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(article starts on next page)

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An ALMA view of the post-AGB object HD 101584

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Abstract. ALMA cycles 1 and 3 observations of CO isotopologues and 1.3 mm continuum are used in a study of the circumstellar environment of the binary HD 101584, a post-AGB star and a low-mass companion that is most likely a post-common-envelope-evolution system. These data are supplemented with new information from OH maser emission. It is inferred that the large-scale circumstellar medium has a bipolar hour-glass structure, seen almost pole-on, formed by an energetic, $\geq 150\,\mathrm{km\,s^{-1}}$, jet. Significant amount of material still resides in the central region. It is proposed that the circumstellar morphology is related to an event which took place $\leq 500\,\mathrm{yr}$ ago, possibly a capture event where the companion spiralled in towards the AGB star. Several observed features remain to be explained, and may hint to a more complicated scenario.

1. Introduction

HD 101584 (V885 Cen, IRAS 11385–5517) is of spectral type A6Ia and bright at optical wavelengths ($V \approx 7\,\mathrm{mag.}$) [1, 2]. The optical and infrared characteristics suggest that it evolved from the asymptotic giant branch (AGB) at most a few hundred years ago [3]. The presence of a binary companion is inferred from photometric and radial velocity variations with a periodicity of ≈ 200 days [4, 5]. The absence of spectroscopic emission from the companion indicates that it is a low-mass main sequence star. The HST images show diffuse circumstellar dust, and a ring-like structure of radius ≈ 1.5", which is roughly centered on the star [6].

Using ^{12}CO and ^{13}CO $J = 1$–0 and 2–1 single-dish map data, [7] inferred that the highest-velocity gas (covering $\approx 300\,\mathrm{km\,s^{-1}}$) show an east-west bipolar outflow, the most blue- and red-shifted emission ≈ 5" to the W and the E, respectively. The velocity gradient is Hubble-like. The rest of the circumstellar gas was found to reside within a few arc seconds of the center. On the contrary, a double-peaked OH 1667 MHz maser line (covering $\approx 80\,\mathrm{km\,s^{-1}}$) shows a symmetry axis along a position angle PA $\approx -60°$ with the most blue- and red-shifted emission ≈ 2" to the SE and the NW, respectively [8].

We present here interpretations of the cycle 1 ^{12}CO, ^{13}CO, and C^{18}O $J = 2$–1 line and 1.3 mm continuum ALMA data on HD 101584, as well as present some indications from the new cycle 3 ALMA data (ADS/JAO.ALMA#2012.1.00248.S and #2015.1.00078.S). In addition to these lines, we have detections of line emission from SiO, CS, H$_2$S, SO, SO$_2$, OCS, H$_2$CO, and some of their isotopologues. We have also re-observed the OH 1667 MHz line, originally observed by [8] using ATCA.

2. Observations

The cycle 1 data were obtained with 35 antennas of the ALMA 12 m array in two frequency settings of Band 6, and the cycle 3 data are obtained with ≈ 40 antennas in one frequency setting. The data contains four spectral windows of 1.875 GHz width and with 3840 channels per frequency setting. The FWHM of the synthesized beam is ≈ 0.6" and ≈ 0.05" (corresponds to a resolution of 35 AU at the distance of the object) for cycles 1 and 3, respectively. The OH observations with ATCA cover the four $^2\Pi_{3/2}$ Λ-doublet lines at a resolution of ≈ 3" and $0.5 \, \mathrm{km \, s^{-1}}$ velocity resolution.

3. Results

3.1. Global characteristics

The cycle 1 1.3 mm continuum map, as well as an initial discussion of the ALMA cycle 1 data, are presented in [9]. The total flux, 112 mJy, is almost a factor of four lower than expected from the extrapolated SED model of [3], suggesting a significant loss of extended flux. There are faint structures surrounding an intense inner region, where $\approx 70\%$ of the total flux comes from inside a central 2" diameter circle. The cycle 3 data shows that a significant fraction of the flux from the central region is still unresolved at an angular scale of 0.05".

The line data points to a systemic velocity, v_{sys}, of $42 \pm 1 \, \mathrm{km \, s^{-1}}$ (LSR). The cycle 1 ALMA total fluxes are 690, 150, and 18 $\mathrm{Jy \, km \, s^{-1}}$ for the ^{12}CO, ^{13}CO, and C^{18}O $J = 2$–1 lines, respectively. Based on a detailed comparison of the ALMA global and the single-dish line profiles, [9] conclude that no flux is missed in the central $20 \, \mathrm{km \, s^{-1}}$ and at the extreme velocity peaks ($| v - v_{\mathrm{sys}} | \geq 90 \, \mathrm{km \, s^{-1}}$), while $\approx 25\%$ of the flux is missed in the intermediate velocity range. At 0.05" resolution significant amount of flux is lost, but it remains to combine these data with the 0.6" and 0.3" (to be obtained during cycle 3) data.

3.2. The morphology and kinematics

The cycle 1 ^{12}CO($J = 2$–1) channel maps are shown in Fig. 1. The morphology of the emission is very symmetric with respect to the systemic velocity. The high-velocity outflow is narrow and directed at PA $\approx 90°$. It covers almost $300 \, \mathrm{km \, s^{-1}}$ and has a Hubble-like velocity gradient. The CO line emission, and in particular that of SiO($J = 5$–4), appear to come from hot spots, presumably regions where a high-velocity jet interacts with the circumstellar medium. The ring-like emission is interpreted in the form of an hour-glass structure, probably formed as a consequence of a high-velocity jet. The inclination angle is uncertain, but it must be small, $\approx 10°$. Adopting a tilt angle of $10°$, a projected expansion length of 4" for the high-velocity flow, and an expansion velocity of $150 \, \mathrm{km \, s^{-1}}$, the age of the high-velocity outflow is estimated to be $\approx 540 \, \mathrm{yr}$. Since this structure is presumably formed by a jet, this gives an upper limit to the time since the jet was launched.

3.3. Mass, energy, and momentum estimates

An estimate of the dust mass using the flux density at 1.3 mm results in $M_{\mathrm{d}} \approx 0.007 \, M_\odot$ (with some considerable uncertainty). This suggests about a solar mass of gas in the central region, assuming a dust-to-gas ratio of 200. A simple estimate of the gas mass using the C^{18}O(2–1) line intensity results in $M_{\mathrm{g}} \approx 0.3 \, M_\odot$ (also with some considerable uncertainty). More than half of it lies in the central $20 \, \mathrm{km \, s^{-1}}$ range, and hence in the central region.

Using the C^{18}O(2–1) line, the kinetic energy and momentum of the gas accelerated to velocities $\geq 10 \, \mathrm{km \, s^{-1}}$ is estimated to be $\approx 4 \times 10^{45} \, \mathrm{erg}$ and $\approx 10^{39} \, \mathrm{g \, cm \, s^{-1}}$, respectively. The estimated momentum rate over 500 yr is $\approx 7 \times 10^{28} \, \mathrm{erg \, cm^{-1}}$, substantially higher than that available from radiation (L/c) using $L = 4000 \, L_\odot$, $\approx 5 \times 10^{26} \, \mathrm{erg \, cm^{-1}}$, a common situation for post-AGB objects [10].
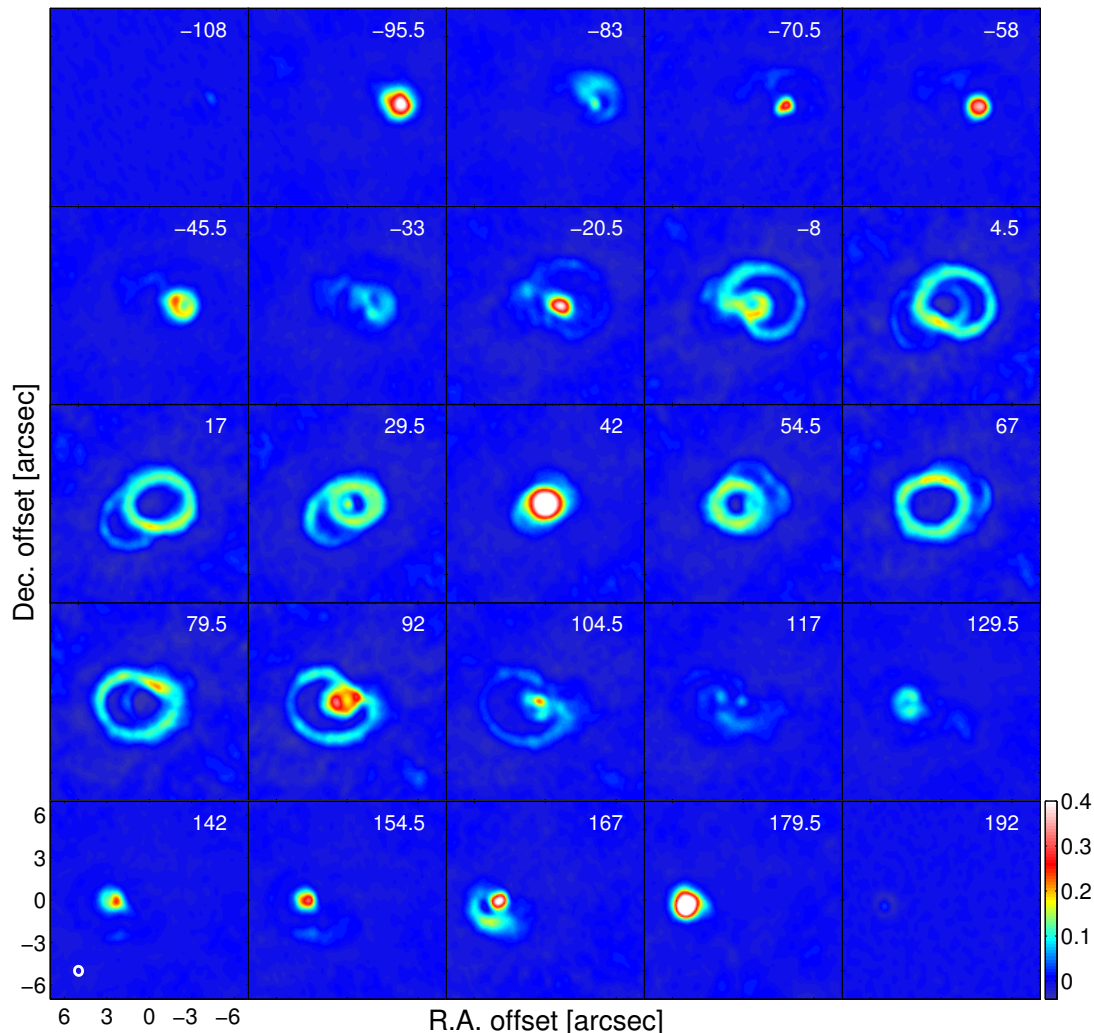
Figure 1. ALMA cycle 1 velocity-channel maps ($\Delta v = 12.5\,\mathrm{km\,s^{-1}}$) of the ^{12}CO($J = 2$–1) emission towards HD 101584 (synthesized beam in the lower left corner). The intensity scale unit is Jy beam^{-1} (noise rms $2\,\mathrm{mJy\,beam^{-1}}$).

3.4. A scenario

We propose that what we observe is the effect of a capture event in which a fair fraction of the mass of the AGB star was released, and the AGB evolution was terminated. Most of the material remains in the vicinity of the binary, presumably in the binary plane, but some of it has been accelerated up to high velocities through the action of a jet. Using information from [3] and [4] and our estimated inclination angle, we infer that the mass of the companion is $\approx 0.6\,M_\odot$ and it lies at a distance of $\approx 0.7\,\mathrm{AU}$ from the primary, suggesting a common-envelope evolution. The amount of orbital energy released is estimated to be $\approx 2 \times 10^{45}\,\mathrm{erg}$. There are considerable uncertainties in both the orbital and energy estimates, and the energy transfer efficiency of the common-envelope evolution is uncertain. Taken at face values the released orbital energy is not enough, and another mechanism must augment, or even dominate, the ejection event.

4. Remaining issues

There exists a number of features in the data that remain to be explained. We briefly identify some of them here. At $\approx \pm 30\,\mathrm{km\,s^{-1}}$ from v_{sys}, the ring-like emission breaks up into a complex structure, yet symmetric w.r.t. the center, resembling a spiral linking the ring to the centre. It is possible that this structure has its origin in the capture and jet-launching events.

In the central velocity range $|v\text{-}v_{\mathrm{sys}}| \leq 10\,\mathrm{km\,s^{-1}}$, the $\mathrm{H_2S}(2_{20}\text{-}2_{11})$ line emission, in particular, outlines an essentially circular structure of radius ≈ 1" that has a sharp outer edge, possibly a truncated disc or a torus. The cycle 3 data resolve out most of this emission, but a significant fraction of it remains in an unresolved region at 0.05" resolution.

At lower brightness level, in the velocity range $|v\text{-}v_{\mathrm{sys}}| \leq 30\,\mathrm{km\,s^{-1}}$, there is evidence for another bipolar structure. Its velocity gradient is opposite to that of the CO outflow and the position angle is different (PA $\approx -45°$).

We have re-observed the OH $^2\Pi_{3/2}$ Λ-doublet lines (Vlemmings et al., in prep). The results are peculiar. We confirm the spatial structure found by [8] with a symmetry axis along PA $\approx -60°$ and a velocity gradient opposite to that of the CO outflow. The most reasonable explanation for this is that the maser emission comes from the walls of the hour-glass structure where the amplification is highest along the line of sight. Curiously, only the 1667 MHz line is detected, and its flux has not varied on a time scale of 25 yr (the S/N ratio of the data is high at both epochs). The line shows no polarisation, and the emission avoids the inner circular structure discussed above.

References

[1] Sivarani T, Parthasarathy M, García-Lario P, Manchado A and Pottasch S R 1999 *Astron. Astrophys. Suppl. Series* **137** 505–519
[2] Kipper T 2005 *Baltic Astronomy* **14** 223–233
[3] Bakker E J, Lamers H J G L M, Waters L B F M, Waelkens C, Trams N R and Van Winckel H 1996 *Astron. Astrophys.* **307** 869–890
[4] Bakker E J, Lamers H J G L M, Waters L B F M and Waelkens C 1996 *Astron. Astrophys.* **310** 861–871
[5] Díaz F, Hearnshaw J, Rosenzweig P, Guzman E, Sivarani T and Parthasarathy M 2007 *IAU Symposium* vol 240 ed Hartkopf W I, Harmanec P and Guinan E F p 127
[6] Sahai R, Morris M, Sánchez Contreras C and Claussen M 2007 *Astron. J.* **134** 2200–2225
[7] Olofsson H and Nyman L Å 1999 *Astron. Astrophys.* **347** 194–202
[8] te Lintel Hekkert P T L, Chapman J M and Zijlstra A A 1992 *Astrophys. J. Lett.* **390** L23–L26
[9] Olofsson H, Vlemmings W H T, Maercker M, Humphreys E M L, Lindqvist M, Nyman L and Ramstedt S 2015 *Astron. Astrophys.* **576** L15
[10] Bujarrabal V, Castro-Carrizo A, Alcolea J and Sánchez Contreras C 2001 *Astron. Astrophys.* **377** 868–897