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The porous envelope and circumstellar wind matter of the closest carbon star, CW Leonis

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Abstract. Recent abrupt changes of CW Leonis may indicate that we are witnessing the moment that the central carbon star is evolving off the Asymptotic Giant Branch (AGB) and entering into the pre-planetary nebula (PPN) phase. The recent appearance of a red compact peak at the predicted stellar position is possibly an unveiling event of the star, and the radial beams emerging from the stellar position resemble the feature of the PPN Egg Nebula. The increase of light curve over two decades is also extraordinary, and it is possibly related to the phase transition. Decadal-period variations are further found in the residuals of light curves, in the relative brightness of radial beams, and in the extended halo brightness distribution. Further monitoring of the recent dramatic and decadal-scale changes of this most well-known carbon star CW Leonis at the tip of AGB is still highly essential, and will help us gain a more concrete understanding on the conditions for transition between the late stellar evolutionary phases.

Keywords. stars: AGB and post-AGB, (stars:) binaries: general, stars: carbon, (stars:) circumstellar matter, stars: evolution, stars: individual (CW Leonis), stars: late-type, stars: mass loss, stars: winds, outflows

1. Introduction

Many pre-planetary nebulae (PPN) consist of newly-formed inner bipolar/multipolar lobes and outer spirals/rings/arcs that are the fossil records of stellar wind matter accumulated during the asymptotic giant branch (AGB) phase. The coexistence of two such morphologically distinct circumstellar structures is a mystery; however, it is widely believed that binaries play a key role. The most direct clue to resolving the mystery of the shape transition along stellar phase evolution may be offered by catching the moment when an AGB star is evolving off the current phase toward the PPN phase. Recent dramatic changes of CW Leonis likely indicate that we are witnessing the moment of transition between these late stellar evolutionary phases.

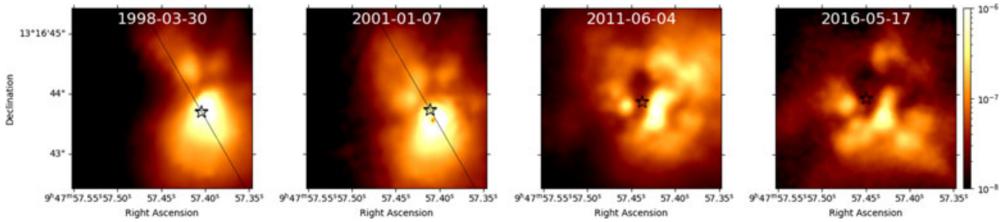

Figure 1. Temporal change of brightness in the central 1.5 arcsec region of CW Leonis. The star symbol indicates the proper-motion-corrected position of the star at each epoch, denoted at the top of each panel. The bipolar-like structure (black line) before 2011, which had likely given a misleading impression for the origin and evolutionary phase of CW Leonis, disappeared in the 2011 and 2016 epochs. From left to right, the Hubble Space Telescope images are taken with the F606W filter ($\sim 0.6\,\mu$m) at the epochs of 1998-03-30 (Prop. ID: 6856, PI: J. Trauger), 2001-01-07 (Prop. ID: 8601, PI: P. Seitzer), 2011-06-04 (Prop. ID: 12205, PI: T. Ueta), and 2016-05-17 (Prop. ID: 14501, PI: H. Kim).

2. Previous Views on CW Leonis

CW Leonis is the closest (distance of about 123 pc; Groenewegen et al. 2012) and the most well-studied carbon-rich AGB star (or carbon star). Multi-wavelength observations suggest that CW Leonis is likely a binary system (e.g., Jeffers et al. 2014; Decin et al. 2015). Its non-concentric ring-like pattern over 200 arcsec is remarkable (Mauron & Huggins 2000), which can be modeled by a spiral-shell structure introduced by an eccentric orbit binary at the center (e.g., Cernicharo et al. 2015). However, neither the carbon star nor the companion has been identified because of obscuration by the dense circumstellar matter ejected from this extreme carbon star at the tip of AGB.

Several near-infrared observations were executed with adaptive optics and speckle interferometry in 1995–2003 (Tuthill et al. 2000; Osterbart et al. 2000; Weigelt et al. 2002; Murakawa et al. 2005) achieving high-resolutions (< 0.1 arcsec) but losing stellar positional information at the cost of field sizes; several clumps were revealed, but their relationship with the central star was unclear. The vigorous debate about which clump corresponds to the carbon star ended in vain through a monitoring study over 2000–2008 showing that the clumps faded out around 2005 (Stewart et al. 2016).

In the optical, before 2011, the core region exhibited an extended bipolar nebula without any distinct point source (Haniff & Buscher 1998; Skinner et al. 1998; Leão et al. 2006), from which this object was thought to have an invisible star residing in a dusty disk lying perpendicular to the bipolar structure. The bipolar-like structure, however, disappeared in the latest Hubble Space Telescope images taken in 2011 and 2016 (Kim et al. 2015, 2021), suggesting a completely different view for CW Leonis.

3. Recent Dramatic Changes and Porous Envelope Scenario

Surprisingly, the latest optical images of CW Leonis, taken using Hubble Space Telescope, in 2011 and 2016 revealed dramatic changes in the core region of the circumstellar envelope from those taken about 10-year earlier in 1998 and 2001 (Figure 1). Besides the disappearance of the long-believed bipolar-like nebula, several important features are identified and become evidences for a porous envelope of the central star (Kim et al. 2021).

In contrast to its absence at the previous epochs, a local brightness peak appears exactly at the expected stellar position (Figure 2, top middle) and it is identified as the reddest spot in the color map (Figure 2, top left). It is compact; its full width at half maximum above the adjacent diffuse emission is slightly larger than the standard point-spread function. This red compact spot at a local peak is interpreted as the direct starlight,

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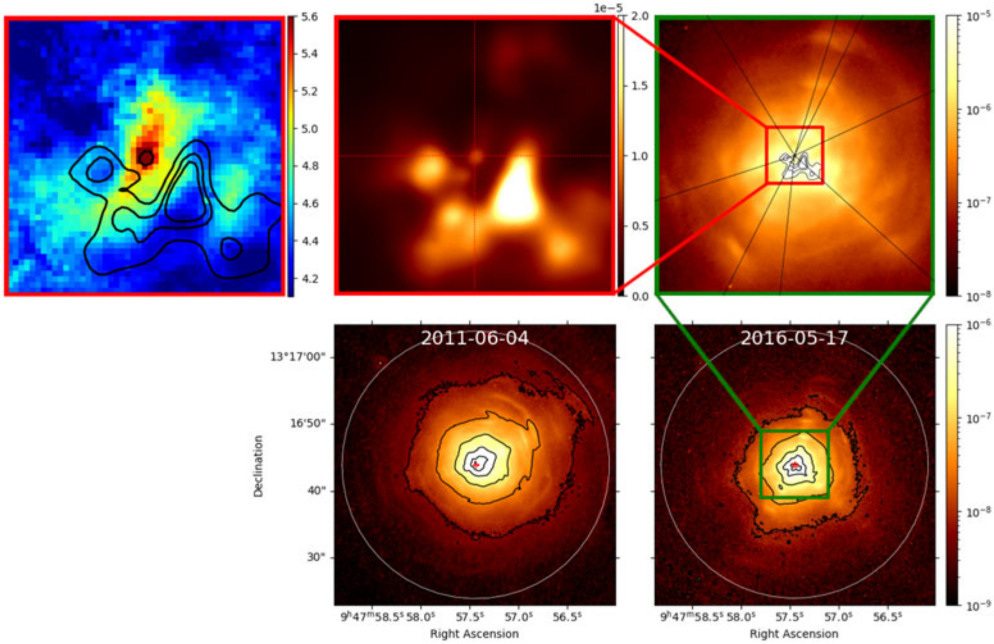

Figure 2. The Hubble Space Telescope image of CW Leonis taken with the F814W filter ($\sim 0.8\,\mu$m) in 2016 (bottom right), compared to the 2011 epoch image (bottom left). The radial beams and multiple rings appearing prominent in the central 5 arcsec region are the intriguing features (top right). The color map for central 1 arcsec region shows the reddest spot coincides with the stellar position, marked by black contours of the F814W brightness (top left) same as the image in the top middle panel. The color bars range the F814W brightness in logarithmic scales, but for the color map in the top left panel being in linear scales for the magnitude difference between the F606W and F814W images.

escaping through one of the gaps in the clumpy envelopes shrouding the star. This radial beam may pulsate around the line of sight with a small angle and be coincidentally aligned with the line of sight at the observed epoch in 2016.

The outer part of the observed image exhibits eight straight lines of brightness that are radially stretched from the central star (Figure 2, top right). In the context of the porous envelope scenario, these searchlight beams indicate the trajectories of starlight penetrating the holes in the inner envelopes, along which adjacent dust particles in the circumstellar envelopes are illuminated. Any other interpretation for their origin is precluded because of the straightness of these beams regardless of the considerably fast stellar proper motion.

The extended halo brightness distribution becomes fairly symmetric about the central star in the 2016 image, compared to the elongated distribution to the northwest in the 2011 image (Figure 2, bottom panels). This change is again beyond the scope of dynamics of matter that would require a very long time to move the whole halo with an extremely large extent. It is speculated that one of the radial beams, that is related to the new emergence of central red compact brightness peak, alters its angle toward the line of sight in 2016 from a slightly misaligned angle pointing toward the northwestern direction in 2011, explaining the redistribution of the halo brightness.

The radial beams appearing in the plane of the sky do not seem to shift their positions much with time (Figure 3). Their position angles with respect to the predicted stellar positions at the individual epochs are almost fixed. Therefore, it is natural that we assume the precession angle for the radial beam relevant to the extended brightness

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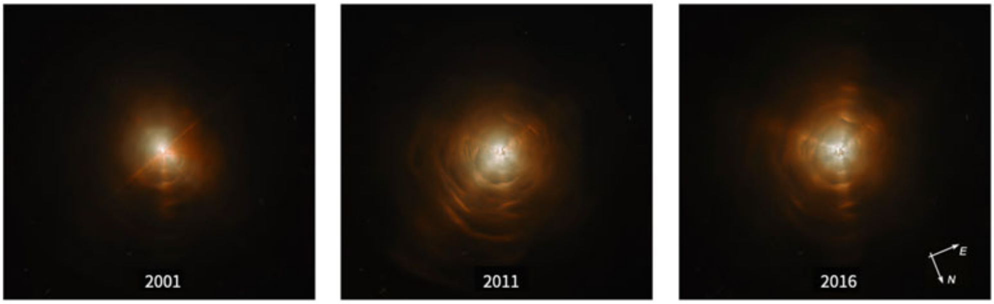

Figure 3. Searchlight beams of CW Leonis are fixed in the relative positions with respect to the proper-motion-corrected stellar position and their relative brightnesses are varying with time. The snapshots are taken from an animation in the Research Gallery of http://hubblesite.org. Image credit: ESA/Hubble, NASA, Toshiya Ueta (Univ. of Denver), Hyosun Kim (KASI).

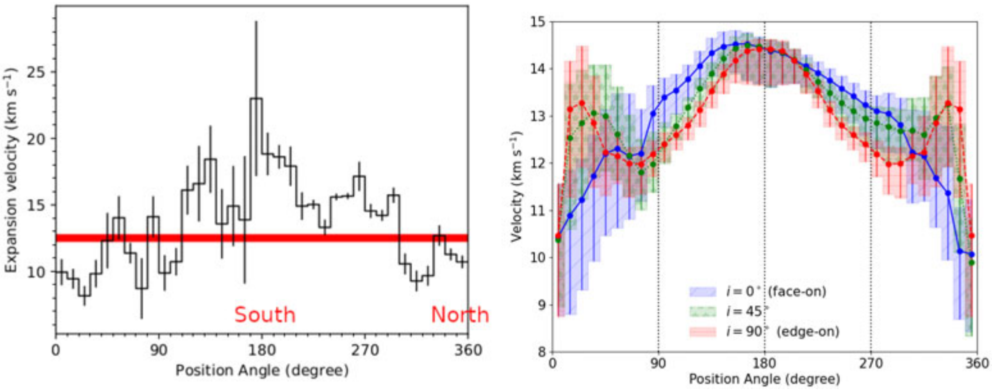

Figure 4. (Left) the expansion velocities in 36 sectors derived from differential proper motion of recurrent ring-like pattern of CW Leonis (Kim et al. 2021); (right) the correspondance in an eccentric-orbit binary model with the pericenter of the mass-losing star to the north (at the position angle of 0°), viewed at three different inclination angles 0° (blue, solid line, hatched area), 45° (green, dotted line, star-filled area), and 90° (red, dashed line, horizontally lined area), respectively (Kim 2022).

distribution is small. In order to verify this scenario, another epoch imaging observations with the same setup is anticipated.

In contrast, the relative brightnesses of the radial beams significantly change and the period seems to be about 10 years (Figure 3). The brightest beams are toward north in the 2001 and 2011 epochs (downward in the figure) while toward south in the 2016 epoch (upward). Indeed, besides the stellar pulsation of 640-day period, a decadal variation has been suggested based on near-infrared and optical photometric data (Dyck et al. 1991; Kim et al. 2021). In particular, the increases of K-band flux and the point source contribution in it during 1980–1990 are quite similar to the event found in 2016. To assess whether the variations are indeed periodic, more frequent longer-term monitoring observations are desired.

4. Anisotropic Wind Expansion induced by an Eccentric Binary

The multiple shell pattern wrapping around the star is one of the most intriguing features of CW Leonis. Our analysis using differential proper motion of the pattern indicates expansion of shells of ejected material from the star. The derived speeds of the expanding

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shells depend on the direction (Figure 4, left). The expansion speeds vary not only across different position angles within the Hubble Space Telescope image (about 7 km s^{-1} faster to the south), but their average speed in the plane of the sky was also about 2 km s^{-1} slower than the wind speed along the line of sight that is derived from molecular line observations in radio wavelengths. This variation of measured speeds indicates an overall nonspherical geometry of the wind matter. We further find that these observations (Figure 4, left panel) are compatible with a binary model having an eccentric orbit (see the right panel of Figure 4, from Kim 2022).

We regard, however, the velocity measurement was somewhat uncertain. The 2016 image was not as deep as the 2011 image, reducing the number of rings used in the analysis. Another obstacle was the relatively small expansion length (the average of positional difference of individual rings between the 2011 and 2016 epochs) due to the short 5-year interval, which was only slightly larger than the size of point-spread function. With these reasons, high-resolution high-sensitivity imaging monitoring is further needed.

5. Conclusion

The recent drastic changes in optical images suggest that the previously-seen bipolar-like structure could not be a concrete structure but could possibly be parts of searchlight beams with varying relative brightnesses along time. These radial beams reveal the pathways of starlight illuminating dusty material after escaping through the gaps in the clumpy envelope enshrouding the star. The appearance of a distinct brightness peak exactly at the predicted stellar position and the abnormal shift of large halo distribution both can be explained by a hypothesized radial beam toward us that is slowly precessing with a small angle and aligned with the line of sight at the latest observation epoch.

Although the complexity of CW Leonis has been well known since its discovery, the three dimensional morphology of its central core and evolving beams is uniquely revealed with recent Hubble Space Telescope optical monitoring of the core images. It also allows to trace the expansion velocity of shells and clumps as seen in the evolving light of the central star. Furthermore, on-going efforts on three dimensional hydrodynamic models fitting the data likely suggests a small inclination of the orbit (close to face-on) with the pericenter of the mass-losing star at North. Further systematic monitoring of this canonical high mass-loss carbon star is mandatory to strengthen our interpretation coupled with our modelling. Hubble Space Telescope allows us to be very near of establishing a robust understanding of the mass loss of this strategic but mysterious AGB (or soon post-AGB) star.

Acknowledgments

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