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

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A bit of history

Our team was born in 1999 when Prof. Pierre Darriulat came to Viet Nam with detectors that had been given to us as gifts, including scintillators, PM tubes, NIM and CAMAC electronics. We assembled a scintillator telescope to measure the muon flux in Ha Noi, which happens to sit at the Earth maximum of rigidity cut-off, giving our measurements unexpected value.

We immediately joined the Pierre Auger collaboration, measuring the high energy end of the cosmic ray spectrum in the Argentinean pampa, and contributed to the analysis of the data, providing material for our first three PhD theses. Thanks to the friendly interest and support of our colleagues in Auger, and in particular of spokesmen Jim Cronin and Alan Watson, we found there a framework in which to grow and come of age.

In parallel, our interest for astrophysics – to the teaching of which we contributed at various universities – kept increasing and we acquired a 2.6 m radio telescope tuned on (and near) the 21 cm hydrogen line. In addition to detailed studies of its response, revealing effects at the permil level, we measured the HI density in the disk of the Milky Way, the black body temperature of the Moon, the polarisation of several solar flares and found evidence for correlations between the periods of solar oscillations (amplitudes at the percent level) observed jointly by us and by an Australian solar observatory. These turned out to be an artefact caused by interferences between the direct signal and its reflexion on ground (multipathing).

For now five years or so, we work exclusively in radio astronomy, using data from major international observatories on both stellar physics (birth and death of stars) and high redshift galaxies (learning about the early Universe). My report is limited to this later phase.


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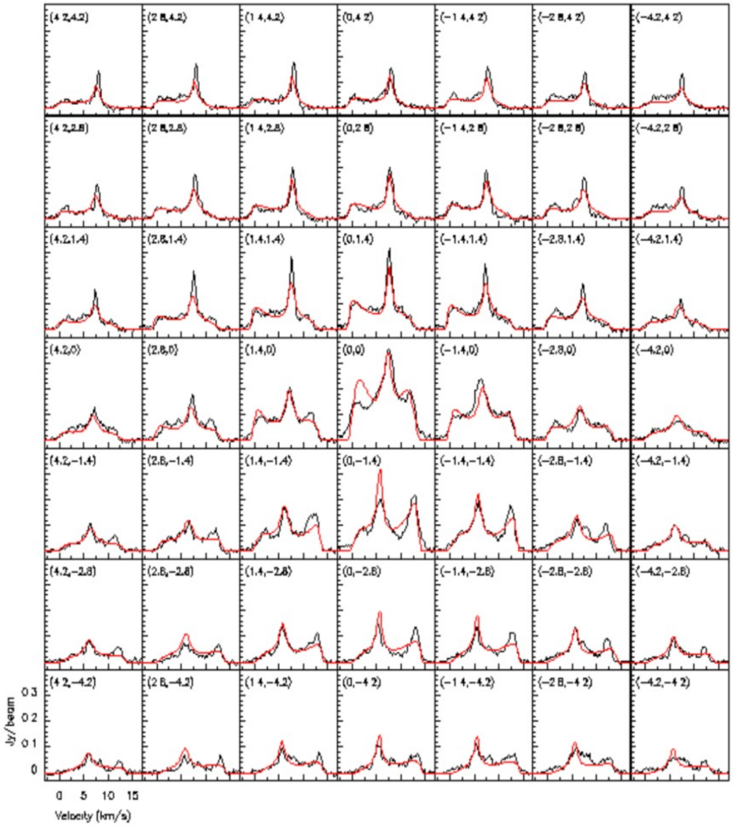
The data

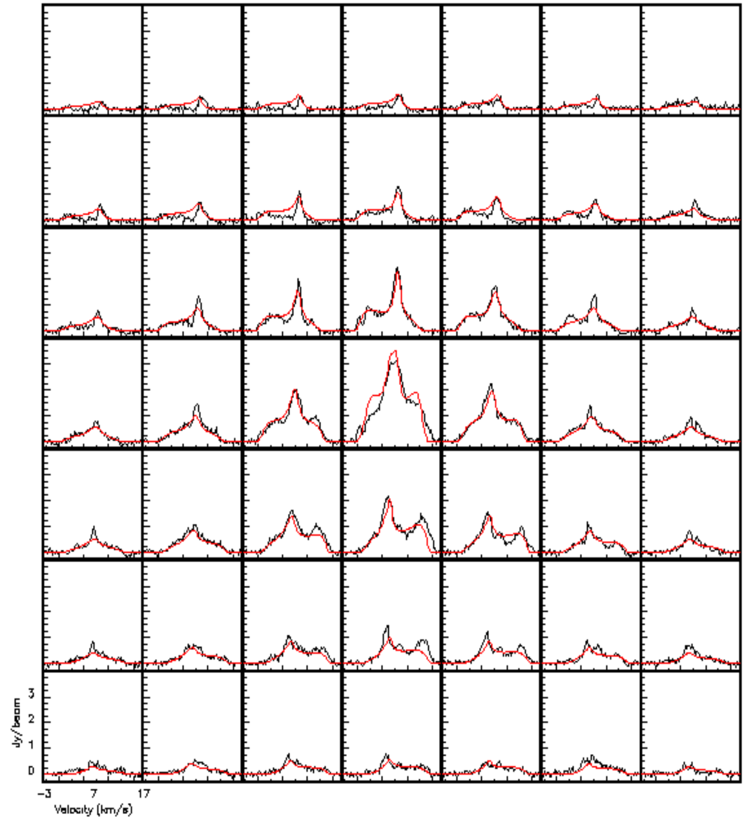
We normally use observations made with radio interferometers: Plateau de Bure (6 antennas), VLA (27 antennas) and ALMA (66 antennas). In most cases, we observe emission from rotating CO molecules, the most efficient tracer for temperatures between ~10 K and ~1000 K. The data are distributed among a number of pixels, typically at the arcsecond scale or fraction thereof, over a field of view at the arcminute scale. 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 but no velocity measurement is available for the 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 that have burned enough of their hydrogen into helium grow a core deprived of hydrogen that becomes hot enough for its electrons to disconnect from the nuclei to which they were bound and form a Fermi gas, leaving the helium nuclei aggregate into carbon and oxygen. In parallel, the stellar envelope around the core blows up to gigantic sizes, at the scale of hundreds of astronomical units, cooling down to temperatures in the ten to few hundred K range, where molecules emit at millimetre and sub-millimetre wavelengths. This is the emission that we study, in particular from rotating CO molecules. After a few hundred thousand years, the circumstellar envelope dilutes into space, forming a Planetary Nebula and ultimately disappears, leaving the core alone – a White Dwarf , of Earth size – but having enriched the interstellar matter with new nuclides that can be used later on to form new stars.

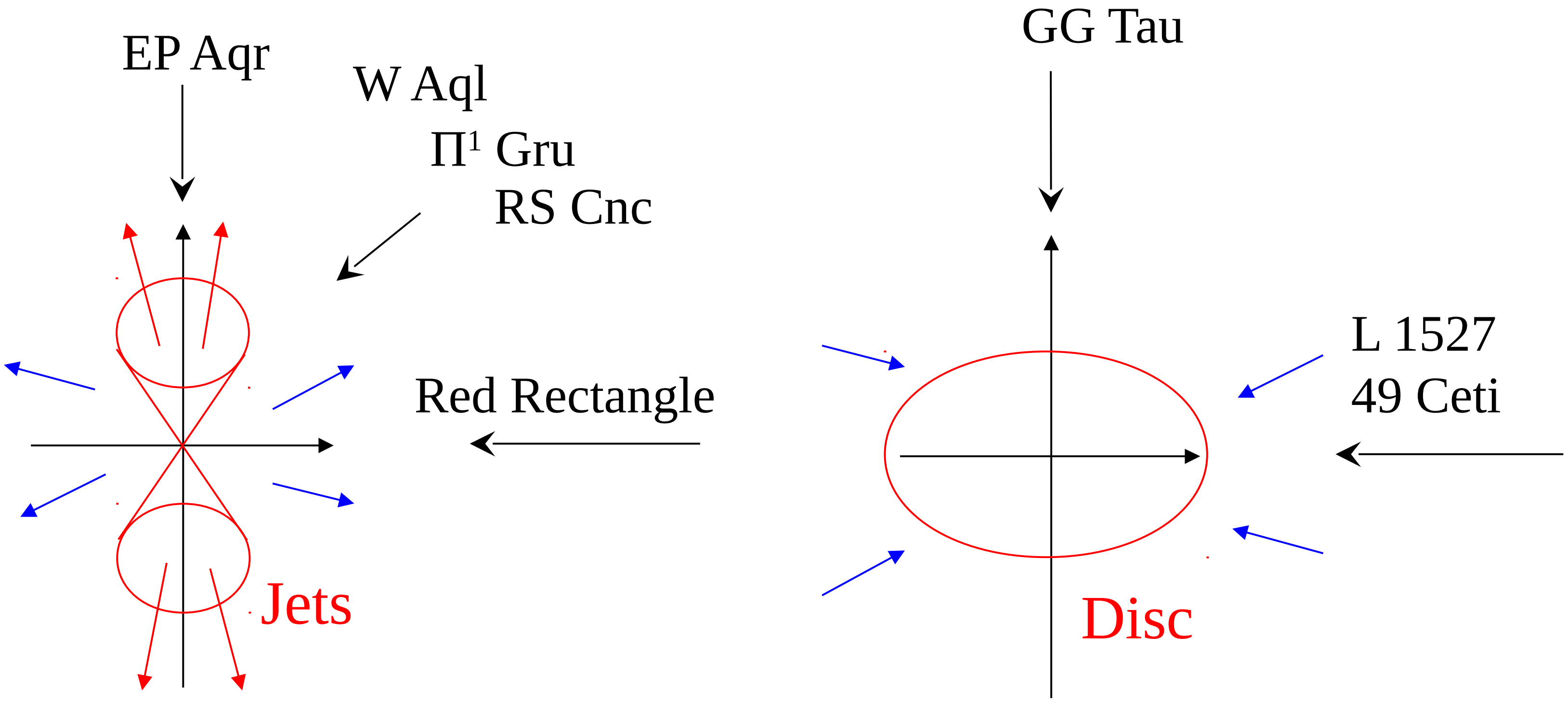
Protostars are to some extent the time reversed process: molecular clouds, which happen to be in an interstellar region where important gravity – and therefore temperature and density – fluctuations are present, start collapsing, gas falling-in toward the cloud centre. Conservation of angular momentum causes the rotation velocity to increase in the process and a disc forms; its temperature and density become so high that atoms ionize and hydrogen nuclei start fusing into helium to form a new star.

Similarities between the two processes are many. For example, in both cases, dust plays a very important role. In evolved stars, it absorbs the light emitted by the central star, radiation pressure producing a wind that causes the growth of the circumstellar envelope, gas being dragged outward by collisions with the dust, which appears therefore as the main motor of expansion. In protostars, cool dust accumulates in the disc plane onto which gas molecules freeze out, forming an ice mantel. Some dust grains aggregate to form larger and larger bodies, ultimately planetesimals and planets.

Another similarity between the two cases is the importance of symmetries. In the case of protostars, one starts from a cloud that has no reason to present important symmetries and ends up with a perfect sphere; in the case of evolved stars, the opposite happens. In both cases, how this comes about is a central issue, with many unanswered questions. For example, magnetic fields are expected to play an important role, but exactly which role is often unclear. Also, in both cases, binaries, an obvious source of symmetry breaking, attract much interest.

One more example of a phenomenon that affects both protostars and evolved stars: the importance of periodic oscillations, taking the form of pulsed accretion in protostars and of thermal pulses in AGB stars.

Partly in collaboration with French astronomers and partly on our own, we studied evolved stars and protostars using high resolution CO emission lines. The former often feature a bipolar molecular outflow, the latter the formation of a disc. I shall illustrate it with some typical examples.



EP Aqr

W Aql

Π^1 Gru

RS Cnc

Red Rectangle

Jets

GG Tau

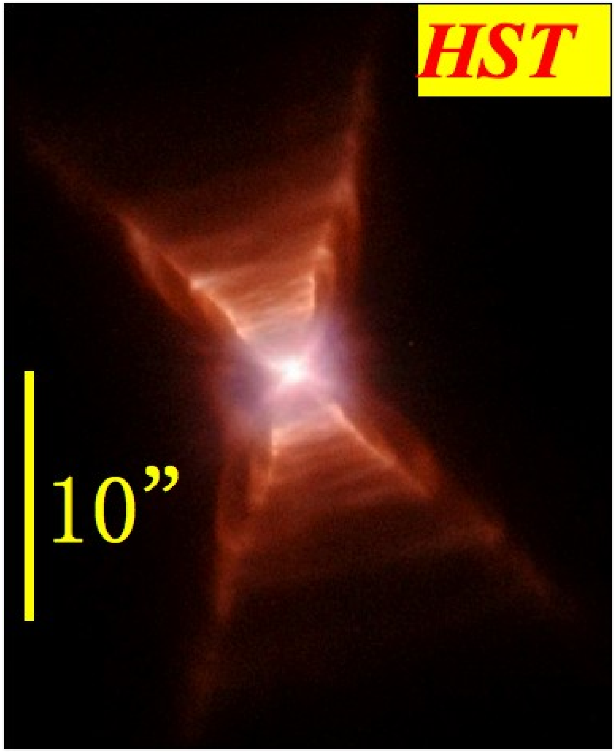
L 1527

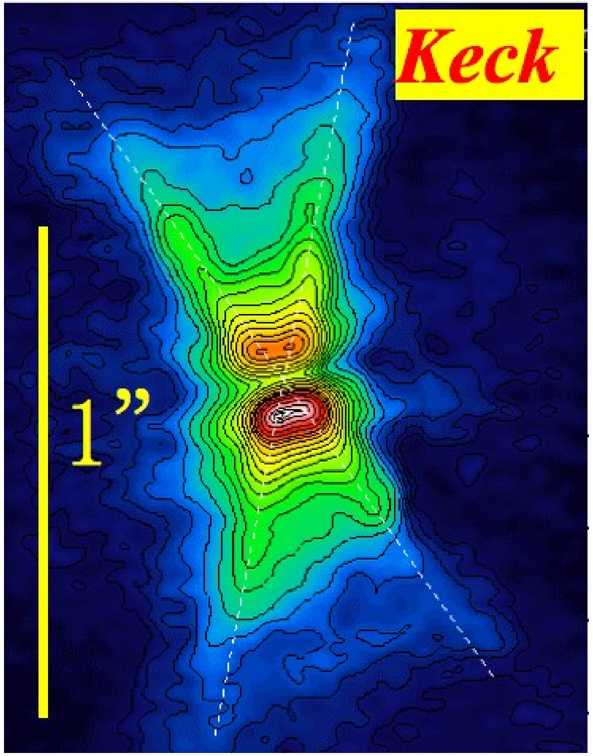
49 Ceti

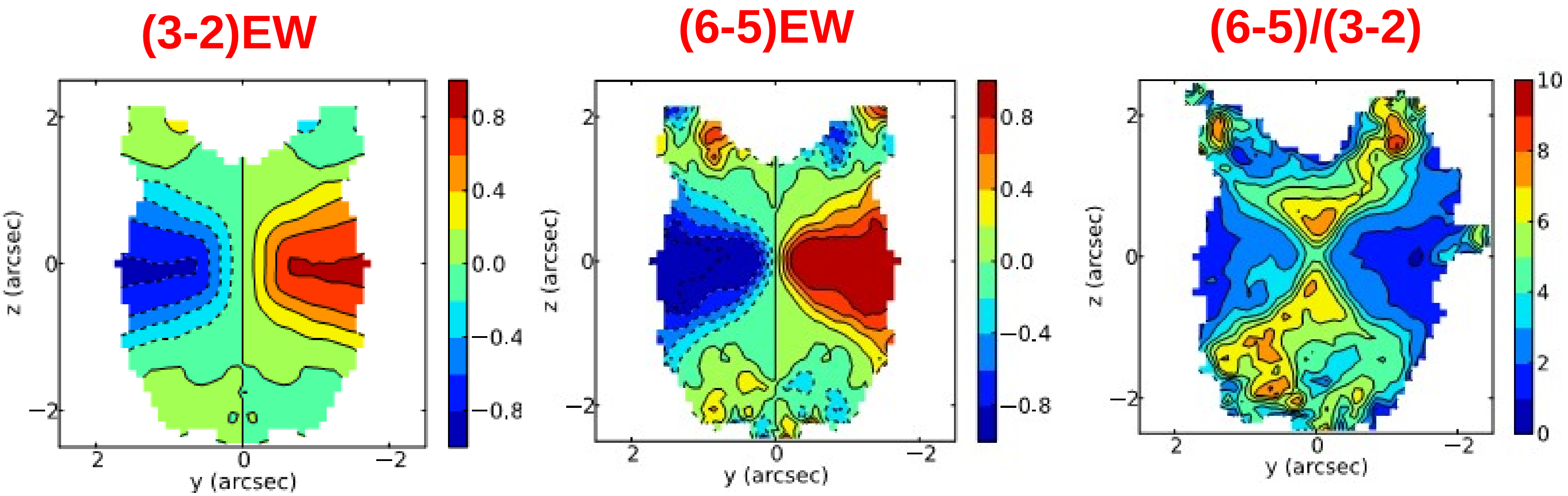
Disc

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.



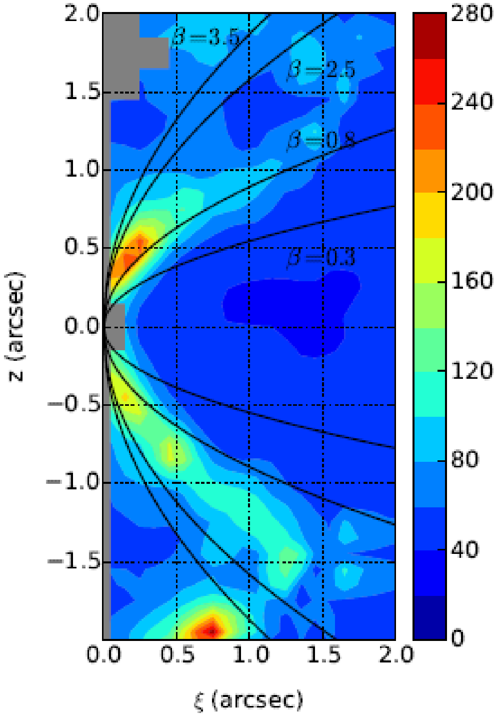


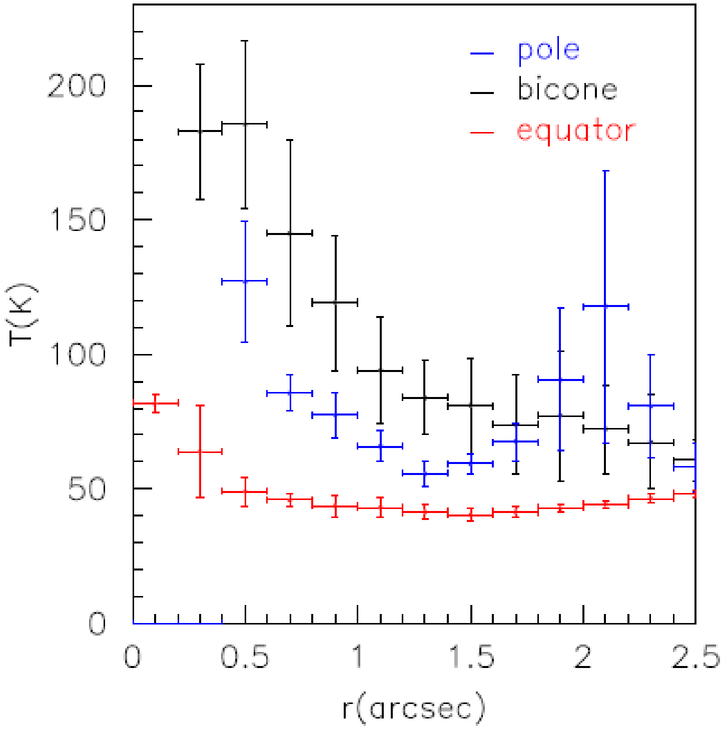


The East-West Doppler velocity asymmetry reveals a very clear **rotation of the equatorial region** about the star axis.

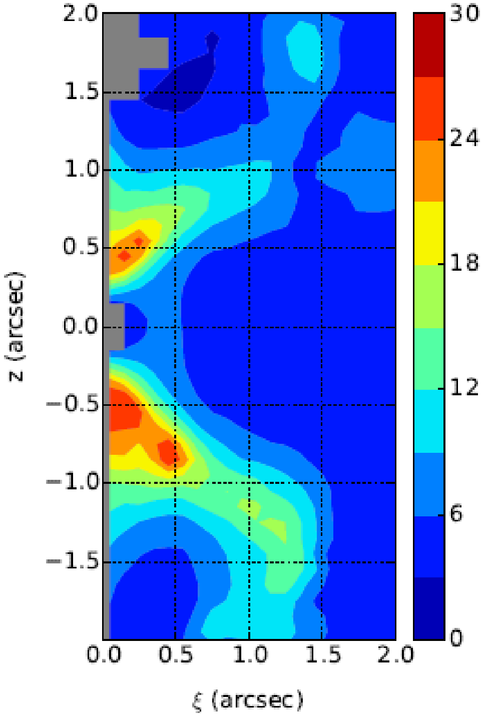
CO(6-5)/CO(3-2) intensity map: evidence for a **temperature distribution** dominated by the biconical structure down to low distances from the star.

Temperature





Density×r^2

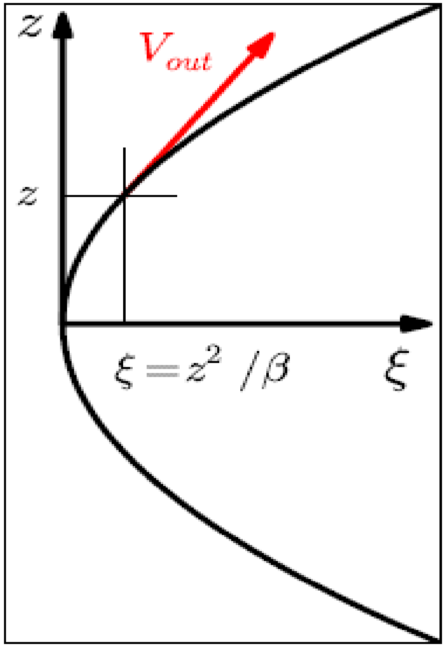


Assuming rotation symmetry about the star axis we reconstruct the gas morphology in space (here shown in the meridian plane).

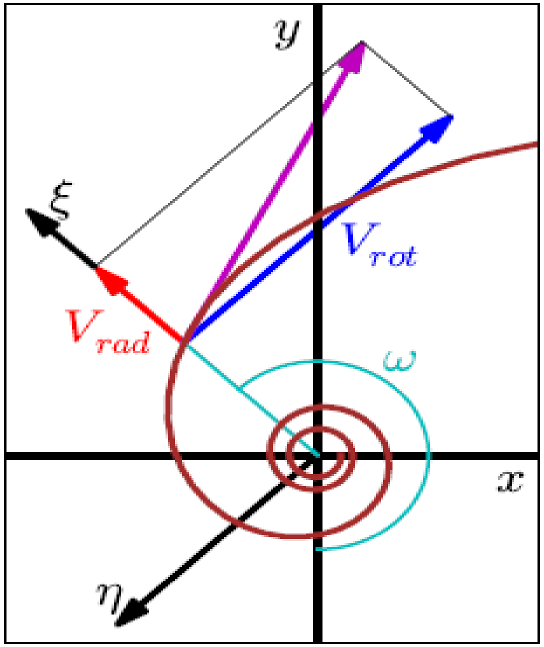
Gas kinematics

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

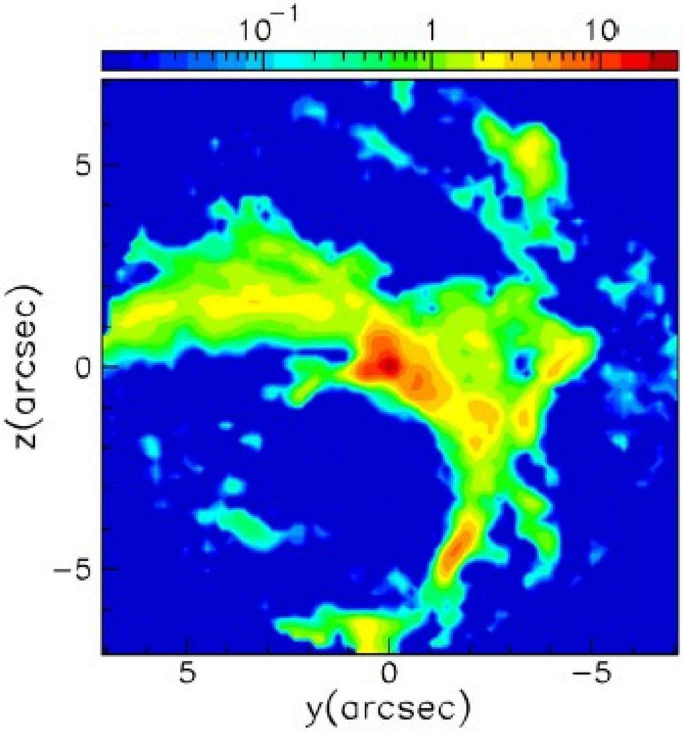


Equatorial region

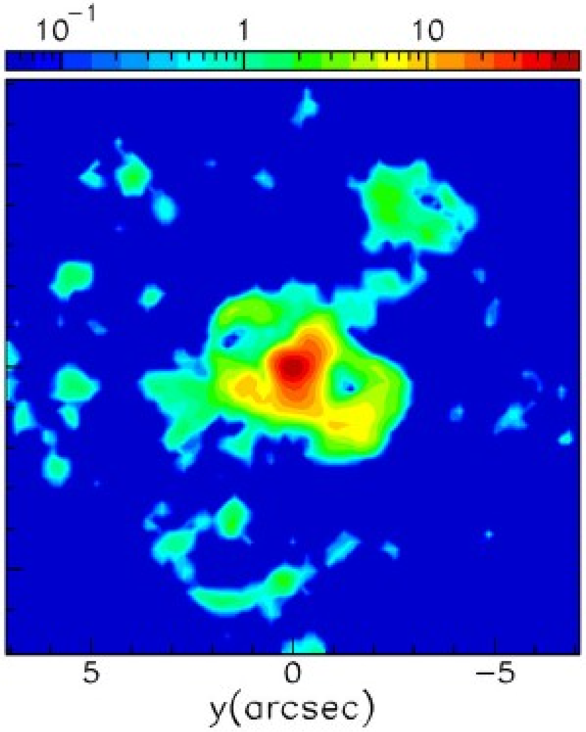
Example 2: a famous binary, Mira Ceti

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

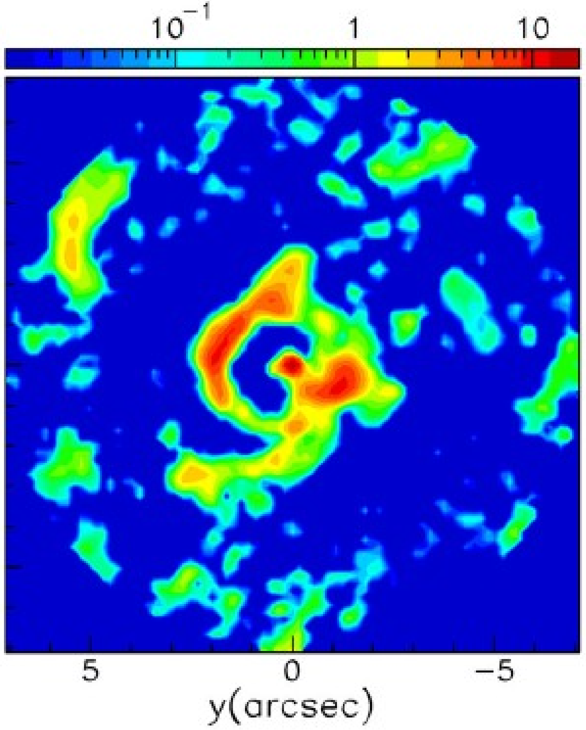
Mira B, is a white dwarf at a projected distance of ~0.5 arcsec from Mira A. We studied CO(3-2) emission observed by ALMA.



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



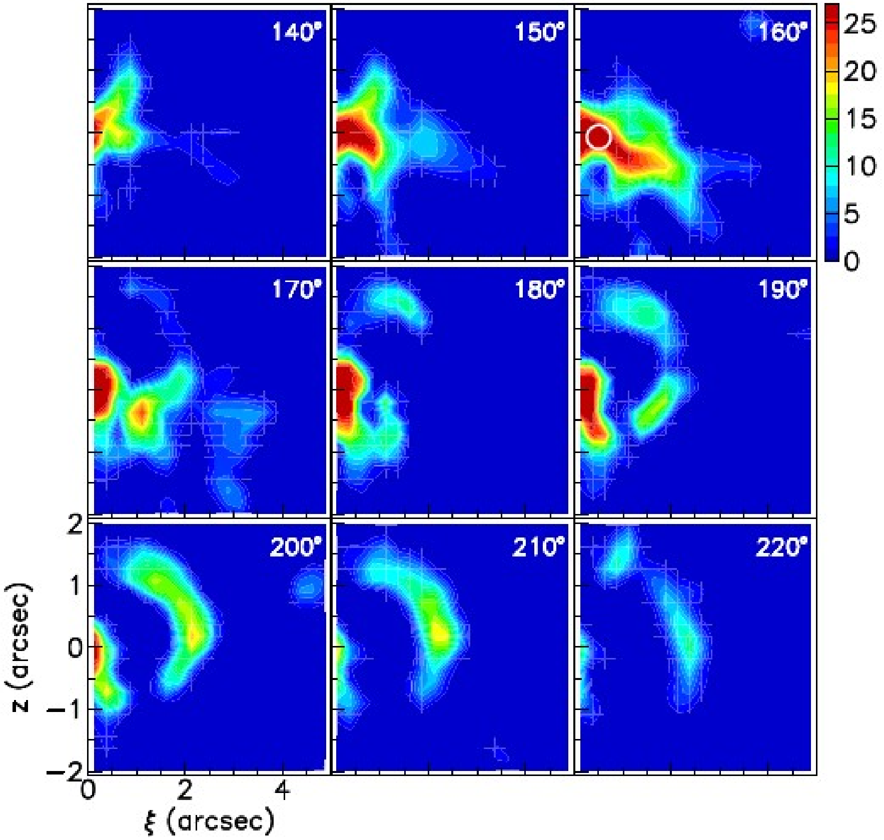
Central velocity region of the circumbinary envelope



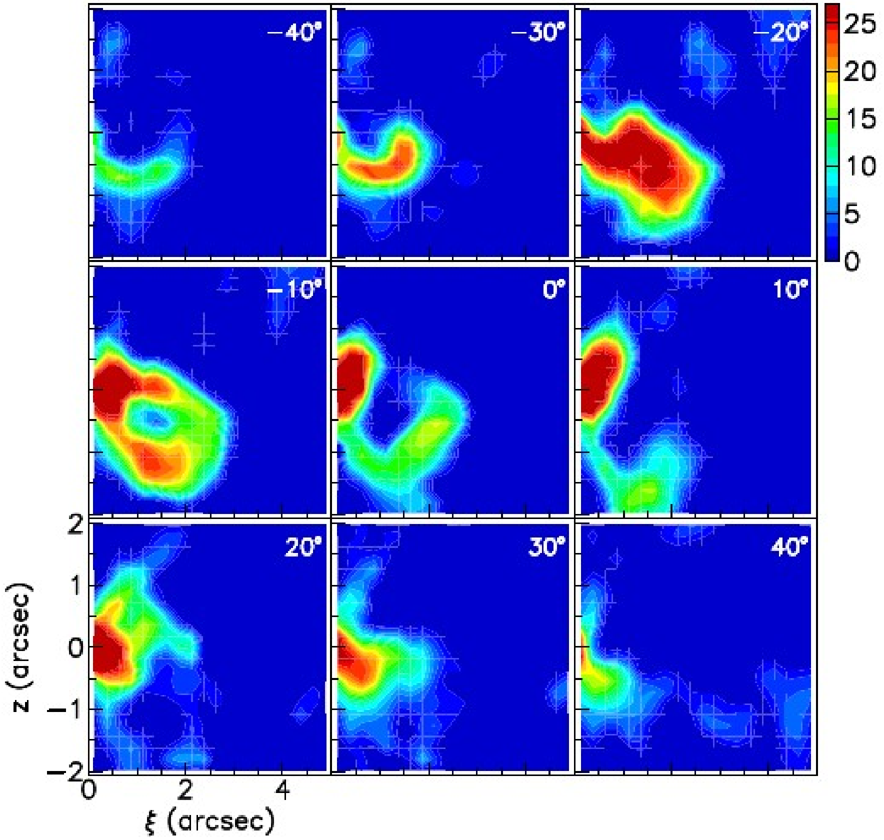
Red-shifted arcs

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.

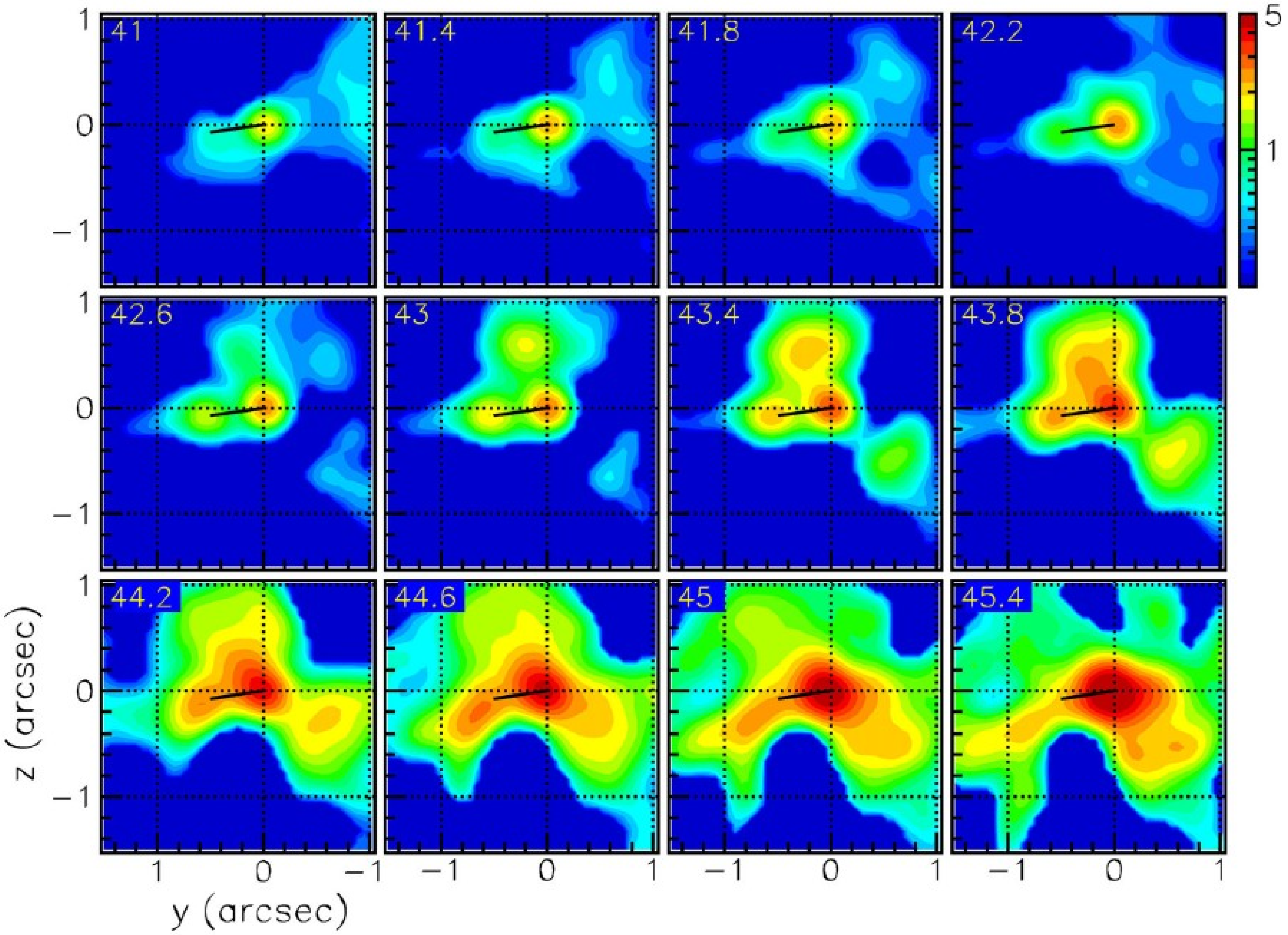
North-eastern outflow



South-western outflows

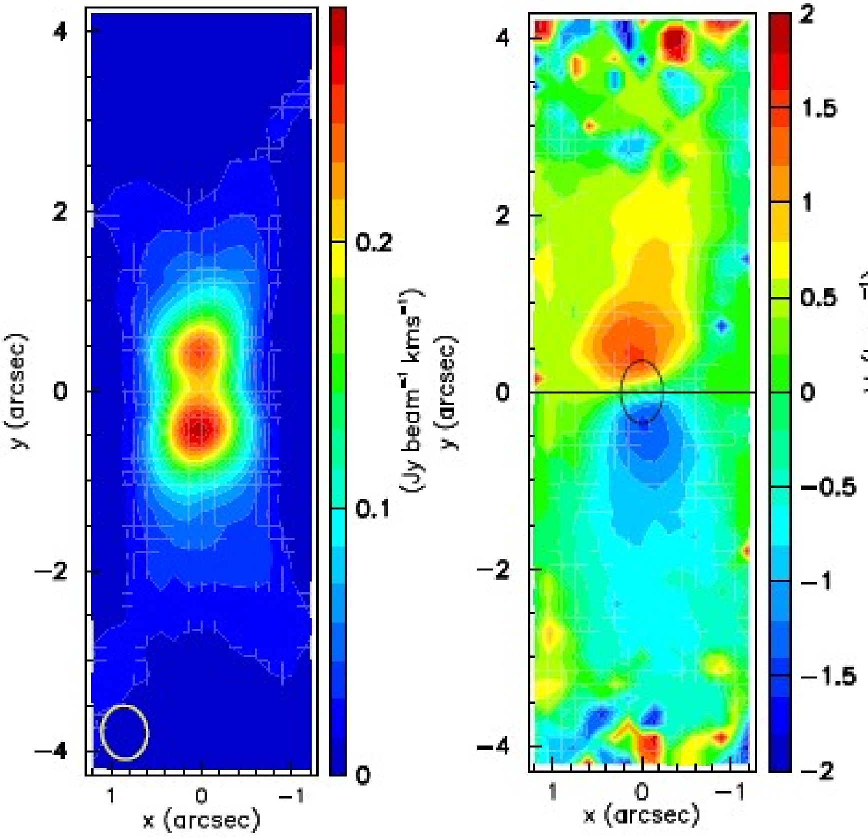


Close to the stars, we observe a mass of gas surrounding Mira B, with a size of a few tens of au, and having Doppler velocities with respect to Mira B reaching ±1.5 km s^{-1}, which we interpret as gas flowing from Mira A towards Mira B.



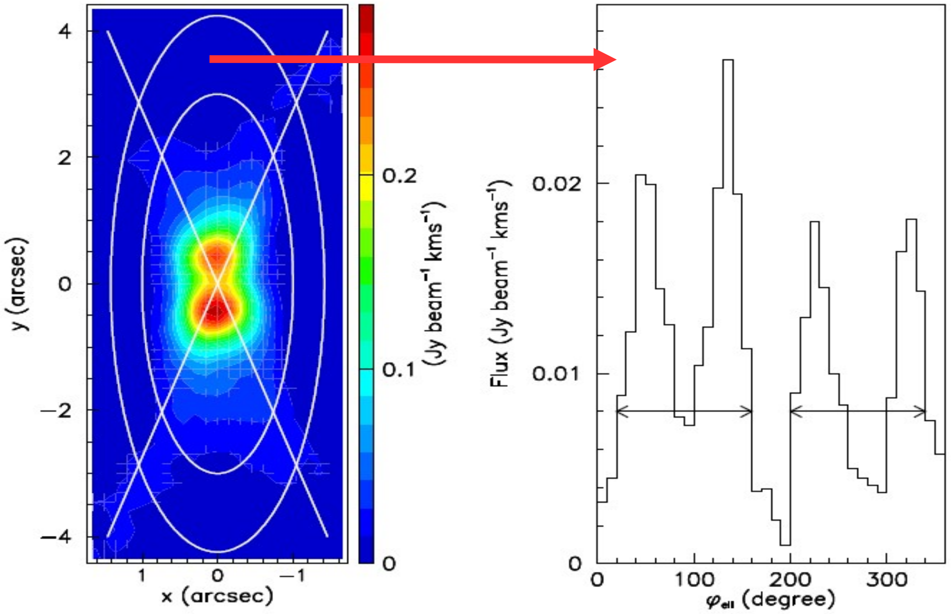
Example 3: L1527, a young protostar

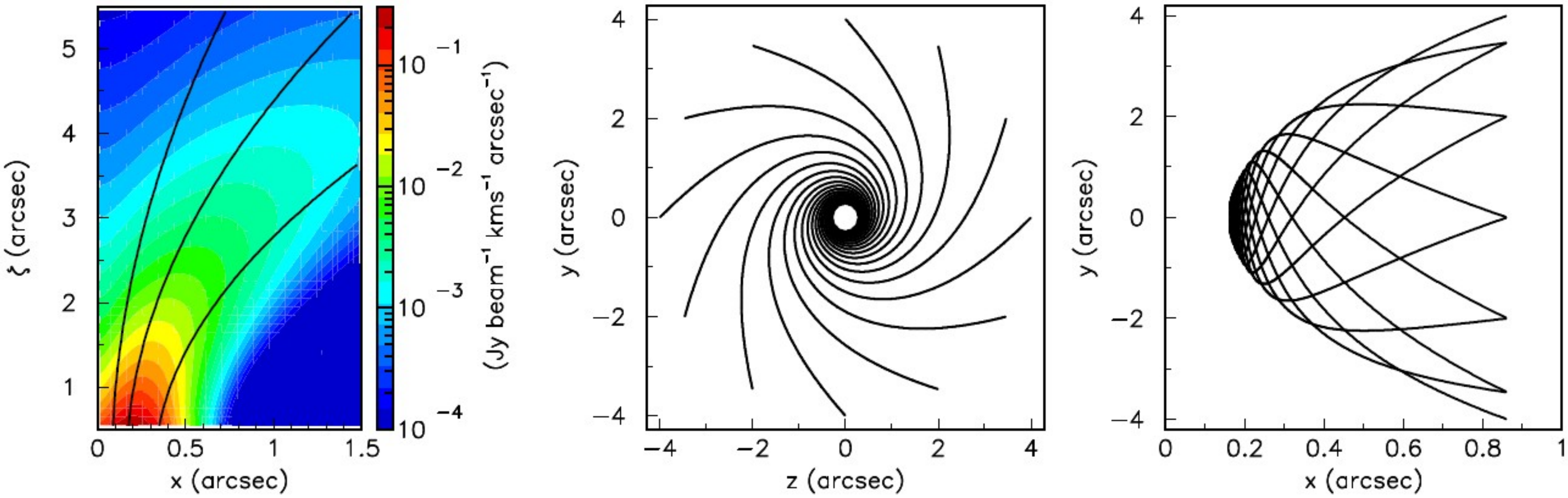
L1527, at a distance of 140 pc, has a mass of 0.2 solar masses and is surrounded by a flared rotating envelope of about one solar mass. We studied its $C^{18}O$(2-1) emission measured by ALMA. The disc is seen edge-on.



Emissivity

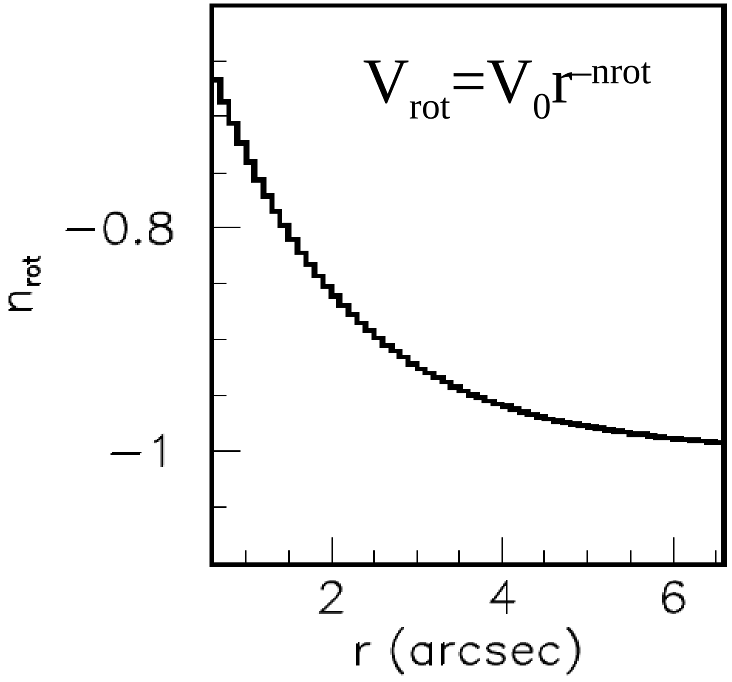
Doppler velocity





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).

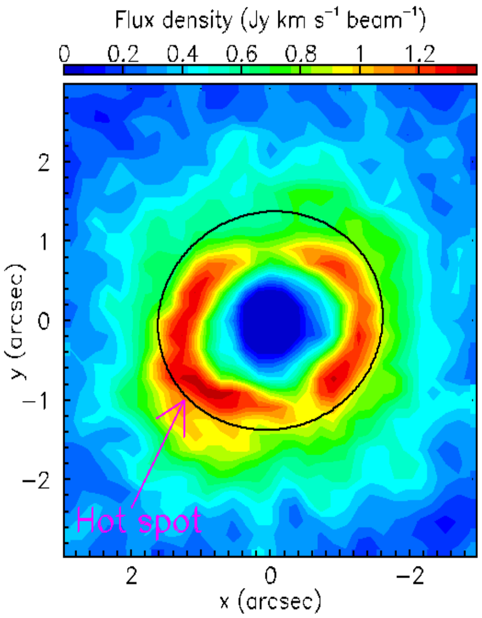
Kinematics provides a measurement of the star mass.

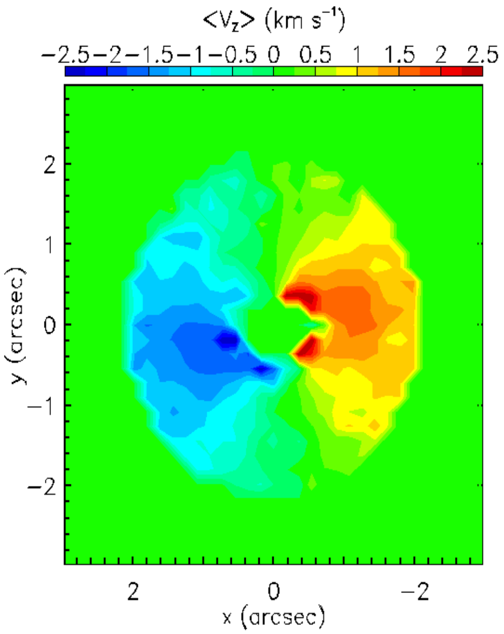


$V_{rot}=V_0r^{-nrot}$

Example 4: GG Tau, a triple protostar

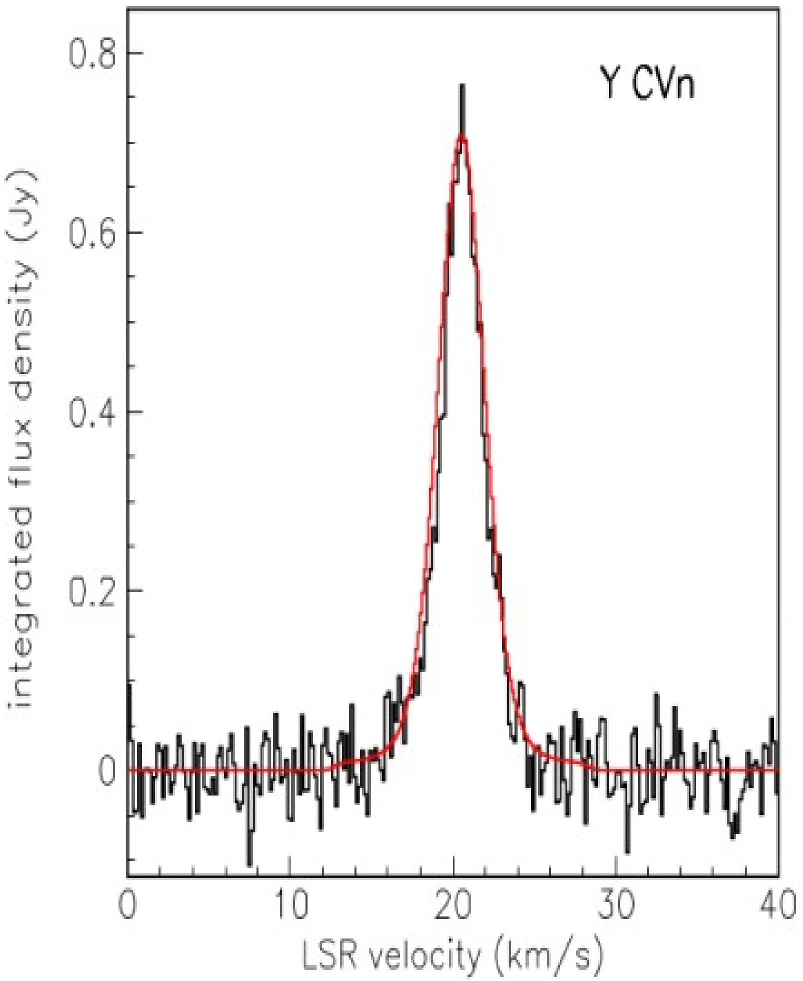
The separation between the main protostar and the close-binary is 35 au. The former consists of gas and dust in a rotating torus making an angle of 35° with the plane of the sky. Tang et al. (2016) have recently published observations of ^{13}CO(3-2) ALMA data. Together with them we have extended their analysis to obtain further detail.





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

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). The emission from the central wind is shielded by the shell, resulting in a HI linewidth narrower than in CO.

High redshift galaxies: a typical example, RXJ0911

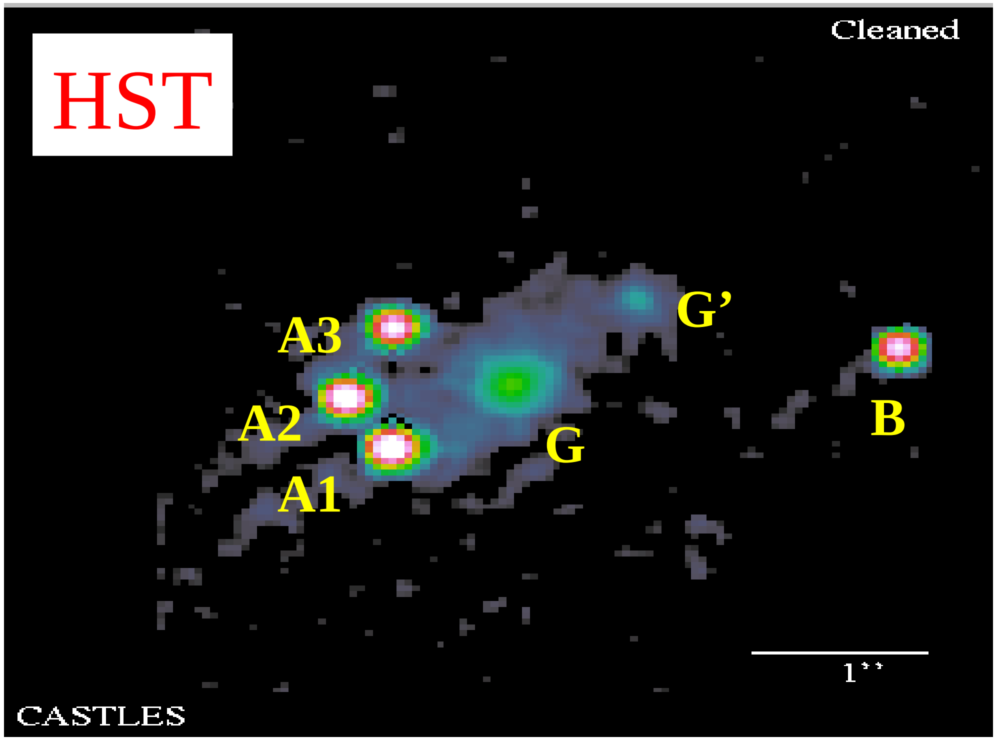
Four main actors of galaxy evolution at early cosmic times, when star formation is maximal, with redshift in the ~2 to ~4.5 range, are accessible to observation: the supermassive black hole in the centre, the gas reservoir from which stars are formed, its dust content – a proxy of star formation – and the stars themselves. The fifth main actor, dark matter, is not directly accessible to observation. Typically, each of these covers a specific frequency range in the rest frame: optical and X rays for the black hole, millimetre/sub-millimetre for the molecular gas, infrared for the dust and optical for the stars. These observations are reduced to a few quantities that summarize our knowledge of the observed galaxy, such as masses and luminosities of the above mentioned components, star formation rate, etc.

It is only recently that some gas and dust components of high redshift quasar hosts could be spatially resolved, usually taking advantage of the important magnification provided by gravitational lensing. From their study, one learns that they are often the seat of mergers that are identified by comparing the respective locations of the optical, gas and dust components. At such early times, galaxies were smaller and closer from each other (expansion of the Universe) than they are today. Mergers cause the gravitational field to strongly increase locally, triggering the local collapse of gas clouds and causing star bursts. These are seen as important sources of dust away from the central black hole.

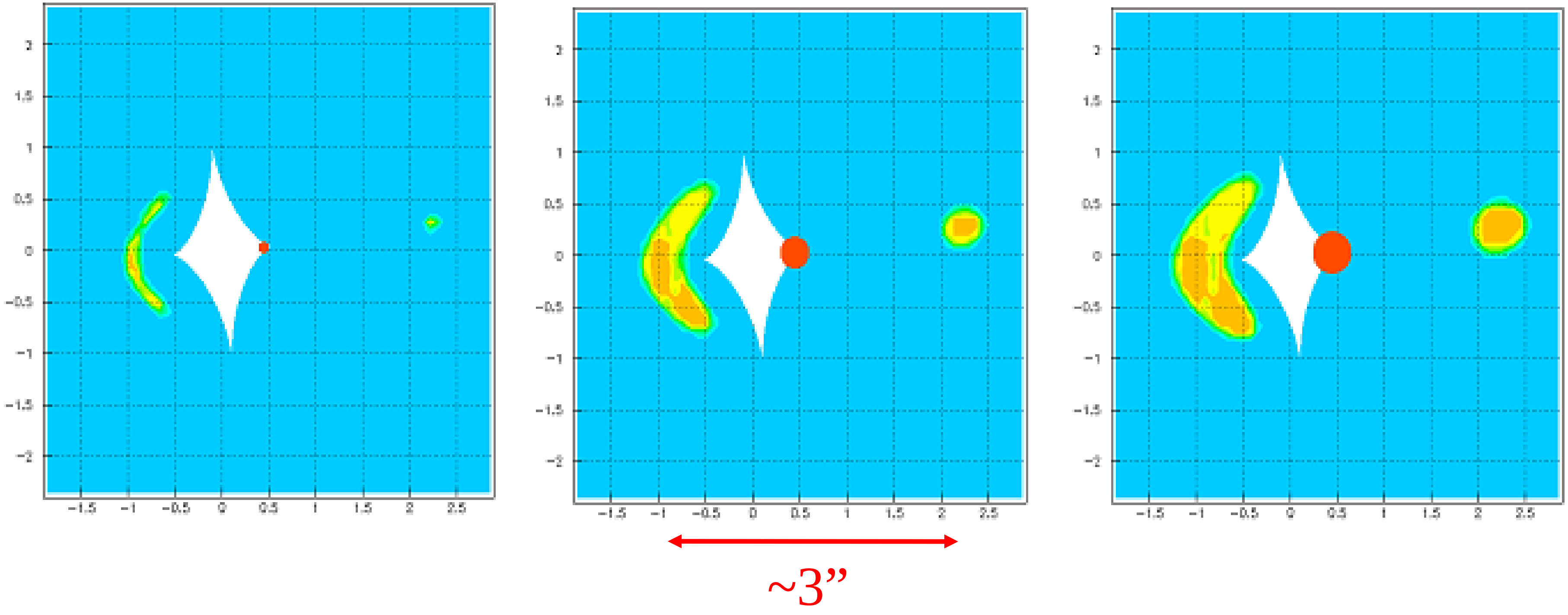
Understanding the genesis of early galaxies requires observations made at different stages of their evolution, in order to reveal the relative roles played by each actor as a function of time. At each stage, multi-wavelength observations are mandatory in order to disentangle the respective morphologies of the gas and dust components and their locations with respect to the central black hole.

Here, I present a detailed study of the host galaxy of a gravitationally lensed high redshift quasar (z~2.8, look back 11.3 Gyr), RX J0911. Detection of the CO(7-6) line by Plateau de Bure 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!).



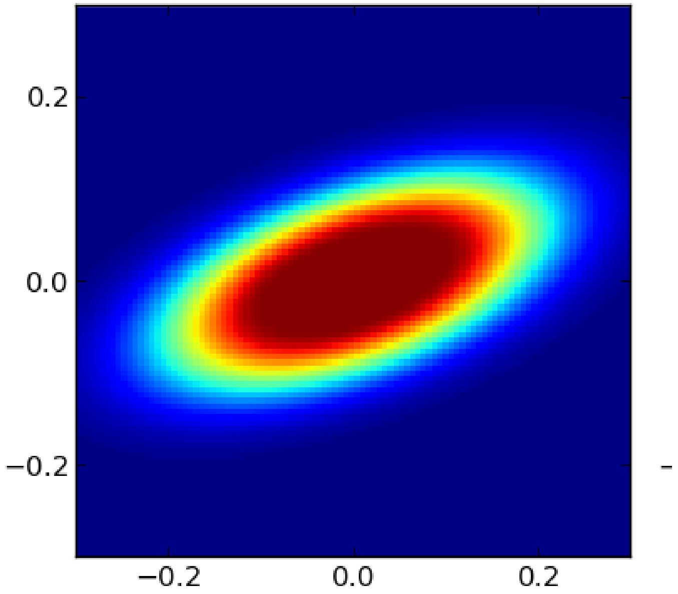
Lensing is complicated by the fact that the extended source overlaps the lens caustic. We studied this peculiar situation in detail.



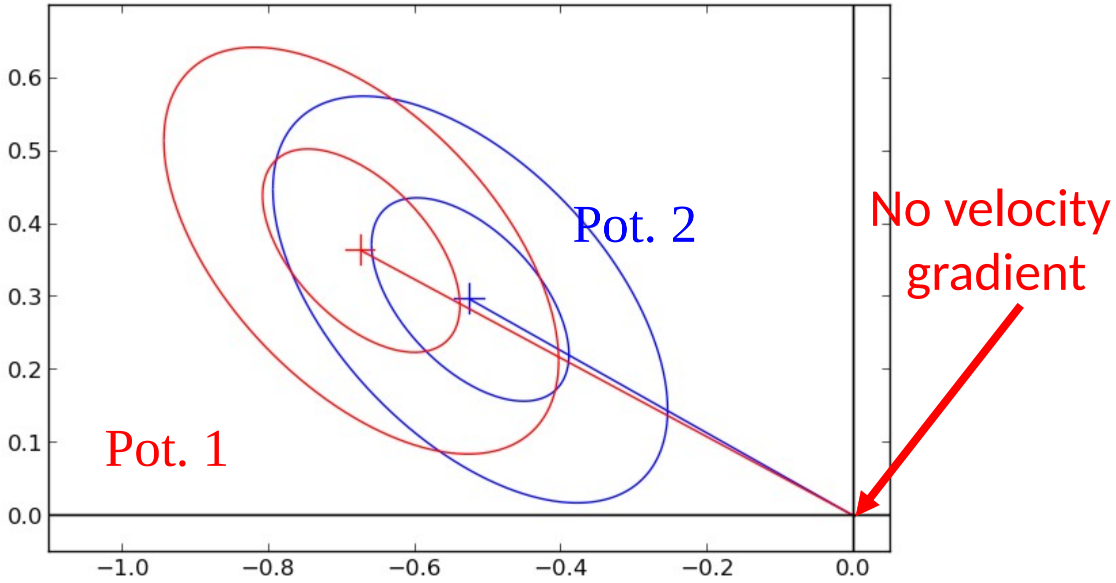
The results show that the gas source has a radius of 850±120 pc on the line (~7 s.d.) and provide evidence for ellipticity and for a significant velocity gradient (molecular outflow and/or rotation)

Ellipticity: 3.3 s.d. away from circular

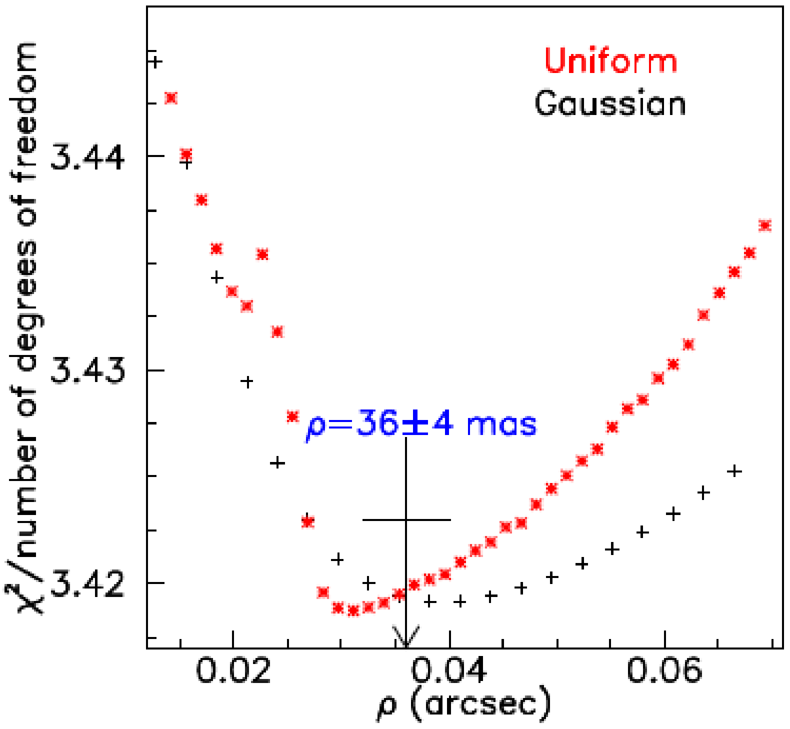
Evidence for velocity gradient at 4.5 s.d.



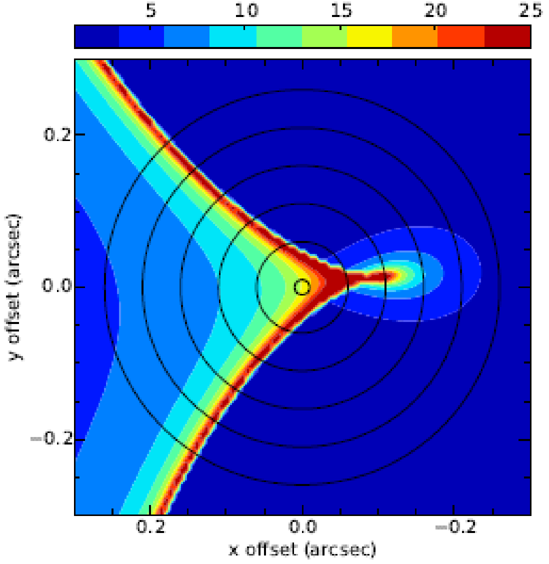
arcsec

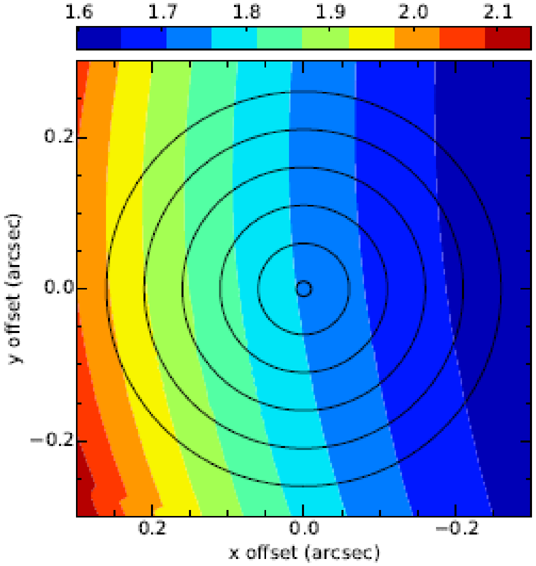


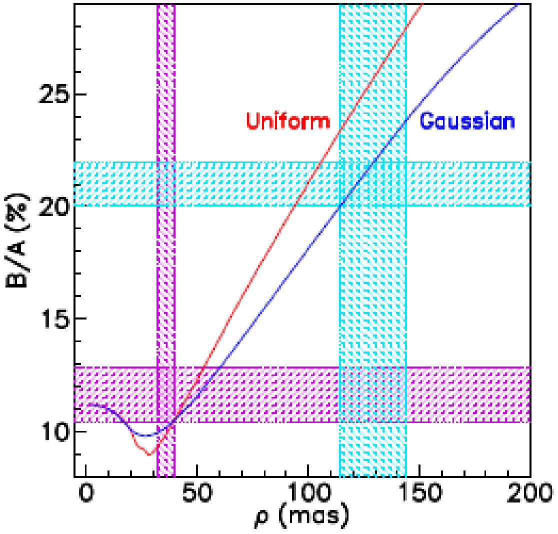
No velocity gradient



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 and conclusion

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!