Unseen companions of V Hya inferred from periodic ejections

Jesus M. Salas,1,⋆ Smadar Naoz,1,2 Mark R. Morris1 and Alexander P. Stephan1,2

1 Department of Physics & Astronomy, University of California, Los Angeles, CA 90095, USA
2 Department of Physics and Astronomy, Mani L. Bhaumik Institute for Theoretical Physics, University of California, Los Angeles, CA 90095, USA

Accepted 2019 May 28. Received 2019 May 5; in original form 2019 February 15

ABSTRACT

A recent study using Hubble Space Telescope observations found periodic, high-speed, collimated ejections (or ‘bullets’) from the star V Hya. The authors of that study proposed a model associating these bullets with the periastron passage of an unseen, substellar companion in an eccentric orbit and with an orbital period of ∼8 yr. Here we propose that V Hya is part of a triple system, with a substellar companion having an orbital period of ∼8 yr, and a tertiary object on a much wider orbit. In this model, the more distant object causes high-eccentricity excitations on the substellar companion’s orbit via the Eccentric Kozai–Lidov mechanism. These eccentricities can reach such high values that they lead to Roche-lobe crossing, producing the observed bullet ejections via a strongly enhanced accretion episode. For example, we find that a ballistic bullet ejection mechanism can be produced by a brown-dwarf-mass companion, while magnetically driven outflows are consistent with a Jovian-mass companion. Finally, we suggest that the distant companion may reside at few a hundred astronomical units on an eccentric orbit.

Key words: binaries: general – stars: evolution – stars: kinematics and dynamics.

1 INTRODUCTION

Observations of the Hubble Space Telescope (HST) over the past two decades have revealed an enormous complexity and diversity of structure in planetary nebulae (PNe; Balick & Frank 2002; Sahai, Morris & Villar 2011). HST surveys have revealed that more than half of PNe are bipolar or multipolar whereas mass-loss during the AGB phase is mostly spherical. This led Sahai & Trauger (1998) to propose that high-speed, collimated (jet-like) outflows during the late AGB phase that can change their orientation could be the reason behind the asymmetric morphology of PNe. These jets could be driven by interactions with a binary companion (Morris 1987); however, direct evidence supporting this idea has been lacking.

The carbon star V Hya is one example where there exists evidence for high-speed, collimated outflows (Lloyd Evans 1991; Knapp, Jorissen & Young 1997; Sahai & Trauger 1998; Sahai et al. 2003; Hirano et al. 2004; Sahai, Sugerman & Hinkle 2009). A recent study by Sahai, Scibelli & Morris (2016) presents new HST observations that span more than a decade and provide, with an unprecedented and detailed view, the extended history and characteristics of the bullet-like ejections from V Hya. Their data show that these high-speed (∼200–250 km s−1) bullets are ejected once every ∼8.5 yr, and that the axis of ejection flip-flops around a roughly eastern direction, both in and perpendicular to the sky plane.

To account for this phenomenon, Sahai et al. (2016) proposed a model in which the bullets are associated with the periastron passage of a binary companion in an eccentric orbit with an orbital period of ∼8.5 yr. The bullets are likely ejected from an accretion disc formed around the companion that results from the gravitational capture of matter levitated into the primary’s wind-formation zone, and perhaps directly from the primary’s pulsating atmosphere. However, this hypothesis faces the difficulty that tidal forces between binary companions tend to shrink and circularize their orbits, or even cause mergers. To overcome this problem, we here propose a more elaborated model in which V Hya is part of a triple system. In such a system, a relatively distant third object can impose an eccentric orbit on the inner companion, and even lead to Roche-limit crossing, thus allowing the inner companion to accrete and eject mass.

Studies of stellar populations have shown that multiple star systems are very common, with ∼50 per cent of Sun-like stars having binary companions, and even higher fractions (∼70 per cent) are found for higher-mass stars (e.g. Raghavan et al. 2010). Moreover, it seems that many of these binaries are in triples or higher multiples. For example, Tokovinin (1997a) showed that ∼40 per cent of short-period binary stars with a low-mass (<0.5–1.5 M⊙) primary have at least one additional companion. Furthermore, among contact binaries it seems that about 42 per cent are in a triple configuration (e.g. Pribulla & Rucinski 2006). These and many other observational endeavours have revealed that triple star systems are common (e.g. Tokovinin 1997b; Tokovinin et al. 2006; Eggleton, Kiseleva-Eggleton & Dearborn 2007; Griffin 2012. See also Tokovinin 2008, 2014a,b).

⋆ E-mail: jesusms@astro.ucla.edu
Dynamical stability considerations dictate that triple systems must be hierarchical in scale, in which the (‘inner’) binary is orbited by a third body on a much wider (‘outer’) orbit. In this set-up, the inner binary undergoes large-amplitude eccentricity and inclination oscillations due to the ‘Eccentric Kozai-Lidov’ (EKL) mechanism (Kozai 1962; Lidov 1962). For a review, see Naoz (2016). These eccentricity excitations can drive the inner binary to have very small pericenter distances and even to merge (e.g. Naoz & Fabrycky 2014; Prodan, Antonini & Perets 2015; Naoz 2016; Stephan et al. 2016; Stephan, Naoz & Zuckerman 2017; Stephan, Naoz & Gaudi 2018).

The star V Hya is currently in its AGB stage with a mass of ∼1–2 M⊙ and a radius of ∼2 au (see Zhao-Geisler et al. 2012). The rapid evolution of an AGB star in a triple system can play a major role in the dynamical evolution of such a system (e.g. Perets & Kratter 2012; Shaplee & Thompson 2013; Michaely & Perets 2016; Naoz et al. 2016; Stephan et al. 2016; Toonen, Hamers & Portegies Zwart 2016; Stephan et al. 2017, 2018). For example, as the AGB star loses mass, it can reduce the separation ratio between the inner and outer orbits, thus re-triggering EKL eccentricity excitations (Shaplee & Thompson 2013). In addition, as the star expands, tidal forces become more efficient since tidal forces are highly sensitive to the stellar radius.

In particular for the V Hya system, EKL combined with post-main-sequence stellar evolution can drive the inner binary to very high eccentricities and even cause it to undergo Roche-lobe crossing, inducing the secondary object to accrete material from its companion, and perhaps eject some of this material lobe crossing, inducing the secondary object to accrete material very high eccentricities and even cause it to undergo Roche-lobe crossing, inducing the secondary object to accrete material very high eccentricities and even cause it to undergo Roche-lobe crossing, inducing the secondary object to accrete material. Numerical simulations have suggested that this parameter can be about 2.7 (e.g. Guillochon, Ramirez-Ruiz & Lin 2011; Liu et al. 2013), and that value may be a lower limit. Other studies sometimes find and adopt a smaller value (q ∼ 1.4–1.6; e.g. Paczyński 1971). Thus, here, we explore two limiting cases, one for which q = 1.66, as was adopted in Naoz, Farr & Rasio (2012), and another for which q = 2.7, adopted in Petrovich (2015). These two limiting cases represent two different physical pictures: interactions with an extended envelope (q = 2.7) and a contained envelope (q = 1.66).

The integration was stopped when the inner orbit pericenter Rp reaches 80 per cent of V Hya’s radius, RVHya, i.e. RP ≤ 0.8RVHya.

We investigated a discrete range of initial values for m1; a Neptune-sized planet (5 × 10⁻⁵ M⊙), a Jupiter-sized planet (10⁻³ M⊙), a brown dwarf (0.01 M⊙), and a range of subsolar stellar companions (0.1, 0.3, 0.6, and 0.9 M⊙). According to Sahai et al. (2016), the inner companion’s mass should be sub-solar, thus we do not consider larger mass companions in our investigation.

The semimajor axis of the inner orbit (a₁) was set so that its period is 8.5 yr. We also note that it is unlikely that a planet around V Hya would have a high initial eccentricity. On the other hand, a stellar companion could have had a high initial eccentricity, but tides would have circularized its orbit by the time the primary entered the AGB phase. Thus, for the eccentricity of the inner companion, we adopt for simplicity an initial, almost circular orbit (e₁ = 0.1).

There is a degeneracy between m₂, a₂ and e₂ that comes from the Kozai time-scale (e.g. Naoz 2016):

\[ t_{\text{quad}} \propto \frac{a_2^3 (1 - e_2^2)^{3/2}}{a_1^2 m_2} \sqrt{m_{\text{VHya}} + m_1} \equiv \frac{1}{\alpha} \sqrt{m_{\text{VHya}} + m_1} \]

and therefore we can restrict these parameters to a narrow range of values because this time-scale must be shorter than the lifetime of V Hya. However, if m₂ is larger than m₁, the system dynamics can be described well by a test particle approximation (m₂ ≳ 7m₁; Teyssandier et al. 2013). In this case, the inner orbit can reach extreme eccentricities in very short time-scales (e.g. Li et al. 2014a,b). Thus, we do not expect differences in the evolution of

\(^1\)Throughout this paper, we use the subscripts 1 and 2 to indicate the values for the inner and outer orbits of the system, respectively. For the mass parameter, the subscripts indicate V Hya (M_{VHya}), the inner companion (m₁) and the outer body (m₂).
systems for which $m_2 \gtrsim 7 m_1$. We chose a lower limit of $m_2$ to be 0.01 $M_\odot$ (a brown dwarf). As with $m_1$, we chose an upper limit of $m_2 = 0.9 M_\odot$.

In the model we propose here, we assume that V Hya is part of a hierarchical triple system. This means that the value for $a_2$ must be much greater than $a_1$. Such a configuration allows us to use the secular approximation equations (Naoz 2016). Furthermore, $a_2$ needs to satisfy the following criterion for the secular approximation to be valid (e.g. Lithwick & Naoz 2011):

$$\epsilon = \frac{a_1 e_2}{a_2 (1 - e_2^2)} < 0.1,$$

where $\epsilon$ is a measure of the relative strengths of the octupole and quadrupole effects on the orbital dynamics. Therefore, we test a range of 200–1000 au in 200 au increments, with eccentricity values ($e_2$) of 0.3, 0.45, and 0.6.

Finally, we test a wide range of mutual orbit inclinations ($i = 35^\circ$–$175^\circ$ in 5$^\circ$ increments). Table 1 summarizes the parameters of our computations, which give a total of 2625 cases that were generated as initial conditions.

### Table 1. Grid of initial conditions for our 3-body model. A combination of all of these values gives a set of 2625 initial conditions. Parameters marked with an (*) were set the same for all computations. The semimajor axis of the inner orbit for each $m_1$ was calculated via $a_1 = (P_1^2 (M_{VHya} + m_1))^{1/3}$.

| Parameter         | Initial values |
|-------------------|----------------|
| $M_{VHya}$          | 2.2 ($M_\odot$) |
| $m_1$              | $5 \times 10^{-3}$, 0.001, 0.01, 0.1, 0.3, 0.6, 0.9 (in $M_\odot$) |
| $m_2$              | 0.01, 0.1, 0.3, 0.6, 0.9 (in $M_\odot$) |
| $a_1^*$            | Set such that $P_1 = 8.5$ yrs ($\sim$5–6 au) |
| $a_2^*$            | 200, 400, 600, 800, 1000 (in au) |
| $e_1^*$            | 0.1 |
| $e_2$              | 0.3, 0.45, 0.6 |
| $i$                | 35, 70, 105, 140, 175 (in degrees) |

3 RESULTS

In this section we present the results from our 2625 simulated triple systems. We note that less than 1 per cent of our simulated systems were inconclusive, and thus we ignore those systems in our analysis.

We divide the simulations into ‘survived’ and ‘merged’ systems. We show examples in Fig. 1, which presents the time evolution of the inner orbit’s semimajor axis (red), periastron distance (blue), and V Hya’s stellar radius (purple) and Roche limit (green and cyan dashed lines). The Late AGB phase is shaded in purple, which lasts for $\sim$3 Myr for the chosen initial value of $M_{VHya} = 2.2 M_\odot$.

(i) **Merged systems**: Here we include all systems in which the inner binary merged at any point of the evolution, which occurs in $\sim$37 per cent of all simulated cases (991/2625). These merged systems can be divided into two groups:

(a) **L-AGB mergers**: systems that merged during the L-AGB period (an example is shown in the middle panel of Fig. 1). These can happen via an EKL-induced high eccentricity (e.g. Shappee & Thompson 2013; Naoz & Fabrycky 2014; Stephan et al. 2018). Furthermore, because tides are highly sensitive to the stellar radius, the likelihood of a merger is increased at this stage of stellar evolution due to circularization and shrinking of the inner binary’s orbit (e.g. Naoz 2016). These systems comprise $\sim$76 per cent of all mergers (752/991).

(b) **Pre-AGB mergers**: systems that merged in previous stages of the stellar evolution of V Hya (right-hand panel of Fig. 1). These occur due to strong EKL effects due to stellar-mass inner and outer companions, as well as strong tidal interactions between the inner binary members. Such systems are likely to give rise to blue stragglers (e.g. Perets & Fabrycky 2009; Naoz & Fabrycky 2014). These systems comprise $\sim$24 per cent of all mergers (752/991).

(ii) **Survived binary systems**: Here we include systems in which the inner companion survives the evolution of V Hya without merging. This occurs in $\sim$62 per cent of all simulated cases (1616/2625). In these systems, the semimajor axis of the inner orbit increases substantially at $\sim$1.146 Gyr, which is when the star sheds its outer layers and becomes a white dwarf. Most of these systems are ‘no interaction’ systems, in which the inner companion survives the evolution of V Hya without interacting with the primary’s Roche limit (an example of such a system is shown in the left-hand panel of Fig. 1). In general, these are systems in which EKL effects were insufficient to induce high eccentricities due to, for example, nearly coplanar orbits (e.g. 35 or 175 deg, such as the example in the left-hand panel of Fig. 1), high $a_2$ values, or ratios $m_2/m_1 \approx 1$. However, there are also systems where EKL effects did increase the inner orbit’s eccentricity, but not enough to make the inner orbit’s periastron cross the primary’s Roche limit (see Fig. 3). Our investigation focuses on the subset of surviving systems in which the inner companion’s periastron reaches the primary’s Roche limit during the L-AGB phase. These occur in $\sim$8 per cent of all cases (examples of these systems’ orbital evolution are shown in Fig. 2), and can be further divided into two subcategories:

(a) ‘Grazing’ systems: where the inner companion’s orbit reaches a high eccentricity ($e_1 > 0.1$) and crosses the primary’s Roche limit during its periastron passage (examples are shown in the left-hand and middle panels of Fig. 2). This configuration is maintained for $\sim$1 Myr until the primary becomes a white dwarf, at which point the inner companion’s orbit increases and exits the Roche limit. During this 1 Myr period, $M_{VHya} \sim$1.5–1.7 $M_\odot$, and $R_{VHya} \sim$1.6 au. In this configuration, the inner companion could, in principle, accrete material during its periastron passage. Then V Hya-like ejections could be produced by a transient accretion disc. The number of systems in this category depends on $q$. For $q = 2.7$, this condition is satisfied in $\sim$9 per cent of surviving systems (138/1616), while it is satisfied in only $\sim$2 per cent of surviving systems (27/1616) for $q = 1.66$.

(b) ‘Temporary close binaries’ (TCBs): systems where the inner companion’s orbit circularizes during the Late-AGB phase and is engulfed by V Hya’s Roche limit, but does not lead to a merger with the latter (an example is shown in the right-hand panel of Fig. 2). We call these systems ‘temporary close binaries’. This condition is only satisfied using a factor of $q = 2.7$ in the definition of the Roche limit, and in $\sim$4 per cent of surviving systems (60/1616). While these cases could not produce V Hya-like systems, they are likely to end up as common envelope configurations because of the drag encountered inside the Roche limit.

2Coplanarity does not guarantee a small eccentricity excitation, as was shown in Li et al. (2014a).

3Drag forces also affect the grazing systems we describe above. To determine whether the primary’s extended envelope significantly affects the grazing companion’s orbit is equivalent to asking whether the orbital average is
illustrate the relationship between $D$ and the evolution of the system. In the left-hand panel we show the eccentricity at the time the inner companion’s periastron (blue line) crosses V Hya’s Roche limit (green-dashed line). The semi-major axis of the inner orbit (red line) increases substantially at $\sim 1$ Gyr. This is because at this time the star sheds most of its mass and becomes a white dwarf. Initial system parameters for this system are $m_1 = 0.001 M_\odot$, $m_2 = 0.01 M_\odot$, $a_2 = 400$ au, $e_2 = 0.3$, $i = 175$ deg. Middle: system in which the inner companion merges with V Hya during the L-AGB phase. Initial system parameters are $m_1 = 0.001 M_\odot$, $m_2 = 0.01 M_\odot$, $a_2 = 200$ au, $e_2 = 0.45$ $i = 70$ deg. Right: system in which strong EKL oscillations of the inner orbit’s periastron prompts the companion to merge with V Hya during the Main Sequence phase. Initial system parameters are $m_1 = 0.01 M_\odot$, $m_2 = 0.3 M_\odot$, $a_2 = 200$ au, $e_2 = 0.6$, and $i = 70$ deg.

Figure 2. Example orbital evolutions of ‘grazing’ systems. The purple-shaded region indicates the Late-AGB phase, which lasts for $\sim 3$ Myr. Left: system in which the inner companion’s periastron (blue line) crosses V Hya’s Roche limit (green dashed line, $q = 2.7$) during the L-AGB phase. Initial system parameters are $m_1 = 0.001 M_\odot$, $m_2 = 0.01 M_\odot$, $a_2 = 400$ au, $e_2 = 0.6$, $i = 105$ deg. Middle: system in which the inner companion’s periastron (blue line) crosses V Hya’s Roche limit (cyan dashed line, $q = 1.66$) during the L-AGB phase. Initial system parameters are $m_1 = 0.01 M_\odot$, $m_2 = 0.01 M_\odot$, $a_2 = 200$ au, $e_2 = 0.6$, $i = 35$ deg. Right: system in which the inner companion’s orbit circularizes, and its semimajor axis (red line) crosses the Roche limit of V Hya (green dashed line, $q = 2.7$). Initial system parameters are $m_1 = 0.6 M_\odot$, $m_2 = 0.6 M_\odot$, $a_2 = 1000$ au, $e_2 = 0.6$, $i = 70$ deg.

We show in Fig. 3 how the mass of the inner companion ($m_1$) affects the evolution of the system. In the left-hand panel we illustrate the relationship between $D_{\text{min}}$ and eccentricity. We define $D_{\text{min}}$ as

$$D_{\text{min}} = \min[(a_1(1 - e_1)) - RL_{VHya}],$$

valid in the secular approximation, compared to the orbital (or less than orbital) effects due to the drag force. In other words, if on an orbital time-scale the companion’s velocity is changing significantly, then the secular approximation is invalid. So the question boils down to which force dominates over the orbital time-scale (the EKL produces forced eccentricity that remains constant over the entire $\sim 1$ Myr in which the companion’s periastron grazes the Roche limit of V Hya). Estimating the drag force as $F_{\text{drag}} \approx 0.5 \rho \pi R_1^2 v_1^2$, using $\rho = 10^{-8}$ g cm$^{-3}$ (Lagadec et al. 2005), we find very small change in velocity of the grazing companions (Jovians and brown dwarf-mass companions) due to the drag force ($< 1$ per cent) over one orbit, the velocity will have been re-established by EKL again.

i.e. the minimum distance between the periastron of the inner orbit and V Hya’s Roche limit ($D_{\text{min}} = 0$ indicates Roche limit crossing, using $q = 2.7$). On the $x$-axis, we show the eccentricity at the time of $D_{\text{min}}$ ($t_{D_{\text{min}}}$), which occurs during the L-AGB phase. It is clear that most surviving stellar companions ($m_1 > 0.1 M_\odot$) circularize (reach final values of $e_1 \sim 0$). This is because stellar companions have larger radii than lower-mass objects, and since tides are highly dependent on the radius, their orbits circularize relatively quickly. Because of the relatively larger mass of stellar objects, the EKL mechanism isn’t as effective since the distant tertiary has lower or similar mass.

Most companions with $m_1 = 0.1 M_\odot$ merge during or before the L-AGB phase, as indicated in the right-hand panel of Fig. 2. Most of the TCB systems contain a stellar mass $m_1 > 0.1 M_\odot$ companion, while brown dwarfs and planets ($m_1 < 0.1 M_\odot$) produce mainly grazing systems.

Most surviving non-stellar companions ($m_1 < 0.1 M_\odot$, i.e. Jovians and Brown dwarfs) follow a linear relation between $D_{\text{min}}$
4 IMPLICATIONS FOR THE V HYA SYSTEM

4.1 Observational interpretation of the orbit

The model introduced by Sahai et al. (2016) suggests that the observed ejections from V Hya are associated with the periastron passage of an unseen companion in an eccentric orbit. Furthermore, their study suggested that the eccentricity of the companion has to be relatively large, $e \gtrsim 0.6$, in order for the companion to approach the primary within its stellar envelope at periastron.

However, here we relax the need for the companion to reach V Hya’s radius, since crossing the Roche limit already provides an opportunity for interactions between V Hya and the companion. Furthermore, the low surface gravity, stellar pulsations, and their associated shocks, coupled with the radiation pressure that drives V Hya’s stellar wind cause an increased scale height of its atmosphere, and therefore a measurable radius is not clearly definable (Zhao-Geisler et al. 2012).

4.2 Launching mechanism

The launching mechanism of the observed bullet ejections is largely uncertain. Here we consider the consequences of a few simple proof-of-concept launching mechanisms on our proposed scenario.

(i) The ballistic approximation (e.g. Dosopoulou, Naoz & Kalogera 2017) yields that the bullet speed $v_b$ should be proportional to the periastron speed $v_p$ plus the escape speed from the companion $v_{esc}$, i.e.

\[
 v_b \sim \sqrt{G(M_{VHya} + m_c) \frac{1 + e}{a(1 - e)}} + \sqrt{\frac{2Gm_c}{r_c}}
\]

where $m_c$ is the mass of the companion and $r_c$ is its radius. A similar estimation was done by Livio (1997). As can be seen from equation (5), the jet’s velocity is highly sensitive to the mass of the companion. In our case, each companion reaches different maximum eccentricity (see Fig. 3), however the pericenter velocity is typically much smaller than the escape velocity. In Fig. 5 we show ejection speed according to these approximations for different companions (Neptune, Jupiter, and brown dwarf). A brown dwarf gives an ejection speed of about $230 \text{ km s}^{-1}$, similar to the observed bullet speeds ($v \sim 200–250 \text{ km s}^{-1}$; Sahai et al. 2016; Scibelli, Sahai & Morris 2019).
Figure 4. Percentages of Neptune, Jupiter, and brown dwarf systems (relative to total of grazing systems) for the values of $m_2$, $a_2$, and $e_2$. For example, in 33 per cent out of 28 systems with a brown dwarf (i.e. 9 systems), the location of $m_2$ is 200 au.

Figure 5. Jet ejection speed versus companion mass (for Neptune, Jupiter, and brown dwarf masses). Black dots represent the approximation by Livio (1997). The blue dots represent the ballistic approximation (Dosopoulou et al. 2017). The magenta-shaded region indicates the range of the observed bullets’ speeds.

(ii) We also consider a magnetically driven launching mechanism. Following Fendt (2003), we consider an outflow velocity from a circum-planetary accretion disc:

$$v_b \approx 63 \text{ km s}^{-1} \left( \frac{\Phi}{5 \times 10^{22} \text{ G cm}^2} \right)^{2/3} \left( \frac{P}{4 \text{ d}} \right)^{-2/3} \times \left( \frac{M_{\text{out}}}{10^{-3} M_{\text{in}}} \right)^{-1/3} \left( \frac{M_{\text{in}}}{6 \times 10^{-5} \text{ M}_\odot /\text{yr}} \right)^{-1/3}$$

(6)

where $\Phi$ is the magnetic flux through the accretion disc, $P$ is the outer edge disc’s period, $M_{\text{in}}$ is the inflow rate, and $M_{\text{out}}$ is the outflow rate. If the companion swings through V Hya’s Roche limit and forms a transient accretion disc, we might expect ejections due to magnetically driven jets. This mechanism is sensitive to the magnetic field of the system. For example, some studies have suggested that Jupiter’s magnetic field could have been as high as $\sim 500$ G during its early formation period (Christensen, Holzwarth & Reiners 2009; Batygin 2018). Furthermore, one version of the model we propose here, i.e. a Jovian planet around V Hya, might resemble the environment of a protoplanetary system, and thus, we could consider magnetic field strengths of 500 G or greater. Similar to Fendt (2003), we adopt $10 \times R_\odot$ as the outer disc edge. We also adopt $M_{\text{out}} = M_{\text{in}}$, i.e. all of the accreted mass is ejected. In Fig. 6 we show the ejection speed as a function of mass accretion rate, using values of $B = 500$ and 2000 G. As shown in the figure, accretion rates of $\sim 10^{-7} \text{ M}_\odot /\text{yr}$ and a strong magnetic field ($B = 2000$ G) are necessary for a Jovian planet to cause ejection speeds of $\sim 200$ km s$^{-1}$.

(iii) Another launching mechanism is described in Goodson & Winglee (1999). In their work, they considered accretion jets from accreting magnetic young stellar objects. They found that the ejection speeds are

$$v_b = 585 P_d^{-2/3} B_{50 G}^{2/3} R^{4/3} M_{\text{jet}}^{-1/3} \sin^{4/3} \theta_{\text{jet}} \text{ km s}^{-1}$$

(7)

where $P_d$ is the stellar rotation period in days, $B_{50 G}$ is the stellar surface magnetic field in kilogauss, $R$ is the stellar radius in solar radii, $M_{\text{jet}}$ is the jet mass flux in units of $10^{-8} \text{ M}_\odot /\text{yr}$, and $\theta_{\text{jet}}$ is the angle of ejection. For simplicity, we assume $\sin \theta_{\text{jet}} = 1$, and a maximally rotating Jovian planet ($P_d \approx 0.2 \text{ d}$). We consider the same values of $B$ and $M_{\text{in}}$ as before, and show the resulting jet speed values in Fig. 6. The speeds resulting from this mechanism are lower than those produced using equation (6).

4.3 Relevance for companions around evolved stars

In recent years a number of evolved stars have been observed to host Hot Jupiter companions (e.g. Johnson et al. 2008; Sato et al. 2008; Johnson et al. 2010, 2011a,b; Johnson, Morton & Wright 2013; Sato et al. 2013; Bieryla et al. 2014; Wittenmyer et al. 2015a,b).
Recent work by Stephan et al. (2018) indicates the existence of a ejection speed values according to equation (7) (Goodson & Winglee, 1999). Figure 6.

jet-like ejections via a strongly enhanced accretion episode. Such an interaction could produce EKL mechanism can potentially drive the inner companion to cross stellar evolution. The eccentricity oscillations associated with the inclinations of the system. Our goal is to constrain the parameter the masses, as well as the orbital separations, eccentricities, and mass companion, and they are orbited by a distant tertiary. We have

In this paper, we propose a dynamical configuration for the AGB star, V Hya, that accounts for its apparently periodic 'bullet' ejections. In our model, V Hya is part of a hierarchical triple system. The inner, 8.5-yr period orbit is composed of V Hya and a low-mass companion, and they are orbited by a distant tertiary. We have evolved a large set (2625) of realizations of this system, varying the masses, as well as the orbital separations, eccentricities, and inclinations of the system. Our goal is to constrain the parameter space for which a V Hya-like system can occur. We include the EKL mechanism, tides, general relativity, and post-main-sequence stellar evolution. The eccentricity oscillations associated with the EKL mechanism can potentially drive the inner companion to cross inside the primary's Roche limit. Such an interaction could produce jet-like ejections via a strongly enhanced accretion episode.

Our results can be summarized as follows:

(i) Mergers. In ~37 per cent of all simulated cases, the inner companion merges with the primary, either due to strong tides during the primary’s Late AGB phase, or due to extreme EKL effects that lead to a merger before the AGB phase.

(ii) Surviving systems. In ~62 per cent of the simulated systems, the inner companion survives the evolution of the primary star until its WD phase without merging. Our investigation focuses on the subset of these cases that achieves Roche-limit crossing at periastron during the primary’s Late AGB phase.

(iii) Late-AGB, grazing systems: cases that could potentially give rise to a V Hya-like system. In these systems, the inner companion’s orbit reaches a high eccentricity ($e_{i} > 0.1$) during the primary’s Late-AGB phase and crosses the primary’s Roche limit during periastron passage. Thus, the inner companion could, in principle, accrete material during this period. The percentage of systems in this category depends on the properties of the evolved star’s envelope as well as the details of the interactions of the close-by companion with the Roche limit (Guillochon et al., 2011; Liu et al., 2013). We characterize this by adopting two different numerical pre-factors for the Roche limit. Specifically, in equation (1), we find that for $q = 2.7$ ($q = 1.66$), ~5 per cent (~1 per cent) of all simulated systems may become V Hya-like systems. It is not surprising that only small percentage of the systems present this behavior as we are constraining ourselves to a very short time-scale in the evolution of the star (the Late-AGB phase represents 1/400 of our simulation time-scale). Grazing systems only occur with brown dwarfs, Jupiter, and Neptune-mass inner companions (Fig. 3). We can then estimate a possible mass and semimajor axis of the distant tertiary (Fig. 4). For example, we find more systems with a brown dwarf inner companion and a relatively close ($a_{2} \sim 200$ au), stellar-mass ($m_{1} \sim 0.6 M_{\odot}$) tertiary.

(iv) Late AGB, temporary close binaries (TCBs). Unlike the systems in which their orbit circularizes and shrinks, in TCBs tides work to circularize the inner orbit during the primary’s Late AGB phase, and the secondary migrates inside the primary’s Roche limit, but a merger does not occur. Specifically, the mass-loss expands the semimajor axis, which helps the companion elude engulfment. We find these systems only when using a value of $q = 2.7$ in the definition of the Roche limit, and in ~2 per cent of all cases we analyzed. While these cases would not produce V Hya-like systems, they are likely to end up as common envelope configurations because of the drag encountered inside the Roche limit. Most systems in this category contain stellar-mass inner companions ($m_{1} > 0.1 M_{\odot}$).

Finally, we consider some possible launching mechanisms that could give rise to V Hya-like ejections. In particular, we examine a simple ballistic approach, as well as magnetically driven ejection processes that were suggested in the literature for proto-planetary systems and young stellar objects. Interestingly, we find (Fig. 5) that a simple ballistic mechanism can produce the observed ejection velocity for a brown dwarf companion. However, this version of our model causes tension with the companion’s suggested eccentricity ($e_{i} > 0.6$; Sahai et al., 2016), since our results indicate that tidal effects may limit a brown dwarf companion’s eccentricity below ~0.2. Note that Sahai et al. (2016) suggested an eccentricity that was based on the companion approaching V Hya’s envelope at periastron ($R_{VHya} \sim 2$ au). We relax this condition in our investigation.

Nevertheless, our results indicate that Jovian companions achieve the highest eccentricities during V Hya’s Late AGB phase ($e_{i} \sim 0.6$ for Neptune-mass companions, in agreement with the eccentricity suggested by Sahai et al. 2016). Here, a purely ballistic ejection does not produce speeds that match observations. Instead, a strong magnetic field ($B > 500 G$) is necessary for magnetically driven outflows.
from a Jovian companion to achieve speeds of \( \gtrsim 200 \text{ km s}^{-1} \) (Fig. 6). This prediction can be used to distinguish competing mechanisms.

This proof-of-concept study suggests that V Hya-like ejections can result from EKL-induced interactions between AGB stars and Jovian or brown dwarf companions. The model presented here also provides a framework to explain the dynamics occurring in interacting binary systems in which the companion is a stellar, sub-stellar, or planetary object. This includes, for example, planets engulfed by giant stars (e.g. Soker, Livio & Harpaz 1984; Livio & Soker 2002; Gaudi et al. 2017; Stephan et al. 2018), the influence of planets on horizontal giant branch morphology (e.g. Soker 1998a), as well as binary progenitor models of bipolar PNe (e.g. Morris 1987; Soker 1998b).

ACKNOWLEDGEMENTS

The authors want to thank the reviewer whose comments and suggestions helped improve and clarify this manuscript. This work used computational and storage services associated with the Hoffman2 Shared Cluster provided by the UCLA Institute for Digital Research and Education’s Research Technology Group. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1144087. S.N. acknowledges partial support from the NSF through Grant AST-1739160.

REFERENCES

Balick B., Frank A., 2002, ARA&A, 40, 439
Batygın K., 2018, AJ, 155, 178
Bieryla A. et al., 2014, AJ, 147, 84
Christensen U. R., Holzwarth V., Reiners A., 2009, Nature, 457, 167
Dosopoulou F., Naoz S., Kalogera V., 2017, ApJ, 844, 12
Eggleton P. P., Kiseleva L. G., Hut P., 1998, ApJ, 499, 853
Eggleton P. P., Kisseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., MNRAS, 487, 2007
Eggleton P. P., Kisseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., MNRAS, 487, 2007
Dosopoulou F., Naoz S., Kalogera V., 2017, ApJ, 844, 12
Eggleton P. P., Kiseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., MNRAS, 487, 2007
Eggleton P. P., Kiseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., MNRAS, 487, 2007
Dosopoulou F., Naoz S., Kalogera V., 2017, ApJ, 844, 12
Eggleton P. P., Kiseleva-Eggleton L., Dearborn X., 2007, in Hartkopf W. I., MNRAS, 487, 2007