminal}$ is known, provides *ionized* mass rate



Carpenter *et al.*, (1999)

Stellar Radio Emission

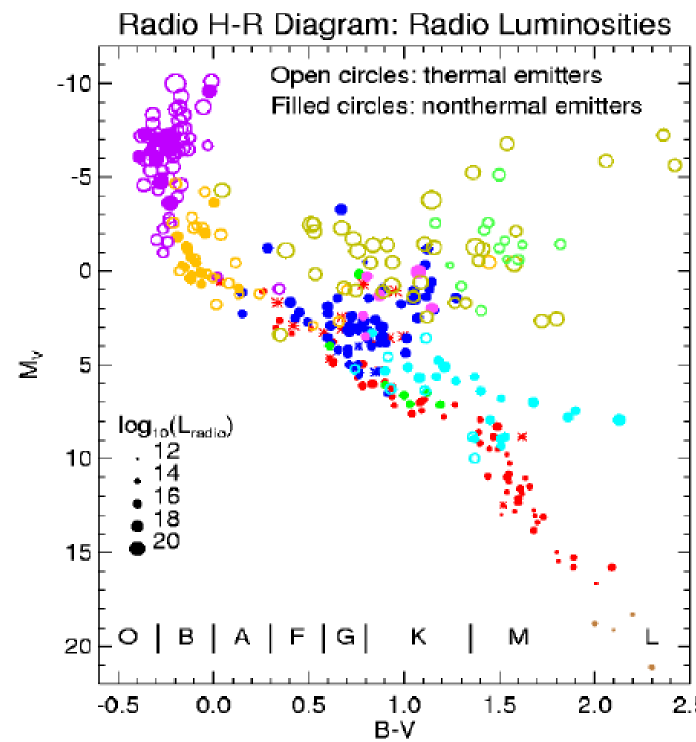
Radio Sky at 4.85 GHz (300ft Green Bank)



Credit: NRAO/AUI

$(P_{radio}/P_{optical})_{\odot} \sim 10^{-15}$

$S_{\upsilon=4.6\,\mathrm{GHz}} \sim 40\ \mu\mathrm{Jy}$ at α Cen
(not detectable with 'old' VLA!)



White (2000)

Red Giants and Red Supergiants

	Red Giants	Red Supergiants
Mass ($M_\odot$)	~ 0.4 → ~ 8	~8 → ~ 40
Radius ($R_\odot$)	~ 50	~ 500
Lifetime (yr)	~ 10^9	~ 5×10^5
dM/dt ($M_\odot$ yr^{-1})	~ 10^{-10}	~ 10^{-5}
Total dM/dt ($M_\odot$)	~ 0.1	~ 5

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$v_{teminal} \sim 0.3 v_{*\ escape}$
$H_P/R \sim 10^{-2}$
$T_{wind} < 10^4$ K

No coronae.
Insufficient dust opacity.
Small pulsation amplitudes.

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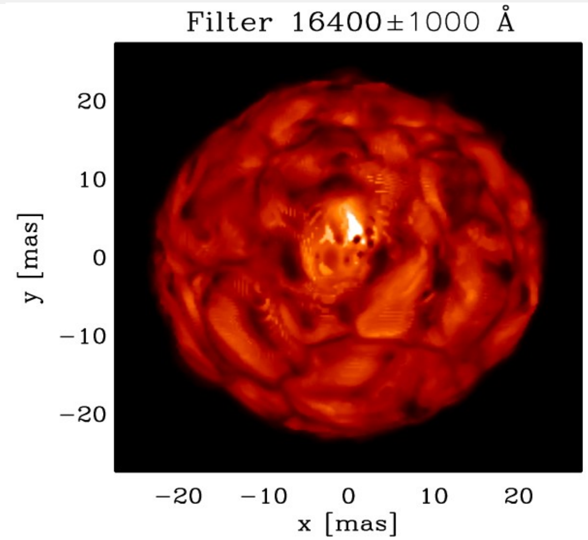
Overview:

1. Red Supergiants (i.e., Betelgeuse)
1 (a): millimeter (CSE)
1 (b): centimeter (inner wind)

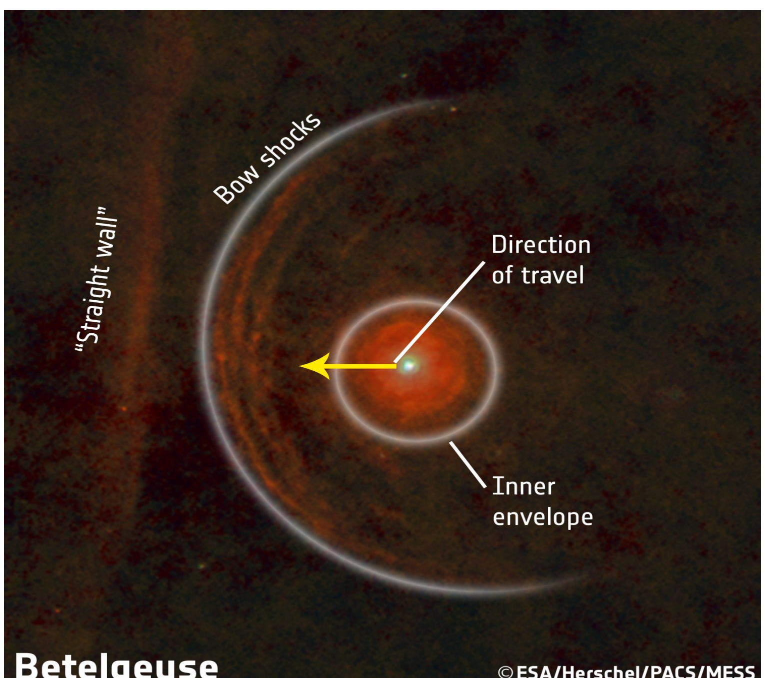
2. Red Giants (i.e., Arcturus and Aldebaran)
2 (a): centimeter (inner wind)
2 (b): thermal balance

1. Betelgeuse



(Chiavassa *et al.*, 2011)

Spectral Type	M2 Iab
Log($L/L_{\odot}$)	5.12
Distance	197 ± 45 parsec
Mass (birth)	~20 $M_{\odot}$
Mass (current)	~15 - 18 $M_{\odot}$
Mass loss rate	$3 \times 10^{-6}\ M_{\odot}\ yr^{-1}$
Rotational Period	17 years
Photospheric Radius	22.5 mas (950 $R_{\odot}$)
Photospheric Temperature	3,600 K (cool star)
Origin	O-type main sequence
Fate	Supernova Type II
$^{12}C/^{13}C$	6 ± 1



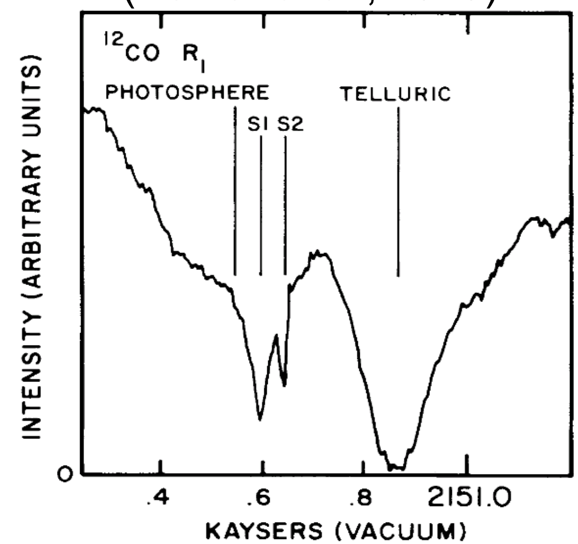
(Decin *et al.*, 2013)

1 (a): Betelgeuse: Circumstellar Environment

- At least two *recent* mass loss phases

- Two distinct shells spectrally resolved at 4.6 µm:
  - A fast, low column flow, S2, moving at 17 km s^{-1}
  - A slower, high column flow, S1, moving at 10 km s^{-1}
  - Spatial extent not directly determined

(Bernat *et al.*, 1979)



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- Plez & Lambert (2002) appear to detect S2 shell at 50"
- IRAM 30 m (θ_{HPBW} ~12") fails to resolve S2 shell at 1.3 mm
- Single dish $^{12}C^{16}O$ mm-observations reveal only high velocity S2 shell.
- Signature of S1 shell not obvious at mm wavelengths.

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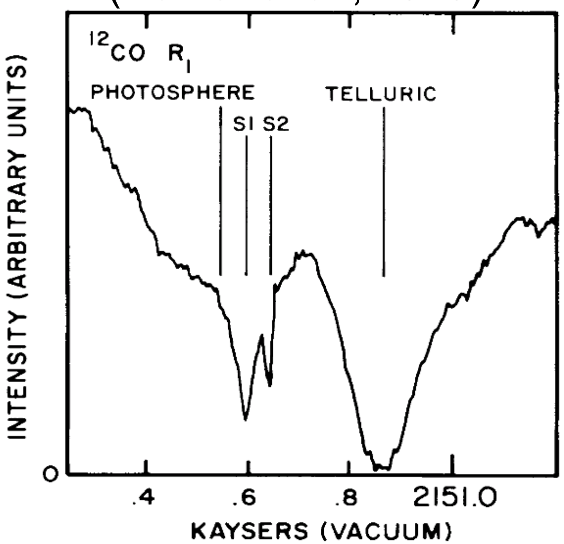
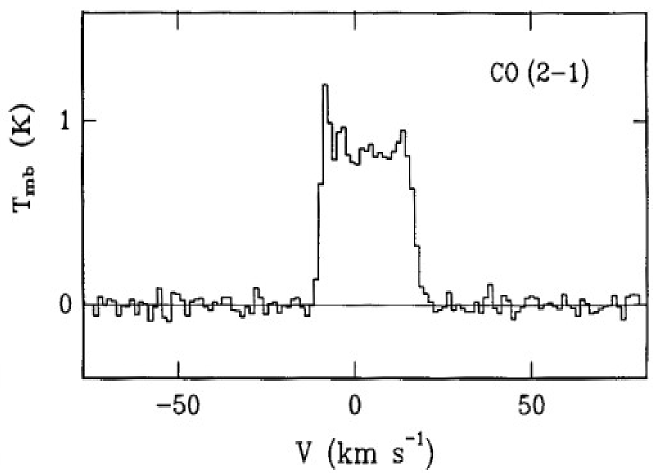


(Huggins *et al.*, 1994)



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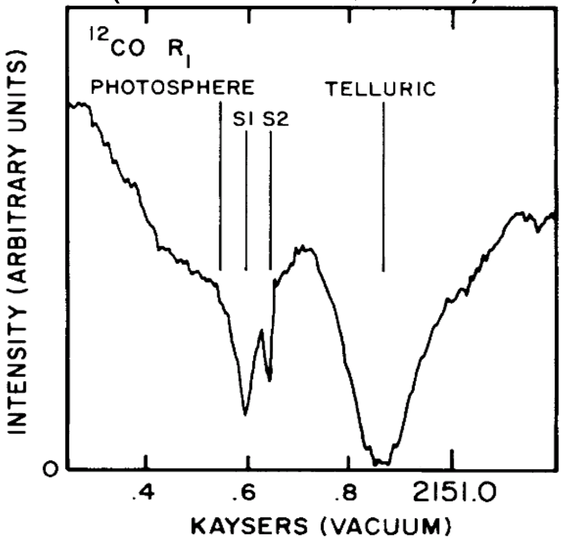
Goal 1 (a): *Measure both the spatial scales and the velocities of Betelgeuse's outflow region using $^{12}C^{16}O$ J = 2-1 line as a tracer to sort out puzzling evidence.*

(Bernat *et al.*, 1979)



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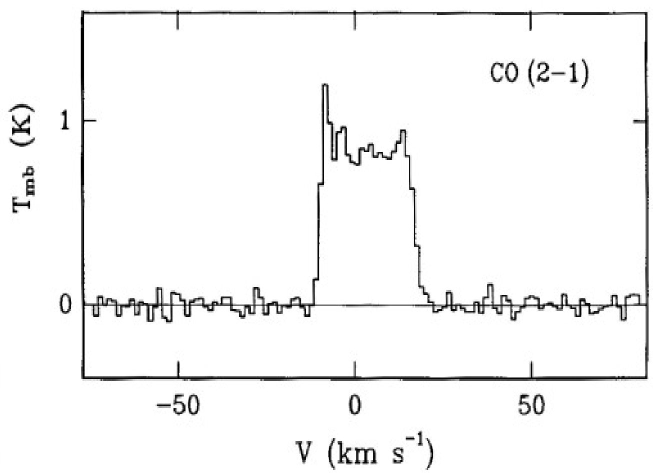


1 (a): CARMA

Combined **A**rray for **R**esearch in **M**illimeter-wave **A**stronomy

Cedar Flat, eastern California (~ 2,200 m)

15 element interferometer (9 x 6.1 m + 6 x 10.4 m antennas)

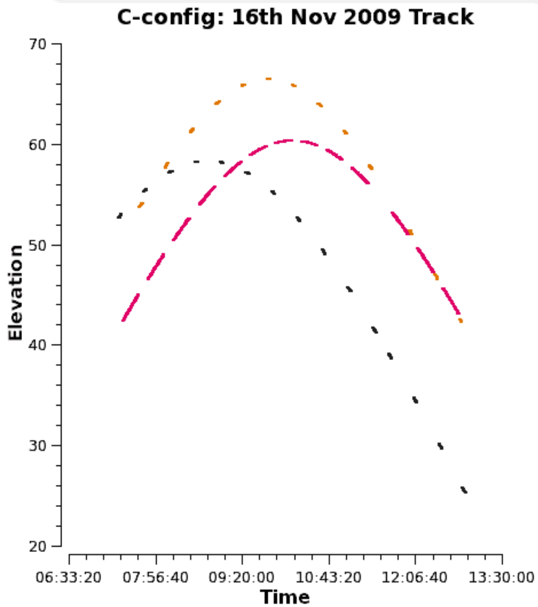
Merger of two independent arrays: BIMA + OVRO (2007)

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

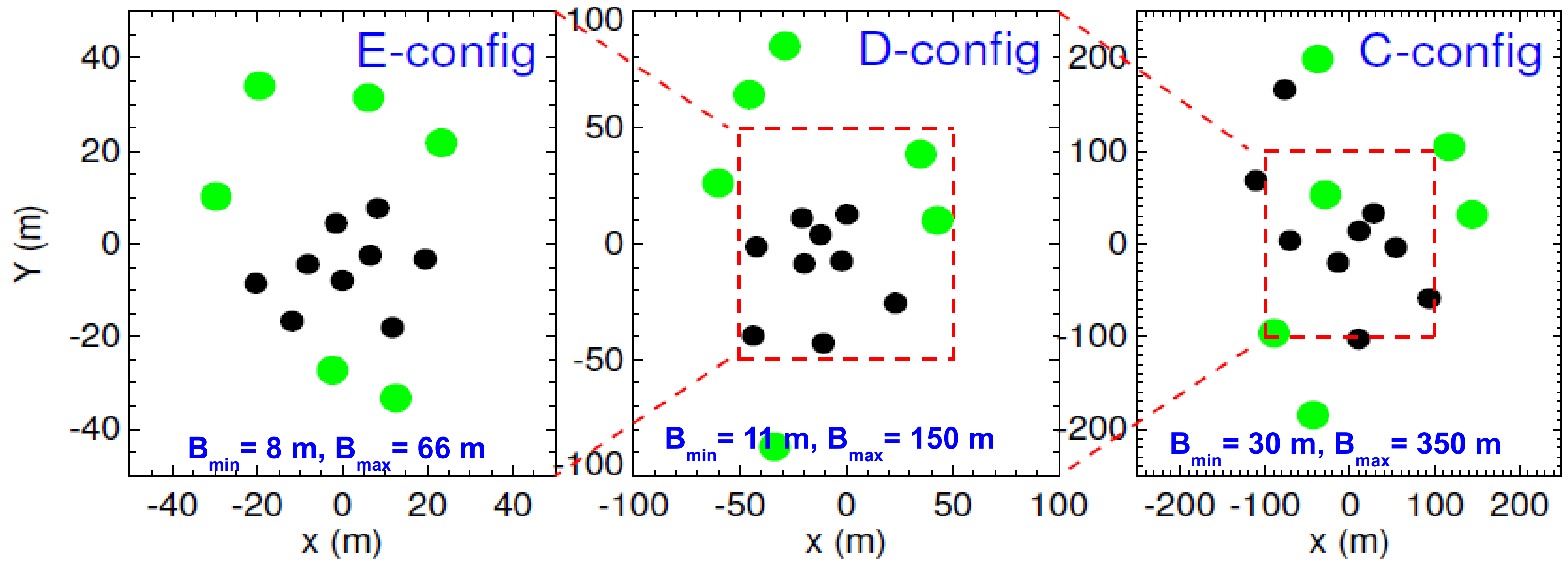
Credit: 2009 John Carlstrom

1 (a): mm Observations

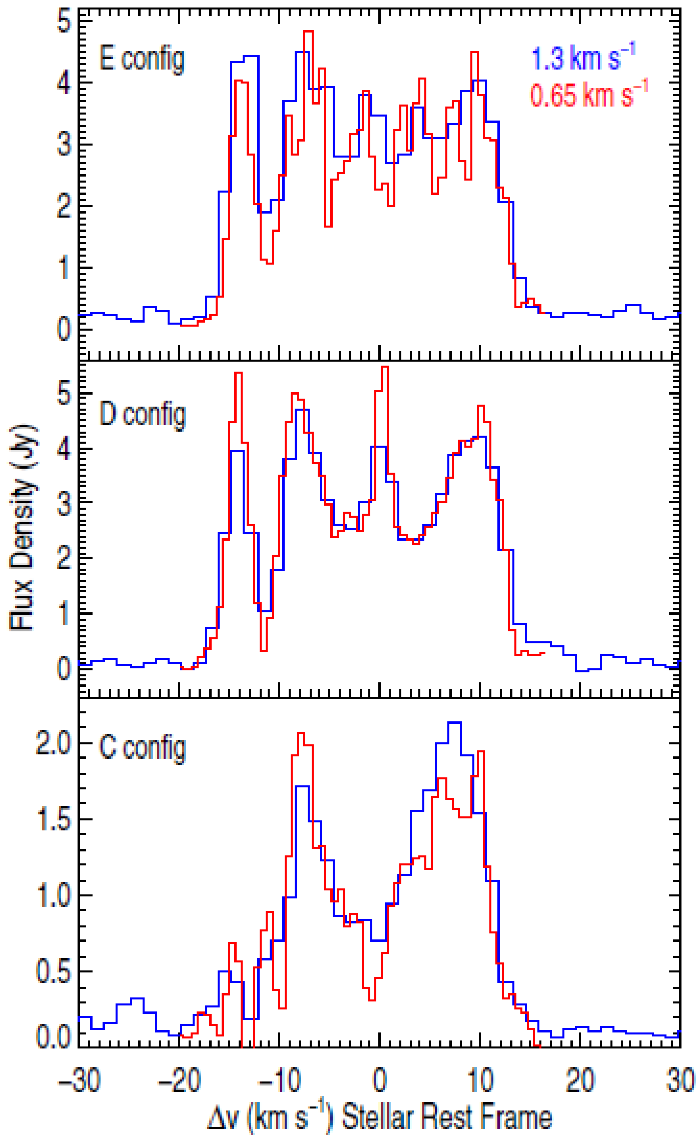


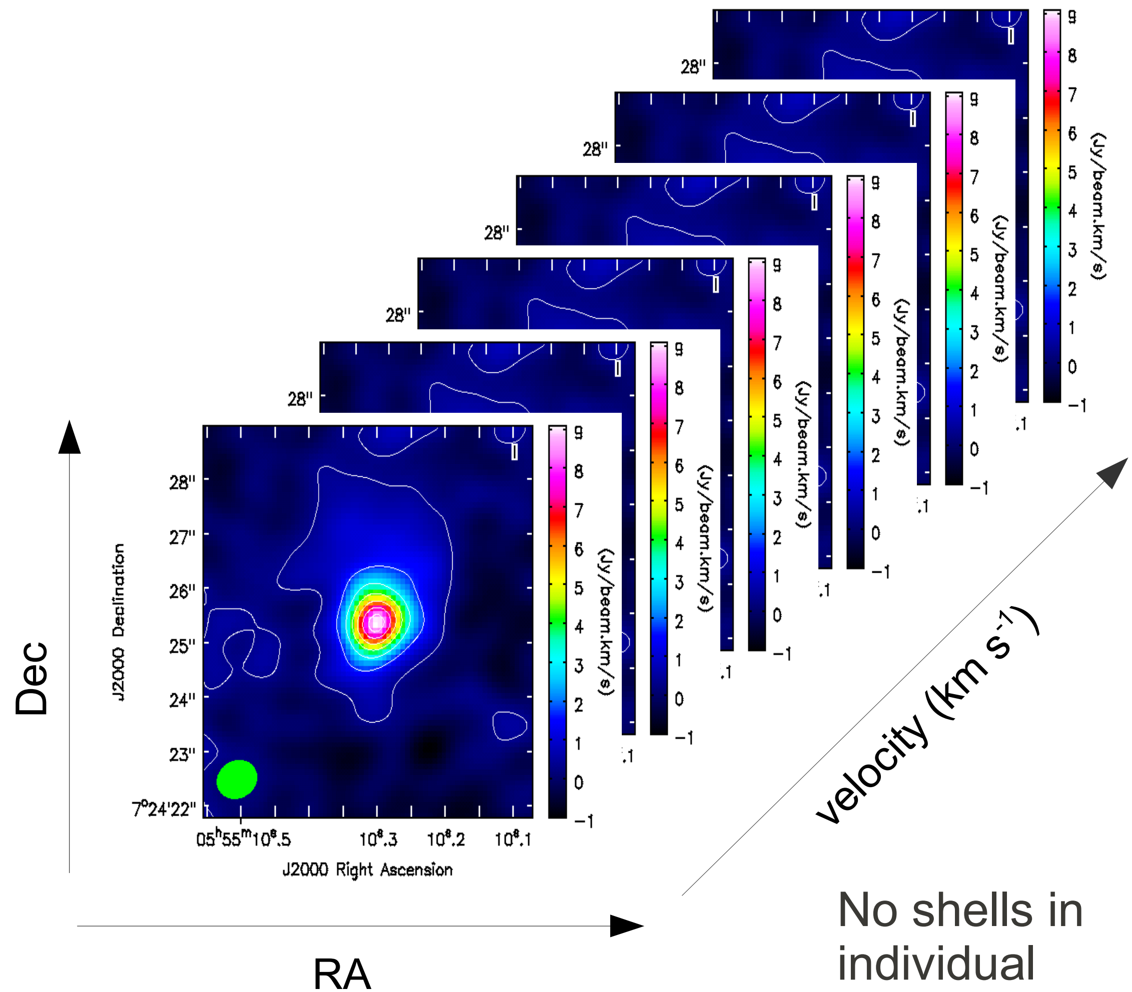
Date	Config	Tracks	Time (hr)	Resolution (")	Max Scale (")
Jun 07	D	5	8.4	2.1	15
Jul 09	E	1	3.2	4.4	19
Nov 09	C	5	8.4	0.9	6

- 1 MHz/1.3 km s^{-1} resolution
- 0.5 MHz/0.65 km s^{-1} resolution



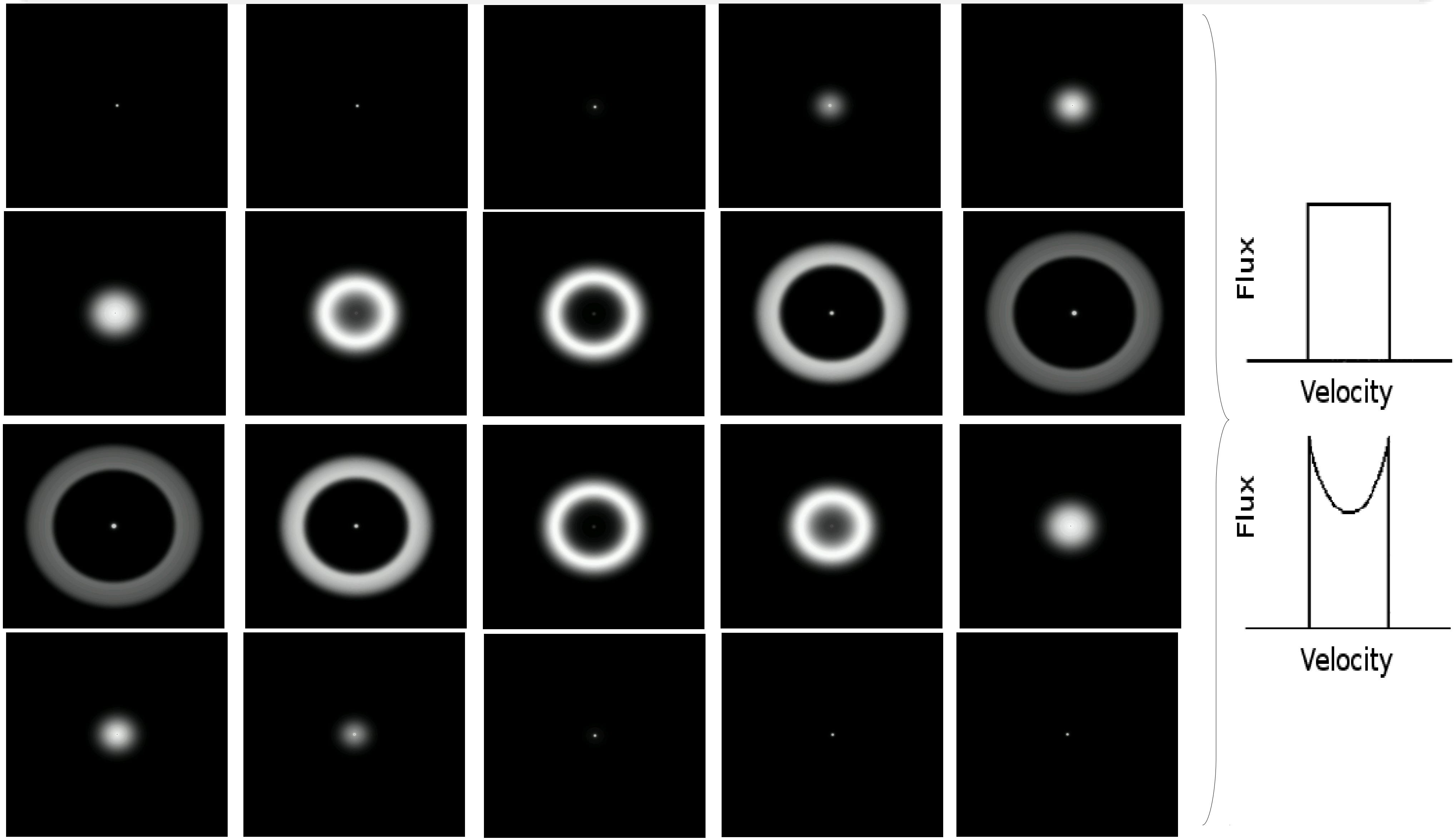
1 (a): Individual Configurations



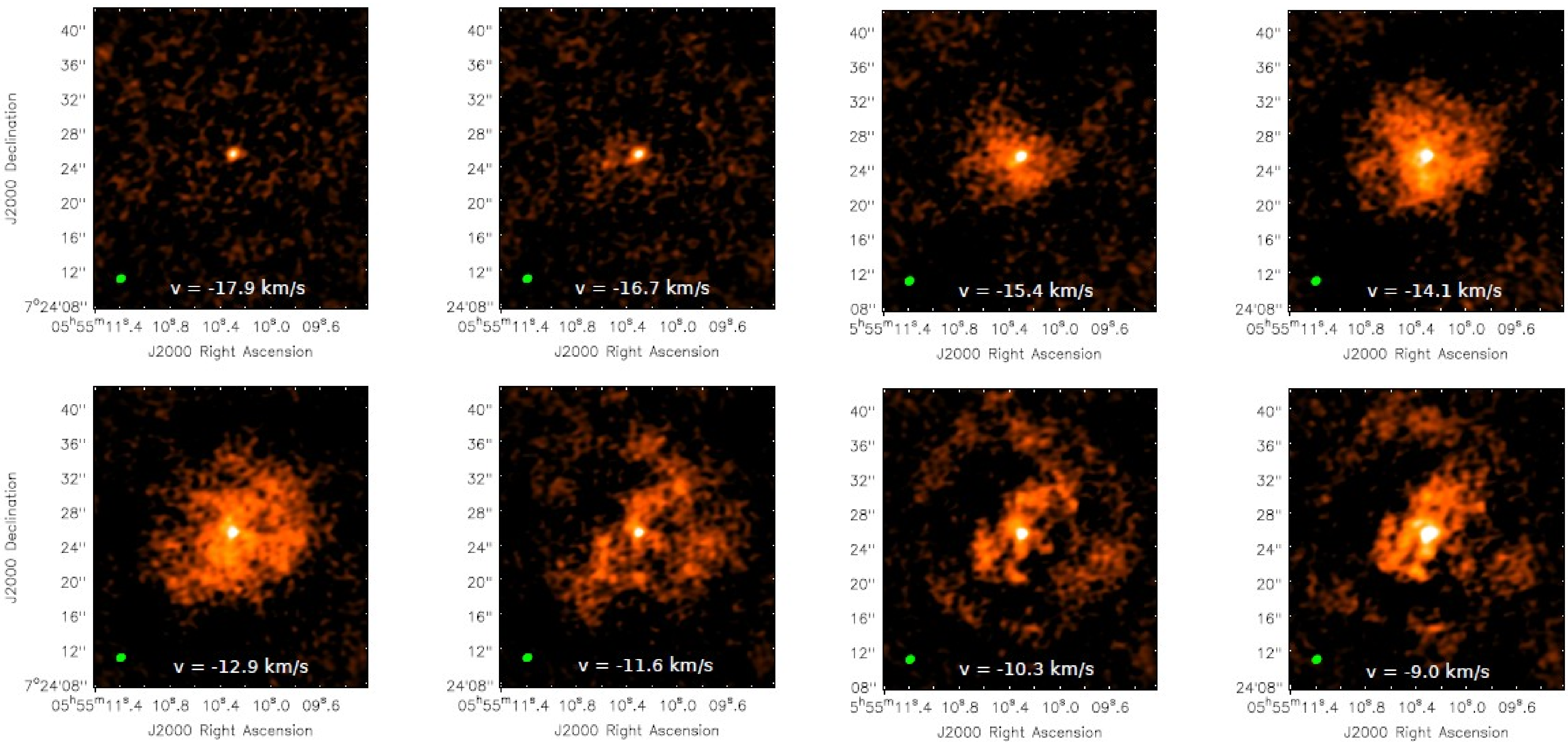


No shells in individual configuration image cubes.

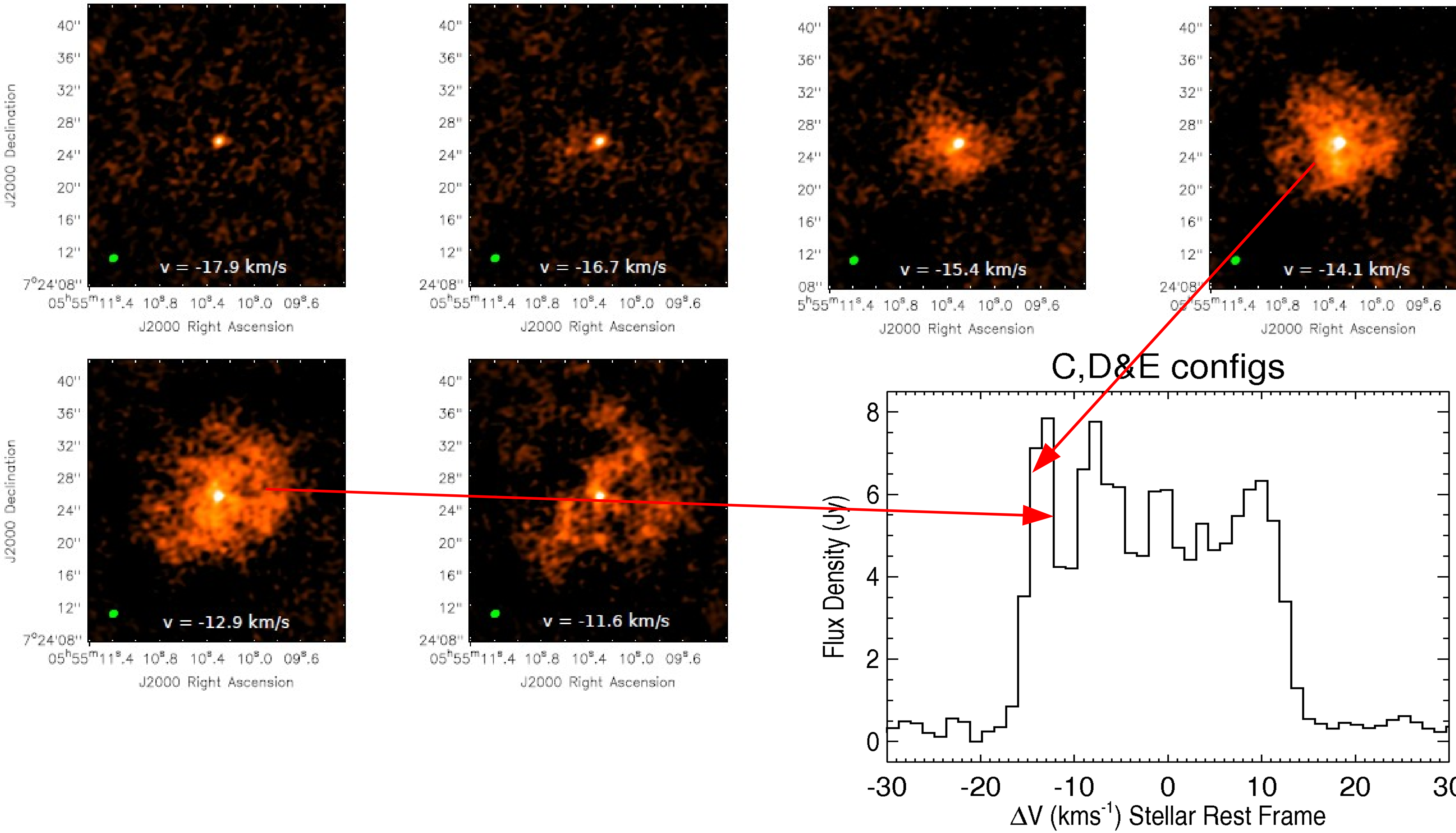
1 (a): Theoretical Shell



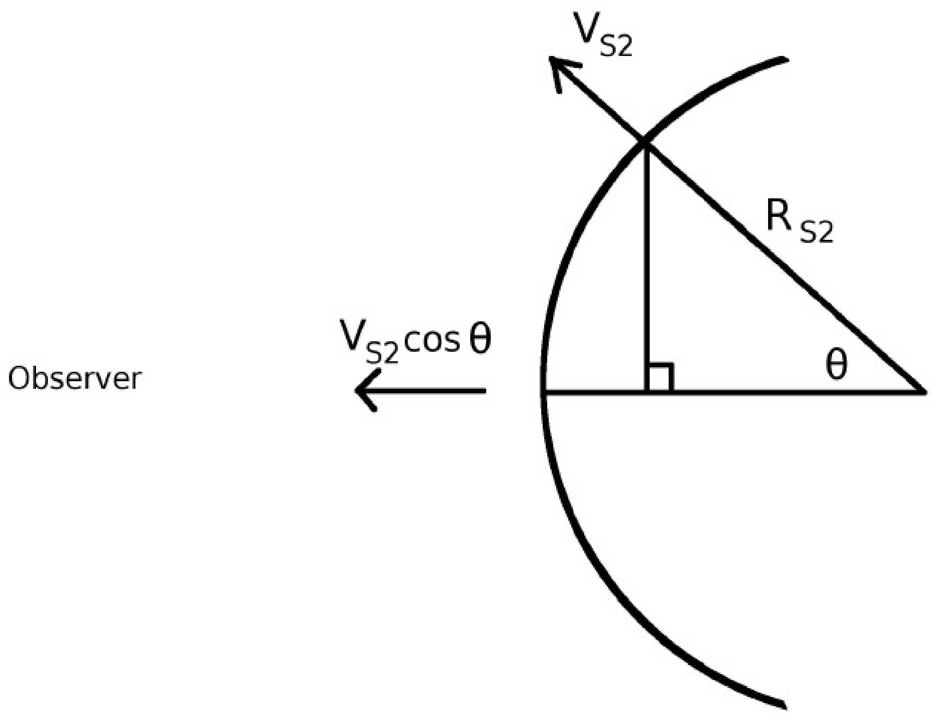
1 (a): Combined Configuration



1 (a): Combined Configurations

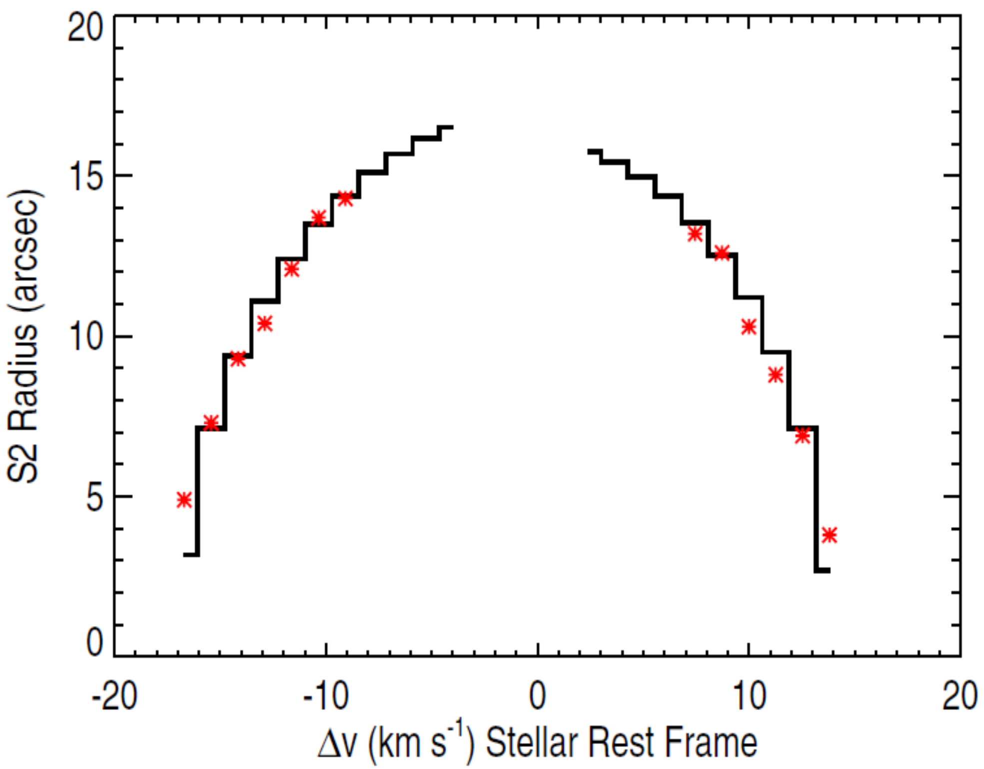


S2 Flow

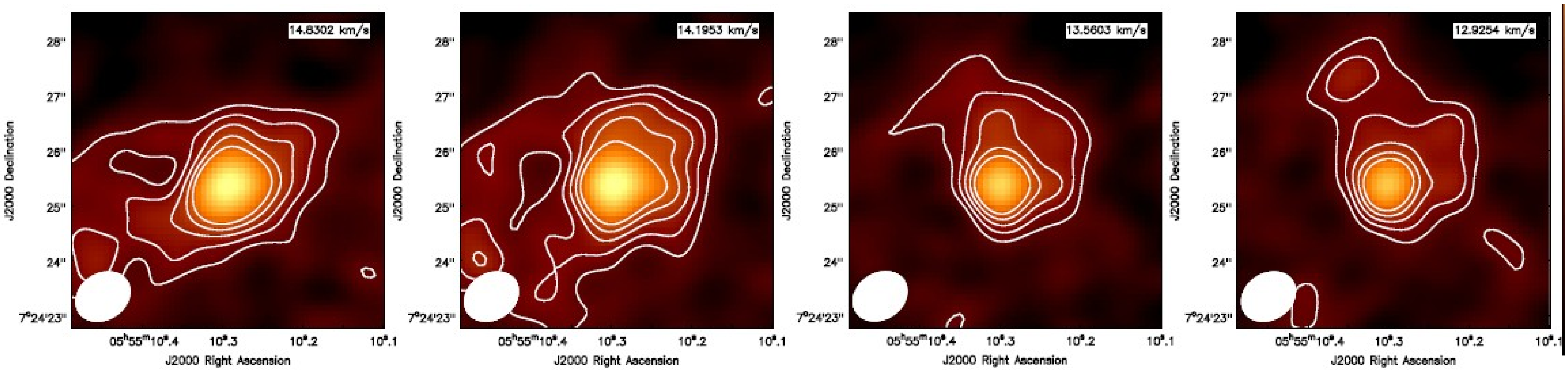


$$r_{\rm chan} = R_{\rm S2} \sin\left[\cos^{-1}\left(\frac{v_{\rm chan}}{V_{\rm S2}}\right)\right]$$

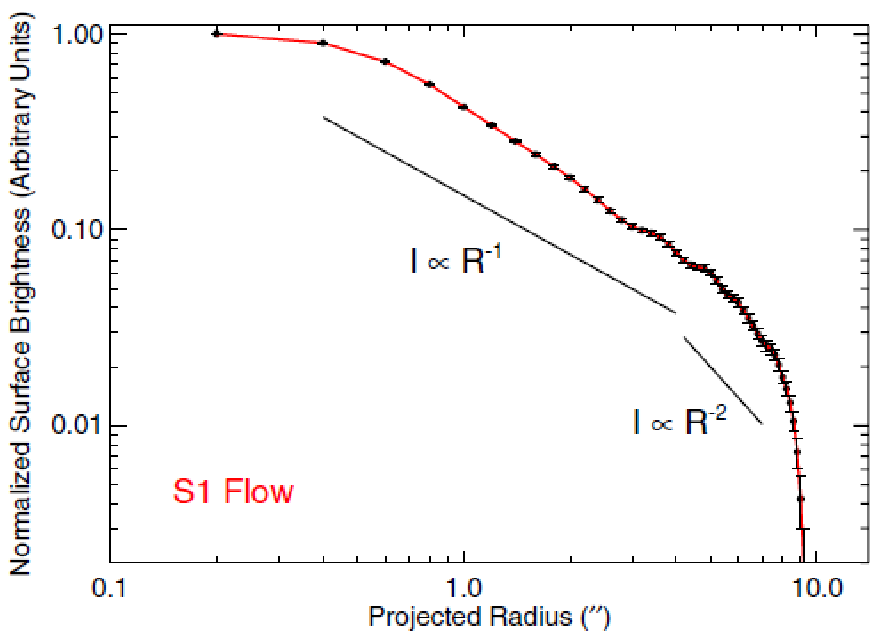
No present at low absolute velocities



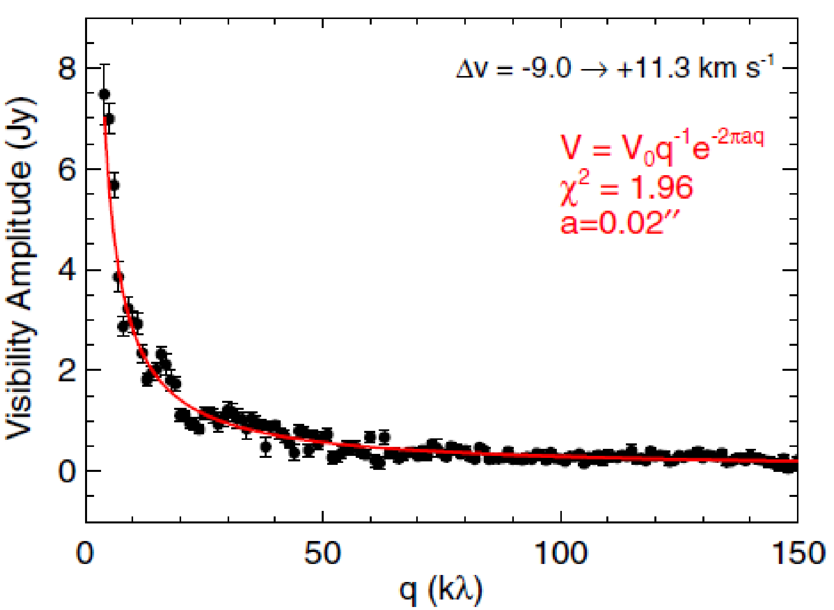
1 (a): S1 Flow



14.8302 km/s
14.1953 km/s
13.5603 km/s
12.9254 km/s
J2000 Declination
J2000 Right Ascension

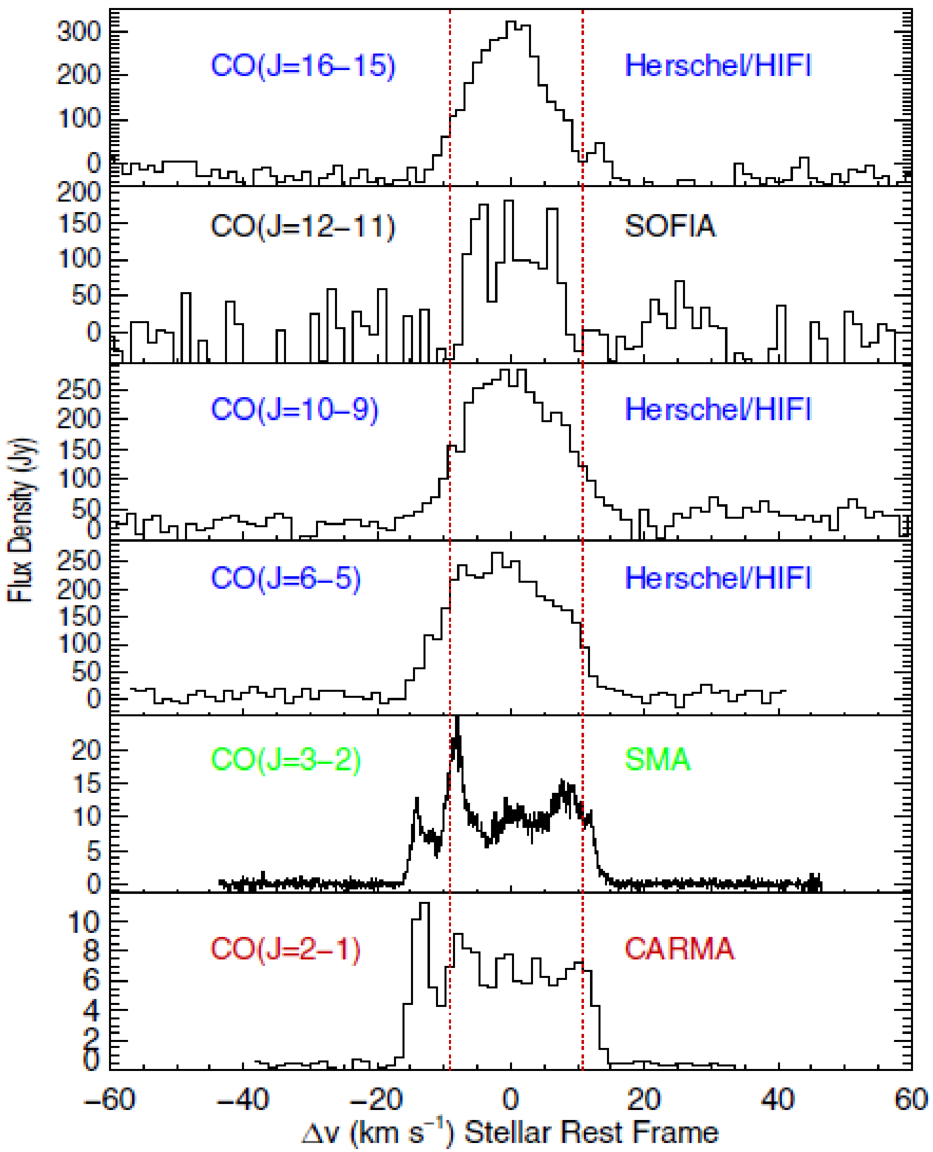


Normalized Surface Brightness (Arbitrary Units)
Projected Radius (″)
I ∝ R^-1
I ∝ R^-2
S1 Flow



Visibility Amplitude (Jy)
q (kλ)
Δv = -9.0 → +11.3 km s^-1
V = V0q^-1e^-2πaq
χ² = 1.96
a=0.02″

1 (a): Higher CO rotational lines



$F_{10\text{-}9} / F_{16\text{-}15} \rightarrow T_{exc\ S1} = 220$ K

Bernat *et al*., (1979) $T_{exc\ S1} = 200^{+50}_{-10}$ K

1 (a): Conclusions

- The high spatial resolution C configuration resolves out extended emission leaving us with S1 emission profile.

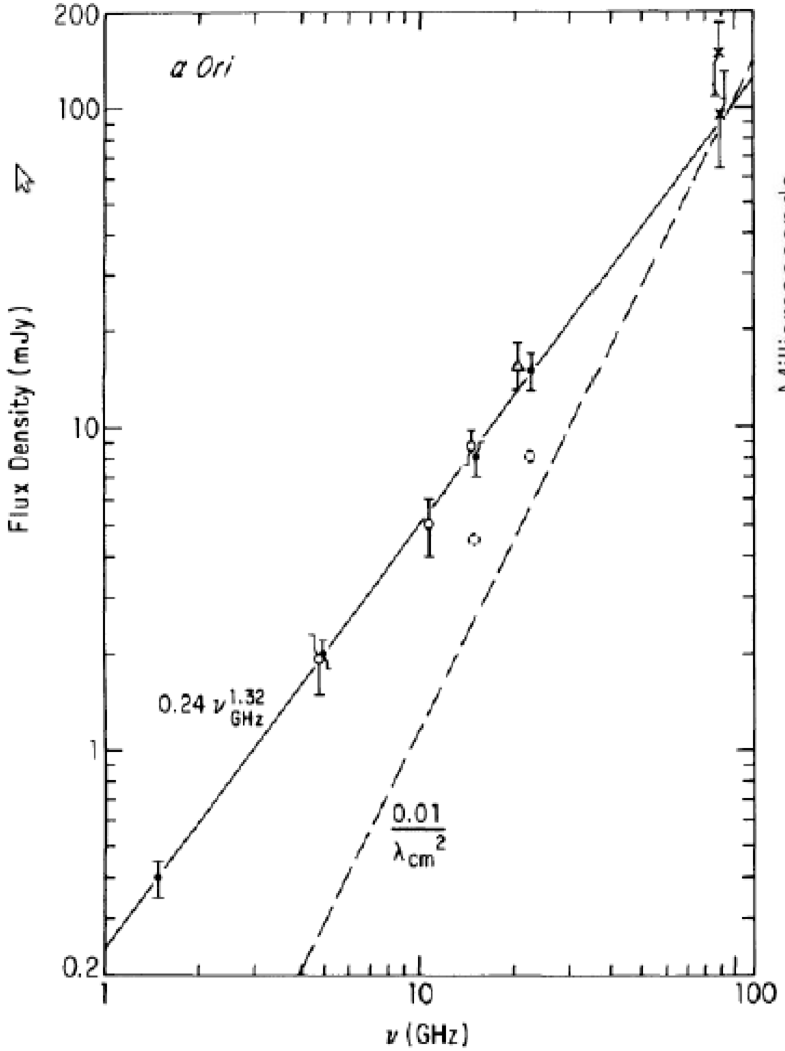
- Multiple CARMA configurations provide the high spatial resolution needed to study the inner S1 shell while also ensuring that larger structures (i.e. S2 shell) are not resolved out.

-

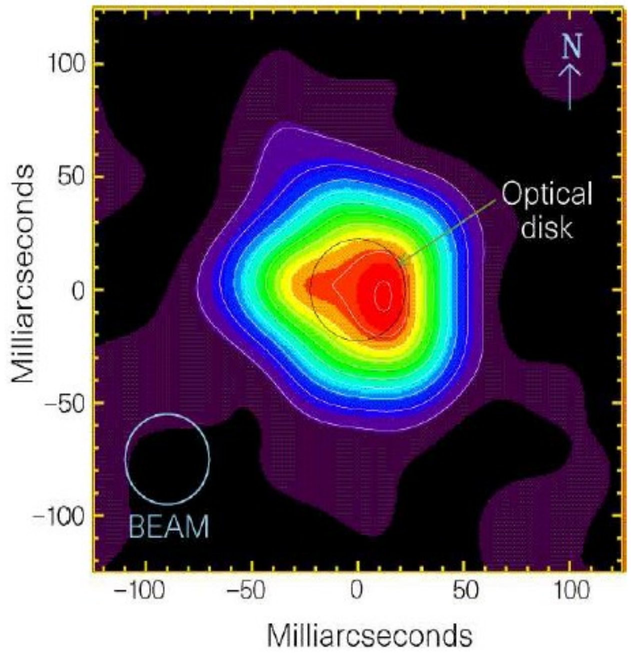
	S1	S2
Outflow Velocities (km s^{-1})	2.1	15
Maximum Spatial Extent (")	4 → 6	17
Age (yr)	400 → 600	1100

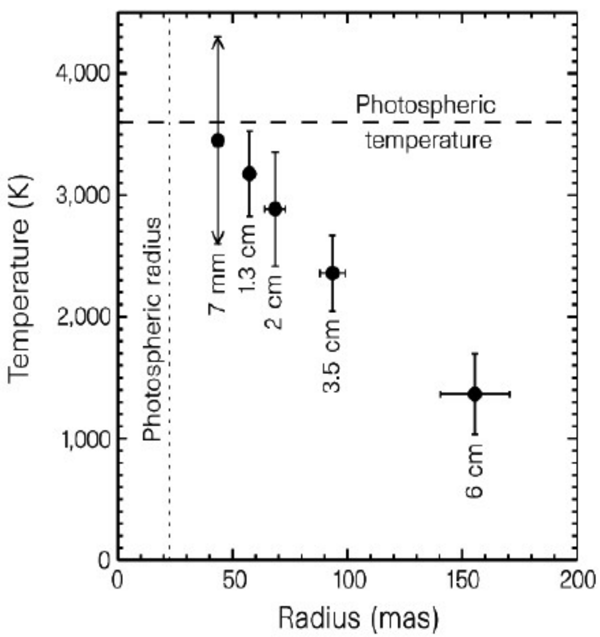
1 (b): Betelgeuse at cm wavelengths

(Newell & Hjellming, 1982)



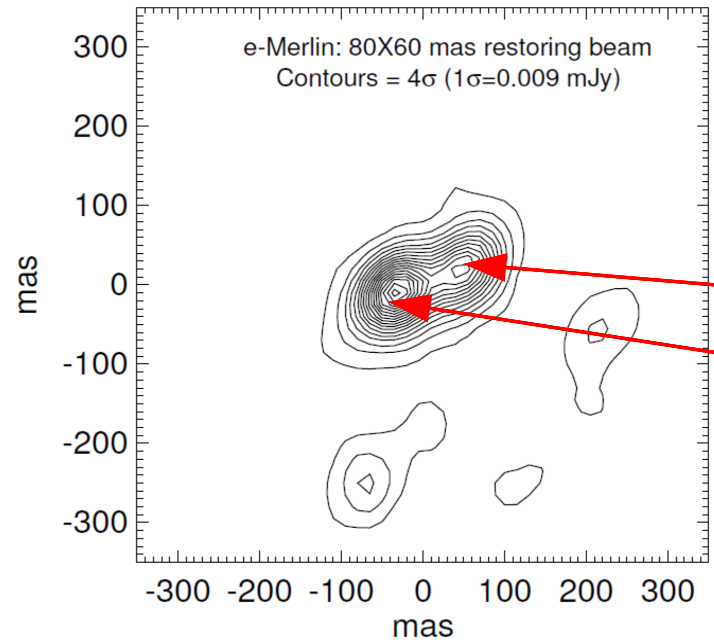
(Lim *et al.*, 1998)





$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$

1 (b): Betelgeuse with e-MERLIN (5.2 cm)

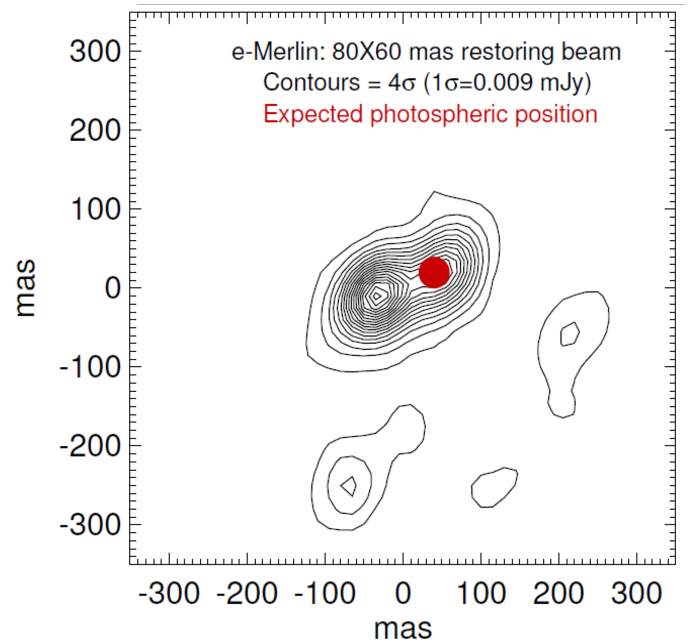


[Richards *et al. (including O'Gorman),* 2013]

Two unresolved *hot spots:*
T_e > 3800 +- 500 K
T_e > 5400 +- 600 K
Where is the photosphere?

Goal 1 (b): *Analyse high resolution archival cm data to look for signatures of hotspots.*

1 (b): Betelgeuse with e-MERLIN (5.2 cm)



Astrometric solution of Harper *et al.*, (2008)

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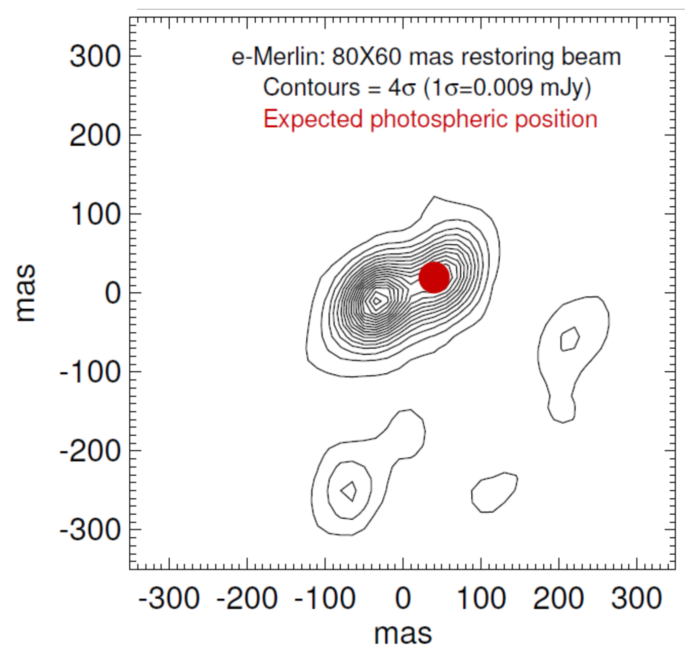

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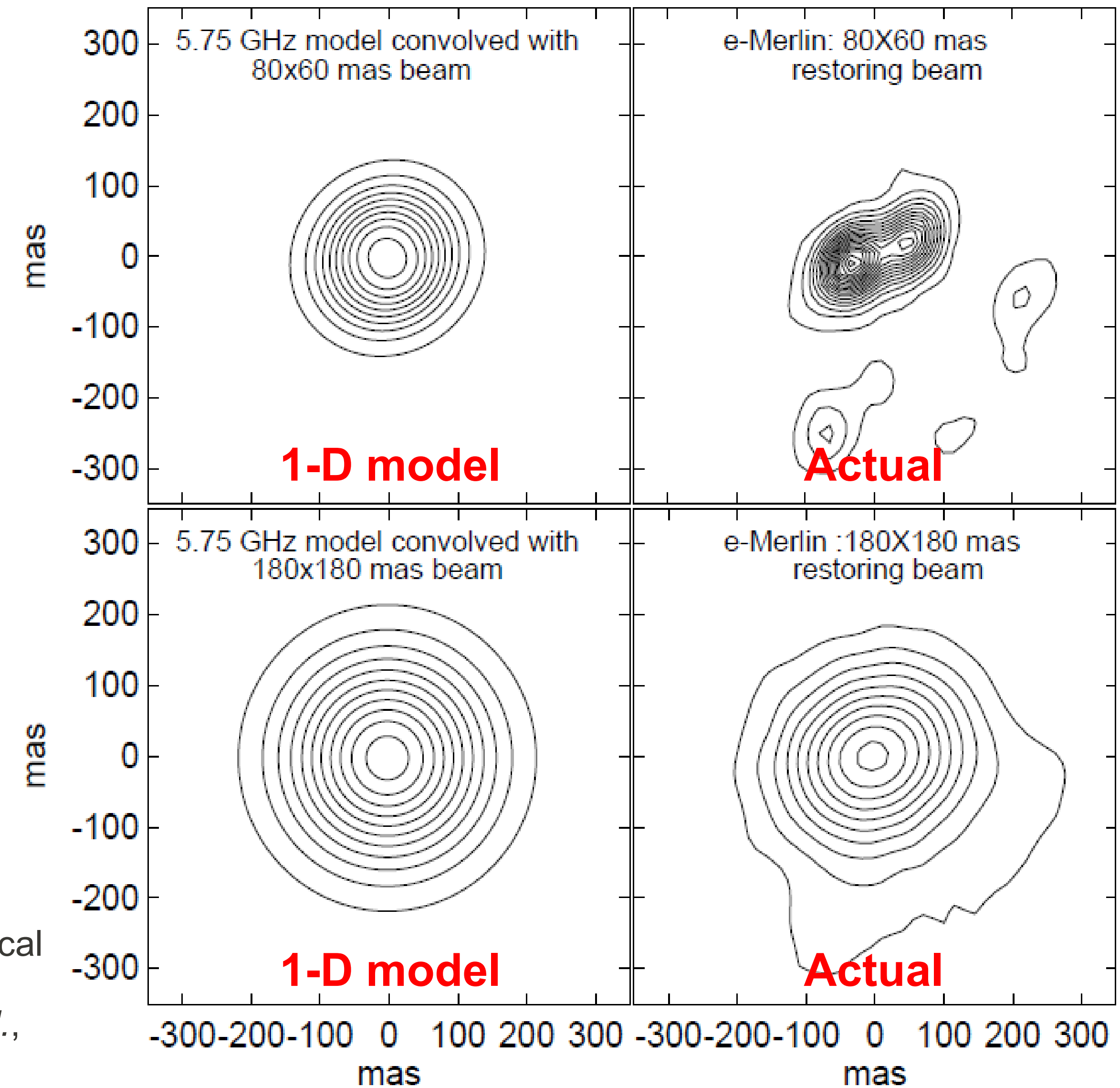
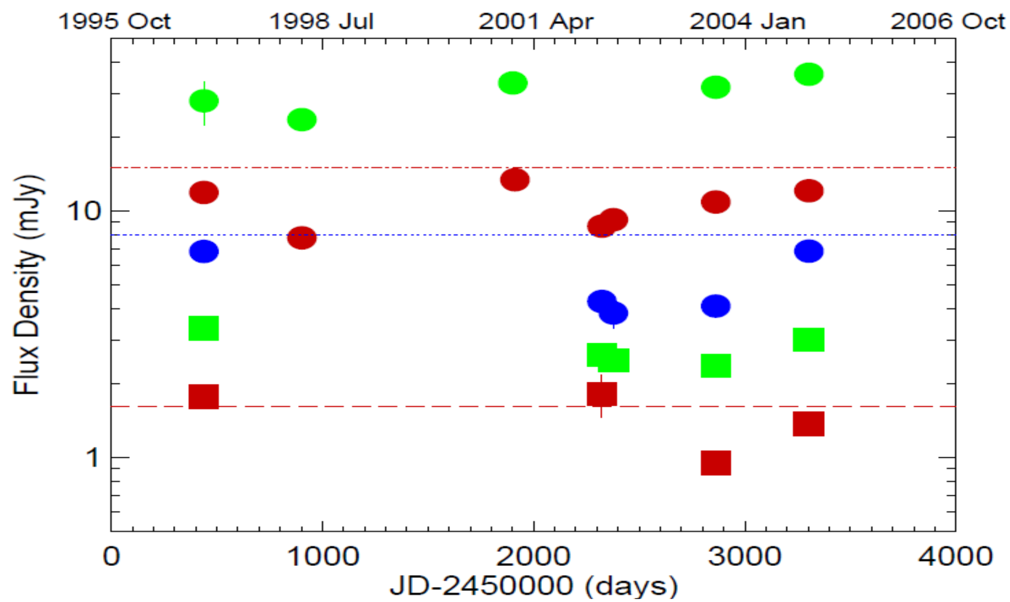


Spherically symmetric semi-empirical model of Harper *et al.*, (2001)

1 (b): Betelgeuse with VLA – Pie Town

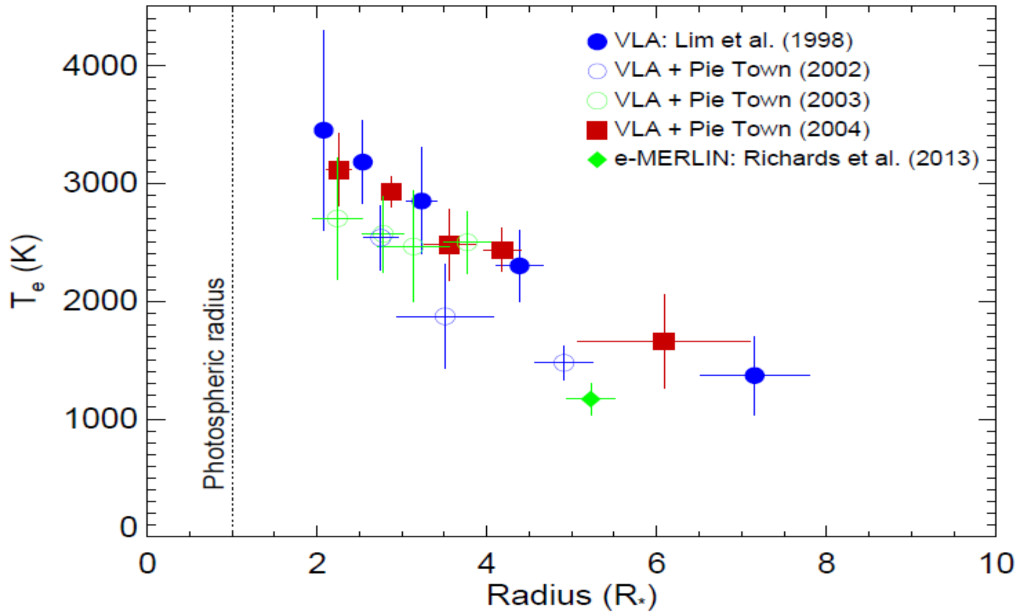
Variability

w/l (cm)	Variability
0.7	23%
1.3	27%
2.0	32%
3.5	21%
6.2	35%



Thermal Profile (beam averaged)

$$F_\nu = \frac{\pi k \phi^2 T_b}{2\lambda^2}$$



1 (b): Betelgeuse with VLA – Pie Town

e-MERLIN

w/l (cm)	Resolution (")
5.2	80 x 60

VLA + Pie Town

w/l (cm)	Resolution (")
0.7	40 x 25
1.3	80 x 40
2.0	120 x 90
3.5	200 x 130
6.2	380 x 270

No asymmetries in maps between 1.3 and 6.2 cm.

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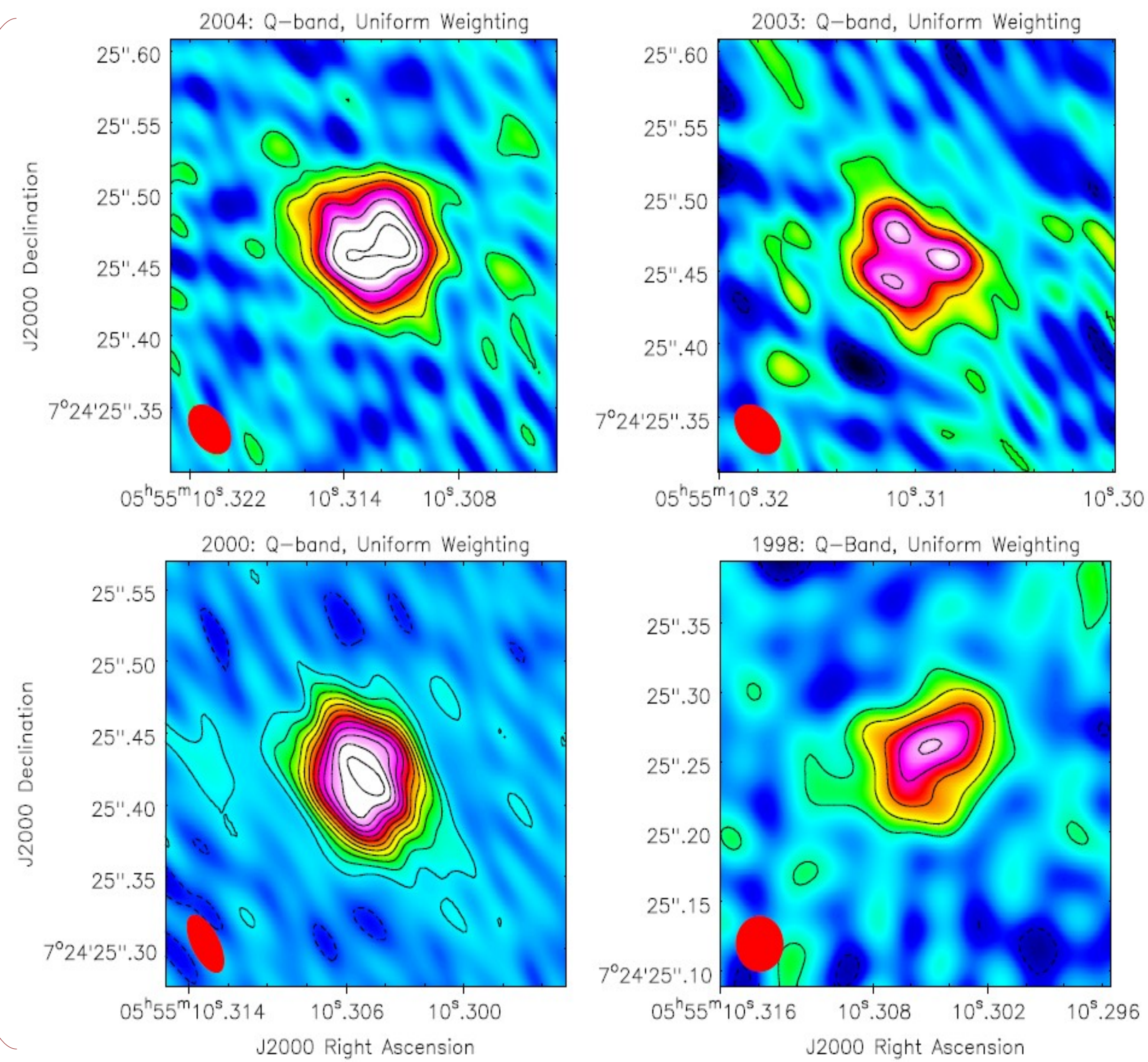
Q-band (0.7 cm) maps using uniform weighting

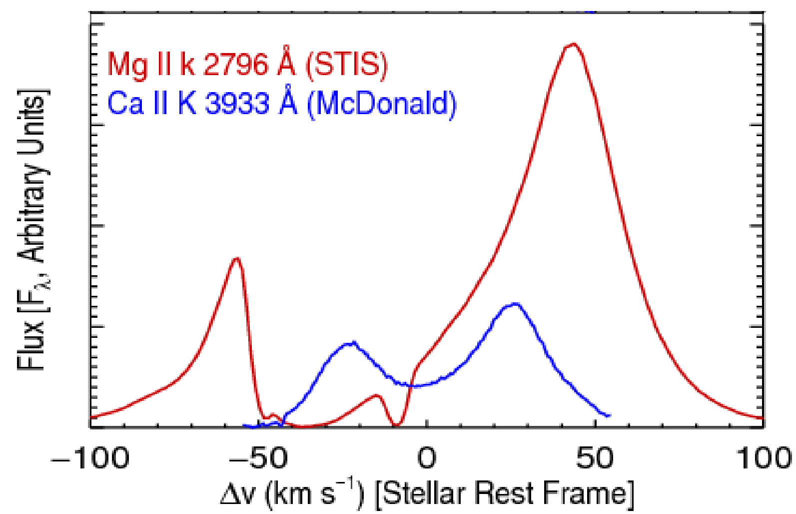


1 (b): Conclusions

- e-MERLIN has revealed two unresolved *hotspots* separated by 90 mas (i.e., 4 R_{star})
- Cooler one may be at the position of photosphere
- VLA + Pie Town data in good agreement with the findings of Lim *et al.* (1998) (i.e., mean thermal profile, asymmetries at 0.7 cm)
- No clear signature of e-MERLIN hotspots in any of the VLA + Pie Town data
  - Time dependant?
  - Opacity? $$\frac{\tau_{6.2\,\mathrm{cm}}}{\tau_{0.7\,\mathrm{cm}}} \sim 100$$

2: Red Giant Radio Emission

- Currently cannot be spatially resolved at radio w/ls
- Wind & chromospheric properties (dM/dt, v_{ter}) generally determined by analysing strong chromospheric resonance lines.
- At cm/mm the thermal continuum Planck function depends linearly on T, unlike the UV.



α-Boo: Blue-shifted absorption component->outflow

- Continuum flux measurements at cm/mm: opacity is proportional to ~ $\lambda^{2.1} n_e n_{ion}$.

Goal 2 (a): *Observe two 'standard' red giants at all possible cm wavelengths allowing the wind temperature to be probed.*

2 (a): The Karl G. Jansky Very Large Array

Credit: NRAO

- 27 25 m antennas, New Mexico. Max baseline ~ 36 km
- Full frequency coverage between 1.0 and 50 GHz
- Continuum sensitivity improvement over the VLA by factors of 5 to 20
- Spectral Capability: A minimum of 16,384 and a maximum of 4,194,304 channels

2 (a): Targets and Observations

Arcturus (α Boo: K2 III) and Aldebaran (α Tau: K5 III)

- Single, non-dusty and non-pulsating
- Nearby (~ 11 pc and 20 pc) with well known stellar parameters
- Semi-empirical 1-D chromospheric and wind models that can be directly tested

Open Shared Risk Observing (OSRO) – B config (128 MHz)

α Boo: S → Q band (13th Feb 2011 - 22nd Feb 2011)

α Tau: S → Q band (11th Feb 2011 - 13th Feb 2011)

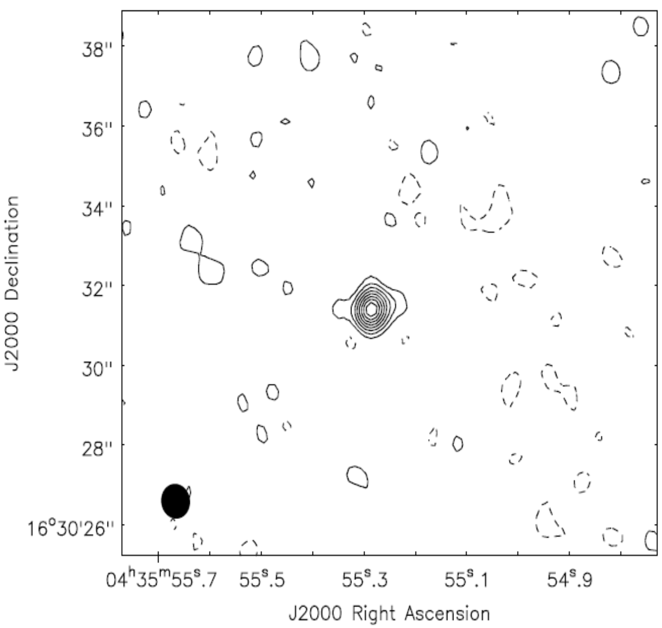
Directors Discretionary Time (DDT) – B config (2 GHz)

α Boo: S & L band (July 2012)

2 (a): Red Giant Radio Maps

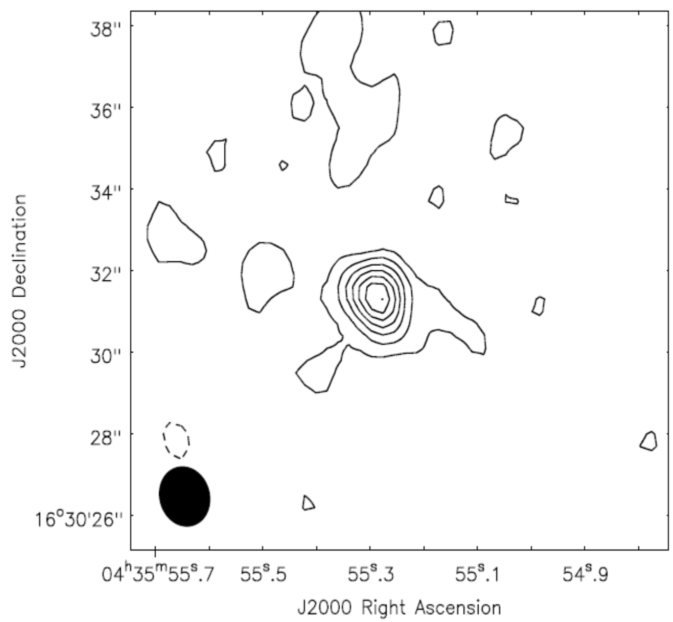
<u>Example: Aldebaran X (3 cm), C (6 cm), and S (10 cm) band</u>

X-band (8 GHz)
S_v = 0.3 mJy



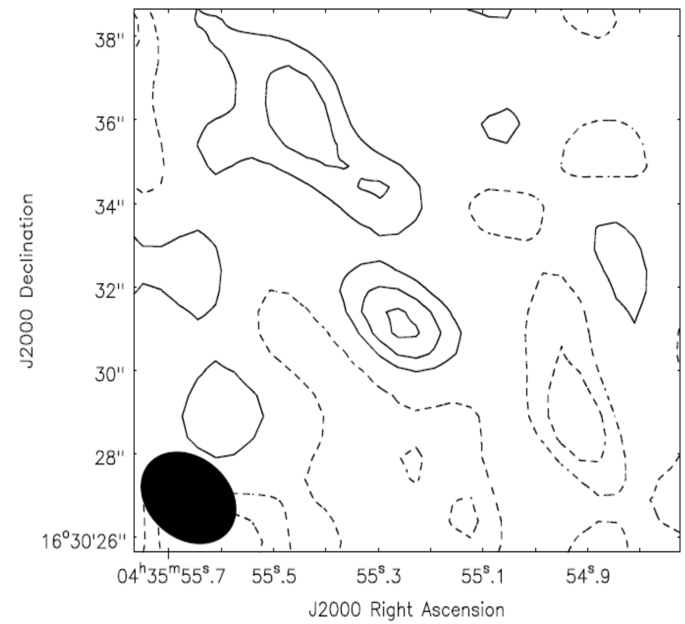
Contours = (-2,2,4......16)xσ
σ = 16 μJy

C-band (5 GHz)
S_v = 0.15 mJy



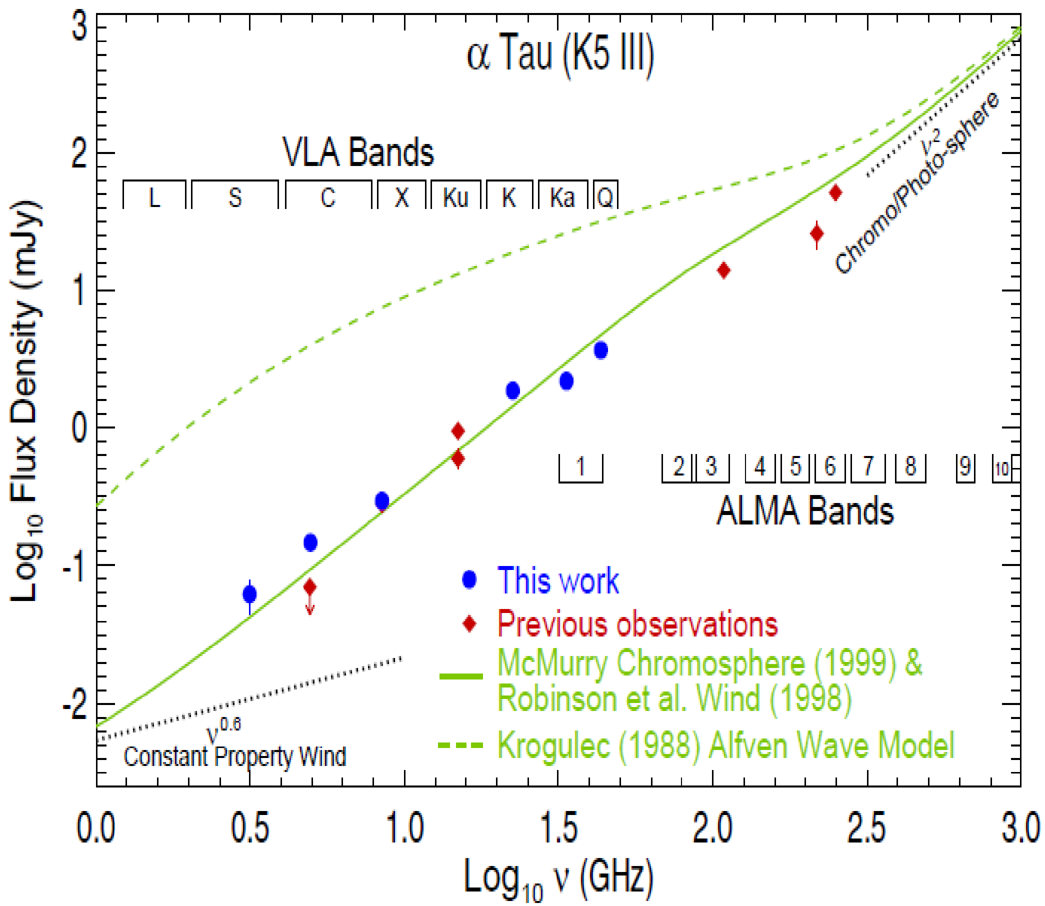
Contours = (-2,2,4,.....14)xσ
σ = 10 μJy

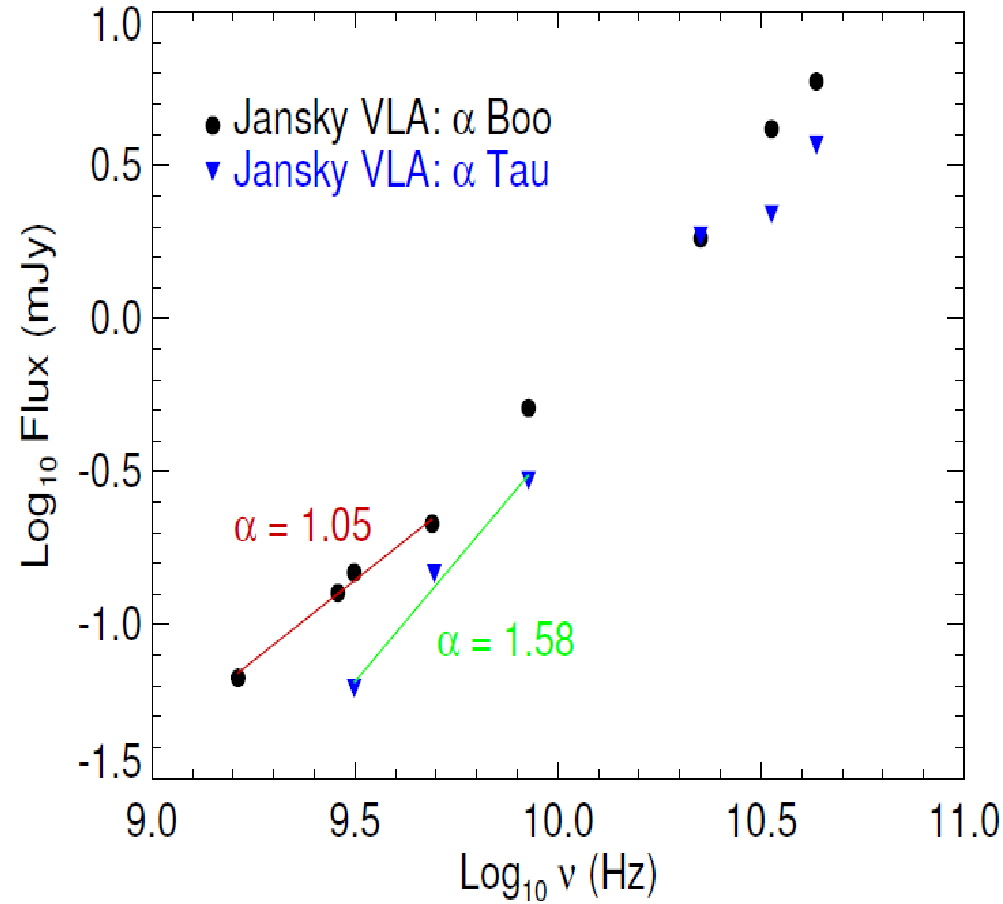
S-band (3 GHz)
S_v = 0.06 mJy



Contours = (-3,-2,-1,1,2,3)xσ
σ = 18 μJy

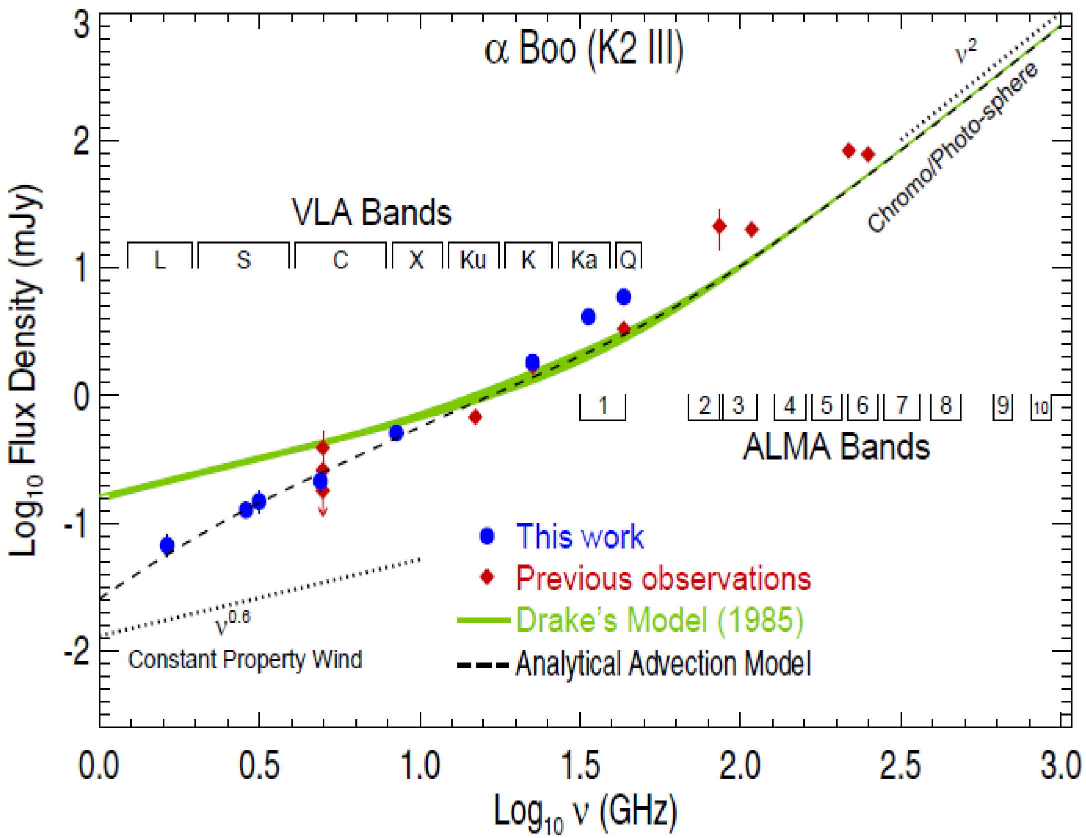
2 (a): Existing Models & Spectral Indices

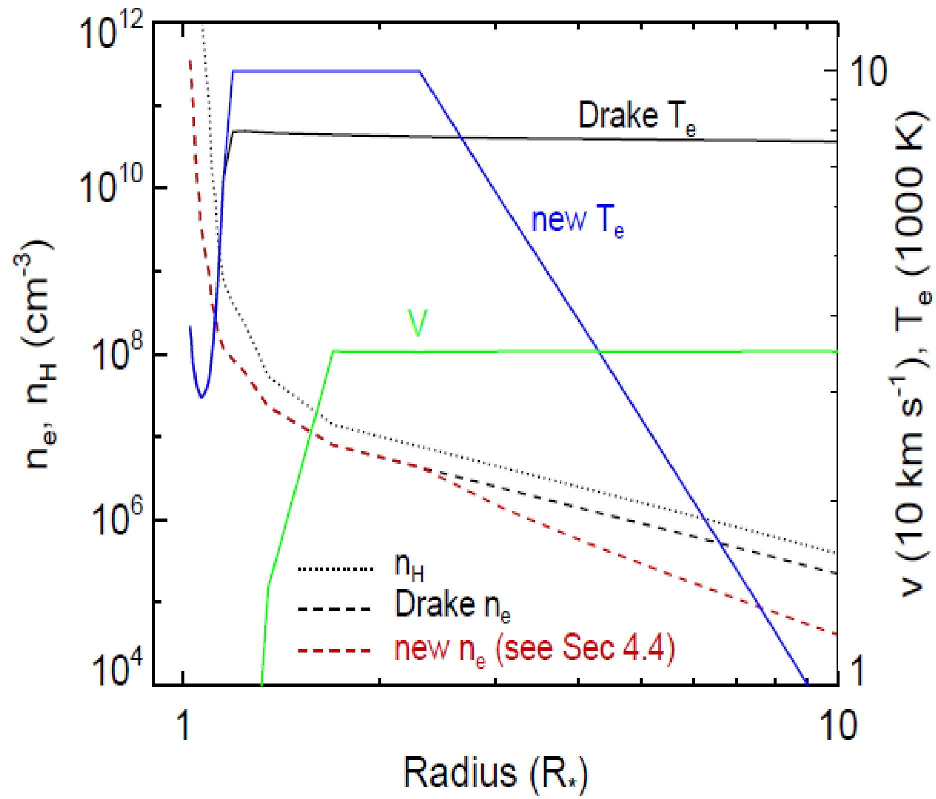




$\alpha = d \log F_\nu / d \log \nu$ Assume $n_e \sim r^{-p}$ & $T \sim r^{-n}$ then $\alpha = \frac{(4p-6.2-0.6n)}{(2p-1-1.35n)}$

2 (a): Arcturus' Wind





2 (a): Conclusions

- The most comprehensive set of multi-wavelength radio continuum observations of two *standard* red giants to date.
- Allows us to test theoretical and semi-empirical atmospheric models.
- Radio spectral indices allow flow properties to be investigated.
    - Optically thin wind for α Tau.
    - Rapidly cooling wind for α Boo.
- Analytical advection model used to develop new outer atmospheric model for α Boo.

2 (b): Thermal Energy Balance

- Close to photosphere: $v^2(r) << v^2_{esc}(r)$
- To escape star: $v^2(r) > v^2_{esc}(r)$
- Energy added in the form of either heat or momentum

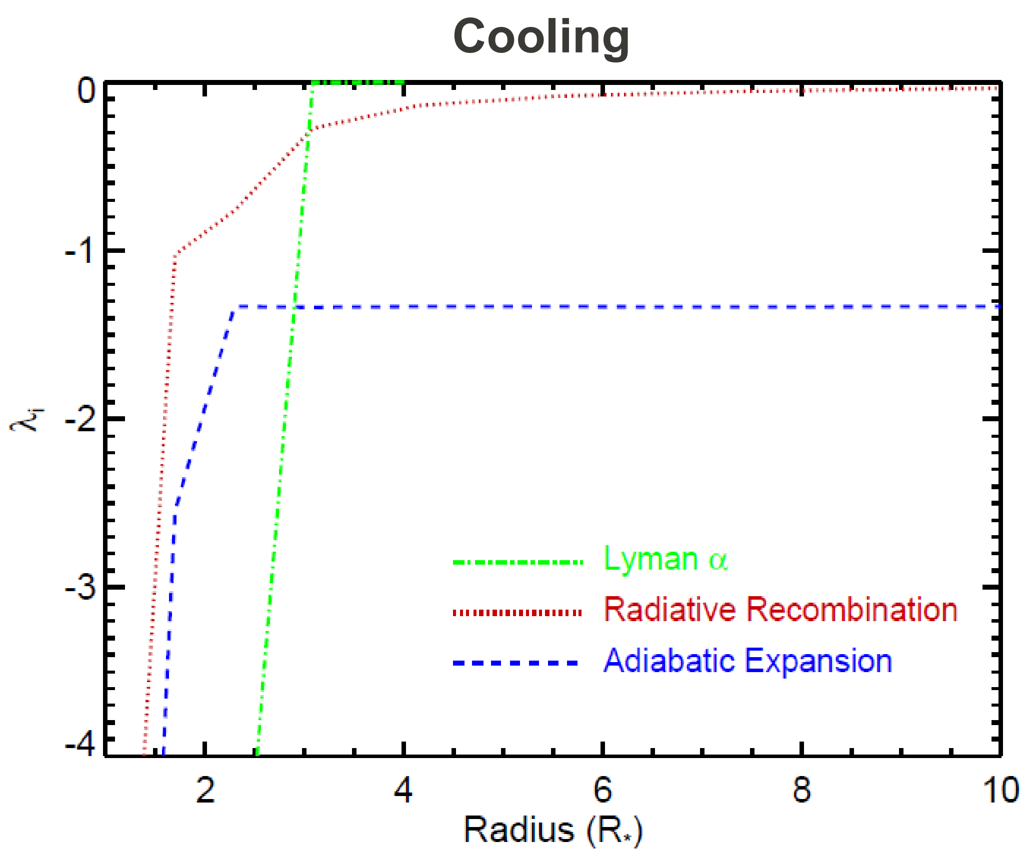
Goal 2 (b): *Carry out a thermal energy balance to investigate possible heating mechanisms in Arcturus' inner outflow region.*

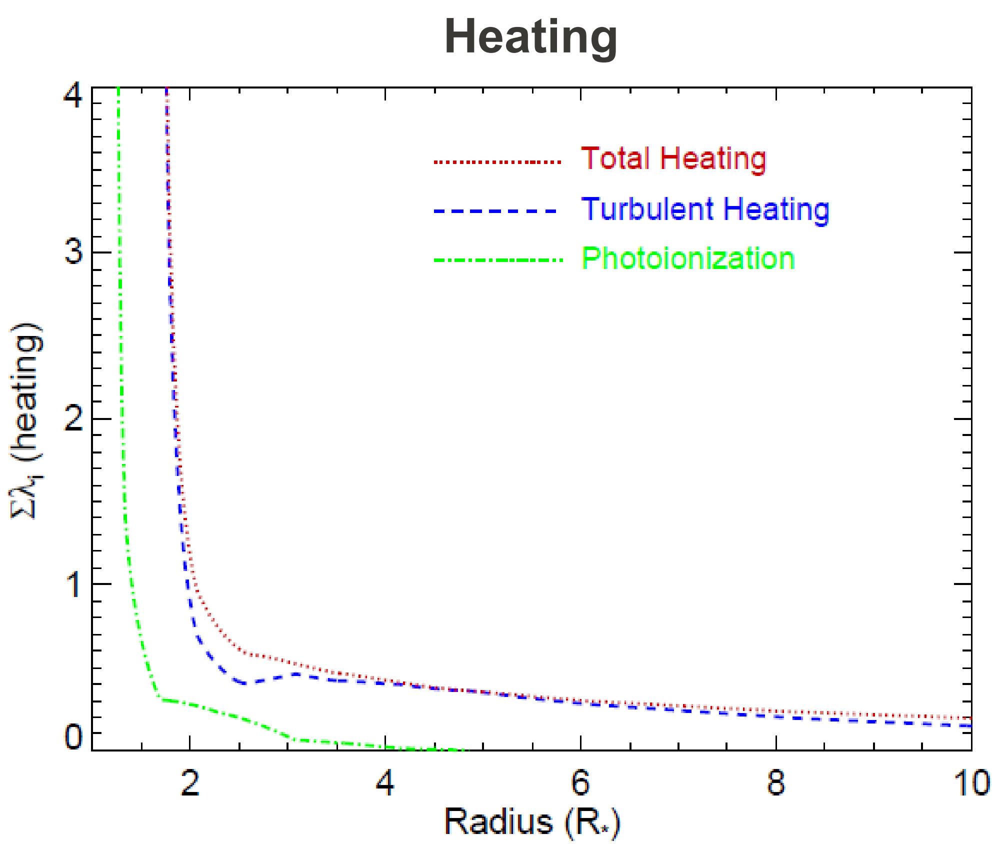
Notation:

$$\frac{d(\ln T)}{d(\ln r)} = \overbrace{-\frac{4}{3} - \frac{2}{3}\frac{d(\ln v)}{d(\ln r)}}^{\text{Adiabatic Expansion}} + \overbrace{\sum_{i=1} \mathcal{H}_i}^{\text{Heating}} - \overbrace{\sum_{j=1} \mathcal{L}_j}^{\text{Cooling}} = \sum \lambda_i$$

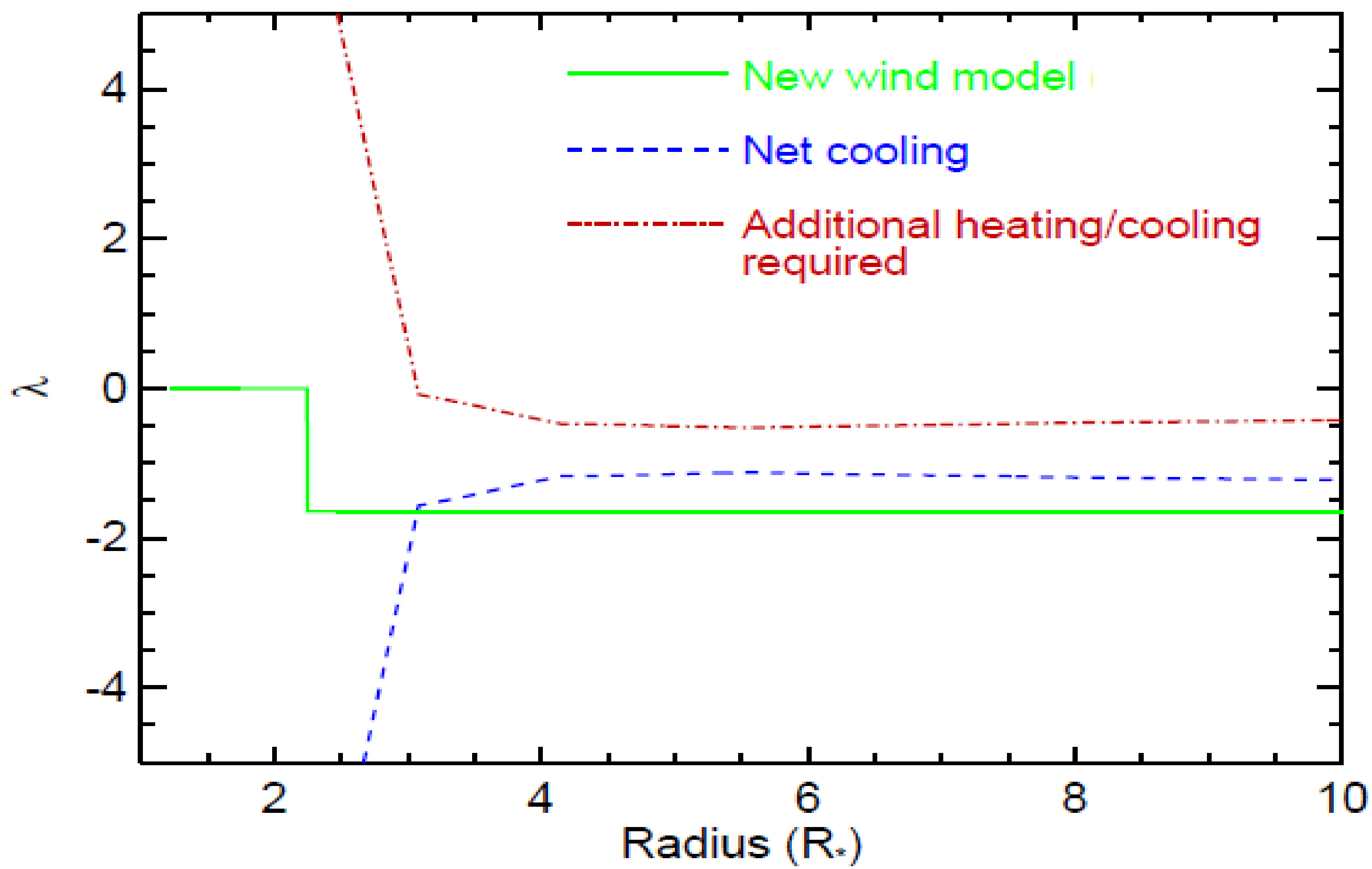
Gas kinetic power law slope

2 (b): Cooling and Heating Processes





2 (b): Cooling and Heating Processes



Concluding Remarks

- Betelgeuse has two unique outflows. Why?
  - Unique epochs of mass-loss in the last ~1100 years.
  - Change in outflow properties at certain distances.

- Evidence for assymetries in both S1 and S2 flows
  - Formed during outflow?
  - Or from mass-loss process?

- e-MERLIN has provided the surprising result of a $T_e > 5400$ *hotspot* at 4 R_{star}. Episodic? No signature in VLA data. Evidence for giant convection cells.

- Multi-wavelength radio continuum observations provide spatial information from point sources. Provide wind diagnostics and updated outflow models.

- Understanding is improving and radio interferometry will continue to play a major role in future developments