A rotating spiral structure in the innermost regions around IRC +10216

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Abstract. ALMA interferometer is providing us molecular maps with unprecedent precision and sensitivity, Key processes in the ejection of matter and dust from these objects occur in their inner zones. We have obtained sub-arcsecond interferometric maps of rotational transitions of metal-bearing molecules towards the prototypical C-rich evolved star IRC+ 10216. While Al-bearing molecular emission presents a roughly spherical shell, the molecular emission from NaCl and KCl presents an elongation in the inner regions, with a central minimum. The presence of the observed features only in KCl and NaCl might be a direct result of their comparatively high dipole moment with respect to the Al-bearing species. The most plausible interpretation for the spatial distribution of the salts is a spiral with a NaCl mass of 0.08 $M_\odot$ with an inner radius of 27 AU. The gas kinematics suggests that it is slowly expanding and rotating. Alternative gas distributions which could result in the presence of the elongation are also explored.

1. Introduction

IRC +10216 is the best studied AGB star. Due to its proximity (∼230 pc) and chemical richness it has been the perfect testbench to study the ejection of material in the AGB phase and the circumstellar chemistry around this type of objects. Indeed, around half of all the molecular species detected in the interstellar medium had been observed for the first time in the ejecta around this object.

The molecular emission observed towards these object has been found, in general, to be roughly spherical, presenting arcs. These arcs have been suggested to be consequence of an spiral structure [1, 2, 3]), which is also a consequence of the presence of a companion star. Infrared observations have shown that the structures present in the innermost region of this star are more complicated than the presence of a spiral. In particular, several authors have shown the presence of a dark-lane with a P.A. of 120° (e.g. [4]) and the presence of an outflow orthogonal to this lane (e.g. [5]). However, while the optical an infrared images could provide better spatial resolution than those reached in the millimeter domain, these former observations lack of kinematical information which is in contrast provided by the molecular emission.

Only recently, the spatial resolution achieved with ALMA is allowing us to probe the structures and, more important, their kinematics of the innermost regions of the circumestellar envelope (CSE).

2. Metal emission as seen with ALMA

We obtained, during ALMA Cycle 0, interferometric maps of the emission from several metal species, such as AlCl, AlF, NaCl and KCl, as well as some of their isotopologues. These maps presented two different spatial distributions. In particular, while the Al-bearing species showed more or less spherical brightness distributions, the emission from the salts KCl and NaCl showed an elongation with a P.A. of $\sim$77° with a central minimum (see Fig. 1). While this elongation seems compatible with the dark-lane already mentioned, there is a clear difference in the P.A. of both structures.

Since it has been shown that the structures of arcs observed towards IRC +10216 might be consequence of the presence of a spiral distribution of dust and gas we simulated the expected result of an ALMA observation of an spiral brightness distribution with the very same characteristics of uv-plane coverage and integration time as the actual observations (see Fig. 2). We found that this spiral distribution is compatible with the structures observed for the salts.

The reason why this structure is not observed in the Al-bearing emission maps is the difference is the dipole moment of the different species. In particular, as the dipole moment of AlCl and AlF (1.00 D and 1.53 D respectively) are much lower than those of the NaCl and KCl (9.0 D and 10.27 D), the excitation of the former molecules is much easier than that of the salts. Due to this, the salts are good tracers of the high density regions. In this particular case, the low density inter-arm regions of the spiral do emit in the Al-bearing species while do not in the salt emission. To reproduce this effect, we created another simulation, this time adding a diffuse inter-arm emission in the brightness distributions. The result showed that for such brightness distribution neither the elongation nor the central minimum are detected, resembling a simulated interferometric map similar to those of the Al-bearing molecules (see Quintana-Lacaci et al. 2016 [6] for more details).

3. Modeling kinematics: rotation

We prepared a simple kinematic model of an spiral structure with both an expansion and rotation velocity field to understand the kinematics of the gas. The expansion velocity field is well known (e.g. [7]). In contrast, no information was available on the possible inclination of the spiral with respect to the plane of the sky, neither on the rotation velocity field. We found that adding a rotation to the velocity field of the spiral resulted in a rotation of the P.A. of the elongation. Therefore, the P.A. of the dark lane and that of the elongation are compatibles if we add rotation.

In order to constrain these parameters, we assumed that the real position of the elongation was that of the dark lane observed in the IR images (i.e images not affect by kinematics). We

Journal of Physics: Conference Series **728** (2016) 022005 doi:10.1088/1742-6596/728/2/022005

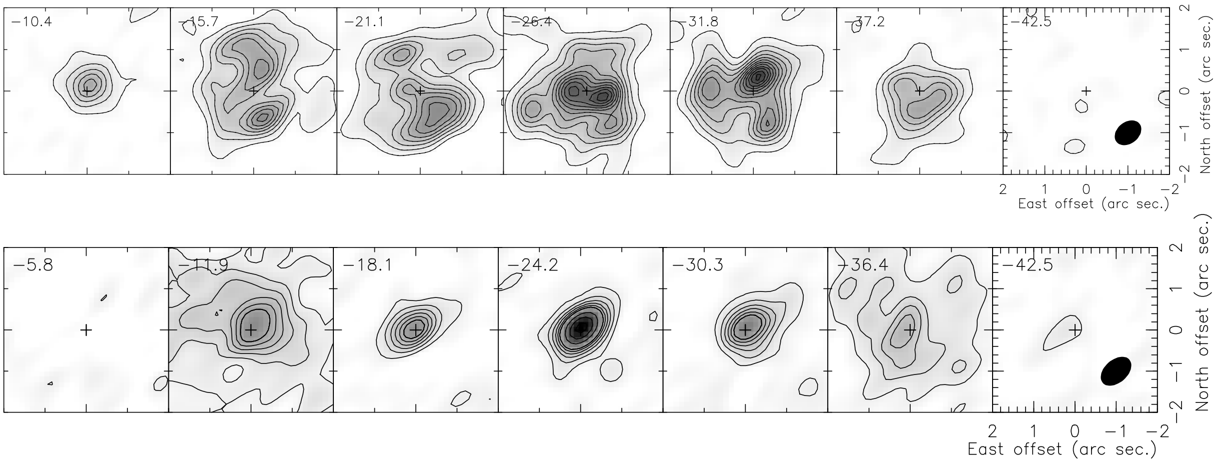

Figure 1. *Top:* Interferometric map of the NaCl $J = 21 - 20$ transition. The HPBW of the synthesized beam is $0''.704 \times 0''.516$ with a P.A. of -52.00°. The lowest contour corresponds to a value of 3σ and the rest are equally spaced in jumps of 5σ with respect to the first contour. *Bottom:* Interferometric map of the AlF $J = 8 - 7$ transition. The HPBW of the synthesized beam is $0''.858 \times 0''.557$ with a P.A. of -228.6°. The lowest contour corresponds to a value of 3σ and the rest of contours until 18σ are equally spaced in jumps of 3σ with respect to the first contour. From 18σ the intensity jump in the contours is 10σ. The rms of the map is $\sigma = 6.4$ mJy/beam. On the **upper-left** corner of each panel is written the v_{LSR} of the channel. The beam size is drawn in the last panel. Flux density scale is in Jy/beam.

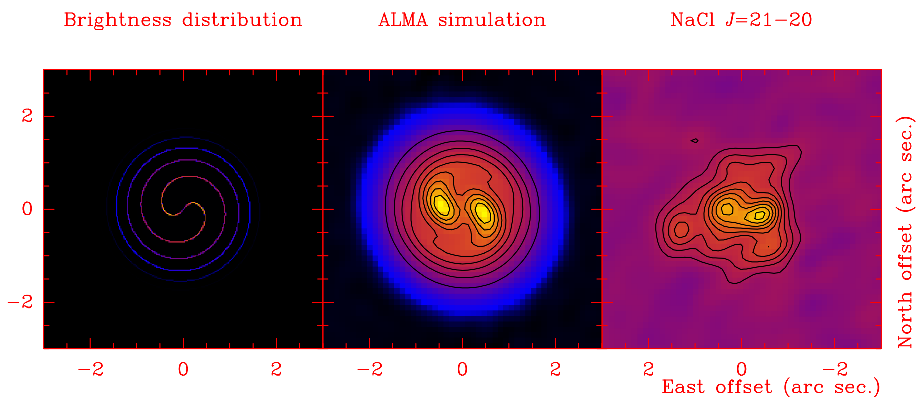

Figure 2. *Left:* Brightness distribution of a face-on Fermat Spiral with $a = 0.2$ at the systemic velocity. *Center:* Result of the ALMA Cycle 0 simulation of the brightness distribution *Right:* NaCl $J = 21 - 20$ emission map for the systemic velocity. The contours of the maps correspond to 10%, 20%, 30%, 40%, 50%, 60% , 70%, 80% and 90% of the peak flux.

found that for a fixed value of the expansion velocity field, the other pair of parameters to by determined, inclination and rotation velocity, where coupled. Therefore, for an expansion velocity of ∼11 km/s, as found for the gas at the radius of the NaCl emission, the found an inclination with respect to the plane of the sky of $i \sim 15 \pm 10°$ and a rotation velocity of 8 km/s. This low inclination with respect to the plane of the sky support the arguments of Cernicharo et al. (2015) [2] in favor of an spiral almost in the plane of the sky, in contrast with the conclusions of Decin et al. (2015) [3] suggesting a spiral almost edge-on.

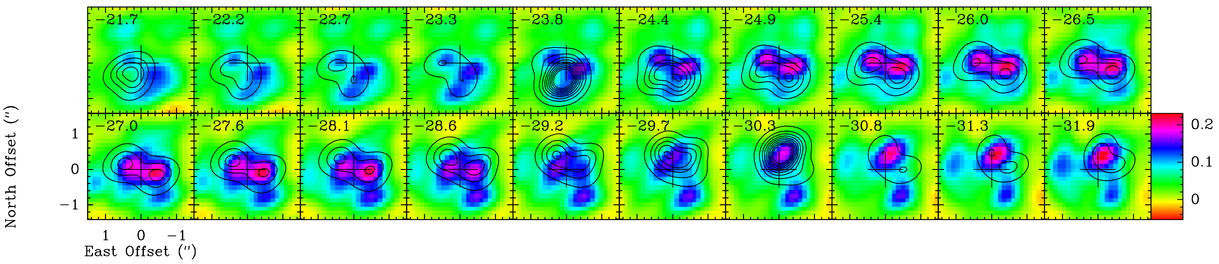

Figure 3. Simulation of an expanding and rotating spiral overplotted to the NaCl $J = 21 - 20$ emission map.

4. Results

Thanks to the capabilities of ALMA and to the high dipole moment of the NaCl and KCl species we have been able to infer a rotation an a tilt in the spiral structure observed around IRC +10216. In fact, this rotation allows to build up a complete picture of the structures around these object. In particular, in the large scale we have an almost spherical structure which responsible is an spiral distribution of gas and dust almost in the plane of the sky. In addition, if we move towards inner regions of the CSE around these object we found that this spiral is rotation, and orthogonal to this rotation plane, an outflow of collimated gas.

Might it be the case that this star is undergoing the shaping process observed for many post-AGB objects, i.e. the appearance of fast bipolar outflows which will carve through the AGB shell, powered by the rotation of a binary star?

Acknowledgments

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 610256 (NANOCOSMOS). We would also like to thank the Spanish MINECO for funding support from grants CSD2009-00038, AYA2009-07304 & AYA2012-32032. YK acknowledges the use of HPC resources of SKIF-Cyberia (Tomsk State University).

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