Study of the gas envelopes of evolved stars and protostars

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Introduction

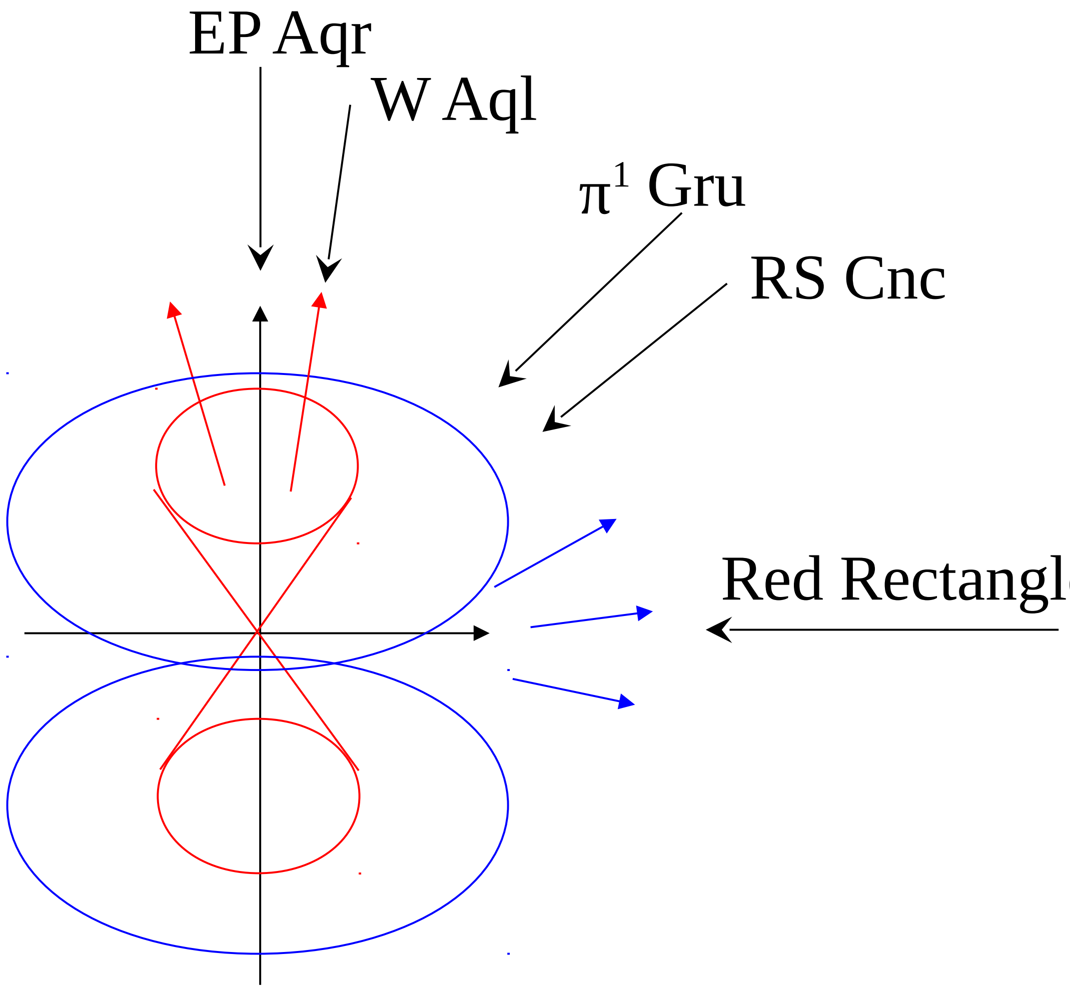
We analyze observations using large installations, in particular the Plateau de Bure radio interferometer (PdBI), the Pico Veleta 30-m telescope, ALMA, etc. partly on our own and partly in collaboration with French radio astronomers.

EVOLVED STARS

Evolution of the morphology

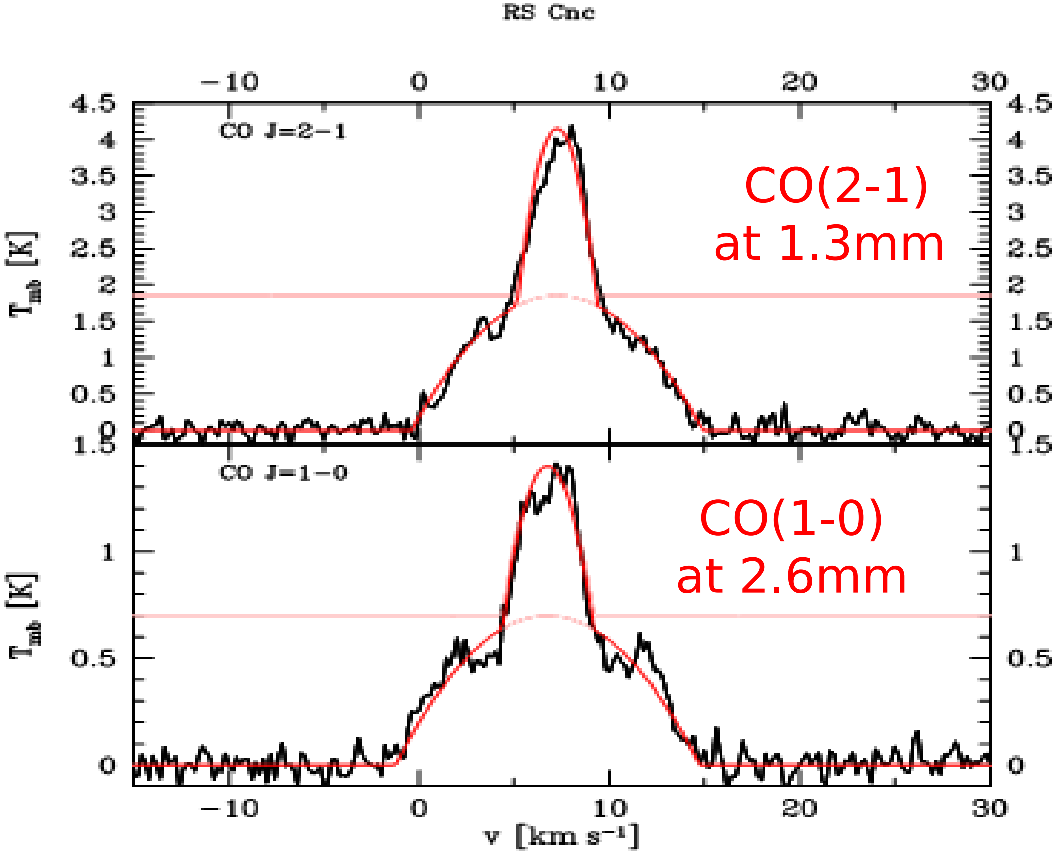
On the AGB, the CSE often evolves from a spherical shape to very irregular morphologies. A common feature is the early appearance of a bipolar outflow breaking spherical symmetry into an axial one. It is commonly believed that binarity plays an important role in this process. However, the details of the mechanism governing the distribution of the angular momentum and magnetic flux of the original star between the contracted core and the CSE are not well understood.

We study evolved stars using high resolution CO emission lines. The stars feature a bipolar molecular outflow.



RS Cnc

CO observations show clearly presence of two components, with ~8(2) km/s winds and 4(0.8) 10^{-7} M_{sun}/yr mass loss.



30m spectra, Libert et al. 2010

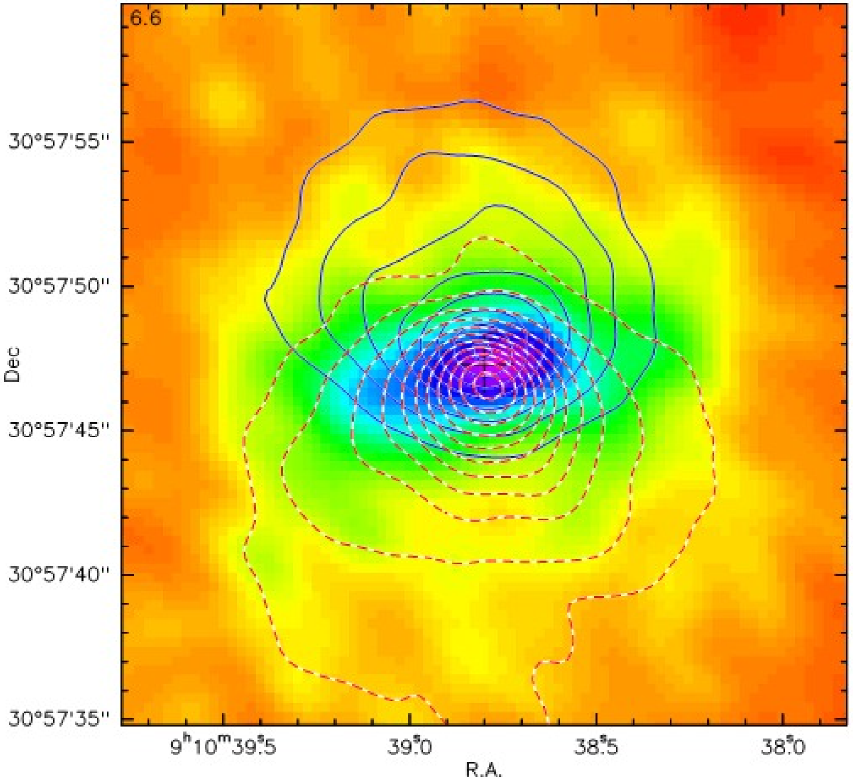
Mapping across the source gives evidence for a strong bipolar flow corresponding to the broad component.

Detailed inspection shows that this flow is along an axis making ~45° with the plane of the sky (AI) and away from North (PA) by only ~10°.

Moreover, it is accompanied by a flow enhanced at the equator associated with the narrow component and normal to the axis of the bipolar flow.

25”

(0.02 pc)



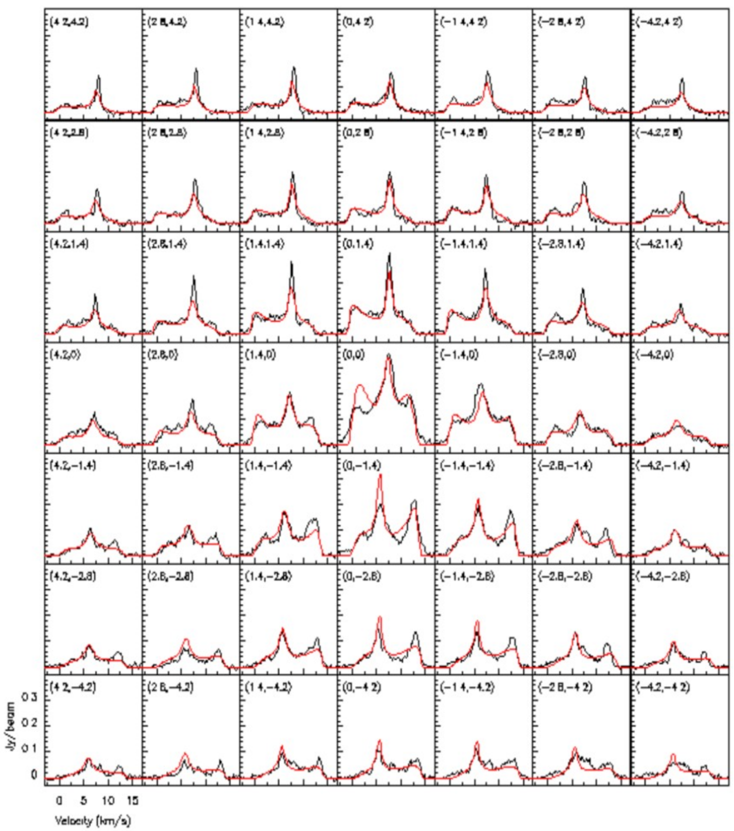
CO(1-0)

Libert et al. 2010, PdBI observation

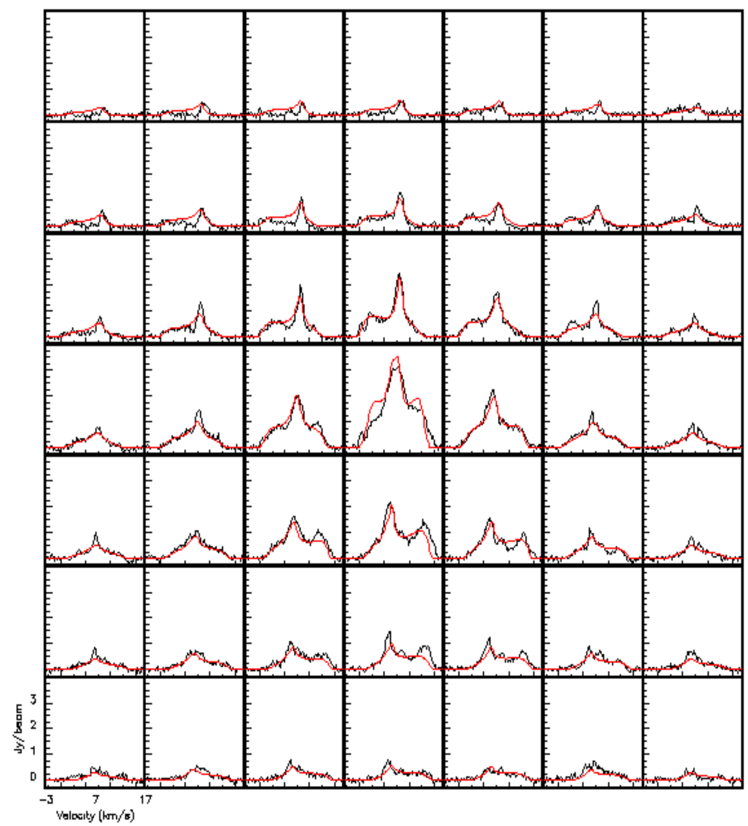
We developed a model with mass loss rate and wind radial velocity decreasing smoothly from the poles to the equator, adjusting the parameters by χ^2 minimization of the fit to the spectral maps.

RS Cnc

CO(1-0)



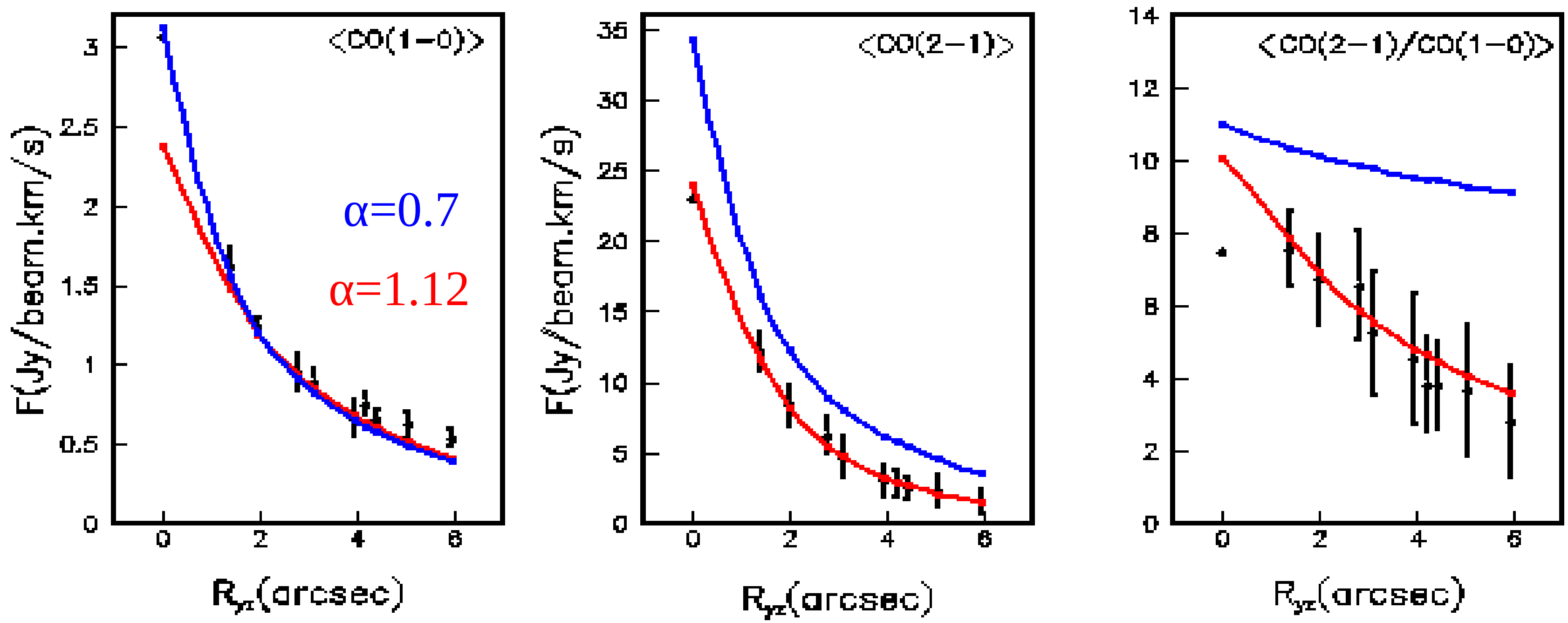
CO(2-1)



Radial dependence of the CO(2-1) and CO(1-0) fluxes

A major difference between the CO(1-0) and CO(2-1) observations is the broader extension of the former with respect to the latter.

The radial dependence of the ratio of the CO(2-1) to CO(1-0) emission constrains the values taken by $T(r)=Ar^{-\alpha}$. A detailed comparison reveals the need for the gas to reach lower temperatures than expected over the radial range probed here.



RS Cnc: a good test case for detailed studies

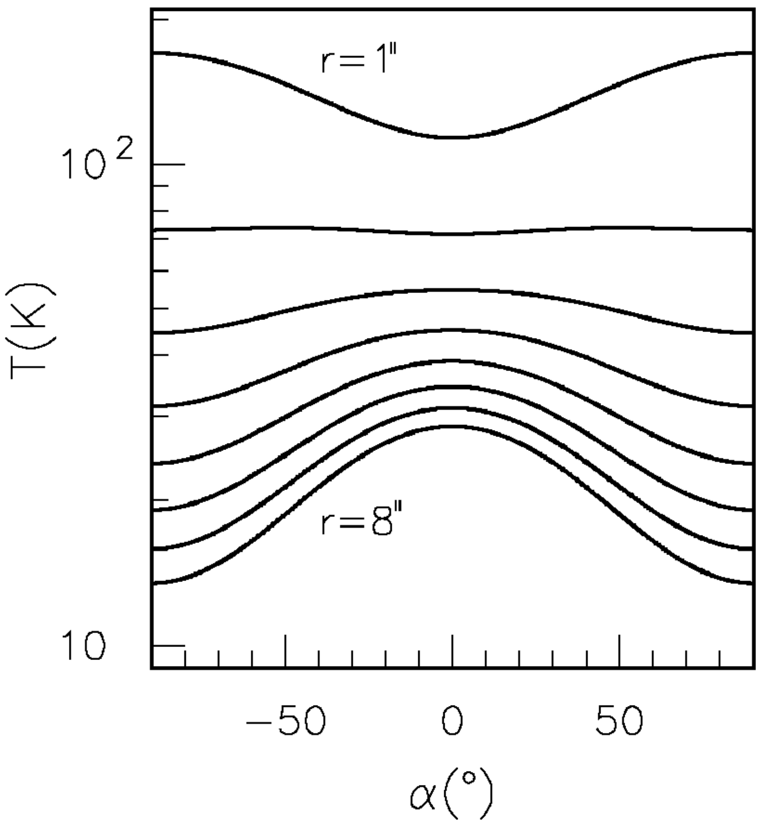
The model best fit for RS Cnc implies a significant velocity gradient which may be interpreted in the frame of two extreme scenarios: assuming either a constant mass loss rate or a constant wind velocity over some 10^5 years. We have shown that both interpretations are plausible, the former being only slightly preferred.

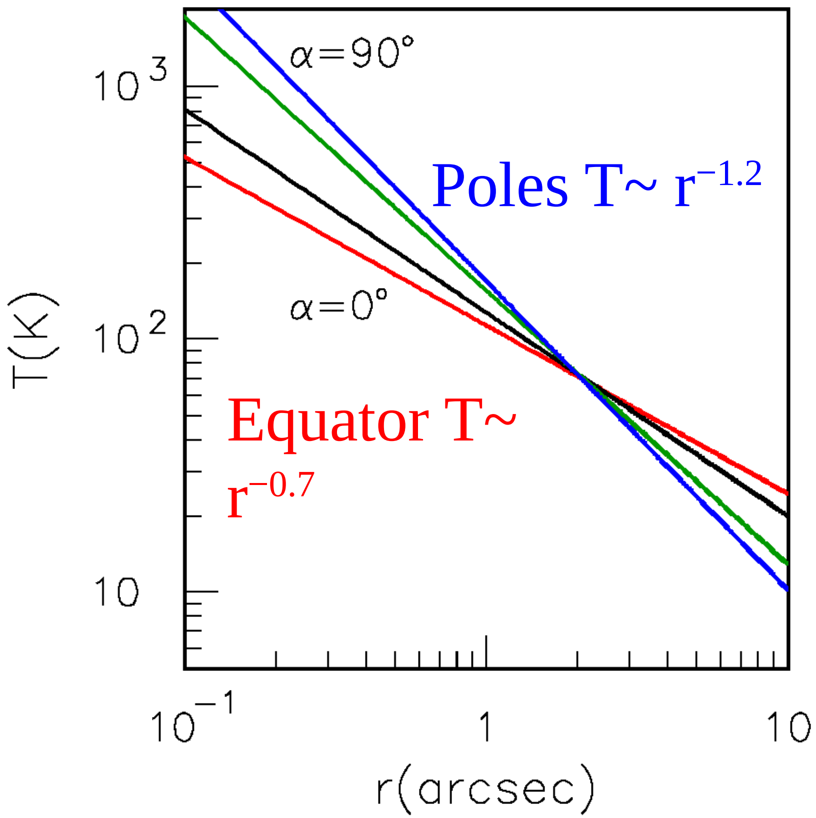
We have also looked for a possible rotation of the envelope (ignored in the simple form of the model) and placed an upper limit on the rotation velocity of ~1 kms^{-1} at a distance of 1 arcsec from the star. These examples illustrate the need for observations of high sensitivity and high spatial and spectral resolution.

EP Aqr

EP Aqr is at the beginning of its evolution on the AGB

The polar axis makes an angle of 13^o to the line of sight





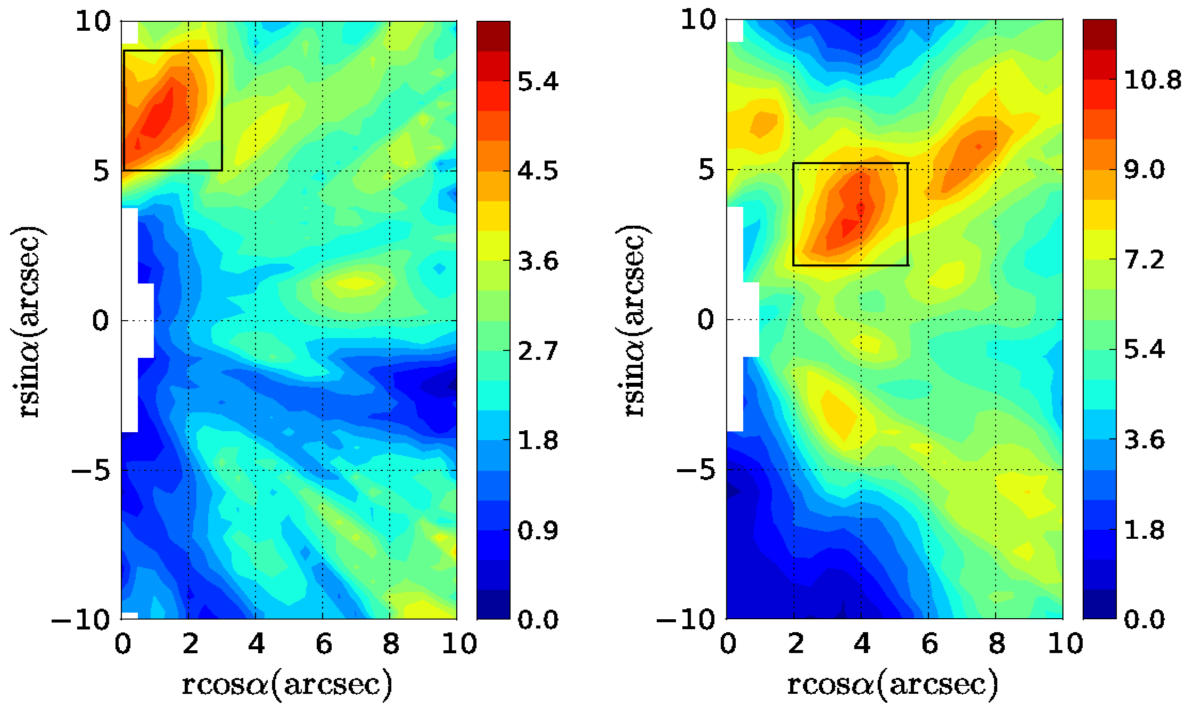
Effective emissivity

Effective emissivity is defined as: $\rho_{eff}(r, \alpha, \omega) = f(y, z, V_x)dV_x/dx$

Under the approximation of LTE and negligible absorption the effective emissivity can be related simply to the density and temperature of the gas.

$\rho_{eff} r^2$
in meridian plane

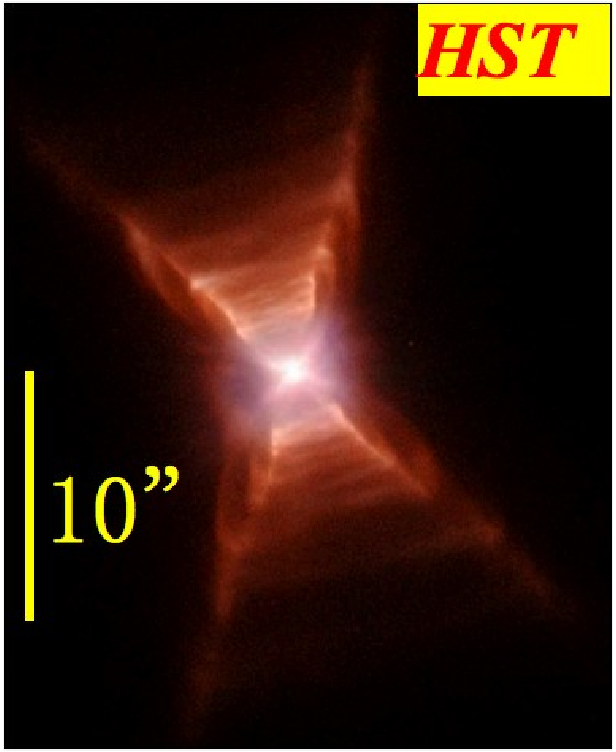
CO(1-0) CO(2-1)

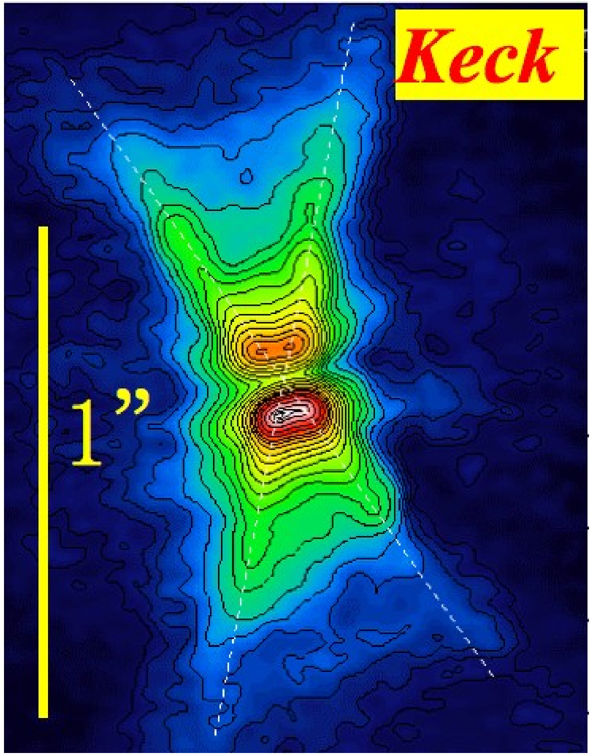


The effective emissivity displays a significant asymmetry between the north and south hemispheres of the star.

Generalities on the Red Rectangle

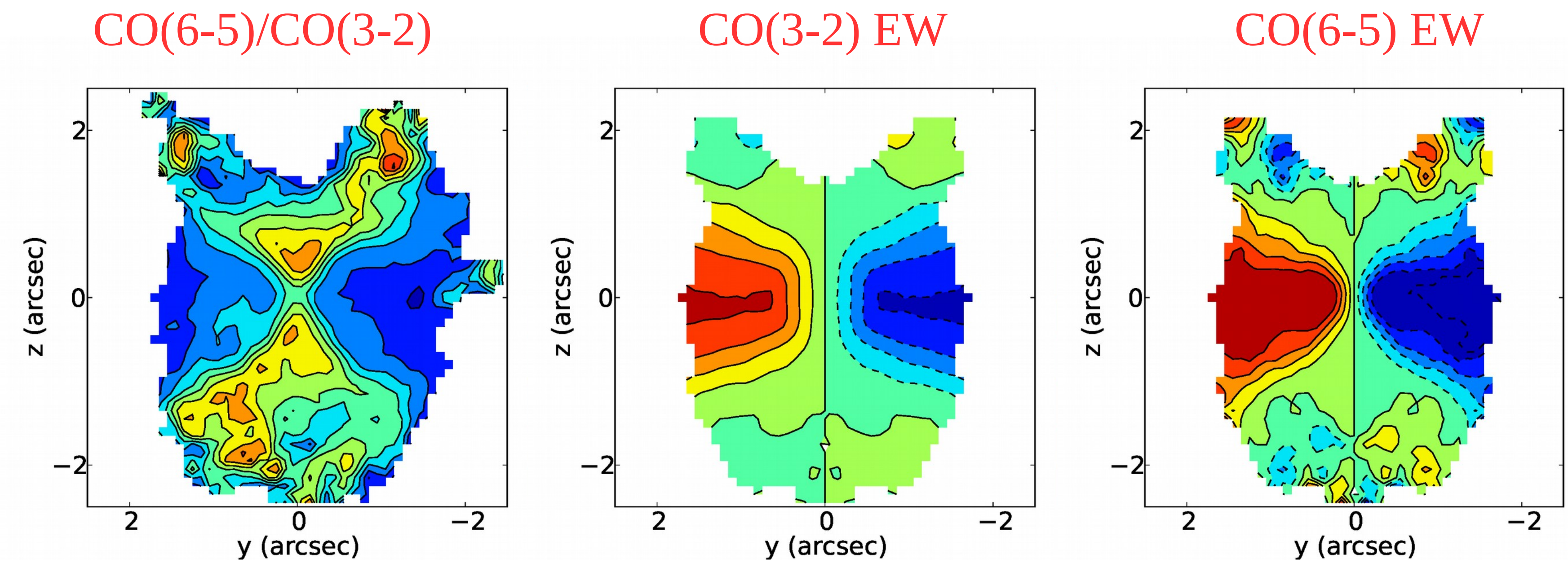
The Red Rectangle is a Post-AGB source, distance d=710 pc
Its axis is perpendicular to the line of sight





In 2005, PdBI observations in CO(1-0) & CO(2-1) having a resolution ~1”: suggested the presence of a disk of gas.

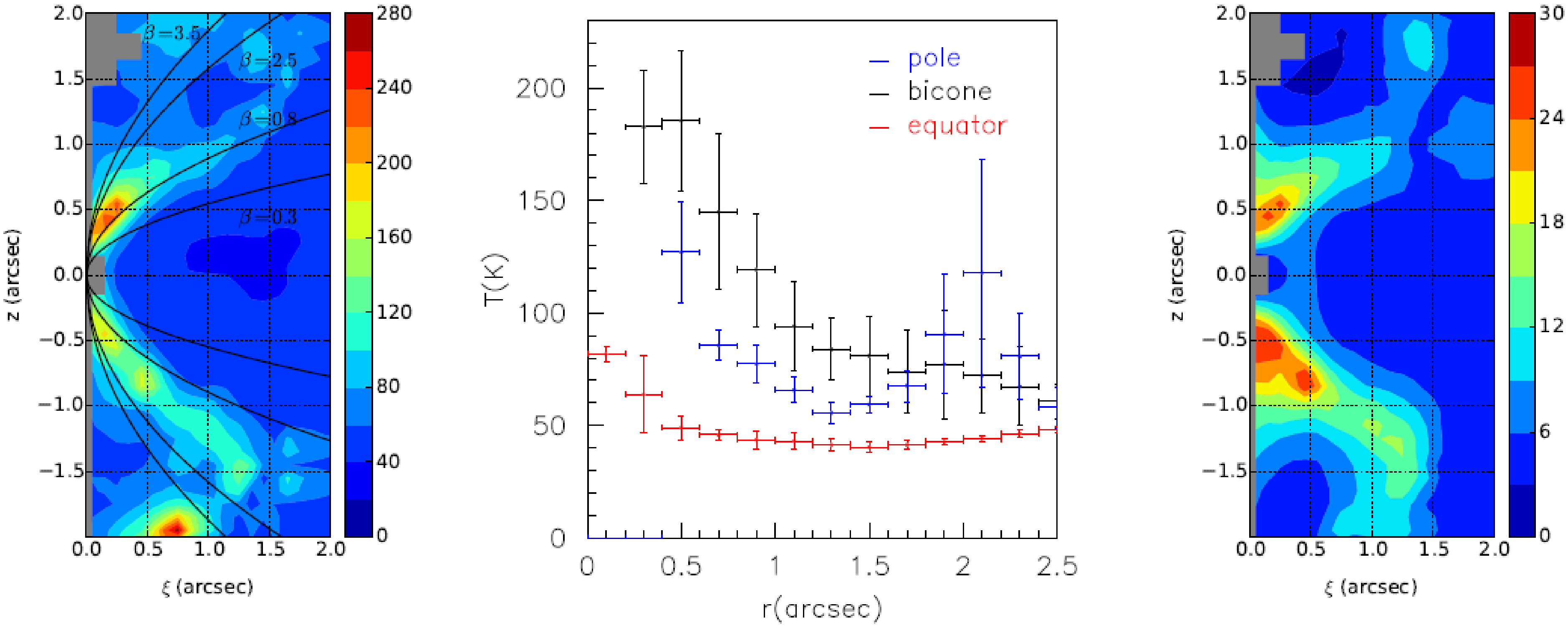
Recently, ALMA observations in CO(3-2) & CO(6-5) having an order of magnitude better resolution have become accessible.



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

The East-West asymmetry reveals a very clear rotation of the equatorial region around the star axis.

Temperature Density×r²

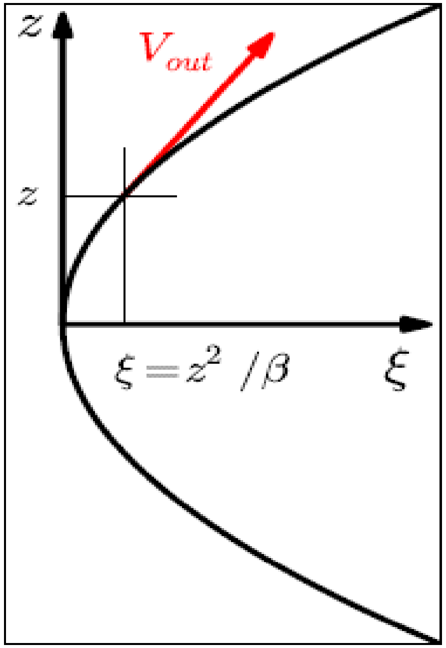


Gas kinematics

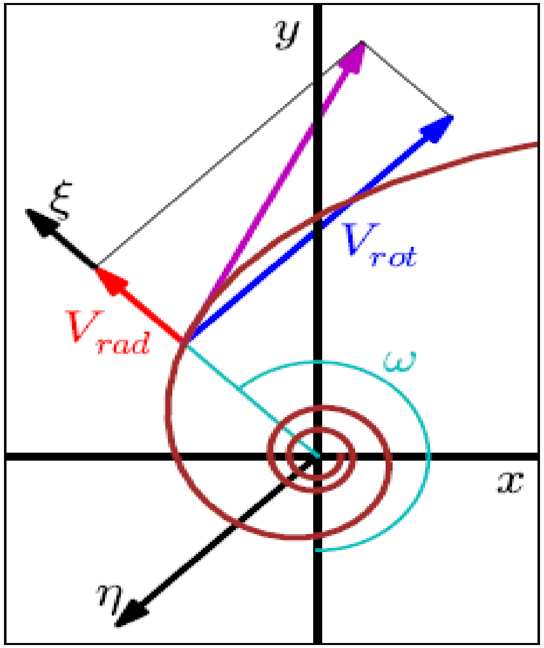
Gas velocities are modeled by using the values of the effective emissivities and fitting the CO(3-2) and CO(6-5) data together with a same velocity distribution.

Equator region: β_0~0.8", V_{rot}~1 km/s, k~1, V_{rad}~1.6 km/s

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



Polar region



Equatorial region

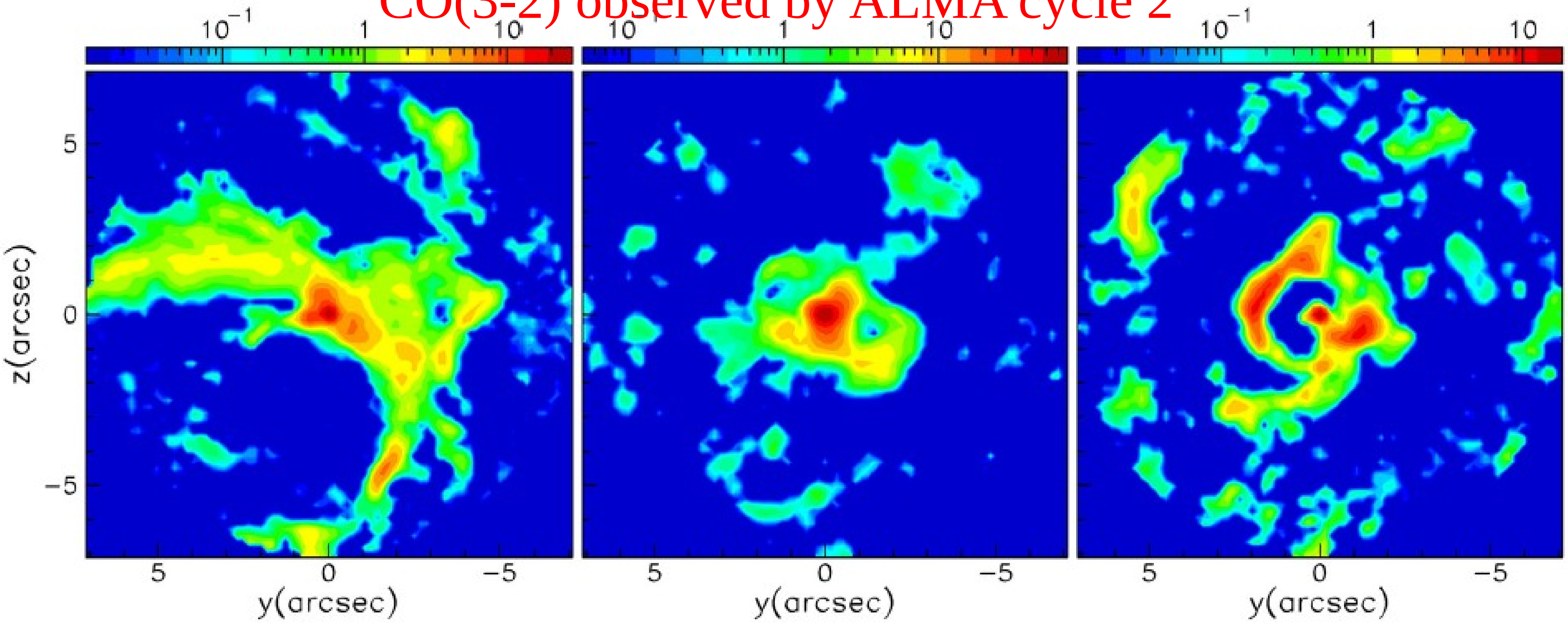
Mira Ceti

Mira Ceti is one of the most studied binary stars.

Mira A, is an AGB star with a mass-loss rate of the order of 10^{-7} $M_{\odot}$/yr.

Mira B, is probably a white dwarf at a projected distance on the plane of the sky of ~0.5 arcsec from Mira A and at a position angle of 8° south of east.

CO(3-2) observed by ALMA cycle 2

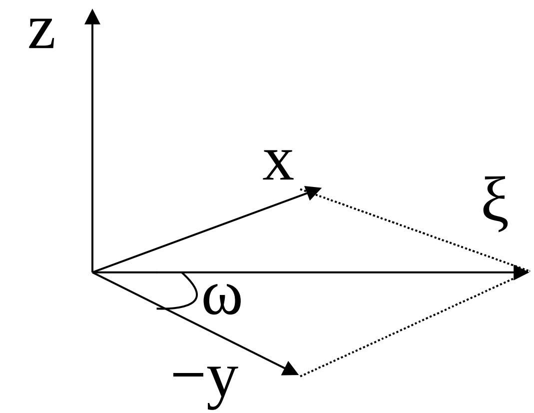


Blue-shifted arc in slow radial expansion, ~1.7 km/s

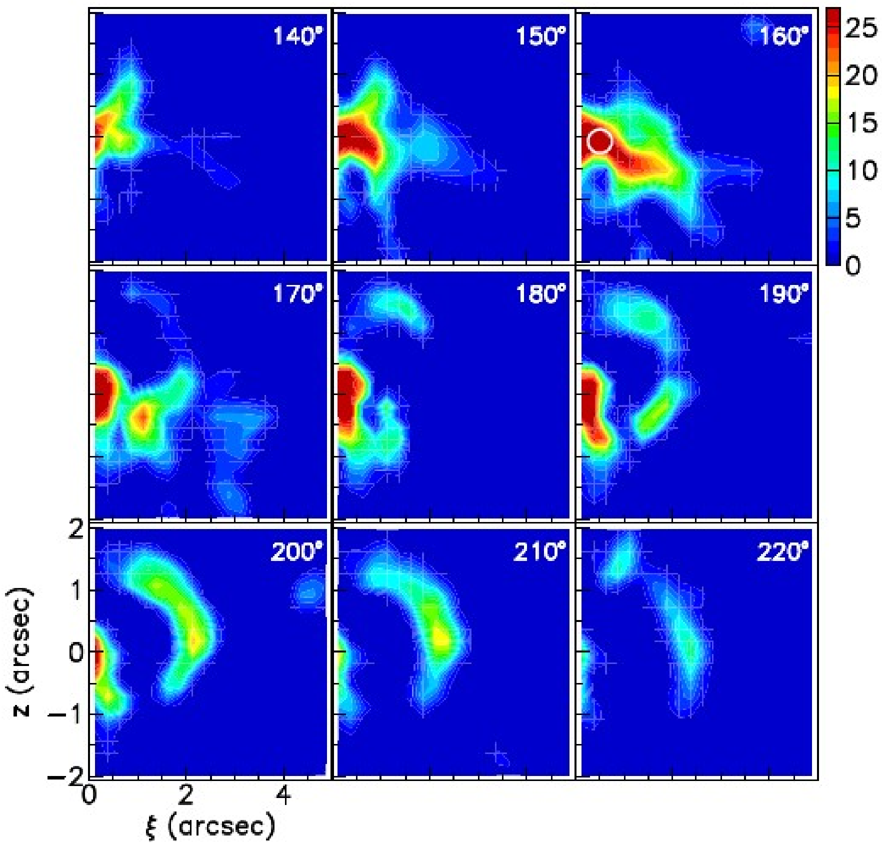
Central region of the circumbinary envelope

Red-shifted arcs

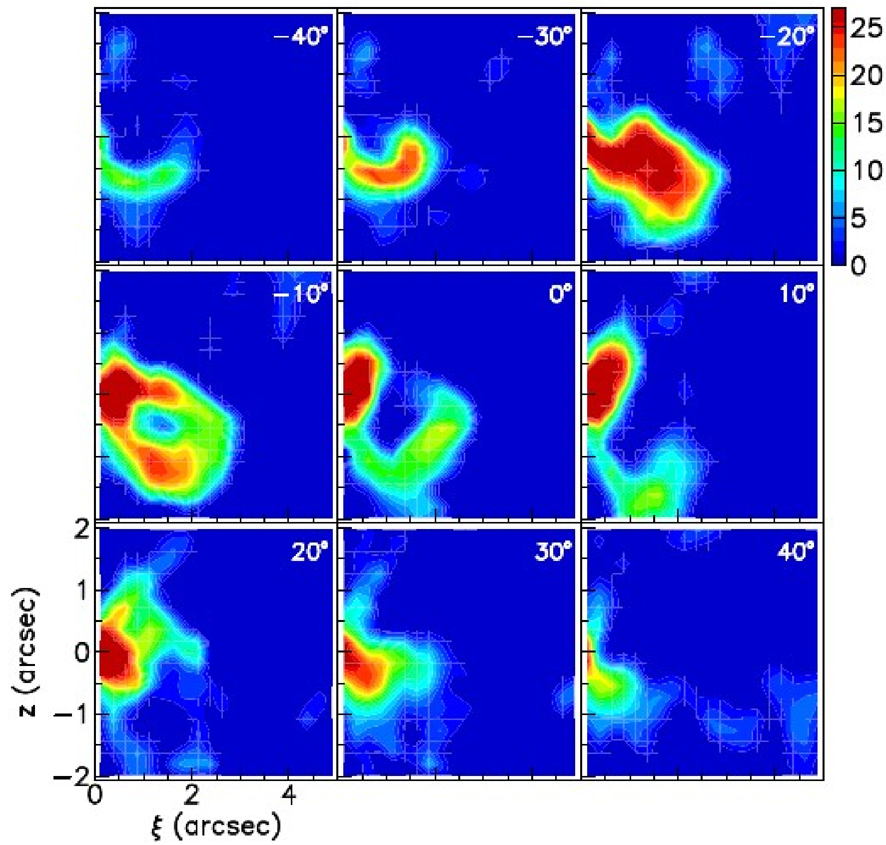
Effective emissivity is reconstructed in space under the assumption of a pure radial expansion at constant velocity of 7 km s^{-1}



North-eastern outflow

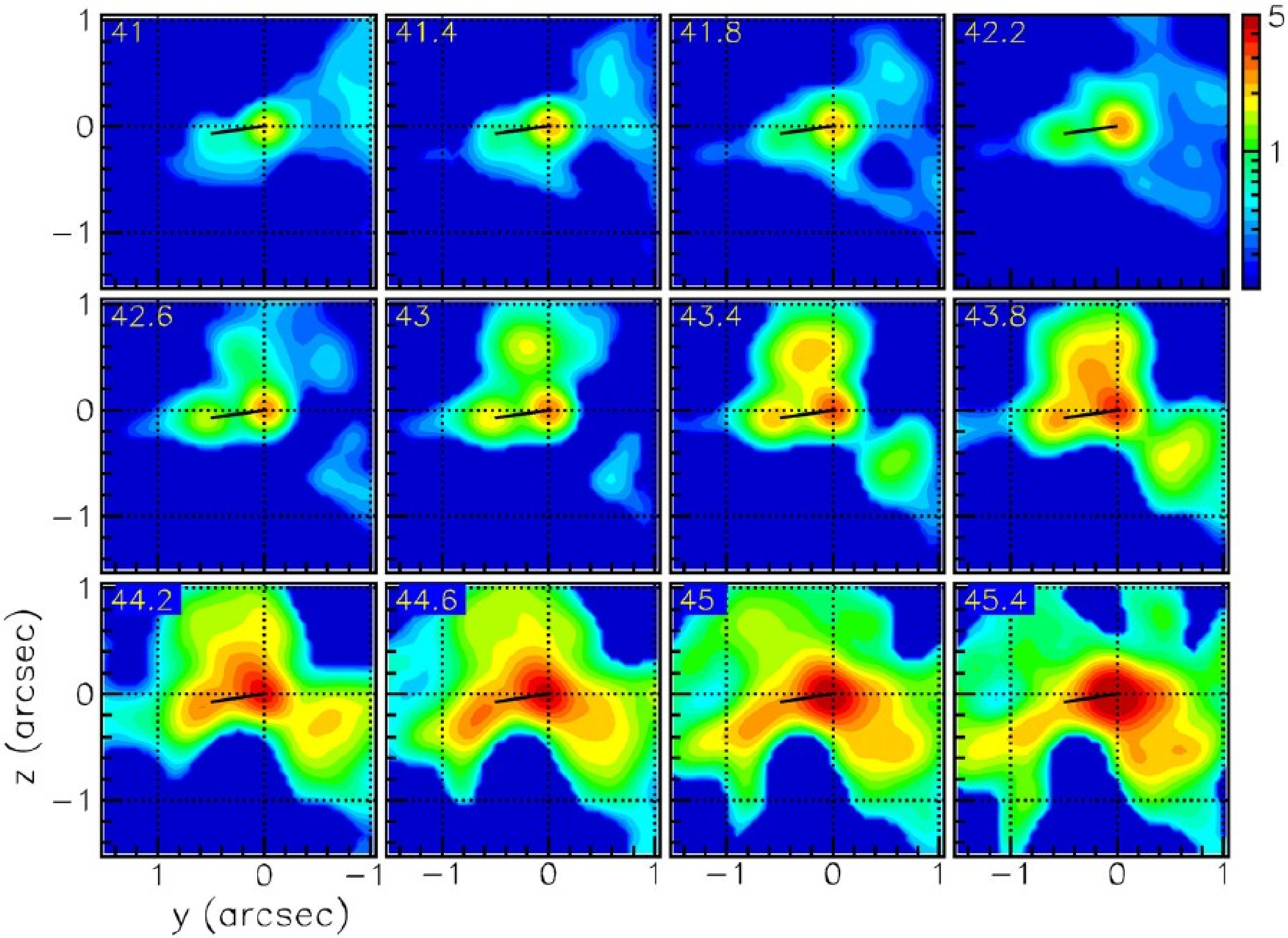


South-western outflows



The close environment of the Mira A+B pair

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.



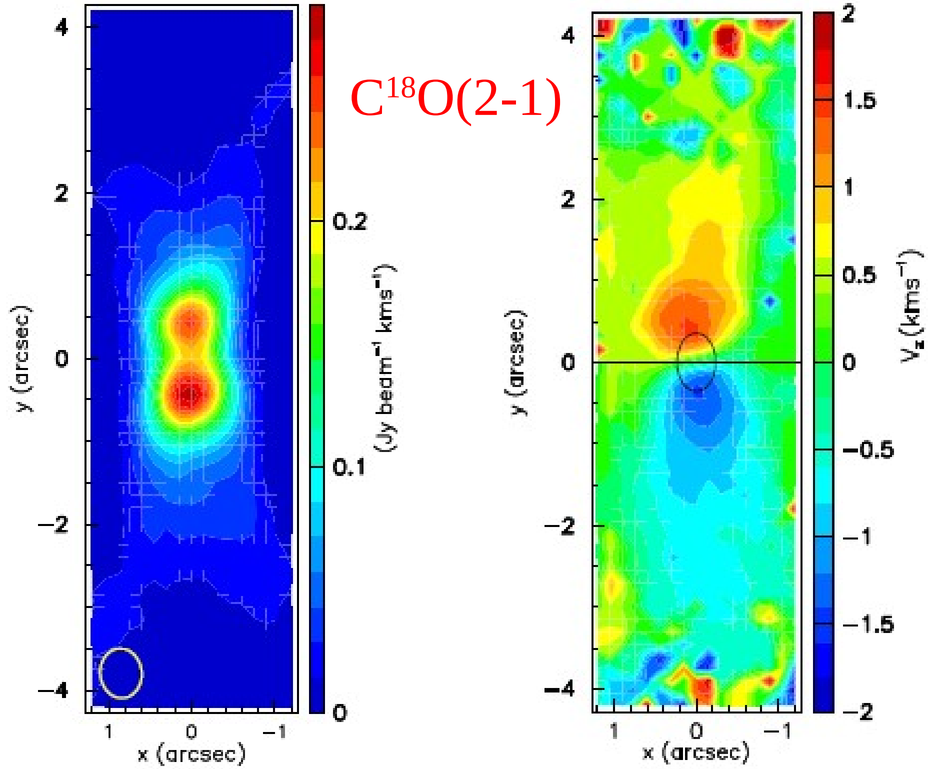
The analysis of CO data from EP Aqr, the Red Rectangle and RS Cnc has made it possible for us to develop a general methodology and to understand its potential and limitations. While the quality of the data in terms of spectral resolution was usually sufficient, the need for as good as possible spatial resolution and high sensitivity was overwhelming.

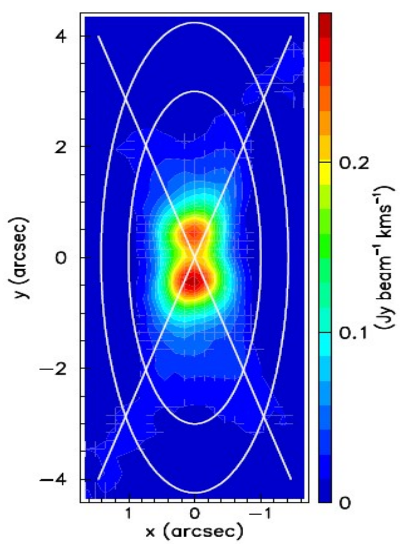
In this sense, ALMA opens a new era in terms of the reliability and precision being now at hand. It opens the door to analyses where the uncertainties on the data can be evaluated reliably, allowing for χ^2 values being translated in terms of quantitative confidence levels for a given model.

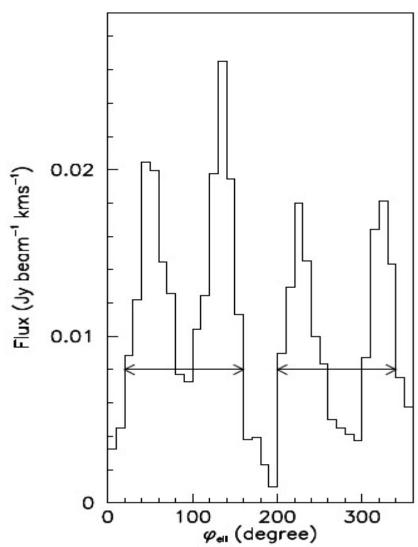
PROTOSTARS

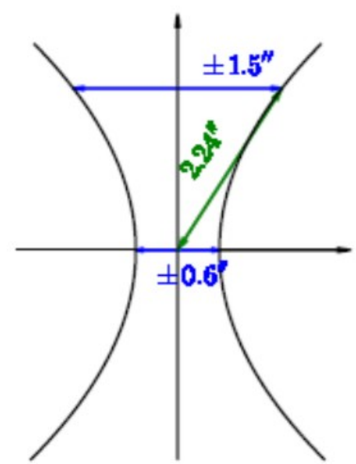
L1527

L1527 is a class 0 protostar, at a distance of 140 pc, in its earliest stages of formation. It has a mass of 0.2 solar masses and is surrounded by a flared rotating envelope of about one solar mass.

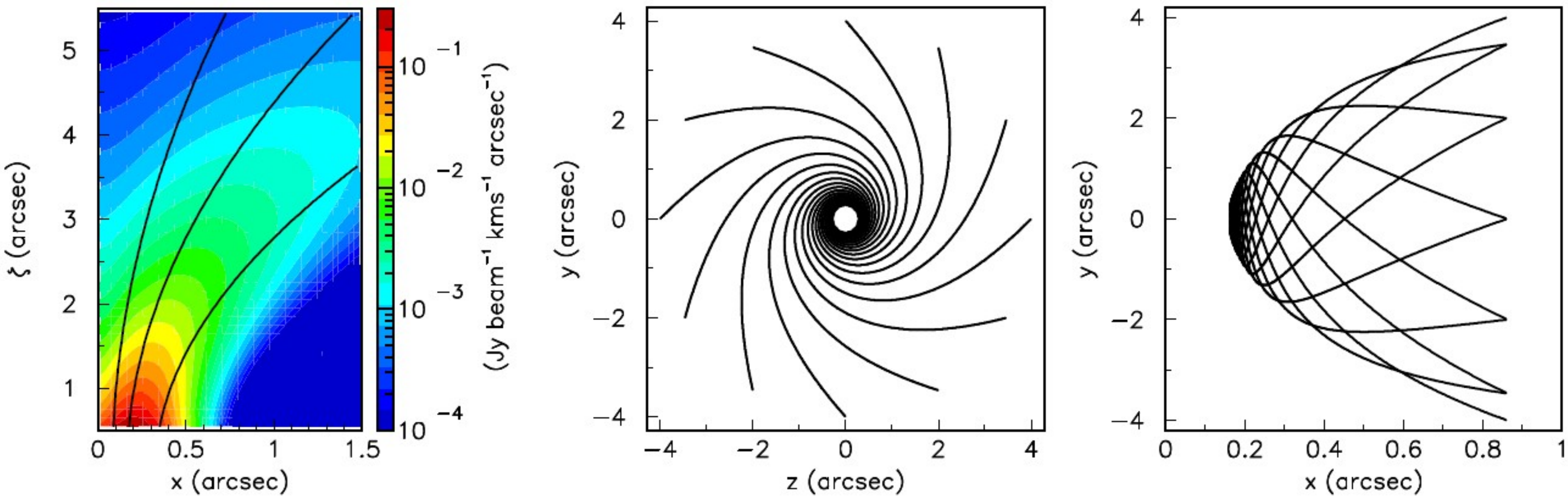




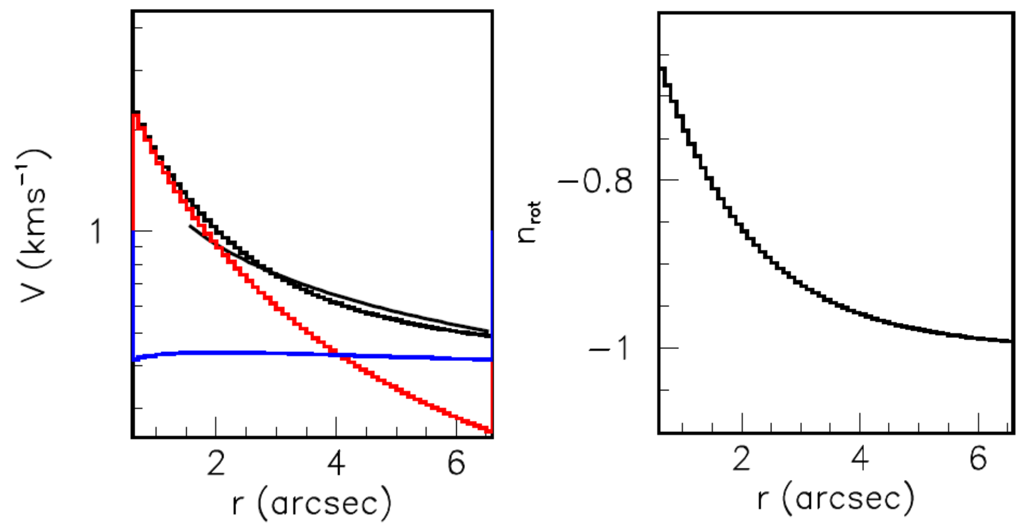




L1527



The rotation velocity decreases from 1.66 to 0.34 kms $^{-1}$ when *r* increases from 1 to 5 arcsec.

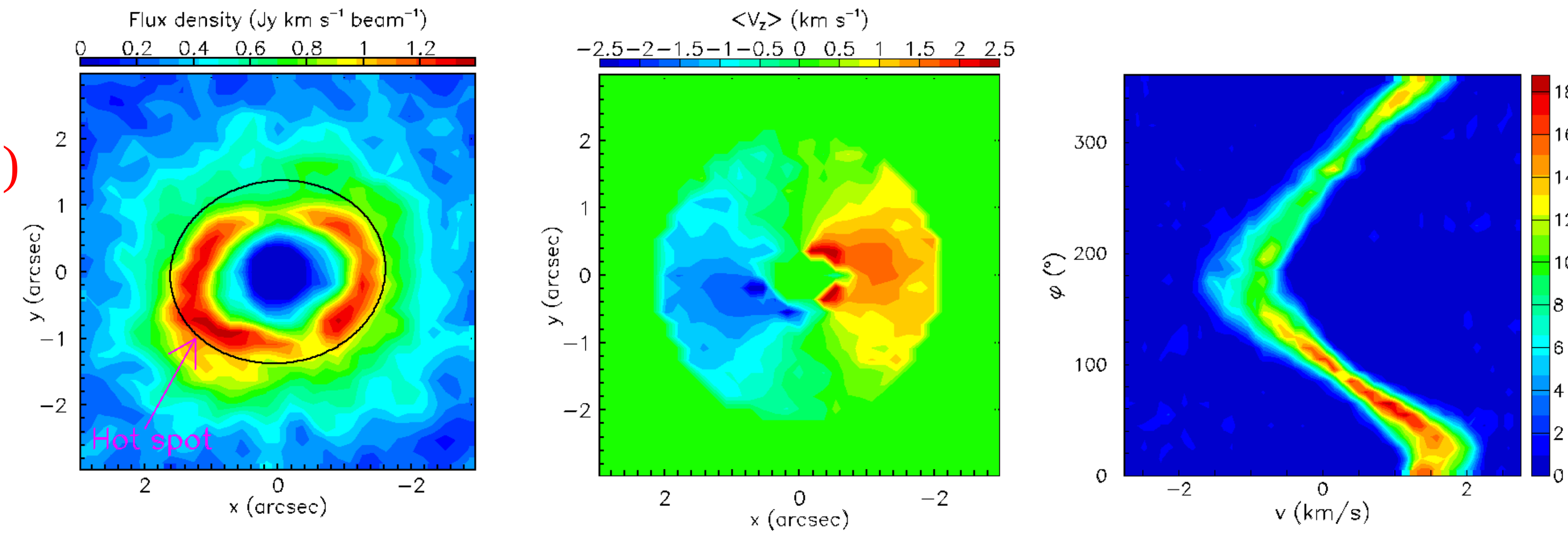


The mean value of in-fall velocity is 0.43±0.10 kms^{-1}, smaller than free fall velocity, with no evidence for a significant *r*-dependence.

GG Tau

A triple stellar system, 1-5 million years old located at 140 pc in the Taurus molecular cloud. The separation between the main protostar GG Tau-A and the close-binary GG Tau Ab is 35 au. GG Tau-A consists of gas and dust with a ring extending from ~190 to 280 au and an outer disc extending up to ~800 au from the central protostar with the total mass ~0.15 $M_{\odot}$.

$^{13}CO(3-2)$



Tang et al. (2016) have recently published observations of $^{13}CO(3-2)$ ALMA data. Together with their team we are extending their analysis to father detail.

The future

What we need most are **observations of high quality** to the analysis of which we can contribute.

We shall continue our work on evolved stars (ALMA and PdBI proposals in collaboration with Paris), protostars (ALMA proposal in collaboration with Bordeaux) and remote galaxies (ALMA proposal). We will continue to exploit the ALMA public data.

We have been considering asking for observing time on FAST when it will operate in collaboration with Chinese teams.

ACKNOWLEDGEMENTS

We are indebted and very grateful to the ALMA partner, who are making their data available to the public after a one year period of exclusive property, an initiative that means invaluable support and encouragement for Vietnamese astrophysics. We particularly acknowledge friendly support from the staff of the ALMA Helpdesk.

We express our deep gratitude to Prof. Thibaut Le Bertre who introduced us to evolved stars and Dr. Anne Dutrey who introduced us to protostars.

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Thank you for your attention!