The Worlds of Planetary Nebulae

Five years of Exciting results

Bruce Balick,
Univ. Washington,
AAS225

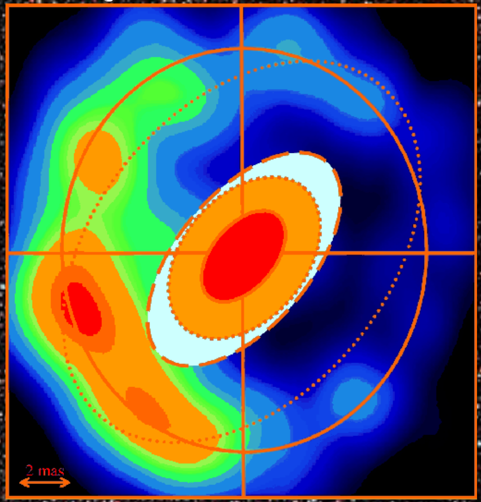
Dedicated to

Olivier Chesneau

1972 in Mozé-sur-Louet, May 17, 2014 in Nice

HR 5171 A (VLTI)
6 A.U. = 1300 $R_{\odot}$, 10^6 $M_{\odot}$
B: oribital period 1304 d

RS Oph

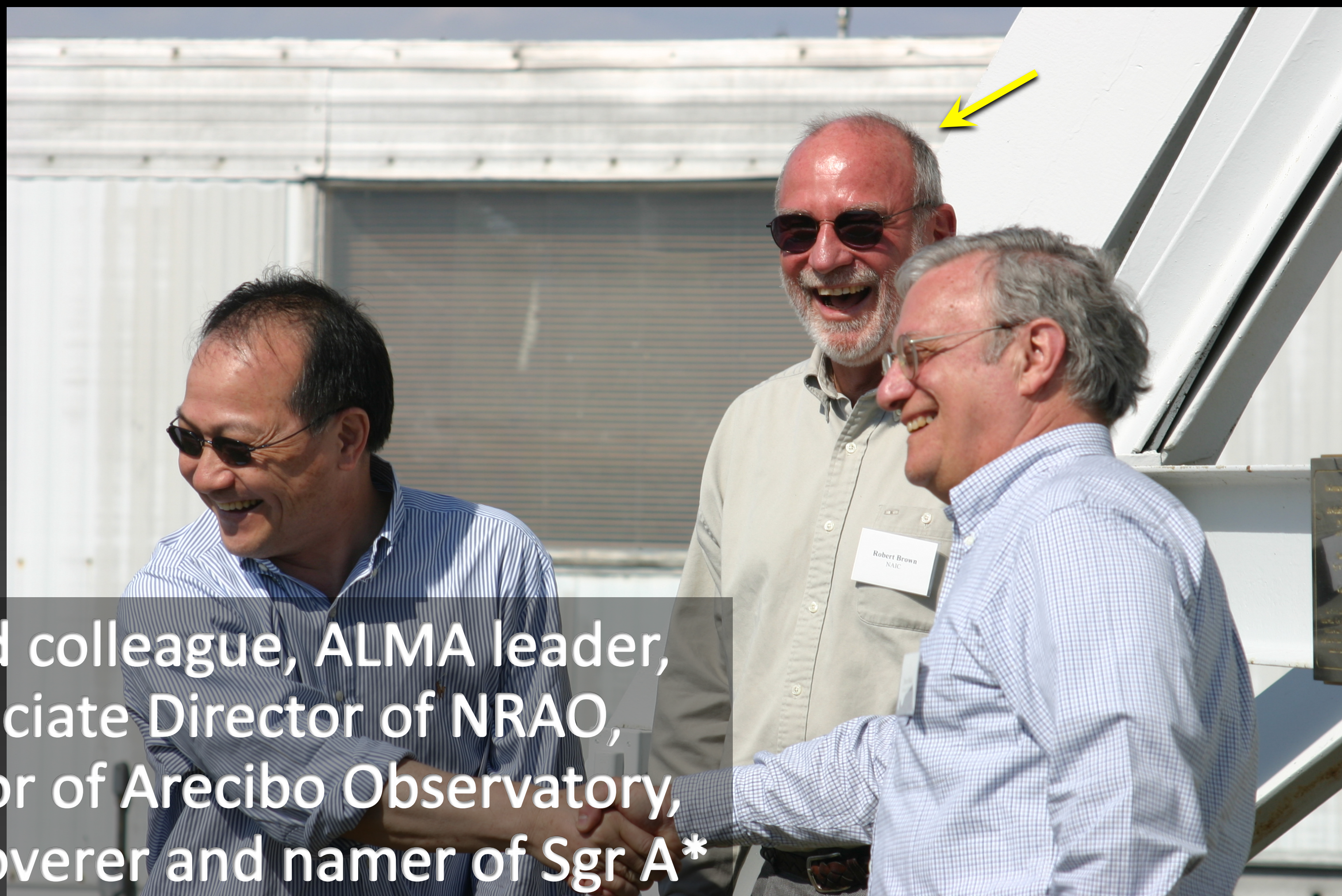


VLTI: The asymmetry in outburst of a very young nova.

Also dedicated to

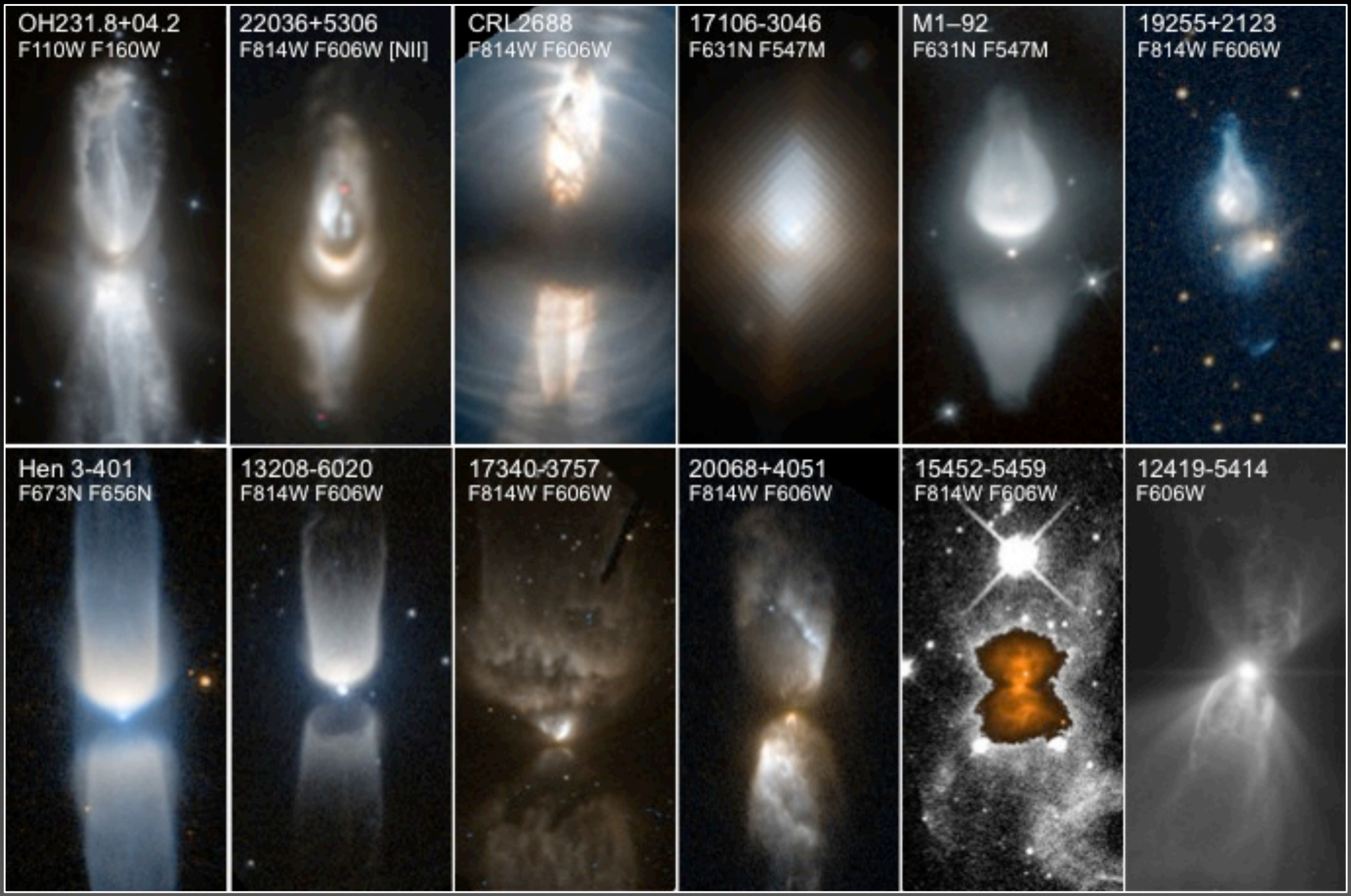
Roblet L. (Bob) Brown

1943 in Los Angeles– December 20, 2014 in Corolla NC



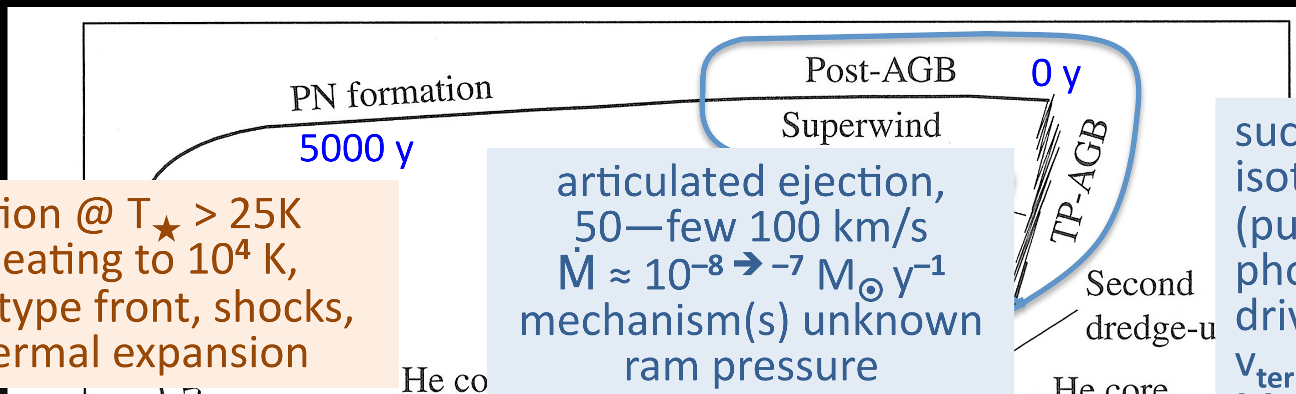
Valued colleague, ALMA leader,
Associate Director of NRAO,
Director of Arecibo Observatory,
co-discoverer and namer of Sgr A*

The Shaping of Stellar Mass loss



Modes, masses, speeds, shapes, and mechanisms

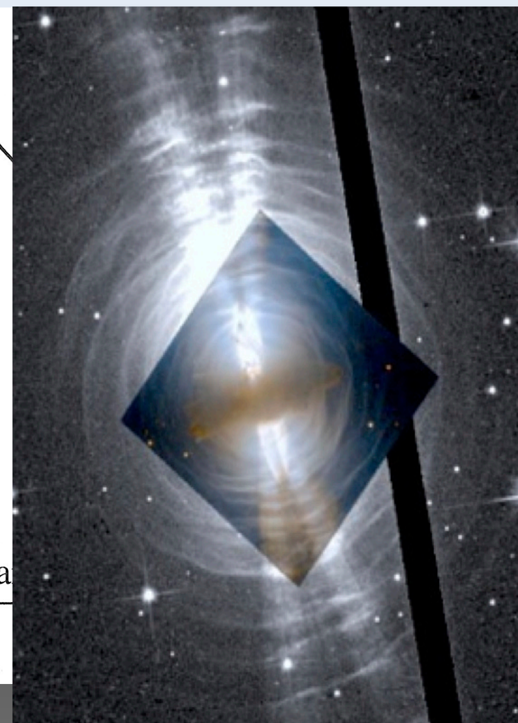
Aging stars: Modes of Mass Loss

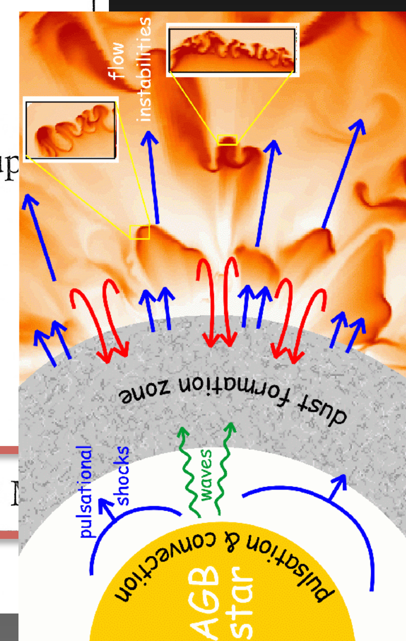


Ionization @ $T_\star > 25K$
flash heating to 10^4 K,
strong D-type front, shocks,
and thermal expansion

articulated ejection,
50—few 100 km/s
$\dot{M} \approx 10^{-8 \rightarrow -7} M_\odot y^{-1}$
mechanism(s) unknown
ram pressure

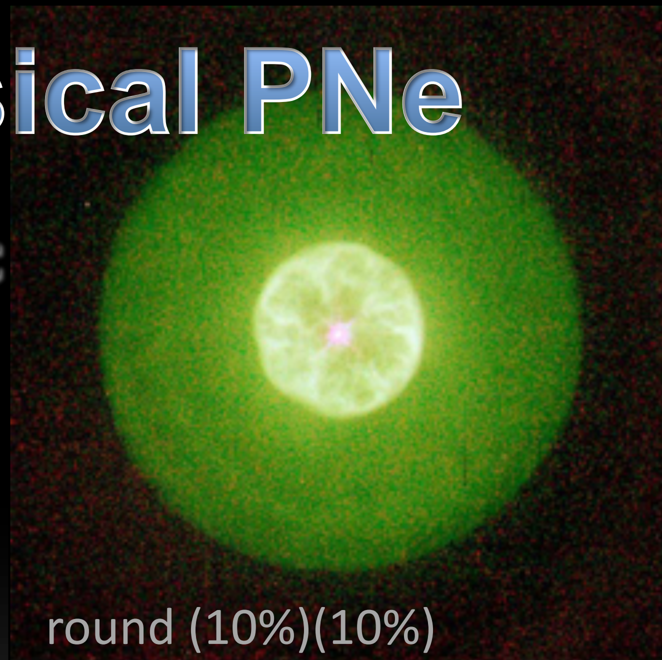
successive,
isotropic ejections
(puffs)
photon-pressure
driven winds?
$v_{terminal} \approx 20$ km/s
$M \approx 0.1 - 1 M_\odot$

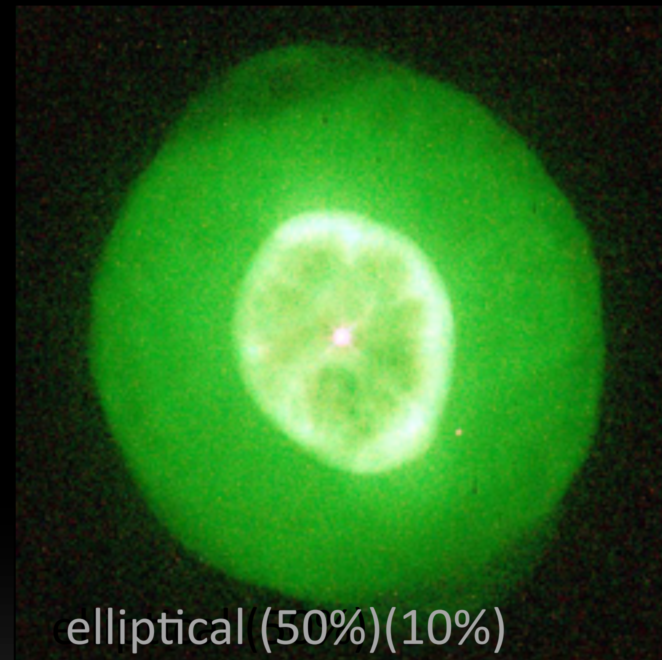




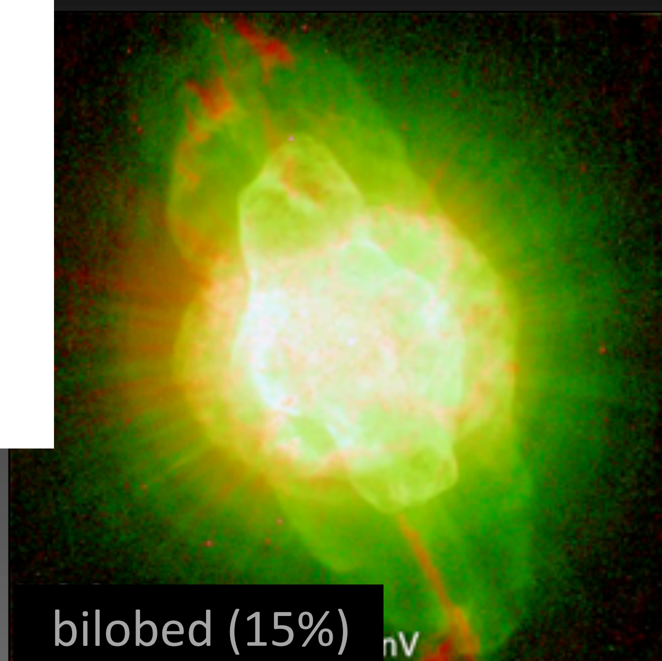
Classical PNe

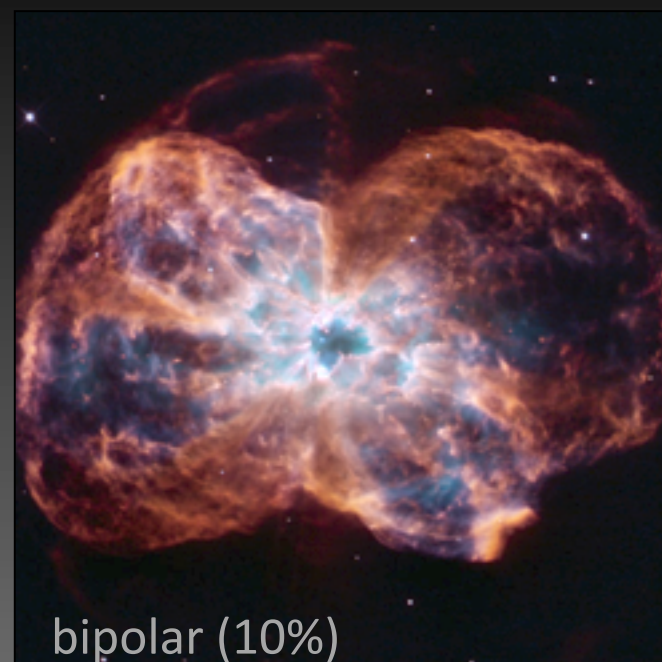
Hydrodynamic Shaping:
Interacting stellar winds


round (10%)(10%)


elliptical (50%)(10%)

1990s: How do the shapes and kinematics of PNe reveal of their origins?


bilobed (15%)


bipolar (10%)

Part 1: What's New?

THE PRESENT AND FUTURE OF PLANETARY NEBULA RESEARCH. A WHITE PAPER BY THE IAU PLANETARY NEBULA WORKING GROUP

K. B. Kwitter[1], R. H. Méndez[2], M. Peña[3], L. Stanghellini[4], R. L. M. Corradi[5,6], O. De Marco[7], X. Fang[8,9], R. B. C. Henry[10], A. I. Karakas[11], X.-W. Liu[8,9], J. A. López[12], A. Manchado[5,6], and Q. A. Parker[7]

Received 2014 January 22; accepted 2014 March 21

RESUMEN

Se presenta un resumen del estado actual de la investigación sobre las nebulosas planetarias y sus estrellas centrales, y temas relacionados como los procesos atómicos en nebulosas ionizadas, y la evolución de las estrellas de la rama gigante asintótica y post-gigante asintótica. Se discuten los avances futuros que serán necesarios para incrementar sustancialmente nuestro conocimiento en este campo.

ABSTRACT

We present a summary of current research on planetary nebulae and their central stars, and related subjects such as atomic processes in ionized nebulae, AGB and post-AGB evolution. Future advances are discussed that will be essential to substantial improvements in our knowledge in the field.

Key Words: ISM: abundances — planetary nebulae: general — stars: AGB and post-AGB — stars: evolution

Kwitter et al. 2014RMxAA..50..203K

What Makes PNe Interesting?

+ New Observations
- High resolution O/IR/ALMA imaging
- Statistics (extensive surveys)
- Mid/Far and λmm spectra and surveys
- Central stars, photometry, variability (& binarity), surface velocity, Zeeman splitting
- GAIA and its impacts

+ Models and Simulations
- Interior Flashes Nucleosynthesis
- C-N production rates In Carbon Stars and AGBs
- Rotation & Convection
- Emergence and Role of Winds and Magnetic Fields
- Understanding Isotopic ratios
- 1-D radiation hydro models with full stellar evolution
- Hydro and MHD simulations of structures & kinematics
- Sky projections of simulations

+ Mass Loss Mechanisms, Binarity, & Shaping
- Mass exchange and overflow in binaries
- Binary orbits and energy losses
- Wind collimation and multiaxial flows

+ Chemistry of AGB atmospheres and winds, impact of dredges

+ Atomic data

+ Atomic excitation mechanisms

+ S- and R-process abundances

+ PNe as probes of SFR, IMF, metal enrichment

+ Molecular formation, isotopic ratios, abundances

+ Galactic structure, kinematics, formation, and assembly

+ Dust/Complex Molecules
- Formation and Destruction mechanisms and rates

+ Related objects (Novae, SNe Ia's, W-C/N/Os)

What Makes PNe Interesting?

Poll of a recent Scientific Organizing Committee

- Gaseous relics of the evolution of low- and intermediate-mass stars
- Major/dominant source of cosmic carbon and nitrogen
- Have been forming continuously in all but the youngest stellar ensembles
- Ubiquitous in the Milky Way, other galaxies, and intra-cluster medium
- Excellent probes of
  - Stellar evolution from the AGB to white dwarf stages; thermal pulses and dynamos
  - Stellar populations, dynamics, and metal enrichments
  - Stellar emission x-ray processes in white-dwarf, high-gravity environments or mass x-fer
  - Stellar winds, acceleration processes, and non-equilibrium dust formation
  - Gas dynamics of collimated and interacting winds,
  - Balance and impacts of thermal, ram, and magnetic pressures in simple environments
  - Magnetized winds and coherent maser amplification
  - Molecular formation rates
  - Photoionization, high-speed shocks, and the excitation state of gaseous systems
  - Chemical history of the disks and halos of spiral galaxies, ellipticals, dwarf galaxies and the intra-galaxy environment
- Mass exchange and ejection processes of close binaries formed of old stars, including SN Ia's, superluminous giants, and some novae
- Universal luminosity function in early- and late-type galaxies (that still largely defies explanation)
- Major/dominant source of interstellar carbonaceous, silicate, and iron dust
  Exoplanet masses and survival (around WDs)

Also: AAS225 session 108

"The Emerging Multiwavelength View of Planetary Nebulae"

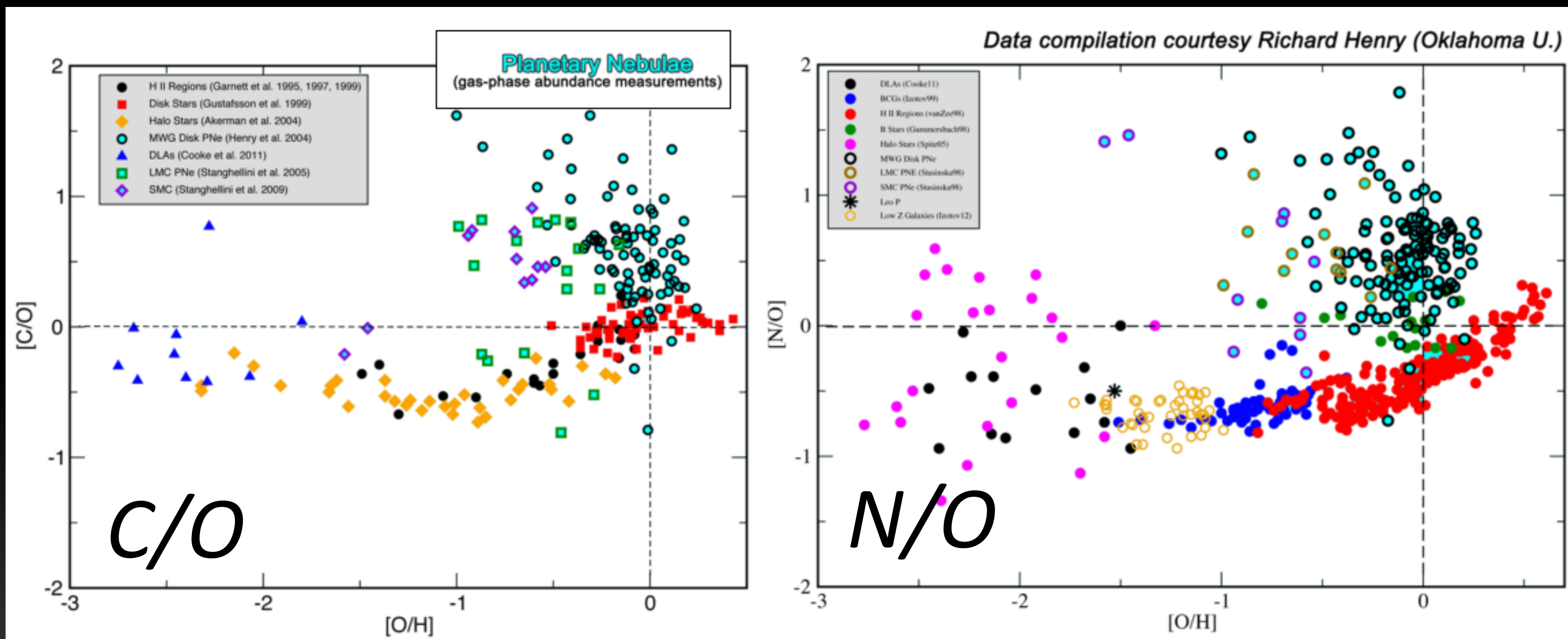
108.01. ChanPlaNS: The Chandra Planetary Nebula Survey   Joel Kastner et al.
108.02. Emerging Trends Gleaned from Central Star and Hot Bubble X-ray Emission of ChanPlaNS Planetary Nebulae   Rodolfo Montez et al.
108.03. Herschel Planetary Nebula Survey: Spectroscopic Probing of the Nebular Components   Toshiya Ueta et al.
108.04. The HerPlaNS far-IR photometric survey of Planetary Nebulae and its contribution to the Emerging Multi-wavelength View   Djazia Ladjal
108.05. Herschel Planetary Nebula Survey (HerPlaNS): First Detection of OH+ in Planetary Nebulae   Isabel Aleman
108.06. The new MQ/AAO/Strasbourg mutli-wavelength and spectroscopic PNe database: MASPN   Quentin A. Parker
108.07. What Are M31 Disk Planetary Nebulae Trying to Tell Us?   Karen B. Kwitter et al.
108.08. Observing Planetary Nebulae with JWST and Extremely Large Telescopes   Raghvendra Sahai
108.09. Binary Interactions and the Formation of Planetary Nebula Adam Frank

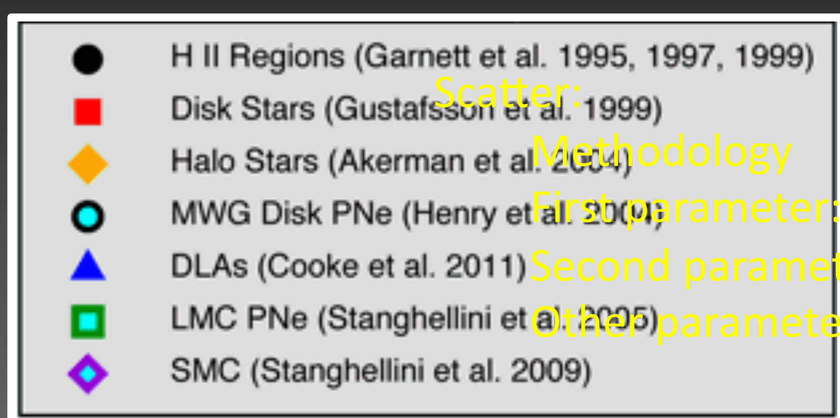
The "Frame": My Favorite 5-year Highlights

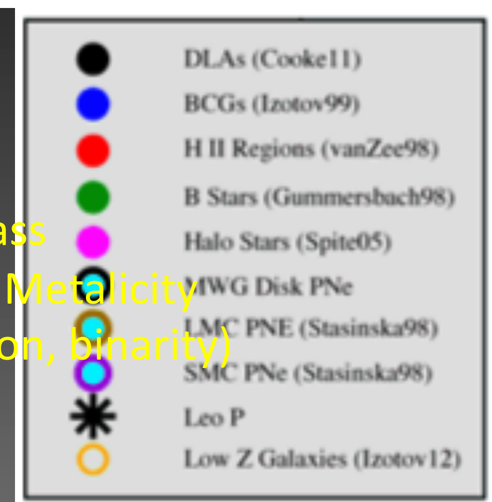
- Carbon/Dust Production processes and rates
- Simulations of jet and disk formation
- Mass transfer in binaries
- Probes of galaxies' histories
- Peering into the Launch Zone: HST, VLTI, etc.

ALMA arrives!!

Carbon/Nitrogen Enrichment







Scatter:

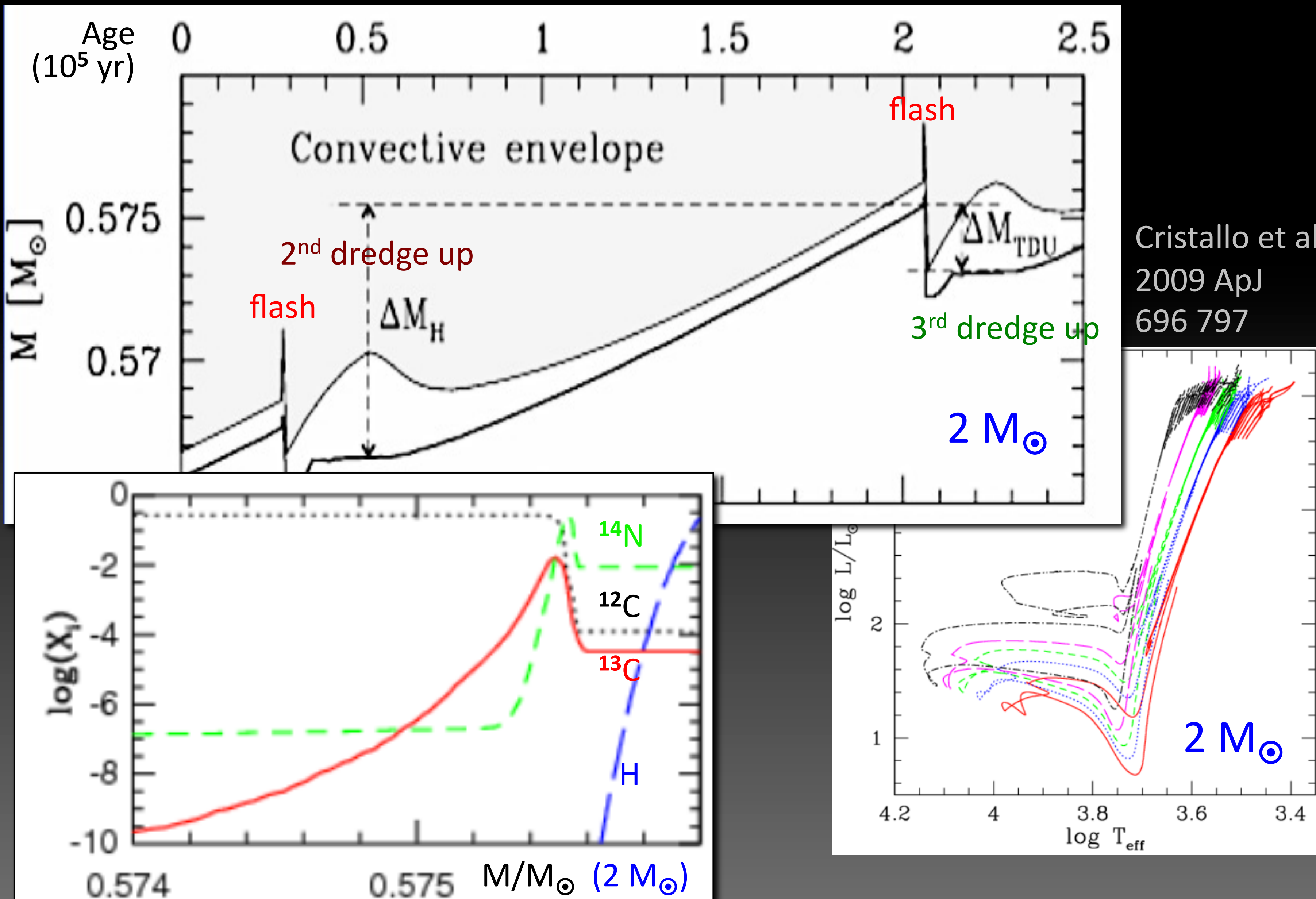
Methodology

First parameter: Initial Mass

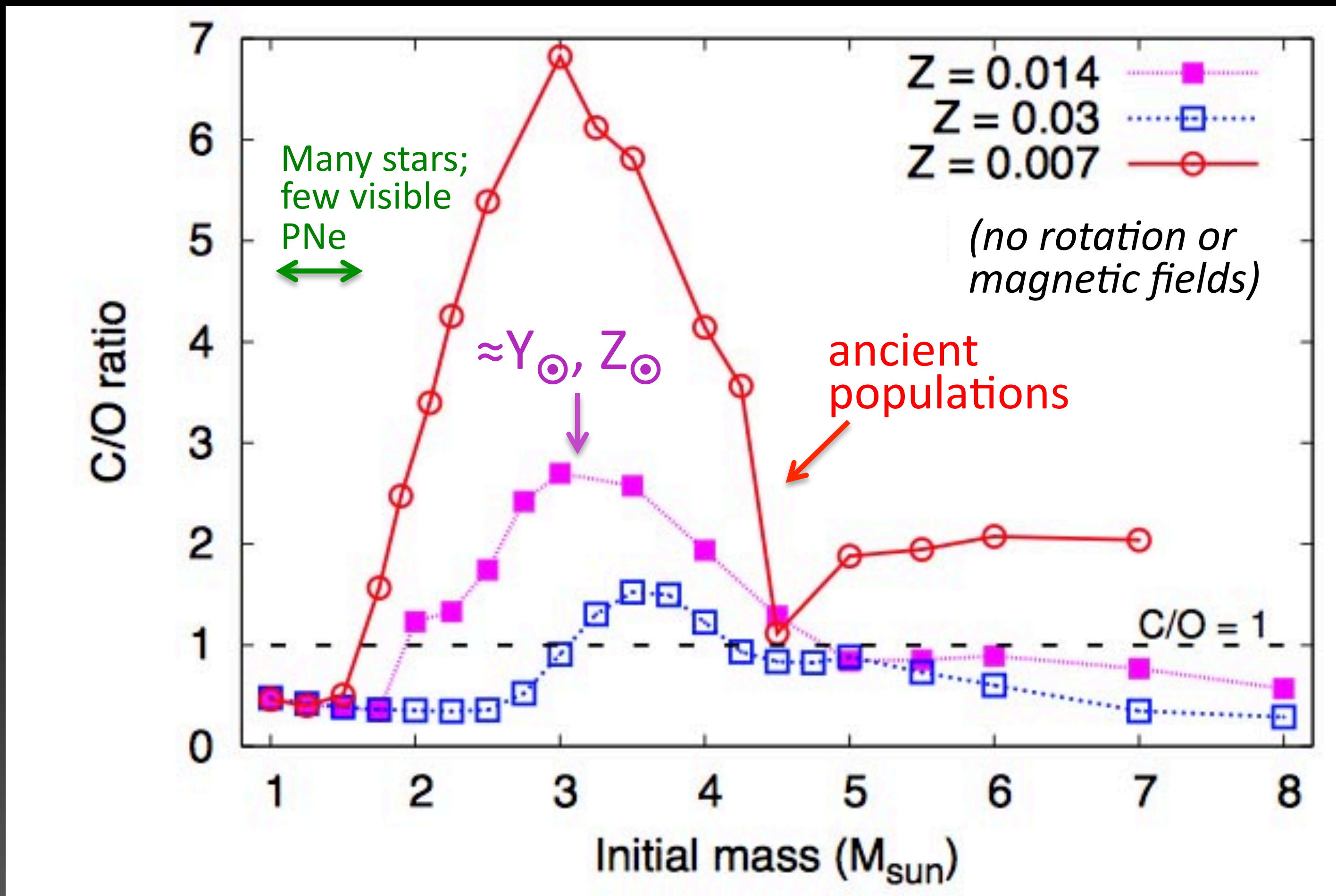
Second parameter: Initial Metalicity

Other parameters: (rotation, binarity)

C, N Production Mechanisms



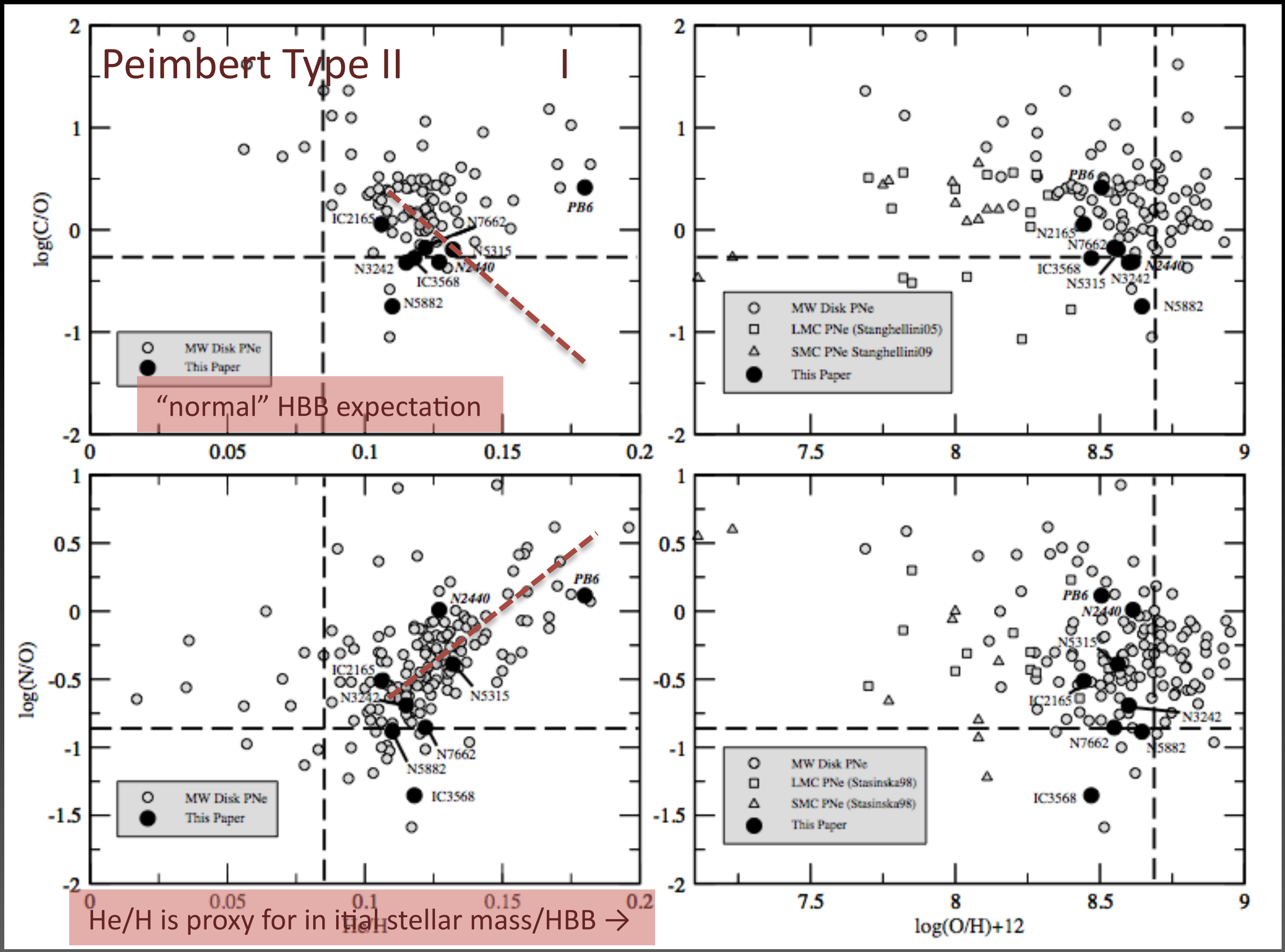
Carbon Enrichment



A. Karakas 2014, MNRAS, 445, 347

Rate of carbon enrichment depends on IMF, $Y/Y_\odot$, $Z/Z_\odot$. Fewer third dredge-ups for stars with $Z/Z_\odot \geq 0.5$ (i.e. nearby disk PNe). C/O ratios and C-star pops also drop for $Y/Y_\odot \geq 1$. Rotation might enhance carbon diffusion and, so surface abundances.

Carbon/Nitrogen Production



Henry et al 2015 (Submitted). Large black dots are new results from deep opt-uv STIS spectra.

Peimbert Type I

- relatively rich in He and N
- tend to be bipolar and to lie near the Galactic equator
- believed to evolve from massive progenitors (>4 $M_{\odot}$)

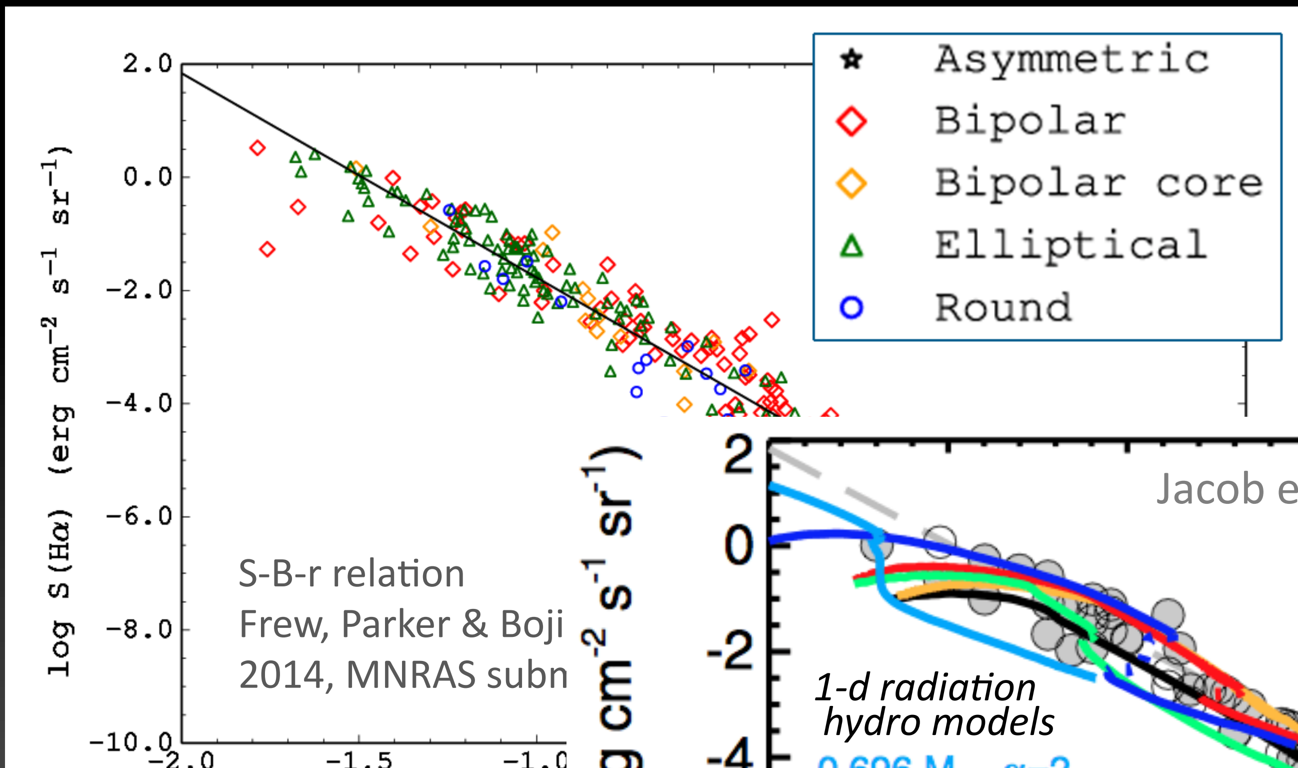
Peimbert Type II

- The rest (ignoring PNe outside the disk)

Hot Bottom Burning predicts that C will be processed into He and N. So a He-N correlation should emerge for a large PN sample and possibly a C-N anticorrelation.

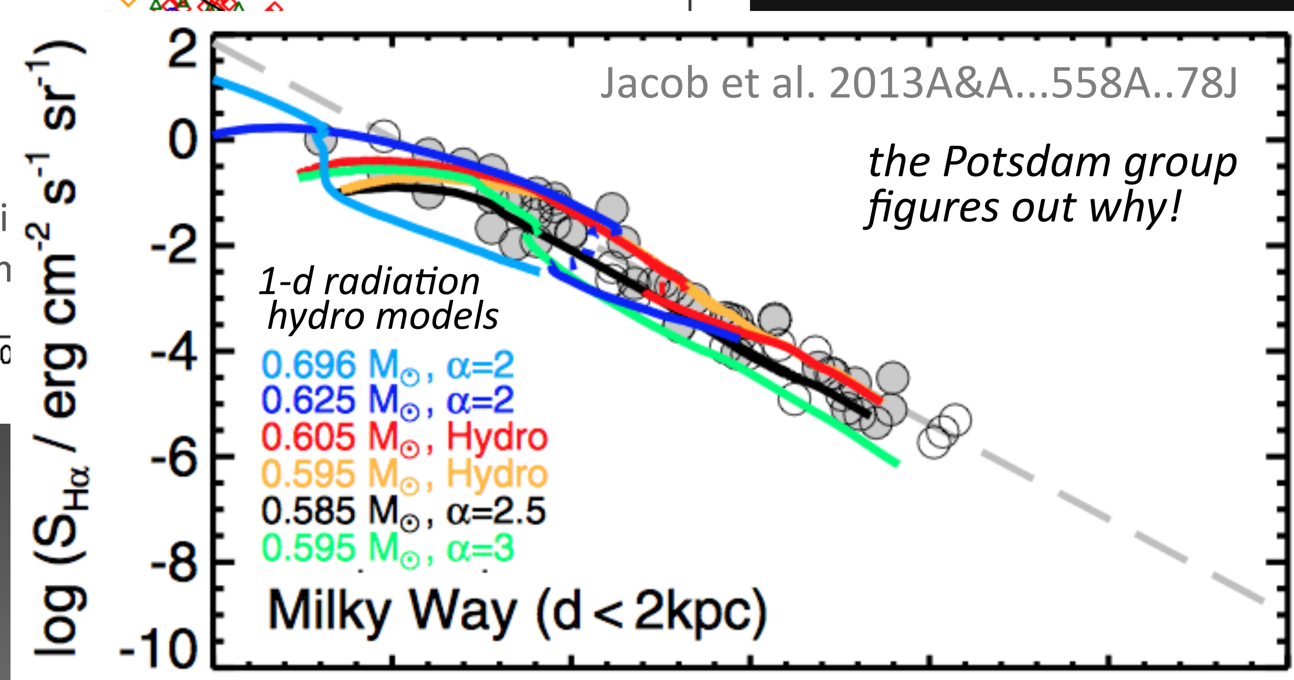
Distances (Finally!!)

…one reason that surveys really matter

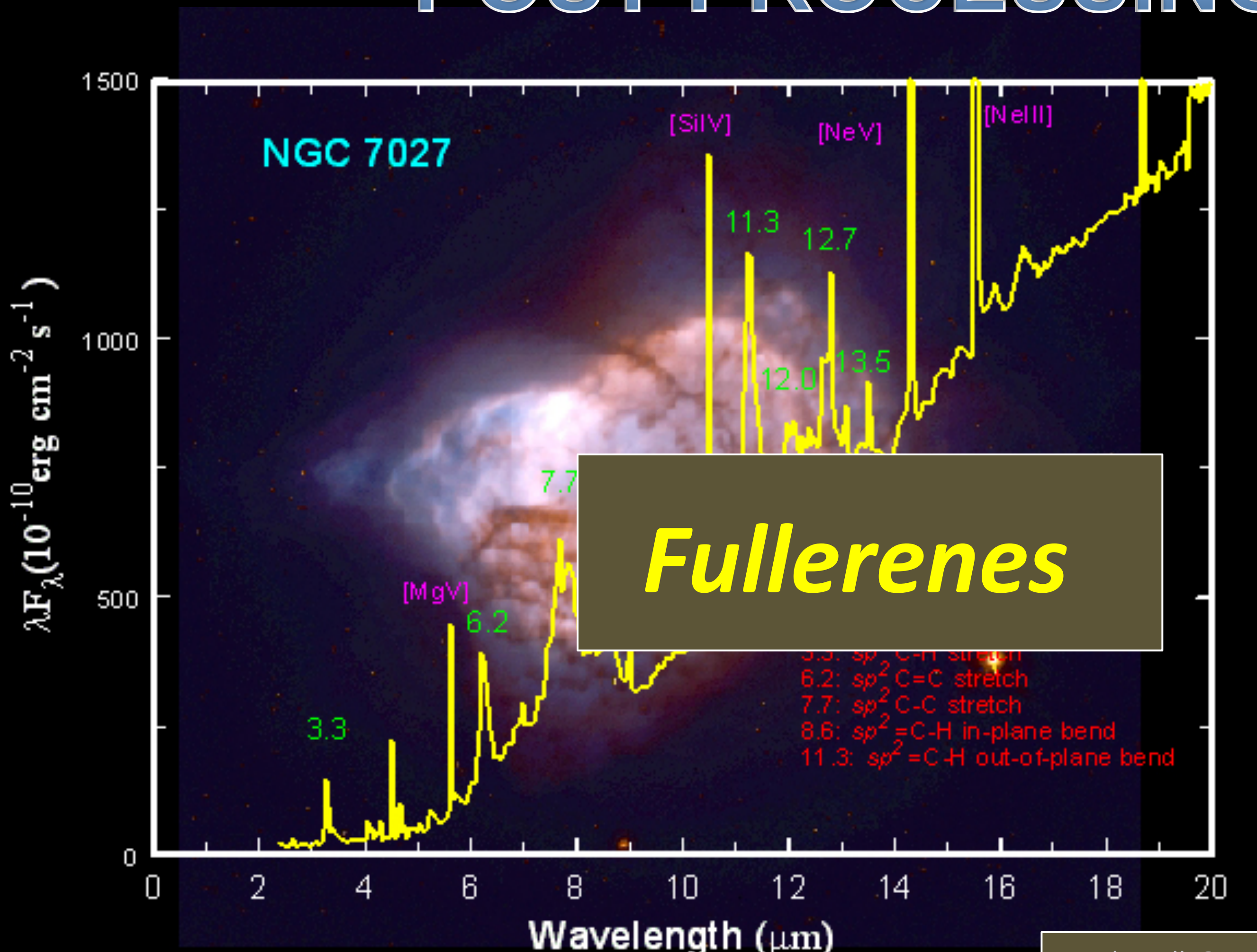


(courtesy Quentin Parker)

the Macquarie PN group discovers standard ***surface brightness – radius relationship*** from their extensive survey results (PNe within < 2 kpc)



Carbon/Nitrogen POST-PROCESSING



prePN Stage

- Prodigious dust and molecule formation in cold, dense winds
- Rich in mixed aromatic/ aliphatic nanoparticles

PN Stage

- UV irradiation and shocks alter the bonded structures

Beyond

- Continues in ISM stage
- dust that settles into YSOs & planetary disks is sputtered and fragmented
- Molecular rings are highly varied fragments, many with chemically receptive bonding sites

Courtesy Sun Kwok

Kwok, Volk & Hrivnak, A&A, 350, L35
Kwok & Zhang, Nature, 479, 80; ApJ, 771, 5
Kwok 2004, Nature, 430, 985

What Drives Mass loss?

Bujarrabal et al. 2001A&A...377..868B

Table 3. Calculations of the mass, momentum and kinetic energy for the sources observed in CO by us.

source	mass $M(M_\odot)$	momentum $P(\mathrm{g\,cm\,s^{-1}})$	kinetic energy $E(\mathrm{erg})$	$\frac{P}{L/c}$ (yr)	comments
IRAS 04296+3429					$L/c = 2.8 \times 10^{34}$ g cm s^{-1} yr^{-1}
slow component	0.13	2.5×10^{38}	1.3×10^{44}	9×10^3	
AFGL 2343					$L/c = 2.3 \times 10^{36}$ g cm s^{-1} yr^{-1}
unique, fast component	4.8	2.8×10^{40}	4.4×10^{46}	1.2×10^4	spherical envelope
IRC+10420					$L/c = 2.8 \times 10^{36}$ g cm s^{-1} yr^{-1}
unique,fast component	2.1	1.5×10^{40}	2.6×10^{46}	5×10^3	spherical envelope; extended
IRAS 19500-1709					$L/c = 6.1 \times 10^{33}$ g cm s^{-1} yr^{-1}
slow component	0.026	5.0×10^{37}	2.5×10^{43}	8×10^3	
fast outflow	6.7×10^{-3}	5.3×10^{37}	1.4×10^{44}	9×10^3	
CRL 2477					$L/c = 1.6 \times 10^{34}$ g cm s^{-1} yr^{-1}

Magnetic Buoyancy

Convective Overshoot

Orbital energy

Part 2: What is the Active Stellar Nucleus?

Like AGNs, the nature of the stellar engine is inferred from its observable impacts

HST/VLTI/Molecular images show highly organized and collimated outflows.

How do we read their messages?

Bipolar Pre-PNe:
Anatomical Tour

Nuclear
Disks

HST images
in dust-
scattered
starlight

and
Gaps

The flow edges are easily visible.

Where are the stellar outflows?

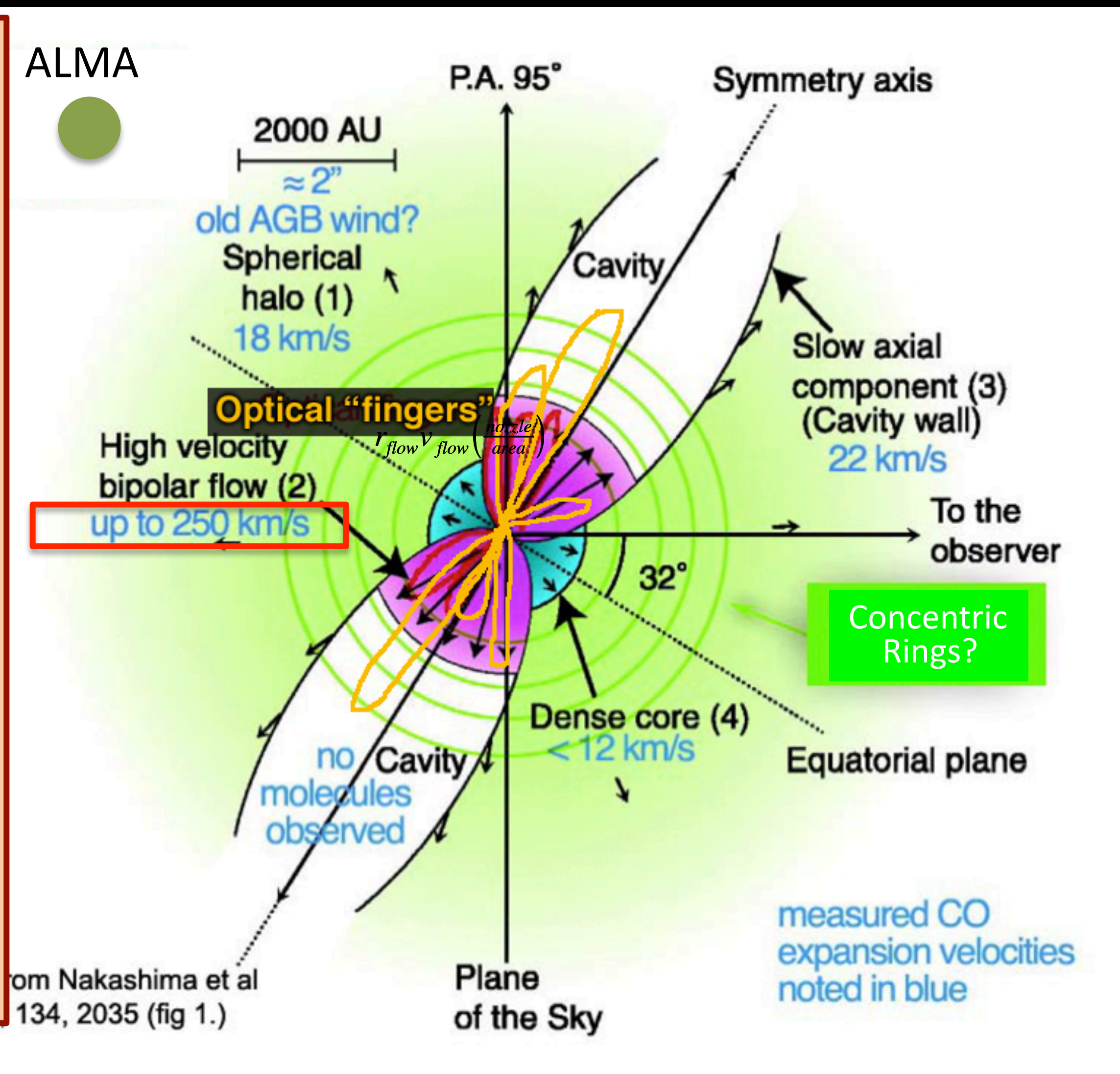
≈50% of prePNe are bipolar. No prePne are perfectly round. (Sahai et al. 2011AJ....141..134S).

Bipoplar prePNe: Anatomy

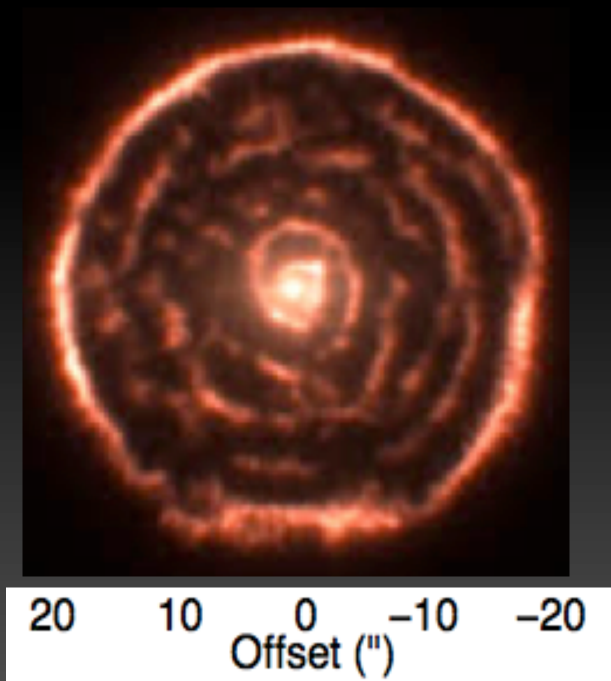
Basic Characteristics
- bilobed (occasionally multi-lobed) envelope
- cold exterior gas.

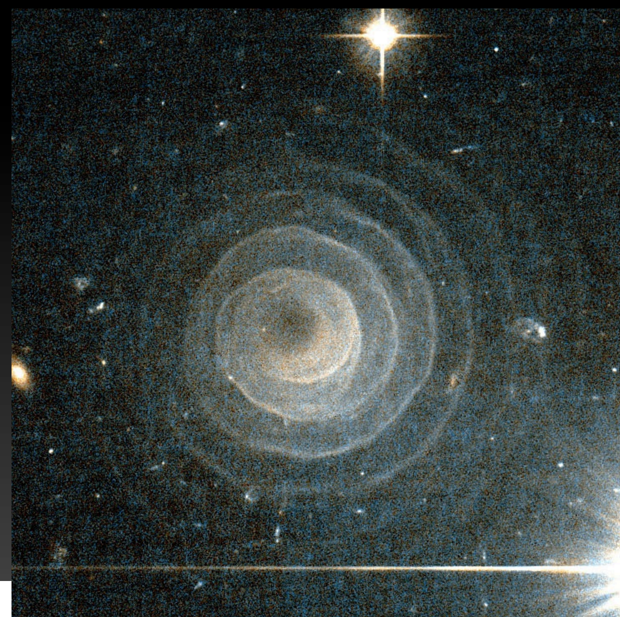
Stellar outflow
- jets, bullets, or cones
- n_{flow}, v_{flow}, T_{flow}, R_{flow}, σ_{flow}, (Θ_{flow})
- mass flux $\dot{M} \approx 10^{-7}$ $M_{\odot}$/y

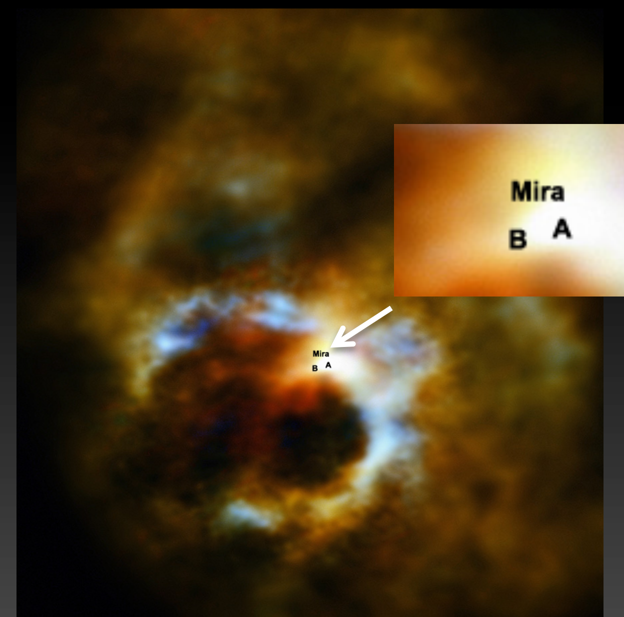
Environment
- uniformly expanding AGB wind
  $n_{AGB} = n_o (R_o/r)^2$,
  $v_{AGB} \approx 20$ km/s,
  $T_{AGB} \approx 10\text{-}100$ K
  ($v_{flow} >> C_s$)
- Equatorial torus



A few show evidence of binary-star shaping







R Sculptoris
^{12}CO (3–2) ALMA (0.87mm)
Maercker et al (2012,2014
Vlemmings et al 2013)

AFGL 3068
HST/ACS F606W/F475W
HST Archives, GO 11676

Mira A and B (0.”5 sep)
^{12}CO (3–2) ALMA (0.87mm)
Ramstedt et al
2014A&A...570L..14R

PrePN History 101

Observables

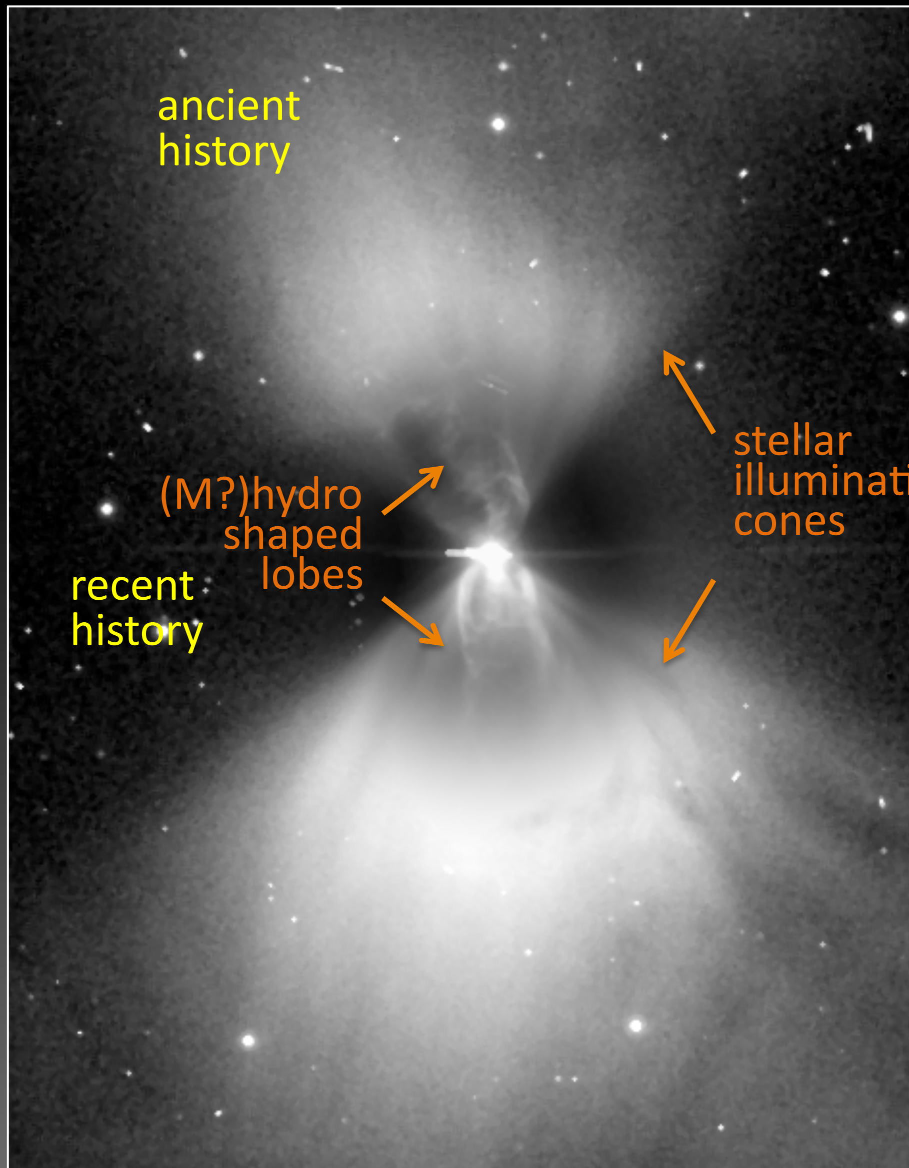
dust-scattered
atar light

shocks
(H_2, [FeII], [SII])

molecular, [CII]
Emission lines
(0.3-10 mm)

polarization

various deriveables



Hydro State
Variables:
distributions of

Density

Flow momentum

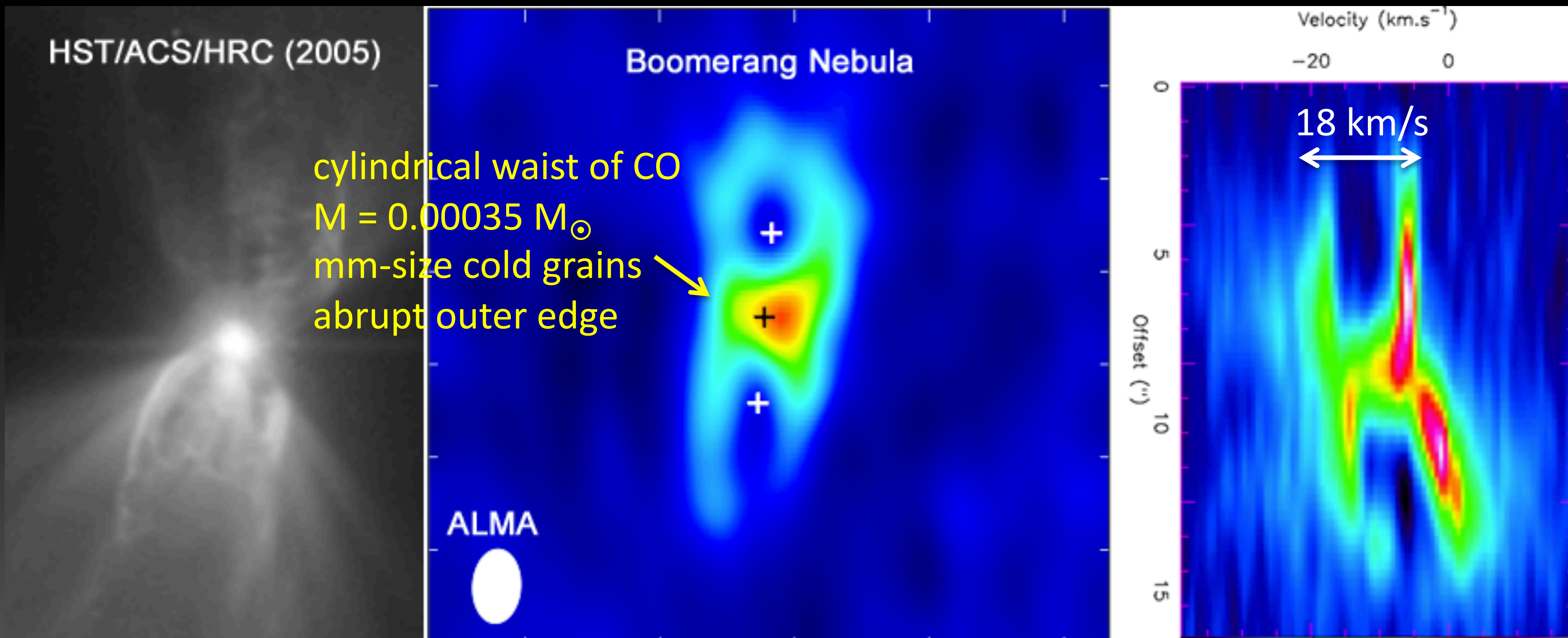
Temperature

Field strength

Pressure
thermal, ram, B

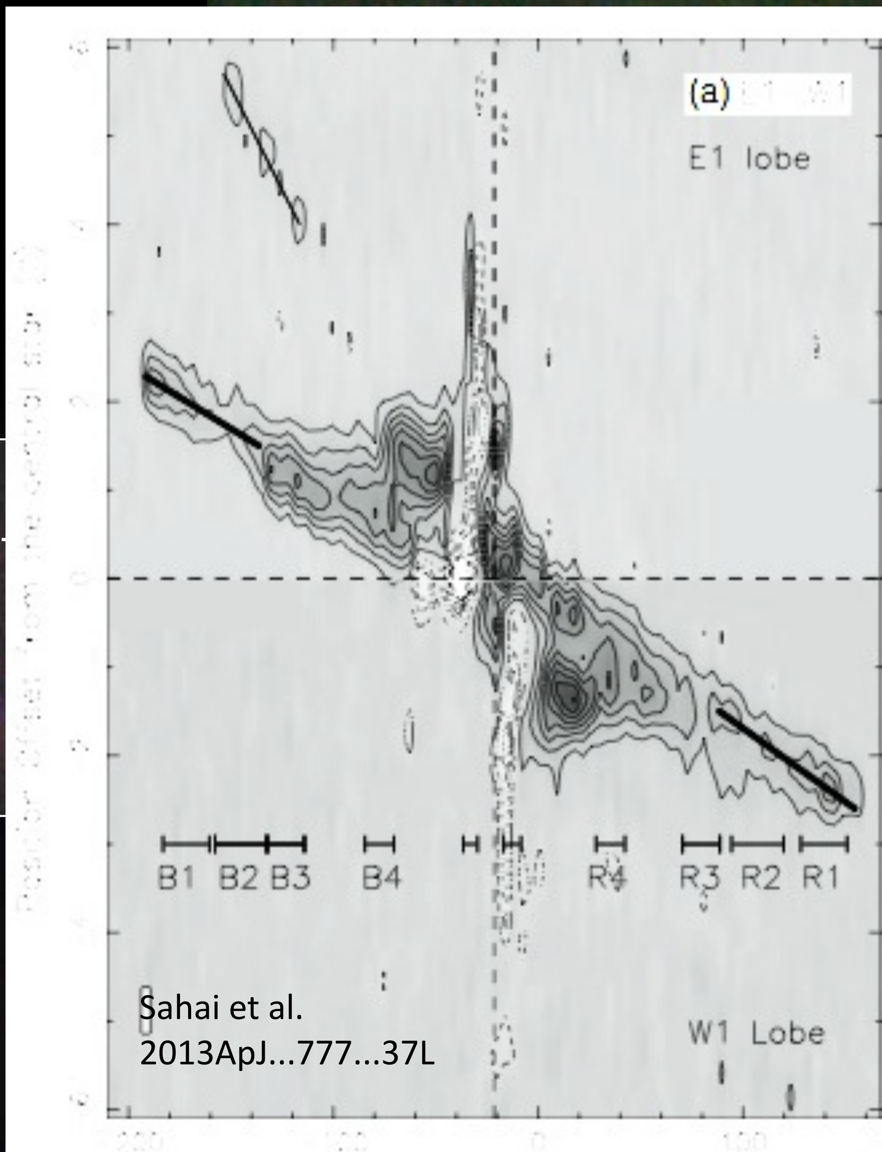
Enter ALMA: Molecular Imaging

Sahai et al. 2013ApJ...777...92S



Terminal speed of an opaque radiation-driven AGB dust wind = 18 km/s
(Ivezić, Ž. & Elitzur, M. 2010MNRAS.404.1415I)

CRL618: best case study



Sahai et al.
2013ApJ...777...37L

WC8)

Kinematics galore!

WFC3 F658N F656N F547M

Balick et al.
2014ApJ...795...83B

WFC3 F110W IR

Simplest flow paradigms

high-pressure puncture
and adiabatic expansion
(thermal pressure dominates)

inertially-constrained
wind (ram pressure)

jet or bullet
(ram pressure)

Deconstructing the stellar engine from its exhaust

Hydro for everyone!

AstroBEAR

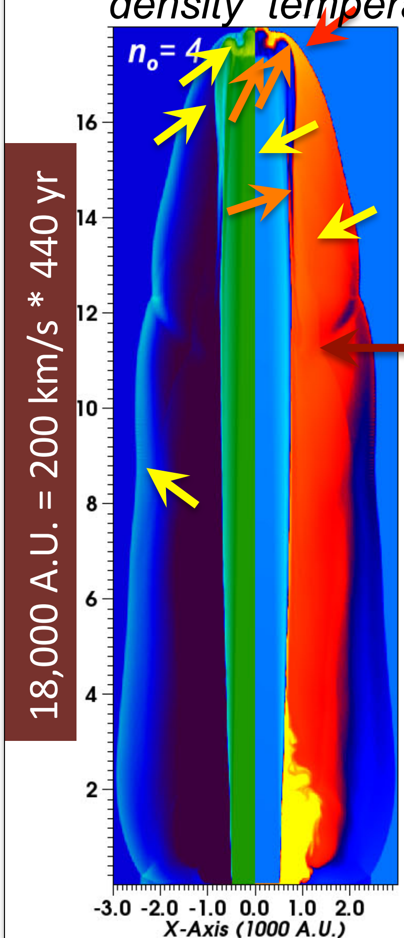
An Adaptive Mesh Refinement Code for Computational Astrophysics

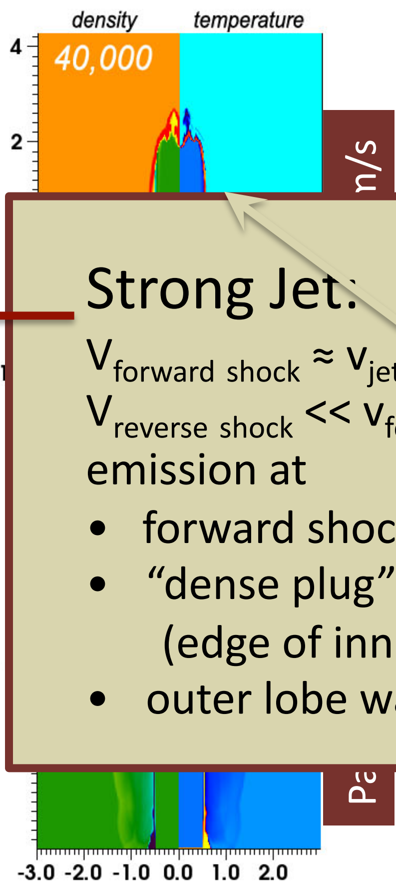
Adam Frank, Martin Huarte-Espinosa, Baowei Liu, and the Rochester Computational Group

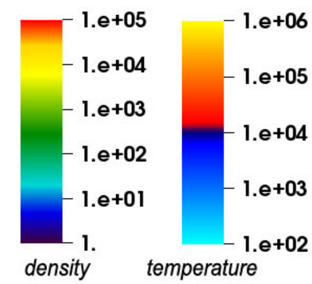
Learning from your students

Idealized Flows: Jets (AstroBear)

Studies of idealized cylindricl jets after 440 years *$n_{cyl\ jet}$ = 400 cm^{-3}, Jet launch speed = 200 km/s*







Strong Jet: $n_{jet} > n_{amb}$

$V_{forward\ shock} \approx v_{jet}$ ≈

$V_{reverse\ shock} << v_{for.}$

emission at

- forward shock
- "dense plug" a
  (edge of inner
- outer lobe wal

Weak Jet: $n_{amb} > n_{jet}$ ("heavy lifter")

$V_{forward\ shock} \approx v_{pattern} << v_{jet}$

$V_{reverse\ shock} \approx v_{jet} >> v_{for.shock}$

emission at

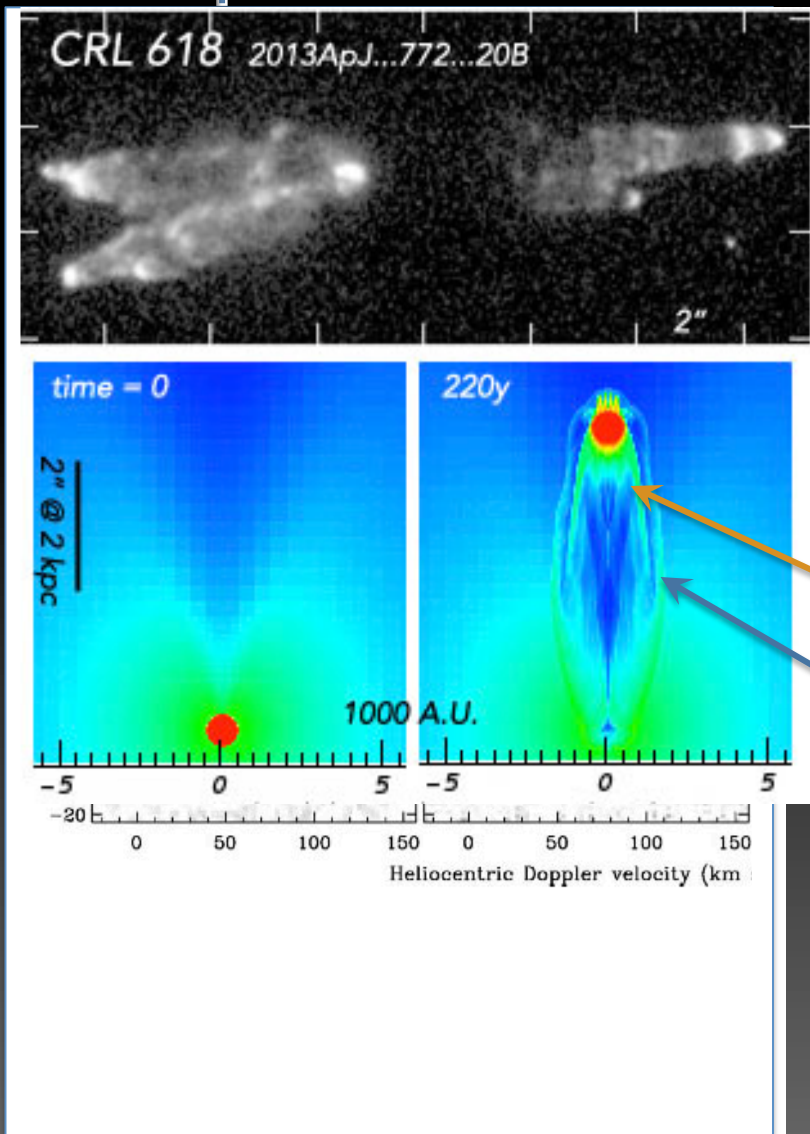
- reverse shock (faint x-rays),
- "dense plug" and its "roll-off tail"
  (edge of inner lobe) ([FeII] and optical lines),
- Dense lobe edges

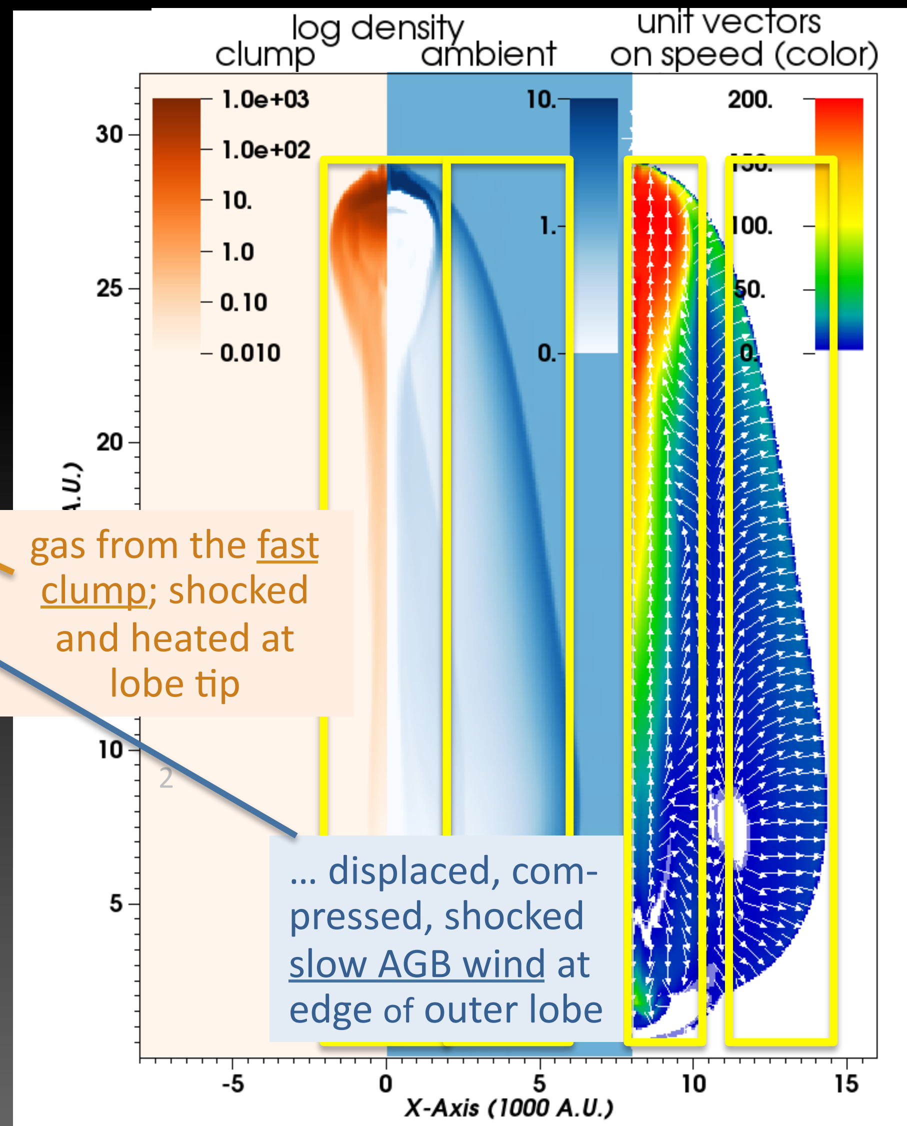
Initial grid: constant density, $n(r) = n_o$

AGB wind, $n(r) = n_o (r_o/r)^2$

Idealized flows: Clumps

Parabolic-tapered clump flow, radius = 1500 AU, launched into stationary constant density n_{amb} = 1 cm^{-3}
v_{clump} = 200 km/s, $n_{clump}(r=0)$ = 400 cm^{-3}, T_{clump} = 1e3 K





Balick, Frank, & Liu, in progress

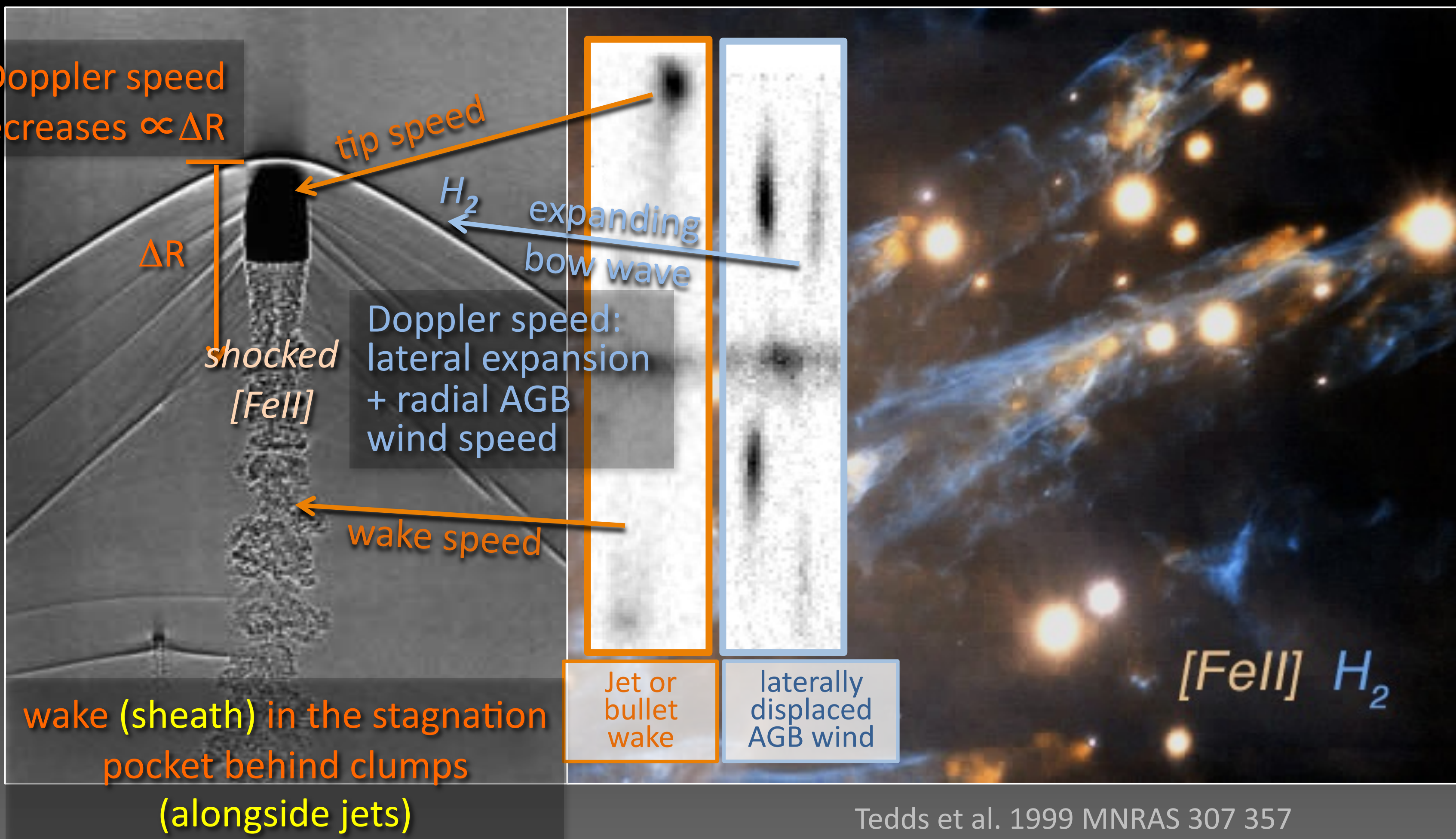
<pattern tip speed>$_{600y}$= 195 km s^{-1}

Realized Flows

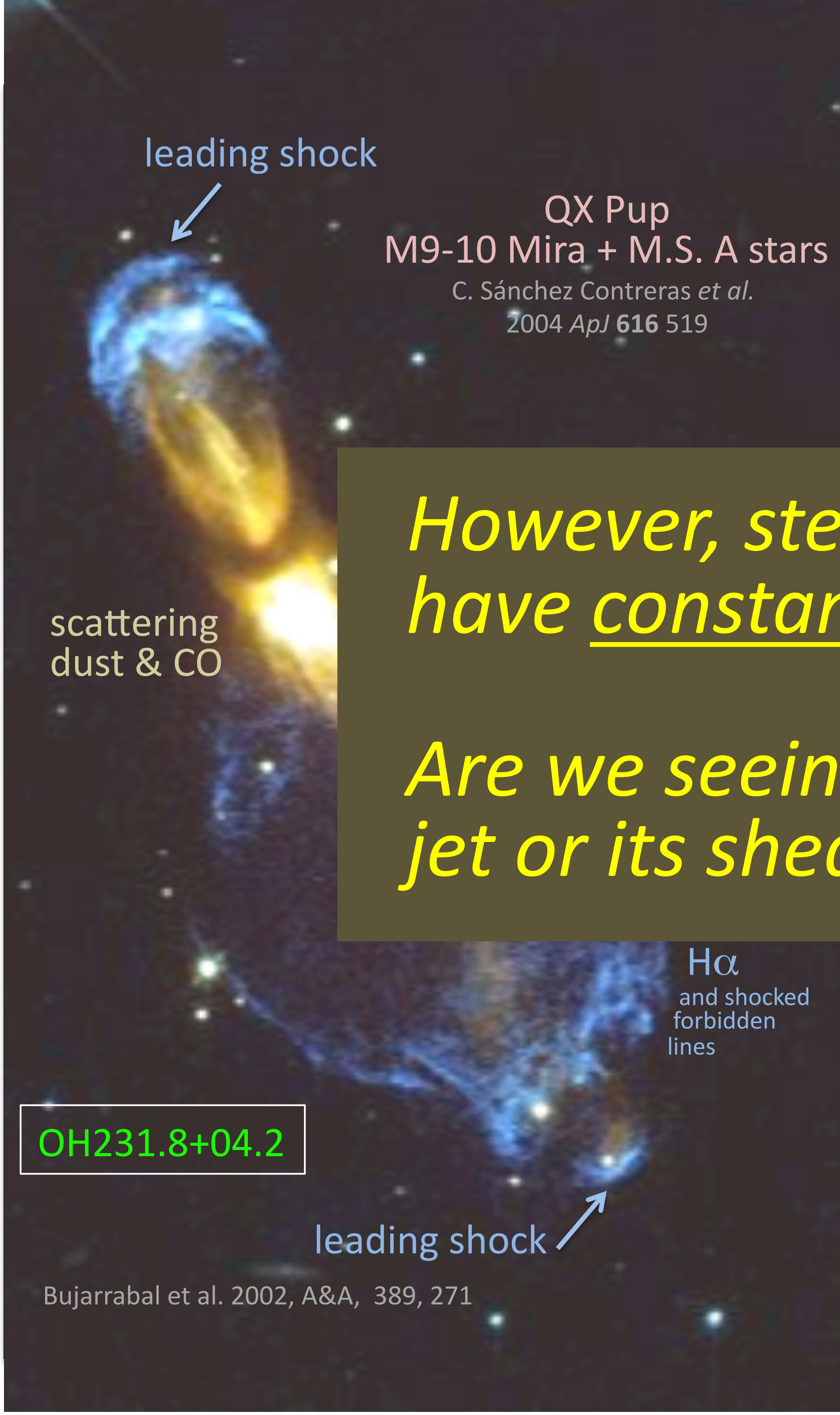
Thin Cylindrical Jets, Filled Conical Jets, & Bullets

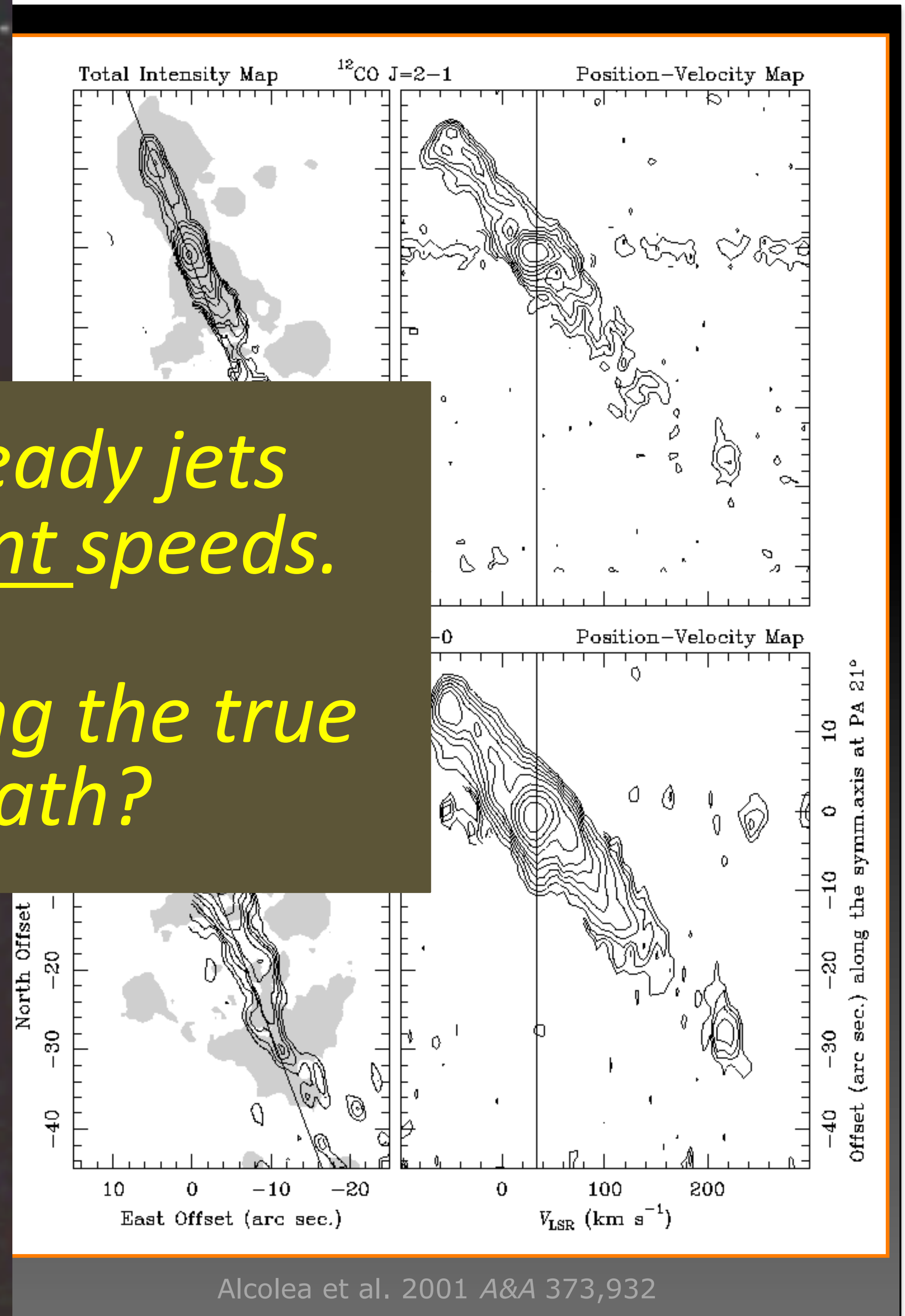
All produce bow shocks and wakes. For small-angle flows and clumps, disks near the star are not important for shaping lobes.

Flows: Shocked-gas Bullets, Jets & Sheaths



Tedds et al. 1999 MNRAS 307 357





Alcolea et al. 2001 *A&A* 373,932

However, steady jets have constant speeds.

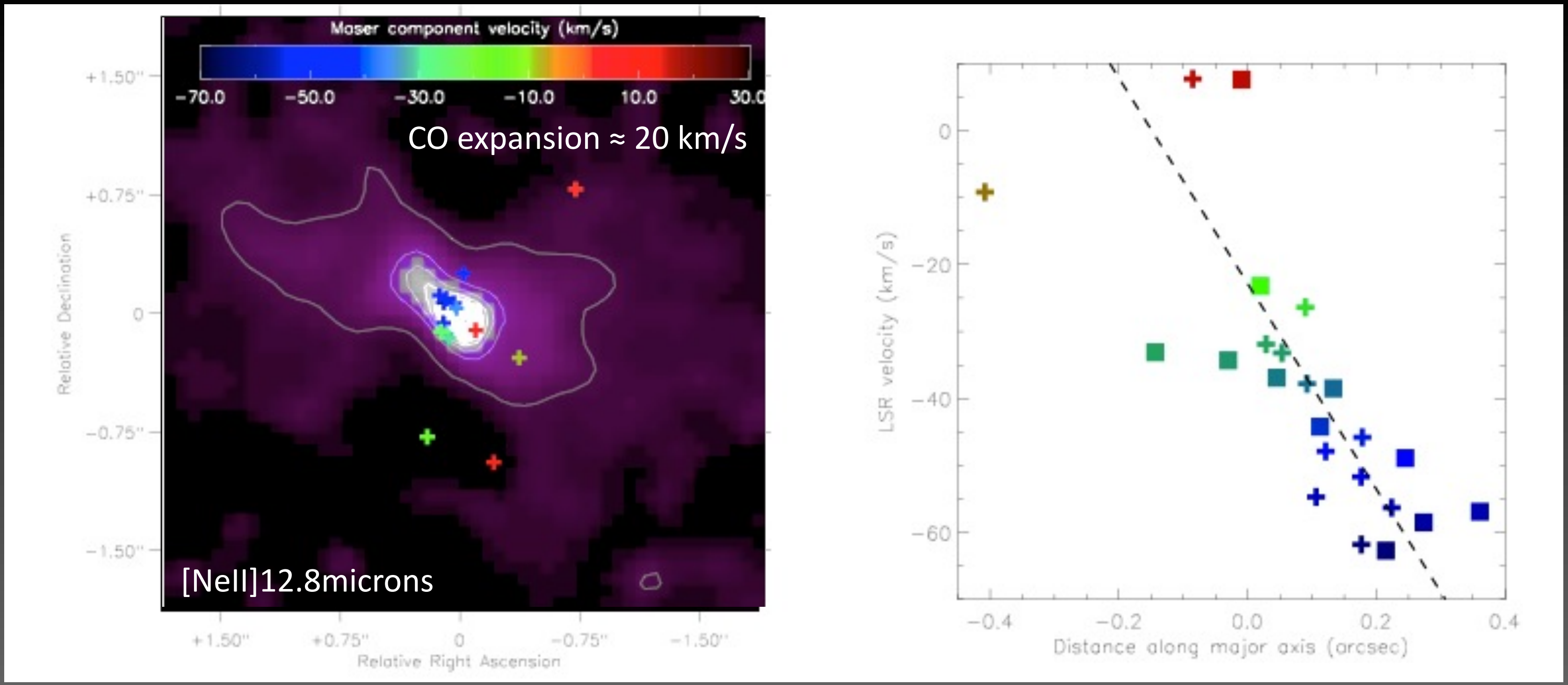
Are we seeing the true jet or its sheath?

Flows and Kinematics

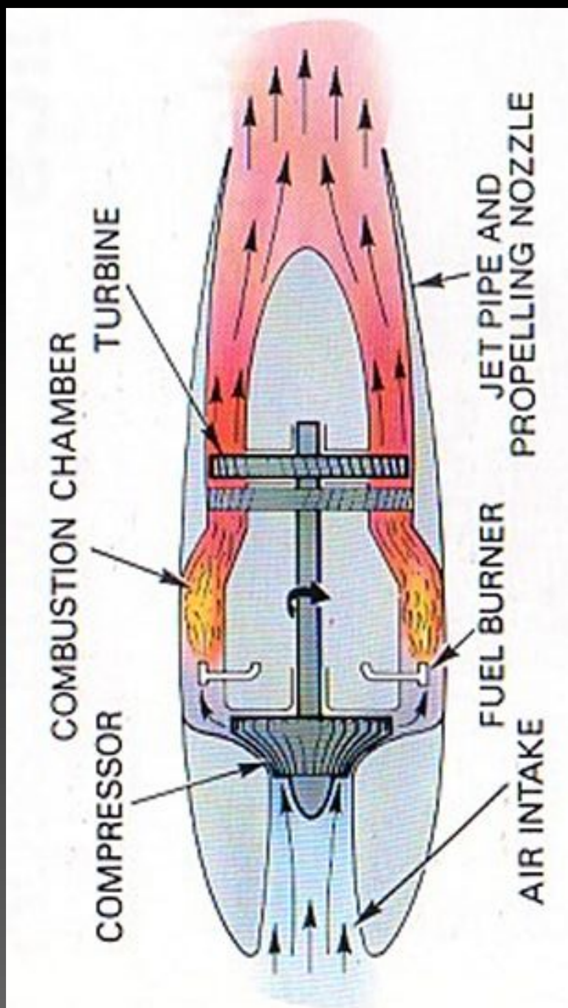
THE FIRST "WATER FOUNTAIN" COLLIMATED OUTFLOW IN A PLANETARY NEBULA

José F. Gómez[1], Olga Suárez[2], Philippe Bendjoya[2], J. Ricardo Rizzo[3], Luis F. Miranda[1,4], James A. Green[5,6], Lucero Uscanga[7], Enrique García-García[3], Eric Lagadec[2], Martín A. Guerrero[1], Gerardo Ramos-Larios[8]

Submitted to the Astrophysical Journal 1412.2327, 24 Dec 2014



Nested Lobes:
A Learning opportunity



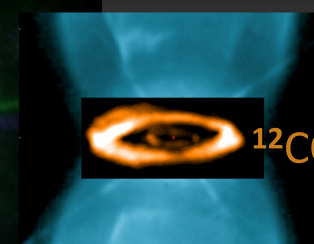
Paradigm?

M2-9

HST/WFPC2
GO 11599
F438W/F555W/F814W

[Fe II] – fast shock +CD
(radial expansion)

H_2 – slow shock + CD
(lateral expansion)



Gemini/Altair

P'teau de Bure
Carrizozo et al
2012A&A...545A...1C

Gaussian-tapered conical flow

v_{cone} = 200 km/s,

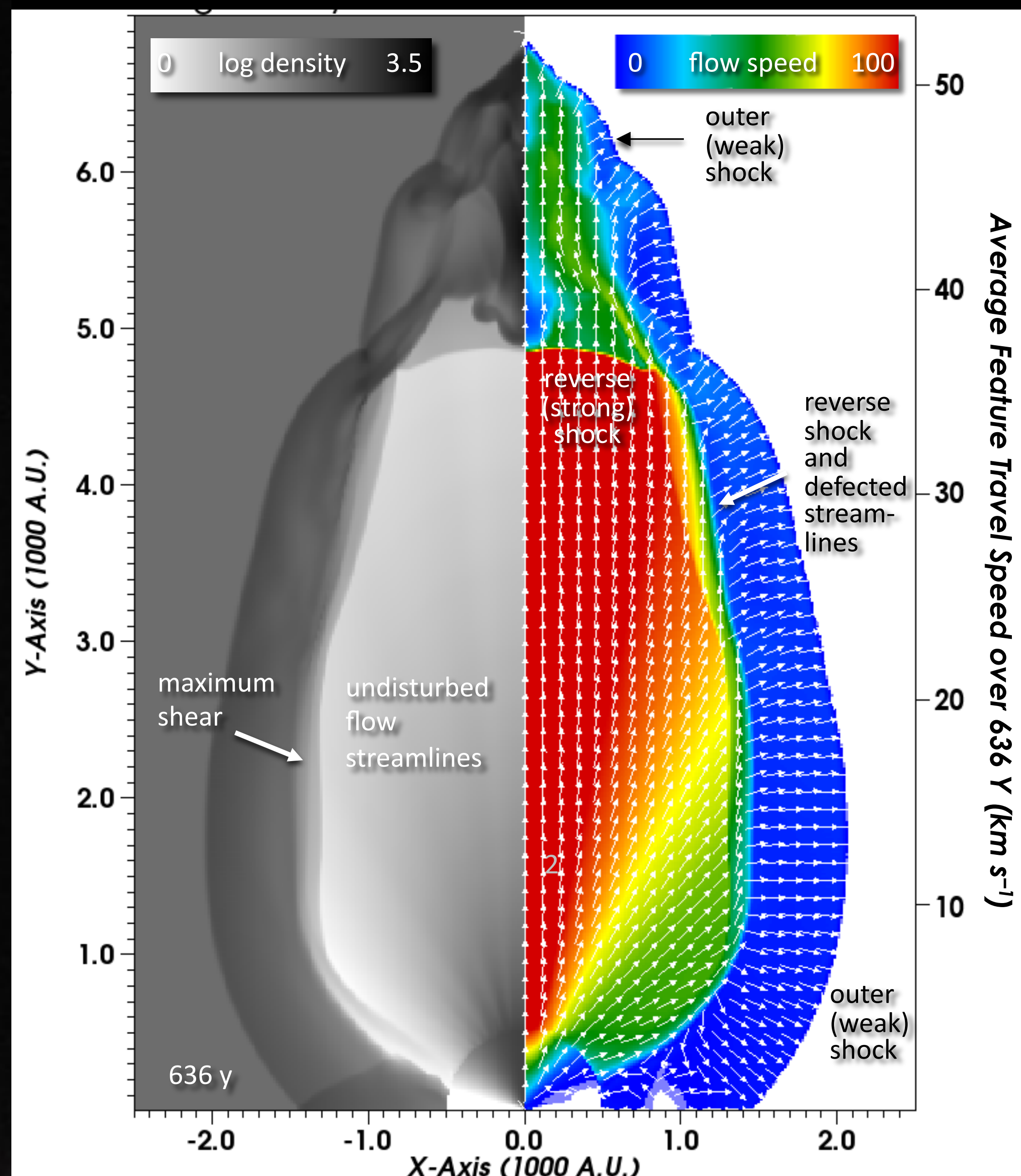
n_{cone} = 400 cm^{-3},

T_{cone} = 1e3 K

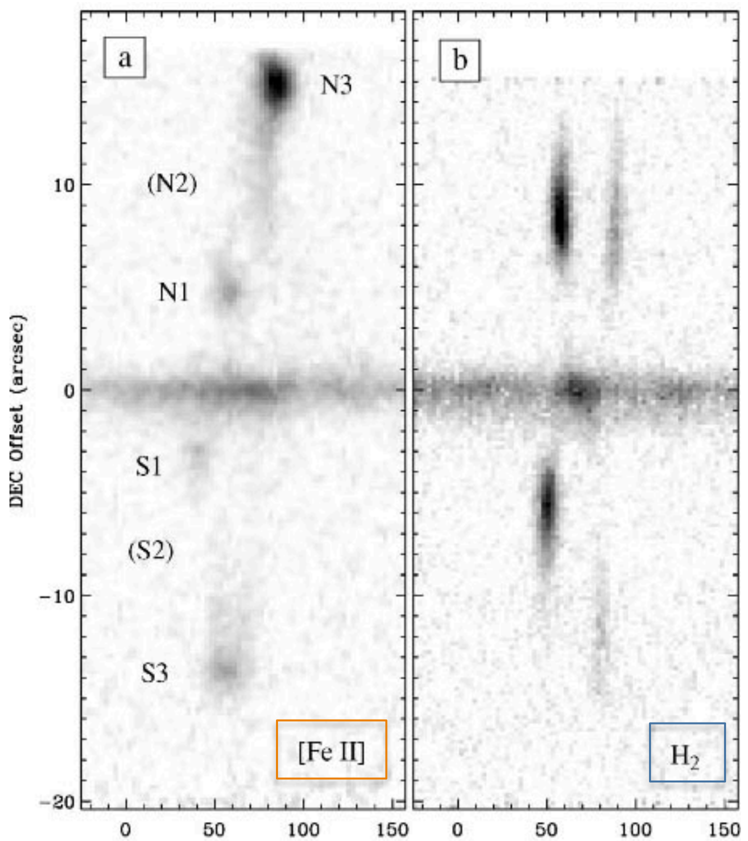
1/e opening angle = 30deg

Launched into constant medium

n_{AGB} = 100 cm^{-3}



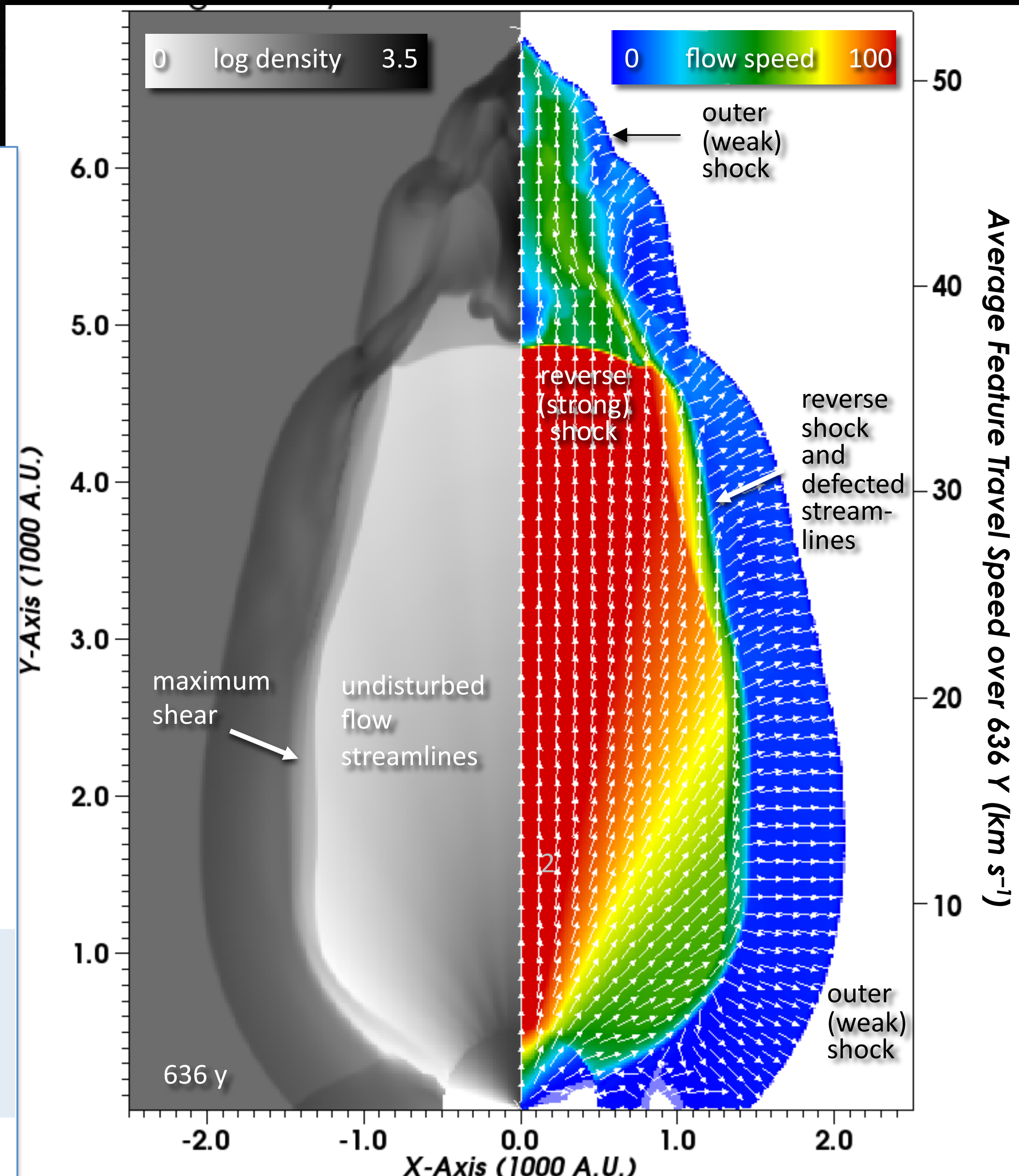
Balick, Frank, & Liu, in progress



gas from the fast stellar wind; shocked at edge of inner lobe

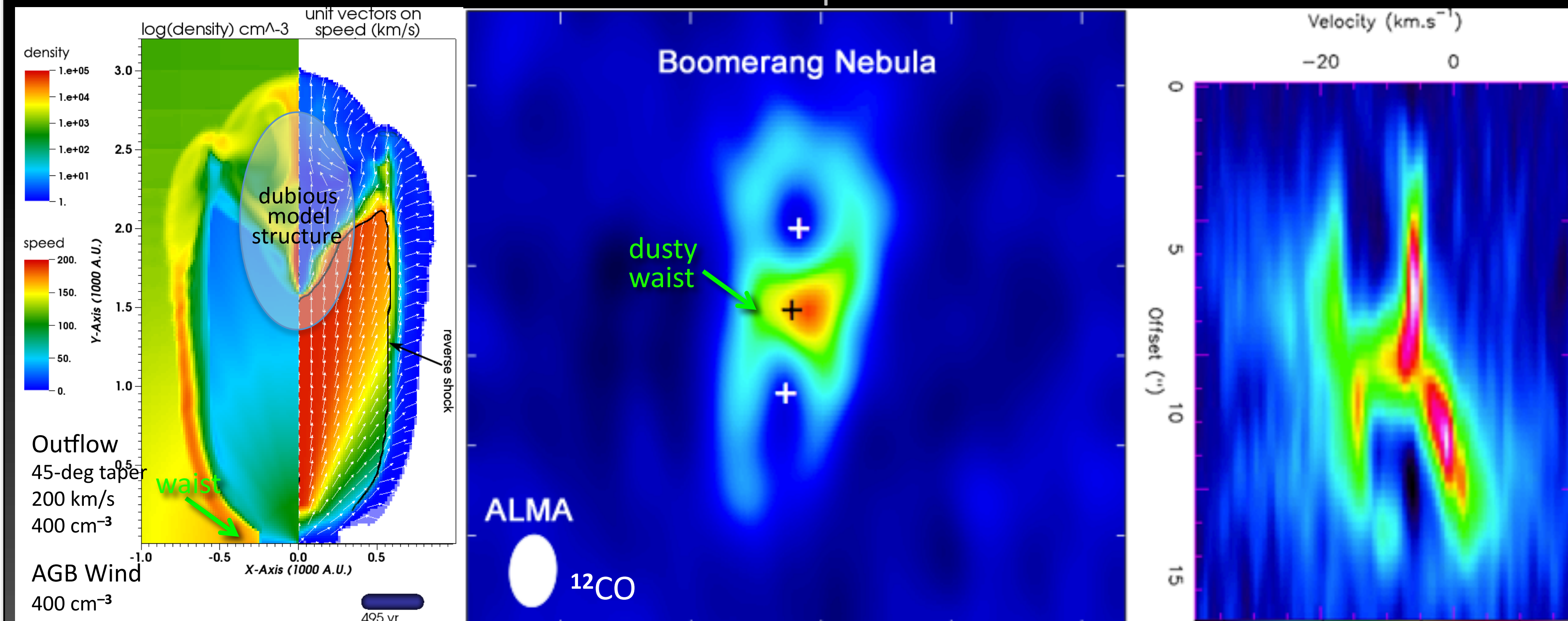
… displaced, compressed, shocked slow AGB wind at edge of outer lobe

Smith et al. 2005AJ....130..853S



Hollow Cylinders
with constant-speed outflow

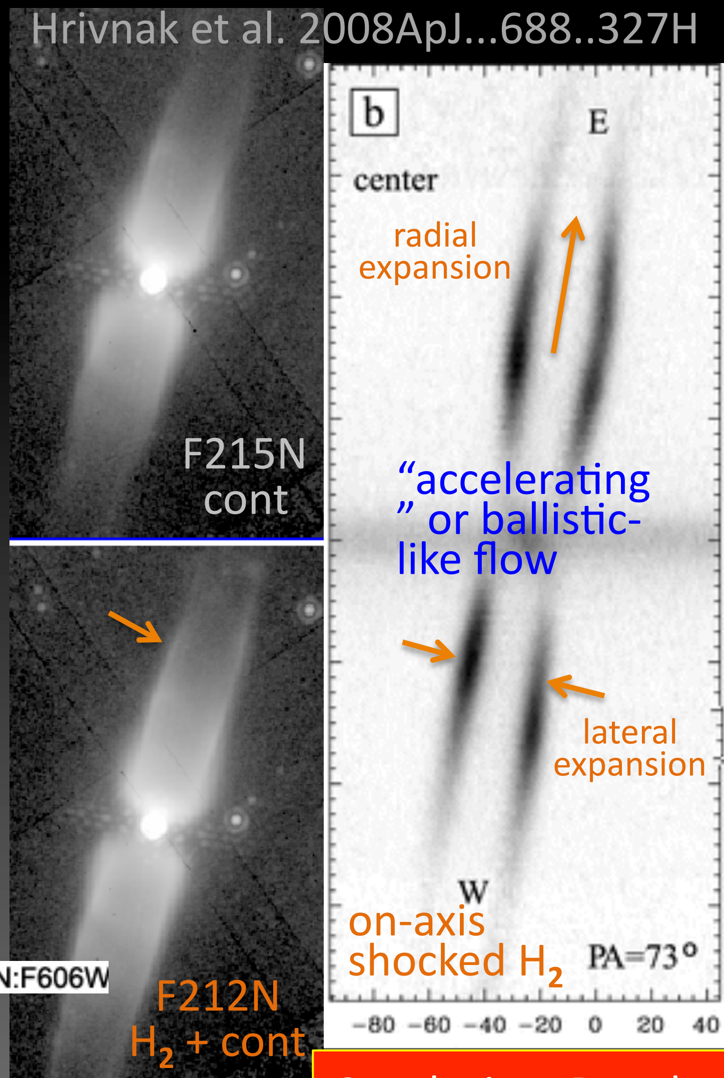
Sahai et al. 2013ApJ...777...92S

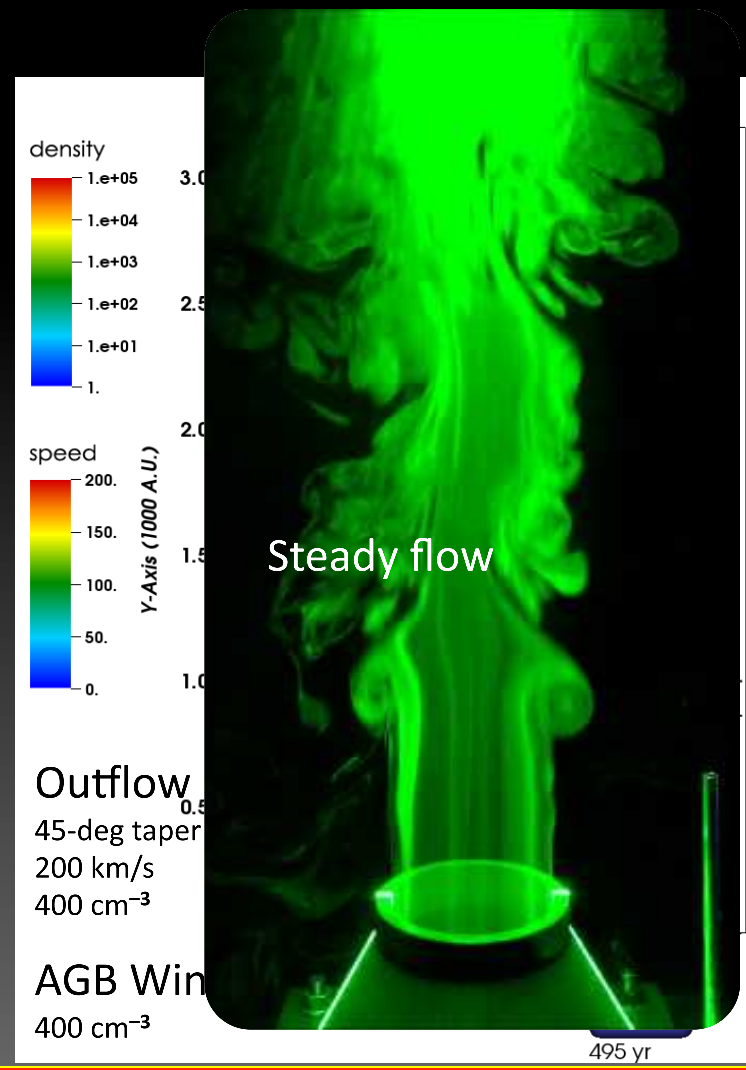


Hollow Cylinders

with increasing-speed outflow

Hrivnak et al. 2008ApJ...688..327H





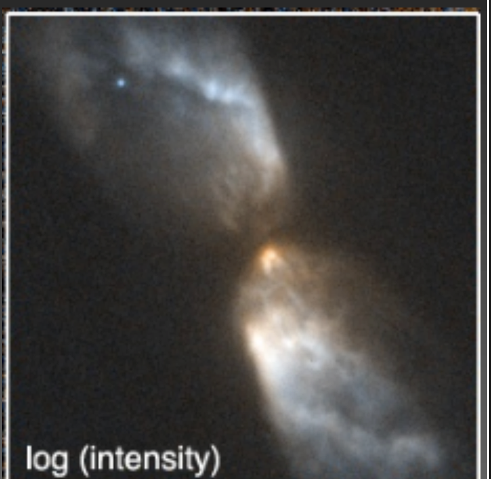
Conclusion: Pure hydro explanation of the kinematics is unlikely.

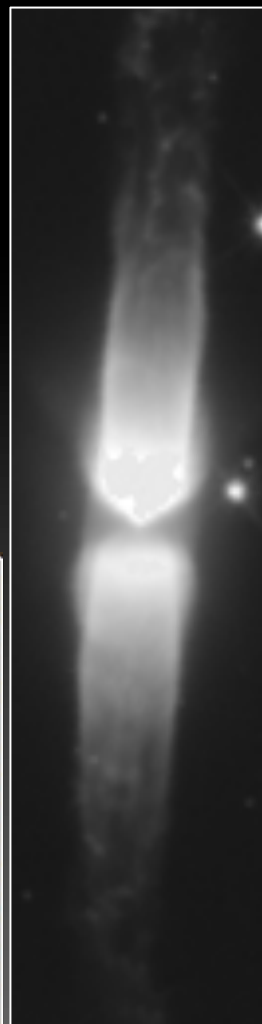
Hollow Cylinders

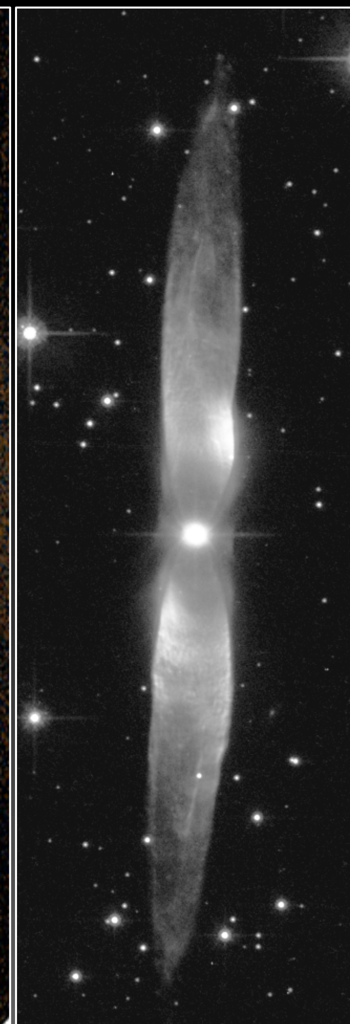
Magnetic Shaping? Hydroforming?

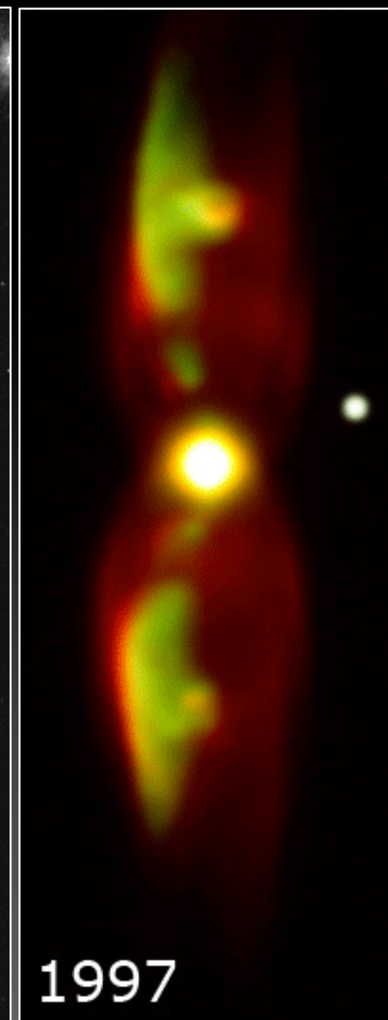
Hoop stresses in emergent toroidal field?

Burrowing by jets from Precessing gas nozzle?









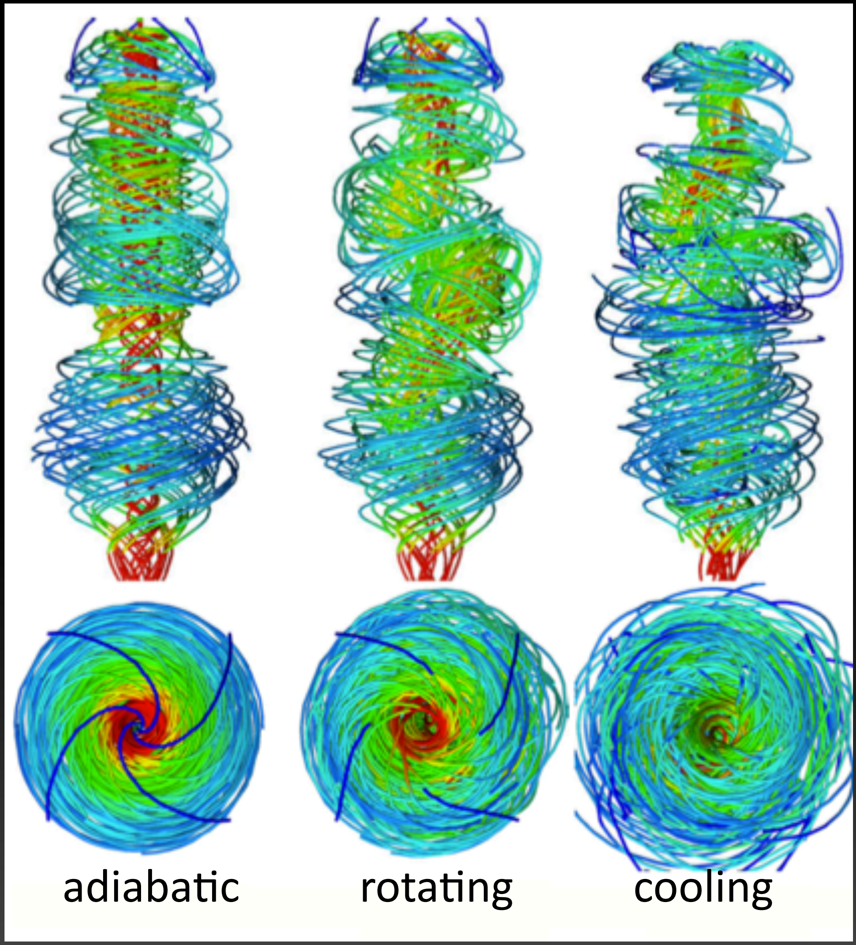
Corradi et al 2011
A&A...529A..43C

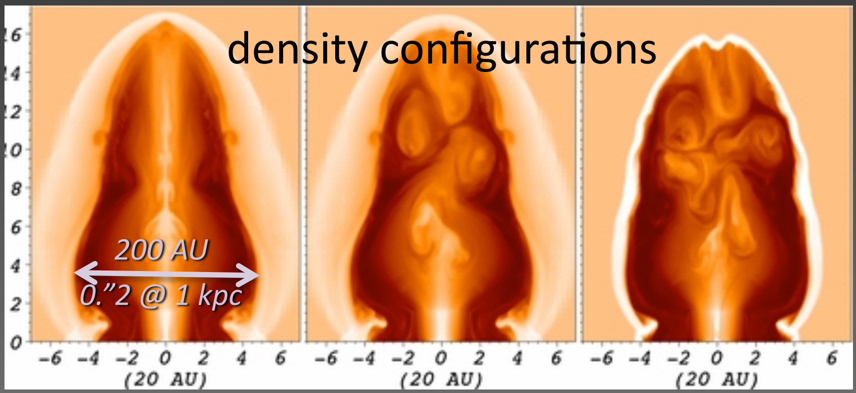
Magnetic Shaping?

On the Structure and Stability of Magnetic Tower Jets

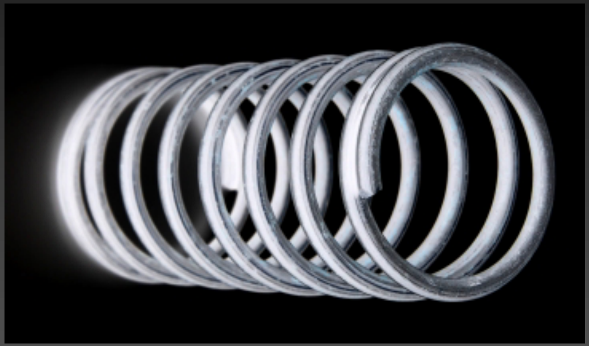
Huarte-Espinosa et al 2012ApJ...757...66H

Three field configurations, t=118 y





uncoilng spring analogy



Expansion speed proportional to distance

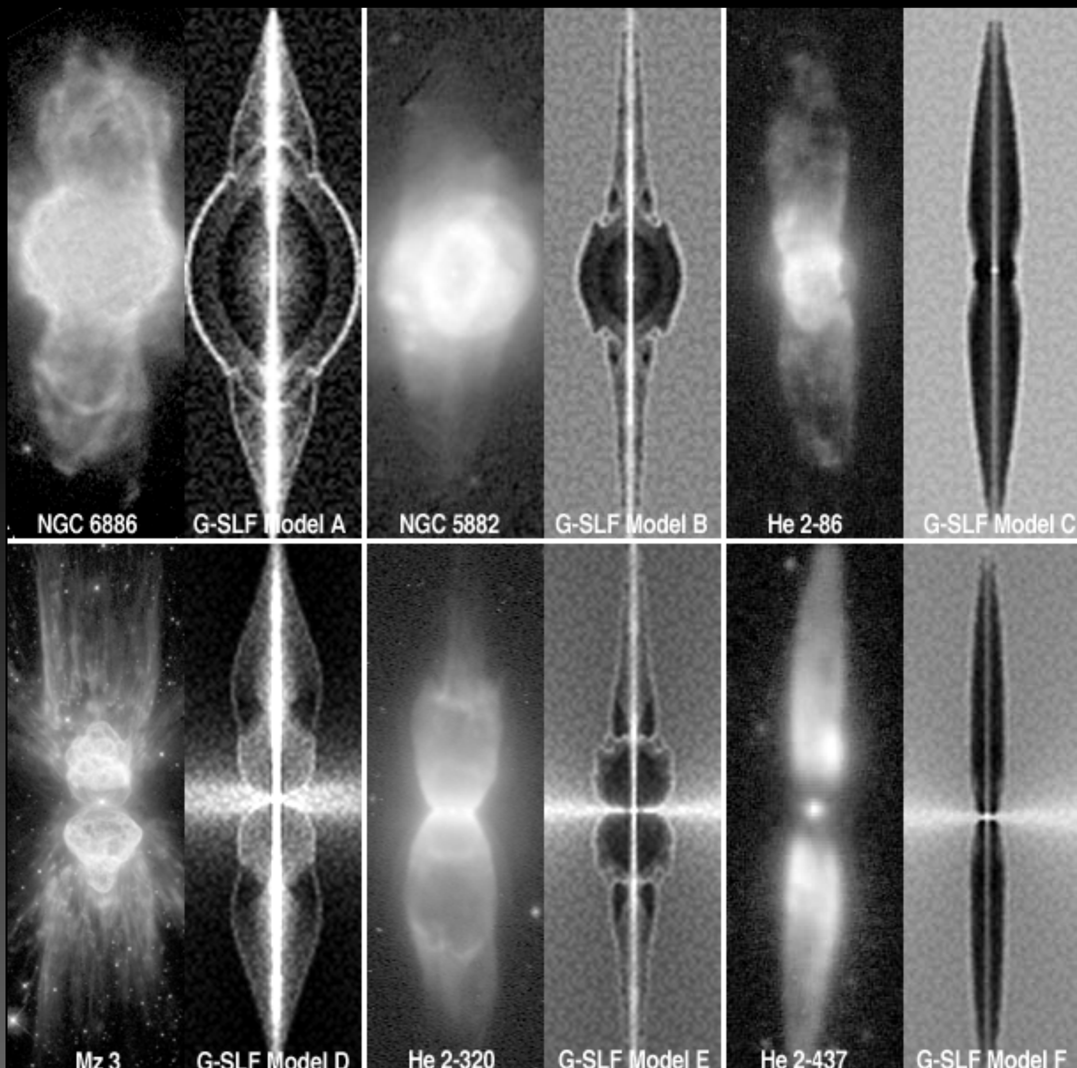
Magnetic Shaping?

Highly collimated jets formed from isotropic winds into an (imposed) poloidal field

A. Ciardi,[1] T. Vinci,[2] J. Fuchs,[2] B. Albertazzi,[2] C. Riconda,[2] H. Pépin,[3] and O. Portugall[4]

(animation)

Magnetic Shaping?

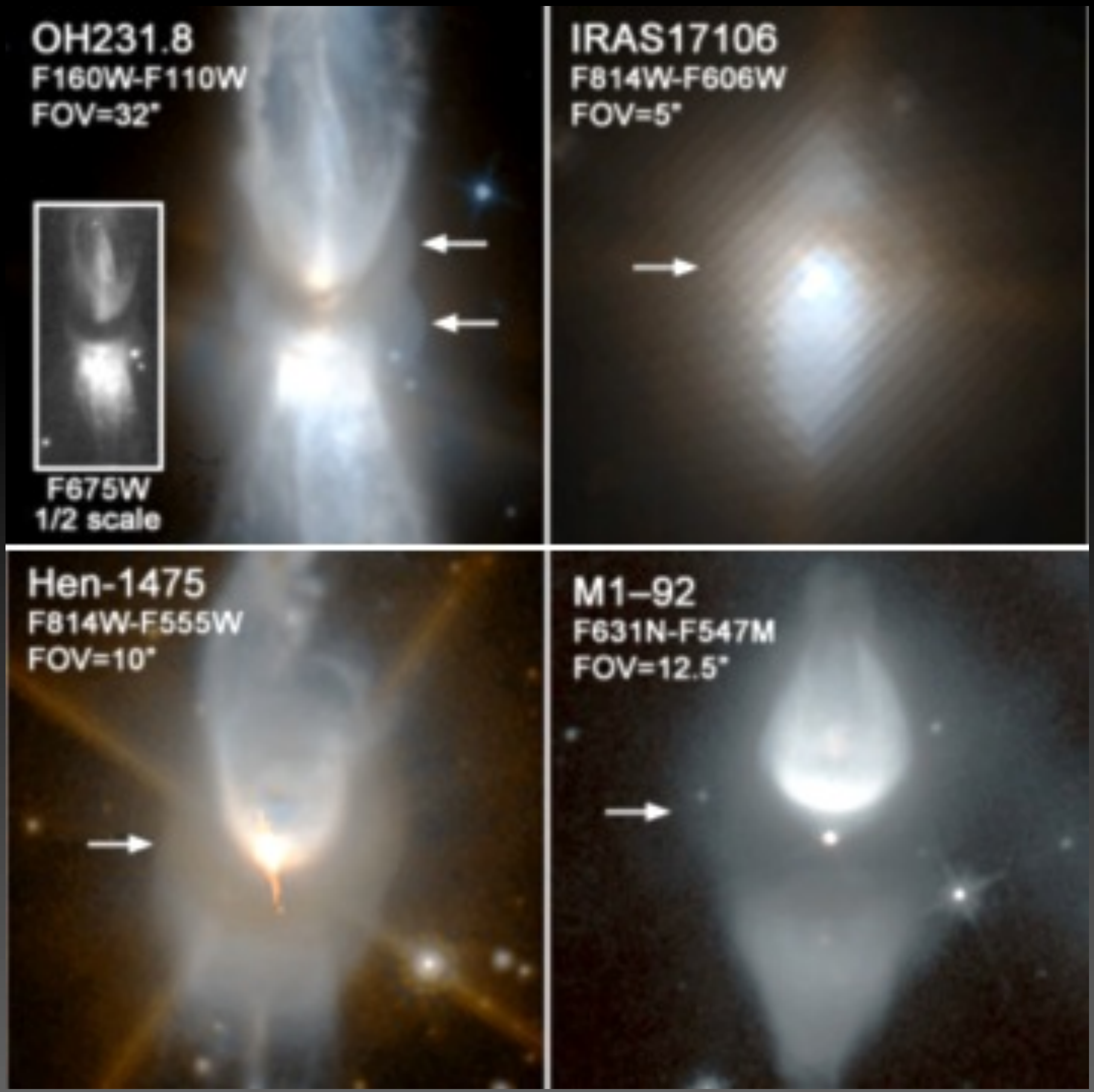


MHD models: Garcia-Segura, Lopez & Franco, 2005 ApJ 618 91

Fields produce thin and magnetically confined jets that plow through the ambient medium.

Lower panels: thin, dense disk imposed to inertially pinch the waist.

Thin Equatorial Disks



Thin disks with sharp outer edges, seemingly translucent and smooth.

Thin Equatorial disks: Binary mass Overflows

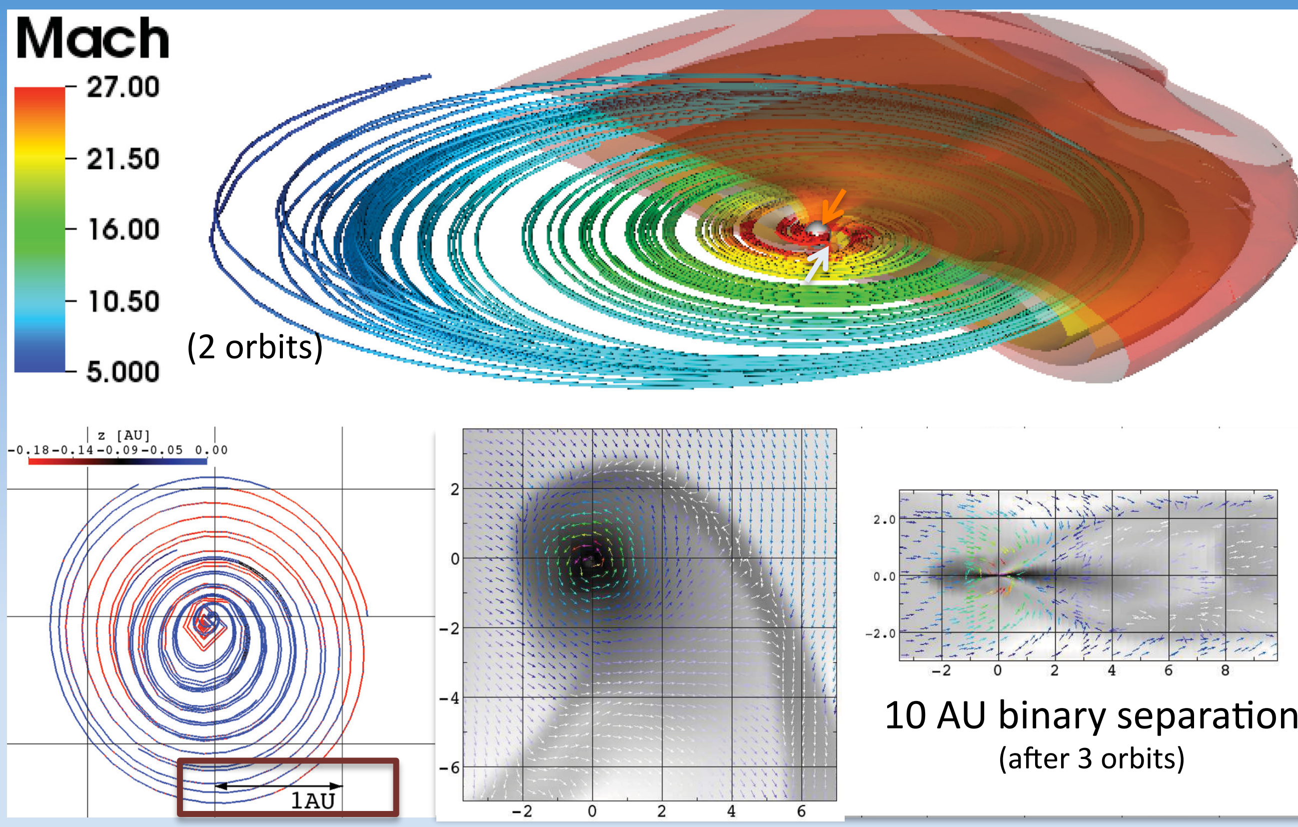


Figure 8. Top: 3D disc gas orbit streamlines and sliced density contours (red) for the 10 AU case at $t = 2$ orbits. The central white small sphere is the secondary. Streamline colours denote orbital speed in Mach units. The wind enters the grid towards the image. Bottom: Disc gas orbit streamlines at $t = 3$ orbits corresponding to the 10, 15 and 20 AU cases, from left to right. The wind enters the grid from the top left-hand corner moving towards the bottom right. Colours denote distance perpendicular to the orbital plane in AU and indicate the orbits inclination.

Huarte-Espinosa et al. 2013MNRAS.433..295H

The Worlds of Planetary Nebulae

Thanks to Many!

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Sun Kwok, Rudy Montez, Dick Henry
Joel Kastner, Raghvendra Sahai, Quentin Parker,
Woter Vlemmings, Amanda Karakas, Karen Kwitter

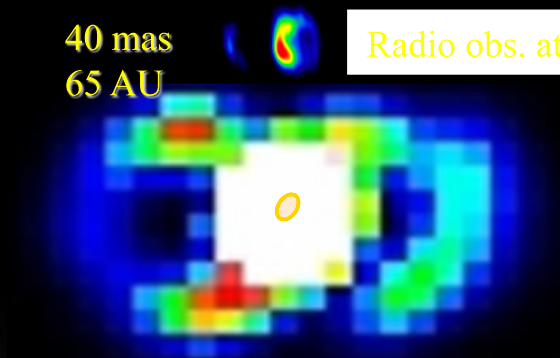
Novae: fast creation of highly bipolar nebulae

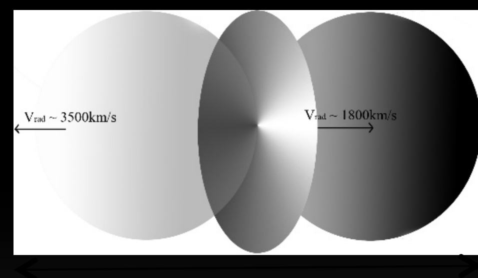
Recent examples of bipolar nebulae observed less than 1-2yrs after outburst

40 mas
65 AU

Radio obs. at t=22 days

240 mas
380 AU



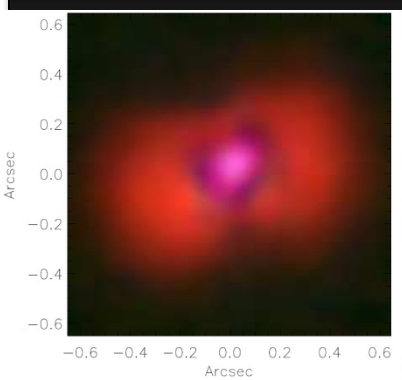


HST visible image at t=150 days

9 mas – 15 AU, t=5d

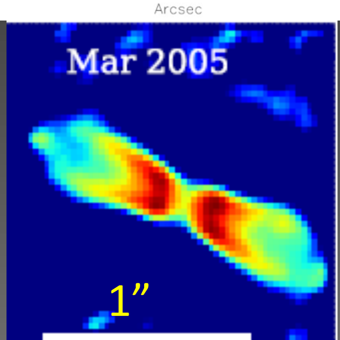
The recurrent RS Oph:

O'Brien et al. 2006,
Chesneau et al. 2007,
Bode et al. 2008…



The classical V1280 Sco:

Chesneau et al. 2008,
Chesneau et al. 2012
A slow nova (Vej~500km/s):
large mass ejection, dust created, no equatorial material



The classical V445 Pup:

Woudt et al. 2009,
Fast nova (Vej~4000km/s): An extremely asymetrical outburst? Dense equatorial material

The recurrent T Pyx: a near-pole on bipolar nebula

Chesneau et al., 2011, wind acceleration observed