Millimetre/Submillimetre Astronomy Studies of Evolved Stars, Protostars and High Redshift Galaxies

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A bit of history

Establishment:

- Born in 1999 when Prof. Pierre Darriulat came to Viet Nam with gifts
- Gifts: scintillators, PM tubes, NIM and CAMAC electronics
- Measure the muon flux in Ha Noi; at the Earth maximum of rigidity cut-off; giving unexpected value

Joined the Pierre Auger collaboration:

- High energy end of the cosmic ray spectrum (Argentinean pampa)
- Analysis of the data (our first three PhD theses).
- Friendly interest and support of our colleagues in Auger (Jim Cronin and Alan Watson) → a framework for us to grow and come of age

Our interest for astrophysics kept increasing:

- Teaching at various universities
- A 2.6 m radio telescope (21 cm hydrogen line):
    - studies of its response (permil level effects);
    - the HI density in the Milky Way;
    - black body temperature of the Moon;
    - polarisation of several solar flares;
    - evidence for correlations between the periods of solar oscillations (percent level amplitudes) observed jointly by us and by an Australian solar observatory (multipathing artefact).

Radio astronomy (for now 5 years or so): stellar physics (birth and death of stars) and high redshift galaxies (learning about the early Universe), using data from major international observatories.

The data

Observations made with radio interferometers:

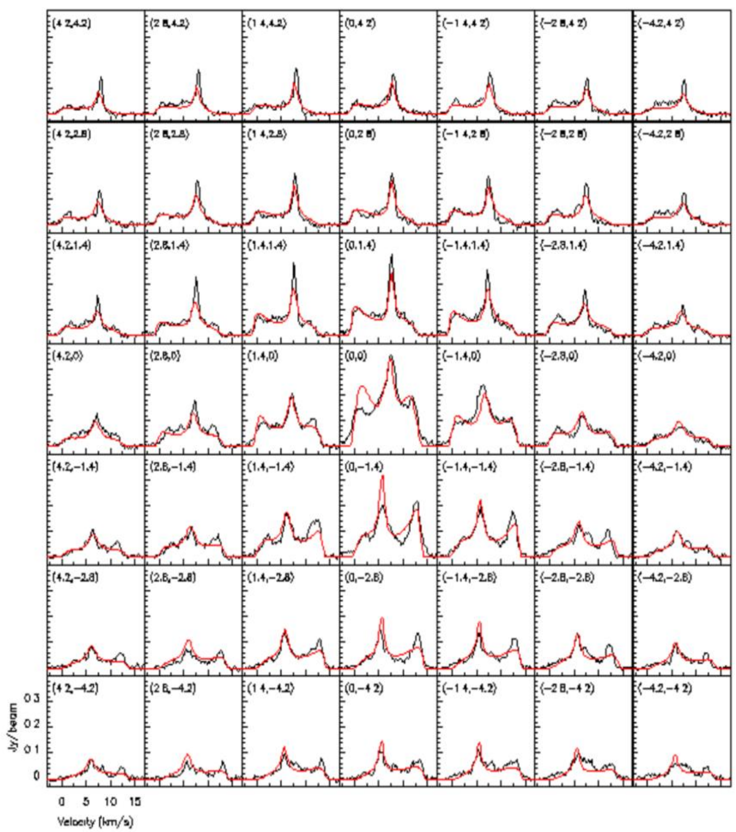
- Plateau de Bure (6 antennas), Very Large Array (27) and ALMA (66).
- Rotating CO molecules (tracer temperatures 10 K ~1000 K)

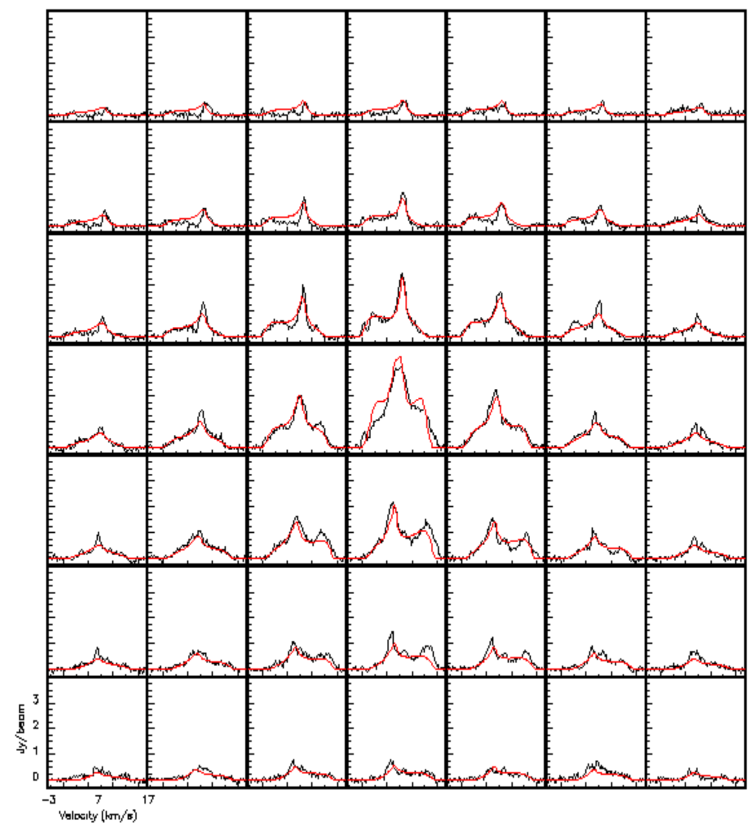
The data are distributed among a number of pixels (arcsecond/sub-arc scale) over a field of view (arcminute). For each pixel, a frequency spectrum is available, providing the intensities of molecular lines emitted by the gas and of the underlying continuum emitted by the dust. The Doppler shift on the molecular lines measures the gas velocity along the line of sight (no velocity info for dust).

Reconstruction of the gas density and temperature in space is strongly underconstrained and can only be done under simplifying asumptions, such as axial symmetry. When measurements are available on two or more molecular lines of a same species, important information is obtained on the gas temperature.

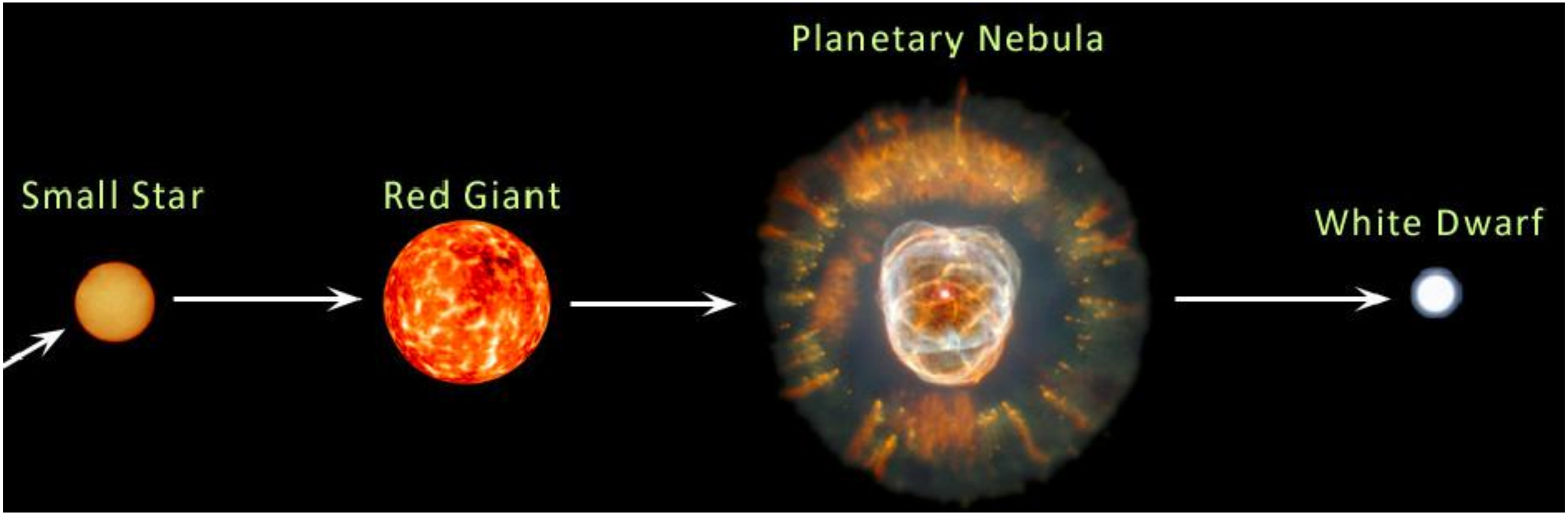
We construct models of the morphology and kinematics of the gas with flux of matter, temperature and wind velocity varying smoothly from poles to equator, adjusting parameters by χ^2 minimization of the fit to the spectral maps (Doppler velocity distribution in each pixel).

CO(1-0) **RS Cnc** CO(2-1)



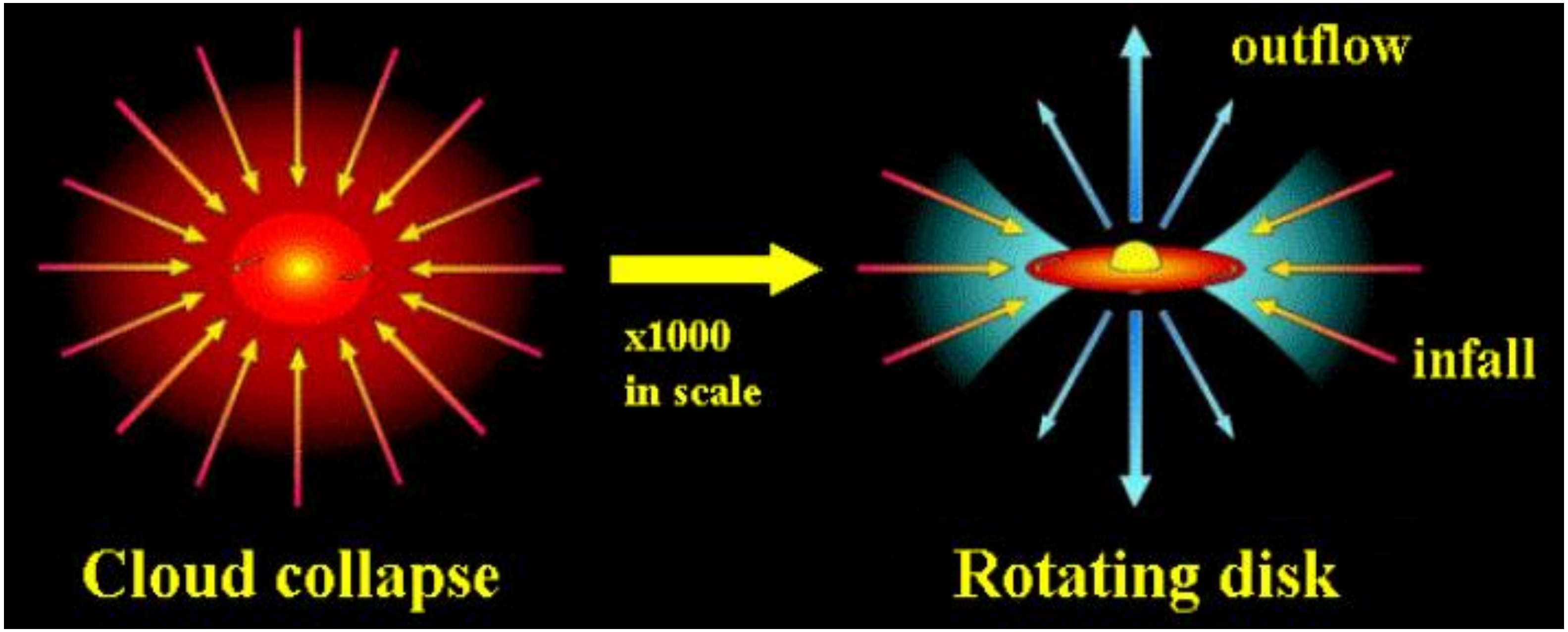


Stellar Physics



Sun-size stars burn their hydrogen into helium → a core deprived of hydrogen → hot enough for its electrons to disconnect from the nuclei → form a Fermi gas; core: helium nuclei → carbon and oxygen.

Stellar envelope → gigantic sizes (hundreds of au) → cooling down 10 ~ 100 K range (CO molecules emission) → forming a Planetary Nebula → leaving the core alone (White Dwarf) → having enriched the interstellar matter.



Protostars (time reversed process): molecular cloud (gravity, density, temperature fluctuations) → collapsing, gas falling-in toward the cloud centre.

Conservation of angular momentum → a disc forms; high temperature and density → atoms ionize → start fusing hydrogen nuclei into helium → a new star.

Similarities between the two processes:

- Dust:

Evolved stars: main motor of expansion; absorbs the light → radiation pressure → wind → growth of circumstellar envelope (gas being dragged outward by collisions with the dust).

Protostars: cool dust accumulates → disc plane onto which gas molecules freeze out → forming an ice mantel. Dust grains → to form larger and larger bodies, ultimately planetesimals and planets.

- Symmetries:

Protostars: a cloud → a perfect sphere

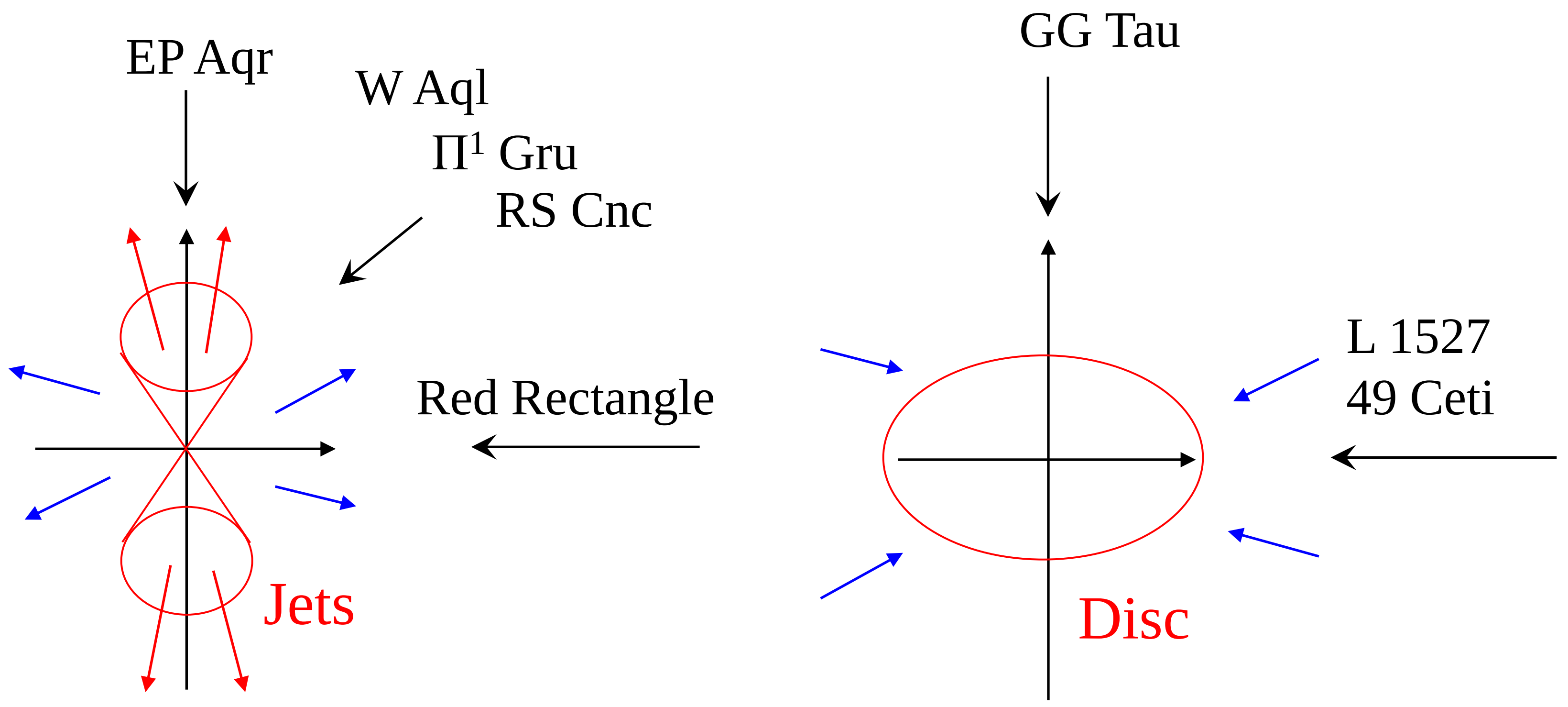
Evolved stars: the opposite happens

How this comes about is a central issue? Many unanswered questions: role of magnetic fields? and binaries (an obvious source of symmetry breaking)?

- Periodic oscillations:

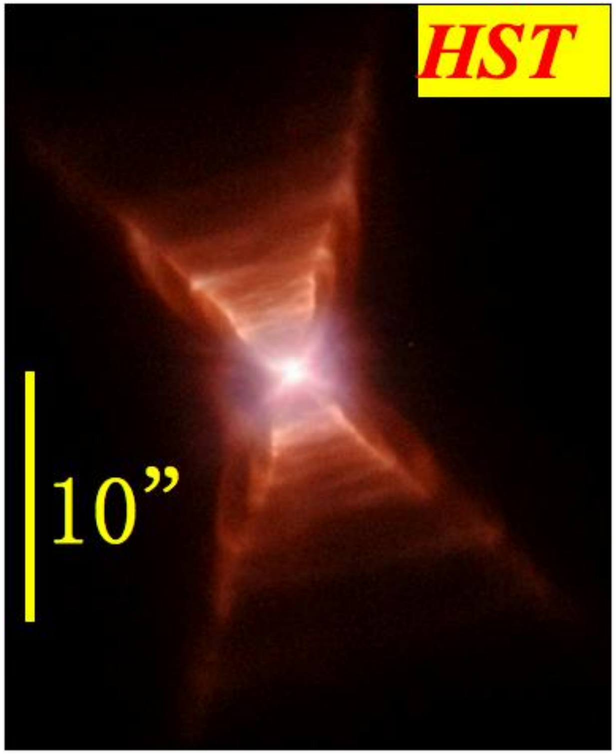
Pulsed accretion in protostars & thermal pulses in AGB stars

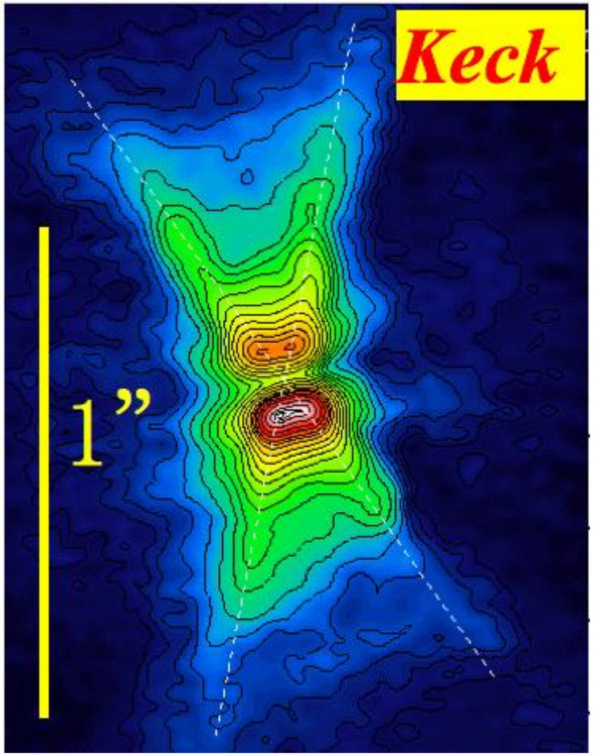
We studied evolved stars and protostars using high resolution CO emission lines (partly in collaboration with French astronomers and partly on our own). The former often feature a bipolar molecular outflow, the latter the formation of a disc.

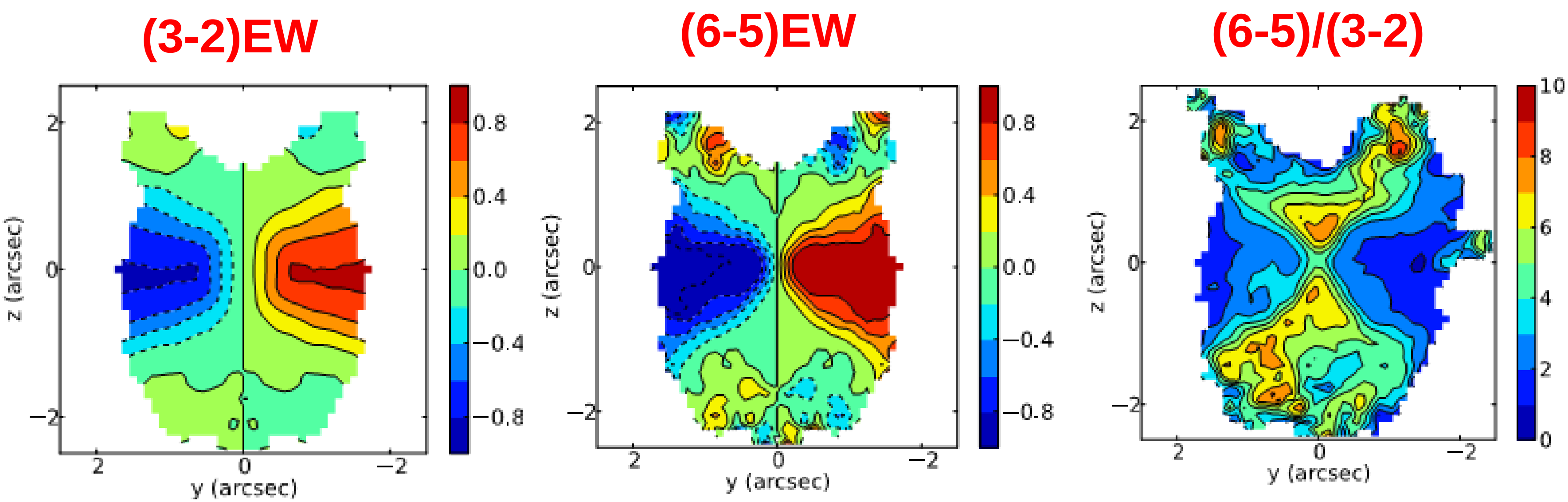


Example 1: an evolved star, the Red Rectangle

The Red Rectangle is a Post-AGB source, having its axis perpendicular to the line of sight. It displays a polar biconal outflow surrounded by a rotating equatorial gas volume. We studied CO(6-5) and (7-6) emissions measured by ALMA.



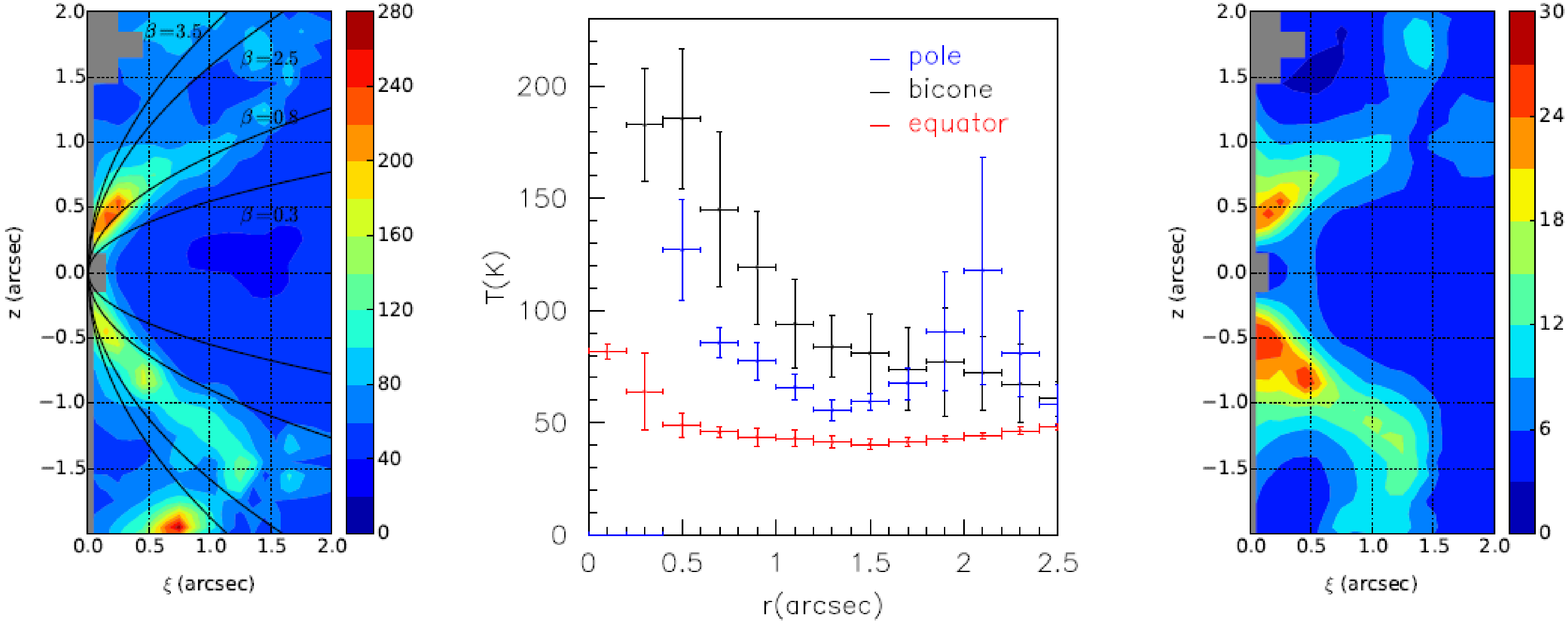




The East-West Doppler velocity asymmetry reveals a very clear **rotation of the equatorial region** about the star axis.

CO(6-5)/CO(3-2) intensity map: evidence for a **temperature distribution** dominated by the biconical structure down to low distances from the star.

Temperature Density×r^2

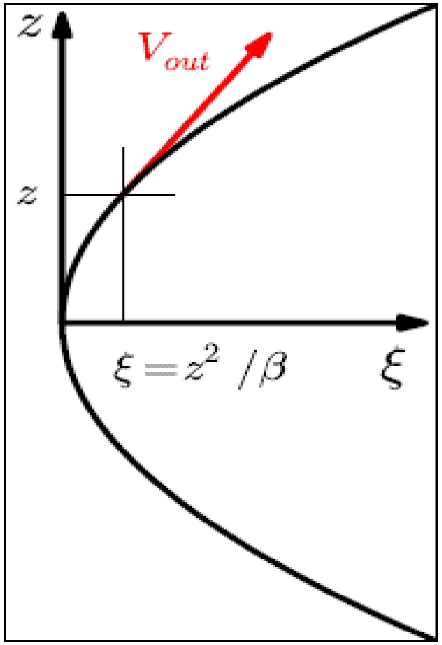


Assuming rotation symmetry about the star axis we reconstruct the gas morphology in space (here shown in the meridian plane).

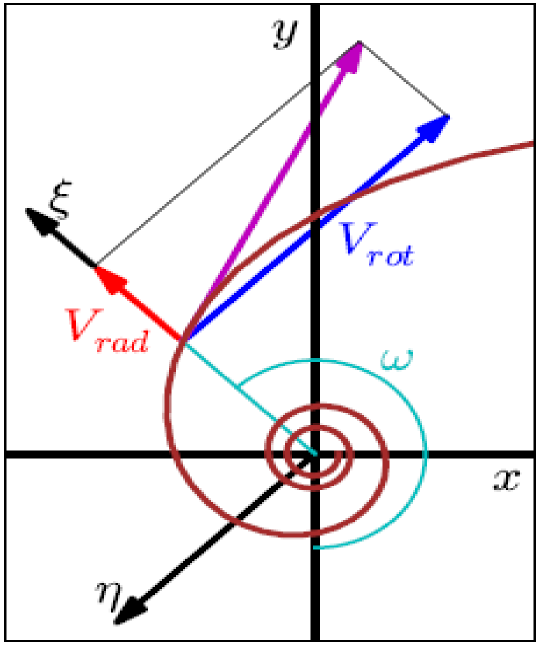
Gas kinematics

Polar regions: parabolic meridian trajectories joining smoothly between the equatorial torus and the star axis with a constant wind velocity of the order of 6 to 7 km/s.

Equator region: spiralling trajectories with ~1 km/s rotation and ~1.6 km/s expansion.



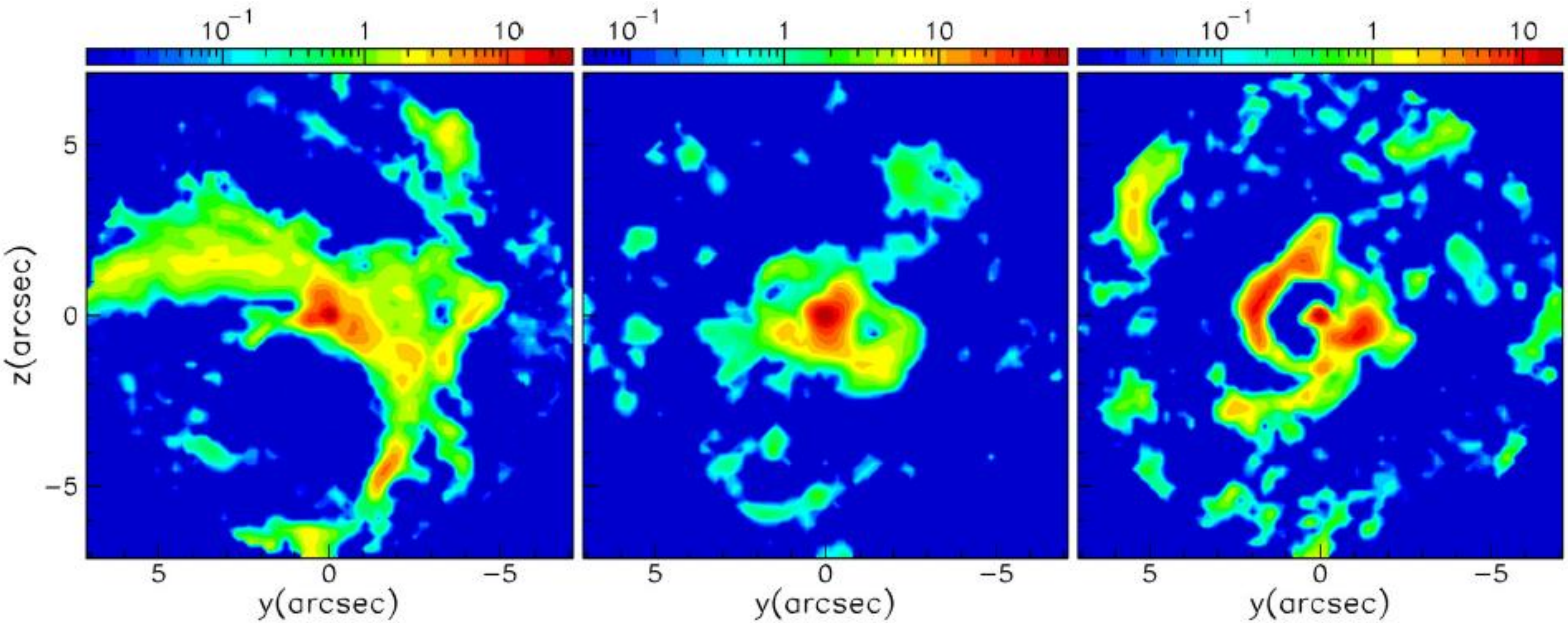
Polar region



Equatorial region

Example 2: a famous binary, Mira Ceti

Mira A, is an AGB star with a mass-loss rate of the order of 10^{-7} $M_{\odot}$/yr. Mira B, is a white dwarf at a projected distance of ~0.5 arcsec from Mira A. We studied CO(3-2) emission observed by ALMA.



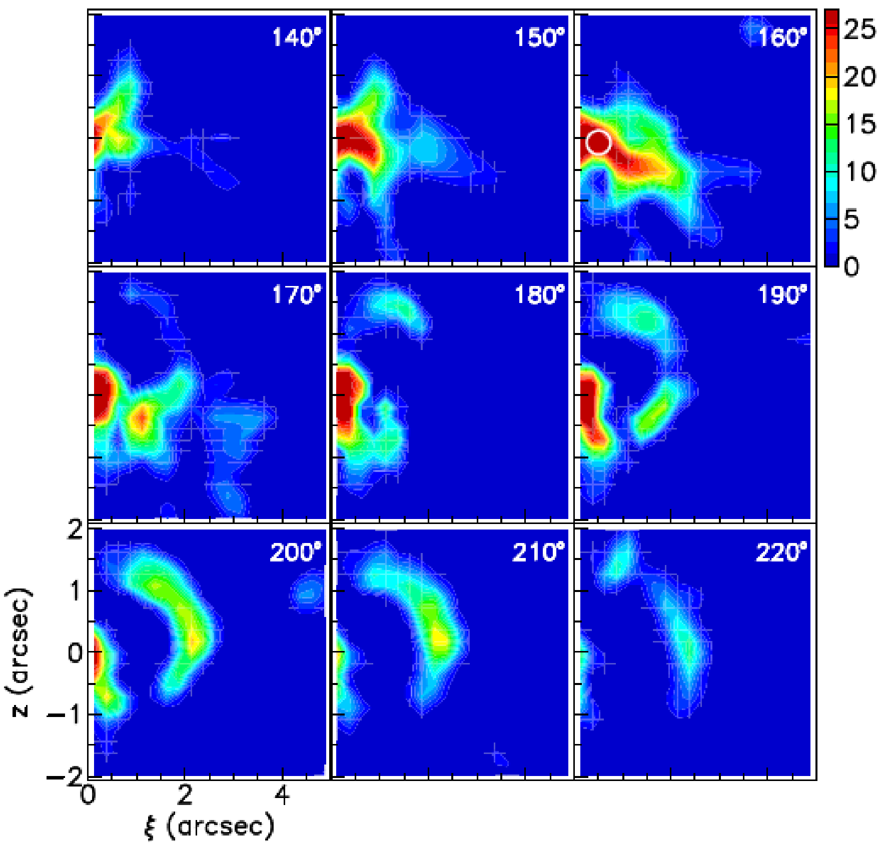
Blue-shifted arc in slow radial expansion, ~1.7 km/s

Central velocity region of the circumbinary envelope

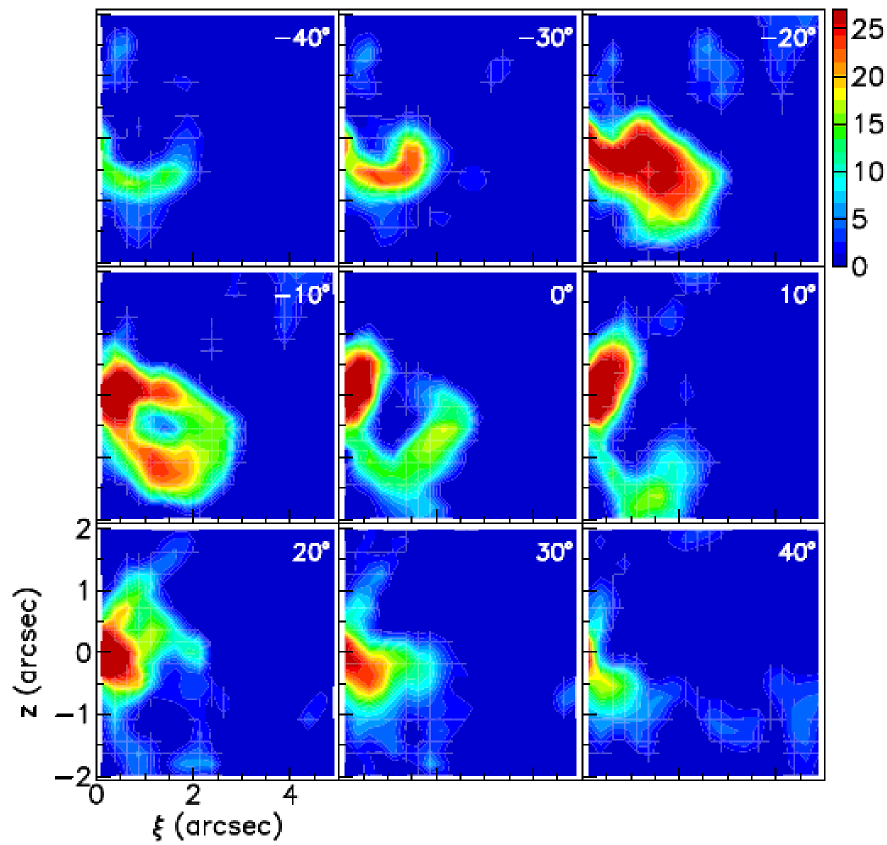
Red-shifted arcs

The very complex morphology reveals outflows in the North-east/South-west direction. We reconstruct the effective emissivity in space under the assumption of a pure radial expansion at constant velocity of 7 km s^{-1}. It gives evidence for detached arcs and cavities suggesting violent past events.

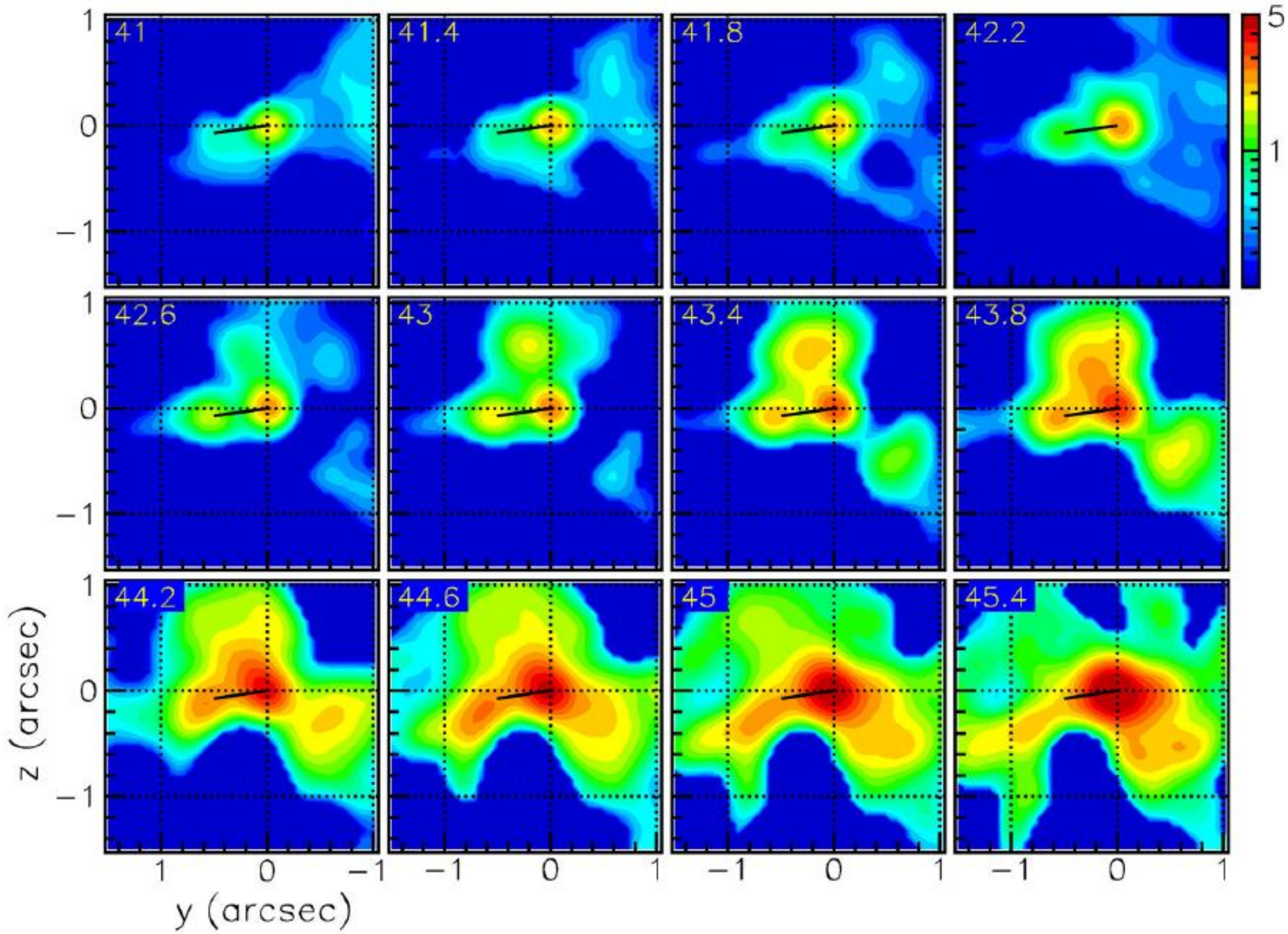
North-eastern outflow



South-western outflows

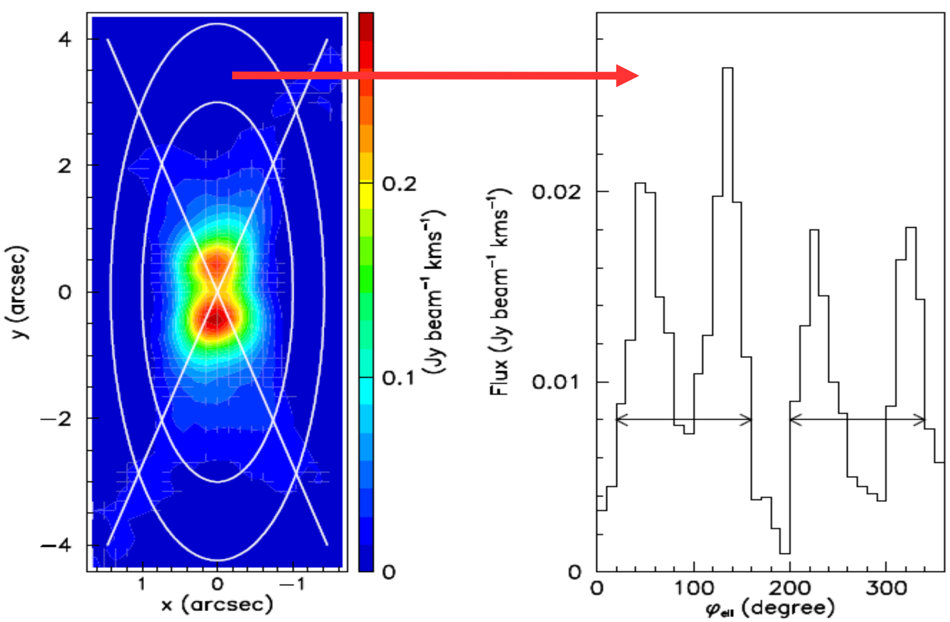


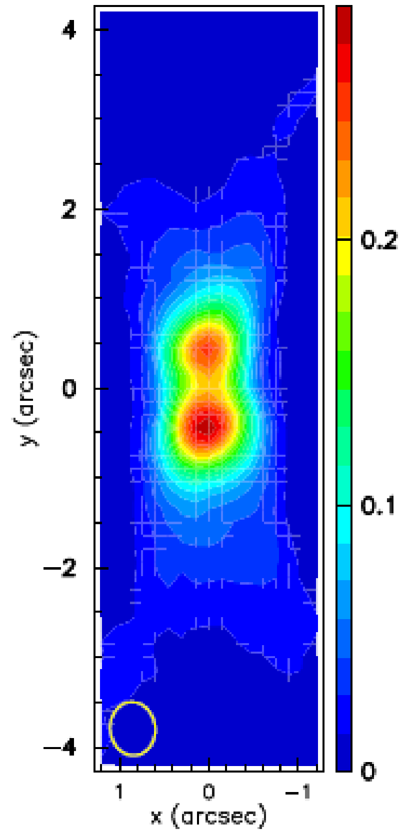
Close to the stars, we observe a mass of gas surrounding Mira B, with a size of a few tens of au, and having Doppler velocities with respect to Mira B reaching 1.5 km s^{-1}, which we interpret as gas flowing from Mira A towards Mira B.



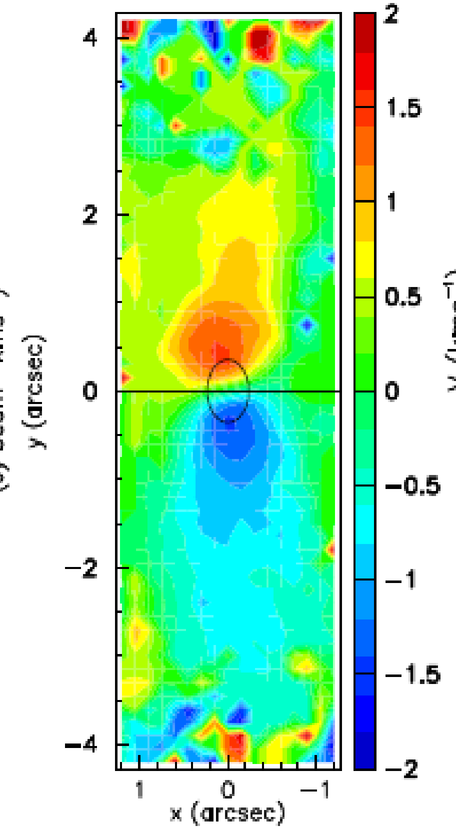
Example 3: L1527, a young protostar

L1527, at a distance of 140 pc, has a mass of 0.2 solar masses and is surrounded by a flared rotating envelope of about one solar mass. We studied its $C^{18}O(2\text{-}1)$ emission measured by ALMA. The disc is seen edge-on.

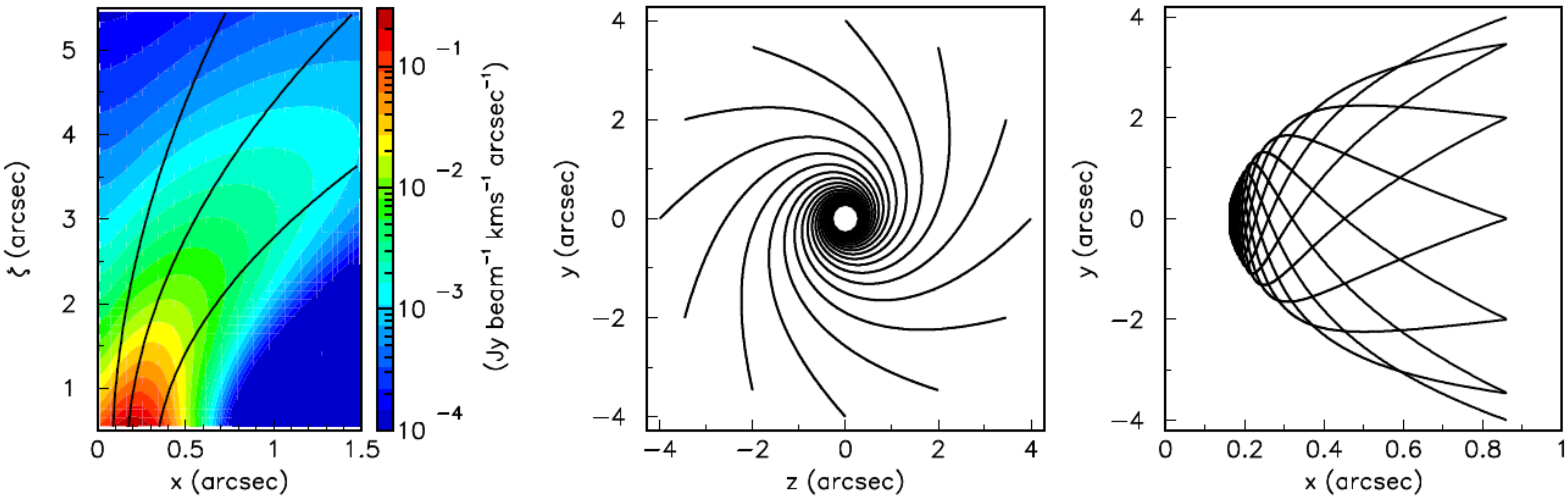




Emissivity

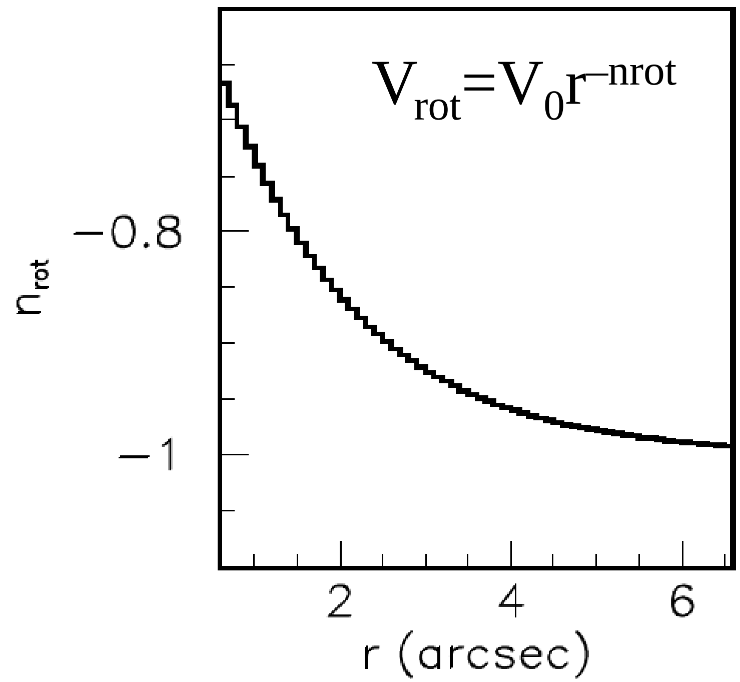


Doppler velocity



We reconstruct the gas morphology and kinematics assuming rotation invariance about the disc axis. The rotation velocity approaches Keplerian at small distances. In-fall is suppressed on the disc axis (hot outflow) and in the disc plane (gas freezing on dust grains).

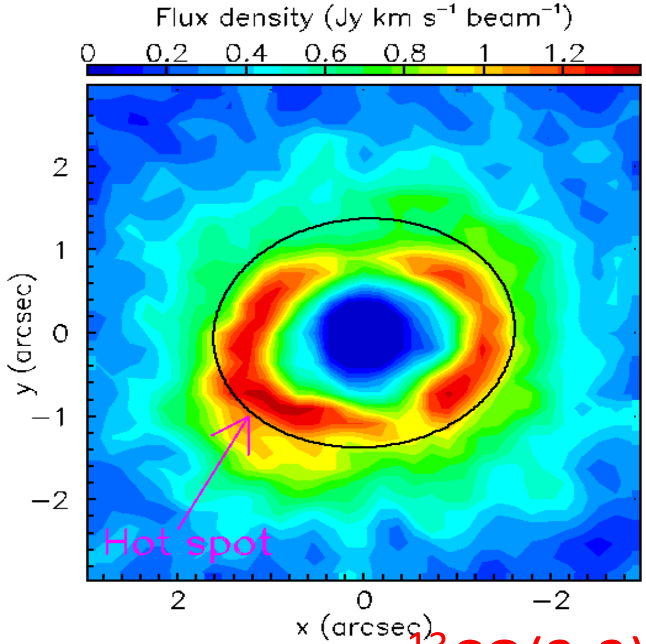
Kinematics provides a measurement of the star mass.

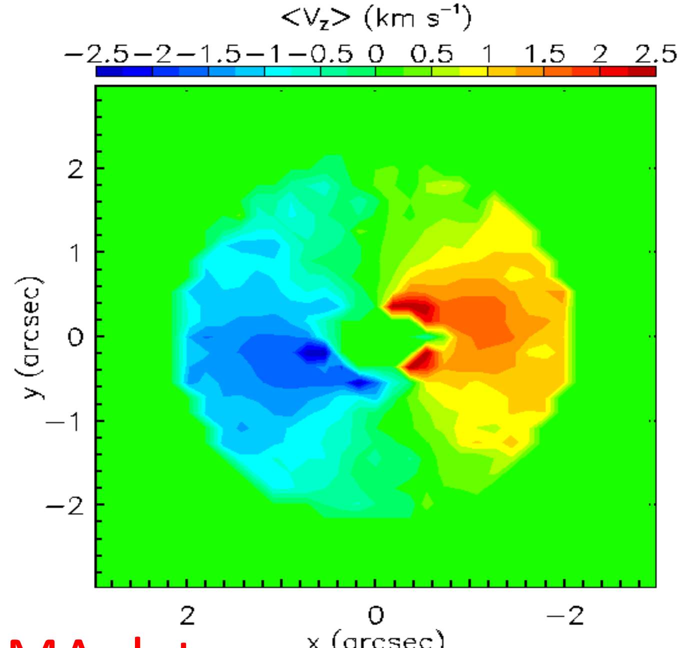


Example 4: GG Tau, a triple protostar

The main protostar consists of gas and dust in a rotating torus making an angle of 35° with the plane of the sky. Recent $^{13}CO(3\text{-}2)$ ALMA data has been published by Tang et al. (2016).

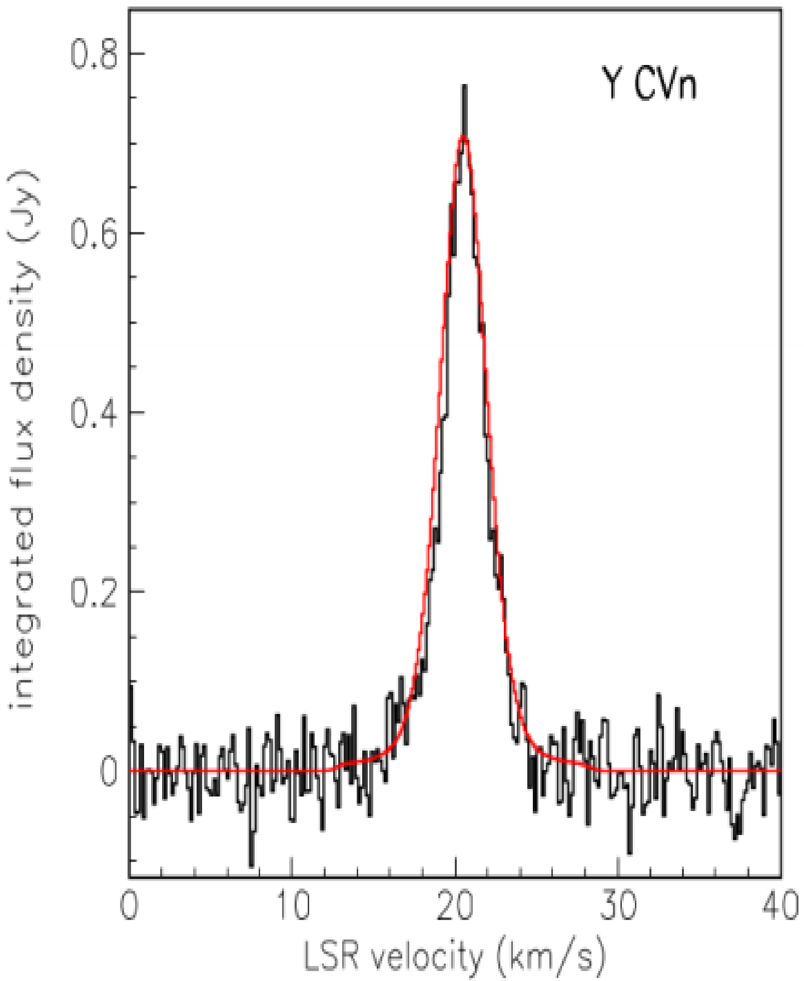
The kinematics is dominated by circular trajectories with Keplerian rotation velocity well described by a form ~2.21 $(r/2\ \text{arcsec})^{-0.48}$ km/s. We have placed an upper limit of 8% of the rotation velocity on a possible in-fall velocity.





$^{13}CO(3\text{-}2)$ ALMA data

HI study



We also contributed new results on the analysis of HI data using the Nançay and VLA telescopes. They probe the circumstellar envelope at large distances from the star where CO molecules are UV dissociated. Examples include the study of the tail in the wake of the star and the modelling of stars including a free wind inside a nearly static detached shell (having slowed down by interaction with Inter Stellar Medium.

High redshift galaxies: a typical example, RXJ0911

Four main actors of galaxy evolution (early cosmic times):

- Supermassive black hole: (optical and X rays)
- Gas reservoir: (millimetre/sub-millimetre)
- Dust content: (infrared)
- Stars: (optical)

Dark matter is not directly accessible to observation

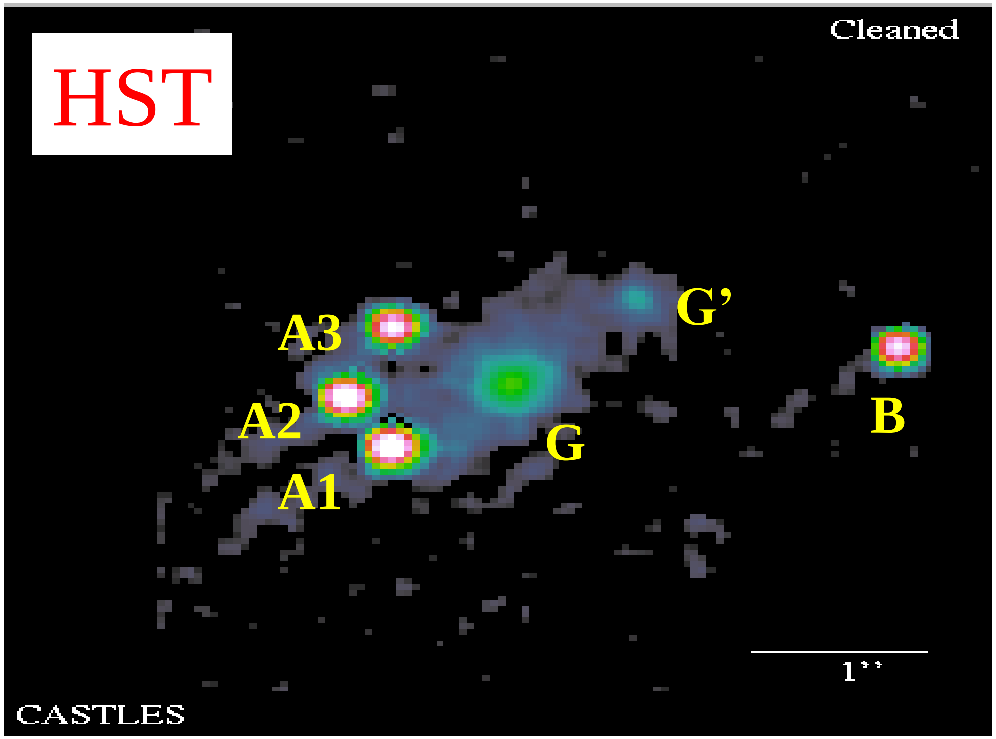
Observed galaxy quantities: mass, luminosity, star formation rate, etc.

Only recently few quasar hosts could be spatially resolved both dust & gas components

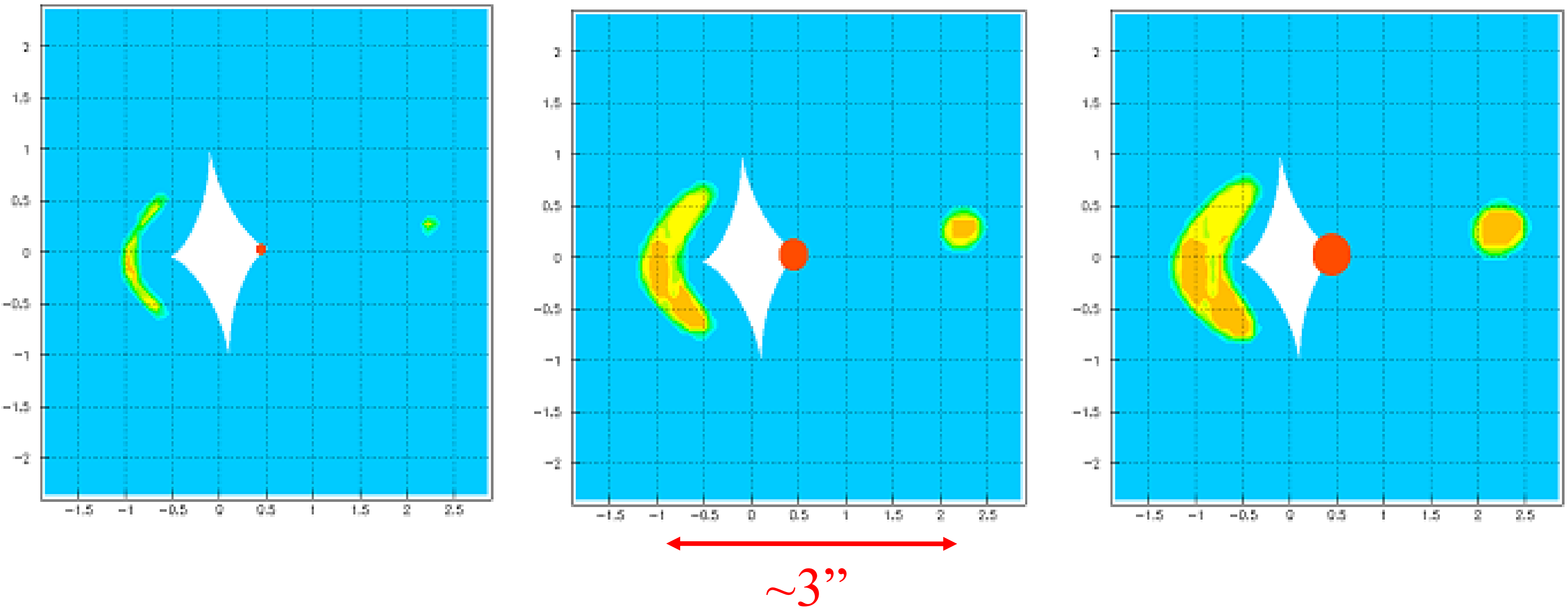
Mergers: identified by comparing the respective locations of the optical, gas and dust components; seen as important sources of dust away from the central black hole

RX J0911: a gravitationally lensed high redshift quasar host galaxy (z~2.8, look back 11.3 Gyr). Detection of the CO(7-6) line by Plateau de Bure Interferometer measures its gas content; and of the continuum underneath by ALMA, its dust content.

Hubble Space Telescope observation of the (pointlike) quasar resolves four lensed images and the lensing galaxy, thereby providing an accurate evaluation of the lensing potential (wavelength independent!).



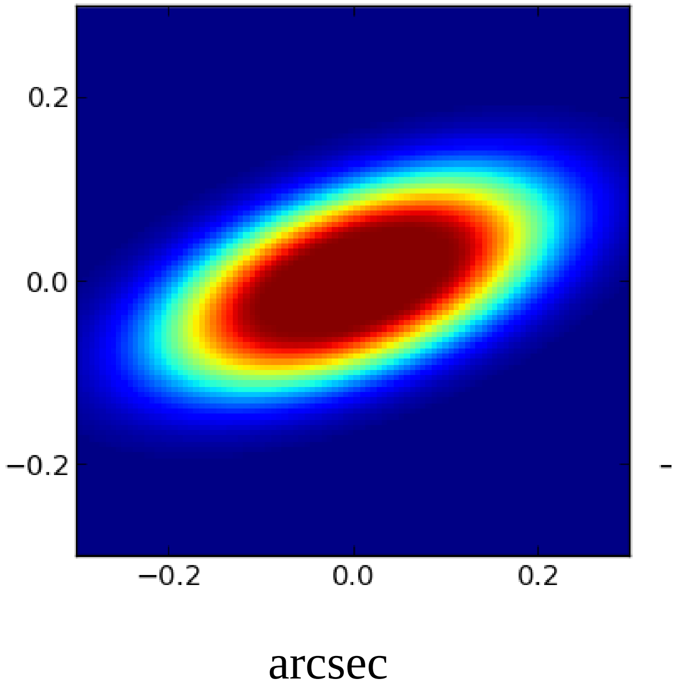
Lensing is complicated by the fact that the extended source overlaps the lens caustic. We studied this peculiar situation in detail.

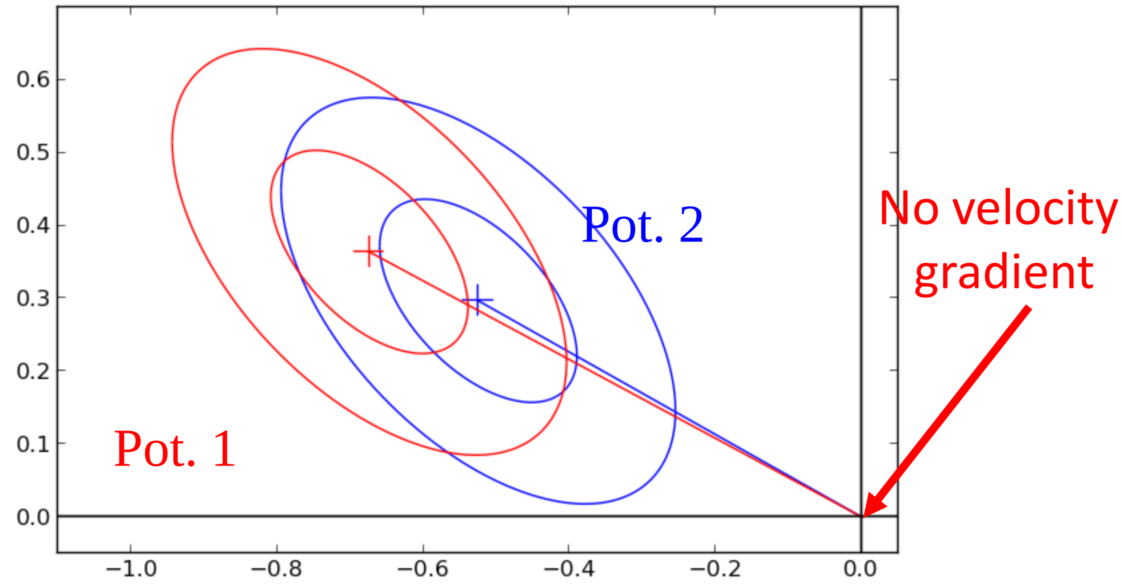


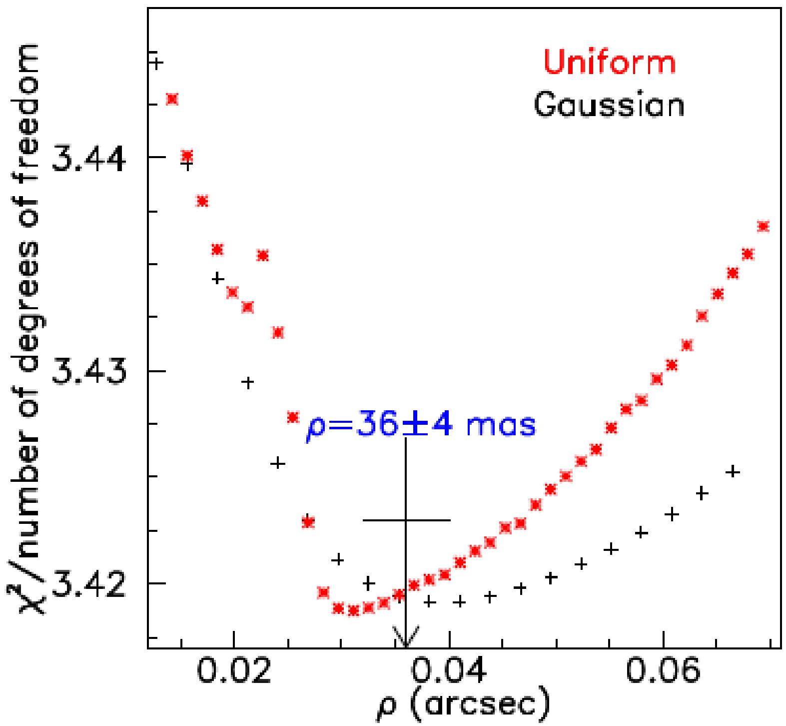
The results show that the gas source has a radius of 850±120 pc on the line (~7 s.d.) and provide evidence for ellipticity and for a significant velocity gradient (molecular outflow and/or rotation)

Ellipticity: 3.3 s.d. away from circular

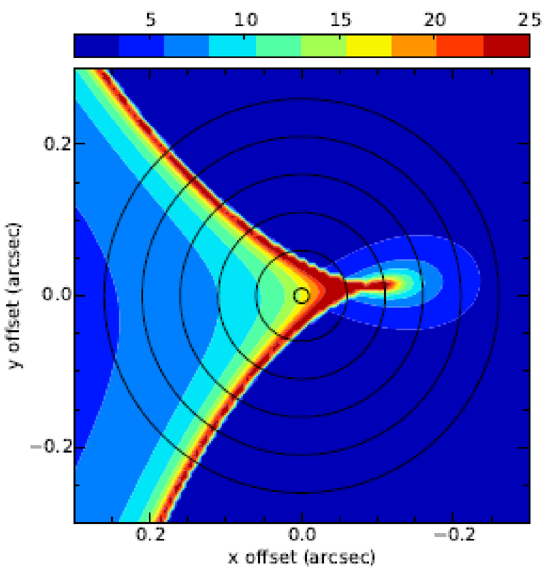
Evidence for velocity gradient at 4.5 s.d.

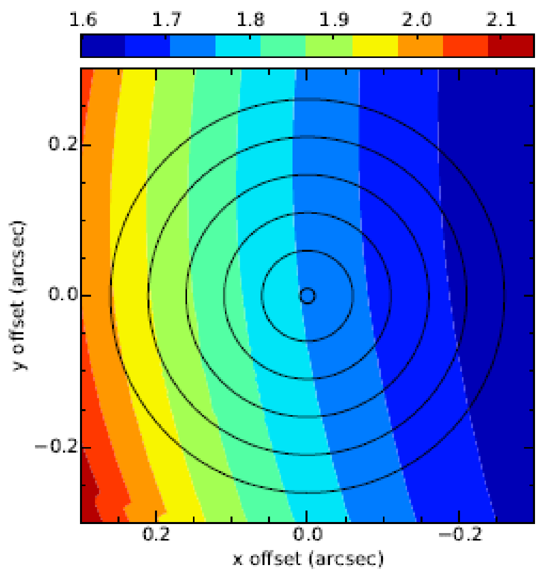


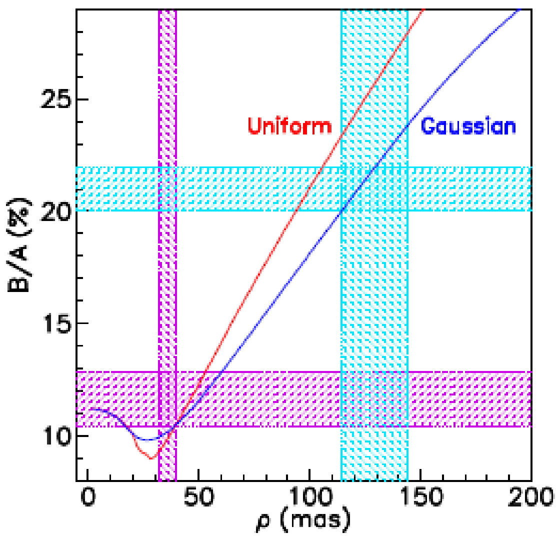




The dust component is found much more compact than the gas component, ~3.4±0.4 times less extended and too small to allow for an ellipticity measurement. Confirmation is obtained from the relative brightness of the B versus A images.







Summary

We have studied a number of evolved stars at different stages of their evolution from the millimetre emission of their CO molecular lines. We have developed models allowing for a space reconstruction of the morphlogy and kinematics of the gas contained in the expanding circumstellar envelopes. In several cases we found evidence for a bipolar outflow superimposed onto a slower expansion and/or rotation enhanced in the equatorial region.

The next challenge, which the high resolution and sensivity observations becoming available, in particular from ALMA, is to understand the precise symmetry breaking mechanism at the beginning of the expansion.

We have also contributed to the study of high redshift galaxies, in particular with the detailed study of a quasar host at z=2.8 that shows no evidence for recent mergers. In the near future, we shall actively pursue both lines of research.

In over sixteen years, we have been able to build up a team having sufficient expertise in radio astronomy to contribute research at international level in stellar physics and in the study of high redshift galaxies.

We owe much to support from foreign scientists, starting with the Pierre Auger collaboration and, presently, with astronomers from Paris and Bordeaux observatories, whom we express our deep gratitude.

Fundamental research is not a priority in Viet Nam and little support is given to team work in the academic and research environment. Recognition of our achievements by our foreign colleagues is therefore most rewarding.

We are making extensive use of the open data policy of the ALMA collaboration (essentially US, ESO and Japan), who make their observations publicly available one year after collection.

The data are reduced and a help desk provides support to handle them properly. This generous policy is an invaluable asset to teams such as ours, working in developing countries having otherwise no direct access to frontier astrophysics. We are immensely indebted and grateful to the ALMA partnership.

We are working toward collaborating with Asian countries, in particular Japan, South Korea, Taiwan and China. In the latter case, we are looking forward making observations using the 500 m diameter radio antenna in current construction in nearby China.

Five hundred meter Aperture Spherical Telescope

In the past 2.5 years, we have published 15 articles in major international journals, of which 8 with our team (currently including 6 PhD's and one PhD student) as only author.

We do our utmost to promote fundamental research in the country by teaching in various universities and taking part in outreach events of various kinds, in particular having contacts with amateur astronomer clubs.

Astrophysics, in addition of being one of the most dynamic branches of modern physics, with several basic and unanswered questions (dark energy, Planck scale, dark matter, inflation), matches well the needs of a team such as ours. In particular, it does not require joining very large collaborations in which it would be difficult for us to preserve our identity.

Thank you for your attention!