Explosive Events in the Multipolar Pre-Planetary Nebula (PPN) CRL 618

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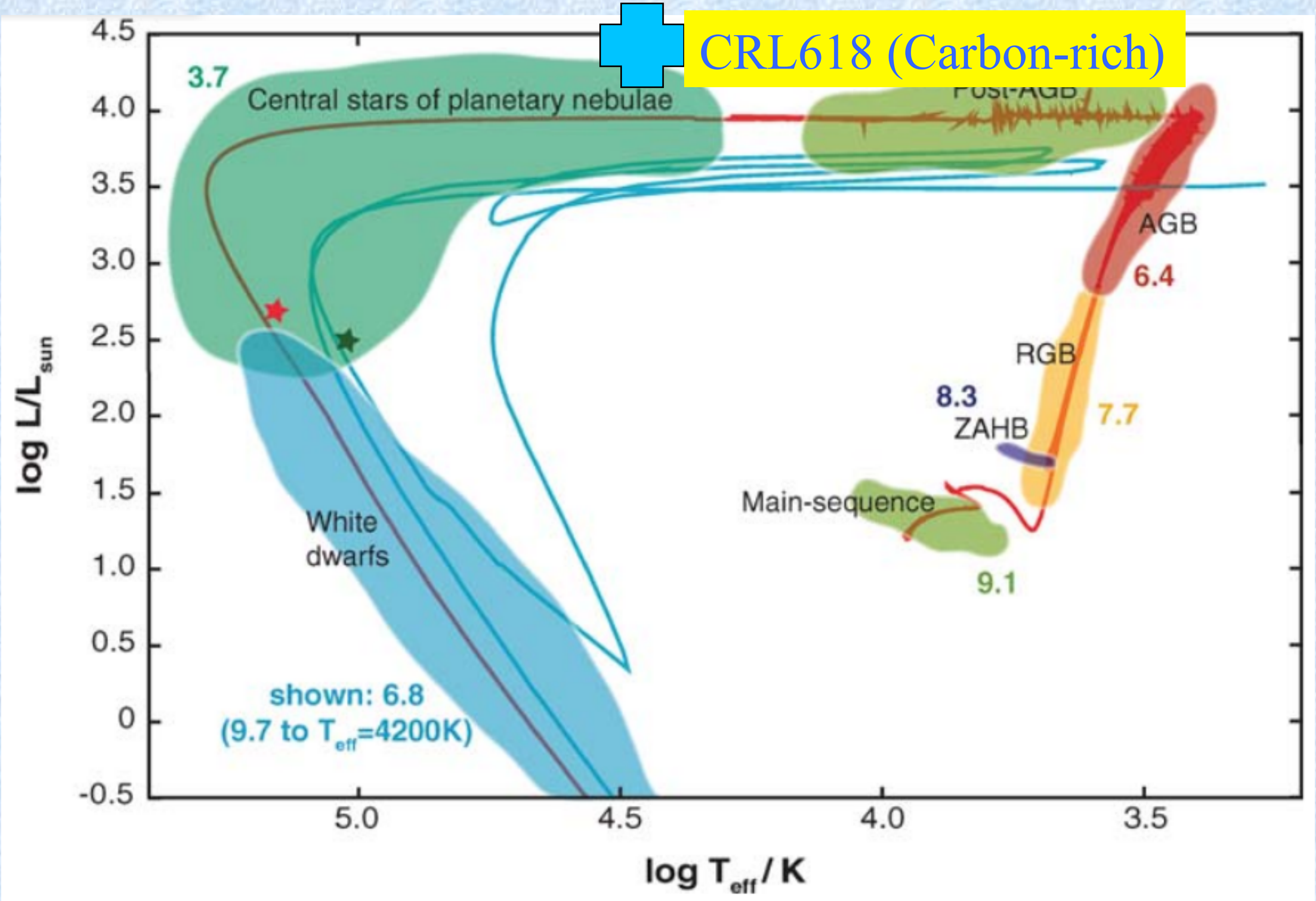
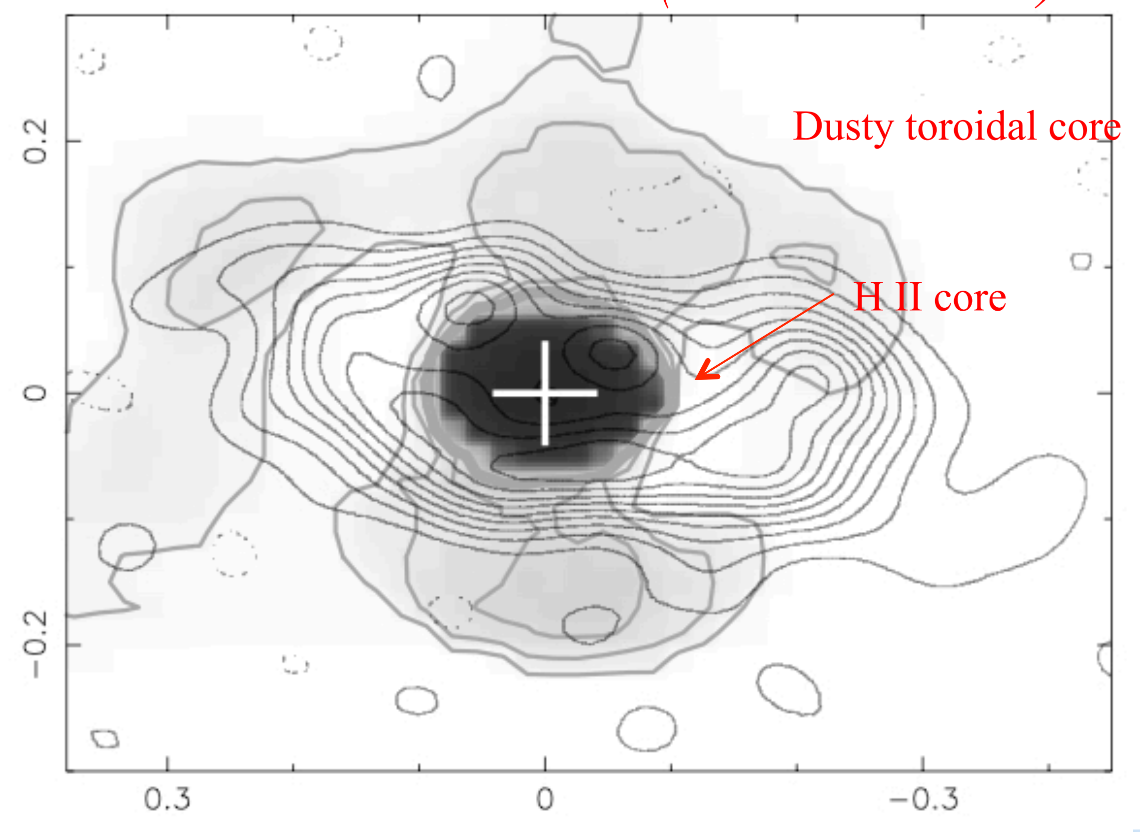
Evolutionary Track of a 2 Ms star



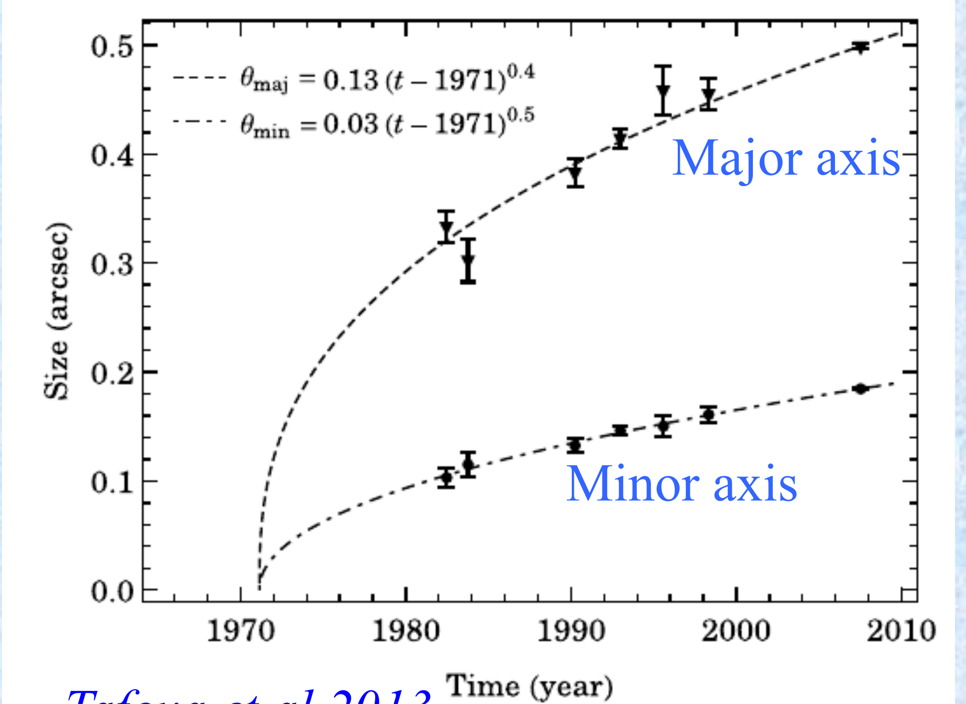
Herwig 2005

About 40 yrs ago, H II region detected at the center at cm (Wynn-Williams 1977) ➔ Entered PN phase about 40 yrs ago

SMA 0.85mm cont. (Lee et al 2013)



1.3 cm cont. (Martin-Pintado et al. 1993)



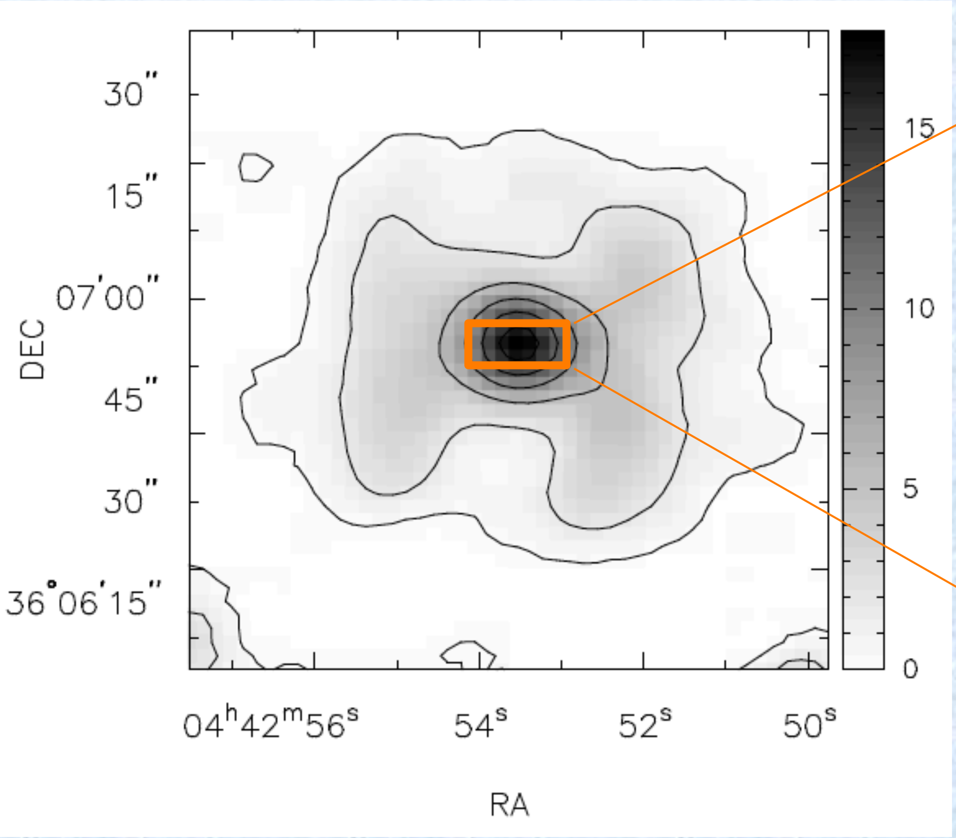
Tafoya et al 2013

Fig. 2. Increase of the size of CRL 618 at 22 GHz as a function of time.

The Ionized region (wind?) is bipolar but not spherically symmetric!

Dusty core confines the (isotropic?) ionized region (wind?) to be bipolar?

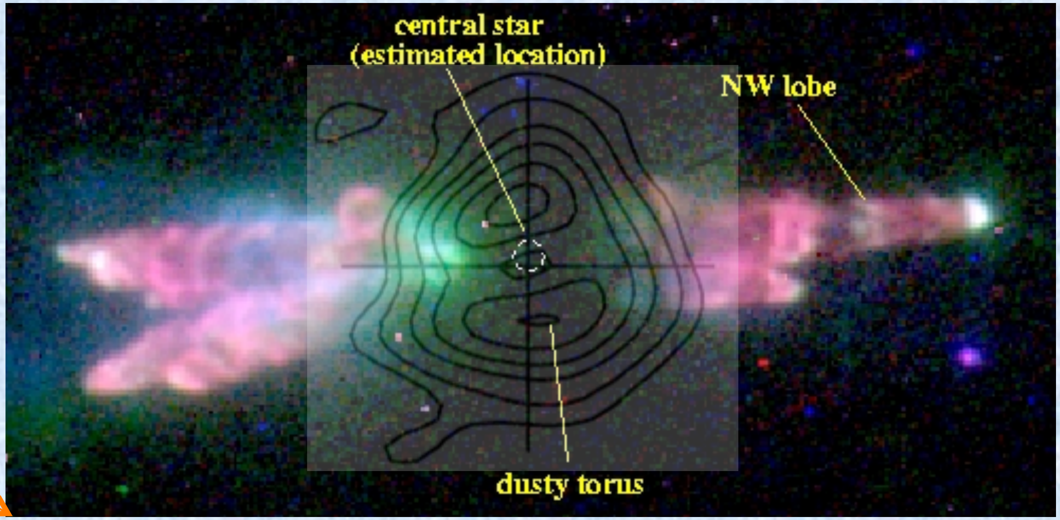
Larger-scale Expanding Components



BIMA CO J=1-0 map, Meixner et al. 1998

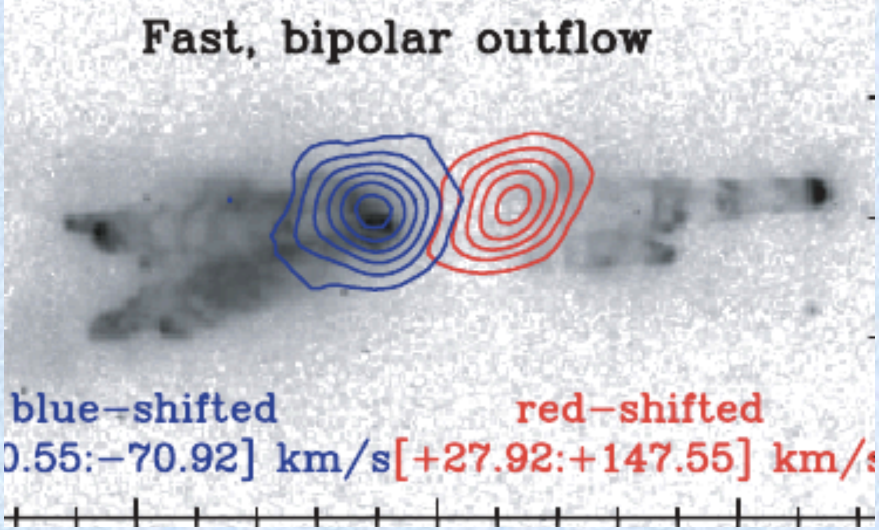
Extended expanding AGB halo

[OI] 6300 + Hα + 0.55μm cont. → Multipolar PPN lobes (Trammell et al. 2002, Sahai)

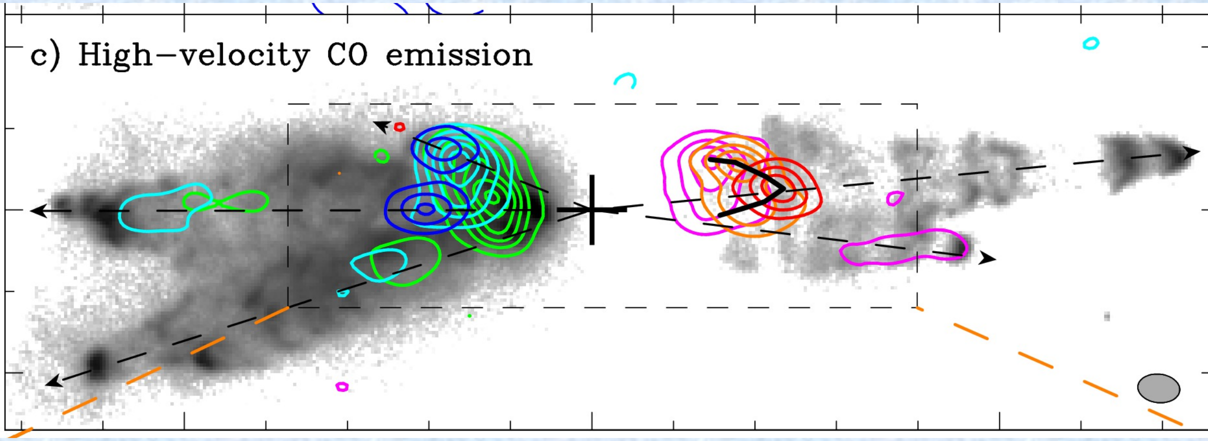


dense HC_3N toroidal core (Sanchez-Contreras et al. 2004). It confines the multipolar PPN to be in East-West direction?

Fast CO outflows



OVRO CO 2-1
(Sanchez-Contreras et al. 2004)



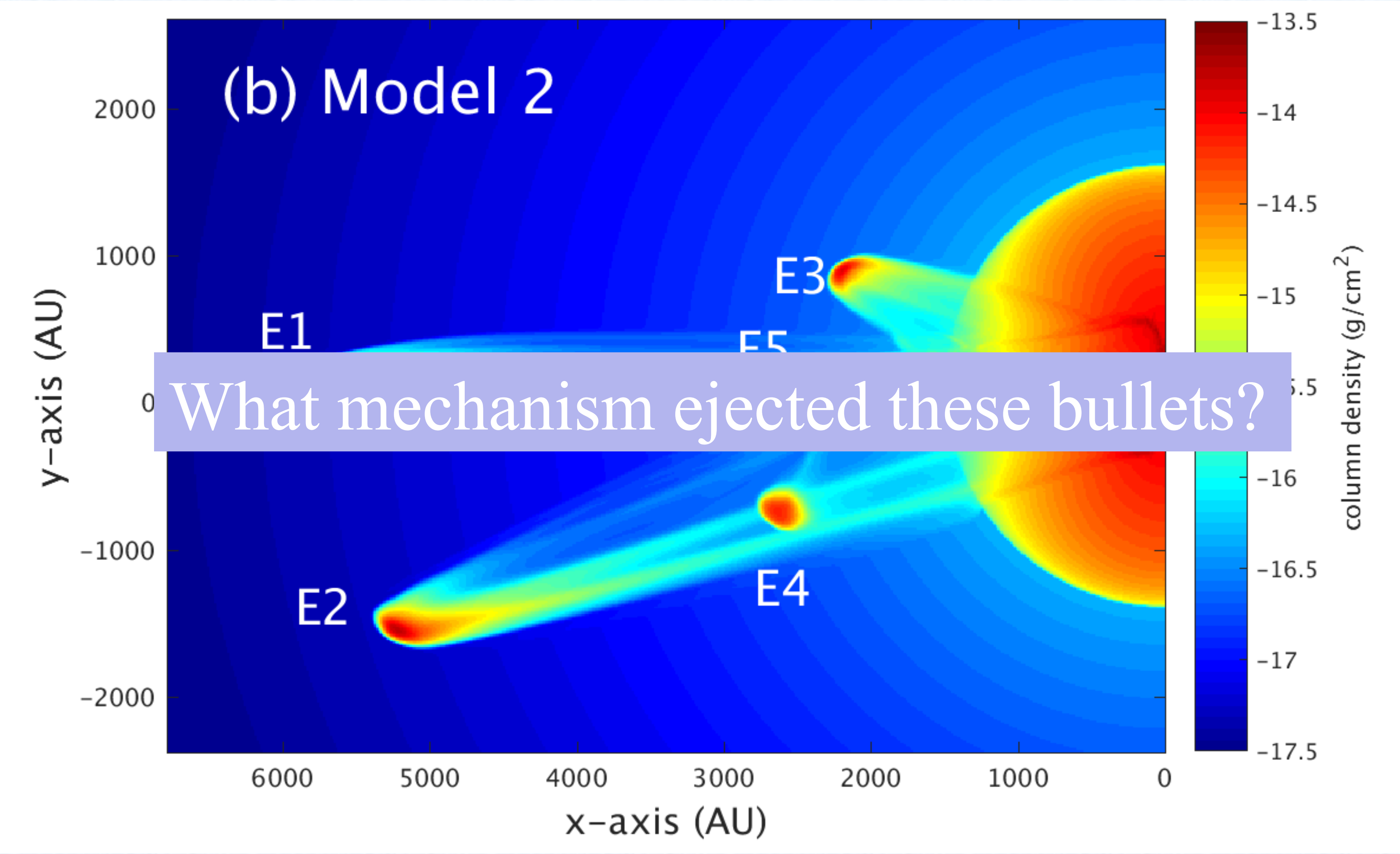
SMA CO J=3-2 (Lee et al. 2013)

Fast outflows are actually multipolar and collimated like bullets!!

Dynamical ages: about 45 yrs for inner ones and 100 yrs near the end of the optical lobes (see also Balick et al. 2013).

INTERESTINGLY: The inner outflows were ejected right before/at the same time when the PN phase started!

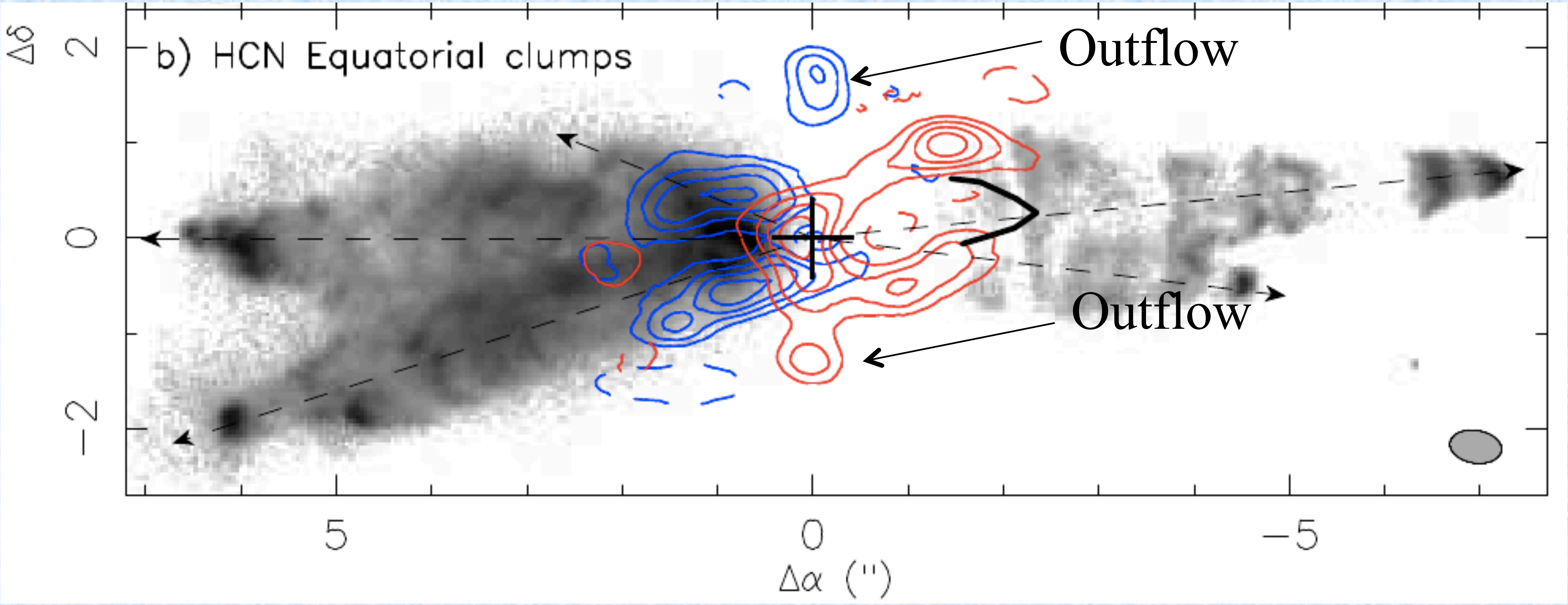
Two-Epoch Multi-Directional Bullet Model For the East-side



What mechanism ejected these bullets?

See Poster by Huang, Lee et al. (Poster Number: P2.05)

Equatorial molecular outflows?



They have opposite velocity sense and thus are unlikely to trace the expanding halo material in the equatorial plane. Their velocity is too high to be due to rotation around the central star. Hence, they likely trace outflows in the equator!?

Explosion driven by a rotating, magnetized, gravitating sphere?

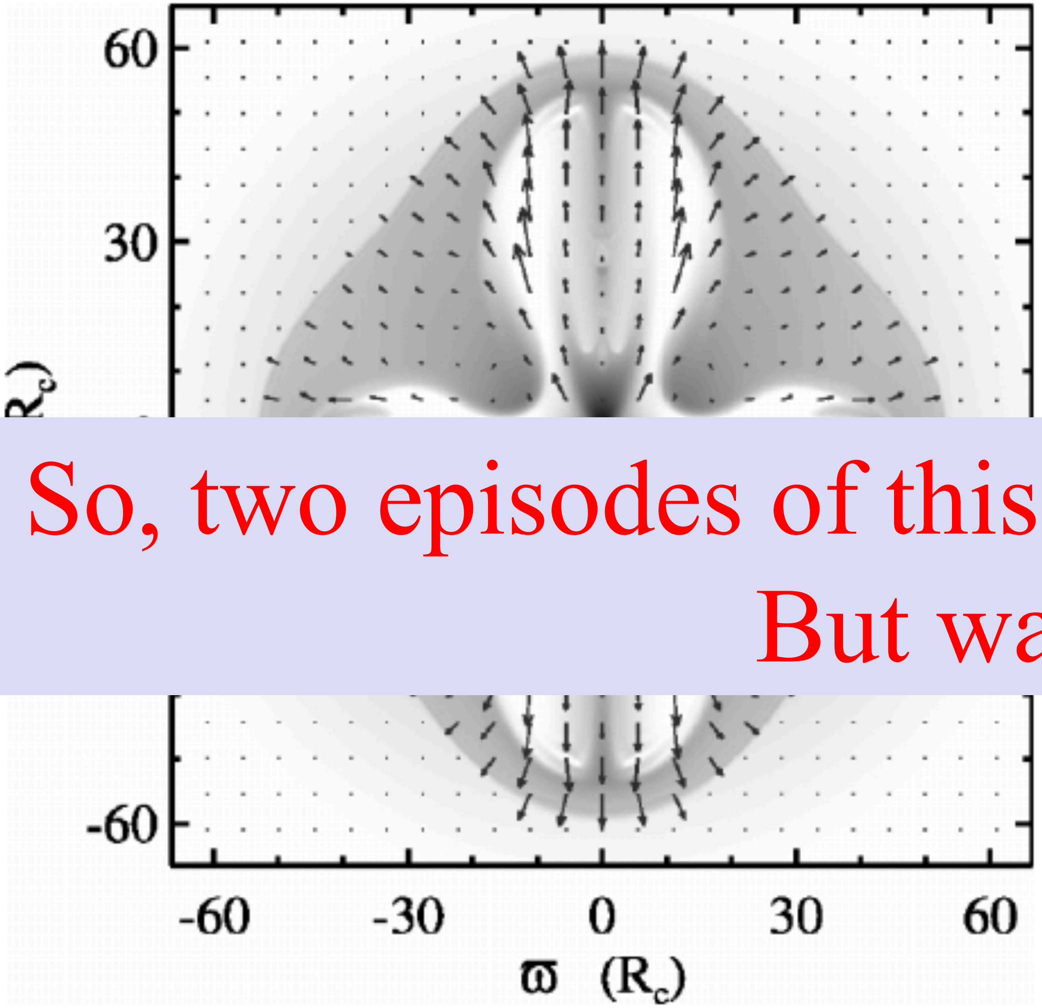


FIG. 2.—Gray-scale image of log density (black is highest density) far from the core, shown after 4.5 rotations of the core. The data are from the fourth simulation grid. The core is indicated by a white circle at the center. Vectors represent the flow velocity, with the maximum vector length corresponding to $4.1v_{rot}$.

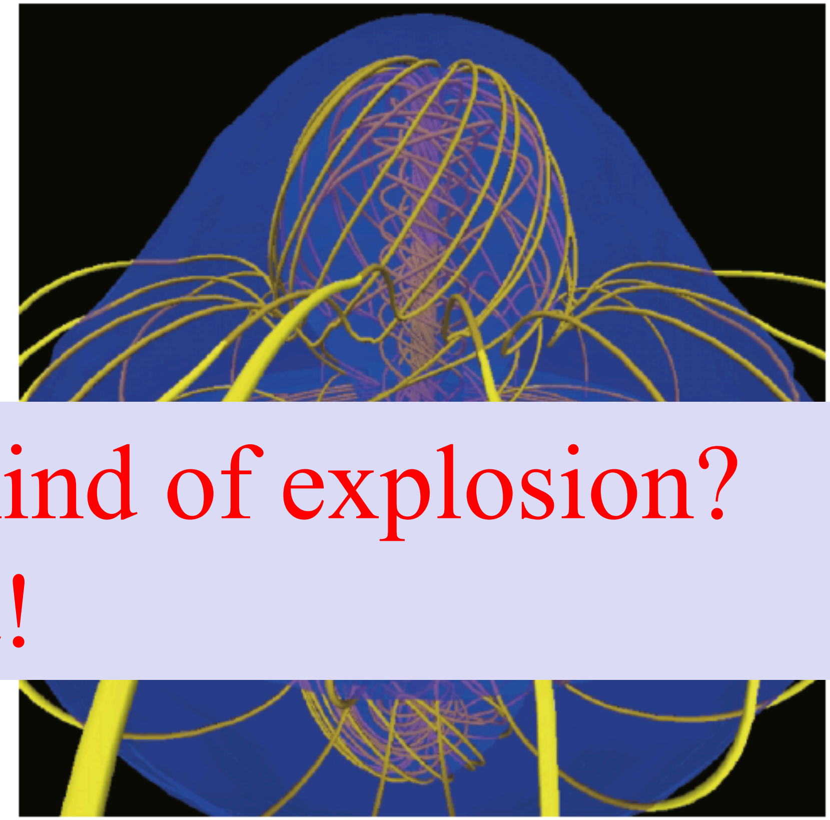


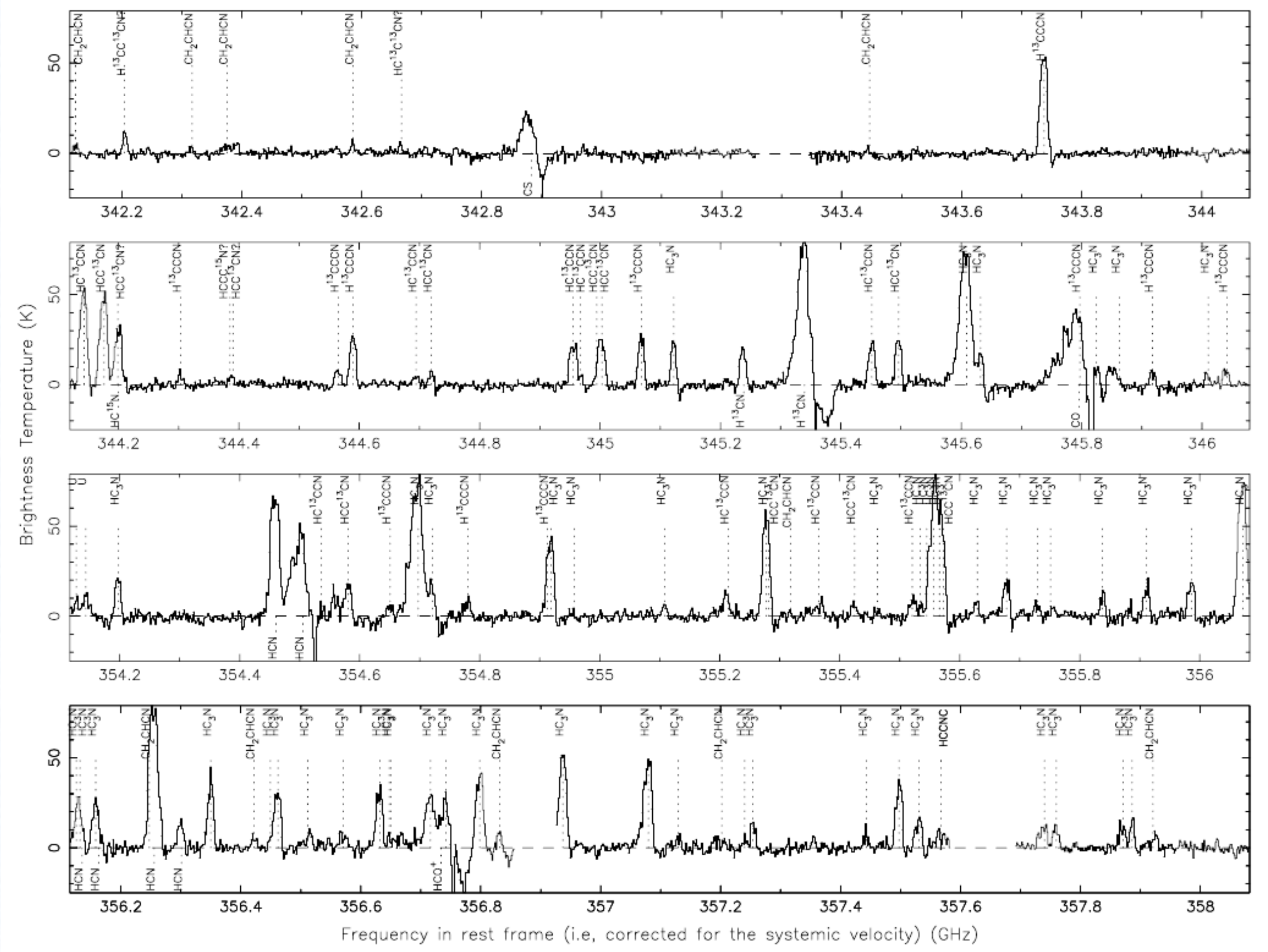
FIG. 3.—Three-dimensional rendering revealing the explosion mechanism, viewed from ~30° above the magnetic equator. The two blue surfaces are contours of constant density, each at the same density value. The dense shell of swept-up envelope material (see Fig. 2) exists between the two surfaces. Gold wires trace the magnetic field lines and illustrate that the field is most highly twisted in the low-density region interior to the shell.

So, two episodes of this kind of explosion?

But wait!

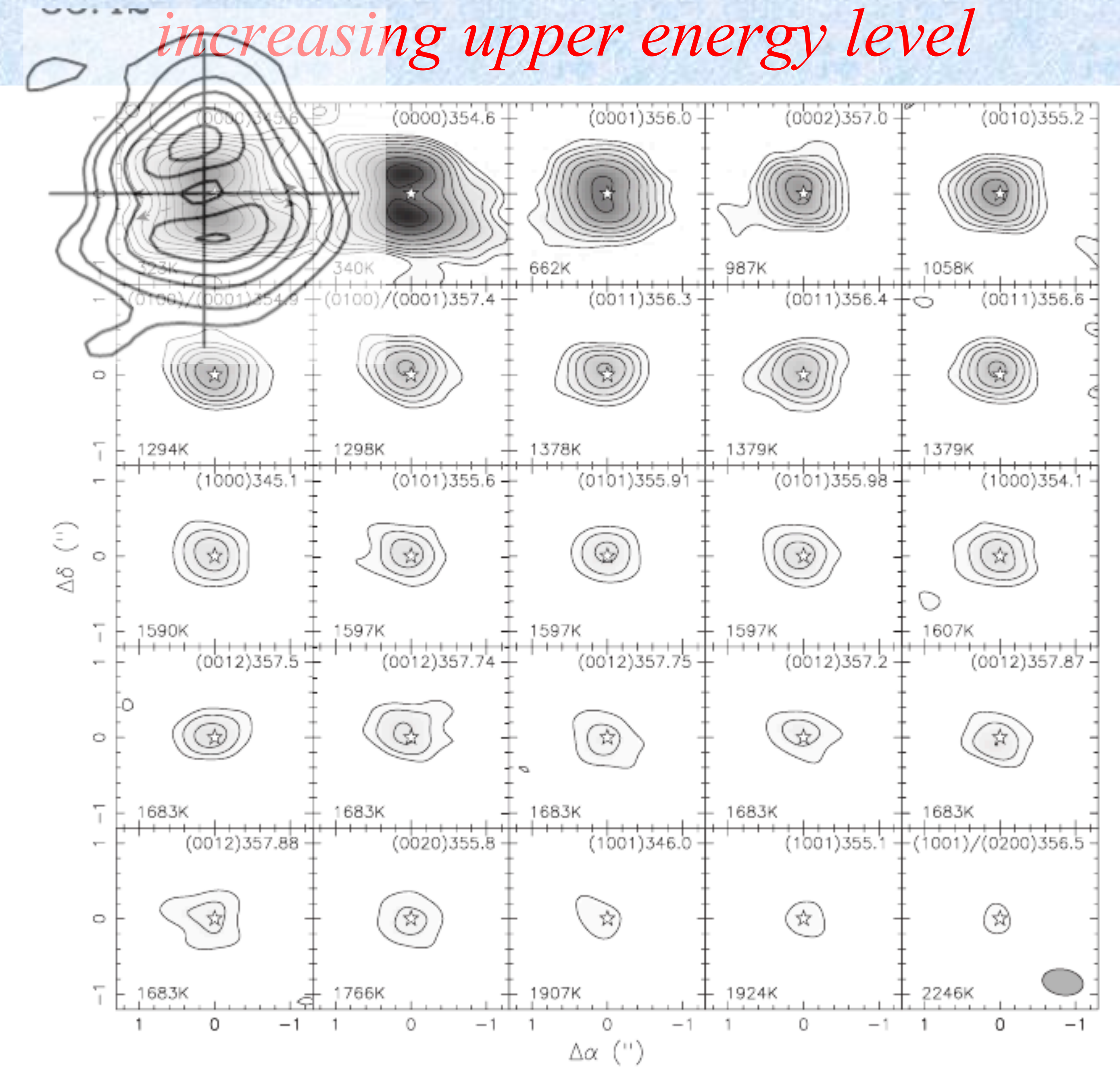
Matt et al. 2003

SMA molecular line spectra of the dense core



Lee et al. 2013

SMA HC_3N maps of the dense core in the order of increasing upper energy level



T increases toward the central star

Model the H II region and dusty core

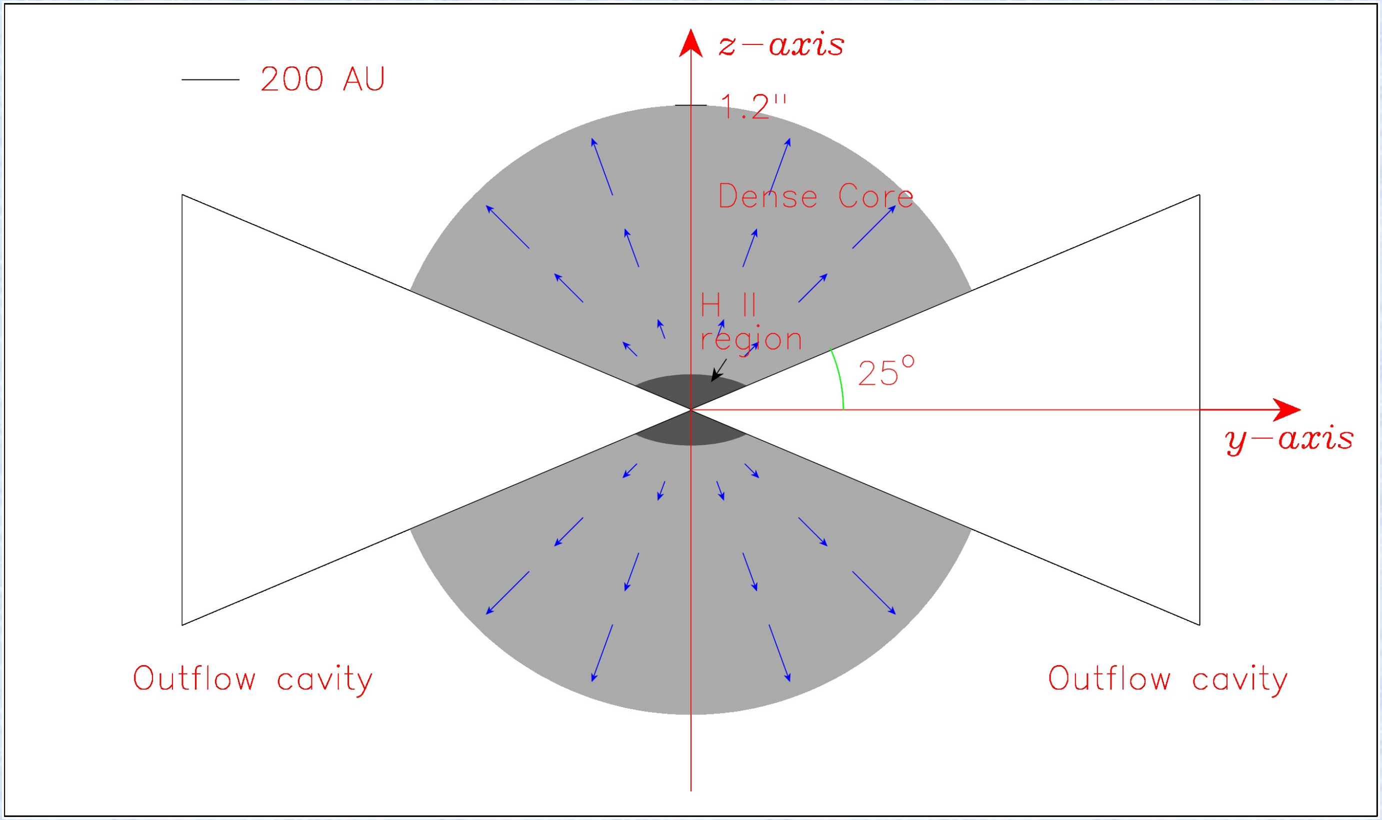


Table 3
Model Parameters

Species	Abundance
HC_3N	$2 \pm 0.4 \times 10^{-7}$
$H^{13}CCCN$ }	
$HC^{13}CCN$ }	$2 \pm 0.4 \times 10^{-8}$
$HCC^{13}CN$ }	
$H^{13}C^{13}CCN$ }	
$HC^{13}C^{13}CN$ }	$2 \pm 0.4 \times 10^{-9}$
$HCC^{13}C^{13}N$ }	
CH_2CHCN	$3 \pm 0.6 \times 10^{-8}$
HCN	$1.4 \pm 0.3 \times 10^{-7}$
$H^{13}CN$	$1.8 \pm 0.4 \times 10^{-8}$
$HC^{15}N$	$1.1 \pm 0.3 \times 10^{-9}$
Parameter	**Value**
n_{e0}	$6.4 \pm 1.3 \times 10^6$ cm^{-3}
r_0	$0''.22 \pm 0''.04$
T_0	440 ± 90 K
p_i	0.8 ± 0.2
p_o	1.8 ± 0.4
n_0	$4.0 \pm 0.8 \times 10^8$ cm^{-3}
v_0	4.9 ± 0.5 km s^{-1}
κ_ν	0.022 ± 0.004 cm^2 g^{-1}

Note. The uncertainties are assumed to be 20% for all parameters.

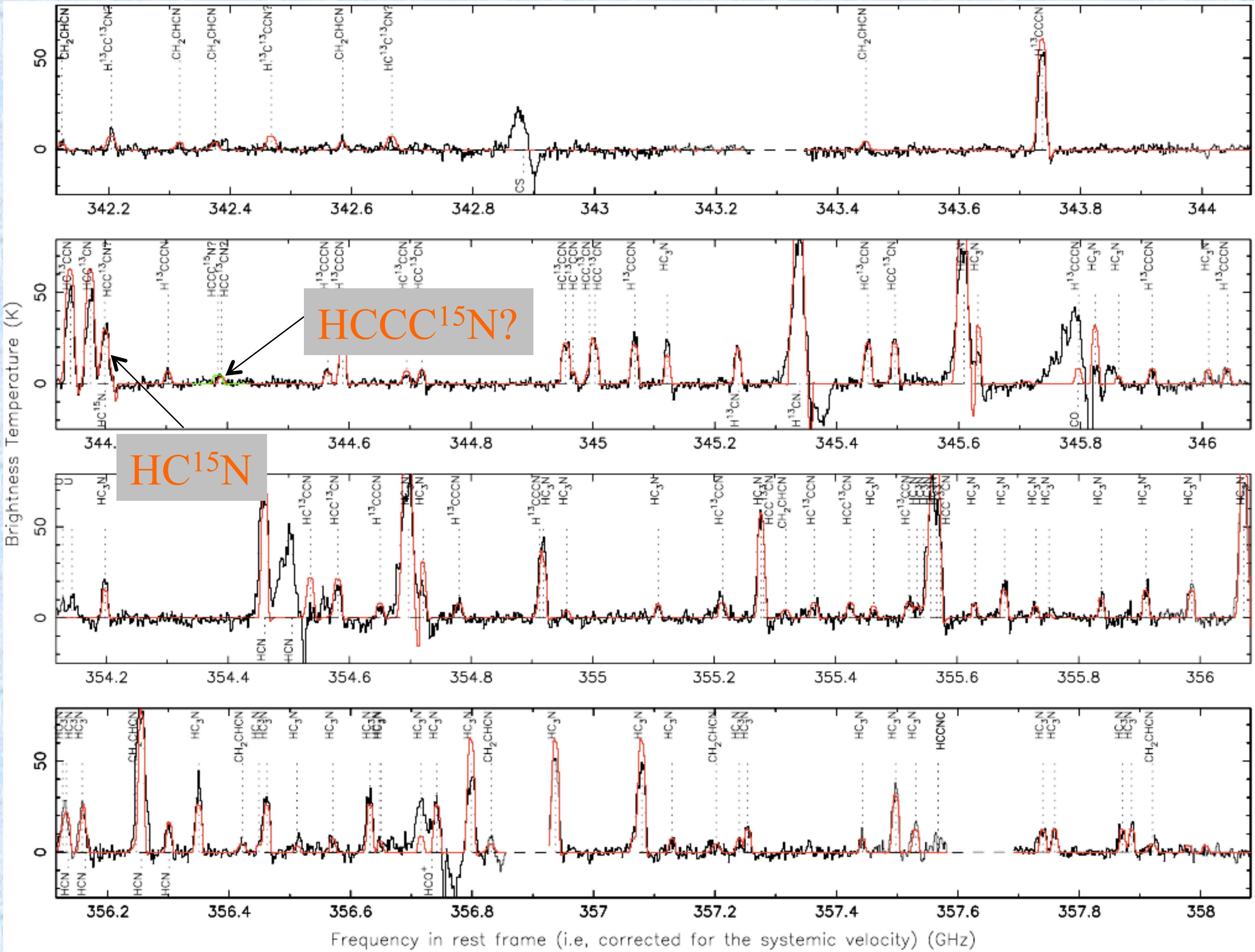
Observation results:

1. Velocity increases linearly with the distance.
2. Temperature increases toward the center.

Assumption: Constant mass-loss rate

Lee et al. 2013

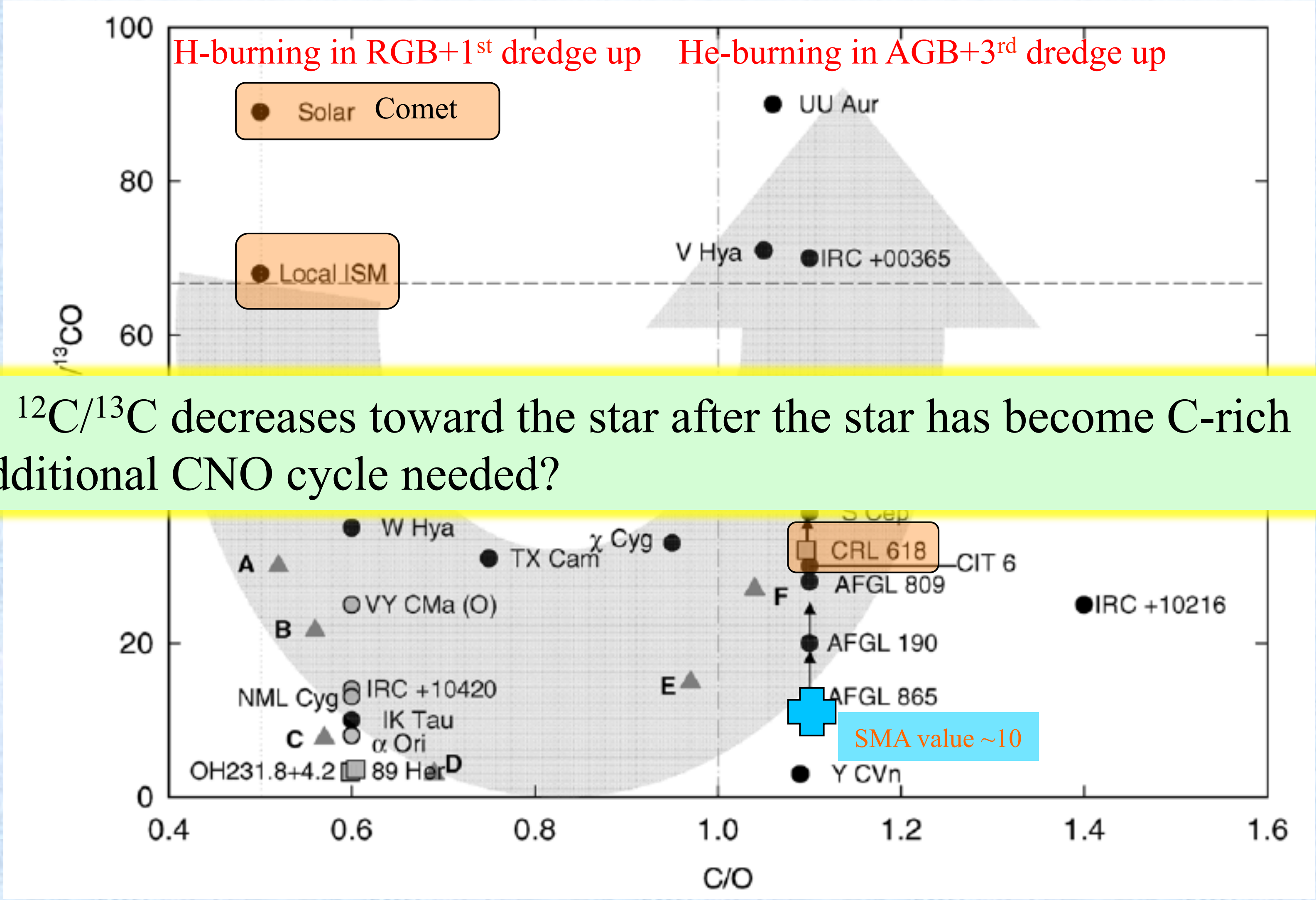
SMA molecular line spectra of the dusty core



Physical Properties of the dense core

- The dense core is expanding, with the velocity increasing roughly linearly from 3 to 16 km/s at 630 AU.
- The dense core has a mass of ~ 0.47 Ms and a dynamical age of 400 yrs.
- The mass-loss rate in the dense core is extremely high with a value of 1.15×10^{-3} Ms/yr.
- It could result from a recent enhanced heavy mass-loss episode that ends the AGB phase.
- Interestingly, *$^{12}C/^{13}C \sim 10$, $^{14}N/^{15}N \sim 150$, both lower than expected.*

Comparing our $^{12}C/^{13}C$ ratio to previous Single-dish Study



➔ $^{12}C/^{13}C$ decreases toward the star after the star has become C-rich
Additional CNO cycle needed?

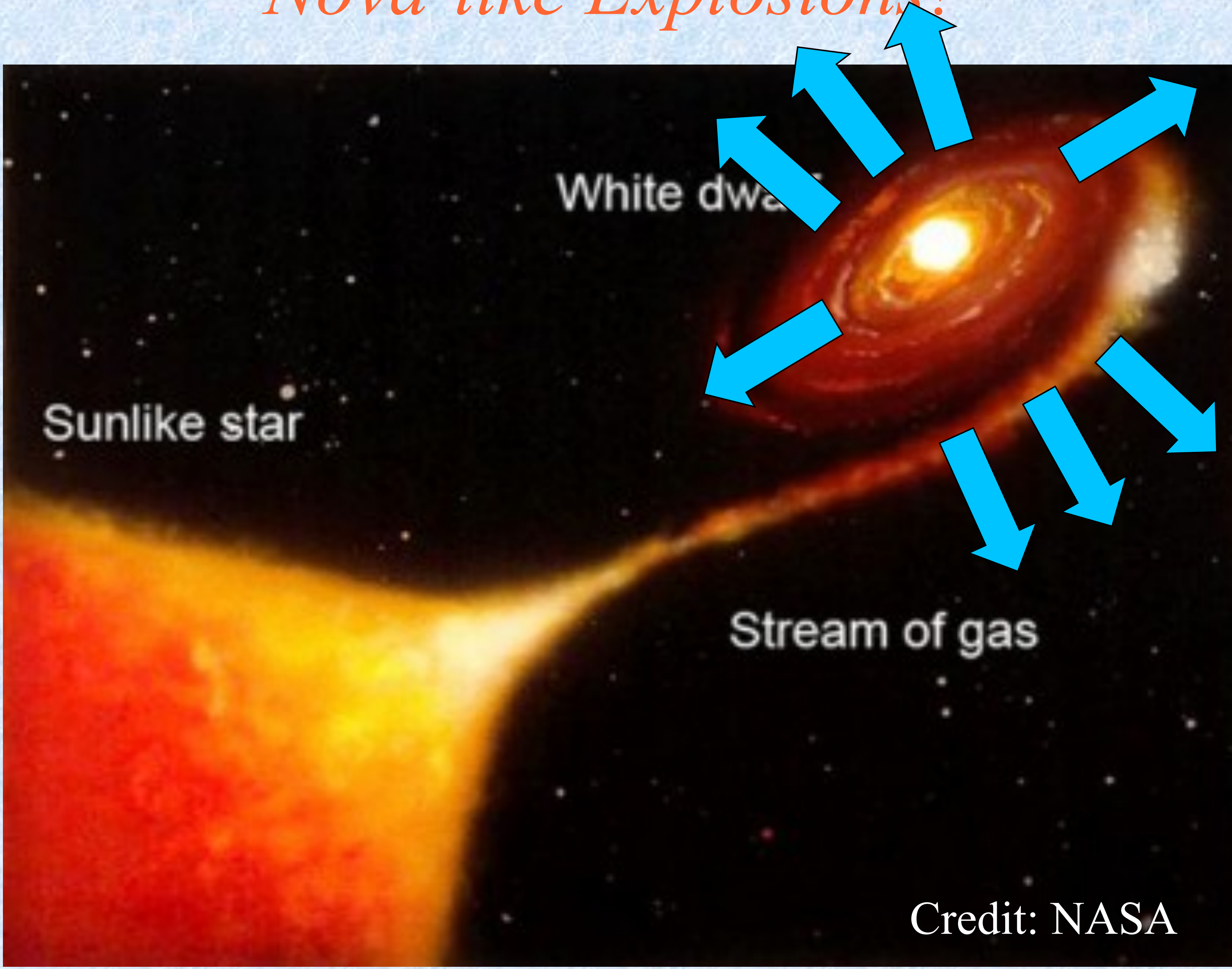
Single-Dish (large-scale) $^{12}CO/^{13}CO$ *results of supergiants (gray cirlces), AGB stars (black circles) and PPNs (gray squares) by Milam et al. 2009*

Our Model Results

Isotope ratio: $^{14}N/^{15}N \sim 150$,
much lower than those found in C-rich AGBs, PPN (Wannier et al. 1991)

Cold CNO cycle tends to destroy ^{15}N, producing $^{14}N/^{15}N > 2000$.
So, may need a hot CNO cycle as in novae to produce our value?

Nova-like Explosions?



Speculations?

About 100 yrs ago, an explosion took place, shooting bullets into the AGB envelope, producing the collimated multipolar outflow lobes.

About 45 yrs ago, a 2^{nd} explosion(?) took place, producing the heavy fast molecular bullets/outflows near the central star.

Right after that, the exposed stellar core photoionizes the surrounding, driving a radiation-driven ionized wind, collimated (bounded) by the dense toroidal core (envelope)?