On the triple-star origin of the planetary nebula Sh 2-71

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ABSTRACT
Recent studies have indicated that triple star systems may play a role in the formation of an appreciable number of planetary nebulae, however only one triple central star is known to date (and that system is likely too wide to have had much influence on the evolution of its component stars). Here, we consider the possibility that Sh 2-71 was formed by a triple system which has since broken apart. We present the discovery of two regions of emission, seemingly aligned with the proposed tertiary orbit (i.e. in line with the axis formed by the two candidate central star systems previously considered in the literature). We also perform a few simple tests of the plausibility of the triple hypothesis based on the observed properties (coordinates, radial velocities, distances and proper motions) of the stars observed close to the projected centre of the nebula, adding further support through numerical integrations of binary orbits responding to mass loss. Although a number of open questions remain, we conclude that Sh 2-71 is currently one of the best candidates for planetary nebula formation influenced by triple-star interactions.

Key words: Planetary Nebulae: Individual: Sh 2-71, PK 036−01 1, PN G035.9−01.1 – celestial mechanics – stars:mass loss – ISM: jets and outflows – ISM: evolution

1 INTRODUCTION

Central star binarity is now the favoured hypothesis for the origins of the most axisymmetric structures found in planetary nebulae (PNe; Jones & Boffin 2017a). However, roughly 10% of solar-type main-sequence stars are found to exist in higher order systems (Raghavan et al. 2010), meaning that these systems may too have an important role to play in PN formation.

In spite of the apparent support for the importance of triples in the formation of PNe, only one confirmed triple central star is known - that of NGC 246 (Adam & Mu-grauer 2014) which is, in fact, so wide that it is unlikely to have played a role in the shaping of the nebula (Bear & Soker 2017). Several other candidates have been found, but none has stood up to rigorous study. The central star of SuWt 2 was frequently cited as a strong candidate triple central star, presenting with a bright binary comprising two, near-identical, A-type stars close to its projected centre (Bond et al. 2002; Exter et al. 2010; Jones et al. 2010). However, the long-term radial velocity study of Jones & Boffin (2017b) led the authors to conclude that the A-type binary was merely a field system found in chance alignment. Similarly, Boffin et al. (2018) found the bright, main-sequence binary close to the projected centre of M 3-2 to also be a chance alignment. A, perhaps, promising candidate is Abell 63 (A 63), the central star of which is known to be a close-binary (being the first such system to be discovered; Bond 1976), but more recently Ciardullo et al. (1999) identified a nearby star (roughly 2.8″ away from the central binary) as a possible wide tertiary companion (finding only a 1.5% chance that the alignment is the result of a chance superposition). The morphology of A 63, however, is rather canonical for a post-CE PN - presenting with a central bipolar/cylindrical region and higher velocity polar ejections, all sharing the same symmetry axis which in turn is perpendicular to the binary orbital plane (Mitchell et al. 2007; Hillwig et al. 2016). Thus, the PN morphology offers no indication that the possible tertiary companion has played any role in the formation of the nebula itself.

Soker (2016) demonstrated that perhaps the lack of known surviving triple central stars could be a result of the difficulties of surviving a common envelope (CE) phase. In some cases, the binary system may be completely destroyed, merging with the nebular progenitor, or could merge with one another to leave a single companion (Hillel et al. 2017).
Furthermore, due to tidal forces and mass-loss as the nebular progenitor ascends the AGB, the stability of the system may be reduced even before reaching a CE phase, perhaps leading to the ejection of one component of the binary system, leading to a wide variety of possible central star configurations (as discussed in detail in section 3.2.1 of Soker 2016).

Sh 2-71 (α = 19h02m00.29s, δ = +02°09’10.97”", PN G035.9−01.1) was discovered by Minkowski (1946) and classified as a “diffuse and peculiar” nebulosity. The object was then later included in the catalogue of HII regions by Sharpless (1959) with the caveat that it may be a PN – a classification which has since been made more definitive by later spectroscopic studies (Chopinet & Lortet-Zuckermann 1976; Bohigas 2001). The detailed spectroscopic study of Bohigas (2001) revealed the PN to be of Peimbert Type i, showing strong signs of shock excitation and significant density variations across the nebula. Furthermore, they reported the requirement for an extremely hot central star (T ∼ 130000 K) consistent with estimate of Feibelman (1999) based on comparison of archival IUE spectra with similar data from other hot central stars.

All of the aforementioned studies confirm the need for a hot central star, however the bright star observed close to the nebular centre (labelled A in figure 1) was found by Kohoutek (1979) to present with colours consistent with a B8V classification. Kohoutek (1979) also showed the star to be variable, concluding that it was likely in a close binary system with the hot nebular progenitor. Since then, there has been much debate around the identity of the true central star, with Frew & Parker (2007) suggesting that the faint, blue star to the North-West of A (labelled B in figure 1) might be a better candidate. The detailed analysis of A by Močnik et al. (2015) concluded it to be a rather exotic system consisting of a Be binary with a misaligned, precessing disc. They surmise that the companion could be a low-mass subdwarf which would then be the nebular progenitor, however they find no definitive evidence for such a hot component in the system.

Based on the nebular morphology, Bear & Soker (2017) classify Sh 2-71 as likely to have originated from a triple system, claiming that the pronounced lack of axial and/or mirror-symmetry is characteristic of such interactions. Furthermore, the hydrodynamical simulations of Akashi & Soker (2017) show that jets launched from a binary system in an inclined orbit with a tertiary AGB companion result in PN morphologies and density variations remarkably similar to those observed in Sh 2-71. This leads us to consider here the possibility that both binary A and star B form or once formed a triple system, the interacting evolution of which led to the formation of Sh 2-71. Section 2 presents the discovery of two extended regions of emission several arcminutes from the central PN shell - the formation of which may be related to the interacting history between binary A and star B. In section 3, we consider the possible history of the A-B system and assess the plausibility of such a configuration resulting in the currently observed positions and proper motions, while in section 4 we conclude with a discussion and outline of possible future analyses.

2 EXTENDED EMISSION REGIONS

Sh 2-71 was observed on 2011 April 25 using the Wide Field Camera (WFC) instrument mounted on the 2.5-m Isaac Newton Telescope (INT) at the Observatorio del Roque de Los Muchachos on the Spanish island of La Palma. Seven 400s exposures were acquired through the Hα+[Nii] filter (ING filter ID#197, central wavelength of 6568Å, FWHM of 95Å) with binning 1×1 for a pixel scale of 0.33‘‘×0.33‘‘, where the four mosaiced chips of the WFC cover a field of view of approximately 34‘×34‘’. The resulting images were debiased, flat-fielded and stacked using standard IRAF routines.

The deep and wide-field nature of the observations reveal, for the first time, the presence of extended knots of emission several arcminutes away from the central nebula as highlighted in figure 2. The bandpass of the filter employed covers Hα as well as both [Nii] 6548Å and 6583Å lines, as such it is not clear as to whether the knots are Hα-bright, [Nii]-bright or both. The features present as faint filamentary structures superimposed on the diffuse background emission associated with the nearby Hii region located to the East (KC97c G036.3−01.7; Kuchar & Clark 1997). As such, in Figure 2 the two emission regions are shown as cutouts with different display stretches in order to fully outline their structures against the varying diffuse background (which shows an appreciable gradient across the image).

The emission features are found in roughly the East-West direction, almost perpendicular to the apparent sym-

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1 It is important to note that the IUE aperture covers a 10‘‘×23‘‘ region which includes both binary A and star B.
metric axis of the central nebular region which extends North-South. Intriguingly, the emission regions lie relatively close to line connecting binary A and star B, with the position angle between the two knots of emission being roughly 100° while the position angle connecting star B to binary A is 136°. Given the location of the newly discovered features (approximately equidistant from and symmetrically placed around the centre of Sh 2-71) as well as their apparent structure (filamentary c.f. the diffuse background), we conclude that they are indeed related to Sh 2-71 and perhaps a consequence of the evolution of the central star(s). We will elaborate further on possible formation scenarios for these features in Sec. 3.4.

3 THE TRIPLE HYPOTHESIS

In Sh 2-71, a binary star with a very peculiar variability pattern but insufficient temperature to ionize the nebula (star A) is projected close to another hot star. The nebula Sh 2-71 itself exhibits an irregular morphology, which has been attributed to interactions in a close triple star system. One may thus consider the hypothesis that at some time the binary system A was much closer, and indeed bound, to the faint, (likely) nebular progenitor, star B. For this to be the case, binary A and star B would have to be at approximately the same distance. Gaia parallaxes put binary A at a distance of 1.62±0.09 kpc (Gaia Collaboration et al. 2016; Bailler-Jones et al. 2018), but unfortunately the faintness of star B prevented a meaningful parallax measurement. As a proxy, one can use the distance to the PN itself. While PN distances are notoriously difficult to derive, the Hz surface brightness-radius relationship of Frew et al. (2016) places Sh 2-71 at a distance of 1.52±0.54 kpc – consistent with that of binary A. Stars A and B are separated by 7.4”, which corresponds to a minimum physical separation of 1.2×10^4 AU at this distance.

Binary A was found by Močnik et al. (2015) to comprise a 2.6 M⊙ B8V star and a low-mass companion. Močnik et al. (2015) did not explicitly determine the orbital period $P_{A\bot}$, but estimated that it is a few days. We label the semi-major axis corresponding to $P_{A\bot}$ as $a_{A\bot}$. Furthermore, Močnik et al. (2015) concluded that the peculiar 68-day period photometric variability, analyzed in detail by Mikulášek et al. (2005, 2007), is the result of obscuration by a precessing disc on a longer period than $P_{A\bot}$. It is thus plausible that formation of such an unstable configuration requires strong mass transfer or a CE event within the binary (e.g. Han et al. 2002, 2003; Jusitham et al. 2011). Star B could have played a significant role in the formation of A either through direct mass transfer (Soker 2004) or by forcing the components of A to strongly interact by the action of Lidov-Kozai cycles (e.g. Fabrycky & Tremaine 2007; Thompson 2011; Perets & Kratter 2012; Shappee & Thompson 2013; Pejcha et al. 2013; Michaeły & Perets 2014; Naoz & Fabrycky 2014; Naoz 2016).

In our fiducial scenario, summarized in Figure 3, binary A and star B were initially much closer and in a bound orbit. The original orbital period of binary A was much greater than that currently observed, $P_{A\bot} \gg P_{A\bot}$. The action of Lidov-Kozai cycles induced by star B would shrink the orbit of A to the current value, possibly inducing mass transfer or a CE thus explaining the peculiar properties of A. Eventually, star B ascended the AGB and lost a significant fraction of its mass, which caused star A to move farther away or end up on an unbound trajectory. We test this hypothesis with simple analytic estimates (Sec. 3.1) and numerical calculations of binary orbit breakup (Sec. 3.2). We perform more consistency checks with observations (Sec. 3.3) and discuss variations on our fiducial triple hypothesis (Sec. 3.5).

3.1 Analytic estimates

If the total mass of binary A is $M_A \sim 3 M_\odot$ (consistent with the estimates of Močnik et al. 2015), then the central star B should have initially been rather massive, $M_B \geq M_A$, to have contemporaneously evolved to its current state2. This high mass would imply that star B has left a roughly $M_{\text{rem}} \approx 1 M_\odot$ remnant. Isotropic mass loss from one component of a binary system will cause the orbit to widen or even break apart. The conditions separating these two outcomes were summarized by Michaeły & Perets (2019).

Let us first consider the case of binary breakup. This happens, for example, when a binary on a circular orbit instantaneously loses more than half of its total mass. Consequently, we assume that $M_B \sim 5 M_\odot$ noting that eccentricity and slow mass loss will allow a range of $M_B$, as we show in Section 3.2. After breakup, the two components fly away with velocities similar to their instantaneous orbital velocity, $v_{\text{orb}} \sim v_{\text{orb}}$. From this velocity, we can put a constraint on the original orbital semi-major axis of A and B, $a_{A\bot}$. The observational constraints on the relative velocity of A and B are uncertain and are discussed in more detail in Section 3.3. For the purposes of analytic estimates, we assume that the relative velocity is $v_{\text{orb}} \approx 4 \text{ km s}^{-1}$ (see Sec. 3.3 for the derivation of this estimate). The semimajor axis $a_{A\bot}$ corresponding to this velocity, assuming circular orbit, was thus

$$a_{A\bot} \sim \frac{G(M_A + M_B)}{v_{\text{orb}}^2} \sim 440 \text{ AU} \left( \frac{8 M_\odot}{M_A + M_B} \right) \left( \frac{4 \text{ km s}^{-1}}{v_{\text{orb}}} \right)^{-2},$$

(1)

and the orbital period was

$$P_{A\bot} = \frac{2 \pi a_{A\bot}}{v_{\text{orb}}} \approx \frac{2 \pi a_{A\bot}}{v_{\text{orb}}} \sim 3300 \text{ yr} \left( \frac{8 M_\odot}{M_A + M_B} \right) \left( \frac{4 \text{ km s}^{-1}}{v_{\text{orb}}} \right)^{-3}.$$

(2)

The constraint on $P_{A\bot}$ is very sensitive to $v_{\text{orb}}$, which in turn depends on uncertain spatial kinematics of binary A, star B, and the PN.

Returning to the possibility that a Lidov-Kozai interaction between binary A and star B could have resulted in the unusual properties of binary A, the timescale connected

\footnote{Technically, star B need only be more massive than the most massive component of A. However, since A likely experienced a rather complex mass transfer history, we consider the conservative case that the evolution of A roughly depends on its total mass.}
with such interactions is

\[ \eta_{\text{LK}} = \frac{8}{15\pi} \frac{M_A + M_B}{M_B} \frac{P_{\text{A},i}^2}{P_{\text{A},i}^2(1 - e_{\text{AB}}^2)^{3/2}} \sim 11 \text{Myr} (1 - e_{\text{AB}}^2)^{3/2} \left( \frac{P_{\text{A},i}}{100 \text{days}} \right)^{-1}, \quad (3) \]

where \( e_{\text{AB}} \) is the eccentricity of the outer orbit (Naoz 2016). In this estimate, we assumed a rather arbitrary value of \( P_{\text{A},i} = 100 \) days to allow for easy rescaling. If Lidov-Kozai cycles operate efficiently and generate high-eccentricity periastron passages, \( P_{\text{A},i} \) decreases due to dissipative processes such as tides or mass transfer. Ultimately, the orbital period stabilizes near its current value \( P_{\text{A},f} \). Our estimate of \( \eta_{\text{LK}} \) is still considerably shorter than the lifetime of a 5 \( M_\odot \) star, at around \( 100 \) Myr (Eggleton 2006, Eq. 2.4).

The mass loss from B could have been sufficiently slow or the total mass lost too small to break up the binary. In this case, stars A and B are still bound on a wide orbit. Without knowing how much mass was lost, we have no handle on \( a_{\text{AB},i} \) and hence no constraint on \( \eta_{\text{LK}} \). However, a bound orbit gives a very specific prediction for the mutual velocity \( v_{\text{AB}} \) of two stars with separation \( r \)

\[ v_{\text{AB}}^2 = G(M_A + M_{\text{rem}}) \left( \frac{r}{2} - \frac{1}{a_{\text{AB},f}} \right). \quad (4) \]

In our case, \( M_{\text{rem}} = 1 M_\odot, r \gtrsim 1.2 \times 10^4 \text{ AU from the projected position on the sky, and } 2a_{\text{AB},f} > r \) from the properties of an elliptical orbit. If the mutual velocity of A and B is found significantly in excess of the highest possible velocity given \( r, \sqrt{2G(M_B + M_{\text{rem}})} / r \approx 0.8 \text{ km s}^{-1} \), then A and B cannot be bound.

### 3.2 Numerical integrations

Evolution of hierarchical triples (or higher multiplicity systems) with tidal effects, stellar evolution, mass transfer, and CE evolution is challenging and has only been attempted in a handful of cases (Hamers et al. 2013; Hamers 2018; Hamers & Dosopoulou 2019; Lu & Naoz 2019). If mass ejection occurs, the commonly employed double averaging of the orbits breaks down and the system should be studied with direct integration. Focusing on this dynamical phase, Michaely & Perets (2019) studied the orbital properties of bound companions to post-CE binaries and constrained the duration of CE to \( t_{\text{CE}} \sim 10^3 \) to \( 10^5 \) years. Following their ideas, we can quantify the constraints illustrated in Section 3.1 and place limits on the mass ejection timescale \( t_{\text{CE}} \) from star B.

Inspired by Michaely & Perets (2019), we employed the software package REBOUND (Rein & Liu 2012) to calculate evolution of two orbiting point masses. The bina-

![Image of Sh 2-71](image-url)
The triple-star origin of PN Sh 2-71

Figure 3. Summary of our fiducial triple model for Sh 2-71 and stars A and B. We start with an hierarchical triple system, where the inner binary A with period $P_{A,i}$ is orbited by companion B with orbital period $P_{AB,i} \gg P_{A,i}$. Star B causes Lidov-Kozai oscillations in binary A, which are accompanied by tides, mass transfer, or common envelope evolution. This leads to formation of a short-period binary, $P_{A,f} \ll P_{A,i}$, with peculiar photometric variability currently observed in A. Star B is initially more massive than A and ejects its envelope seen today as the PN Sh 2-71. The mass ejection disrupts the orbit of A and B and both objects fly away with velocity $v_{AB}$.

Figure 4, we present the fraction of disrupted binaries as a function of initial $M_B$, $a_{AB,i}$, and $t_{ml}$ when marginalized over initial eccentricity and true anomaly. Binaries disrupt only if $t_{ml}$ is approximately shorter than the initial orbital period, as expected. Even binaries which lose less than half of their total mass can be disrupted for certain eccentricities, but the probability is lower. For each initial $M_B$ and $a_{AB,i}$, we also show the median mutual velocity of the binary after breakup (white contours). Binaries with larger $a_{AB,i}$ lead to slower disruption, but mutual velocities also decrease close to bound/unbound boundary. There is order of unity scatter in the mutual velocities after disruption. We also show contours of $t_{LK}$ (Eq. [3]), but only when it is shorter than the main sequence lifetime of star B (Eq. 2.4 of Eggleton 2006).

3.3 Observational constraints

Figures 4 and 5 suggest that the past evolution of A and B can be constrained from their precise relative velocity. The proper motion difference of A and B from Gaia DR2 is $2.3 \pm 1.4$ mas yr$^{-1}$ (Gaia Collaboration et al. 2016), which at the distance of A (and likely also Sh 2-71) corresponds to tangential velocity of $18 \pm 11$ km s$^{-1}$. The large uncertain-
ties on the proper motion values of the faint star B have a detrimental impact on derivation of both the direction\(^3\) and magnitude of proper motion difference, limiting the usefulness of these estimates for our purposes.

There is an alternative way of estimating the relative velocity of A and B. If the disruption of the original binary occurred at the same time as the Sh 2-71 was ejected, the relative position of A with respect to the bright nebular shell gives us an approximation of the ratio of projected velocities. Binary A is roughly quarter-way between star B and the nearest “wall” of the nebula, implying that the orbital velocity at break-up could be roughly one quarter of the PN expansion velocity. The expansion velocity of the PN was found by Sabbadin (1984) to be \(v_{\text{PN}} \approx 16\, \text{km s}^{-1}\), implying a break-up velocity of \(v_{\text{orb}} \approx 4\, \text{km s}^{-1}\). Finally, the difference in systemic velocities between binary A and the PN was found by Močnik et al. (2015) to be of order \(2\, \text{km s}^{-1}\).

All of this information together suggests that the relative velocity of A and B is likely few \(\text{km s}^{-1}\). As an illustration of what can be inferred from the relative velocity, we now assume that it was measured to be \(4\, \text{km s}^{-1}\), as suggested by the relative positions of A, B and the PN. From Figure 5 and Equation (4), we see that a bound orbit for A and B is very unlikely. Instead, A and B have to be on an hyperbolic trajectory. Figure 4 then illustrates that the timescale for mass-loss \(t_{\text{ml}}\) had to be shorter than about \(10^4\) years. For longer \(t_{\text{ml}}\), only binaries with wide \(a_{\text{AB,i}}\) and slow \(v_{\text{orb}}\) are disrupted, which result in too small relative velocities \(v_{\text{AB}}\). Finally, unless \(t_{\text{ml}} \lesssim 10^2\) years (inconsistent with typical PN

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\(^3\) Indeed, the direction of proper motion difference is found not to be aligned with the axis between A and B, but with particularly large uncertainty.
formation timescales, e.g; Szyszka et al. 2011), a relatively high $M_\text{B}$ would be required to explain the relative velocity. As previously highlighted, for binary A and star B to be coeval and to accommodate the kinematical constraints on A and B, the initial mass of star B would have had to be rather massive. Sh 2-71 was classified by Bohigas (2001) as a Peimbert type i nebula - a classification generally associated with massive progenitors (Phillips 2005).

A further consistency check can be performed using the observed properties of star B. Firstly, one can ask: are the observed colours of the star (for example, those provided in the second data release of the VPHAS+ survey; Drew et al. 2014, as shown in Table 1) consistent with a post-AGB star, with a post-AGB age roughly comparable to that of the PN at ~ 10 kyr, while originating from a sufficiently high-mass progenitor? The $5 M_\odot$ track of Vassiliadis & Wood (1994) reaches $\log T_{\text{eff}}=5.2$, consistent with the temperature of the ionising source required to reproduce the observed nebular spectrum (Bohigas 2001; Preite-Martinez et al. 1989), at approximately 10 kyr. A blackbody of that temperature, accounting for an extinction of E(B-V)=0.64 (Frew et al. 2016) and assuming the reddening law of Cardelli et al. (1989), would have colours $u-g= -0.92$ (c.f. 0.97±0.09 in VPHAS+), $g-r = 0.34$ (c.f. 0.4 ± 0.09) and $r-i = 0.21$ (c.f. 0.26 ± 0.12) - perfectly consistent with those values observed (see Table 1). Furthermore, scaling for the model luminosity of log$L/ L_\odot$= 2.0 at that point on the track and placing the system at the Gaia distance of binary A, the predicted observed apparent magnitudes (calculated using synphot; STScI Development Team 2018) shown in Table 1 are strikingly similar to those observed especially considering the various uncertainties involved (distance, reddening, evolutionary track, blackbody assumption).

### 3.4 The origins of the extended emission regions

Within the context of our fiducial model, it is interesting to consider the possible origins of the newly-discovered extended emission regions described in Section 2. As the PN originating from B expands, binary A accretes material
within its Bondi-Hoyle-Lyttleton radius $r_{\text{BHL}} = 2GM/v_{\text{PN}}^2 \sim 21\text{ AU}(v_{\text{PN}}/16\text{ km s}^{-1})^{-2}$. The fraction of material accreted on A is about $r_{\text{BHL}}/a^2 \sim 0.04(a/100\text{ AU})^{-2}$, where $a$ is the instantaneous separation of A and B. As the PN expands, $a$ increases as the binary loses mass and the PN velocity at A either stays constant or decreases depending on the PN velocity profile. The PN material captured by A will be accreted onto the binary likely through a circumstellar disk and smaller disks around individual components (Soker 2004). Spiral modes excited in the circumstellar disk can further remove angular momentum from the orbit (e.g. Artymowicz & Lubow 1996; Muñoz et al. 2019), although this effect is likely much smaller than the previous evolution driven by Lidov-Kozai. It is tempting to speculate that the putative obscuring disk responsible for the peculiar 68-day photometric variability in A (Mońkin et al. 2015) is a remnant of this phase, although the plausibility of this speculation depends on the disk mass and lifetime, which remain uncertain. Nonetheless, we expect that a fraction of the circumbinary material will be mixed and shocked due to binary motions and will be accelerated to leave the system with roughly the binary orbital velocity, $v_{\text{orbA}} = \sqrt{GM_A/a_{\text{A}}^3} \sim 180\text{ km s}^{-1}$, where $a_{\text{A}}$ is the current semi-major axis of the binary in A, which we assume to have orbital period $P_{\text{A}} \approx 5\text{ days}$. This is about ten times higher than $v_{\text{PN}}$ and the binary-accelerated material would thus be located at proportionally larger distances from the PN center.

Figure 2 shows that the extended emission is located roughly five times further out than the PN edge - vaguely consistent with the hypothesis considered providing one allows for deceleration due to interaction with surrounding interstellar medium. We note that different mass ejection mechanisms from binary stars will lead to different ejection velocities and correspondingly different positions of the putative ejecta. We expect the velocities to range from escape velocity from a stellar surface (or higher if a magnetohydrodynamic jet operates; Huarte-Espinosa et al. 2012) to the escape velocity from an outer boundary of a circumstellar disk, which is lower than the binary orbital velocity. Nonetheless, $v_{\text{orbA}}$ provides a rough scaling sufficient for our order-of-magnitude estimates. A more detailed analysis would be warranted once we know with greater certainty the origin of the extended emission and the orbital properties of star A.

The extended emission could, alternatively, be associated with binary evolution in A. One may speculate that they could be the product of non-conservative mass transfer in A, perhaps driven by Lidov-Kozai interactions with B, or dense wind from B focused into the orbital plane with A (perhaps during periastron passage, a dynamical instability, or a thermal pulse event on the AGB). However, this would require significant mass loss in A happening almost concurrently with PN ejection in B due to short visibility times associated with both the PN and the extended emission regions compared to stellar lifetimes.

### 3.5 Variations on the triple hypothesis

We now discuss several variations of our fiducial scenario as presented in Figure 3.

#### 3.5.1 Inefficient Lidov-Kozai

Firstly, binary A could have evolved to its current state independently of B. In particular, the Lidov-Kozai cycles might have been inefficient, for example due to unfavorable relative inclination of the orbits. Binary A would have evolved essentially in isolation and any strong binary evolution processes must have happened a sufficiently long time ago, because the components of A are too cool to ionise Sh 2-71 (based on the various estimates detailed in Sec. 1). Removing the Lidov-Kozai constraint does not significantly affect our conclusions, except that we would require $M_A > M_B$ to have A evolve before B. This is not impossible, even though the probability of disrupting the binary by PN ejection from B is somewhat lower as can be seen from Figure 4. The Lidov-Kozai constraint would become important for $v_{\text{AB}} \lesssim 2\text{ km s}^{-1}$.

#### 3.5.2 Triple CE evolution

It is possible that Sh 2-71 experienced a true triple CE ejection, where all three stars strongly interacted, ejected B’s envelope, and formed the peculiar binary A. We cannot exclude or straightforwardly constrain this scenario, because it has not been sufficiently theoretically explored. Although we do not require triple CE ejection to explain Sh 2-71, the odds might change in the future if more observational data cannot be accommodated within our model or its modifications. Furthermore, Sh 2-71 offers us a potential system with which to probe kicks associated with PN ejection if we were able to accurately measure the true space velocities of stars A and B.

#### 3.5.3 Higher order multiplicity

Given that we know so little about star B, it is possible that is was initially (or may still be) a binary star as well, thus making the Sh 2-71 progenitor system a quadruple of 2+2 hierarchy. This setup would not significantly affect our scenario except for changing the main-sequence lifetime of B and potentially making the Lidov-Kozai cycles more efficient (e.g. Pejcha et al. 2013; Fang et al. 2018).

### 4 DISCUSSION AND CONCLUSIONS

Based on the inferred properties of stars A and B and a few simplifying assumptions, we have shown that it is plausible that at some point binary A formed a triple system with star B. The interactions within such a triple system

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**Table 1.** VPHAS+ photometry of star B (Drew et al. 2014), alongside synphot model magnitudes for a post-AGB star (of initial mass 5 $M_\odot$; Vassiliadis & Wood 1994) at the distance of binary A.

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<thead>
<tr>
<th>Band</th>
<th>VPHAS+</th>
<th>Synphot</th>
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<tbody>
<tr>
<td>u'</td>
<td>19.23</td>
<td>±0.05</td>
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<tr>
<td>g'</td>
<td>20.20</td>
<td>±0.04</td>
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<tr>
<td>r'</td>
<td>19.80</td>
<td>±0.05</td>
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<tr>
<td>i'</td>
<td>19.34</td>
<td>±0.07</td>
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as star B (the nebular progenitor in this scenario) lost its AGB envelope could feasibly have led to the formation of the unusual precessing disc found by Močnik et al. (2015) in binary A. Similarly, mass transfer between star A and binary B could have led to the formation of jets (perhaps blown from the disc in binary A) which directly impacted upon the shaping of the nebula - leading to the “messy” morphology of the PN (considered to be a tell-tale sign of triple interactions; Akashi & Soker 2017; Bear & Soker 2017) as well as the observed shocks (Bohigas 2001). Furthermore, the newly identified extended emission regions, lying several arcminutes away from the centre of the PN but approximately aligned with the current positions of binary A and star B, may well be signposts of interactions within binary A or between binary A and the mass lost from star B during the PN formation episode.

While the proposed triple scenario for Sh 2-71 is apparently plausible, and perhaps even favourable in explaining the nebular morphology, the ultimate test of this hypothesis will likely be improved parallax and proper motion measurements later in the Gaia mission. Such measurements will hopefully prove conclusive in assessing the association of star B not only to binary A but to the PN itself. Tracing the PN expansion relative to A and B, for example with two well-separated epochs of high-resolution images, could further elucidate the kinematics and past evolution of the system. Alternatively, one may consider a spectral analysis of star B to check whether it is consistent with a high mass remnant (as implied by the relative evolutionary timescales discussed in Sec. 3) and/or whether its radial velocity is coincident with that of the systemic velocity of the nebula. Understanding the peculiar variability of A could shed more light on its relation with the PN ejection. Similarly, UV observations of binary A could be used to search for the presence of the proposed hot subdwarf nebular progenitor. Unfortunately, none of these observations would be easy given the dearth of UV observatories and the very faint nature of star B. However, they could prove critical in understanding the origins of this fascinating nebula.

In conclusion, the fact that the currently available observations of Sh 2-71 stand-up to the (somewhat circumstantial) tests to which they have been subjected here means Sh 2-71 remains one of the most promising candidates to host (or rather have hosted) a triple central star.

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