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The Nearby Evolved Star L_2 Puppis as a Portrait of the Future Solar System

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The impact of the dramatic terminal phases of the lives of Sun-like stars on their orbiting planets is currently uncertain. Observations with NAOS CONICA and SPHERE/ZIMPOL in 2014–2015 have revealed that the nearby red giant star L_2 Puppis is surrounded by an almost edge-on disc of dust and gas. We have observed several remarkable features in L_2 Pup: plumes, spirals, and a secondary source (L_2 Pup B) which is embedded in the disc at a projected separation of 2 au. ALMA observations have allowed us to measure a mass of $0.659 \pm 0.043\ M_\odot$ for the central star. This indicates that L_2 Pup is a close analogue of the future Sun at an age of 10 Gyr. We also estimate the mass of L_2 Pup B to be $12 \pm 16\ M_{Jup}$, implying that it is likely a planet or a brown dwarf. L_2 Pup therefore offers us a remarkable preview of the distant future of our Solar System.

Five billion years from now, the Sun will grow into a red giant star, more than a hundred times larger than its current size. It will also experience intense mass loss in the form of a stellar wind. The end product of its evolution, seven billion years from now, will be a white dwarf star — about the size of the Earth and extremely dense (density ~ 5×10^6 g cm^{-3}).

This metamorphosis will have a dramatic impact on the planets of the Solar System, including the Earth. While Mercury and Venus will be engulfed by the giant star and destroyed, the fate of the Earth is still uncertain. The brightening of the Sun will make the Earth hostile to life in about one billion years. As an aside, assuming that life appeared on Earth 3.7 billion years ago (Ohtomo et al., 2014), this implies that life on Earth has already exhausted ~ 80 % of its development time. However, we do not know whether our then-lifeless rock will be destroyed by the burgeoning Sun, or survive in orbit around the white dwarf.

To address the question of the impact of the final phases of stellar evolution on planetary systems, hydrodynamical models have been proposed (see, for example, the recent review by Veras, 2016). But observational constraints on the star-planet interaction models are still rare. Planets of asymptotic giant branch (AGB) stars are embedded in complex circumstellar envelopes and are vastly outshone by their parent star. The observation of this critical phase of planetary system evolution thus presents considerable, and as yet unsolved, technical challenges. As a result, there currently exists only indirect evidence of the presence of planets orbiting AGB stars (Wiesemeyer et al., 2009). In addition, the masses of AGB stars are notoriously difficult to estimate from observations, preventing accurate determinations of their evolutionary states.

The discovery of the disc of L_2 Puppis with NACO

At a distance of only 64 pc (van Leeuwen, 2007), L_2 Pup is the second nearest AGB star after R Doradus. In addition to its regular pulsation with a period of 141 days and an amplitude of ~ 2 magnitudes in the visible, L_2 Pup has experienced a remarkable, slow photometric dimming over the last decades by more than 2 magnitudes in the visible. Bedding et al. (2002) interpreted this long-term dimming as the consequence of the obscuration of the star by circumstellar dust.

We observed L_2 Pup on the night of 21 March 2013 with NAOS CONICA (NACO) as part of a survey aimed at imaging the circumstellar environments of selected nearby evolved stars (Kervella et al., 2014a). We used 12 narrow-band filters spread in wavelength between 1.04 and 4.05 μm. We processed the image cubes using a serendipitous imaging approach (also known as "Lucky imaging"). Using 8400 very short exposures (8 milliseconds each) in each filter, we were able to freeze the residual atmospheric perturbations. After selecting the best 50 % of the series of images, we recentred and averaged them to obtain the 12 final, diffraction-limited images. They were finally deconvolved using a point spread function (PSF) calibrator star. The morphology of L_2 Pup in these images (Figure 1) was very surprising. From a seemingly double source between 1.0 and 1.3 μm, the star became a single source with an east-west extension at 2.1 μm, and exhibited a spectacular spiral loop at 4.0 μm!

We proposed (Kervella et al., 2014a) that L_2 Pup is surrounded by an equator-on dust disc. In this framework, the opacity and thermal emission of the dust change dramatically between 1 and 4 μm, providing a natural explanation for the changing aspect of the circumstellar envelope. At 1 μm, the dust efficiently scatters the light from the star, which therefore appears masked behind the dust band. The dust becomes progressively more transparent as the wavelength increases. At 2.2 μm, the thermal emission from the hot inner rim of the disc is observable through the dust. A colour composite image of L_2 Pup in the near infrared is presented in Figure 2. It shows the intrinsically red colour of the equatorial dust band due to the stronger scattering at shorter wavelengths.

Our hypothesis of an edge-on dust disc was initially relatively fragile. But a 3D

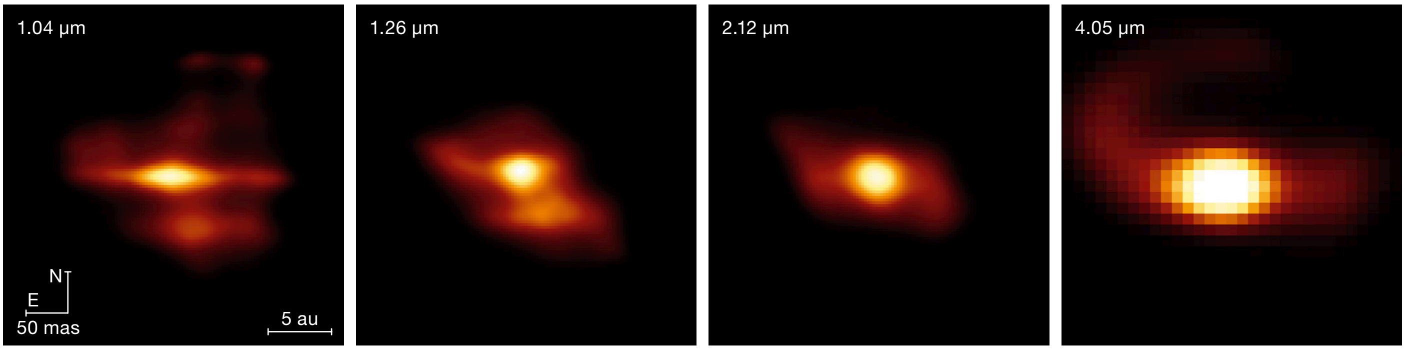

Figure 1. NACO deconvolved images of L_2 Puppis at a range of wavelengths from 1 to 4 µm. From Kervella et al. (2014a).

radiative transfer model using the RADMC-3D code (Dullemond, 2012) confirmed that this interpretation of the NACO images is consistent with the observations, reproducing convincingly both the spectral energy distribution and the morphology of the disc (Kervella et al., 2014a).

Stunning features from SPHERE polarimetric imaging

We took advantage of the Science Verification of the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) to observe L_2 Pup in visible light imaging polarimetry with the Zurich IMaging POLarimeter (ZIMPOL) camera (Kervella et al., 2015). The observation was carried out on the night of 7 December 2014. The combination of the high brightness of L_2 Pup and good seeing resulted in spectacular image quality. The Strehl ratio produced by the SPHERE adaptive optics reached more than 40 % at a wavelength of 646 nm for an atmospheric seeing of ~ 0.7 arcseconds. In one hour of telescope time, the observation of L_2 Pup and a PSF calibrator star (β Col) confirmed unambiguously our hypothesis of an edge-on circumstellar dust disc (Figure 3, upper left). In addition to revealing the overall geometry of the dust disc — as relatively thin, moderately flared and extending to at least 13 au — the collected images in the *V*- and *R*-bands showed remarkable structures in the envelope of L_2 Pup (Figure 3, upper right). We detect several spiral arms in the nebula, as well as two intriguing thin plumes. The central source appeared significantly elongated, and the subtraction of the central star revealed the presence of a second source, L_2 Pup B, at a separation of 32 milliarcseconds (mas) from the star to the west (Figure 3).

The polarimetric imaging capability of ZIMPOL has been particularly important in revealing the structure of the envelope of L_2 Pup (Figure 3, right). As the star is embedded in a dust-rich environment, the scattering of the starlight by the dust grains induces a linear polarisation of the photons. For small dust grains, the degree of linear polarisation p_L is a smooth function of the scattering angle, with a maximum p_L value obtained for ~ 90° scattering. Knowing the degree of polarisation therefore allowed us to estimate the scattering angle θ over the envelope. Knowing θ and the projected position of the dust relative to the star in the image, then allowed us to retrieve the 3D distribution of the scattering material. This polarimetric tomography technique was previously employed, for example, by Sparks et al. (2008) and Kervella et al. (2014b).

Apart from the scattered light on the disc's upper and lower surfaces, a very striking signature in the p_L map (Figure 3, right panel) comes from the two plumes emerging from the disc. Their high degree of polarisation (~ 30 %) indicates that they contain dust and that the scattering angle is large at $\theta \sim 50°$. These thin plumes, whose transverse diameter is smaller than 1 au, have a length of more than 10 au. The large scattering angle implies that they emerge from the disc close to perpendicular, and propagate in the northern cone cavity that is otherwise essentially devoid of dust.

The map of the degree of polarisation also shows well-defined local maxima at a radius of 6 au, symmetrically east and west of the star. The degree of polarisation reached at these positions is very high, up to p_L = 60 % in the *R*-band, corresponding to scattering of the light at

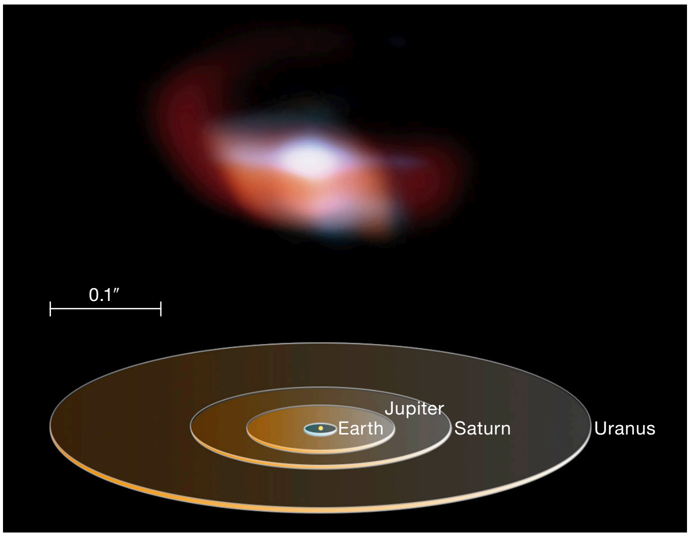

Figure 2. Colour composite image of L_2 Pup at infrared wavelengths assembled from NACO observations. The orbits of four Solar System planets are represented in the lower part of the figure to give the overall scale of the L_2 Pup disc.

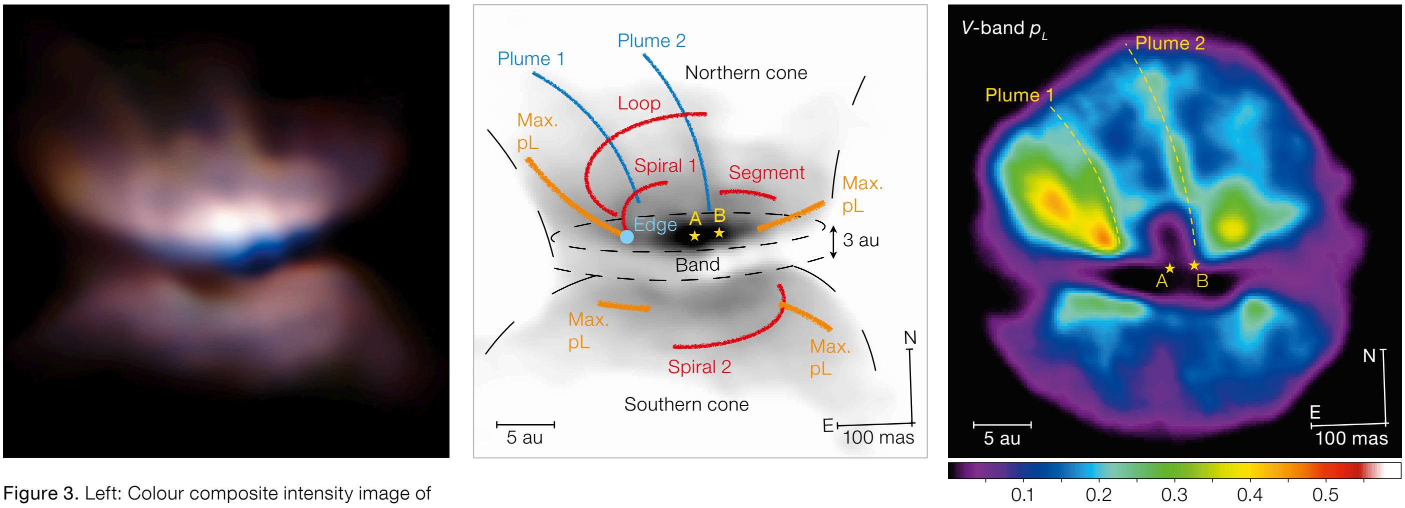

Figure 3. Left: Colour composite intensity image of L_2 Pup assembled from SPHERE/ZIMPOL *V*- and *R*-band images. Middle: nomenclature of the observed structures in the circumstellar environment of L_2 Pup. Right: degree of linear polarisation, p_L, of L_2 Pup measured with ZIMPOL. The two plumes sketched in the middle panel are also indicated.

~ 90°. We interpret these maxima as the scattering of the starlight by the inner rim of the dust disc, that is, the minimum radius at which the dust is present with a high density. The existence of an inner rim is due to the very high brightness of the central star (2000 times Solar luminosity), which would lead to the sublimation of any dust grains closer to the star (Homan et al., 2017).

An analogue of the future Sun, 5 billion years from now

L_2 Puppis was observed with the Atacama Large Millimeter/submillimeter Array (ALMA) in Cycle 3 in Band 7 (340 GHz, wavelength ~ 0.8 mm) using the longest available configuration of the interferometer with baseline lengths of up to 16 km (Kervella et al., 2016). This configuration provided the highest possible angular resolution currently achievable by ALMA, with a beam size of only 15 mas. It is interesting to remark that this resolution matches very well that of SPHERE/ZIMPOL in the visible (16–20 mas). We selected velocity resolutions of 100 to 400 m s^{-1} for the molecular line spectral windows, corresponding to a spectral resolution of R ~ 1 000 000. This powerful combination of very high spatial and spectral resolution is permitted by the high brightness of L_2 Pup and the high sensitivity of the array. We detected several molecular emission lines in the selected spectral windows, from ^{12}CO, ^{13}CO, H_2O, SO_2, ^{29}SiO, SiS and SO. We focus our discussion here on the $^{29}SiO(\nu = 0, J = 8–7)$ molecular line at a rest frequency of 342.981 GHz. The continuum subtracted integrated intensity in this line is presented in Figure 4 (upper left panel).

Our analysis is based on the position-velocity diagram (PVD) formalism. The PVD is computed by integrating the ALMA spectro-imaging data cube over a 0.02 arcsecond wide pseudo-slit aligned with the disc plane (east-west direction). The resulting diagram (Figure 4, lower left) shows the velocity of the molecular gas as a function of the position along the slit. Thanks to the excellent signal-to-noise ratio of the ALMA data, we can measure very accurately the orbital motion of the gas in the disc plane, and more precisely the maximum velocity of the gas as a function of the separation from the centre of rotation. We determined that this maximum velocity profile closely follows Kepler's law up to a radius of 5–6 au from the star. Figure 4 (lower left and right panels) clearly shows the two rotation regimes: Keplerian within the inner 5 au (that is, $v \sim R^{-1/2}$), and sub-Keplerian beyond 6 au ($v \sim R^{-0.85}$). A smooth transition is observed between 5 and 6 au. From the Keplerian motion of the inner 5 au, we could determine with very high accuracy (± 6.6 %) the present mass of the AGB star, finding that it is two-thirds the mass of our Sun (0.653 ± 0.043 $M_\odot$). It is remarkable that the error budget of this measurement is fully dominated by the uncertainty in the parallax of L_2 Pup, as the error from the ALMA data fit is only ± 1.7 %.

The coincidence of the radius where the rotation becomes sub-Keplerian and the radius of the inner rim (maximum of p_L, Figure 3) of the dust disc observed with ZIMPOL indicates that the rotation of the gas becomes sub-Keplerian precisely when it enters the dust disc. This very interesting effect is likely due to the viscous coupling of the gas and dust within the disc. The dust is sensitive to the strong radiative pressure from the central star, and is thus subject to a reduced effective gravity resulting in a slower orbital velocity than the gas. As the internal cavity within 5 au contains very little dust, the gas rotates freely there. But when it reaches the inner rim of the dust disc, it is slowed down by friction with the dust, which explains its sub-Keplerian rotation.

From the measured mass of L_2 Pup, stellar evolution models predict that its age is ~ 10 Gyr. The mass, radius and pulsation period are all consistent with a main sequence mass identical to that of the Sun. The missing third of a solar mass has been lost by L_2 Pup during its evolution. The extraordinary coincidence of having a Sun-like AGB star in the close vicinity of the Sun thus provides us with a privileged preview of the very distant future of our own star.

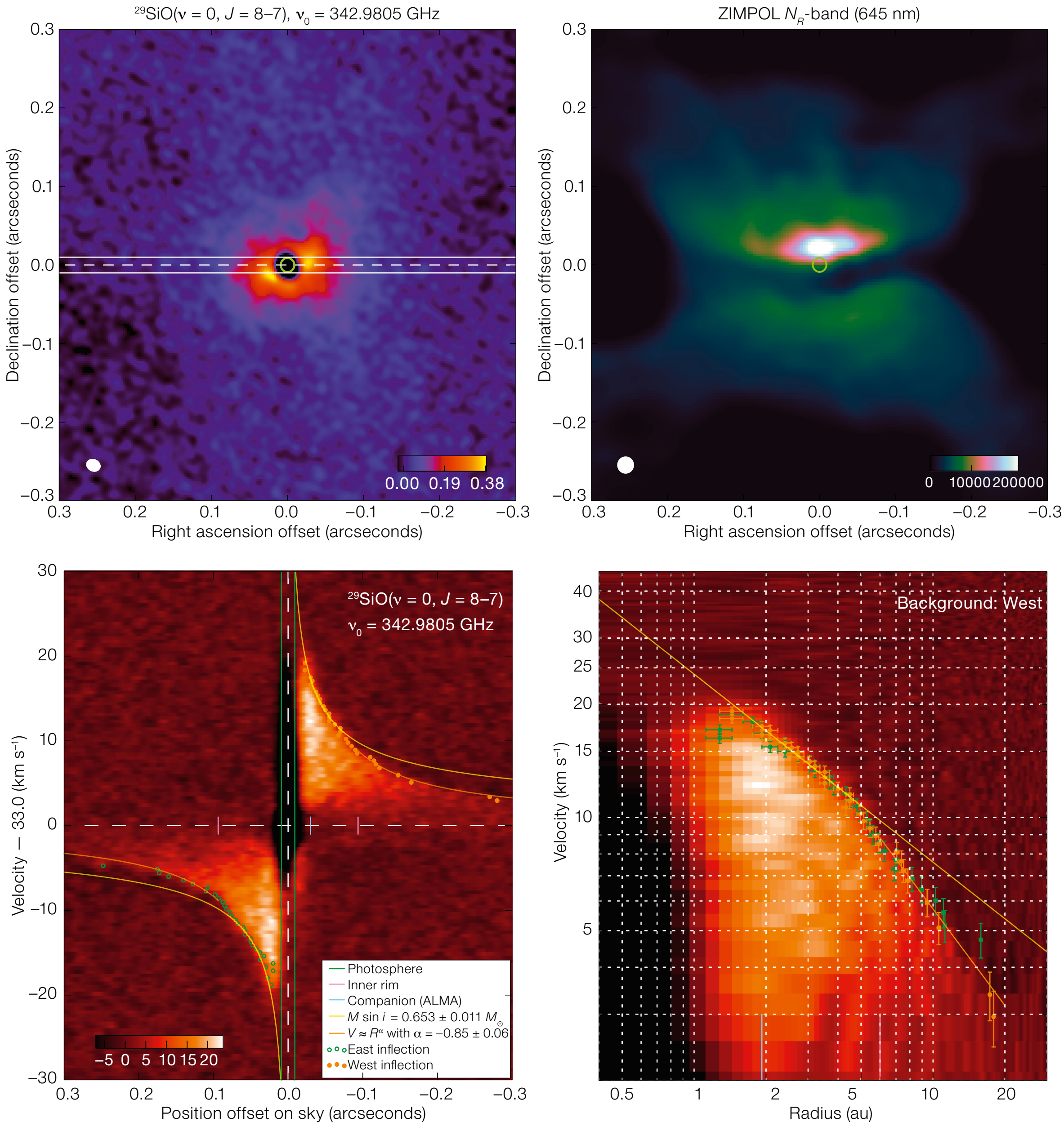

Figure 4. Upper left: ALMA integrated intensity image in the ^{29}SiO ($v = 0$, $J = 8$–7) molecular line. The dark spot on the star is caused by gas absorption along the line of sight. Upper right: ZIMPOL image in R-band at the same scale. Lower left: Position-velocity diagram (PVD) constructed from the east-west pseudo-slit displayed in the upper left panel. Lower right: PVD in logarithmic velocity and radius scales to show the different power law regimes of the velocity profile. The domain and positions of various features are indicated according to the legend. The envelope of the maximum velocity profile defines the central star mass, and the inflection points corresponding to the inner edge of the dust disc are shown for the east and west edges.

A candidate planet orbiting in the disc of L_2 Pup

The ALMA data in the continuum showed the presence of an excess of emission in the western wing of the disc (Figure 5), contributing 1.3 % of the central star's flux. This emission coincides almost perfectly with the secondary source L_2 Pup B detected with SPHERE/ZIMPOL one year before the ALMA observations. This continuum emission could be produced by a dusty envelope or by an accretion disc surrounding L_2 Pup B.

We estimated the mass of the companion by comparing the position of the centre of rotation of the molecular disc and the position of the continuum emission peak. The centre of rotation of the molecular disc is very well defined from the ALMA PVD (Figure 4), and it corresponds to the centre of gravity of the mass enclosed by the disc. The continuum emission peak provides the position of the AGB star. We determined that the two points are coincident within 0.55 ± 0.75 mas. As we know the mass of the central star and the current separation of L_2 Pup B, we can convert this offset into a mass of 12 ± 16 M_{Jup} for this companion, which corresponds to a planet or a low mass brown dwarf.

We also detected excess emission in the PVD of the molecular lines ($v = 0$, $J = 3$–2) of ^{12}CO and ^{13}CO at the location of the candidate planet, at a velocity of 12 km s^{-1} (Figure 6). We propose that this emission comes from the extended molecular envelope accreted by L_2 Pup B from the wind of the AGB star. This measured velocity is consistent with the line-of-sight projection of the velocity vector of a planet in circular Keplerian revolution at a radius of 2.4 au from a 0.65 $M_\odot$ central star, that is, with an orbital period of 5 years.

This candidate planet is, to our knowledge, the first planet whose emission is detected with ALMA. We also observe a signature at 6 au in the PVD that may be linked to the plume #1 detected in the ZIMPOL images (yellow arrow in Figure 6).

The persistence of L_2 Pup B between the ZIMPOL and ALMA observations is an indication that this is a compact object rather than a coreless aggregate of gas and dust. The strong Keplerian shear and the radiation pressure would very quickly blow such a clump into the dust disc (R > 6 au). Moreover, the presence of a plume originating from the position of L_2 Pup B and launched perpendicular to the dust disc plane is an indication that accretion is occurring. Such a possibility is plausible, as the Roche lobe of a planet embedded in the dust- and gas-rich environment surrounding L_2 Pup will sweep up a considerable volume and therefore accrete a significant quantity of material.

The presence of a candidate planet orbiting L_2 Pup provides a remarkable test case to observe the interactions between the evolved star's wind and a low-mass companion. Figure 7 shows our hypothesised structure of the detected features in the L_2 Pup system. We propose that the large dust loop observed at 4 µm in the NACO images is created by dust condensation in the shadow of L_2 Pup B. The highly collimated plume is ejected from a putative accretion disc surrounding the planet.

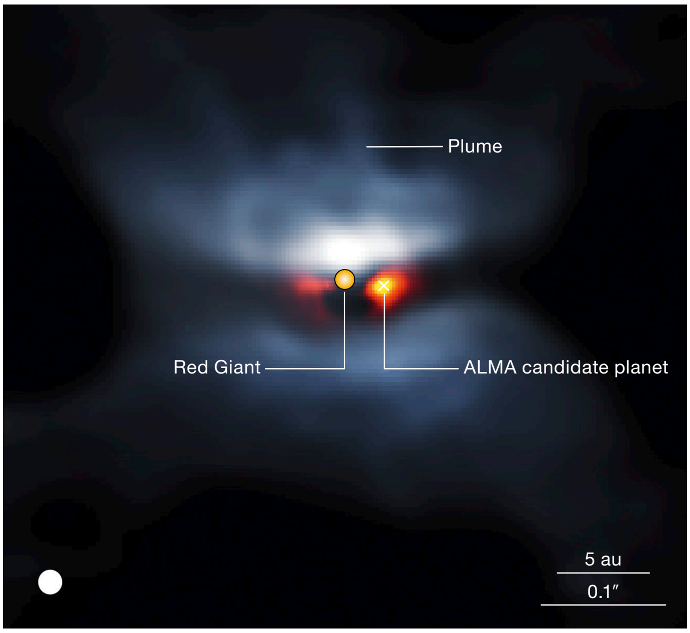

Figure 5. Composite view of L_2 Pup in visible light (ZIMPOL image in the *R*-band, blue colours) and ALMA continuum (orange colours). The central star light has been subtracted from the ALMA image to better show the companion object. The size of the star's photosphere is represented to scale. The white circle in the bottom left corner represents the resolution of the image (beam size).

Compared to other AGB stars observed at high angular resolution, the morphology of the circumstellar disc of L_2 Pup stands out as remarkably singular. R Dor (Khouri et al., 2016) and W Hya (Ohnaka et al., 2016), although they are at a comparable stage of their evolution to L_2 Pup, do not host axially symmetric circumstellar structures but irregular, mostly spherical envelopes. We suggest that the axial geometry of the envelope of L_2 Pup is due to the presence of its companion. Its biconical shape is also strongly evocative of the bipolar planetary nebulae, and L_2 Pup may hold the key to demonstrating the link between binarity (including sub-stellar companions) and bipolarity of planetary nebulae.

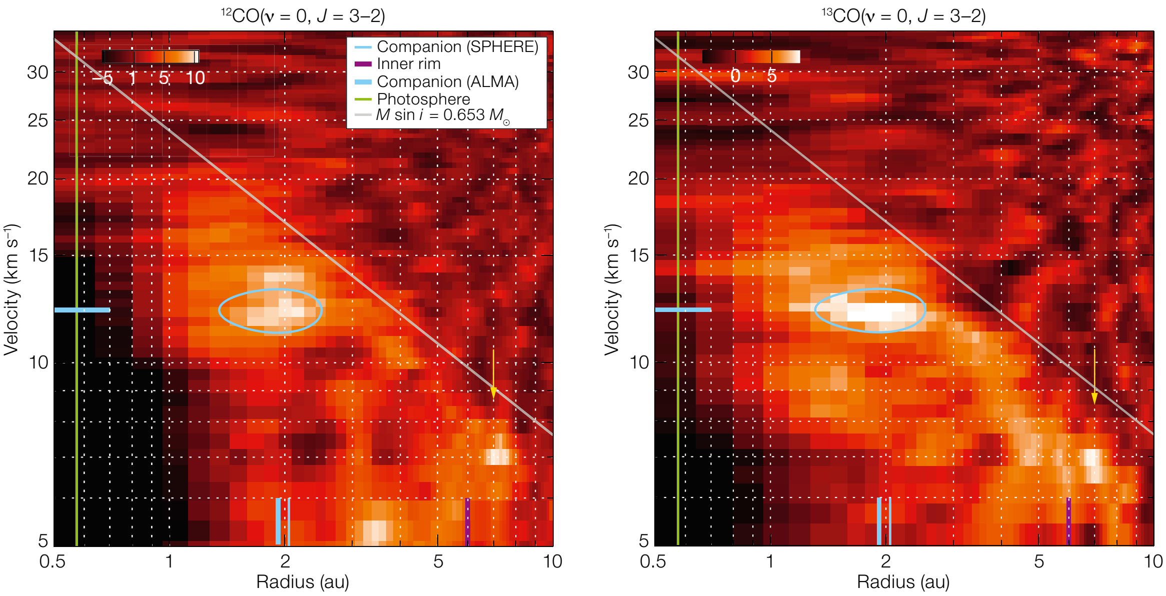

Figure 6. Emission of L_2 Pup B in two CO molecular isotopologue lines (^{12}CO to the left and ^{13}CO to the right) in position-velocity diagrams with logarithmic velocity and radius scales. The emission from the east wing of the disc has been subtracted. The positions of various key features are indicated in the legend, cf. Figure 4. The yellow arrow marks a feature tentatively ascribed to the Plume 1 (cf., Figure 3).

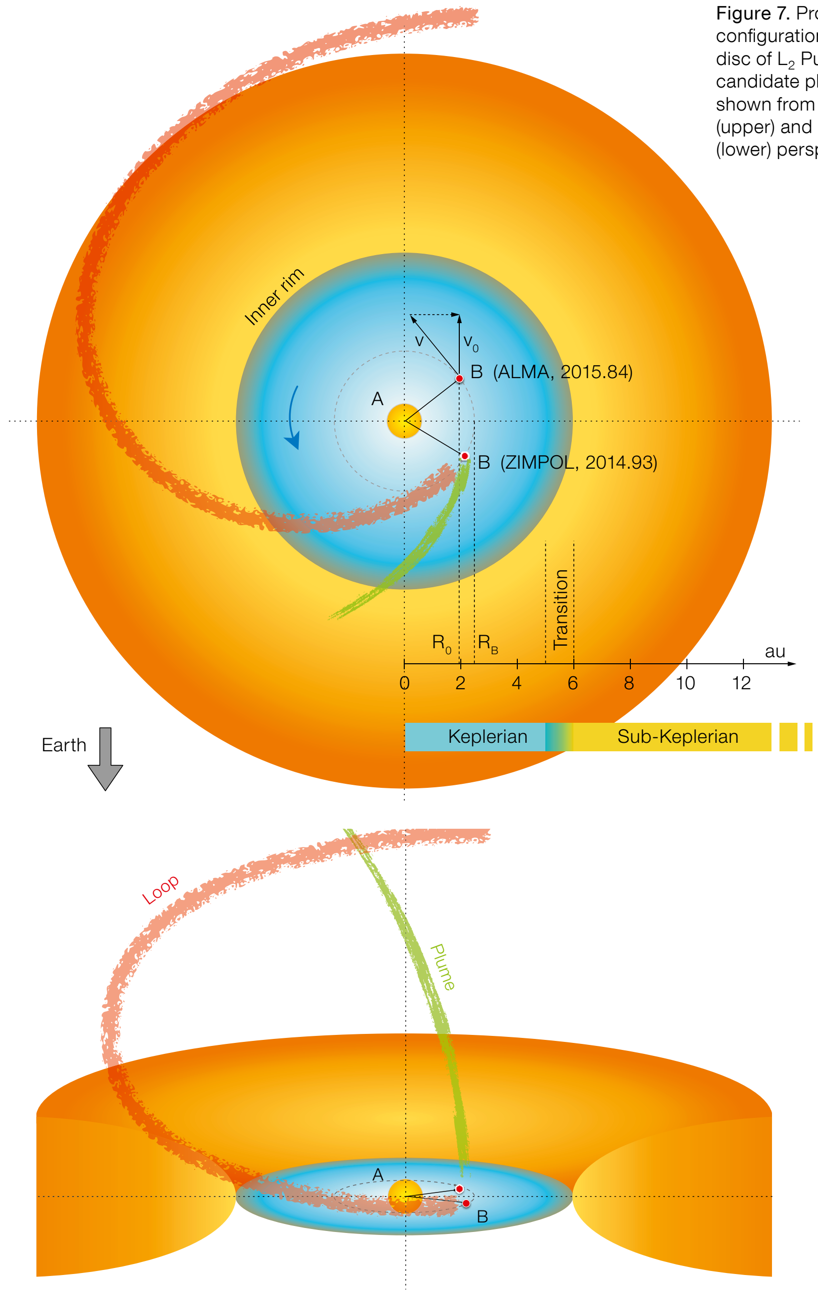

Figure 7. Proposed configuration of the dust disc of L_2 Pup and its candidate planet is shown from a pole-on (upper) and equator-on (lower) perspective.

Prospects for future observations

The longest ALMA baselines of 16 km combined with the shortest wavelengths (Bands 9 and 10) will soon give access to an angular resolution ~ 6 mas. Assuming a mass of 12 M_{Jup} for L_2 Pup B, its Roche lobe has a diameter of about 0.6 au, or 10 mas. This means that it will be possible to resolve the putative accretion disc around L_2 Pup B (particularly in CO molecular emission) and directly determine its mass from its Keplerian velocity amplitude.

Optical interferometry with the Very Large Telescope Interferometer (VLTI) commissioning instrument VINCI has been used by Kervella et al. (2014a) to measure the angular diameter of the central AGB star of L_2 Pup. The VLTI second-generation instruments GRAVITY (Eisenhauer et al., 2011) and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE: Lopez et al., 2014; Millour et al., 2016) will enable milliarcsecond spectro-imaging of the photosphere and structures present around the star (plumes, loop, companion). We plan to develop the observations of L_2 Pup with these new instruments to monitor its pulsation cycle and its close-in molecular envelope (the molsphere, located within 1–3 stellar radii). The interaction of the molsphere with the orbiting planet L_2 Pup B may be an important ingredient in the accretion of gas.

The forthcoming Extremely Large Telescope (ELT) will provide an angular resolution of 60 mas at 10 μm, 12 mas at 2.2 μm and 3 mas in the visible. Observing L_2 Pup with the ELT will be easy: it is very bright (m_V ~ 7.5, m_K ~ −2), and thus provides an excellent natural guide star for adaptive optics wavefront sensing. With its 0.4 arcsecond extension, the circumstellar disc is easily resolved spatially, and high-resolution spectroscopy will provide a Doppler map of the molecular envelope. The interactions of the candidate planet with the dust disc and the wind of the central star will thus be observable in very fine detail, revealing the accretion of a stellar wind onto a planetary-mass object.

As an older sibling of our Sun, and thanks to the powerful existing and foreseen high angular resolution instrumentation available at the VLT and ALMA, L_2 Pup will undoubtedly continue to surprise us in the coming years with key discoveries pertinent to the distant future of the Solar System.

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