THE NATURE OF THE STRONG 24 μm *SPITZER* SOURCE J222557+601148: NOT A YOUNG GALACTIC SUPERNOVA REMNANT

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ABSTRACT

The nebula J222557+601148, tentatively identified by Morris et al. as a young Galactic supernova remnant (SNR) from *Spitzer* Galactic First Look Survey images and a follow-up mid-infrared spectrum, is unlikely to be an SNR remnant based on Hα, [O III], [S II] images, and low-dispersion optical spectra. The object is seen in Hα and [O III] λ5007 images as a faint, roughly circular ring nebula with dimensions matching that seen in 24 μm *Spitzer* images. Low-dispersion optical spectra show it to have narrow Hα and [N II] $\lambda\lambda$6548,6583 line emissions with no evidence of broad or high-velocity ($v \geqslant 300$ km s^{-1}) line emissions. The absence of any high-velocity optical features, the presence of relatively strong [N II] emissions, the lack of detected [S II] emission which would indicate the presence of shock-heated gas, plus no coincident X-ray or nonthermal radio emissions indicate that the nebula is unlikely to be an SNR, young or old. Instead, it is likely a faint, high-excitation planetary nebula (PN) as its elliptical morphology would suggest, lying at a distance $\sim$2–3 kpc with unusual but not extraordinary mid-IR colors and spectra. We have identified an $m_{r'} = 22.4 \pm 0.2$ star as a PN central star candidate.

Key words: ISM: supernova remnants – planetary nebulae: individual (J222557+601148)

1. INTRODUCTION

Of the 274 Galactic supernova remnants (SNRs) currently known (Green 2009), few are believed to be relatively young with ages of 3000 yr or less. The list of young Galactic SNRs includes the historic guest stars of SN 1604 (*Kepler*'s SNR), SN 1572 (*Tycho*'s SNR), SN 1054 (Crab Nebula), SN 1006 (G327.6+14.6), SN 386 (G11.2−0.3), and SN 185 (RCW 86).

There are also about a dozen remnants that do not have firmly established ages but are probably less than a few thousand years old. These include the recently recognized very young remnant G1.9+0.3 (age $\simeq$ 150 yr; Reynolds et al. 2008; Green et al. 2008) and Cassiopeia A (SN $\approx$ 1680; Thorstensen et al. 2001; Fesen et al. 2006).

With so few young SNRs known, the discovery of even one more young Galactic SNR is significant. Young SNRs are of special interest since they offer a host of details on supernova explosions on finer spatial scales than from extragalactic SNR investigations, including expansion asymmetries, ejecta abundances, and clues regarding the nature of the progenitor star and its pre-SN environment.

Hence the discovery of a small symmetric nebula, SST-GFLS J222557+601148 (hereafter J222557), detected in 24 μm *Spitzer* Galactic First Look Survey (GFLS) images and tentatively identified as a possible SNR with an age $\sim$1000 yr by Morris et al. (2006), is worth investigating. Here we present optical images and spectra which indicate that this nebula is likely not an SNR but instead a faint, high-excitation planetary nebula (PN).

2. OBSERVATIONS

Both narrow and broad passband optical images of J222557 were obtained in 2006 September using a backside-illuminated 2048 × 2048 SITe CCD detector attached to the McGraw-Hill 1.3 m telescope at the MDM Observatory (MDM) at Kitt Peak. The CCD's 24 μm size pixels gave an image scale of 0$.''$508 and a field of view of approximately 17$'$ square.

The nebula was imaged on 2006 September 27 using a pair of matched on and off Hα interference filters centered at 6568 and 6510 Å (FWHM = 30 Å), a [O III] λ5007 filter (FWHM = 30 Å), and a [S II] $\lambda\lambda$6716,6731 filter (FWHM = 50 Å). On September 28, broadband images using a Harris *B* filter were also taken. Individual image exposure times for all filters were 1000 s taken in sets of two or three.

Additional images of J222557 were obtained on 2008 July 30 using the MDM 2.4 m Hiltner telescope with the RETROCAM CCD camera (Morgan et al. 2005). Images were taken using Sloan Digital Sky Survey (SDSS) filters g' and r' with exposure times of 2 × 1200 and 2 × 900 s, respectively. Conditions at the time of the observations were believed to be photometric with seeing around 1$.''$5. Images were flux calibrated with standard stars from Smith et al. (2002). Standard pipeline data reduction of all images was performed using IRAF/STSDAS.[1] This included debiasing, flat-fielding, and cosmic ray and hot pixel removal.

Follow-up low-dispersion optical spectra of J222557 were obtained on 2008 July 31 using the MDM 2.4 m telescope with a Modular Spectrograph and 2048 × 2048 pixel SITe CCD detector. A north–south (N–S) 1$.''$2 × 5$'$ slit and a 600 line mm^{-1} 5000 Å blaze grism was used to obtain 2 × 900 s exposures spanning the spectral region 4300–7500 Å with a resolution of 6 Å. The slit was placed over the bright southeast region as seen in the 24 μm *Spitzer* image. Conditions were good but not photometric with 1$.''$5 seeing. These spectra were reduced and calibrated employing standard techniques in IRAF with standard stars from Strom (1977).

3. RESULTS AND DISCUSSION

As shown in Figure 1, a faint Hα emission shell at the location of J222557 can be seen amidst considerable diffuse Hα emission and numerous dust lanes. In Figure 2, we show enlargements of the Hα, Hα-continuum, and [O III] λ5007 images of this

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[1]   IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. The Space Telescope Science Data Analysis System (STSDAS) is distributed by the Space Telescope Science Institute.
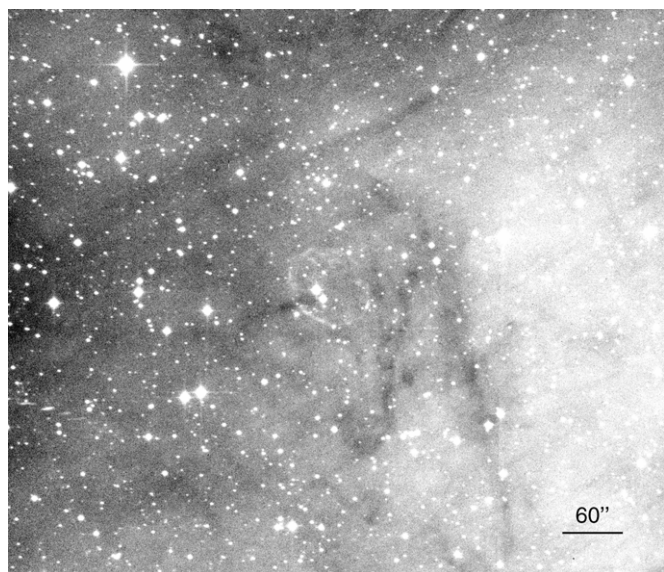
Figure 1. Hα image of the J222557+601148 region showing the detection of a faint emission shell. North is up and east is to the left.

optical shell. The [O III] and Hα-continuum images are shown smoothed by a five-point Gaussian. The optical shell has angular dimensions of $84'' \times 70''$. This size is consistent with dimensions of $86'' \times 75''$ reported by Morris et al. (2006) based on the *Spitzer* MIPS 24 μm image which is also shown, smoothed by a three-point Gaussian. No emission from the shell was seen in the [S II]

$\lambda\lambda 6716,6731$ image despite being of similar or longer exposure times to those of Hα and [O III].

In Figure 3, we present our low-dispersion optical spectra of J222557 taken with an N–S oriented slit positioned along the eastern portion of the ring (see Figure 2, middle panel). Narrow, unresolved (FWHM < 6 Å) emission lines of Hα and [N II] $\lambda\lambda 6548, 6583$ were detected from both southern and northern limbs. No high-velocity emission was detected from either the nebula's shell or from any possible interior emission not visible in our narrow passband images. The observed Hα flux from the brighter southern limb knot is approximately 2.4×10^{-16} erg s^{-1} cm^{-2} with an uncertainty around 50% due to non-photometric conditions. The [N II] $\lambda 6583$ line was stronger than the Hα for both northern and southern portions of the nebula's shell, with $I([N II]\, 6583 + 6548)/I(H\alpha) \simeq 2.7$ for the bright southern knot.

No [S II] $\lambda\lambda 6716,6731$ emission was detected in our spectra from the nebula, consistent with the lack of any emission seen on the narrow passband [S II] image. There was also no [O III] line emission detected in the spectrum despite the detected [O III] $\lambda 5007$ emission from the shell in the [O III] image. We attribute the absence of detected [O III] in the spectrum due to a combination of a $I([O III]\, \lambda 5007/I(H\alpha) \lesssim 1$, considerable line-of-sight extinction as suggested by the numerous dust lanes in the region (see Figure 1), and a lower sensitivity of our spectral setup at 4500–5500 Å compared to the 6000–7500 Å region.

As noted by Morris et al. (2006), there is no previously known optical, radio, or X-ray nebula at the location of J222557.
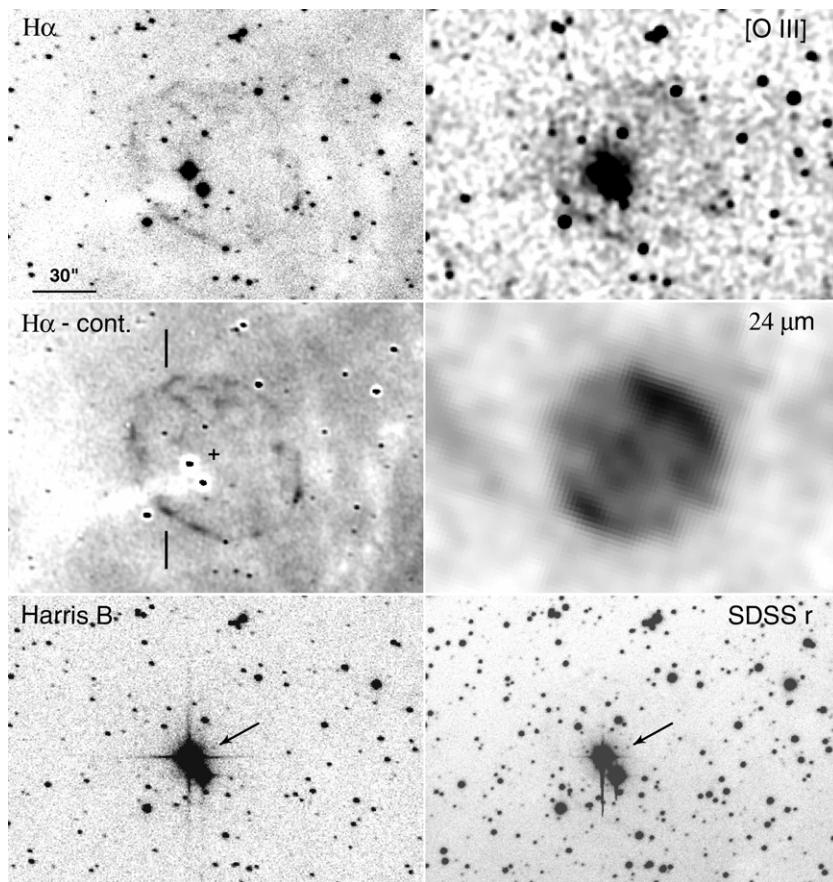
Figure 2. Enlarged optical and infrared images of J222557+601148. North is up and east to the left. Top row: MDM 1.3 m images showing faint Hα (left) and [O III] (right) emission shells. Middle row: Hα minus 6510 Å continuum (left) and 24 μm *Spitzer* MIPS (right). The position where we obtained the optical spectrum using an N–S slit placed across the nebula is indicated in the Hα minus 6510 Å continuum image. Bottom row: broadband Harris *B* and SDSS *r* filter images with the CSPN candidate indicated by the arrows. This star's position relative to the emission shell is shown above in the Hα minus continuum image by a "+" symbol.
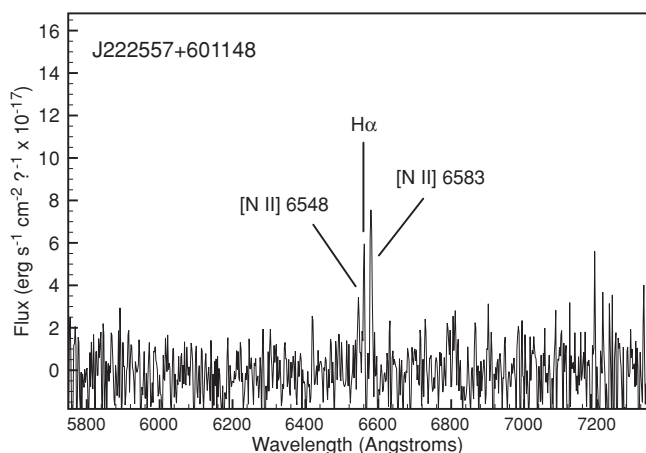
Figure 3. Optical spectrum of J222557+601148 showing narrow Hα and [N II] $\lambda\lambda$6548,6583 line emissions.

The object is not a cataloged PN (Acker et al. 1992) or a known Galactic nebula (Neckel & Vehrenberg 1987), there is no coincident radio source in either the Westerbork 325 MHz Northern Sky Survey (WENSS) or the NRAO Very Large Array Sky Survey 1.4 GHz, and no associated X-ray emission is visible in the *ROSAT* All Sky Survey. The shell is also unlikely to be a Wolf–Rayet ring nebula due to the lack of a luminous point source in the *I* band, Two Micron All Sky Survey, and Infrared Array Camera (IRAC) images. Below, we discuss the nature of the J222557 nebula in light of these optical observations, first discussing a young SNR scenario and then the object as a possible PN.

3.1. A Young Supernova Remnant?

Unusual infrared colors and a pure emission line 7.5–37.5 μm spectrum with no sign of dust continuum or hydrogen emission lines led Morris et al. (2006) to examine the possibility of J222557 being a young SNR. Although SNRs are usually relatively strong emitters of X-rays and nonthermal radio emissions, they argued that the object's lack of any such emissions did not exclude it from being identified as an SNR if the object were relatively distant and/or if the SNR were relatively young with little interaction with the interstellar medium (ISM). They noted that the nebula's size (diameter $\approx 80''$) was consistent with a young SNR at a distance $\sim$10 kpc with an average expansion velocity of a few 1000 km s^{-1}. Such a large distance would also place the object well above the Galactic plane ($z \simeq 400$ pc) which would help explain the lack of ISM interaction and hence its low radio and X-ray luminosity.

As additional support for an SNR identification, Morris et al. (2006) cited J222557's similar morphology and size to the Small Magellanic Cloud (SMC) remnant 1E 0102.2−7219 and the young Galactic SNR Cassiopeia A (Cas A), both of which are oxygen-rich, core-collapse remnants. They noted 1E 0102.2−7219's strong 24 μm emission and absence in other *Spitzer* IR imaging bands (Stanimirović et al. 2005) much like that seen for J222557. Indeed, many SNRs exhibit strong 24 μm emission and a faintness in shorter IR bands and this type of spectral energy distribution (SED) is illustrated in the 3.6, 8.0, and 24 μm composite color image of the young galactic core-collapse SNR G11.3−0.3 shown in Carey et al. (2009).

Morris et al. (2006) also compared J222557's IRS spectrum with that of Cas A (Arendt et al. 1999). They found similar and

consistent line ratios if J222557 had higher shock velocities than Cas A's 150–200 km s^{-1} in the ejected SN material of around 450–500 km s^{-1}.

However, the presence of only narrow Hα and [N II] emissions with no high-velocity ($v \geqslant 300$ km s^{-1}) emission lines seen in either the optical or IR, plus no coincident X-ray or nonthermal radio emissions make an SNR interpretation unlikely. While much of the observed emission structure seen in our optical images is concentrated in a thin shell where large radial velocities would not be expected, there is some interior optical emission (Figure 1) and one of the two *Spitzer* IRS spectra obtained by Morris et al. (2006) was taken of the shell's center yet showed no hint of high velocity.

Our optical spectrum also revealed no emission from [O I] $\lambda\lambda$6300,6364 or [O II] $\lambda\lambda$7319,7330 which would be expected if the nebula contained O-rich ejecta as seen in 1E 0102.2−7219 and parts of Cas A. Moreover, the absence of [S II] $\lambda\lambda$6716,6731, which is the dominant line emission in much of Cas A's ejecta, also greatly weakens an analogy with this remnant.

Morris et al. (2006) also discussed the possibility that J222557 might be a young SNR associated with a thermonuclear Type Ia SN explosion, noting that strong 24 μm emission but weaker emission at 3.6–8 μm has been observed in SNRs associated with this type of SN. For example, Borkowski et al. (2006) studied four Large Magellanic Cloud (LMC) Type Ia remnants and found none were detected in the *Spitzer* IRAC bands. Williams et al. (2006) found a similar situation in some outer regions of the LMC remnants N49 and N63A which were attributed to line emissions from [O VI] 25.9 μm and [Fe II] 24.5 and 26.0 μm.

The morphology of the J222557 nebula certainly resembles the faint thin shells of young Type Ia SNRs such as *Tycho* and several young LMC remnants, and Morris et al. (2006) made a cautious comparison of J222557 to the bilaterally symmetric shell of the Type Ia SN 1006 remnant. Young Type Ia SNRs exhibit a spectrum dominated by low-velocity Balmer lines of hydrogen as a result of high-velocity shocks moving through a partially neutral medium leading to the production of strong narrow and much weaker broad Balmer lines before complete ionization occurs (Chevalier & Raymond 1978; Chevalier et al. 1980; Heng 2010).

However, a young Type Ia SNR scenario for J222557 is also inconsistent with its observed optical spectrum. Elements other than hydrogen are also collisionally ionized in the postshock region and may emit line photons, but in the case of neutral atoms and relatively low-ionization ions, a line's luminosity is proportional to its ionization time and elemental abundance. This leads to relatively weak metal lines compared to the hydrogen Balmer lines. Thus, the [N II] λ6583 line emissions seen in the J222557 spectrum at levels actually stronger than Hα for both north and south rims effectively rules out the optical nebula being due to a fast shock like that seen in the spectra of young Type Ia SNRs.

Finally, the lack of detected [S II] $\lambda\lambda$6716, 6731 in either our deep [S II] image or optical spectra of J222557 is also inconsistent with the J222557 nebula being an older, more evolved SNR. Due to an extended postshock cooling zone in remnants with shock velocities below 1000 km s^{-1}, the presence of strong [S II] emission is one of the chief identifiers of shock heated gas and has been widely used to discriminate between photoionized nebulae such as H II regions and PNe. Virtually all evolved SNRs show [S II]:Hα $\geqslant 0.4$, whereas H II regions

typically exhibit values $\leqslant 0.2$ (Blair et al. 1981; Fesen et al. 1985).

3.2. A Planetary Nebula?

The axial symmetry and limb-brightened emission observed in J222557 are strongly suggestive of a PN nature as Morris et al. (2006) themselves discuss. However, they rejected this identification based on its peculiar infrared colors, the absence of an IR bright central source often seen in PNe, and its *Spitzer* IRS spectrum which showed no continuum emission or hydrogen lines and no dust emission features commonly seen in PNe.

Nonetheless, a PN nature seems more likely given its optical properties. Emission line expansion velocities under $100 \, \mathrm{km \, s^{-1}}$, relatively weak [S II] $\lambda\lambda 6716,6731$ emission ($I([\mathrm{S\,II}])/I(\mathrm{H}\alpha) < 0.2$,) and a morphology consistent with a limb-brightened shell with some interior emission knots are properties frequently seen in PNe. The observed high $I([\mathrm{N\,II}]\, 6583 + 6548)/I(\mathrm{H}\alpha) = 2.7$ ratio is also often observed in PNe due to an overabundance of nitrogen in post-main-sequence mass-loss material (Acker et al. 1989, 1991).

Small ($<1'$) ring and shell morphology nebulae bright at $24 \, \mu$m but faint at 3.6–8.0 μm are not unusual in the Galactic plane and some of these are suspected PNe (Carey et al. 2009; Flagey et al. 2009). J222557's observed infrared flux of less than $0.1 \, \mathrm{MJy \, sr^{-1}}$ at the four IRAC channels (3.6, 4.5, 5.8, and 8.0 μm) but about $10 \, \mathrm{MJy \, sr^{-1}}$ at 24 μm indicates a steeply rising SED. This SED is commonly seen for PNe due in part to significant continuum emission from warm dust (Zhang & Kwok 2009). The bright appearance of PNe in MIPS 24 μm images is due to both dust emission and [Ne v] 24.3 μm and [O IV] 25.9 μm line emissions (Zhang & Kwok 2009).

The chief difficulty in assigning a PN identification to the J222557 nebula lies in an absence of appreciable dust continuum emission. The nebula's non-detection in the four IRAC 3.6–8.0 μm images and the 70 or 160 μm MIPS images (Morris et al. 2006) sets strong limits on the presence of warm or cool dust. The IRS spectrum of J222557 is consistent with the IRAC and MIPS images, showing a purely emission line spectrum with virtually no continuum or dust features, but with strong [O IV] 25.9 μm line emission explaining its detection in the MIPS 24 μm image.

However, Chu et al. (2009) found that the relative importance of nebular line emissions and dust continuum emission in the 24 μm band for PNe depends on the temperature of the central star and distribution of dust and gas in the nebula. Using a sample of 28 PNe, they also found that smaller PNe exhibited 24 μm emission that was more extended than their Hα emission and concluded that this extended 24 μm emission was dominated by dust emission. Larger PNe, in contrast, show much weaker dust emission with the [O IV] line tending to dominate the emission in the MIPS 24 μm band. These results are in accord with Stanghellini et al. (2007) who found the largest PN in the LMC and SMC exhibited the least dust continuum emission.

Our optical spectral data are also consistent with J222557 being a PN in terms of its size. We measured $v_{\mathrm{LSR}} = -70 \pm 20 \, \mathrm{km \, s^{-1}}$ from the observed Hα line emission, which is consistent with galactic rotation at its $l = 105°.8$ and a location inside the Perseus Arm at a distance of 2–3 kpc (Russeil et al. 2007). With $b = 2°.3$, a distance of ≈ 2.5 kpc, J222557 would lie some 100 pc above the Galactic plane. At a distance of 2–3 kpc, J222557's angular radius of $40''$ implies a linear radius of around 0.5 pc $\times$ ($d/2.5$ kpc) which is near the median size of PNe (Cahn et al. 1992; van de Steene & Zijlstra 1994; Ciardullo

et al. 1999; Bensby & Lundström 2001; Frew & Parker 2010). Interestingly, some 20% of all PNe are not detected in the radio and a size $\geqslant 0.5$ pc would indicate a well-evolved PN which might help explain J222557's lack of detected radio emission.

Finally, we have identified a possible planetary nebula central star (CSPN) candidate. A bluish point source near J222557's center is detected in our B, g', and r' images, with $m_{g'} = 22.8 \pm 0.2$ and $m_{r'} = 22.4 \pm 0.2$. Figure 2 (bottom row) shows our Harris B and SDSS r' filter images of the nebula with the candidate central exciting star indicated. This star's location places it nearly centered in the nebula as shown by the cross in the Hα− continuum difference image.

With an uncertain distance and line-of-sight extinction, and only very weak detections in our broadband images, it is difficult to accurately assess the CSPN candidate's intrinsic color or luminosity. At $m_V \approx 22.5$, it would rank among the faintest Galactic CSPN known (Tylenda et al. 1991). However, adopting a distance of 2.5 kpc and an $A_V = 4$ mag based on H I measurements (Kalberla et al. 2005) for $l = 105°.8$ and $b = 2°.3$ and conversions of $N(\mathrm{H})$ into A_V values for a typical gas-to-dust ratio (Bohlin et al. 1978; Predehl & Schmitt 1995), the candidate would have $M_V \simeq 6.5$, a value quite consistent for CSPNs in evolved PNe (Phillips 2005; Benedict et al. 2009). Moreover, given the strength of [O IV], the nebula is likely to have considerable He II emission which would place a lower limit of $\simeq 60,000$ K for the star's effective temperature (Kaler & Jacoby 1989).

4. CONCLUSIONS

Morris et al. (2006) tentatively identified the Galactic nebula J222557+601148 as an SNR based on *Spitzer* GFLS images. However, Hα, [O III], [S II] images, and low-dispersion optical spectra reveal it to only exhibit narrow Hα and [N II] $\lambda\lambda 6548,6583$ line emissions with no evidence of broad or high-velocity line emissions.

The absence of any high-velocity optical or infrared features, the presence of relatively strong [N II] emissions, the lack of detected [S II] emission, which would indicate the presence of shock-heated gas, plus no coincident X-ray or nonthermal radio emissions suggest the nebula is unlikely to be an SNR, young or old. Instead, it is likely a faint, high-excitation PN as its elliptical morphology would suggest, lying at a distance ~ 2.5 kpc with strong [O IV] emission rather than dust continuum emission dominating its detection in 24 μm *Spitzer* images. We have identified a possible central star candidate with $m_{r'} \simeq 22.4$.

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