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CHARACTERISATION AND DETERMINATION OF THE ORBIT OF AN AGB STAR'S COMPANION: COMBINING ALMA, VLT, GAIA OBSERVATIONS AND PHOTOMETRIC ARCHIVES

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Abstract. π^1 Gru is an Asymptotic Giant Branch (AGB) star of the Southern Hemisphere. Its photospheric convection has been imaged by the VLTI. It has a companion similar to the Sun, orbiting at more than 450 au. Long suspected, the large ALMA ATOMIUM programme has made it possible to directly detect a closer stellar companion that is sculpting the mass loss of the AGB star. By combining ALMA observations in continuum and molecular lines, VLT/SPHERE observations, the Hipparcos-*Gaia* proper motion anomaly, and photometric archives, we propose an orbital solution for the motion of the inner companion to π^1 Gru, named π^1 Gru C. This star is either an orange dwarf on the main sequence or a white dwarf. In either case, it must be surrounded by an accretion disc. If it is a white dwarf, at a distance of about 160 pc, it could produce the closest nova to Earth, but only erupts every 900 years. The characterisation of the π^1 Gru system represents an important step forward in better understanding the great diversity of planetary nebula geometry.

Keywords: stars: AGB and post-AGB, binaries: close, circumstellar matter, stars: imaging, stars: mass-los, stars: individual: π^1 Gru

1 Introduction

Low- and intermediate-mass stars (with initial masses lower than 8 $M_\odot$) end their lives as planetary nebulæ (PNe). Before this ultimate stage, they go through the asymptotic giant branch (AGB) phase. There, they become large (with a stellar radius $R_\star \sim 1$ au), cool (the effective temperature, $T_{\rm eff}$, is lower than 3500 K) stars. They also experience an important mass loss (from 10^{-8} to 10^{-4} $M_\odot$ yr^{-1}). The gas leaves the photosphere thanks to a combination of convective motions and large scale pulsations (Höfner & Olofsson 2018). Within the cooling gas, dust is forming through a chemical pathway that has yet to be determined. These outflowing winds are important contributors to the chemical enrichment of the Universe (Decin 2021).

PNe shows a large diversity of shapes (spherical, bipolar, hourglasses, various arcs...). Simulations from Mastrodemos & Morris (1999) showed that wind-interacting close companions could be at the origin of these structures. This hypothesis has been shown to be fully compatible with Atacama Large Millimeter/submillimeter Array (ALMA) observations of the gaseous environment of AGB stars within the large program Atomium (Decin et al. 2020; Gottlieb et al. 2022). Only a handful of these companions have been confirmed, among those are Mira (Karovska et al. 1997), L_2 Pup (Kervella et al. 2016), R Aqr (Merrill 1935; Alcolea et al. 2023), and V Hya (Planquart et al. 2024).

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π^1 Gru is a S-type AGB star from the Southern Hemisphere. It is located at 161.7 ± 11.7 pc (Gaia Collaboration et al. 2023). We refer to the primary AGB star as π^1 Gru A. It possesses a distant G0V companion, π^1 Gru B, at 2.8 arcsec (Feast 1953), which translates into 453 ± 33 au. This is too far away to allow for this companion to interact with the outflowing wind of the AGB star. Shaping of the inner wind of π^1 Gru A has long been suspected to be caused by a second close companion (Chiu et al. 2006; Sacuto et al. 2008; Mayer et al. 2014). It has been first observed by Homan et al. (2020) through ALMA band 6 continuum imaging. In Montargès et al. (2025, hereafter M25), we present an orbital solution for this companion thanks to a compilation of various observations, and discuss its nature.

2 Observations and data analysis

The observations were of diverse nature. The ALMA band 6 continuum image from 2019 shows the relative positions of the two components (Homan et al. 2020 and Fig. 1) The gas motion in the HCN $v = 0$ $J = 3-2$ and SiO $v = 0$ $J = 5 - 4$ emission lines with an angular resolution of 19 mas thanks to the extended configurations of ALMA (C43-8/C43-9) shows a Keplerian motion of the material (Fig. 1).

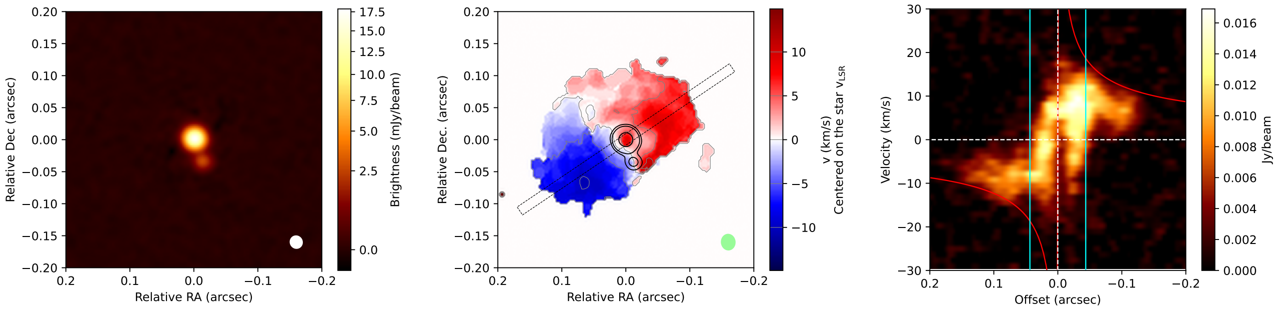

Fig. 1. ALMA observations of the π^1 Gru system with the extended configurations of the array (C43-8/C43-9). Figure from M25. *Left:* Band 6 continuum. The brightest component is the AGB star. The white ellipse in the bottom right corner shows the ALMA beam. *Center:* Moment 1 map of the SiO $v = 0$ $J = 5 - 4$ emission line. The black contours at 1, 2, and 10 mJy/beam indicate the continuum A and C components from the left panel. The dashed rectangle represents the slit used for the P-V diagram. The green ellipse in the bottom right corner shows the ALMA beam. *Right:* P-V diagram from the pseudo-slit of the center image. The red line corresponds to the Keplerian velocity field for the central mass $M_A + M_C$ derived in M25, and the cyan vertical line marks the position of the C component semi-major axis.

The proper motion anomaly (PMa) measures the difference between the *Gaia* short-term and HIPPARCOS-*Gaia* long-term proper motion. Kervella et al. (2022) performed a survey over the entire HIPPARCOS catalogue. We assume that the PMa tracks only the photocenter displacement of the primary. Using the sensitivity function of Kervella et al. (2022), we demonstrate in M25 that the PMa is entirely caused by the π^1 Gru C. It can be used to constrain the orbital solution as previously performed by Mayer et al. (2014). We use observations obtained at the Very Large Telescope (VLT) obtained with the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument (Beuzit et al. 2019). The degree of linear polarization (DoLP) obtained in the visible detected close to the photosphere, thanks to the adaptive optics, traces the light scattered by dust grains (Fig. 2). Finally, we collected archival photometric data through the VizieR service*. Three short wavelengths (360, 450, and 550 nm) were retrieved using PySSED (McDonald et al. 2024).

3 Deriving the orbital solution

The various conventions adopted to model the orbit of π^1 Gru C around π^1 Gru A are detailed in M25. We fed the relative positions of the two components in 2019, the direction of the transition between blue-shifted and red-shifted motion of the SiO $v = 0$ $J = 5-4$ moment 1 map, and the PMa (derived at the 2016 epoch) to `Ultranest` (Buchner 2021). This code derives the posterior probability distributions and Bayesian evidence using the nested sampling Monte Carlo algorithm `MLFriends` (Buchner 2016, 2019). The best orbital solution is summarized

*`http://vizier.cds.unistra.fr/vizier/sed/?submitSimbad=Photometry`

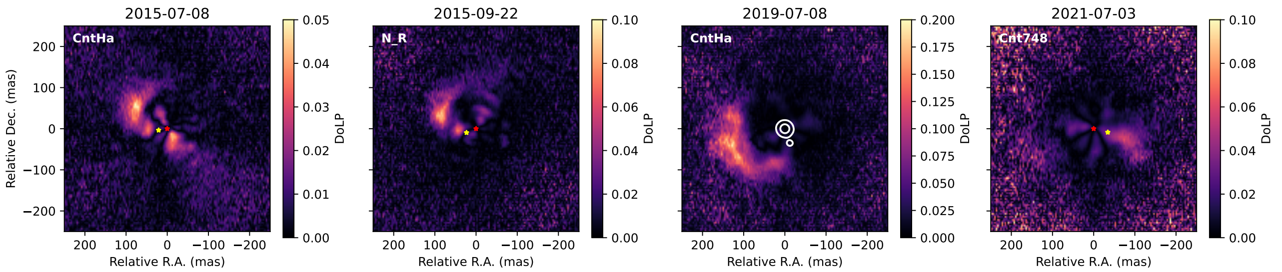

Fig. 2. Degree of linear polarization in the visible measured with SPHERE from M25. North is up, and east is to the left. The epoch is indicated above each image. The filter for each epoch is indicated in the top left corner of each image and was chosen to show the most prominent feature. Red stars indicate the position of the AGB star from the intensity frame and yellow stars indicate the C companion expected position at the epoch of the corresponding ZIMPOL observation, derived from the best orbit fit of M25. For the 2019 epoch, the 2 and 10 mJy/beam contours of the ALMA continuum image (Fig. 1) replace these symbols.

in Table 1 of M25, with figures showing how well the input observations are reproduced. The accuracy of the orbital solution is confirmed by its ability to predict a position of the C companion always at the head ot the dust tail observed with VLT/SPHERE (Fig. 2). The companion mass is $M_C = q.M_A = 0.86^{+0.22}_{-0.20}$ M$_\odot$, with an orbital period of $T = 11.0^{+1.7}_{-1.5}$ yr.

4 Discussion

According to its mass, the companion could be a K-type main sequence star (using the stellar properties[†] from Pecaut & Mamajek 2013), or a white dwarf (WD). Indeed, the photometry from the far ultraviolet to the sub-millimeter domain does not allow reaching a conclusion. In either cases, the companion should not be detected in the ALMA band 6 continuum (Fig. 1). This observation is the signature of an accretion disk around π^1 Gru C that is most probably channelling material from the AGB star through the Lagrangian point L1 of the system. The material transfer seems to be detected through masers (see Fig. 12 of Homan et al. 2020).

In this context, the excess far ultraviolet (UV) emission detected by the Galaxy Evolution Explorer (GALEX), and retrieved through VizieR, could result from various sources: chromospheres, emission of the companion, accretion disk. Using considerations from Sahai et al. (2022), we show in M25 that the UV excess in unlikely to be due to chromospheric activity and must be related to binarity: hot regions of the accretion disk, or WD companion.

5 Conclusions

Using a heterogeneous set of observations (astrometry from ALMA imaging, motion of the gas, and Hipparcos-*Gaia* PMa), fed to the Bayesian inference code `Ultranest`, we derive an orbital solution for the inner companion π^1 Gru C to the S-type AGB star π^1 Gru A. With a mass $M_C = 0.86^{+0.22}_{-0.20}$ M$_\odot$, the companion is either a K-type main sequence star or a WD. The ALMA band 6 continuum photometry shows it is surrounded by an accretion disk, channelling material from the wind of the AGB star. If the companion is a WD, and accreting 10% of the mass-loss rate of the AGB star ($\dot{M} = 7.7 \times 10^{-7}M_\odot$ yr^{-1}, Doan et al. 2017), predictions from Hachisu & Kato (2001) show it would lead to a nova explosion every 900 years.

The orbital solution derived in M25 has an orbital period of $T = 11.0^{+1.7}_{-1.5}$ yr, leading to a next periastron in April 2026. This should be the opportunity to observe the system in more details for signatures of enhanced accretion, and stronger tidal interactions (i.e., Roche lobe filling).

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[†]]`https://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt`

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