The Binary and the Disk: The Beauty is Found within NGC3132 with JWST

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Abstract

The planetary nebula (PN) NGC 3132 is a striking example of the dramatic but poorly understood mass-loss phenomena that (1–8) $M_\odot$ stars undergo during their death throes as they evolve into white dwarfs (WDs). From an analysis of JWST multiwavelength (0.9–18 $\mu$m) imaging of NGC 3132, we report the discovery of an extended dust cloud around the WD central star (CS) of NGC 3132, seen most prominently in the 18 $\mu$m image, with a surface-brightness-limited radial extent of $\gtrsim 2''$. We show that the A2V star located 1''7 to CS’s northeast (and 0.75 kpc from Earth) is gravitationally bound to the latter, as evidenced by the detection of relative orbital angular motion of $0.24 \pm 0.045$ between these stars over $\sim 20$ yr. Using aperture photometry of the CS extracted from the JWST images, together with published optical photometry and an archival UV spectrum, we have constructed the spectral energy distribution (SED) of the CS and its extended emission over the UV to mid-IR (0.091–18 $\mu$m) range. We find that fitting the SED of the CS and the radial intensity distributions at 7.7, 12.8, and 18 $\mu$m with thermal emission from dust requires a cloud that extends to a radius of $\gtrsim 1785$ au, with a dust mass of $\sim 1.3 \times 10^{-2} M_\oplus$ and grains that are 70% silicate and 30% amorphous carbon. We propose plausible origins of the dust cloud and an evolutionary scenario in which a system of three stars—the CS, a close low-mass companion, and a more distant A2V star—forms a stable hierarchical triple system on the main sequence but becomes dynamically unstable later, resulting in the spectacular mass ejections that form the current, multipolar PN.

Unified Astronomy Thesaurus concepts: Circumstellar matter (241); Planetary nebulae nuclei (1250); Stellar mass loss (1613); White dwarf stars (1799); Circumstellar dust (236); Planetary nebulae (1249); James Webb Space Telescope (2291); Hubble Space Telescope (761); Gaia (2360); Ultraviolet spectroscopy (2284); Close binary stars (254); Orbit determination (1175)

1. Introduction

In our quest to identify the signatures of extraterrestrial life, the search for planets and planetary systems around stars other than our Sun has become one of the most exciting areas of current astrophysical research. Planets are found to be common around other solar-type stars, but the disks in which these are produced dissipate as the stars reach the main sequence. A Spitzer 24 $\mu$m survey of main-sequence A-type stars shows that up to $\sim 50\%$ of young ($\lesssim 30$ Myr) stars have little or no 24 $\mu$m excess emission from debris disks, that large debris-disk excesses decrease significantly at ages of $\sim 150$ Myr, and that much of the dust detected in these is likely produced (episodically) by large planetesimal collisions (Rieke et al. 2005). The dust in these debris disks would have dissipated long before the stars evolved off the main sequence. Thus, it is remarkable that once these stars reach the end of their life cycle, observational surveys reveal disks or equatorially flattened disk-like or toroidal structures (e.g., Sahai et al. 2007, 2011; Hillen et al. 2017)—i.e., both the birth and the death of stars represent similar highly aspherical states that sandwich the more spherical life of stars on the main sequence (MS).

The demise of most stars in the universe that evolve in a Hubble time (i.e., in the 1–8 $M_\odot$ range) is believed to occur as a result of heavy mass loss (with rates up to $10^{-4} M_\odot$ yr$^{-1}$) on the Asymptotic Giant Branch (AGB), when the stars are very luminous ($L \sim 5000–10,000 L_\odot$) and cool ($T_{\text{eff}} < 3000$ K) (see, e.g., the review by Decin 2021). After mass loss, which may be via a quasi-steady wind over $\sim 10^5$ yr or rather sudden (if driven by a strong binary interaction)—as, e.g., in the Boomerang Nebula; Sahai et al. 2017), has depleted most of the stellar envelope, the stars evolve to higher temperatures through the post-AGB phase at almost constant luminosity, fading and becoming white dwarfs (WDs) at the ends of their lives. It is during these post-AGB and WD phases that the renewed presence of puzzling disk-like structures around the central stars becomes obvious. How are such disks formed? Are there multiple mechanisms that can make disks during this phase? Can some of these be sufficiently dense (and long-lived) to lead to a second phase of planet formation?

Such disks can generally be divided into two broad observational classes by their sizes: Type 1, very small disks that are contained within the Roche limits of the central WD stars (less than 0.01 au); and Type 2, large disks extending to radii of $\sim 10–100$ au. The majority of the Type 2 disks are found around the central stars of PNe (CSPNe; e.g., Bilkóvá et al. 2012) and around post-AGB stars (e.g., De Ruyter et al. 2006),
whereas most Type 1 disks have been identified around old, naked WDs (i.e., those for which the PN shell is no longer visible). Type 1 dust disks around WDs were first detected around G29-38 and GD 362 through their excess IR emission (confirmed spectroscopically to be continuum), and since their discovery, it has been commonly accepted that they originate from tidally disrupted planetesimals (Jura 2003; Becklin et al. 2005; Kilic et al. 2005), especially because the chemical compositions of these planetesimals are similar to those of rocky bodies in the inner regions of our Solar System. The required gravitational scattering of planetesimals toward the WD implies the presence of a planet, and recent discoveries provide indirect and direct evidence for these. The WD J091405.30+191412.25 is found to be accreting hydrogen, oxygen, and sulfur, materials that likely come from the deep atmospheric layers of an icy giant planet (Gänsicke et al. 2019). From TESS data, Vanderburg et al. (2020) find a giant planet transiting the WD 1856+354 every 1.4 days. However, tidal shredding of a companion during a common envelope phase can also make such a disk (Kuruwita et al. 2016).

The origin(s) of Type 2 disks is(are) more difficult to understand. Using Spitzer/MIPS imaging and IRS spectroscopy, Su et al. (2007) found evidence for the presence of a compact dust cloud around the central star of the Helix Nebula (WD 2226–210: $T_{\text{eff}} = 110$, 000 K) with a temperature of 90–130 K, located 40–100 au from the central star, and inferred it to be a dusty disk.

A more extensive search for 24 μm excesses around a sample of CSPNe by Biliková et al. (2012) and Chu et al. (2011) revealed spectral energy distributions (SEDs) and spectra (for a few objects) with a variety of IR excess characteristics, implying the operation of a different mechanism than planetesimal destruction for producing the dusty disk responsible for the excess emission. This mechanism involves the presence of a binary companion—binaries provide a source of angular momentum and free energy to form accretion discs. Several mechanisms for making disks in binary systems with a mass-losing companion have been identified (including Bondi–Hoyle–Eddington accretion, Roche-lobe and wind Roche-lobe overflow, common envelope ejection, and grazing envelope ejection). Numerical simulations of binary systems where the companion is detached show that the latter can gravitationally capture a fraction of the mass outflow from an AGB star into a small disk (hereafter Type 1b, ~1 au; Mastrodemos & Morris 1998)—too small to be representative of Type 2 disks. Thus, the large Type 2 disks, if resulting from binarity, likely require interaction with a close binary companion that results in the ejection of a substantial fraction of the AGB mass outflow being directed along directions near the orbital plane forming a disk-like structure. But it has been observationally difficult to confirm the association of dust disks with binary CSPNe, which requires the detection of companions and disks around the same CSPNe. The spectral-type distribution for companions of WDs (which should be representative of CSPNe) peaks at spectral types M3–4 (Farihi et al. 2005). Spectra or sensitive photometry in the ∼0.6–5 μm range can reveal a companion—e.g., an M3V companion would emit ∼210(D/0.5 kpc)$^2$ μJy at 5 μm—or provide upper limits.

In this paper, we report the detection of a dust cloud around the central star (CS) of the planetary nebula NGC 3132 using data from the JWST’s Early Release Observations (Pontoppidan et al. 2022). This PN, also known as the Southern Ring, has been well-studied, with high-resolution optical images obtained with HST (e.g., Monteiro et al. 2000), 2D spectroscopic imaging (Monreal-Ibero & Walsh 2020), and mapping of molecular-line emission at 2.1 μm H$_2$ (Storey 1984) and 1.3 mm CO $J = 2$–1 (Sahai et al. 1990). These data reveal that NGC 3132 belongs to the primary morphological class “multipolar” (Sahai et al. 2011), with a bright central elliptical shell structure surrounded by fainter structures aligned along different axes. Located at the center of the elliptical structure, the CS of NGC 3132 is a hot white dwarf (discovered by Kohoutek & Laustsen 1977) with $T_{\text{eff}} \sim 105$, 000 K. Monreal-Ibero & Walsh (2020). Northeast of the CS, at a separation of 1.669”, lies a companion (HD 87892) that is a slightly evolved main-sequence star of spectral type A2V (Méndez 1978).

We focus in this study on the CS and its immediate surroundings; description and analysis of the full PN morphology are not within the scope of this paper, but has been reported by De Marco et al. (2022).

2. Observations

We retrieved the pipeline-calibrated Level3 data on NGC 3132 (Proposal 2733, PI = K.M. Pontoppidan) from the MAST archive. NGC 3132 was imaged using filters F090W, F187N, F212N, F356W, F405N, and F470N with NIRCam (plate scale 0.031 for $\lambda \lesssim 2.1 \mu$m and 0.063 for longer wavelengths) (Jakobsen et al. 2022), and F770W, F1130W, F1280W, and F1800W with MIRI (plate scale 0.11) (Bouchet et al. 2015). JWST is diffraction-limited at wavelengths $\gtrsim 2 \mu$m with a PSF size (FWHM) of 0.075 $\lesssim 2 \mu$m (Rigby et al. 2022). The images have been processed and calibrated using data processing/calibration software version nos. “2022_2a” and “1.5.3.” Each of the Level 3 images is a combination of eight dithered images (hereafter “subimages”). For NIRCam data, 6/8 subimages in each of the filters F090W, F187N, and F202N include the CS in the FOV; for the remaining filters, the CS is within the FOV for all eight. For MIRI data, 6/8 subimages in each of the filters include the CS in the FOV. We have examined each of these subimages to look for artifacts that may affect the CS, and found that only one of these, for F090W, has four bad pixels at the location of the CS. Hence, for this filter only, the photometry described in the next section (Section 3) was carried out on each of the five good subimages, and the reported value is a median average of these.

3. Observational Results

The JWST images of NGC 3132 reveal the well-known, extended multipolar morphology of this object, the hot central star that excites the nebular material, and the nearby A2V star. The images (in selected filters) of the CS and its immediate surroundings, are shown in Figure 1. A small but clearly extended emission region is seen around the CS in the F1800W image. In addition, the emission is not circularly symmetric in its outer parts (i.e., at radial offsets $\gtrsim 0.65$)—the contours appear flattened on the side closest to the A2V star, thus giving the emission source an overall elongated shape (Figures 2(a) and (b)). Furthermore, there is a small “tail” at the northern side of the emission source that bends toward the A2V star. Radial intensity cuts centered on the CS, averaged over 90° wedges pointing toward and away from the A2V star, clearly show a significant mismatch between the intensities at offsets $\gtrsim 0.7$.
(Figure 2(c)). Although there is considerable structure in the foreground/background of the CS due to the PN itself, it is very unlikely that the above asymmetries are the result of a chance projection of a large extended nebular feature coinciding with the central dust clump, distorting its shape and producing such a specific tail shape curved toward the A2V star. Also, no hint of such an extended feature close to the compact dust clump is seen in the large-scale 18 μm image of the nebula (Appendix).

A comparison of the CS’s radial intensity with that of relatively bright field stars in the field of view of these images shows that, at 18 μm, the width (FWHM) of the emitting region (0̊.96) is significantly larger than that of the PSF (0̊.66). The observed radial extent of the dust cloud is surface-brightness-limited, e.g., on the side away from the A2V star, it falls to an intensity equal to the standard deviation of the sky background, ~4 MJy sr⁻¹, at r ~ 2̊.5.

The 12.8, 11.3, and 7.7 μm images also appear mildly extended, but to a progressively lesser extent; for shorter wavelengths, the CS appears to be point-like.

### 3.1. PSF Subtraction

The CS images are affected by the presence of the bright A2V type star, which spreads its flux through its PSF. We describe our five-step (iterative) PSF subtraction process below:

1. Generate a simulated PSF (“sPSF”) using the PSF simulator tool (webbpsf²), taking into account the spectral type of the source (A2V) and its offset from the center of the FOV in the NIRCam and MIRI images. The optics of the system are affected by additional effects (jitter, deformations, ...), which are equivalent to an additional Gaussian smoothing but are not accounted for in the simulator. We therefore applied a Gaussian smoothing function to “sPSF,” whose FWHM was set iteratively (see step 3 below).

2. Remove a median-averaged sky background from the image. The value for the box size used for estimating a median background was set iteratively for each filter/camera.

3. Apply the Gaussian smoothing function to the sPSF, and scale the sPSF peak (central) intensity to that of the A2V star when the latter was not saturated in the center (F1800W, F1280W, F1130W, and F770W) or to the intensity in the wings when the A2V star is saturated in the center (F090W, F187N, F212N, F356W, F405N, and F470N). The width of the Gaussian was set iteratively for each filter/camera.

4. Compare intensity slices along the vertical and horizontal axis crossing through the center of the A2V star and the sPSF, and check the result of the subtraction of the current sPSF with the background-subtracted image. This allowed us to estimate the background subtraction performed in step 3, as well as readjust the Gaussian spread applied to the PSF. Also, the registration of the sPSF relative to that of A2V star was readjusted, which is especially important in the NIRCam images for which the central pixels covering the A2V star are saturated.

5. Iterate steps 2–4 (i.e., Gaussian smoothing, registration, and flux scaling) to bring the average flux in the region close to the A2V star as close to the median error in the sky background in this region.
The background estimate and removal were performed by using the photutils9 package (Bradley et al. 2022). We estimated a 2D median background by dividing the field of view into boxes and substituting the pixel intensities in each box with the median background for that box. This generated a low-resolution background, which was subtracted from the image. The box size was estimated to remove as much background as possible but avoid removing any sources, including the PSF side lobes. The box size, the width of the Gaussian smoothing function, and the error in the PSF scale factor10 are given in Table 1. The images of the CS and its immediate surroundings with the A2V star subtracted, for the same set of selected filters as in Figure 1, are shown in Figure 3. Most of the negative residuals in these images lie relatively close to the sharp diffraction structures and most likely are a result of inherent limitations in the PSF simulator tool’s ability to reproduce the observed PSF.

### 3.2. Photometry

We have carried out aperture photometry of the CS in the NIRCam and MIRI images as follows. Except for the F1800W image, we have used circular apertures with sizes adjusted to include as much of the light from the CS and exclude as much light from the surrounding structured background as possible.

For F1800W, we have used multiple methods to extract the photometry. Using the pipeline Level 3 image, we use an elliptical aperture of size $1'' \times 1''$ that roughly matches the observed elongated shape of the source. Second, we extracted the average radial intensity over an angular wedge covering the position angle (PA) range $100^\circ$–$315^\circ$ that best excludes the region contaminated by the PSF of the A2V star; the background intensity was estimated from the cut intensity at large radii and subtracted. The resulting radial intensity was then integrated over circular apertures with varying outer radii to estimate the flux density as a function of aperture radius (Table 2). Radial intensity cuts have also been extracted from the F770W, F1130W, and F1280W filter images in a similar manner as for F1800W.

The background appears to be dominated by nebular emission in the F1130W, F1280W, and F1800W filters; for shorter wavelengths, the PSF of the A2V star becomes progressively fainter. Aperture corrections have been determined using relatively bright field stars in the images and applied to the aperture photometry of the CS (Table 2). In order to assess errors, for each filter, we used apertures of different sizes.

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9 https://photutils.readthedocs.io/en/stable/background.html
10 The actual value of the scale factor is unimportant because it depends on the normalization of the PSF, which is arbitrary.
diameters, each with its own aperture correction; the results shown in Table 2 are those obtained with largest aperture that could be feasibly used. We have assigned conservative errors of ±15% to the NIRCam photometry and ±10% to the MIRI photometry. Noting the 0.1 to 0.2 mag difference between pipeline and manually determined photometry for the HST data at 0.44 and 0.56 \( \mu \text{m} \) (Table 2), we have assumed ±15% errors for the published photometry at shorter wavelengths, i.e., \( \lambda < 0.9 \mu \text{m} \). The aperture photometry was also carried out for the PSF-subtracted images, and yielded consistent results. We have verified that our photometry methodology is correct by measuring the F356W and F770W flux densities for a few field stars and comparing these to those measured with Spitzer IRAC 1 and IRAC 4 (Spitzer Science Center, 2021—we find that our photometry is in good agreement with the latter (Table 3), accounting for the possibility of temporal variability in these stars.

### 3.3. UV Spectrum

We downloaded a FUSE UV spectrum of NGC 3132 that covers the 910–1190 Å wavelength range with a spectral resolving power \( R \sim 20, 000 \) (Moos et al. 2000; Sahnow et al. 2000) from the Mikulski Archive for Space Telescopes, calibrated with the final version of the CalFUSE calibration pipeline software package, CalFUSE 3.2.3 (Dixon et al. 2007). The spectrum was obtained as part of FUSE program ID P133 (PI: L. Bianchi), and an analysis of the same (reporting the discovery of Ge III \( \lambda \) 1088.46 in NGC 3132 and other PNe) was first presented in Sterling et al. (2002). The spectrum is of relatively modest S/N at the short-wavelength end, and we have rebinned it to reduce the resolution by a factor 50. The spectrum was taken through the LWRS aperture, which has a size of 30″ \( \times \) 30″, and therefore covers not only the CS but also the A2V companion and a significant fraction of the ionized region. However, the continuum flux in the 910–1190 Å wavelength region is dominated by the CS, allowing us to use the FUSE spectrum to complete the SED of the CS to 0.091 \( \mu \text{m} \) at the short-wavelength end (see Section 4.2).

### 4. Analysis

#### 4.1. A Central Binary and Orbital Motion

We have investigated the relationship between the CS and the A2V star as follows. First, there is little doubt that these two stars are a physical pair (De Marco et al. 2022), given the close agreement in their Gaia-based proper motions (A2V star: \( \text{PMra} = -7.747 \pm 0.027 \text{ mas yr}^{-1}, \text{ PMdec} = -0.125 \pm 0.031 \text{ mas yr}^{-1} \); CS: \( \text{PMra} = -7.677 \pm 0.235 \text{ mas yr}^{-1}, \text{ PMdec} = 0.197 \pm 0.28 \text{ mas yr}^{-1} \)) and radial velocities (A2V star: \( \text{VLSR} = -24.1 \pm 1.6 \text{ km s}^{-1} \); CS: \( \text{VLSR} = -25 \pm 0.9 \text{ km s}^{-1} \)). We have therefore inferred a distance to NGC 3132 of 0.75 kpc by inverting the parallax of the A2V star companion11 (1.3198 \( \pm \) 0.0344mas) listed in the Gaia DR3 database (Gaia Collaboration 2022). Hence, the separation between the CS and its A2V companion and the CS is 1277 \( \pm \) 34 au.

We have found direct evidence for the CS and the A2V star to be a gravitationally bound binary system from the detection of orbital motion, over a time interval of \( \sim 20 \text{ yr} \) between the epoch of the first high-angular-resolution image of the CS-A2V pair with HST (Epoch 1) and the epoch for Gaia measurements (Epoch 2), as follows. We used the Epoch 1 F555W image (from GO 06119, PI: H. Bond; image taken on 1995 Dec 04),

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11 No parallax is available for the CS.
Table 2

Photometry of the Central Star of NGC 3132

| Filter | Wavelength (µm) | Flux (mJy) | Error (%) | Apert. Rad.(") | Apert. Corr. | Phot. References |
|--------|----------------|------------|-----------|----------------|--------------|-----------------|
| U      | 0.36           | 2.15       | 15        | ...            | ...          | 14.8(1)         |
| F438W  | 0.438          | 1.80       | 15        | ...            | ...          | 15.76(3)        |
| F438W  | 0.438          | 1.62       | 15        | ...            | ...          | 15.876(2)       |
| F555W  | 0.555          | 1.45       | 15        | ...            | ...          | 16.0(3)         |
| F555W  | 0.555          | 1.19       | 15        | ...            | ...          | 16.212(2)       |
| G-band | 0.639          | 1.18       | 15        | ...            | ...          | (4)             |
| F814W  | 0.814          | 0.56       | 15        | ...            | ...          | 17.03(3)        |
| F1800W | 0.90           | 0.38       | 15        | 0.010          | 0.76         | (5)             |
| F187N  | 1.17           | 0.11       | 15        | 0.010          | 0.75         | (5)             |
| F212N  | 2.12           | 0.106      | 15        | 0.010          | 0.74         | (5)             |
| F356W  | 3.56           | 0.037      | 15        | 0.015          | 0.71         | (5)             |
| F405N  | 4.05           | 0.020      | 15        | 0.015          | 0.73         | (5)             |
| F470N  | 4.70           | 0.018      | 15        | 0.015          | 0.72         | (5)             |
| F770W  | 7.7            | 0.070      | 10        | 0.035          | 0.76         | (5)             |
| F1130W | 11.3           | 1.16       | 10        | 0.075          | 0.97         | (5)             |
| F1280W | 12.8           | 1.2        | 10        | 0.075          | 0.93         | (5)             |
| F1800W | 18.0           | 9.9        | 10        | 1°71 × 1°73   | ...          | (5)             |
| F1800W | 18.0           | 10.3(4)    | 10        | 1°76           | ...          | (5)             |
| F1800W | 18.0           | 11.1(4)    | 10        | 1°8            | ...          | (5)             |
| F1800W | 18.0           | 12.1(4)    | 10        | 2°0            | ...          | (5)             |

Notes.

a Percentage error in flux in previous column.

b References for photometry: (1) Kohoutek & Laustsen (1977), (2) photometry on UVIS/WFC3 images (HST proposal 11699) from Monreal-Ibero & Walsh (2020), (3) Hubble Source Catalog V.3 (Whitmore et al. 2016), (4) Gaia DR3, and (5) this work; when photometry reference provides magnitudes, they are listed here.

c Vega magnitude.

d AB magnitude.

e Flux derived from integration of radial intensity to outer radius in Col. (3).

obtained with the PC camera of WFPC2 (pixel size of 0°05), to determine the coordinates of the CS and the A2V star. Because the S/N is quite high (>50 for the CS, > 4000 for the A2V), the uncertainty in the location of the CS is ~1 mas, and that of the A2V star much smaller. The position angle of the separation vector of the A2V, CS pair12 in the HST image is PA(HST) = 47°82 ± 0°045 (Figure 4). The position angle of this vector during the Gaia measurement epoch (Epoch 2: ~JD ~2457410), estimated from the DR3 coordinates of the CS and A2V stars, is PA(gaia) = 47°43.

The JWST data could not be used to determine the current orientation of the CS-A2V separation vector accurately enough, because the locations of these stars cannot be measured with the required accuracy—at the shortest wavelengths, where the telescope is diffraction-limited and the PSF is small (e.g., 0°075 at ~2 µm) the A2V star is badly saturated and the CS is very faint and its image is partly contaminated by the wings of the A2V star’s PSF.

We have checked for any (minute) difference between the cardinal directions in the Gaia DR3 reference frame (Gaia CRF3; Gaia Collaboration et al. 2022) and the HST image reference frame, PA(gaia-HST), using the following methodology. We identified four field stars in the HST image (fs1, fs4, fs6, and fs8)13 and computed the PAs of their separation vectors (Table 4). Then, using the proper motions of these stars from Gaia DR3, we have computed their expected locations in Epoch 1, and from these, the expected PAs of their separation vectors in Epoch 1 (Table 4). Because the separation vectors for these stars are quite large, the errors in the PAs are quite small (≤0°01). The average of the PA(gaia-HST) values is 0°147 ± 0°016. Applying this correction to the value of PA(HST) computed above, the corrected value of the PA of the CS-A2V separation vector is PA(HST,c) = PA(HST)-0°147 = 47°67. Thus, the separation vector has rotated by

Figure 4. HST 0.55 µm (F555W) image of the CS and the A2V stars at the center of NGC 3132. Dashed yellow line shows the vector separating the two stars, with length 1°693 and PA = 47°82. North is up and east is to the left.

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12 Measured from N toward E, using the CS as the origin.
13 These are the 4/5 stars seen in the full FOV for which Gaia DR3 data are available.
0.2 ± 0.045 (clockwise) in 20.1 yr (time interval between Epoch 1 and Epoch 2), in good agreement with the expected 0.2 cos (i)/cos 45° rotation for an orbital period of P ∼ 25, 500 yr, based on the measured separation of 1277 au, assuming an intermediate angle between the orbital and sky planes of i = 45° and masses of 0.7 and 2.5 M_⊙ for the CS and A2V stars.

The angular distance between the CS-A2V pair in Epoch 1 is ε(HST) = 1°693 ± 0′′001, compared to 1°696 in Epoch 2. We have checked the “plate scale” of the HST image, using the same four fields stars and a similar methodology as above. We computed the angular distances between the star pairs used above for Epoch 1 using their current Gaia DR3 coordinates and proper motions to compute their Epoch 1 coordinates, and compared these with the directly measured angular distances in the HST image (Table 4): the average fractional difference for the distances between star pairs between Epoch 1 and 2 (Table 4) is (3.92 ± 1.35) × 10⁻³. This difference is too small to affect the value of ε(HST) derived above. Therefore, there is weak evidence for an increase in the angular distance between the CS-A2V pair of 2.7 ± 1 mas from Epoch 1 to Epoch 2.

Although additional HST imaging is available at intermediate epochs, these images proved to be inadequate for determining the locations of the two stars with sufficient accuracy, because of one or more of the following factors: (i) the pixel size was twice as large (e.g., 0′′1 using the WFPC2 Wide Field cameras); (ii) only emission-line images were available, providing inadequate S/N to centroid the CS accurately; (iii) the core of the PSF of the A2V star appeared noncircular and distorted.

### 4.2. Dust Radiative Transfer Modeling

We have used the MIRI and NIRCam photometry, together with the FUSE UV spectrum and published optical photography, to construct the observed SED of the CS and the dust cloud around it over the UV to mid-IR (0.091–18 μm) region (Figure 5).

The photometry is not coeval; we assume that there are no significant variations in the CS’s spectrum over the ∼4 decades spanned by an epoch of the U-band photometry and that of the JWST observations. However, the CS is included in the catalog of large-amplitude variables from Gaia DR2 (Gaia DR2 5420219732233481472; Mowlavi et al. 2021) is probably erroneous. Mowlavi et al. (2021) report a variability amplitude proxy of 0.356 mag for the CS—this proxy was computed from the uncertainty (keyword “pho_g_mean_mag_error”) in the G-band magnitude (keyword “phot_g_mean_mag”) published in DR2. A comparison of the Gaia DR2 and DR3 G-band magnitudes—15.216140 (mean magnitude based on 125 single-epoch measurements) for DR2 and 16.105730 (mean magnitude based on 193 single-epoch measurements) for DR3—shows that the CS was almost one order of magnitude fainter in DR3 compared to DR2. However, because the DR3 data supersede the DR2 data, it is likely that the DR2 G-band magnitude and error are incorrect, and they may result from incorrect removal of the contribution by the bright A2V star’s PSF to the measured photometry of the CS.

Table 3

| Star* | Wavelengthb (μm) | Fluxc (mJy) | Errord (%) | Wavelengthb (μm) | Fluxc (mJy) | Errord (%) | Instr. | Publ.Phot. Referencesf |
|-------|------------------|-------------|------------|------------------|-------------|------------|--------|------------------------|
| fs3   | 3.56             | 0.38        | 5          | 3.56             | 0.359       | 0.4        | IRAC 1 | 1                      |
| fs3   | 7.7              | 0.085       | 10         | 7.91             | 0.075       | 7          | IRAC 4 | 1                      |
| fs4   | 7.7              | 0.22        | 5          | 7.91             | 0.27        | 2.5        | IRAC 4 | 1                      |
| fs5   | 7.7              | 3.9         | 5          | 7.91             | 4.6         | 0.2        | IRAC 4 | 1                      |

Notes.
* Coordinates (RA, Dec) of stars, from reference in last column, are: fs3 (51.7718533, −40.4307750); fs4 (151.7579802, −40.4208553); fs5 (151.7463684, −40.4185993)
* Wavelength of JWST filter passband.
* Measured photometry from this study.
* Percentage error in flux in previous column.
* Instrument/detector for published photometry.
* Reference for published photometry: (1) The Spitzer (SEIP) source list (SSTSL2) (Spitzer Science Center (SSC) & Infrared Science Archive (IRSA), Vizier Online Data Catalog 2021).

Table 4

| StarPairg | PA(HST)b | PA(Gaia, Epoch1)f | Ang. Dist. | Err(HST)g | Frac.Diff. h |
|-----------|----------|--------------------|------------|-----------|-------------|
| fs6, fs1  | 22.016   | 21.850             | 98.1236    | 0.00055   | −2.58       |
| fs6, fs8  | 21.219   | 21.071             | 162.7896   | 0.0012    | −4.25       |
| fs1, fs8  | 20.031   | 19.912             | 64.6894    | 0.0011    | −6.36       |
| fs4, fs8  | 13.816   | 13.674             | 141.6898   | 0.0017    | −3.55       |
| fs4, fs1  | 8.647    | 8.486              | 77.6963    | 0.0013    | −2.85       |

Notes.
* The Gaia DR3 coordinates (RA, Dec) of the stars are: fs1 (151.75381877513, −40.44227853299); fs4 (151.75801934706, −40.42093855870); fs6 (151.76714757082, −40.41697502534); fs8 (151.74573126685, −40.49510857380)
* PA of separation vector between star pair in Epoch 1, using HST image. PA is measured from N toward E, with the second star in the pair as the origin.
* PA of separation vector between star pair in Epoch 1, estimated from Gaia DR3 data.
* Angular distance between star pair in Epoch 1, using HST image.
* Error in angular distance between star pair in Epoch 1, using HST image.
* Angular distance between star pair in Epoch 1 (using HST image) minus the angular distance between star pair in Epoch 1 (estimated from Gaia DR3 data), divided by the average angular distance between star pair.

* These include the 125 measurements used for the DR2 photometry.
The simplest explanation for the extended emission seen most clearly at 18 μm is that it arises from thermal emission from warm dust. Although there are strong nebular emission lines that have been detected in NGC 3132 in the wavelength bands covered by the filters listed above, it is very unlikely that such gas is present in the immediate vicinity of the CS. We have made a rough estimate of the width of the intrinsic radial intensity distribution at 18 μm (FWHMint) as follows. We approximated the observed radial intensity distribution as well as the PSF at 18 μm, using Gaussians of widths FWHMobs ~ 1.0° and FWHMpsf ~ 0.7°, and determined FWHMint ~ 0.7° using FWHMobs = FWHMint + FWHMpsf.

This intrinsic width implies a radial extent of ∼260 au at NGC 3132’s distance of 0.75 kpc. Any gas this close to the star would be quite hot, >10⁴ K, and at the sound speed for such gas, 10 km s⁻¹, would expand to radii >10,000–20,000 au in (say) a typical post-AGB age of >5000–10,000 yr. Furthermore, the SED of NGC 3132’s CS dust emission is similar to that of the Helix, for which a spectrum of the CS shows no obvious line emission.

We have used the DUSTY dust radiative transfer code (Ivezić et al. 2012) to model the CS and its dust emission. Although it is plausible, depending on its origin, that the dust cloud is flattened or disk-like (see Section 5), because we have no direct information about this aspect, we have chosen to use 1D modeling. This is not a limitation, because (as shown below), the optical depth of this cloud is ≪1, even at relatively short wavelengths (≤0.001 at λ ∼ 0.05 μm); hence the results are not sensitive to the specific geometry (i.e., sphere or disk) of the cloud. Even if the dust cloud had a disk configuration, the radial optical depth near and in the equatorial plane would remain well below unity.

The main input parameters are (i) the dust temperature at the inner shell boundary (Tint), (ii) the total radial optical depth at 0.55 μm (τtot), (iii) the shell density (iv) the grain-size distribution for a choice of grain composition, (v) the relative shell thickness (r̃ = ratio of the shell’s outer radius, Rout, to its inner radius, Rin), and (vi) the spectrum of the central star. The shell density was assumed to be a single power-law exponent, n, of the power law (ρd(r) ∝ r⁻ⁿ), or a combination of two power laws (described below). We have computed the stellar spectrum using the Tübingen NLTE Model Atmosphere Package (TMAP; Rauch & Deetjen 2003; Werner et al. 2003, 2012) for T_eff = 105, 000 K—as derived by Monreal-Ibero & Walsh (2020) using photoionization modeling. We have accounted for nebular extinction by using a visual extinction of A_V = 0.31—derived by Kohoutek & Laustsen (1977)—to attenuate and redden the model SED.

We require the grains to be relatively cool (∼100 K at r ∼ 1") in order for the average slope of the model spectrum from 7.7 μm to 18 μm to match the observed one (Figure 5). The shape of the model SED longward of ∼5 μm, where dust emission is the dominant component, is most sensitive to the dust grain properties (composition, size distribution). We have investigated models with “cold” (“Sil-Ow”), “warm” silicate grains (“Sil-Oc”), and amorphous C (amC) grains in DUSTY. The SED has a very distinctive shape in the wavelength region dominated by dust emission, i.e., longward of ∼5 μm, there is a steep rise from ∼7 to ∼11 μm, followed by a flat region between 11 and 13 μm, and then a rise toward

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15 DUSTY provides six built-in choices for grain composition.
longer wavelengths. While models with silicate grains produce the observed roughly flat shape of the SED in the 11–13 μm region, pure amC-grain models produce a smooth rise with increasing wavelength, discrepant from the observed SED. Warm silicates produce modestly smaller ratios of flux, F(18 μm)/F(12.8 μm), F(18 μm)/F(11.3 μm), and F(18 μm)/F(7.7 μm), compared to cold silicates. We used a modified version of the Mathis–Rumpl–Nordsieck (MRN) distribution function for grain radius $a$, $n(a) \propto a^{-q}$ for $a_{\text{min}} \leq a \leq a_{\text{max}}$ (Mathis et al. 1977), with $q = 1$. Models with a substantial fraction of large grains, e.g., $a_{\text{max}} \gtrsim 1 \mu m$, produced radial intensity profiles that are significantly more compact than observed; in addition, the detailed shape of the SED between 7.7 and 18 μm (described above) cannot be reproduced—large grains produce a dust emission spectrum in which there is a smooth rise with increasing wavelength. De Marco et al. (2022) present a simple large-grain (size ~100 μm) dust shell model, which suffers from these deficiencies. Keeping the grain-size distribution the same but allowing the grains to be cooler by decreasing $T_d$ results in a decrease in the 7.7 μm to 18 μm flux ratio—and simultaneously makes the model emission more extended due to an increase in $R_{\text{disk}}$. Keeping the value of $T_d$ fixed, an increase in the proportion of larger grains caused by increasing $a_{\text{max}}$ or decreasing $q$ makes the dust emission more compact. The model radial intensity distribution, especially at the longer wavelengths (~11–18 μm) is sensitive to (i) $T_d$ and (ii) the radial density gradient of the dust shell. Lower values of $T_d$ lead to smaller values of $R_{\text{disk}}$ and therefore a more compact radial intensity distribution of the dust emission. Higher values of $n$ also result in more compact dust emission.

The above competing constraints allow us to provide reasonable constraints on the model parameters.

The DUSTY code generates a model SED, normalized to the bolometric flux, $F_{\text{bol}}$. We find that $F_{\text{bol}} = (6.5 \pm 0.5) \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (implying a CS luminosity of 114 $L_\odot$) by scaling the (reddened) model SED to match the observed SED (Figure 5(a)). The value of $F_{\text{bol}}$ is well-constrained (for a given choice of $T_{\text{eff}}$), independently of the specific dust model, because the model SED in the optical to near-IR wavelength range (~0.1–3 μm) (Figure 5(d)) is only affected by nebular extinction (which is modest), and not by the dust cloud which has a very low optical depth. While determining the best-fit model, we have ignored (i) photometry from the narrowband filters F187N, F212N, F405N, and F470N, as the data from these are most affected by the presence of nebular atomic or molecular hydrogen lines, as well as (ii) Gaia DR3 photometry, due to potential imperfect removal of the PSF of the A2V star. We did not convolve the SED with the filter responses, but we have checked that the difference between convolved and non-convolved model photometry is relatively small and well below difference between the best-fit model and the data.

In order to quantitatively distinguish between models, we have defined a “goodness-of-fit” measure for the SED modeling.

G(sed), as follows: $G(\text{sed}) = \sum \left( \frac{O_j - M_j}{\sigma_j} \right)^2$, where $O_j (\sigma_j)$ is the observed flux (error), $M_j$ is the model flux, and the index $j$ refers to different wavelengths. The summation was carried out only for $\lambda > 3.56 \mu m$, because at shorter wavelengths, the SED is dominated by the central star, and including the data for these would reduce the sensitivity of $G(\text{sed})$ to the contribution of the dust emission. The “goodness of fit” for the radial intensity distributions, $G(\text{Fx})$, where Fx is F770W, F1280W, or F1800W, is $G(\text{Fx}) = \sum r_j \delta r_j (O(\text{int}, - M(\text{int},)) - r_j)^2 / \sum r_j \delta r_j^2$, where

$^{16}$ The standard MRN parameters are: $q = 3.5$, $a_{\text{min}} = 0.005 \mu m$, and $a_{\text{max}} = 0.25 \mu m$. 

![Figure 6](image-url) Observed (azimuthally averaged) and model radial intensity distributions of the CS (+dust) of NGC 3132 as seen in the (a) F1800W, (b) F1280, and (c) F770W filters, together with (d) the radial distribution of density, visual optical depth, and dust temperature for the best-fit one-shell model. All distributions have been normalized to their peak values. This one-shell model uses a grain mixture consisting of 70% warm silicates and 30% amorphous carbon (amC). The model intensities (blue) have been convolved with the PSFs at 18, 12.8, and 7.7 μm, to generate the convolved models (green), for direct comparison with the observations (red). The sharp intensity peaks in the intrinsic model correspond to the inner radius of the dust shell. The F1280W and F770W intensities are shown over a smaller range of offsets compared to F1800W, because the observed radial intensity distributions for the former are much more narrow than for the latter.
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The one-shell models provide a reasonably good fit to the SED (Figure 5(a)) as well as the radial intensity in the F1800W, F1280W, and F770W images (Figures 6(a), (b), and (c)). The grain composition needed to fit the specific shape of the SED, requires a mixture of 70% cold silicate (Sil-cW) and 30% amorphous carbon (amC) grains. However, there are small but noticeable discrepancies: (i) the F1800W model radial intensity lies a little below the observed one for radial offsets $r \lesssim 1.0$, and (ii) the F1280W model radial intensity lies a little above the observed one for radial offsets $r \gtrsim 0.65$.

Because the radial dust emission intensity is sensitive to the dust radial density distribution $\rho_d(r)$, we explore the possibility that a more complex density structure than the ones used for the one-shell models can reduce the above discrepancy. We have investigated models in which $\rho_d(r)$ is described by a broken power law, such that $\rho_d(r) \propto r^{-n_1}$ for $1 \leq Y \leq Y_1$, and $\rho_d(r) \propto r^{-n_2}$ for $Y_1 \leq Y \leq Y_2$ (hereafter “two-shell” models).

We find that a two-shell model with $n_1 = 0.2$, $n_2 = -0.4$, and $Y_1 = 5$ provides the best fit (Figures 7(a)–(c)). For this model, the value of $G(\text{sed})$ is a factor of 0.75 times and the value of $G(\text{F}\lambda)$ is a factor of 1.2, 0.96, and 0.41 times (for $\lambda$ equal to F770W, F1280W, and F1800W, respectively) that of the one-shell model. While comparing the $G(\text{F}\lambda)$ values for these models, we give the most weight to $G(\text{F}1800W)$ and the least weight to $G(\text{F}770W)$ because the dust distribution is most resolved at 18 $\mu$m ($7.7 \mu$m). Thus, the two-shell model provides an overall better fit to both the SED and the radial intensity distribution.

The density structure in the two-shell model suggests that the dust cloud around the CS has two shells with a low-density region in between. The presence of double shells is not uncommon for the central stars of PNe that show dust emission — Biliková et al. (2012) find the presence of double shells in $\gtrsim50\%$ of the CSs with IR excesses due to dust.

We have therefore also investigated models with a different variant of the two-shell density structure—in this class of models (hereafter “gap” models), we have a geometrically thin shell close to the star, separated by a density gap from the extended shell. In these models, we varied $T_d$, the ratio of the density in the inner shell (assumed constant) to the density of the outer shell at the outer edge of the gap, the radius and width of the gap, and the power-law density exponent for the outer shell. We find that, although the best “gap” model can fit the SED and the F1800W and F1280W radial intensities as well as the one-shell and two-shell models, the F770W radial intensity distribution is significantly narrower than observed. Hence, we do not discuss these models further.

We have derived the mass of the dust shell as follows, because DUSTY does not provide a direct measure of the dust mass shell. For objects obeying a $r^{-n}$ density distribution, the dust mass in the circumstellar component is given by (for $n = 1, 3$):

$$M_d = 4\pi \left[ (n - 1)/(3 - n) \right] \gamma(\text{Y}) R_{\text{out}}^2 (\tau_{18}/\kappa_{18}),$$  

where $\gamma(\text{Y}) = (Y^{1-n} - 1)/(1 - Y^{-1-n})$, and $\tau_{18}$ and $\kappa_{18}$ are, respectively, the radial optical depth of the shell and the dust mass absorption coefficient, at 18 $\mu$m. We assume $\kappa_{18} = 10^3$.
The dust cloud around the central star of NGC 3132 is relatively old and may be a stable disk in Keplerian or quasi-Keplerian rotation. As mentioned earlier (Section 1), disks have been found to be associated with quite evolved WDs, often too old to show detectable PNe around them (e.g., Tokunaga et al. 1990; Manser et al. 2020). These disks are very small, occupying just a few au, and have been proposed to be the result of disruption of planets or planetoids from a former planetary system. Central stars of relatively young PNe tend to show disks with smaller radii, inferred to typically ~50 au (Su et al. 2007; Bilíková et al. 2012). Many post-AGB stars (which are less evolved than old WDs) also show disks (e.g., de Ruyter et al. 2006; Bujarrabal et al. 2013, 2016), but in this case their extents are much larger, ~1000 au. In this case, the rotating disks are systematically associated with the presence of tight binary systems and probably consist of material ejected during the previous AGB phase, which gains angular momentum from interaction with the system and forms rotating circumbinary disks.

We will next discuss possible origins of the dust cloud around NGC 3132’s CS.

### 5.1. An Oort Cloud

The large radial extent (>1500 au) of the dust cloud in NGC 3132 makes it unlikely that it is formed from material extracted from a planetary system or a Kuiper Belt/debris-disk analog—the typical radius of the latter is about ~50–150 au. However, an Oort cloud analog might explain the origin of this dust cloud. The Oort cloud in our Solar System is thought to occupy a radius between 2000 and 5000 au and may extend as far as 50,000 au from the Sun.

The dust cloud around the CS of NGC 7293 may also be extended—Su et al. (2007) find that the 24 μm emission from this cloud, after background subtraction, appeared slightly resolved with an FWHM of ~9″, 1.5 times that of a true point source—although, as stated by Su et al. (2007), this could be due to an imperfect subtraction of the background, it may also be real (as in the case of NGC 3132).

We now estimate the survival probability of Oort’s rocky bodies after collisions with the gas and dust ejected by the CS while it was on the AGB or RGB. For a cometary nucleus with a typical radius of ~1 km, located at a distance of >2000 au, only about 0.56 × 10^10 g of circumstellar ejecta will hit the...
nucleus, assuming a total $\sim 1 M_\odot$ ejected via mass loss, much smaller than the typical mass of the comet nucleus ($>10^{16}$ g). So the cometary nuclei in the Oort cloud should easily survive the impact of the CS ejecta. Assuming that the impacting gas is expanding at 15 km s$^{-1}$, and all of its linear momentum is transmitted to the cometary nucleus, the latter will gain a velocity of 0.85 cm s$^{-1}$, which is significantly smaller than the escape velocity at 2000 au ($\sim 1$ km s$^{-1}$), implying that an Oort cloud will easily survive the AGB mass-loss phase. Thus, the Oort cloud, with an estimated mass of $\sim 1.9 M_\odot$ (Weissman 1983), can easily supply the mass of dust observed around the CS.

However, in this scenario, we require a mechanism to transport the dust inward, because the inner radius of the dust cloud in our model is $\sim 70$ au. We think it is possible that the A2V companion provides sufficient perturbation to the orbits of the cometary bodies in the Oort cloud, causing them to collide and/or increase their eccentricity sufficiently so as to reach the inner regions of the dust cloud.

5.2. Interaction with a Binary Companion

As mentioned earlier, the central star of NGC 3132 has a detached A2V spectral type companion (Section 4.1). A closer companion has not been detected, but the possibility cannot be discarded (we discuss this in more detail below). The highest-mass unresolved main-sequence companion that can be present and remain undetected is of lower mass than that of an M dwarf with spectral type M6V (with $L \sim 7 \times 10^{-4}$ and $T_{\text{eff}} \sim 2500$ K; see, e.g., Cifuentes et al. 2020), $\sim 0.1 M_\odot$. Including the theoretical spectrum of such a companion (BT-NextGen (AGSS2009) model with $T_{\text{eff}} = 2500$ K, log($g(\text{cm s}^{-2})$) = 5, extracted from http://svo2.cab.inta-csic.es/theory/newov2/index.php; Allard et al. 2011) increases the model SED flux in the F356W filter by 30%, well above the observed value (see inset of Figure 5(d)). De Marco et al. (2022) propose that the CS has at least two, and maybe even three close companions, in order to explain the origin of the dust cloud and the morphological structure of the extended PN.

From angular momentum balance considerations alone, the dust cloud may be a result of interaction with either such a close companion or the detached A2V companion. The angular momentum of the cloud, assuming it has a disk geometry and is in Keplerian rotation around a $\sim 0.65 M_\odot$ CS, is low ($\lesssim 0.5 \times 10^{-4} M_\odot$ km$^2$ s$^{-1}$), orders of magnitude less than that of a compact binary system even if the secondary is just a large planet—e.g., the angular momentum of a Jupiter-mass planet in a 1 au orbit around the CS is $3.54 \times 10^{-10} M_\odot$ km$^2$ s$^{-1}$. The A2V star’s angular momentum, $\sim 1.5 \times 10^{11} M_\odot$ km$^2$ s$^{-1}$, is also much larger than that of the CS’s dust cloud, assuming the latter has a disk geometry.

From the point of view of the momentum transfer mechanism, however, the situation is very different for the above two scenarios. The currently adopted wind Roche-lobe Overflow (wRLOF) mechanism of hydrodynamical interaction between a companion and a stellar wind in the red giant phase predicts strong effects when the separation of both stars is small, typically under 50–100 au (Mohamed & Podsiałdowski 2012; Chen et al. 2017; Kim et al. 2019). The circumstellar gas at such distances is still being accelerated and shows a relatively low velocity, which is a basic ingredient for allowing strong interaction effects, including the formation of rotating circumbinary disks and symbiotic phenomena (e.g., Sánchez Contreras et al. 2022). Rotation in inner suborbital regions can also be induced in those cases of strong interaction (e.g., Bermúdez-Bustamante et al. 2020). However, when the distance between the two stars is significantly larger, the circumstellar expansion velocity is expected to be large and models predict that the gas passes by the companion with a minor interaction; the main effect is then the formation of spiral arcs due to the oscillation of the mass-ejecting primary. Formation of rotating disks is therefore not expected in detached binary systems. Hence, if the dust cloud is a disk resulting from binary interaction, we require that the CS has (or had in the past) another companion that is (was) much closer than the A2V star, and that this close companion (hereafter “Comp”) underwent a strong gravitational interaction with the CS.

The A2V star may have played an active role in inducing the strong gravitational interaction of Comp with the CS. In this scenario, three stars—the CS, Comp, (say at a separation of $\lesssim 5$ au), and the A2V star (in a more distant orbit, say at $\sim 400$ au)—formed a stable hierarchical triple system while these stars were on the main sequence. Such systems can become dynamically active on much longer timescales, due to the “Eccentric Kozai–Lidov” (EKL) mechanism causing the inner binary to undergo large-amplitude eccentricity and inclination oscillations (Kozai 1962; Lidov 1962; Naoz 2016). The oscillations tend to drive the inner binary to have very small pericenter distances and even to merge (e.g., Prodan et al. 2015; Stephan et al. 2018). Salas et al. (2019) have simulated such a triple system with a $2.2 M_\odot$ primary, a close companion (with a range of masses $\lesssim 0.9 M_\odot$) and a tertiary star with a range of masses $M \lesssim 0.9 M_\odot$—they find that, in 37% of their simulations, the tight binary merges. Although, the tertiary star is more massive ($>2.5 M_\odot$) in the case of NGC3132, the results of Salas et al. (2019) indicate that there is a significant possibility for the inner binary to merge. Such a merger would lead to a common envelope ejection of most of the stellar envelope of the primary star—the multipolar morphology observed in NGC 3132 would then be a result of interaction of multipolar collimated outflows with the ejecta, as appears to be the case in the Boomerang Nebula (Sahai et al. 2017). The Boomerang is a preplanetary nebula that has most likely resulted from CEE while the central star was still on the RGB and therefore in a much earlier post-AGB phase than NGC 3132. Because the primary must be initially more massive than the A2V star, say $\sim 2.8 M_\odot$, simple conservation of angular momentum indicates that the tertiary’s orbit, if initially equal to $\sim 400$ au, would expand to a semimajor axis of $\sim 1200$ au after the merger, bringing it to its current observed location.

5.3. The A2V Companion’s Effects on the Dust Cloud around the CS

The JWST images show that the radial extent of the dust cloud is almost identical to the orbital radius of the CS-A2V detached binary system. In addition, there is a flattening of the $18 \mu$m intensity contours defining the shape of the dust cloud on the side facing the A2V star. These two features suggest a physical interaction between the dust cloud formation and the A2V companion; we will now discuss several physical mechanisms for such an interaction. The first is that the A2V star preferentially illuminates the dust closest to it, making it relatively hotter, and therefore causing an extra brightening of
the dust emission, relative to the diametrically opposed side of the dust cloud, contrary to what is observed.

Next, we consider the effect of radiation pressure and a possible wind from the A2V star on the dust cloud around NGC 3132’s CS. The ratio of the stellar wind force ($F_{sw}$) to the gravitational force of star ($F_{gr}$) on a dust grain, is given by

$$\beta_{sw} = 3M_{sw}V_{sw}C_D/(32\pi GM_{\ast}\rho g a_g),$$

where $M_{\ast}$, $M_{sw}$, and $V_{sw}$ respectively are the mass, mass-loss rate, and outflow velocity for the A2V star, $G$ is the gravitational constant, $\rho g$ and $a_g$ are the dust grain material density and radius, $r$ is the radial distance from the A2V star, and $C_D$ is a coefficient $\sim2$ (e.g., Equation (28) in Augereau & Beust 2006). Taking $M_{sw} = 10^{-10} M_{\odot} \text{yr}^{-1}$ (e.g., Lanz & Catala 1992), $V_{sw} = 300 \text{ km s}^{-1}$, $\rho g = 3 \text{ g cm}^{-3}$, $a_g = 0.25 \mu m$, and $M_{\ast} = 2.5 M_{\odot}$, we get $\beta_{sw} = 0.45$. The ratio of the radiation pressure force ($F_{rad}$) to the gravitational force of star ($F_{gr}$) on a dust grain, $\beta_{rad}$, has been computed by Lamy & Perrin (1997) for stars of various spectral types and luminosity classes, two of which bracket the A2V star—these are $\alpha$ Aql (A5 IV–V) and $\alpha$ CMi (F6 IV–V). This study shows that, for silicate grains of radii in the range $0.1–1 \mu m$, $\beta_{rad} \sim 1–3$, i.e., significantly greater than the value of $\beta_{sw}$ derived above. Thus, radiation pressure is much more effective in pushing the grains away from the A2V star than the A2V star’s wind. Adopting an intermediate value, $\beta_{rad} = 2$, the acceleration due to radiation pressure at a radial offset that is (say) halfway between the A2V star and the CS, i.e., at $r = 0''85$, is $\sim7.2 \times 10^{-6} \text{ cm s}^{-2}$ (and varies as $r^{-2}$). Thus, within about 1000 yr, radiation pressure will move the grains that are located (say) halfway between the A2V star and the CS, roughly 100 au or $0''13$ toward the CS. This pressure would push the outer regions of the dust cloud on the side facing the A2V star toward the CS, providing a plausible explanation for the observed flattening of the 18 $\mu m$ intensity contours defining the shape of the dust cloud on the side facing the A2V star. But this process would also lead to an increase in the column density near this edge, which would result in a brightening of the dust emission compared to the outer regions of the dust cloud that are located on the side facing away from the A2V star, contrary to what is observed.

A plausible explanation of why the dust cloud closer to the A2V star does not show enhanced emission is that the wind from the A2V star also destroys some fraction of dust grains via sputtering. For example, Gray & Edmunds (2004) have studied sputtering as a function of impact energy of hydrogen nuclei, and their Figure 2 shows a substantial sputtering yield for impact energies of $\sim1 \text{ keV}$ (H and He nuclei moving at 300 km s$^{-1}$ have energies corresponding to 0.47 and 1.9 keV).

Given the clockwise rotation that we find for the A2V star around the CS, the grains in the dust cloud must also be rotating clockwise (set by the sign of the global angular momentum of the primordial dense core in which these stars were formed). Hence, the dust grains approach the A2V star from the southeast as a result of their orbital motion. When they are far from the separation vector, the dominating force is the gravitational attraction to the CS, but that force becomes progressively less as the grains get closer to the A2V star. The “tail” seen in the 18 $\mu m$ image in the north/northwest direction is thus a signature of grains trapped by the A2V star (as they pass from a dynamical regime dominated by gravitation attraction toward the CS to one that is dominated by attraction toward the A2V star) or perhaps escaping the CS-A2V system (because they pass a region with a very weak net gravitational force).

5.4. The Origin of the Density Discontinuity in the Dust Cloud

The discontinuity in the two-shell dust model suggests the presence of a radial gap in the dust cloud density, at a radius of $\sim350 \text{ au}$. A plausible origin of this gap is the presence of a giant planet or brown dwarf with an initial orbital radius of $\sim10 \text{ au}$; following the mass loss from the central star as described above (Section 5.2), the orbital radius (as in the case of the A2V companion) would increase to $\sim350 \text{ au}$. This giant planet/brown dwarf could then open up a fairly wide gap in the disk—e.g., Crida et al. (2006) have computed gap density profiles using semi-analytic calculations and numerical simulations for a Jupiter-mass planet in a disk, and they find that the widths are comparable or larger than the orbital radius for low viscosities. The migration of the giant planet/ brown dwarf radially outward could also contribute to further broadening the gap. Multiple planets would produce larger gaps but with shallower depths (e.g., see Figure 1 of Duffell & Dong 2015).

6. Conclusions

We have analyzed new imaging data of the central star (CS) of NGC 3132 obtained using its NIRCam and MIRI instruments on board JWST, through a set of filters spanning the 0.9–18 $\mu m$ range. Our main findings are as follows:

1. The CS is located at an angular distance of 1''696 from a bright A2V star to its northeast. We find that these stars form a wide gravitationally bound system, separated by 1277 au and located at a distance of 0.75 kpc from Earth. The proper motions and radial velocities of these stars are consistent within uncertainties. In addition, we detect relative orbital motion between the two stars over a 20 yr period, which is consistent with the expected value from the 25,500 yr period of the binary system estimated from the current separation and assuming an intermediate inclination angle of 45° between the orbital and sky planes.

2. The A2V star outshines the CS at all but the longest wavelength of 18 $\mu m$. Using PSF subtraction of the A2V star, we find that CS is clearly seen in the JWST images even at the shortest wavelength, i.e., at 0.9 $\mu m$. The CS is surrounded by extended emission, seen directly at 18 $\mu m$. Radial intensity cuts show that the emission is extended in the 7.7–12.8 $\mu m$ range as well. This emission, which is surface-brightness-limited, extends to a radius $\gtrsim1600 \text{ au}$ and most likely results from thermal dust emission.

3. We have carried out aperture photometry of the CS in the JWST images. Using these data, together with an archival UV spectrum and published optical photometry, we have constructed the spectral energy distribution (SED) of the CS and its extended emission over the UV to mid-IR (0.091–18 $\mu m$) range. The SED has a very distinctive shape in the $\sim5–18 \mu m$ region.
4. Using dust radiative modeling, we have fitted the SED of the CS and the radial intensity distributions at 7.7, 12.8, and 18 μm with a dust cloud that extends to a radius of \( \geq 1785 \) au. Models with a dust composition of 70% silicate, 30% amorphous carbon, and a modified MRN grain-size distribution that increases the proportion of larger grains, i.e., one in which the number of grains with radius \( a \) varies as \( n(a) \propto a^{-q} \) for \( a = 0.005-0.25 \) μm, with \( q = 1 \), provide the best fit to the specific shape of the SED in the 5–18 μm range. The radial dust optical depth of this cloud is \( \sim 10^{-4} \) at 0.55 μm, and the dust temperature decreases from about 232 to 73 K from the inner to the outer radius. Our best-fit models give a total dust mass of \( (1.3 \pm 0.15) \times 10^{-2} M_{\odot} \) within a radius of 1785 au; the dust mass estimate has a conservative uncertainty of about ±25%.

5. The material in the dust cloud may have come from a pre-existing Oort cloud analog, or it may lie in a disk-like structure produced as a result of binary interaction.

6. The radial extent of the dust cloud is almost identical to the orbital radius of the CS-A2V binary stellar system; the cloud appears flattened on the side facing the A2V star. These features suggest a physical interaction between the disk and the A2V companion, due to a combination of radiation pressure (due to the A2V star’s radiation), together with partial destruction of the dust grains by sputtering (due to a tenuous wind from the A2V star).

7. A plausible evolutionary scenario that explains the spectacular mass ejection that has resulted in the current, multipolar planetary nebula is one in which three stars—the CS, a close low-mass companion (with, say, \( a \lesssim 5 \) au), and a much more distant A2V star (with, say, \( a \sim 400 \) au)—formed a stable hierarchical triple system on the main sequence but then became dynamically active much later, due to the eccentric Kozai–Lidov mechanism causing a strong binary interaction between the inner pair and leading to a loss of most of the primary’s envelope. The resulting severe reduction in the CS mass caused the A2V star’s orbit to expand, resulting in its current separation from the CS.

8. We set an upper limit of \( \sim 0.1 M_{\odot} \) on the mass of any main-sequence star, i.e., spectral type M6V (\( L \sim 7 \times 10^{-4} L_{\odot}, T_{\text{eff}} \sim 2500 \) K) or later, that may be located close enough to the CS to be unresolved and faint enough to be undetectable. Such a star could be the close binary companion in the above evolutionary scenario, provided the binary interaction did not lead to its merger with the CS.

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Appendix

We show here the large-scale structure of the PN, NGC 3132, imaged through the F1800W (18 μm) filter (Figure A1). The image does not show the presence of any extended nebular feature (background or foreground) close to the compact dust clump around the central star (CS).
Figure A1. The PN NGC 3132 imaged with MIRI, through the F1800W (18 μm) filter, displayed using a square-root stretch. The green dashed circle (diameter 5″) encloses the dust cloud around the CS, and the A2V star to its northeast. The panel size is 80″ × 80″.

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