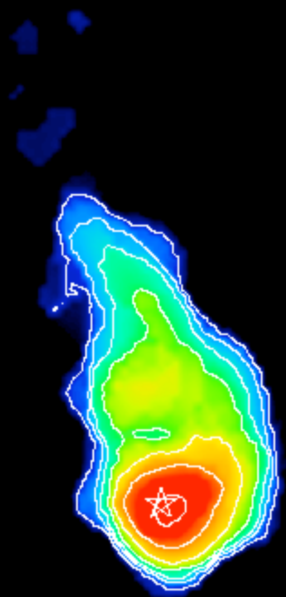
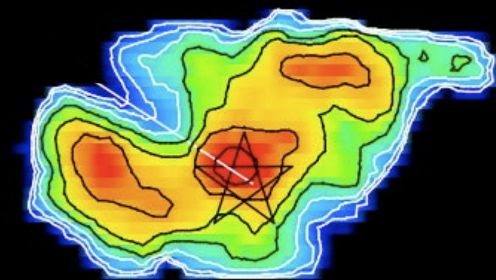
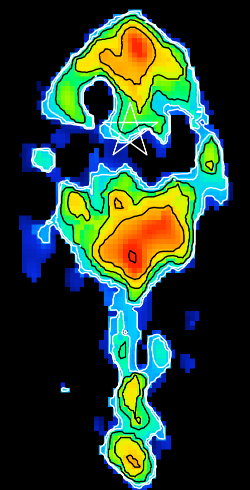
Mass-Losing Stars and Their Environments as Traced by the HI 21-cm Line







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Circumstellar HI as a Probe of Stellar Mass-Loss

Atomic hydrogen is expected to be present in the extended atmospheres and CSEs of most AGB and related stars.

Observations of circumstellar HI (via its 21-cm line) can play an important role in improving our understanding of stellar mass-loss:

(1) HI is not readily destroyed by the interstellar radiation field

⇒ *a means to sample circumstellar material to significantly larger distances from the star than molecular line tracers (>10^{16} cm)*

⇒ *ability to sample larger fraction of the stellar mass-loss history (>10^{5} yr)*

(2) Supplies independent estimates of mass-loss parameters and CSE mass

(3) Provides *kinematic* information on a variety of scales

(4) Can probe the *interaction* between the CSE and the ambient ISM

Interferometric imaging studies of evolved stars in the HI 21-cm line provide:

- more detailed characterization of velocity field and geometry of the emission

- effective filtering of Galactic contamination along the line-of-sight

The HI imaged sample of red giants:

- 16 stars observed to date (12 detected; 4 undetected)

- Sample includes:
  - singles, binaries
  - a range of
    - chemistries (C/O>1; C/O<1; C/O~1)
    - variability classes (Mira, SRa, SRb, Lb)
    - temperatures (~2000-3650 K)
    - mass-loss rates (~10^{-8} to 10^{-5} $M_{\odot}$ yr^{-1})
    - ouflow speeds (~4 to 22 km/s)

- Selection criteria:
  - robust detection from single-dish observations

    and/or
  - position/velocity displaced from strong Galactic emission

    and/or
  - comprehensively studied at other wavelengths

A VLA Imaging Study of Circumstellar HI: Observational Details

Array Configuration: D (most compact)

Angular resolution: ~1′

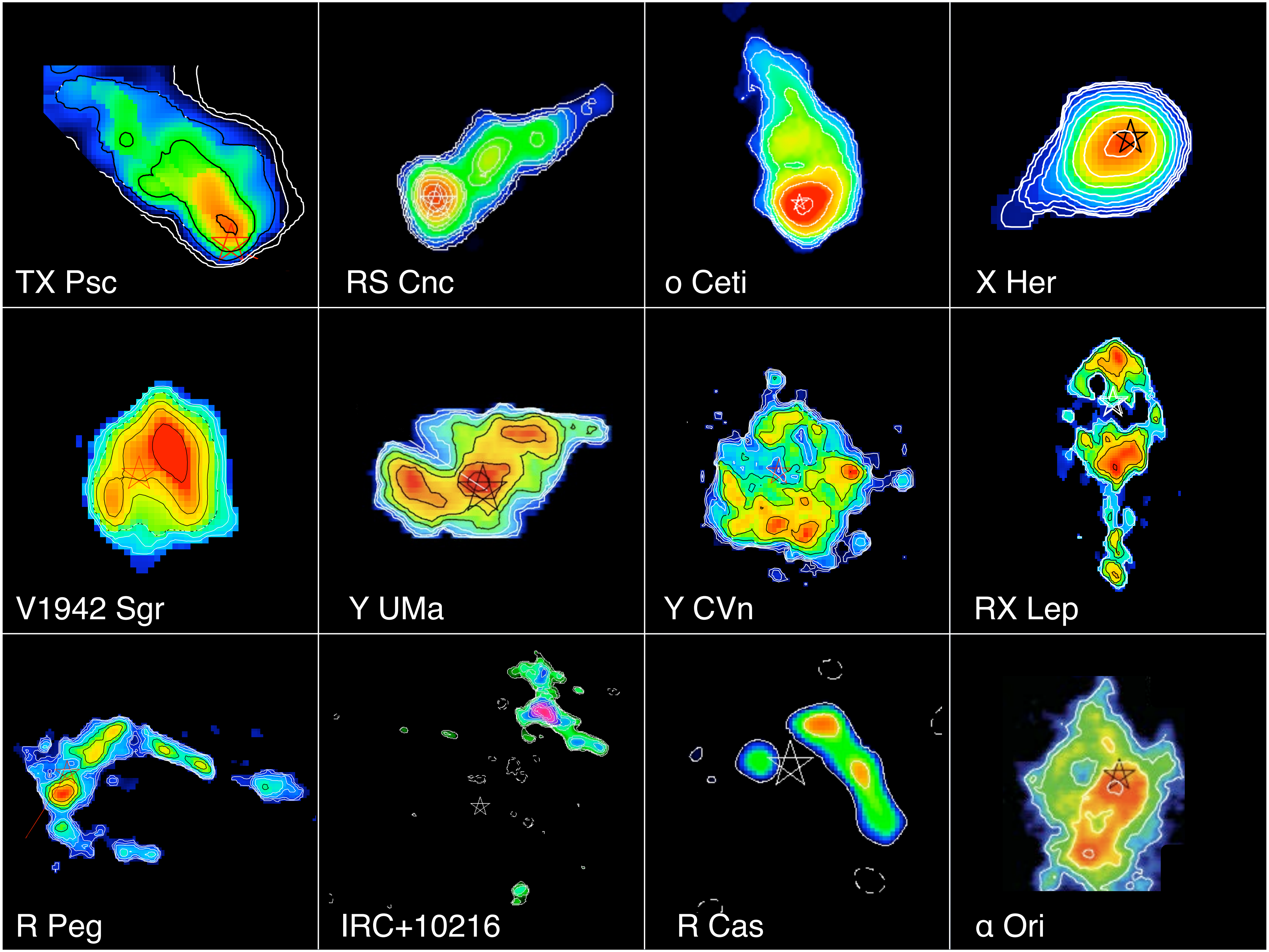
Maximum angular scales: ~15′

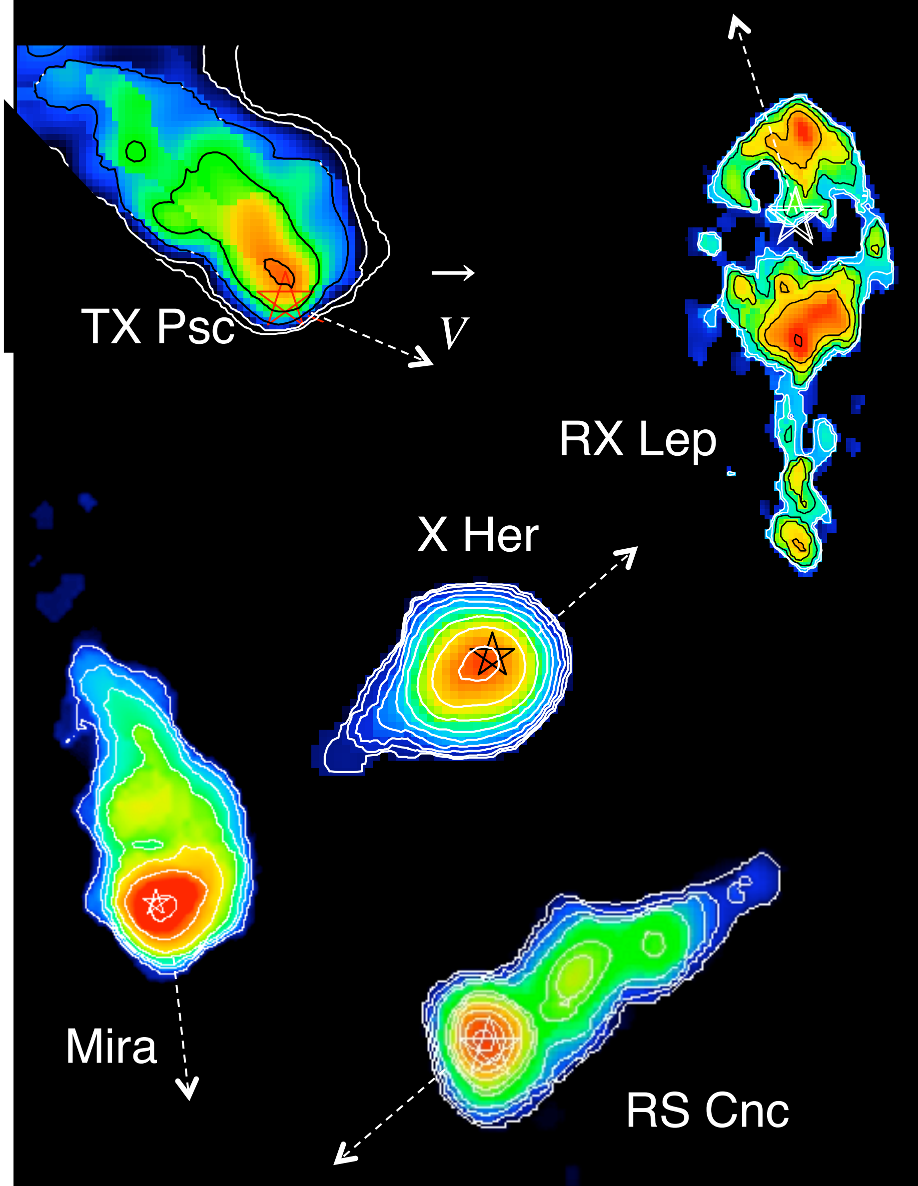
Primary beam: ~30′

Spectral resolution: 0.6 –1.3 km/s

Integration times: ~1.5 – 10 hours

Sensitivity: ~1 – 2 mJy/beam

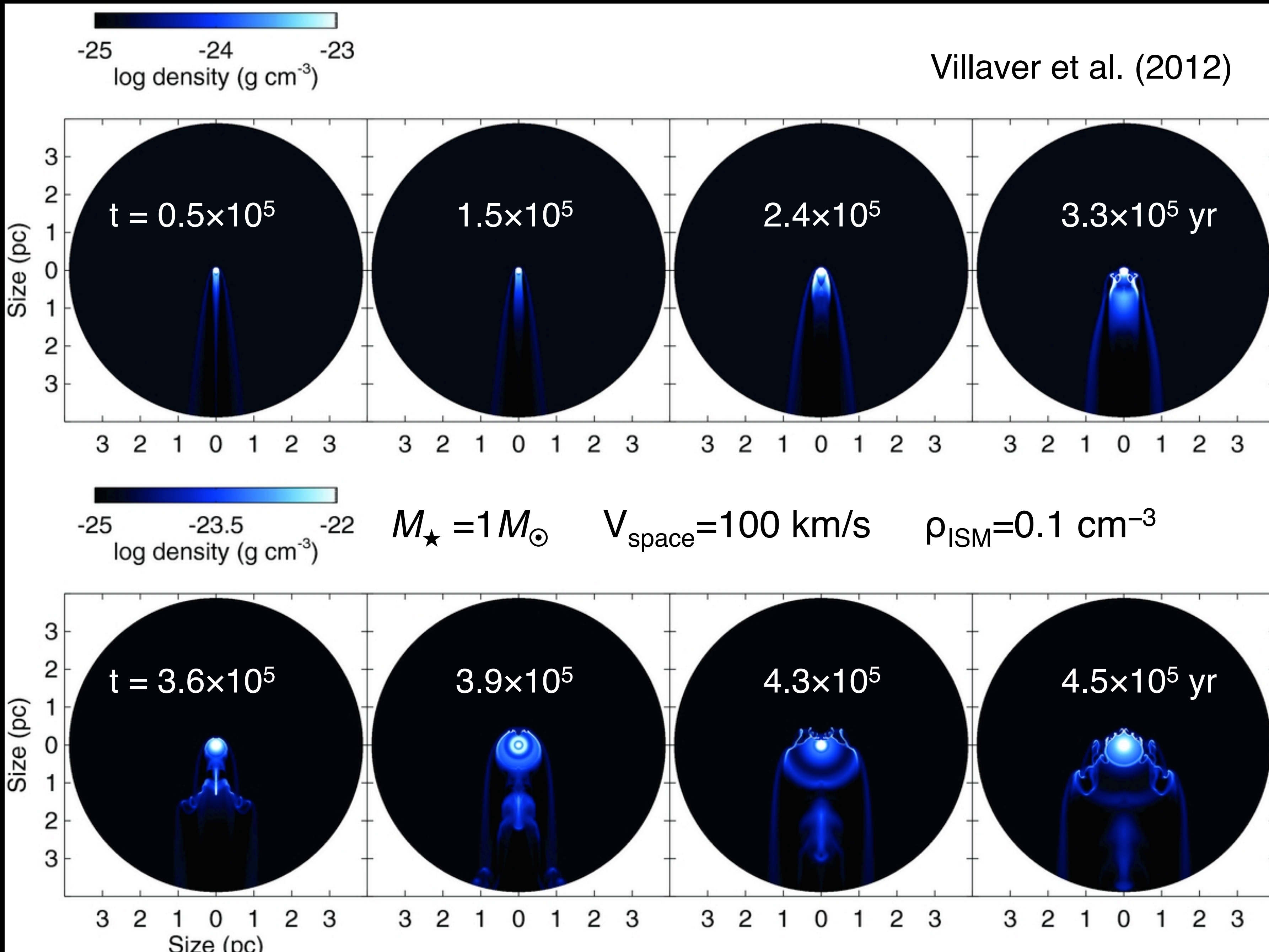

TX Psc
RS Cnc
o Ceti
X Her
V1942 Sgr
Y UMa
Y CVn
RX Lep
R Peg
IRC+10216
R Cas
α Ori



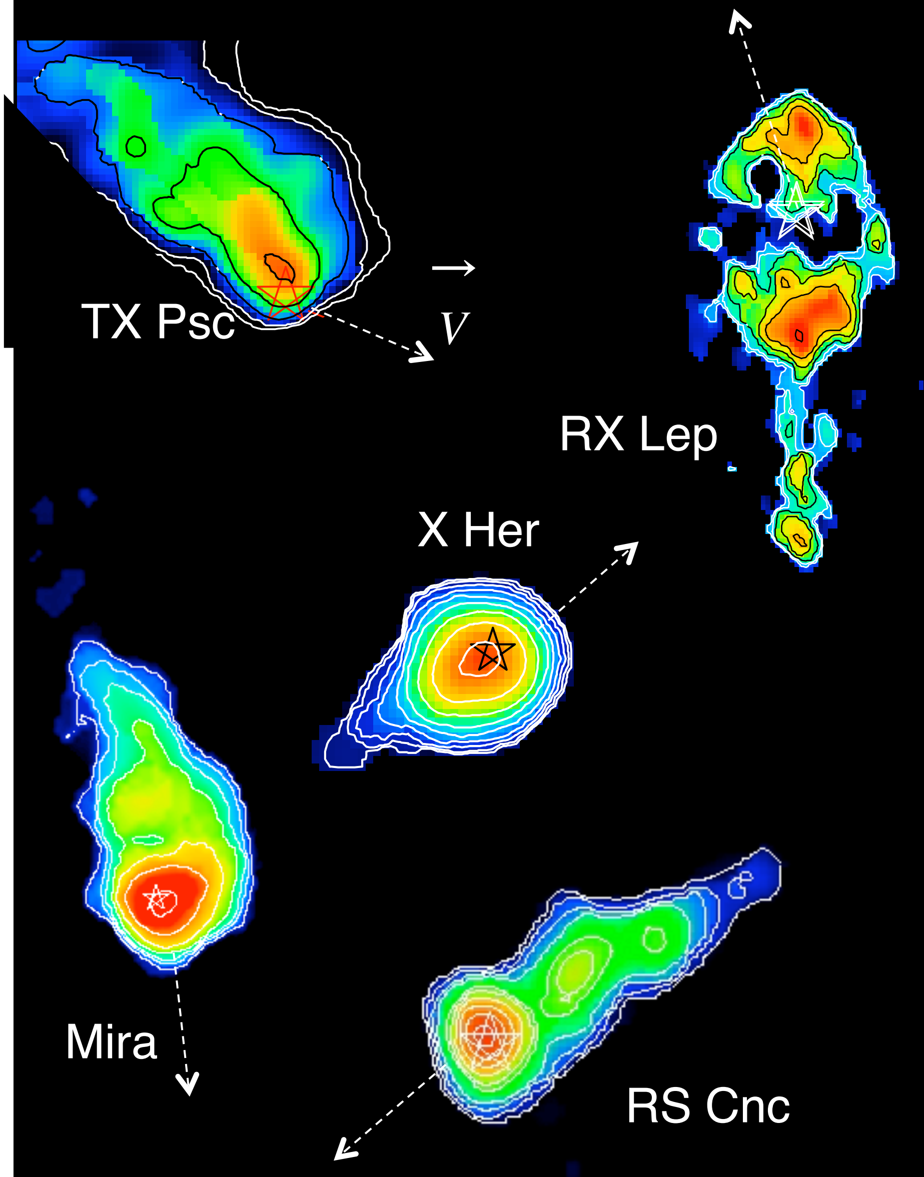
Extended HI “tails”:

- Trail the direction of space motion
- Arise from ram pressure effects
- 4 of 5 “tail stars” have $V_{space} > 60$ km/s
- Span ~0.2 pc to ~0.6 pc on the sky
- Provide record of extended mass-loss history, interstellar recycling
- Supply unique kinematic information on extended gas

see Matthews & Reid 2007; Matthews et al. 2008, 2011 & in prep.



-25
-24
-23
log density (g cm-3)
Villaver et al. (2012)
t = 0.5×10^5
1.5×10^5
2.4×10^5
3.3×10^5 yr
Size (pc)
-25
-23.5
-22
log density (g cm-3)
M★ =1 M☉
V_space=100 km/s
ρ_ISM=0.1 cm−3
t = 3.6×10^5
3.9×10^5
4.3×10^5
4.5×10^5 yr
Size (pc)



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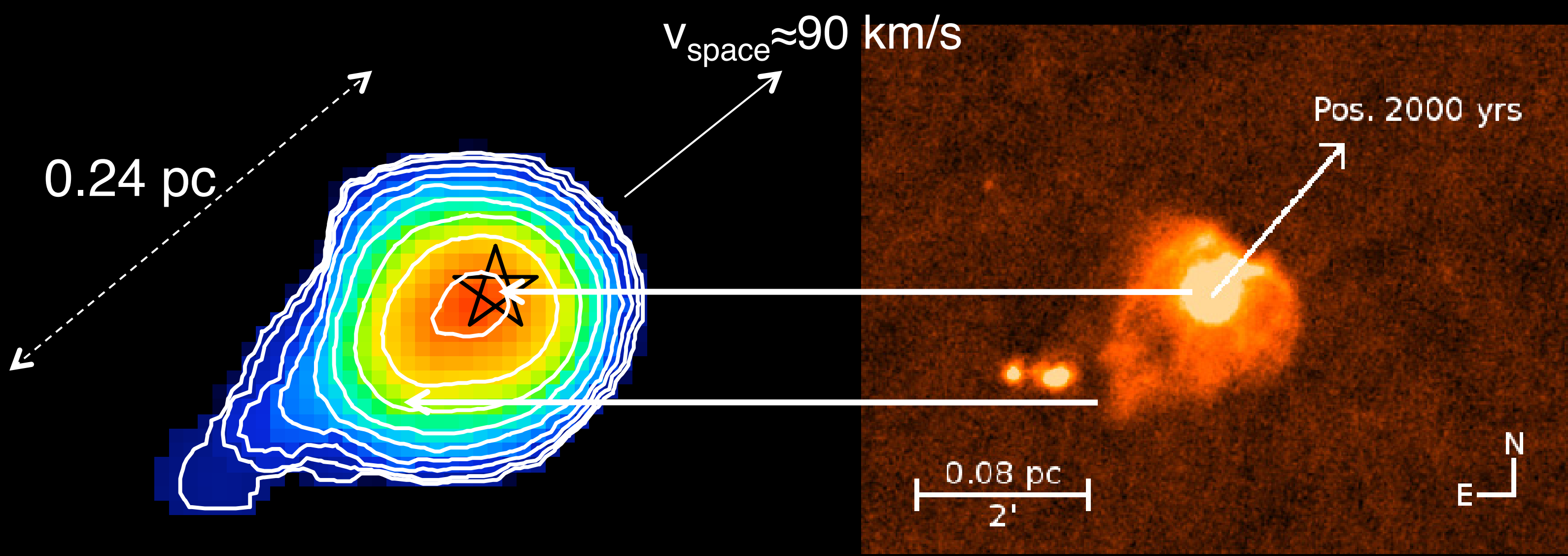
Two views of the circumstellar envelope of X Her:

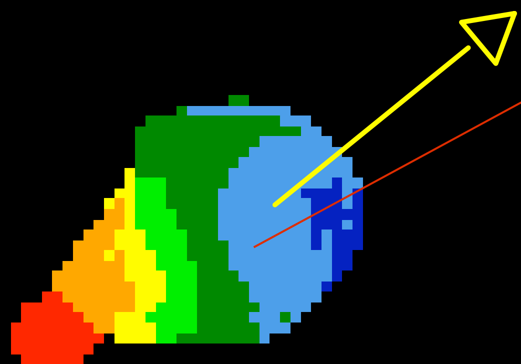
VLA HI | *Herschel* PACS (70µm)

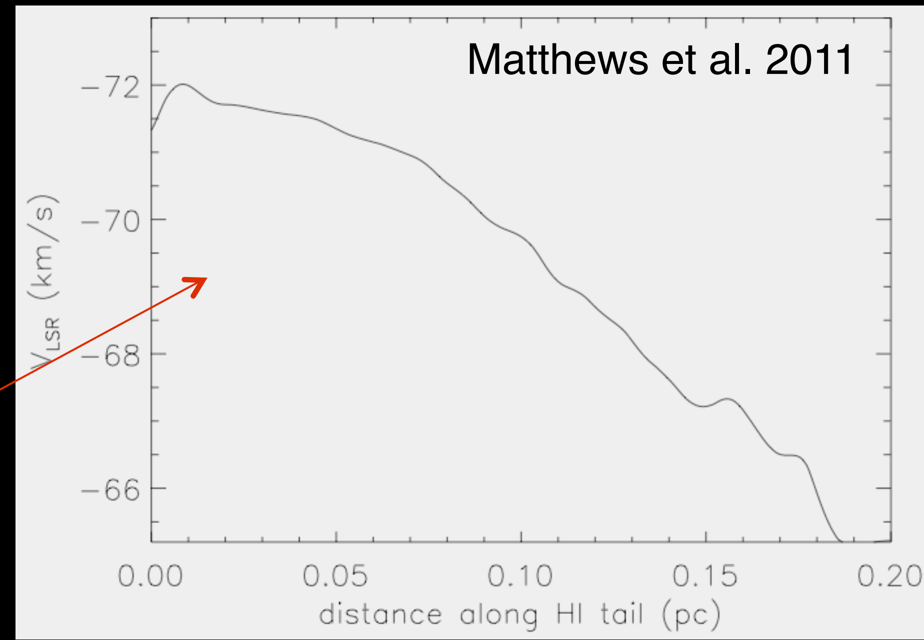


Matthews et al. 2011 | Jorissen et al. 2011

Type: Semi-regular variable
Chemistry: O-rich
$T_{eff} \approx 3200$ K
$V_{outflow} \approx 3$ & 9 km/s (2-component)
$\Delta M \approx 1.4\times10^{-7} M_\odot$ yr^{-1}
$M_{HI}=2.1\times10^{-3}\ M_\odot$

HI velocity field of X Her





The HI tail of X Her exhibits a systematic velocity gradient (ΔV~6.5 km/s) along the direction of motion.

⇒ *Material in the tail is decelerated through interaction with the ambient ISM (~21 km s^{-1} pc^{-1})*

⇒ *Ability to "age-date" the mass loss history of the star*

Estimating the ages of HI tails

1. Adopt a reference frame with star at rest and ISM streaming past it.

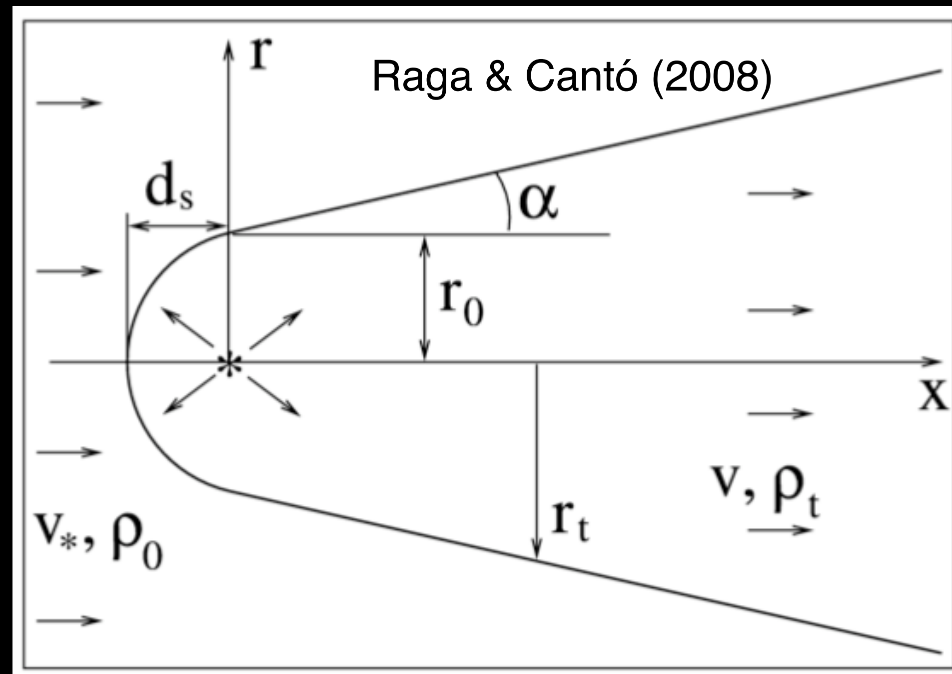
2. Deproject measured radial velocities and distances along tail to stellar rest frame.

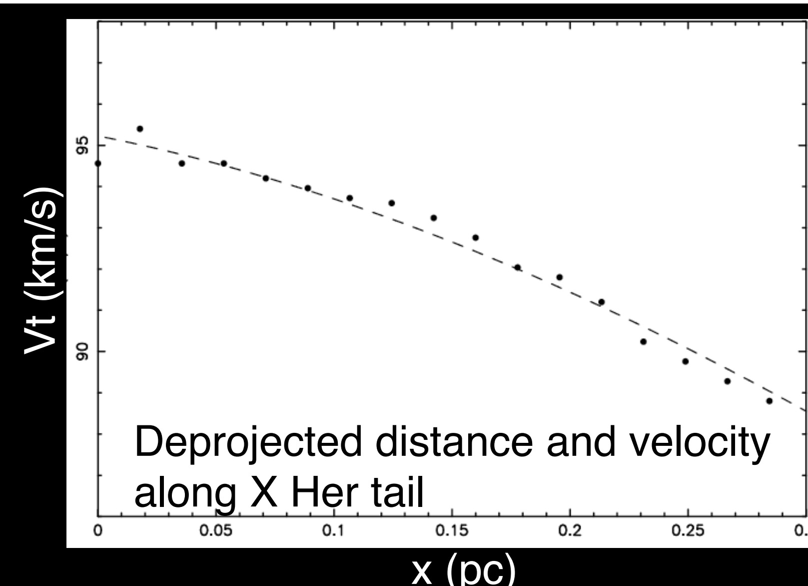
3. Determine polynomial coefficients from least squares fit to position-velocity data.

4. Solve:

$$t_{tail} = \int_0^{x0} [V_{space} - v(x)]^{-1}\, dx$$

(see Raga & Cantó 2008; Matthews et al. 2008, 2011)





Result from age-dating X Her's HI Tail: $t_{tail} \approx 1.2 \times 10^5$ yr

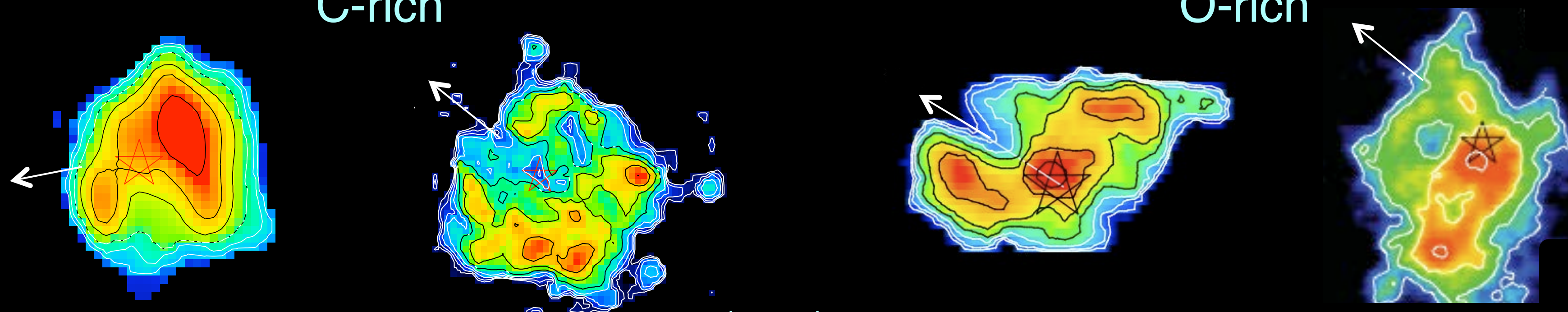
- X Her has been losing mass for ~4 longer than inferred from FIR studies alone (Young et al. 1993; Jorissen et al. 2011)

- Similar analysis for Mira revealed a ten-fold increase in the mass loss time scale (Matthews et al. 2008) which has been corroborated by hydrodynamic simulations (Wareing 2012)

⇒ A new tool for empirically characterizing timescales of AGB mass loss

Detached HI shells:

C-rich O-rich



V1942 Sgr Y CVn Y UMa α Ori

- Space velocities $V_{space} < 40$ km/s
- Diameters ~0.2 pc to ~0.7 pc
- Shapes distinctly non-spherical
- Stars offset from center

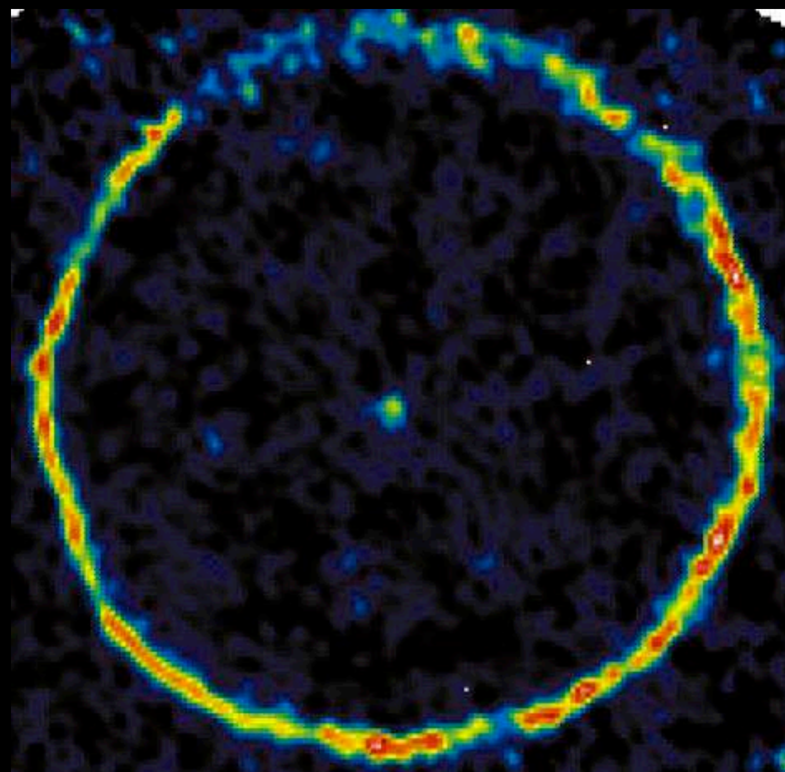
⇒ distorted by motion of star through ISM

- Found surrounding both O and C stars
- Geometrically thick

⇒ origin distinct from detached molecular shells

Matthews et al., in prep.;
Le Bertre et al. 2012;
Le Bertre poster

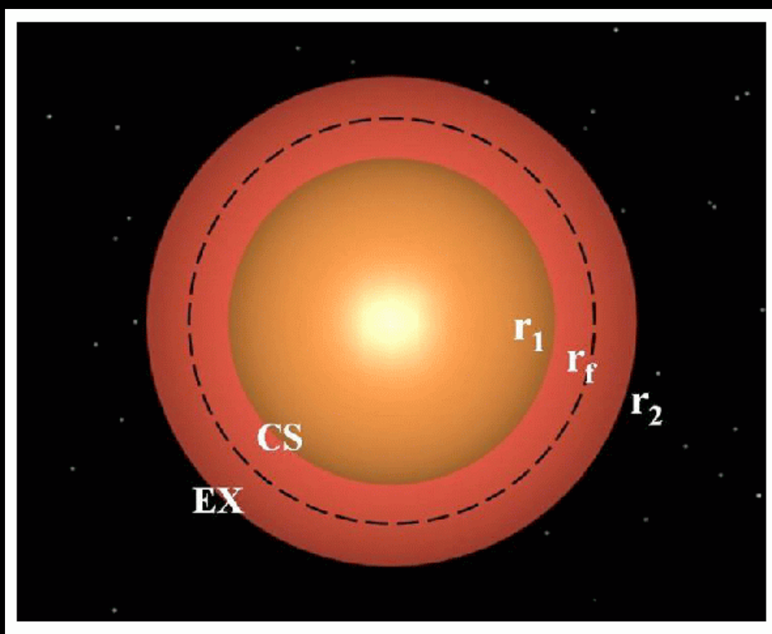
CO shell observed around carbon star TT Cyg



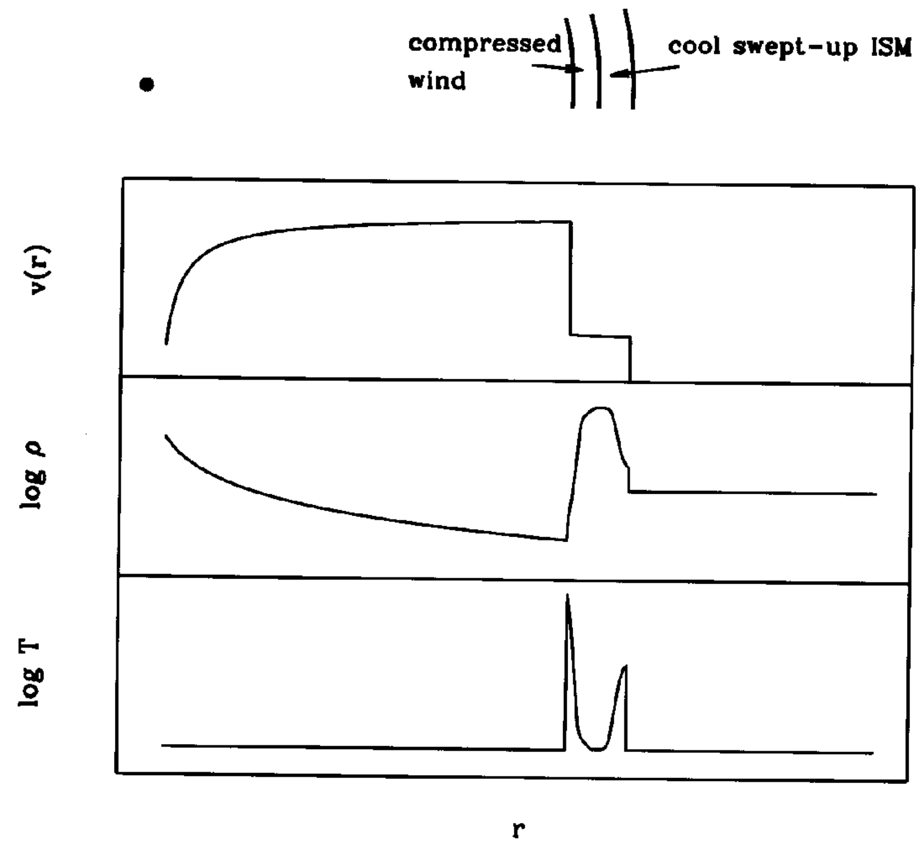
Olofsson et al. 1998

~0.15 pc

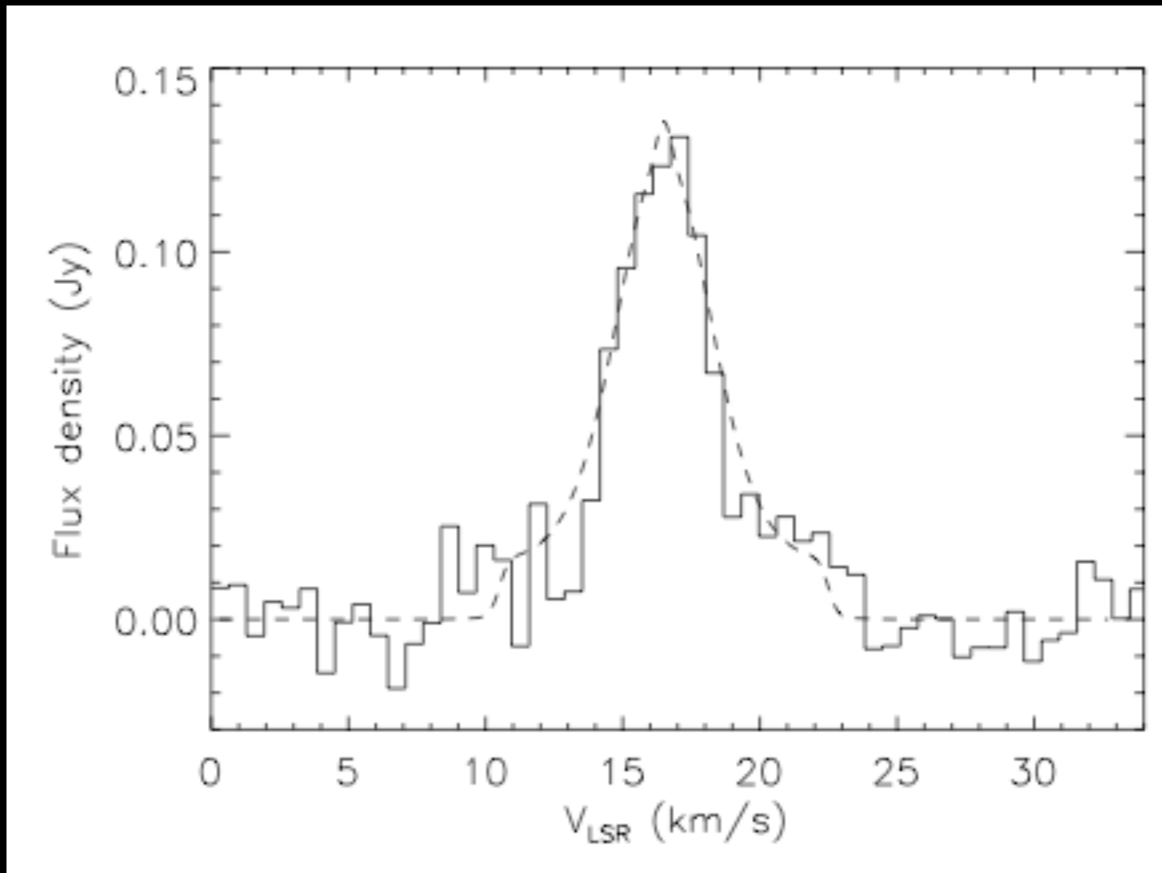
Numerical modeling ⇒ shells result from stellar outflow abruptly slowed at termination shock where wind meets ambient material (e.g., Young et al. 1993; Libert et al. 2007; Libert 2009 PhD thesis; Le Bertre poster)



after Lamers & Cassinelli (2004)



Global HI spectrum of Y UMa with detached shell numerical model fit overplotted.

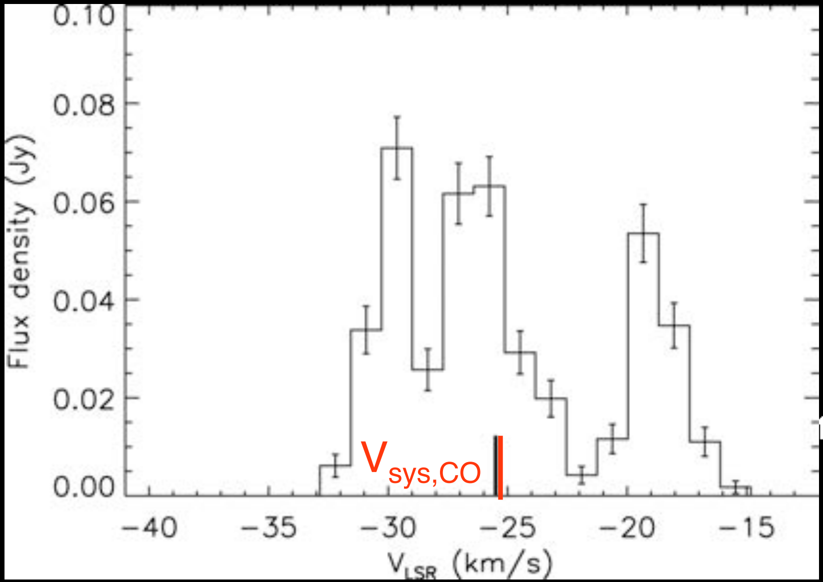


Matthews, Le Bertre et al., in prep.

⇒ No need to invoke intense, discrete mass loss episode to explain the origin of the HI shell (see also Libert et al. 2007, 2008)

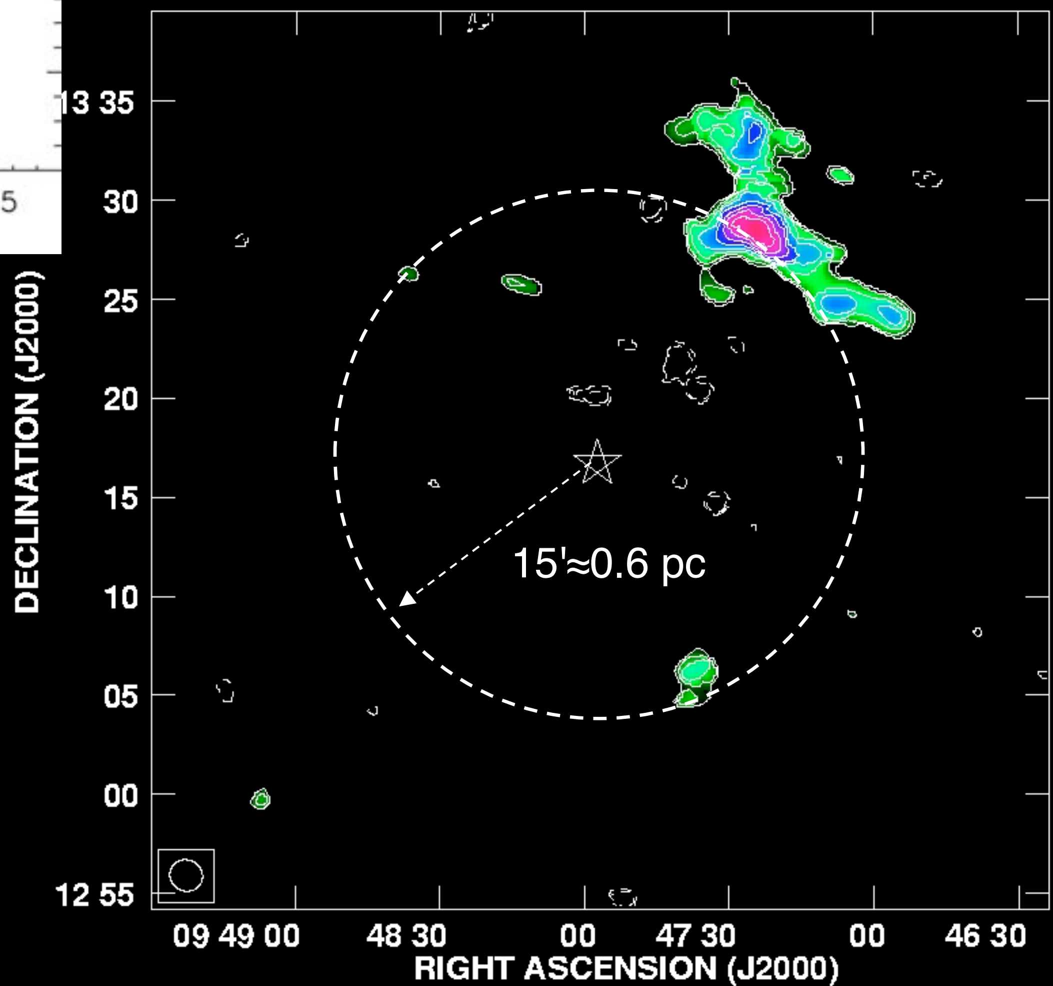
⇒ Estimated mass loss time scale ~ 9×10^4 years

VLA HI spectrum and total intensity map of IRC+10216

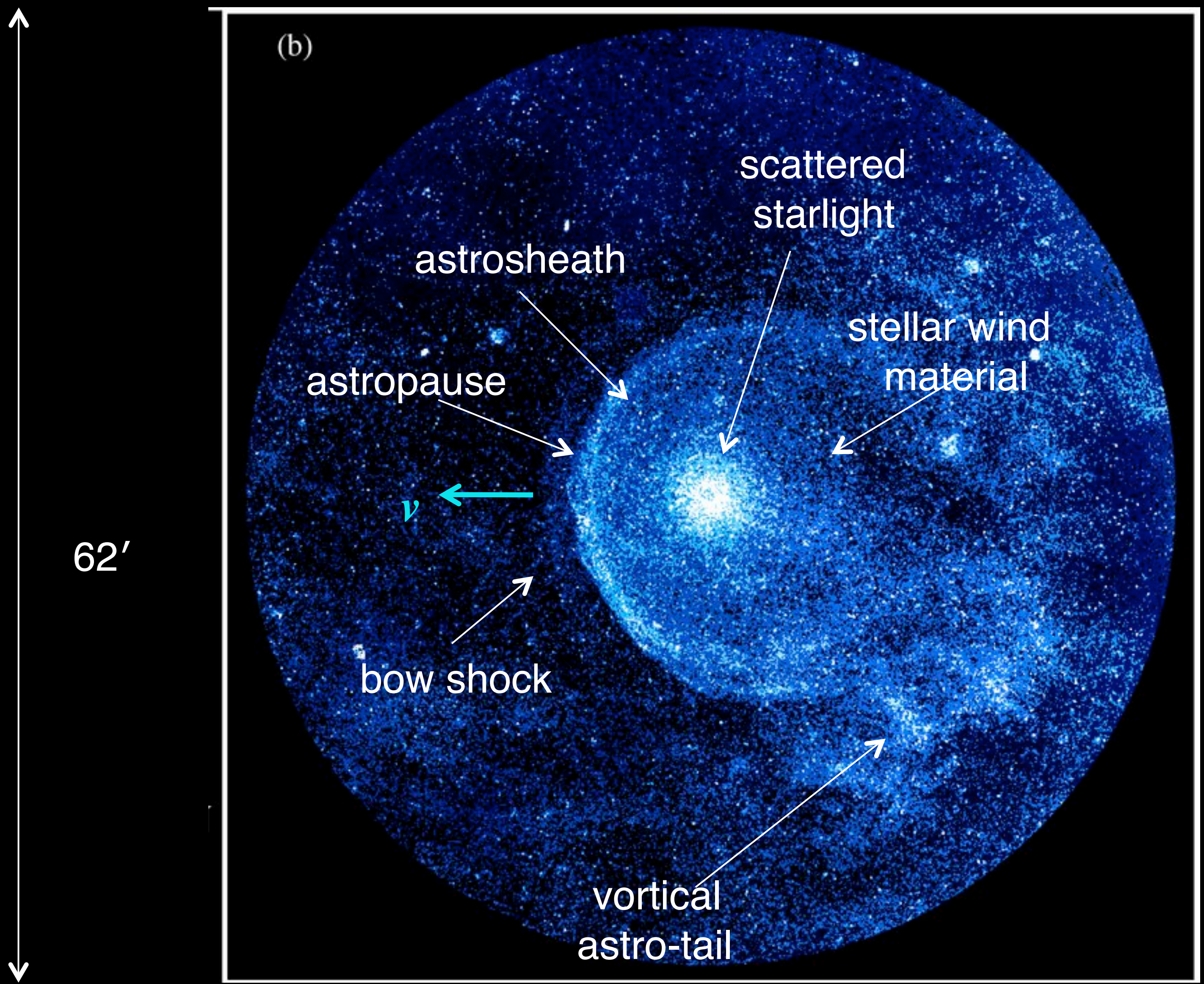


Integrated HI emission

$\Rightarrow M_{HI} \approx 2.4\times10^{-3} M_\odot$

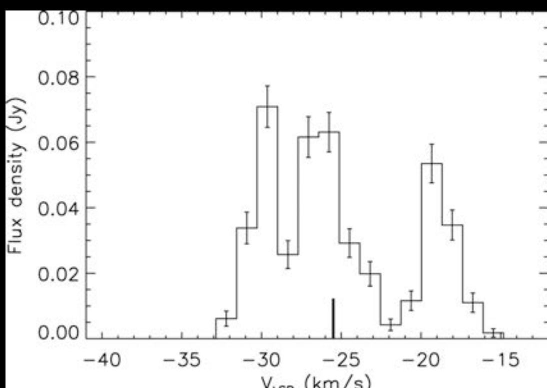


Matthews & Reid (2007)

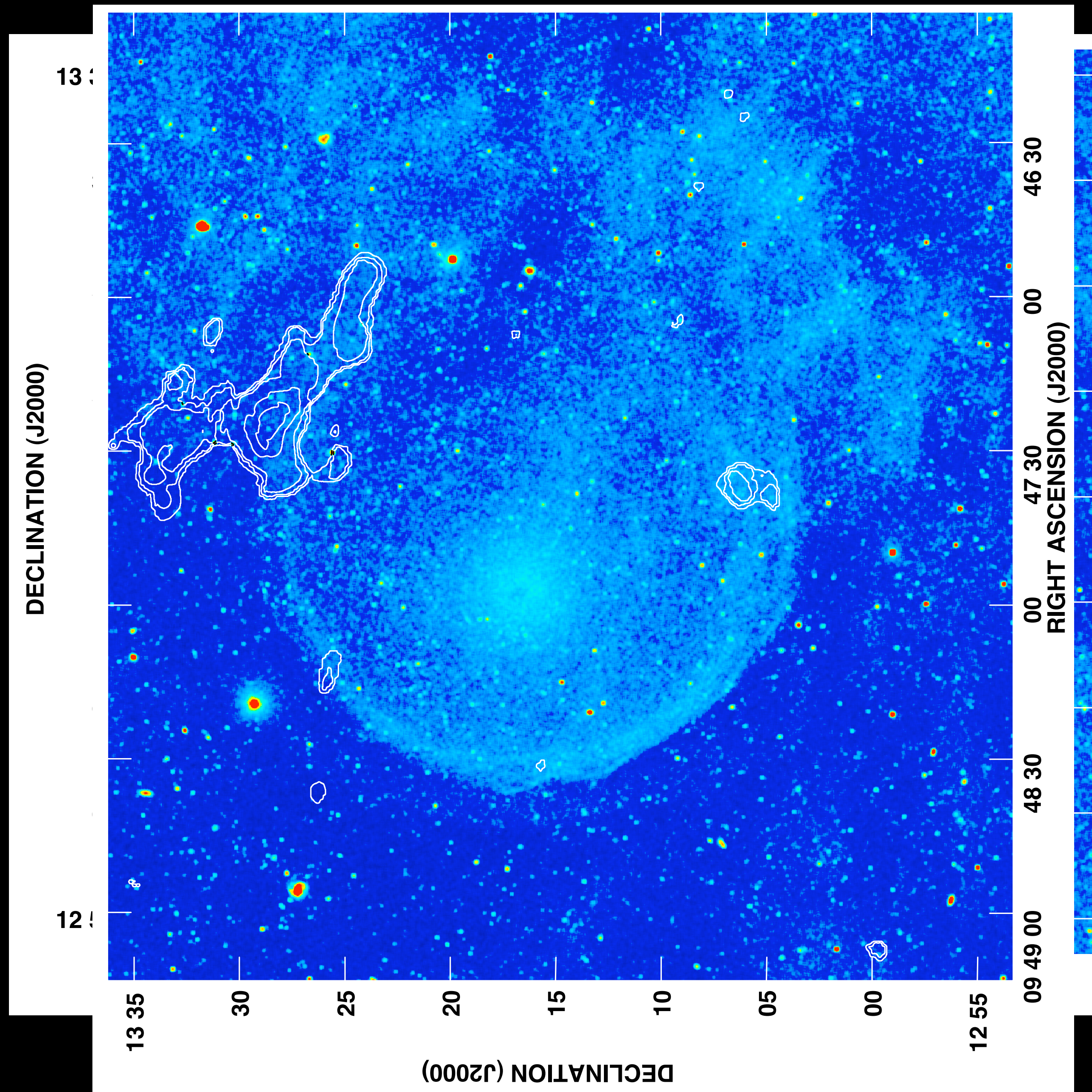


GALEX FUV image of IRC+10216 from Sahai & Chronopoulos (2010)

- HI seems consistent with dissociated H_2
- HI spectrum may help characterize velocity dispersion in the vertical tail



Matthews et al. 2011



HI contours overlaid on *GALEX* FUV image of IRC+10216

A New Application of Stellar HI Studies: Seeking Evidence for Mass Loss from Cepheids

A "Cepheid mass discrepancy" has persisted for decades: Masses derived from stellar evolution models are systematically ~10-15% higher than those derived from stellar pulsation models (or orbital dynamics).

Mass loss during the Cepheid phase has been suggested as a key to resolving this discrepancy (e.g., Cox 1980).

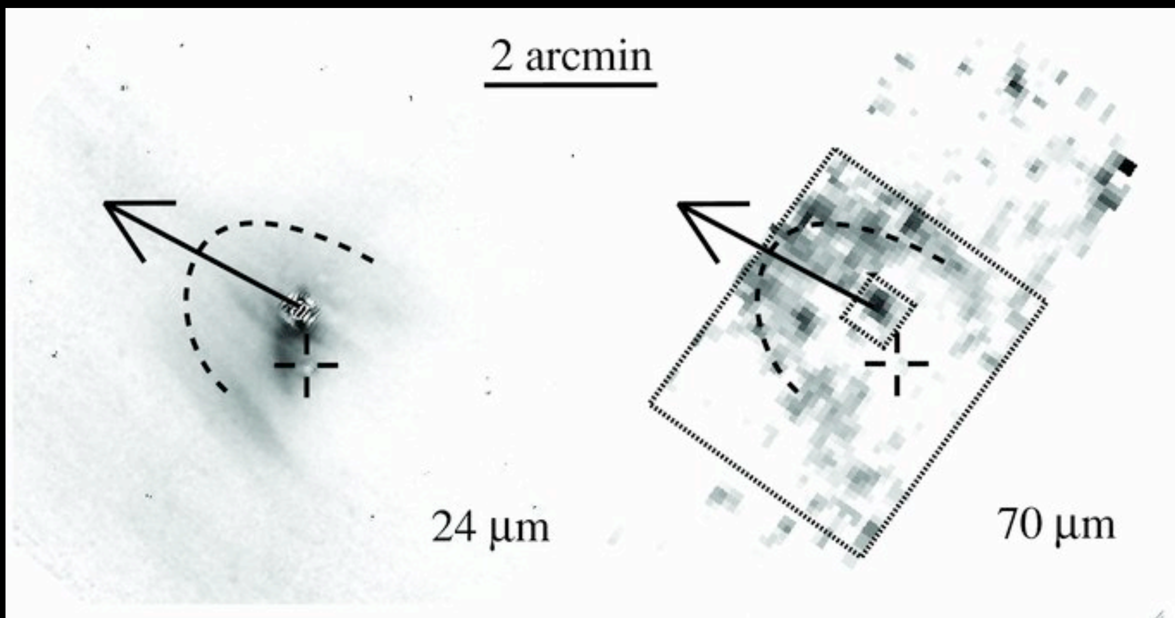
Mass loss is also predicted as a natural consequence of stellar pulsation models (Iben 1976; Willson & Bowen 1984; Neilson & Lester 2008)

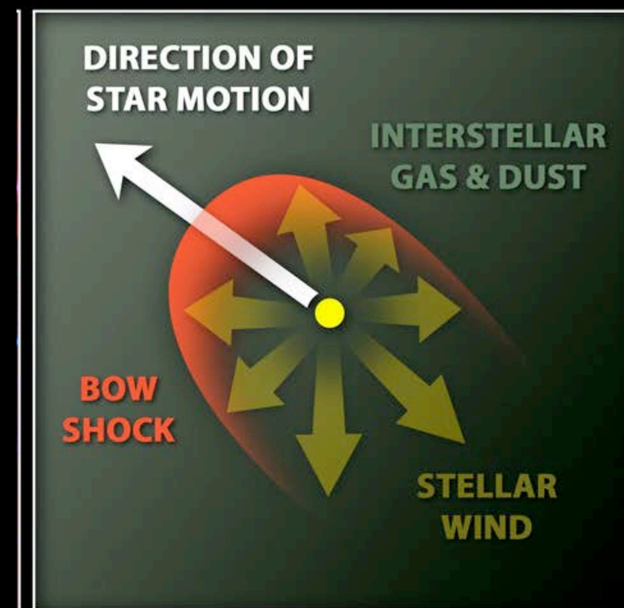
But...

Direct empirical evidence of Cepheid mass loss has remained elusive.

(cf. Deasy & Butler 1986; Deasy 1988; Welch & Duric 1988; Bohm-Vitense & Love 1994; Mérand et al. 2007; Kervella et al. 2006, 2009; Neilson et al. 2009)

In 2010, *Spitzer Space Telescope* imaging uncovered an infrared bow shock associated with the archetype of Cepheid variables, δ Cephei:

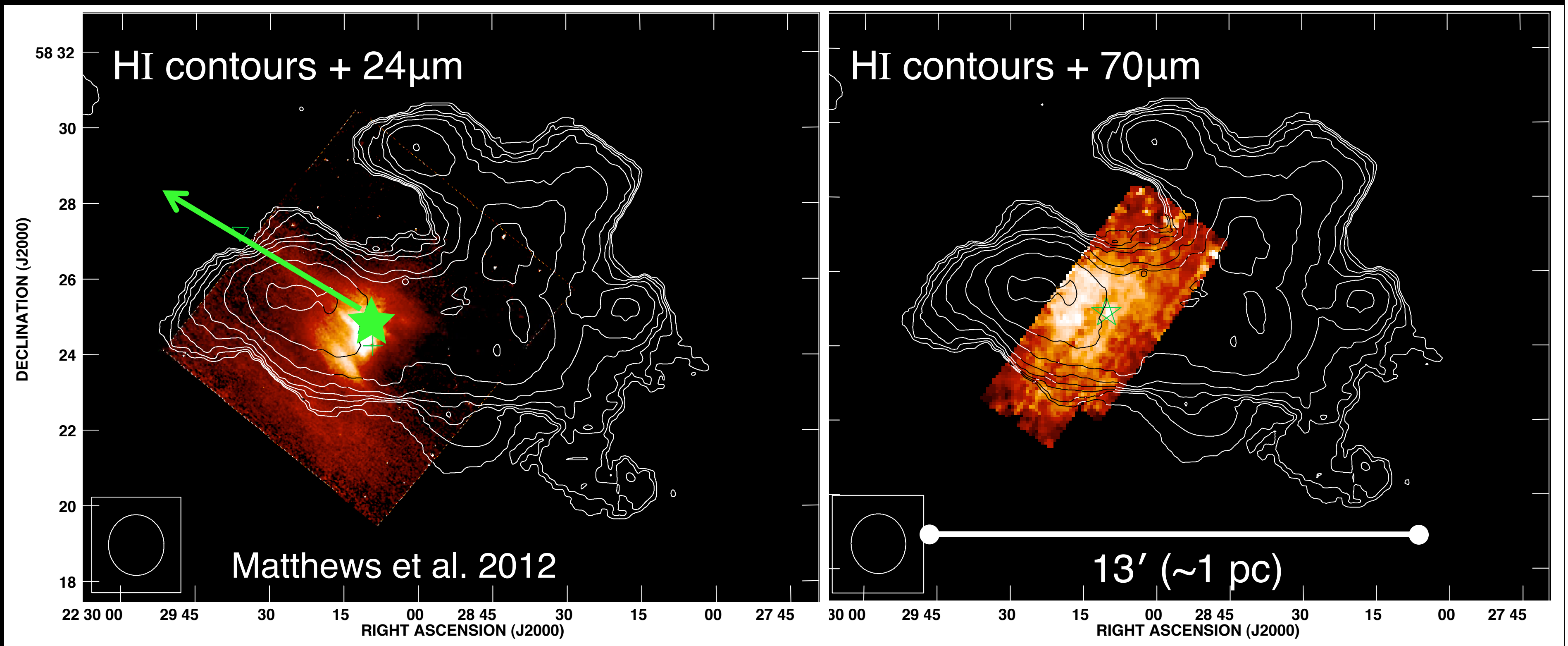




from Marengo et al. 2010

⇒ *Strong evidence of ongoing mass loss during the Cepheid phase*

Our follow-up imaging study with the VLA uncovered an extended HI nebula surrounding δ Cepheid:



Results:

$M_{HI} \approx 0.07\ M_\odot$ ($M_{CSE} \approx 0.09 M_\odot$)

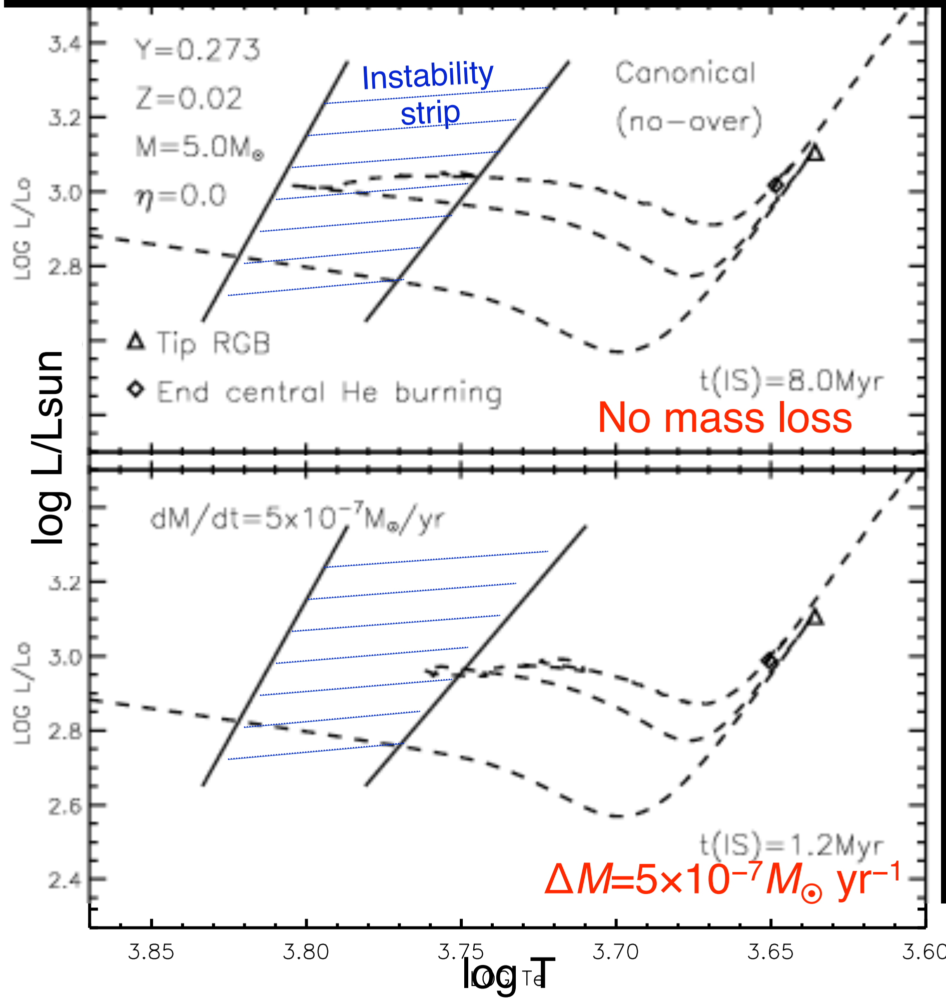
$\Delta M \approx 10^{-6}\ M_\odot\ yr^{-1}$

$V_{out} \approx 35$ km/s

⇒ *CSE mass comprises significant fraction of that needed to resolve the mass discrepancy for δ Cep (M_e–M_p~0.3-1.0 $M_\odot$)*

Theoretical evolutionary tracks for δ Cephei

$M_\star = 5 M_\odot$



from Matthews et al. 2012

- Mass loss rates ~$5\times10^{-7} M_\odot \mathrm{yr}^{-1}$ during the Cepheid phase can be accommodated by our models.

- Higher rates ($\Delta M > 10^{-6} M_\odot$ yr $^{-1}$) destroy the “blue loop”, leading to implausibly short Cepheid lifetimes.

$\Delta M = 5\times10^{-7} M_\odot \mathrm{yr}^{-1}$ predicts at current age of δ Cephei:

$$M_{CSE} \approx 0.04 \text{ to } 0.15 M_\odot$$
$$M_e - M_p \approx 0.2 \text{ to } 1.6\ M_\odot$$

We <u>measure</u>: $M_{CSE} \approx 0.09 M_\odot$

⇒Model is self-consistent

⇒*Mass loss sufficient to resolve much (most?) of the mass discrepancy.*

Summary

- The HI 21-cm line is a powerful probe of the evolutionary histories of evolved, mass-losing stars.

- HI observations provide diagnostics of the interaction between circumstellar and interstellar material, including *kinematics*.

- Analysis of HI "tails”, shells, and other large-scale structures are leading to a revised view of stellar mass-loss geometries and timescales, and the interactions of evolved stars with their environments.

- Structures seen in HI may help in the interpretation of the evolution of PNe, SNe

- HI observations have provided some of the most compelling evidence to date of ongoing mass loss along the Cepheid instability strip.