Constraints on common envelope magnetic fields from observations of jets in planetary nebulae

James Tocknell, Orsola De Marco and Mark Wardle

ABSTRACT
The common envelope (CE) interaction describes the swallowing of a nearby companion by a growing, evolving star. CEs that take place during the asymptotic giant branch phase of the primary may lead to the formation of a planetary nebula (PN) with a post-CE close binary in the middle. We have used published observations of masses and kinematics of jets in four post-CE PN to infer physical characteristics of the CE interaction. In three of the four systems studied, Abell 63, ETHOS 1 and the Necklace PN, the kinematics indicate that the jets were launched a few thousand years before the CE and we favour a scenario where this happened before Roche lobe overflow, although better models of wind accretion and wind Roche lobe overflow are needed. The magnetic fields inferred to launch pre-CE jets are of the order of a few gauss. In the fourth case, NGC 6778, the kinematics indicate that the jets were launched about 3000 yr after the CE interaction. Magnetic fields of the order of a few hundreds to a few thousands gauss are inferred in this case, approximately in line with predictions of post-CE magnetic fields. However, we remark that in the case of this system, we have not been able to find a reasonable scenario for the formation of the two jet pairs observed: the small orbital separation may preclude the formation of even one accretion disc able to supply the necessary accretion rate to cause the observed jets.

Key words: magnetic fields – ISM: jets and outflows – planetary nebulae: individual: Abell 63 – planetary nebulae: individual: ETHOS 1 – planetary nebulae: individual: Necklace – planetary nebulae: individual: NGC 6778.

1 INTRODUCTION
A common envelope (CE) interaction between a giant and a more compact companion happens when the envelope of the primary giant star grows sufficiently large as to engulf the secondary. The orbital energy unbinds the envelope, leaving either a close binary composed of a white dwarf (the core of the giant) and the companion or, if the secondary lacks sufficient energy to unbind the envelope, a merger (Paczynski 1976; Ivanova et al. 2013). The shapes of most planetary nebulae (PN) diverge significantly from spherical (Parker et al. 2006). The reason may be that a companion has played a role during the mass-losing asymptotic giant branch (AGB) phase during which the PN gas was ejected (Soker 1997; De Marco, Farihi & Nordhaus 2009). While for most PN with non-spherical shapes we presume the action of a companion, for approximately one in five PN we know that a companion has ejected the envelope (Bond 2000; Miszalski et al. 2009). CE PN are identified by the presence of a close binary in the centre of a PN.

On occasion a PN surrounding a post-CE central binary turns out to be a Stroemgren sphere around a post-red giant branch star, rather than a proper PN (Frew & Parker 2010; e.g. EGB 5; Geier et al. 2011). PN around post-CE binaries are not only interesting because they are cases for which we know the mechanisms that imparted the PN its shape (e.g. Miszalski et al. 2009), but also because they provide a unique tool for the study of the CE interaction. In post-CE PN, the existence and brightness of the PN guarantees that the CE interaction only took place a few thousand years ago at most. Also, the aftermath of the ejection is there to be studied.

In this paper, we focus on four PN around post-CE binaries, which exhibit jet-like structures. These have been measured and their kinematics indicate that three of the four objects launched their jets before the main nebula, a clear indication that an accretion disc formed before the companion plunged into the primary. In the fourth case not one, but two pairs of jets are observed. Both these jet pairs are kinematically younger than the nebula, demonstrating that they were launched after the CE interaction had taken place.

We assume here that all CE jets are launched via an accretion disc threaded by a magnetic field (Blandford & Payne 1982). The launch efficiency, or the fraction of accreted mass that is ejected, is
between 10 per cent and 50 per cent in this model (Sheikhnezami et al. 2012). We also assume that the magnetic field responsible for the jet launching and collimation is also responsible for the loss of angular momentum and accretion of disc material (Wardle 2007). Within this model, we use the jet properties to determine the magnetic field responsible for the mass accretion and jet launching in pre and post-CE phases.

In Section 2, we review the four PN which will be analysed in this paper, outlining the kinematics and morphology of these objects. Section 3 contains our examination of a number of different scenarios for launching the jets. In Section 4, we discuss the magnetic fields that are implied for the four PN under the assumptions of our models and compare them, in the case of the post-CE PN, to the magnetic fields theoretically derived in a model by Regos & Tout (1995). In Section 5, we discuss scenarios for the formation of the post-CE jets of NGC 6778 and in Section 6, we briefly discuss two additional post-CE PN. Finally, in Section 7, we summarize and conclude.

### 2 POST-CE SYSTEMS WITH JETS

A few PNe with jets are known to contain post-CE central star binaries, but in only four cases we have sufficient information to carry out our study: the Necklace (PN G054.2–03.4; Corradi et al. 2011), Abell 63 (PN G053.8–03.0, whose central stars is known as UU Sagittae; Mitchell et al. 2007; Afzal & Ibanoglu 2008), ETHOS 1 (PN G068.1+11.0; Miszalski et al. 2011a) and NGC 6778 (PN G034.5–06.7; Guerrero & Miranda 2012; Miszalski et al. 2011b). In order to develop a model for launching the observed jets, we need values for the kinematic parameters and masses of the circumstellar material. These are summarized in Table 1.

#### 2.1 The Necklace

The Necklace PN (PN G054.2–03.4; Fig. 1, left-hand panel) consists of a ring with radius $6.5 \pm 0.5$ arcsec expanding at $28 \pm 3$ km s$^{-1}$ on a plane inclined by $59 \pm 3$° to the line of sight, where $0^\circ$ is in the plane of the sky (Corradi et al. 2011). Two polar caps are assumed to be perpendicular to the plane of the ring. The northern cap is quite compact and spans a distance of 38 to 46 arcsec from the star. The southern cap is more extended and spans a distance of 37 to 59 arcsec (measured by us on fig. 4 of Corradi et al. 2011).

All the gas in each cap appears to move with the same velocity: deprojected velocities are 95 and 115 km s$^{-1}$, for the northern and southern caps, respectively. We gauged the errors on these velocities to be 3 km s$^{-1}$ from fig. 4 of Corradi et al. (2011). The kinematic ages are determined by dividing the ring radius (or the deprojected distance between the star and the base or tip of each jet cap) by the deprojected ring expansion velocity (or deprojected velocity of the caps). For the ring, Corradi et al. (2011) find a kinematic age of $1100$ yr kpc$^{-1}$. The error on this estimate can be estimated to be $25$ per cent. The kinematic age of the innermost part of the southern cap is $1900$ yr kpc$^{-1}$, while for the outermost part it is $2800$ yr kpc$^{-1}$. The northern cap has an average age of $2500$ yr kpc$^{-1}$. The error on these estimates can be determined to be $20$ per cent. The lack of a velocity gradient along the caps implies that material was ejected during a certain period of time, as opposed to during a quick outburst. The distance to this PN was kindly measured by D. Frew to be $4.6 \pm 1.1$ kpc by applying the surface brightness–radius relation (Frew 2008). At that distance the ring has an age of $\sim5000$ yr while the age of the polar caps would be in the range $8700$–$13000$ yr. Using this distance estimate, the time over which the jet was launched is $\sim4000$–$8000$ yr, which agrees with the assertion that the ejection was not a quick outburst.

The ionized mass of the entire nebula was estimated from the integrated $H_\alpha$ flux and a filling factor of $0.4$ to be $0.5 \pm 0.03 M_\odot$. The ionized mass of the caps is of the order of $10^{-3} M_\odot$ (Corradi, private communication). These mass estimates as well as the estimates of the kinematic ages determined above, will suffer from an additional source of uncertainty, which is hard to quantify, but which we argue to be smaller than an order of magnitude. All ejected material impacts the circumstellar ambient medium. This will potentially increase the mass of the ejected structures and decrease their speeds over time.

We argue here that it is unlikely that the PN body and jets have slowed down dramatically. The velocities measured along the cap (particularly the southern cap which spans a range of about $20$ arcsec) are surprisingly constant with no real indication that the

#### Table 1. Properties of the CE PN in our sample.

| Object         | The Necklace | Abell 63 | ETHOS 1 | NGC 6778 |
|----------------|--------------|----------|---------|----------|
| Deprojected expansion velocity of main nebula/ring (km s$^{-1}$) | 28 ± 3 | ~26 | ~55 | ~26 |
| Deprojected velocity of jets (km s$^{-1}$) | 95(N), 115(S)$^a$ | 126 ± 23$^a$ | 120 ± 10$^d$ | 270$^c$, 460$^c$ |
| Ionized gas mass of nebula/ring ($M_\odot$) | 0.06 ± 0.03 | 0.09 | – | – |
| Ionized gas mass of jets ($M_\odot$) | $\sim10^{-5}$ | – | – | $\sim1.5 \times 10^{-3}$|
| Radius of nebula/ring (arcsec) | 6.5 ± 0.5 | ~14 | ~9.7 | ~8.5 |
| Distance to jet tips from star (arcsec) | ~60 | ~142 | ~31.3 | ~35 |
| Age of nebula/ring (yr) | ~5000 | ~11200 | ~5400 | ~4400 |
| Age of jets (yr) | ~8700$^b$–13000$^f$ | ~17100 | ~10500 | ~1700 |
| Jet ejection time-scale (yr) | 3700 – 8000 | 5900 | 5100 | 1700 |
| Jet mass-loss rate ($M_\odot$ yr$^{-1}$) | 1 – 3 \times 10$^{-7}$ | – | – | 8.8 \times 10$^{-7}$ |
| Period of central binary (d) | 1.2 | 0.46 | 0.53 | 0.15 |
| Distance to object (kpc) | 4.6 ± 1.1 | 3.2 ± 0.6 | 6.0$^e$\pm1.5 | 2.6\pm0.8 |

$^a$Average velocity of caps. 
$^b$Edge of southern cap closest to central star. 
$^c$Edge of southern cap furthest from central star. 
$^d$Velocity of jet tips. 
$^e$Linear jet. 
$^f$Curved jet. 
$^g$Mass of each pair.
material launched most recently is significantly faster (if anything the gas closest to the star is slowest). We also present circumstantial evidence that the measured velocities are not much smaller than the ejection velocities, and in any case not by more than a factor of 2: the jet velocities measured for the PN A63 (Section 2.2), ETHOS 1 (Section 2.3) and FLEMMING 1 (Section 6) are all approximately 100 km s$^{-1}$, something that would be unlikely were they slowed down considerably by material in four different circumstellar environments.

The momentum conservation considerations presented by Blackman (2009) could be applied in the current case to estimate the amount of mass loading and the velocity decrease. However, contrary to the case described by Blackman (2009), where the pre-PN jets are punching through the entire AGB star envelope (which has just been ejected in the superwind phase), the present case is different. The CE is likely to take place before the super wind ensues. We argue this on probabilistic grounds. The chance that the capture of a companion coincides with the very short, final, phase of the AGB star life is unlikely. It is more likely that at some point in the upper AGB, but before the superwind phase, the companion was captured. In such case the circumstellar material encountered by the jet would be far less dense than in the case of a jet perforating the super wind-formed shell, which is effectively the entire AGB envelope. Even wanting to follow through with the calculation of Blackman (2009), the uncertainty in determining the swept-up mass would outweigh that of assuming that the jet mass today is the same as the ejected mass, which, we argued above, should only be within a factor of less than 2.

Finally, we note that for the central star of the Necklace PN, there is independent observational evidence that accretion has occurred on to the companion (Miszalski, Boffin & Corradi 2013), because of the pronounced carbon abundance of this otherwise normal main-sequence star. The estimated amount of accreted matter was $0.03 - 0.35$ M$_\odot$ for a 1.0 - 0.4 M$_\odot$ companion. Inspection of the equations used by Miszalski et al. (2013), reveals that in the case of a 0.3 M$_\odot$ main-sequence companion, which is almost fully convective, we expect between 0.10 and 0.42 M$_\odot$ of gas accreted to raise the C/O ratio to unity from the solar value, for a range of AGB C/O ratios of 1.5 - 3. In Section 3.2, we will consider whether such a large accreted mass is in line with the deduced accretion rates and jet mass-loss rates.

### 2.2 Abell 63

Abell 63 (PN G053.8–03.0) is a faint PN discovered by Abell (1966), with the binarity of central star discovered by Bond, Liller & Mannery (1978). Like the Necklace, it appears as an edge-on ring with two caps. Mitchell et al. (2007) provided detailed kinematic and morphological measurements of the PN. The inclination of the system was determined to be 87.5° (where 0° is in the plane of the sky), assuming that the inclination of the system is the same as the inclination of the binary.

Mitchell et al. (2007) measured the expansion velocity of the ring or torus structure to be $\sim 26$ km s$^{-1}$. The average radial velocities of the caps are $5.5 \pm 1$ km s$^{-1}$, and when the inclination of the system is taken into account, the average velocities of the caps are $126 \pm 23$ km s$^{-1}$. Frew (2008) measured the ionized mass of Abell 63 to be $0.09$ M$_\odot$, using a filling factor of 0.4, similar to the total PN mass of the Necklace nebula. No jet mass estimate exists for this object. Mitchell et al. (2007) derived kinematic ages of the structures using a distance of 2.4 kpc, which they attributed to Pollacco & Bell (1993). However, those authors actually derived a distance of $3.2 \pm 0.6$ kpc from the eclipsing binary system, which directly determined distance which we use in the present study. The surface brightness–radius relation of Frew (2008) results in a smaller distance estimate of $2.6^{+0.5}_{-0.4}$ kpc which is consistent with the eclipsing binary distance estimate within the large error bars. We have rescaled the dynamical ages of the nebular structures of Abell 63 to the distance of $3.2$ kpc: $\sim 11$ 200 yr for the ring and $\sim 17$ 100 yr for the jets. These larger age values are in line with the appearance of Abell 63, characteristic of an old nebula. According to these figures, the jet predates the nebula by $\sim 5900$ yr. We gauge the errors on these estimates to be similar to those estimated for the Necklace PN case (Section 2.1). Finally, Mitchell et al. (2007) suggests that the ejection was fairly rapid, contrary to the case of the Necklace PN, because the morphology of the jets of Abell 63...
match those of Mz 3, which is known to have had launched the jets over a short amount of time.

2.3 ETHOS 1

ETHOS 1 (PN G068.1+11.0) was discovered by Miszalski et al. (2011a), as part of a survey of the Super COSMOS Science Archive (Hambly et al. 2004). This nebula appears as a torus, with two perpendicular outflows. The angle of inclination of the disc was given as 60 ± 5° at the time of sight, where 0° is in the plane of the disc. The torus has radius of ~10 arcsec and a radial velocity gradient with a maximum velocity of 55 km s⁻¹, possibly implying a short time-scale for the ejection. The SE jet has radial velocity −55 ± 5 km s⁻¹ and the NW jet has radial velocity 65 ± 5 km s⁻¹. The deprojected velocities of the jets are 120 ± 10 km s⁻¹ (Miszalski et al. 2011a), assuming that the jets are symmetric. Miszalski et al. (2011a) give kinematic age calculations for both the jets, 1750 ± 250 yr kpc⁻¹, and for the inner nebula 900 ± 100 yr kpc⁻¹. There are no distance estimates for ETHOS 1 in the literature. Using the surface brightness–radius relation, a distance of 6.0^{+2.5}_{-1.3} kpc can be derived (Frew 2008). With this distance the age of the jets is 10 500 yr, and the age of the ring is 5400 yr, implying that the jets predate the nebula by ~5100 yr. We estimate the errors on these estimates to be similar to those estimated for the Necklace PN case (Section 2.1). No mass estimates exist for this PN.

2.4 NGC 6778

The PN NGC 6778 (PN G034.5−06.7; Fig. 1, right-hand panel) was discovered to harbour a post-CE central star by Miszalski et al. (2011b), Maestro, Guerrero & Miranda (2004) and Guerrero & Miranda (2012) carried out detailed kinematical analysis of the nebula. The equatorial ring has a radius of 9.5 arcsec. The ring has an inclination to the line of sight of ~75°–78° (where 0° is in the plane of the sky) and was observed to expand with a deprojected velocity of 26 km s⁻¹. From the ring protrude two lobes extending approximately 20 arcsec from the centre of the nebula. The deprojected expansion velocity at the tip of the lobes is 50 km s⁻¹. The authors note that the lobes lack a typical velocity structure, and suffer instead from great complexity, as if they had been bored along selected directions.

The agent responsible for the shaping seems to be two pairs of collimated features extending farther than the lobes, to ~35 arcsec from the centre of the nebula. One pair is linear and is approximately aligned with the bipolar lobes. The second pair starts near the star with the same inclination but curves at the tips with point symmetry. Both pairs of jets exhibit a velocity gradient, with velocity increasing as the distance from the centre. Assuming the normal to the disc plane makes an angle of 78° with the line of sight, the jets have deprojected velocities of 270 km s⁻¹, for the linear jets and 460 km s⁻¹, for the curved jets. The kinematic ages of the ring and lobes are 1700 yr kpc⁻¹ and 1600 yr kpc⁻¹, respectively, while for the linear jets it is 650 yr kpc⁻¹. This clearly indicates that the jets of NGC 6778 were launched after the main nebula, contrary to those of the other three post-CE PN analysed here. This is one of two post-CE PN for which the jets are kinematically younger than the main nebula (the other, NGC 6337, is described in Section 6).

The lack of any change in the images taken three years apart imposes a lower limit on the distance of 1 kpc. The nine distance estimates listed in the ESO PN catalogue (Acker 1992) range between 1.9 and 3.1 kpc, with only one estimate at 8.1 kpc. The surface brightness–radius distance to this object is 2.6^{+0.7}_{−0.5} kpc (Frew 2008). Using this distance estimate, we calculate that the jets are 1700 yr old, while the main nebula is 4400 yr old. In this nebula, the jets lag the nebular ejection by 2700 yr.

The mass of the jets was kindly obtained by M. Guerrero. The average Hβ surface brightness in the jets is ~1.0 × 10⁻¹⁰ erg cm⁻² s⁻¹ arcsec⁻², with an uncertainty of 15 per cent to account for the spectroscopic calibration and extinction correction uncertainties, and for the slit location on the nebula. Then, assuming the jets to be ‘cylinders’ of radius 2 arcsec and height 27 arcsec for the linear jets and 23 arcsec for the curved jets a root mean square density N_e ~ 110 × 10⁻⁵ cm⁻³ is obtained. This leads to masses of 1.2 × 10⁻⁴ e⁶⁵D⁻³ M⊙ for each linear jet, and 9.9 × 10⁻⁵ e⁶⁵D⁻³ M⊙ for each curved jet, where D is the distance to the object in kiloparsecs and e is the filling factor. If we adopt a filling factor of 0.4 and a distance of 2.6 kpc, we obtain jet masses of 1.6 × 10⁻³ M⊙ and 1.4 × 10⁻³ M⊙ for the linear and curved jet pairs, respectively.

The formal error in the determination of the ring radius and location of the caps from the spatio-kinematic analysis is approximately 2 arcsec, while the velocity error is due to the width of the line and can be (generously) determined to be 10 km s⁻¹. The error in the inclination is approximately 3°. So the formal error on the distance-independent ages is approximately 40 per cent. Applying this error in opposite directions to the kinematic age of the jets and the ring, so as to reduce their difference, brings the two values to be within 100 yr of one another. Although this would effectively indicate co-variation of the structure, it is unlikely that the sequence of the ejection would be completely reversed (jets before nebula as is the case for the three PN described above). As we will point out later on, these jets have many differences to the ones just described but do have commonalities with another object, NGC 6337, which we describe in Section 6.

Another concern is that the slit that measured the curved jet did not overlap its tip. This may work to our advantage, because the tip likely turns away in space and its velocity would suffer from an additional projection effect, which would not be easily quantified. As for determining the jet length, if the jet curved because of precession then we have indeed calculated a smaller jet length and underestimated its age. Similarly, if the angle of the jet is larger than 12°, as assumed, then the deprojected velocity should be smaller and the jet older. It is possible that the time lag between CE ejection and jet be not so extreme, something that would help the interpretation of a post-CE jet as resulting from fall back of material (Section 5).

As is the case for the other analysed PN, a final concern is that the structures were decelerated by ploughing up mass on their way. If the structures have been decelerated both their sizes and current velocities would be smaller than they should be. We ventured to guess that the jets would have been launched in a more evacuated environment since, as has been discovered by CE simulations (e.g. Sandquist et al. 1998; Passy et al. 2012), the CE ejection is equatorial. As a result, it is likely only a small amount of mass would be swept up. In addition, if the jet material had been significantly decelerated, then the original launch velocities would be higher, something that would be hard to reconcile with typical accretors encountered in PN. We argue here, as we have done in Section 2.1 that any deceleration and mass loading should be within a factor of 2 and that this is supported by circumstantial evidence of the similarity of these jet speeds with those found in the other known post-CE jet PN, FLEMING 1 (Section 6).
2.5 Conclusions from the data

For the jets in the PN Abell 63, Necklace and ETHOS 1 we can say that

(i) the jets predate the main nebula by \( \sim 5000 \) yr;
(ii) the jets have velocities of \( \sim 100 \) km s\(^{-1}\);
(iii) for at least one central star (that of the Necklace PN), between 0.03 and 0.45 \( M_\odot \) were accreted on to the companion (Miszalski et al. 2013);
(iv) for at least one of our three jet pairs, the mass is \( \sim 10^{-3} \) \( M_\odot \).

As explained in Sections 2.1, 2.2 and 2.3, the uncertainties are large. However, we argue that the sequencing of jet and PN ejection is correct. We also argued that the jet speeds and ejected masses at the time of launch would not have been much higher than they are today. An additional cautionary note on the jet masses is that some gas may have recombined and was therefore not accounted for in our measurements.

The mass-loss rate of the jets is calculated using the jet mass estimate for the Necklace PN and assuming that the jet was launched for the entire dynamical age minus the dynamical age of the nebula, equivalent to assuming that the jet was launched continually up to when the ejection of the CE took place. This results in a jet lifetime between \( \sim 4000 \) and \( \sim 8000 \) yr for the Necklace nebula, \( \sim 6000 \) yr for A 63 and \( \sim 5000 \) yr for ETHOS 1. If the jet ejection time-scales are lower, the jet mass-loss rates would be larger. We will further comment on this possibility in Section 3.

The PN NGC 6778 is different in that

(i) the jets formed after the main nebula by \( \sim 3000 \) yr;
(ii) there are two pairs of jets;
(iii) the velocities of both pairs of jets are higher \( \sim 300–500 \) km s\(^{-1}\);
(iv) the velocities of the two jet pairs are different.

From these characteristics, we can already deduce that the jets from NGC 6778 are a post-CE event. The jet launch points are either closer to the central accretor(s) or the accretor(s) are more massive than for the pre-CE jet objects. The jet mass-loss rate is derived from the jet mass and a maximum jet lifetime of 1700 yr.

It has to be emphasized that, although the formal errors could bring the age estimates of jets and ring to be much closer to one another, it is unlikely that the relative age estimates are completely unreliable. Looking at the data for the four objects in Table 1 and for the two additional objects which we discuss briefly in Section 6, we see a pattern, not only of relative ages, but also of jet speeds (slow for the pre-CE jets, faster for the post-CE jets). Although only improved measurements will refine this statement, it does appear that there are two distinct classes of CE jets.

Below we consider three physical mechanisms for the accretion and ejection of mass: ejection of mass by radiative pressure (Section 3.1) and jet formation via an accretion disc formed at the time of Roche lobe (RL) overflow (Section 3.2) or before RL overflow (Section 3.3). In order to be consistent with the calculations in each model, we have adopted the following parameter ranges.

(i) Mass of the jets: \( M_{\text{jet}} \sim 10^{-3} \) \( M_\odot \), this is based on the jet masses of Necklace PN and NGC 6778.
(ii) Velocity of the jets: \( v \approx 100 \) km s\(^{-1}\) or 400 km s\(^{-1}\).
(iii) Maximum duration of jet launching: 4000–8000 yr for pre-CE jets, \( \tau \approx 1700 \) yr for post-CE ones.
(iv) The mass-loss rate of the jets is \( 1 - 3 \times 10^{-7} \) or 8.8 \( \times 10^{-7} \) \( M_\odot \) yr\(^{-1}\) for the pre- and post-CE jets, respectively.
(v) Mass of the companion: \( M_{\text{acc}} \sim 0.3 \) \( M_\odot \).

The mass assumptions are appropriate for a 1.2 \( M_\odot \) main-sequence star, which is the median mass of the PN population (Moe & De Marco 2006). Such stars leave behind a \( \sim 0.55 \) \( M_\odot \) core (Weidemann 2000; De Marco et al. 2011). At the time of interaction, the star is a giant and has a mass smaller than its main-sequence mass. We therefore account for an envelope mass of 0.45 \( M_\odot \), so that our giant’s total mass is 1 \( M_\odot \). The most represented stellar companion around white dwarfs has a spectral type M3.5V (Farhi, Becklin & Zacherman 2005) which translates in a mass of \( \sim 0.3 \) \( M_\odot \) (De Marco et al. 2013).

3 ACCRETION AND EJECTION MECHANISMS FOR JETS FROM COMMON ENVELOPE SYSTEMS

In our jet launching model, we assume that the accretion rate through the disc is \( \sim 10 \) times the jet mass-loss rate derived in Section 2.5 (Sheikhnezami et al. 2012). Before we use these values of the accretion rate to derive the magnitude of the magnetic field (Section 4), we consider the likely accretion rates in a series of probable accretion scenarios. Although many assumptions are made to derive values of accretion rates, such estimates provide one additional consistency check, which helps to gauge the reliability of the overall jet launch scenarios.

3.1 Radiative pressure

To calculate the radiative pressure exerted, we use the brightest possible post-AGB star with \( L \approx 10^4 \) \( L_\odot \). Hence the radiative force, \( p = L/c \), is 10\(^{25}\) dyne. This is the largest possible force, exerted if the entire radiation field of the star were intercepted by jet matter and converted to kinetic energy with maximum efficiency.

The smallest jet force in our sample is obtained for the pre-CE jets by using \( M_{\text{jet}} = 10^{-3} \) \( M_\odot \) and velocity \( v = 100 \) km s\(^{-1}\) (Section 2.5) with an accretion time-scale of 8000 yr. This results in \( p_{\text{jet}} \geq 8 \times 10^{25}\) dyne. A larger momentum limit can be obtained by using the fast jets of NGC 6778 (Table 1) with a mean jet velocity of 460 km s\(^{-1}\); \( p_{\text{jet}} \geq 2 \times 10^{27}\) dyne.

Comparing the lower limit range \( 8 \times 10^{23}–2 \times 10^{27}\) dyne to the upper limit of 10\(^{27}\) dyne, it is easy to convince ourselves that radiation is unlikely to be responsible for the acceleration of these jets, not to mention that even if it were, there would be no explanation for the collimated nature of the outflows. We next turn our attention to accretion as a means to launch the jets.

3.2 The accretion rate at the time of Roche lobe overflow

The most logical moment to form an accretion disc in the life of a binary about to enter a CE interaction is at the time of RL overflow. To determine the mass accretion rate through the inner Lagrangian point we adopt, as a typical configuration, a 1 \( M_\odot \) giant with a 300 \( R_\odot \) radius, entering RL contact with a 0.3 \( M_\odot \) companion at 3 au. Such system may be close to reaching synchronization at the time of RL overflow.
A formalism for the accretion rate through the inner Lagrangian point is given by Ritter (1988). They define the accretion rate as

$$\dot{M} = \frac{2\pi}{\sqrt{g}} F(q) \frac{R_{\text{L},1}^2}{GM_1} \left( \frac{R_{\text{eff},1}}{\mu_{\text{ph},1}} \right)^{3} \rho_{\text{ph},1},$$

where $R_{\text{L},1}$ is the RL radius of the donor, in our case the primary giant, $\mathcal{R}$ is the RL radius of the donor, $M_1$ is the mass of the primary, $T_{\text{eff},1}$ the effective temperature of the primary, $\mu_{\text{ph},1}$ is the mean molecular weight of the primary’s atmosphere and $\rho_{\text{ph},1}$ is the density at the photosphere. $F(q)$ is defined as

$$F(q) = (g(q) [g(q) − q − 1])^{-1/2} \left( \frac{R_e}{a} \right)^{-3},$$

with $g(q) = q/x^3 + 1/(1 − x)^3$ and where $x$ is the distance of $L_1$ to the secondary in units of $a$. The value for $x$ can be calculated numerically based upon the orbital parameters of the system (Sternberg, Willems & Kalogera 2007, fig. 4). The value of $x$ is 0.40 or 1.35 $\times R_{\text{L},2}/a$. We also used $T_{\text{eff},1} \sim 3000 K$, $\mu_{\text{ph},1} \sim 0.8$ (appropriate for a neutral cosmic mix) and $\rho_{\text{ph},1} \sim 10^{-9} \text{ g cm}^{-3}$ (appropriate for our AGB star’s atmosphere). Finally, from Eggleton (1983) the equation for the unit-less Roche radius of the primary is

$$r_{\text{L},1} = \frac{R_{\text{L},1}}{a} = \frac{0.49q^{-4/3}}{0.6q^{-4/3} + \ln (1 + q^{-4/3})},$$

where $q = M_{\text{sec}}/M_{\text{prim}}$, $R_{\text{L},1}$ is the RL radius for the primary, donor star and $a$ is the separation between the two objects. In this way we found $M = 4 \times 8 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$. We conclude that the RL overflow generates an accretion rate that may generate jets with a higher mass-loss rate and overall larger masses. This could either indicate that the pre-CE jets are launched before RL contact, or that the time over which they were launched is smaller, of the order of several decades, compared to the time-scales we have adopted.

Finally, we remark that for an accretion rate of $8 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ and an accreted mass of $0.4 M_{\odot}$ (see Section 2.1), the accretion time-scale would be 500 yr. This time-scale is lower by a factor of a few than the maximum ejection time-scales listed in Table 1. As scenarios and data are refined, all these time-scales need to be reconciled.

### 3.3 Wind accretion

The issue of how long the system remains in RL contact before the onset of a CE is important, because the more the envelope is transferred to the companion the easier it will be for the companion to unbind the remaining envelope during the CE phase (both because the envelope is lighter and because the companion is more massive). In Section 3.2, we have concluded that the phase may not be particularly short because we have assumed that the mass accretion that gives rise to the observed jets takes place due to RL overflow. Here, we consider the possibility that the accretion takes place before RL overflow via accretion from the wind of the primary. If this took place it may release the constraint of needing much accretion to take place at the time of RL overflow.

The Bondi–Hoyle mass accretion approximation (BH; Bondi & Hoyle 1944) cannot be used to investigate accretion at separations of a few au, or just outside the RL overflow separation. The BH capture radius, $b = 2GM/(v_K^2 + v_{\text{wind}}^2)^{1/2}$, where the Keplerian ($v_K$) and wind ($v_{\text{wind}}$) velocities are similar, is of the order of the orbital separation. In such case, the BH approximation cannot be valid since the medium through which the accretor/companion is moving is all but homogeneous.

Unfortunately, there are no analytical accretion models for the region just beyond RL contact. However, a few simulations have explored this region, either through the simulation of both the primary and the secondary (Mohamed & Podsiadlowski 2007, 2011; Kim & Taam 2012), or considering only one star (Huarte-Espinosa et al. 2013). Mohamed & Podsiadlowski (2007, 2011, 2013) propose an intermediate accretion mechanism that they call ‘wind RL overflow’, where instead of the envelope of the primary filling the RL, its wind is channelled through the inner Lagrange point, allowing for an accretion rate that can be as high as half the mass-loss rate of the primary $(10^{-6} \text{ to } 10^{-4} M_{\odot} \text{ yr}^{-1})$, for upper AGB stars) and much higher than the typical BH efficiency of a few per cent. However, wind RL overflow may not always be applicable, as it requires that the velocity of the AGB wind at the RL radius be less than the escape velocity from the same location which will be sensitive to the details of the wind acceleration model.

Huarte-Espinosa et al. (2013) simulated disc formation around a mass in a box with uniform fluid. Their disc mass for simulation setups that represented orbital separations between 10 and 20 au ranged between $7 \times 10^{-6}$ and $6.5 \times 10^{-7} M_{\odot}$. Such disc masses would be on the low side to explain our jets masses. However, better measurements and models that cover a wider parameter space, such as a smaller orbital separation may find some agreement.

### 3.4 Accretion during the CE dynamical phase

Ricker & Taam (2008) and Ricker & Taam (2012) determined the accretion rate on to the companion during the early phase of the fast dynamical inspiral. Although they conclude that the BH prescription would lead to an overestimate of the accretion rate by a factor of $\sim 100$, their estimated average mass accretion rates are of the order of $10^{-2} M_{\odot} \text{ yr}^{-1}$, which is a large value in the present context. In fact such rates would lead to jets with much larger accretion rates than we have measured and the only way to reconcile the numbers would be if the accretion time-scales were lower than we have considered leading to larger jet mass-loss rates.

There are several issues with the estimate of Ricker & Taam (2008) and Ricker & Taam (2012) that prevent us from simply using their figure. First of all, from the scenario point of view a jet that developed because of accretion during the dynamical infall phase of the CE would have approximately the same dynamical age as the main nebula, something that is not observed in any of our systems, unless by some fluke of nature the uncertainties conspired in masking this coevality in all systems (Section 2).

Secondly, these estimates are the result of a series of approximations, because the hydrodynamic simulations are not adequate to reproduce and hence measure the physics involved. The simulations do not model the surface of the accretor, but use instead a series of nested control surfaces. It is not clear that the mass that enters the control surfaces around the accreting companion actually accretes. This will depend on the angular momentum involved. The control
surfaces also give discrepant rates, as is understandable, with the larger ones leading to higher accretion rates. Finally, such high accretion rates would be super-Eddington, which is also not included in the simulation. This said, accretion during the CE phase would be a natural way to explain two jets since both the core of the giant and the companion may accrete material from the CE. It remains a priority of CE hydrodynamic simulations to establish when and how much accretion takes place.

4 THE MAGNETIC FIELD

Once an accretion disc forms, we require a mechanism to cause the material in the disc to lose angular momentum and launch the jets. The mechanism for the angular momentum loss that allows material to accrete on to the central object is a matter of debate (see e.g. Vishniac & Diamond 1993; Gammie & Johnson 2005). Here, we assume that the angular momentum transport is provided by the magnetic field that is also responsible for launching the jets. This in turn allows us to use the magnitude of the accretion rate to estimate the magnetic field strength.

Wardle (2007) derived an estimate of field strength required in order to accrete given the radius of the disc and the accretion rate (cf. section 2.1 of Blackman et al. 2001a). The derivation considers the azimuthal component of the momentum equation for the system, and assumes that the azimuthal component of the disc’s velocity can be approximated by its Keplerian velocity, given the disc is thin. Under such conditions, we have a minimum magnetic field strength (in gauss) of

$$B \approx 0.2 \frac{M_{\odot}^{1/2}}{\dot{M}^{5/4}} \left( \frac{M}{M_{\odot}} \right)^{1/4} r_{\text{rad}}^{-3/4} \left( \frac{M}{M_{\odot}} \right)^{1/4},$$

(4)

where $M$ is the mass of the accretor, where $\dot{M}_{\gamma}$ is the mass accretion rate in units of $10^{-7} M_{\odot} \text{ yr}^{-1}$ and $r_{\text{rad}}$ is the disc radius, in au, at which the field has that strength. This formalism applies locally, meaning that for a disc with an inner and an outer radii, one would derive a range of values of the magnetic field strengths. Below, we apply this approximation to derive the magnitude of the magnetic field in our systems. We emphasize here that while the formalism above is a reasonable predictor of the needed magnetic field strengths, the accretion rates and disc sizes are not well constrained. However, as observationally derived quantities become better known (likely from a larger sample, rather than better measurements) PN observations should put more stringent constraints on the CE interaction.

4.1 The magnetic fields in systems where the jets predate the nebula

Huart-Espinosa et al. (2013), modelling wind accretion on to a companion orbiting at 10, 15 and 20 au from the primary, obtained accretion disc sizes of $\sim 1$ au. A similar estimate for the disc radius is obtained in the case of RL overflow. Using the tidal equations of Zahn (1989) and the radius evolution of stars in the mass range 1–4 $M_{\odot}$, the maximum separation for a tidal capture is $5–8$ au, but for the more common lower mass stars it is closer to $2–3$ au (e.g. Villaver & Livio 2009; Mustill & Villaver 2012), which is also the distance at which our typical 300 $R_{\odot}$ giant will fill its RL. For a separation of 2.5 au and a mass ratio of $M_{\gamma}/M_{\ast} = 0.3$, as adopted previously, we therefore expect the accretion disc radius to be smaller than the accretor’s RL radius, or smaller than about 0.7 au. Table 2 shows the required field strength using equation (4) with a range of accretion rates appropriate for wind and RL overflow accretion which also encompass the values deduced from the jet mass-loss rates (Table 1) and for accretion disc radii of 0.5, 1 and 2 au which encompass likely values of such discs. We emphasize that these disc radii are to be interpreted as distances from the accretor where disc material would be losing angular momentum at a rate dictated by the local magnetic field and at which point a certain fraction of that material, assumed to be 10 per cent, would be launched vertically into a jet. Therefore, the disc may extend to smaller and larger radii than the radius considered, but the magnetic field strength derived is for that location in the disc.

We finally note that the escape velocity from the gravitational field of accretors with masses between 0.3 and 1 $M_{\odot}$, from a point located between 0.5 and 2 au from the centre of the accreting secondary, are in the range 16–60 km s$^{-1}$. These are lower than the jet speeds of $\sim 100$ km s$^{-1}$ measured for systems where the jets predate the CE ejection. To obtain such larger jet velocities, we would need disc radii of 0.05–0.2 au or 10–45 $R_{\odot}$. So if we adopted a purely empirical approach, where we took a disc radius based on the jet speeds and an accretion rate of $2 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ (or ten times the jet mass-loss rate from Table 1), we would derive magnetic field strengths of $\sim 5$–30 G (see Table 2).

4.2 The magnetic field in NGC 6778: an indirect measurement of a post-CE magnetic field

For the post CE PN NGC 6778, we know with reasonable certainty that the jets were launched after the CE dynamical infall phase. The two pairs of jets appear to be kinematically distinct so we also infer that they are not an optical illusion, part of the same kinematic structure under specific illumination conditions (as is the case for M2-9; Livio & Soker 2001). It is however difficult to construct a physical scenario for the launching of these jets because the post CE orbital separation leaves but a small space within which to form a sufficiently massive accretion disc (but see Section 5).

However, on the assumption that these post-CE jets are indeed launched by a disc, we use their mass-loss rate to infer a lower limit on the strength of the magnetic field necessary using equation (4). Using the mass-loss rate in the jets of $8.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (Table 1) and assuming, as we have done throughout this paper, that the accretion rate must be 10 times higher, and for a disc radius of 1 and 10 $R_{\odot}$, we obtain a magnetic field of 80–1400 G (see Table 3). The orbital period of the binary today (Table 1), implies an orbital separation of approximately 1 $R_{\odot}$ for any plausible range of stellar

**Table 2.** Minimum field strengths required to launch jets in the systems where jets predate the main nebula.

| Mechanism                | Approximate separation (au) | Accretion rate ($M_{\odot} \text{ yr}^{-1}$) | Field strength for $r_{\text{disc}} = 0.1$ au (G) | Field strength for $r_{\text{disc}} = 0.5$ au (G) | Field strength for $r_{\text{disc}} = 1$ au (G) | Field strength for $r_{\text{disc}} = 2$ au (G) |
|--------------------------|-----------------------------|---------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Wind accretion           | ~3–5                        | $10^{-6}$–$10^{-5}$                        | 8–26                                             | 1.1–3.5                                         | 0.5–1.5                                          | 0.2–0.5                                          |
| RL overflow              | ~2–3                        | $10^{-4}$–$10^{-3}$                        | 83–260                                          | 11–35                                            | 5–15                                             | 2–6                                             |
masses. We include a larger disc radius in Table 3 to encompass the possibility that at the time of the jet launching either the orbital separation was larger or that the disc was circumbinary (see Section 5). We note that for an accretor in the mass range 0.3–1.0 M⊙ and a launch point between 1 and 10 R⊙, the escape velocity ranges between 110 and 620 km s⁻¹, a range encompassing the deprojected velocities measured for the jets of NGC 6778 (Table 1).

We leave speculation of the actual scenario that gave rise to the post-CE twin jets to Section 5.

### 4.3 The origin of the magnetic field

For the three systems, where the jets predate the nebula, gauss-sized magnetic fields are implied. These fields should thread the disc approximately vertically for the launching to happen according to commonly adopted jet launching models (Blandford & Payne 1982). The magnetic field could originate in the envelope of the giant as it gets spun up by the tidally infalling companion. The field would have to be dragged as the envelope material moves towards the companion. It is less likely that the magnetic field would originate in the companion itself, because of the relative old age of post-AGB binaries. One may also speculate that the field may be somehow self-generated in the disc itself (for a discussion on different field configurations see Pudritz et al. 2007). Magnetic fields strengths on the surface of Miras have been measured and are consistent with a few gauss. For example, Amiri et al. (2012) measured a field strength of 3.5 G at 5.4 au from the centre of the Mira star OH44.8–2.3.

For NGC 6778, whose launch model is so uncertain, it is paradoxically easier to hypothesize that the strong fields are created during the dynamical phase of the CE interaction, as detailed by Regos & Tout (1995) and Nordhaus, Blackman & Frank (2007). Nordhaus et al. (2007) modelled a CE dynamo in a 3 M⊙ primary with secondaries in the mass range 0.02–0.05 M⊙. They find that the toroidal field, Bₜ ≈ 1–2 × 10⁵ G, while the poloidal component, responsible for the jet launching, Bₚ ≈ 200–300 G.

Regos & Tout (1995) provide an analytical formalism which we use here to derive the magnetic field components Bₚ and Bₜ. We start with the equation for the poloidal component of the magnetic field (Regos & Tout 1995, equation 2.14):

\[
Bₚ = 10γ \left( \frac{3Menv}{Renv} \right)^{1/2} \left( \frac{L_{\text{star}}}{ηM_f} \right)^{1/3},
\]

where the efficiency of the dynamo regeneration term is γ ≈ 10⁻², η = 3Renv/lₑ ≈ 30, Renv is the radius of the base of the envelope, lₑ is the mixing length parameter, L is the total energy generated in the envelope and Mₚ = Menv + Mₚ + Mₜ, where Menv is the mass of the envelope, Mₚ is the mass of the secondary (the ‘red’ star) and Mₜ is the mass of the core (the future white dwarf). The total luminosity is \( L = L_{\text{star}} + L_{\text{orb}} \), where

\[
L_{\text{star}} = \frac{1.869 \times 10^8 Mₚ^2 + 7.205 \times 10^8 Mₚ Mₜ + 1.803 \times 10^9 Mₜ^2}{1 + 7.543 \times 10^5 Mₚ Mₜ + 1.903 \times 10^8 Mₜ^2}.
\]

(Regos & Tout 1995, equation 5.1) with \( L_{\text{star}} \) and \( Mₚ \) in solar units. By combining their equations 4.6 and 4.9 to 4.11 and solving the resulting quadratic equation, we derive

\[
L_{\text{orb}} = \frac{L_{\text{star}} \left( 1 + \sqrt{1 + 4a} \right)}{2a},
\]

where \( ΔΩ = |Ω_{\text{orb}} - Ω_{\text{env}}| \) is the difference (or shear) between the angular velocity of the orbit (\( Ω_{\text{orb}} = \sqrt{G(Mₚ + Mₜ)/d^3} \), where \( d \) is the orbital separation), and that of the envelope. We read the value of the shear from Fig. 5 of Regos & Tout (1995). Finally, to determine \( Bₚ \), we use their equation 2.4: \( Bₚ = Bₜ/ε \), with

\[
ε = \sqrt{\frac{0.01 \left( \frac{R_{\text{env}}}{R_{\text{MSS}}} \right)^{1/3}}{ΔΩ R_{\text{env}}}}.
\]

Using a primary composed of an envelope with mass ranging between 0.5 and 2.5 M⊙ and a core ranging between 0.5 and 1 M⊙ and a secondary with mass ranging between 0.5 and 1.5 M⊙, we found that \( Bₚ ≈ 0.5–1 \times 10^5 \) G and \( Bₜ ≈ 100–500 \) G. Therefore, Regos & Tout (1995) and Nordhaus et al. (2007) agree on the magnitudes of the magnetic fields generated during a CE interaction.

They both suggest that the field in post-CE primaries would be mostly toroidal, but that their poloidal component is still relatively strong and similar to what we have determined using our jet observations, for the larger of the disc radii considered (Table 3). What we have not considered here is that the magnetic field would likely be transported out with the ejection of the CE, so that its strength at the location of the remnant binary would decrease in time.

### 5 A SCENARIO FOR NGC 6778

Explaining the post-CE jet pairs observed in NGC 6778 is extremely difficult. At first sight, the two jets may indicate the formation of two accretion discs, possibly due to the infall of material that was not fully ejected by the CE interaction (see e.g. Akashi & Soker 2008). Such scenario may naturally explain the different jet velocities and even their morphologies. A simpler model whereby the jets are promoted by accretion of secondary star gas overfilling the RL and transferring to the primary via a disc may also be considered as was done by Soker & Livio (1994). This is a plausible scenario since in a binary with only 1 R⊙ separation, the secondary star, with a radius of 0.5–1 R⊙ may indeed overflow its RL.

In both scenarios the limited space between the two stars may limit excessively the mass of the disc that can form. In the RL-overflow scenario of Soker & Livio (1994), it would be hard to explain the two jets with their distinct kinematics. A third scenario already considered by Kashi & Soker (2011) may be the formation of an accretion disc around both stars in the binary. However, this would again not justify the two jet pairs. Additional scenarios may be constructed, for example one where the primary core spins down and strong magnetic fields expected after the CE ejection may form a jet in addition to one formed by a disc (Blackman, Frank & Welch 2001b). However, such scenarios rely on complex physical mechanisms which may or may not be at play in these stars.

A further constraint on any scenario is the time between the CE ejection and the post-CE jet ejection (~3000 yr). Despite the difficulties mentioned above, we try here to determine whether the fall-back disc would form within such a time frame. We here

---

Table 3. Field strengths required to launch jets in NGC 6778.

| Accretion rate (M⊙ yr⁻¹) | Field strength for r_disc = 1 R⊙ (G) | Field strength for r_disc = 10 R⊙ (G) |
|--------------------------|-------------------------------------|-------------------------------------|
| ~10⁻⁶                   | 475 G                               | 26 G                                |
| ~10⁻⁵                   | 1.6 kg                              | 92 G                                |
| ~10⁻⁴                   | 4 kg                                | 215 G                               |
consider the infall of bound CE material and determine at what distance it would come to rest if we consider a simple ballistic trajectory and conservation of energy and angular momentum. By solving

\[ J_z = m v_{\theta,h} h, \]

\[ m v_{\theta,h} h = m v_{\theta,disc} r_{disc}, \]

\[ \frac{1}{2} v_{\theta,h}^2 = \frac{GM}{h} = \frac{1}{2} v_{\theta,disc}^2 = \frac{GM}{r_{disc}}, \]

(6)

where \( J_z \) is the angular momentum vector perpendicular to the orbital plane, \( m \) is a mass element of infalling material, \( v_{\theta,h}, v_{\theta,disc}, h \) and \( r_{disc} \) are the orbital velocities and orbital radii of the material at altitude \( h \) above the compact binary and at the altitude at which the disc comes to rest; \( M \) is the mass of the central binary.

In order to put some numbers into the solution, we refer to the CE simulations of Passy et al. (2012) for our estimates of the angular momentum of the infalling envelope gas and its initial distance from the central binary. The \( z \) component of the total angular momentum of the system, \( J_z \approx 2.5 \times 10^{52} \text{ g cm}^2 \text{ s}^{-1} \), was estimated by Passy et al. (2012) using a binary with \( M_1 = 0.88 M_\odot \), \( M_2 = 0.6 M_\odot \) and \( a = 83 R_\odot \) (see their fig. 8), where the angular momentum of the orbit and the envelope were considered. Of this, approximately 1/5 belongs to bound matter (Passy et al. 2012, see their fig. 8). Bound material is distributed at \( h \sim 1 - 4.5 \times 10^3 R_\odot \) (Passy et al. 2012, see their fig. 19). If we divide the bound angular momentum by the mass of the bound envelope, using 95 per cent of an envelope of 0.49 \( M_\odot \), we get the value of the specific angular momentum of the infalling material: \( v_{\theta,h} h \sim 5 \times 10^{18} \text{ cm} \text{ s}^{-1} \), which in turn gives \( v_{\theta,h} \approx 1.5 - 7 \times 10^4 \text{ cm} \text{ s}^{-1} \). Hence, using equation (6), we calculate that the gas should come to rest at a distance from the binary centre of mass of approximately 0.06-20 \( R_\odot \). Hence, some of the fall-back material will move closer to the centre of the binary than the orbital separation. Some of this material may have the correct angular momentum to form accretion discs around the binary or ejected from the system.

In order to determine the time-scale of falling matter, we note that the gas follows half a Keplerian orbit with semimajor axis \( a = (h + r_{disc})/2 \), so by symmetry, the time taken is half the orbital period, or

\[ t = \pi \sqrt{\frac{a^3}{GM}}, \]

The result of this is the time taken for the mass element to fall to the equilibrium position, \( t \sim 2 - 14 \text{ yr} \). A more accurate ballistic calculation kindly carried out by J.-C. Passy using the results of his simulations (Passy et al. 2012), results in slightly longer time-scales of 8-50 yr, because this calculation accounts for the fact that the bound material is still carrying some outward velocity.

Other physical mechanisms can be present that can slow down the infall: a fast wind from the central binary as well as radiation pressure. Using equation 6 from Soker (2001)

\[ \frac{L/c}{M_{\text{wind}} v_{\text{wind}}} = 10 \left( \frac{L}{5000 L_\odot} \right) \left( \frac{M_{\text{wind}}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^{-1} \times \left( \frac{v_{\text{wind}}}{1000 \text{ km s}^{-1}} \right)^{-1}, \]

where \( L \) is the luminosity of the giant’s core, \( M_{\text{wind}} \) and \( v_{\text{wind}} \) are the mass-loss rate and velocity of the wind, respectively and \( c \) is the speed of light. Here, we have rescaled his values to those of an intermediate mass central stars (0.58 \( M_\odot \)) transiting towards the white dwarf cooling track. The ram pressure of the wind is therefore a tenth of the radiation pressure and will not play a significant role in slowing down the infall.

To estimate the radiation pressure, we can again use Soker (2001). Using their equations 1, 2, 4 and 5, we can compute the ratio of the gravitational force to the radiative force, given by

\[ \frac{f_R}{f_r} = \frac{GMm}{r^2 \beta (1 - e^{-\tau})}, \]

(7)

where \( m \) is a mass element at distance \( r \) from the central binary with total mass \( M \) and luminosity \( L \), subtending a solid angle \( \Omega \) such that \( \beta = \Omega/2\pi \) and where \( \tau \) is the optical depth of the mass element. The optical depth of the infalling envelope is not easy to determine at present. However, even assuming that the material is optically thick, and that it subtends the entire solid angle, the gravitational force dominates by more than four orders of magnitude. Thus, we deduce that radiation would not have much of a retarding effect on the infalling material. Lacking a way to retard the formation of a fall-back disc, we must conclude that such a short return timescale is at odds with the thousand-year time-scale indicated by the kinematics (unless the kinematic age of the jets were lower, or that of the disc higher).

6 COMPARISON WITH CE PN FLEMING 1 AND NGC 6337

There are two additional PN with jets known to harbour post-CE binaries: Fleming 1 and NGC 6337. We have not included them directly in our study because of the lack of nebular mass information. Below we review those characteristics which can be found in the literature and compare them to those of the four cases studied here.

Fleming 1 has jets that pre-date the nebula (Lopez, Meaburn & Palmer 1993; Palmer et al. 1996), as is the case for A 63, ETHOS 1 and the Necklace nebula. Fleming 1, with a 5000 yr old main nebula and 16 000 yr old jets has the highest time interval between jet and CE formation. Its orbital period today is 1.19 d, similar to the Necklace nebula. Its flat jet caps are more similar to those of A 63. This nebula is thought to harbour a double degenerate star (Boffin et al. 2012). The deprojected fastest velocity of the knotty jets of Fleming 1 is \( \sim 100 \text{ km s}^{-1} \), assuming, as Boffin et al. (2012) have done, an inclination of 45\(^\circ\) to the line of sight. This speed is in line with those of the other pre-CE jets.

NGC 6337, has post-CE jets as is the case for NGC 6778. The post-CE jets of NGC 6337 have many similarities with those of NGC 6778. Using the distance of Frew (2008) of 0.86 ± 0.20 kpc (instead of the distance of 1.3 kpc of García-Díaz et al. 2009), the ages of the nebula and jets are \( \sim 8000 \) and \( \sim 1000 \) yr, respectively, a 7000 yr delay between the CE and the jet ejection (cf. with almost 3000 yr for NGC 6778). The jet velocity is \( \sim 200 \text{ km s}^{-1} \), smaller than the velocity of the jets of NGC 6778 (270 and 460 km s\(^{-1}\), for each of the two pairs), but larger than all the pre-CE jet speeds. The jets in NGC 6337 are bent as is one of the jet pairs in NGC 6778. The binary inside NGC 6337 has an orbital period of 0.17 d, similar to the very short period of the binary inside NGC 6778 (0.15 d).

Hillwig et al. (2010) modelled the lightcurve of the central binary in NGC 6337 and, by assuming a central star mass of 0.6 \( M_\odot \), derived a companion mass of 0.2 \( M_\odot \) (quoting the hotter of the two models presented, but the differences are not large). This results in a situation where the companion, with a radius of 0.34 \( R_\odot \), is close to filling its RL (the inner Lagrangian point is only 0.56 \( R_\odot \)).
away from the centre of the secondary). While we have considered a model where the disc is formed by re-accretion of nebular material, we must wonder whether the coincidence of both binaries with post-CE jets being so close to RL overflow may not be telling us that the jet is actually due to accretion of secondary material on to the primary as proposed by Soker & Livio (1994). It is possible that in this case there differences in composition between the bulk of the nebula and the jet may be observed, since the jet may come from the unprocessed envelope of the main-sequence secondary, rather than processed AGB envelope gas. Of course, this would be the case only if the envelope of the secondary were not highly contaminated by AGB envelope material accreted during the CE phase.

7 CONCLUSION AND DISCUSSION

We have analysed the jets and nebulae of four post-CE PN, starting with their masses and kinematics. Three of the PN, the Necklace, Abell 63 and ETHOS 1, have jets that predate the main nebula by a few thousand years. They may have arisen when an accretion disc formed around the companion at the time of RL overflow, although that may lead to accretion rates higher than needed to explain the observed jets. Alternatively, the pre-CE jets may have formed before RL contact, from wind accretion, in which case accretion rates could be lower. The latter hypothesis is also more in line with the relatively long time-scales of jet formation before the CE infall phase. Furthermore, studies of systems like this could enable their use as constraints on the pre-CE phase which is at the moment ill constrained.

The fourth PN, NGC 6778, has jets that lagged the main nebula by about 3000 yr. The two pairs of jets with different velocities, both higher than the jet velocities in the pre-CE jets, are difficult to explain by any scenario. Appealing to RL overflow of the companion after the CE ejection makes sense in view of the very small orbital separation of todays binary. However, the two pairs of jets are then difficult to explain. A scenario where fall back of envelope material forms one or two accretion discs around the binary or its components meets with difficulties both due to the need to delay the disc formation and the fact that the orbital separation is small enough that forming two discs would be difficult. Despite these difficulties it is clear that post-CE jets (of which there is at least another one in the PN NGC 6337) will be useful in constraining future simulations of the CE interaction.

Independently of the scenario that formed the accretion discs, we have derived the strength of the magnetic field that launches the jets using the assumption that it removes angular momentum at the rate needed for accretion of material and launches the jets according to the mechanism of Blandford & Payne (1982). If so, the magnetic field strengths are of a few to 10 G, for pre-CE jets and hundreds to a few kilogauss in the case of post-CE jets. While it is unclear how to bring gauss-strength fields to the proximity of the companion in a pre-CE binary, the strength of the post-CE fields is in line with the independent theoretical predictions of post-CE fields by Regos & Tout (1995) and Nordhaus et al. (2007).

Finally, we remark that the jet masses and kinematics can provide us with the indication of how much envelope has been ejected before the CE via the jets, and how much has accreted to the companion. Both these phenomena will facilitate the envelope ejection, something that could explain the lack of a full CE ejection witnessed in the simulations of Passy et al. (2012). Frew (2008) found that all CE PN have low ionized masses compared to the masses of other PN. This observation could be in line with the hypothesis of a decreased envelope mass.

Accretion on to the companion is supported by the observation of carbon-rich material on the secondary star in the post-CE central binary of the Necklace nebula (Miszalski et al., 2013). Accretion on to the companion during the dynamical infall phase may contribute (Ricker & Taam 2008, 2012), although their mass accretion rates of $10^{-2}$ $M_\odot$ yr$^{-1}$ is likely overestimated and we would then expect an episodic jet or pair of jets launched at approximately the same time as the rest of the CE. An appealing feature of such scenario would be that the magnetic field at the time of launch would be naturally large, having been wound by the inspiral, and because the CE would not have departed yet, weakening the field in the proximity of the binary. Undoubtedly, upcoming hydrodynamic simulations of the CE phase will be used to explore further this possibility.

ACKNOWLEDGEMENTS

We are thankful to Martin Guerrero and Romano Corradi for sharing their observations and deriving for us jet masses. We are also indebted with David Frew for providing us with a homogeneous set of distances to these PN, which may have improved the comparison between them. Jean-Claude Passy is thanked for calculating the ballistic trajectories of his CE simulations and confirming the analytical estimates of the fall-back discs. Overall we are grateful for Noam Soker’s extensive comments and criticisms. We are thankful to Jan Staff for sharing his theoretical knowledge of jets. Finally, we thank an anonymous referee for comments which allowed us to improve the paper. OD acknowledges Australian Research Council Discovery grant DP120103337 and Future Fellowship grant FT12000452; MJW acknowledges Discovery grant DP120101792.

REFERENCES

Abell G. O., 1966, ApJ, 144, 259
Acker A., 1992, in Heck A., Murtagh F., eds, Proc. ESO Conf., Vol. 43, Astronomy from Large Databases, II, ESO, Garching, p. 163
Afşar M., Ibañoglu C., 2008, MNARS, 391, 802
Akashi M., Soker N., 2008, New Astron., 13, 157
Amiri N., Vlemmings W. H. T., Kemball A. J., van Langevelde H. J., 2012, A&A, 538, A136
Blackman E. G., 2009, in Strassmeier K. G., Kosovichev A. G., Beckman J. E., eds, Proc. IAU Symp. 259, Cosmic Magnetic Fields: From Planets, to Stars and Galaxies. Cambridge Univ. Press, Cambridge, p. 35
Blackman E. G., Frank A., Markiel J. A., Thomas J. H., Van Horn H. M., 2001a, Nature, 409, 485
Blackman E. G., Frank A., Welch C., 2001b, ApJ, 546, 288
Blandford R. D., Payne D. G., 1982, MNARS, 199, 883
Boffin H. M. J., Miszalski B., Rauch T., Jones D., Corradi R. L. M., Napiwotzki R., Day-Jones A. C., Küpper J., 2012, Science, 338, 773
Bond H. E., 2000, in Kastner J. H., Soker N., Rappaport S., eds, ASP Conf. Ser. Vol. 199, Asymmetrical Planetary Nebulæ II: From Origins to Microstructures. Astron. Soc. Pac., San Francisco, p. 115
Bond H. E., Liller W., Mannery E. J., 1978, ApJ, 223, 252
Bondi H., Hoyle F., 1944, MNARS, 104, 273
Corradi R. L. M. et al., 2011, MNARS, 410, 1349
Davis P. J., Siess L., Deschamps R., 2013, A&A, 556, A4
De Marco O., Farihi J., Nordhaus J., 2009, J. Phys. Conf. Ser., 172, 012031
De Marco O., Passy J.-C., Moe M., Herwig F., Mac Low M.-M., Paxton B., 2011, MNARS, 411, 2277
De Marco O., Passy J.-C., Frew D. J., Moe M., Jacoby G. H., 2013, MNARS, 428, 2118
Eggleton P. E., 1983, ApJ, 268, 368
Farihi J., Becklin E. E., Zuckerman B., 2005, ApJS, 161, 394
Frew D. J., 2008, PhD thesis, Macquarie University, Sydney, Australia
Frew D. J., Parker Q. A., 2010, Publ. Astron. Soc. Aust., 27, 129

Downloaded from https://academic.oup.com/mnras/article-abstract/439/2/2014/1017438 by guest on 30 July 2018
