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FORMATION OF BIPOLAR PLANETARY NEBULAE BY INTERMEDIATE-LUMINOSITY OPTICAL TRANSIENTS

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ABSTRACT

We present surprising similarities between some bipolar planetary nebulae (PNe) and eruptive objects with peak luminosity between novae and supernovae. The latter group is termed ILOT for intermediate-luminosity optical transients (other terms are intermediate-luminosity red transients and red novae). In particular, we compare the PN, NGC 6302 and the pre-PNe OH231.8+4.2, M1-92, and IRAS 22036+5306 with the ILOT NGC 300 OT2008-1. These similarities lead us to propose that the lobes of some (but not all) PNe and pre-PNe were formed in an ILOT event (or several close sub-events). We suggest that in both types of objects the several months long outbursts are powered by mass accretion onto a main-sequence (MS) companion from an asymptotic giant branch (AGB, or extreme-AGB) star. Jets launched by an accretion disk around the MS companion shape the bipolar lobes. Some of the predictions that result from our comparison is that the ejecta of some ILOTs will have morphologies similar to those of bipolar PNe, and that the central stars of the PNe that were shaped by ILOTs should have an MS binary companion with an eccentric orbit of several years long period.

Key words: planetary nebulae: general

Online-only material: color figure

1. INTRODUCTION

Peak supernova (SN) luminosities are about four orders of magnitude above those of novae. This gap is slowly filled with observations of eruptive events (e.g., Barbary et al. 2009; Berger et al. 2009, 2011; Bond et al. 2009; Kulkarni et al. 2007; Kulkarni & Kasliwal 2009; Kasliwal et al. 2011; Ofek et al. 2008; Rau et al. 2007; Mould et al. 1990; Mason et al. 2010; Pastorello et al. 2010; Prieto et al. 2008, 2009; Botticella et al. 2009; Smith et al. 2009). We term these outbursts intermediate-luminosity optical transients (ILOTs; other terms in use are Intermediate-Luminosity Red Transients and Red Novae).

The pre-outburst objects of some of the ILOTs were identified to be asymptotic giant branch (AGB) or extreme-AGB stars, with NGC 300 OT2008-1 (Bond et al. 2009; hereafter NGC 300OT) being the prototype. If the AGB star loses a substantial amount of mass in such an event (but not necessarily its entire envelope) and the event takes place not too long before the AGB star becomes a planetary nebula (PN), then the descendant PN is expected to have the following characteristic properties:

1. *A linear velocity–distance relation*. The ILOTs last for a time period Δt_I of weeks to several years. When the ejected mass is observed at a time $t_{\rm PN} \gg \Delta t_I$ (hundreds to tens of thousands of years) later, each mass element is at a distance of its velocity times $t_{\rm PN}$. Therefore, the PN component that was ejected during the ILOT is expected to posses a linear relation between velocity and distance. Elements that are slowing down will have a velocity lower than the fastest parts of the nebula at a similar distance from the center. Other PN elements that were lost before or after the event will not share this velocity to distance linear relation. It might be hard to tell whether slower elements come from an earlier mass loss episode or were part of the ILOT event but have since been slowed down.
2. *Bipolar structure*. As the ILOT is expected to result from a binary interaction (Kashi & Soker 2010b; Soker & Kashi 2011), the PN component ejected during the ILOT is expected to have a bipolar structure, for example, two lobes or a point-symmetrical structure if the jets are launched during the ILOT process. In that respect, most PNe that have been formed by an ILOT event, and hence are bipolar, are expected to host a binary system with an orbital separation of ∼1 AU. Another possibility is that the ILOT event took place just as the companion entered the common envelope.
3. *Expansion velocity of a few × 100 km s^{-1}*. As we think that most ILOTs are powered by accretion onto a main-sequence (MS) star (Kashi & Soker 2010b; Soker & Kashi 2011) that blows jets, the maximum outflow velocity is similar to that of the escape velocity from MS stars. The fastest moving elements will be dense parcels of gas that were only slightly slowed down by the interaction with the AGB wind. The average velocity of the ejecta will be several times lower than the escape velocity from the companion because of the interaction with the slower AGB wind, but still much faster than the AGB wind velocity. Therefore, the faster parts of the PN component that was ejected by an ILOT are expected to move at velocities of ∼100–1000 km s^{-1}.
4. *Total kinetic energy of* $\sim 10^{46}$*–*10^{49} *erg*. As typical ILOT energy is in this range, we expect the kinetic energy of the ejected component to be in this range.

In this paper, we argue that some bipolar PNe that have components showing these four properties might have been formed in an ILOT event. When such a PN is observed, we have no information on the exact duration of the mass ejection event. If the event was too long, then even if the total energy is as expected, the luminosity might have been too low (below typical nova luminosity) and the event was not an ILOT. Bearing this in mind, we nonetheless go ahead and compare, in Section 2, the PN NGC 6302 with the ILOT NGC 300OT. We note that Prieto et al. (2009) already made a connection between the ILOT NGC 300OT and pre-PNe. Based on that they raised the possibility that the progenitor of NGC 300OT was of mass

Table 1
Comparing PN and ILOT

	NGC 6302[a]	NGC 300OT[b]	OH231.8+4.2[c]
Type of object	PN	ILOT	pre-PN
Mass source	AGB star	Extreme-AGB star	Mira star (AGB)
Early mass loss[d]:	Equatorial torus		
Mass loss rate ($M_\odot$ yr^{-1})	$\sim 5 \times 10^{-4}$	$\sim 6 \times 10^{-4}$	
Ejection Velocity (km s^{-1})	~ 10	~ 12	
Duration (yr)	~ 5000	$< 10^4$	
Total mass ($M_\odot$)	~ 2	~ 5	
Dust	$\sim 0.03\ M_\odot$	Like in pre-PNe[e]	
Eruption:			
Duration (yr)	$\lesssim 100$	~ 0.22	< 125
Ejected mass ($M_\odot$)	0.1–1	~ 0.5	~ 0.3
Velocity range (km s^{-1})	0–500	75–1000	0–$\gtrsim 400$
Total energy[f] (erg)	$0.4\text{–}2 \times 10^{47}$	$\sim 2\text{–}10 \times 10^{47}$	$\sim 3 \times 10^{46}$
Stellar Mass ($M_\odot$) on the ZAMS[g]	$M_1 \simeq 6$	$M_1 \sim 6\text{–}15$	$M_1 \simeq 3.5$ $M_2 \simeq 2$
Prediction (P orbital period; e eccentricity)	A solar-like MS companion at $\sim$2–5 AU, possibly in an eccentric orbit: $e \gtrsim 0.3$; $P \sim 3\text{–}10$ yr	(1) Bipolar ejecta from the ILOT. (2) A $\sim 3\text{–}10\ M_\odot$ MS companion. Orbit: $e \gtrsim 0.3$; $P \sim 5\text{–}50$ yr	(1) The companion orbit has $e \gtrsim 0.3$ and $P \sim 3\text{–}10$ yr. (2) The system might go through an ILOT event in the near future.

Notes.
[a] Data for NGC 6302 are from Meaburn et al. (2008), Szyszka et al. (2009, 2011), Matsuura et al. (2005), and Wright et al. (2011).
[b] Data for NGC 300OT from Kochanek (2011), Prieto et al. (2009), Bond et al. (2009), and Kashi et al. (2010).
[c] Parameters for OH231.8+4.2 are from Kastner et al. (1992, 1998), Sánchez Contreras et al. (2002, 2004), Alcolea et al. (2001), and Bujarrabal et al. (2002).
[d] The mass loss episode prior to the eruption.
[e] The optical similarity to pre-PNe is discussed in Prieto et al. (2009).
[f] Large fraction of the mass in lobes of PNe moves at low velocity.
[g] Zero-age main sequence.

$<8\ M_\odot$. In Section 3, we discuss three pre-PNe that we suggest are formed by ILOTs. Motivated by the similarities between the ILOT and these PNe, in Section 4 we discuss plausible scenarios for the formation of a PN in an ILOT. Our discussion and summary are in Section 5.

2. COMPARING THE ILOT NGC 300OT WITH THE PN NGC 6302

The basic characteristics of the PN NGC 6302 are summarized most recently by Szyszka et al. (2011). The relevant properties are summarized in Table 1. The fundamental property that motivated us to make the comparison with an ILOT is the velocity–distance linear relation, $v_r \propto r$, that points to a short lobe-ejection event (Meaburn et al. 2008; Szyszka et al. 2011). It is important to emphasize that some components of the nebula do not obey this relation, implying they were ejected over a relatively long time before or after the lobe-ejection event. Such is the dense massive torus of mass $\sim 2\ M_\odot$ (Matsuura et al. 2005; Peretto et al. 2007; Wright et al. 2011; we note that Dinh-V-Trung et al. 2008 obtained that the mass of the torus is only $0.087\ M_\odot$) that was ejected over $\sim$5000 yr prior to the lobe-ejection event (Peretto et al. 2007).

Prieto et al. (2009) make the connection between the ILOTs NGC 300OT and SN 2008S to pre-PNe and suggest similar progenitors. Prieto et al. (2009) based their conclusions on the similarities of the mid-IR spectrum, optical spectra, kinematics, and dusty circumstellar medium. By kinematics they refer to the expansion velocity and bipolar morphology. We here add the similar properties of total energy and short ejection event, and discuss the formation of the bipolar structure in PNe and pre-PNe by ILOT events.

The kinetic energy of the gas in the lobes suggests to us that the lobe-ejection event was of the same magnitude as the ILOT events. To demonstrate this we draw the kinetic energy of the lobes on the energy–time diagram (ETD) that is used to characterized ILOTs (Kashi et al. 2010; Kashi & Soker 2010b). The ETD (Figure 1) presents the *total energy* of the transients, radiated plus kinetic, as a function of the duration of their eruption, defined as a drop of 3 mag in the V band. When there is more information on a transient from observations or modeling, we present in the ETD the *available energy*, i.e., total gravitational energy available for the event, namely, the gravitational energy that could have been released if all the mass is accreted by the accreting star. However, for most ILOTs the observations and models are not yet detailed enough to perform this estimate, and we can only present the estimated radiated plus kinetic energy.

The upper-right region of the Optical Transient Stripe (OTS) is occupied by observed major luminous blue variable (LBV) eruptions. For major LBV eruptions the available energy is equal to the radiated plus kinetic energy, as there is no inflated envelope. The observed lower-left region is occupied by ILOTs. There are no observed objects yet in the farther lower-left of the

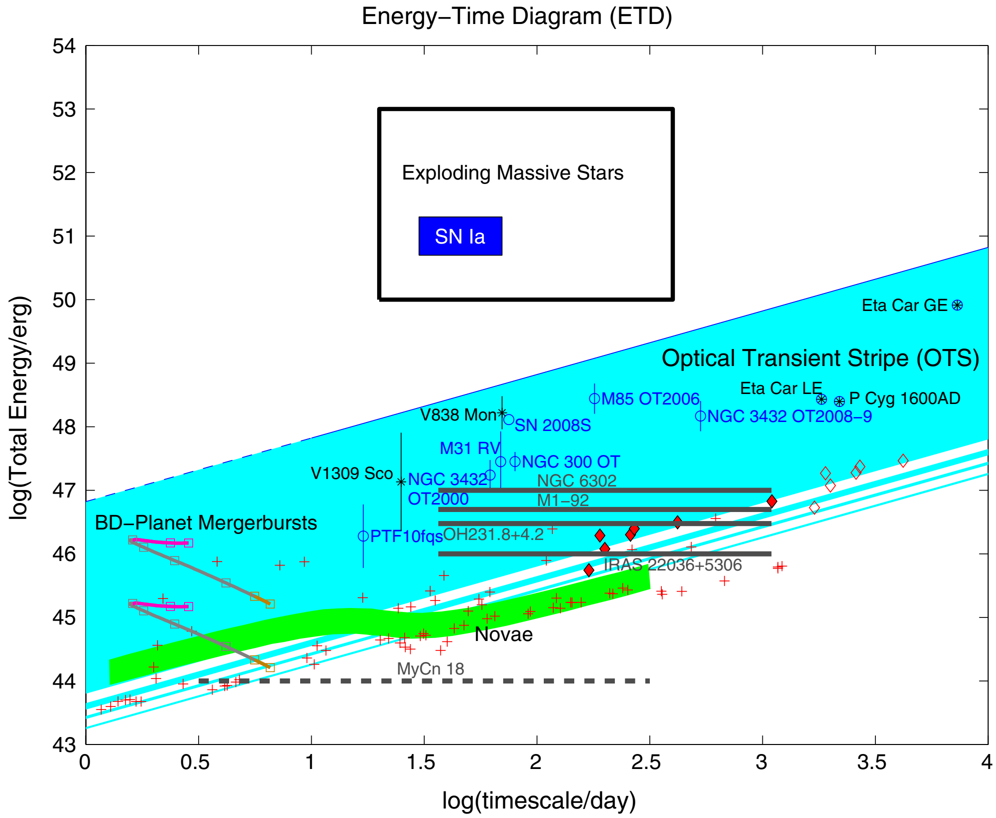

Figure 1. Observed transient events on the energy–time diagram (ETD). Blue empty circles represent the total (radiated plus kinetic) energy of the observed transients as a function of the duration t of their eruptions. The Optical Transient Stripe (OTS) is a more or less constant luminosity region in the ETD. It is populated by accretion powered events such as ILOTs (including mergerbursts), major LBV eruptions, and predicted BD-planets mergerbursts (Bear et al. 2011). The green line represents nova models computed using luminosity and duration from della Valle & Livio (1995). Nova models from Yaron et al. (2005) are marked with red crosses, and models from Shara et al. (2010) are represented with diamonds. The total energy does not include the energy deposited in lifting the envelope that does not escape from the star. Where a model exists to calculate the gravitational energy released by the accreted mass (the available energy), it is marked by a black asterisk. The kinetic energies of the components that expand with a linear velocity–distance relation in each of the five bipolar planetary nebulae and pre-PNe discussed in this paper are marked by horizontal lines. The energy of each object is derived from observations (for uncertainties see Table 1), while the timescale is an estimate of our proposed model. MyCn 18 is an exception, as it was formed by a nova eruption rather than by an ILOT.

(A color version of this figure is available in the online journal.)

OTS, but this region is predicted to be occupied by brown dwarf (BD)–planet mergerbursts (Bear et al. 2011). In this process the planet is shredded into a disk, and the accretion leads to an outburst. The destruction of a component in a binary system and transforming it to an accretion disk is an extreme case of mass transfer processes in binary systems.

The ILOT NGC 300OT was discovered by Monard (2008), with a bolometric luminosity of $L_{\rm bol} = 1.6 \times 10^{40}\,{\rm erg\,s^{-1}}$ at discovery (Bond et al. 2009). The pre-outburst progenitor was later reported by Prieto et al. (2008). Spectra taken by *Spitzer* revealed that most of the energy was emitted in the IR (Prieto et al. 2009). It was enshrouded by dust (Bond et al. 2009; Berger et al. 2009) and had a luminosity of about $6 \times 10^4\,L_\odot$, corresponding to an $M = 10$–$15\,M_\odot$ extreme-AGB star (Thompson et al. 2009; Botticella et al. 2009). A more massive red supergiant of mass $M = 12$–$25\,M_\odot$, as suggested by Gogarten et al. (2009) based on stellar evolution considerations, may also be consistent with the data. Prieto et al. (2009) noticed the similarity of NGC 300OT to pre-PNe and put the lower mass range to be $\sim 6\,M_\odot$. They also raised the possibility that the progenitor can be a C-rich AGB star. Kochanek (2011), on the other hand, favors a $9\,M_\odot$ progenitor.

Berger et al. (2009) attributed the $\sim 10^3\,{\rm km\,s^{-1}}$ red wing of the Ca II H&K absorption lines either to infalling gas from a previous eruption or to the wind of a companion star. In either case the star accreting this matter is likely to be an MS star. Together with the evidence for the supergiant nature of the progenitor, this implies that there are two different stars in the system. Bond et al. (2009) interpreted the hydrogen Balmer lines and the Ca II IR triplet's double features as indicating the presence of a bipolar outflow expanding at a velocity of $\sim 75\,{\rm km\,s^{-1}}$. Bond et al. (2009) suggested that NGC 300OT originated from an evolved massive star on a blue loop to warmer temperatures and was subjected to increased instability due to prior mass loss.

Patat et al. (2010) observed an asymmetric dusty environment extending a few thousand AU surrounding NGC 300OT that hints at a previous possible eruption. This asymmetry may further hint at the presence of a companion star, although we note that up to now there has been no definite observation proving the existence of a companion. Thompson et al. (2009) suggested that ILOTs occur due to single star processes, e.g., electron-capture SN, an explosive birth of a massive WD, or an enormous outburst of a massive star. In their model for NGC-300OT-like events, the progenitors are luminous ($\sim(4$–$6) \times 10^4\,L_\odot$) dust-enshrouded stars, at the end of their AGB stage.

In Kashi et al. (2010) we suggested that NGC 300OT was powered by a mass transfer event of a few $\times 0.1\,M_\odot$ from an extreme-AGB star to a 3–10 $M_\odot$ MS companion. One of the arguments for the presence of a companion is that a faster observed outflow of up to $\sim$600 km s^{-1} (Berger et al. 2009) fits the escape velocity from MS stars better. The total energy of the eruption (radiated and kinetic), $E_{\rm tot} \simeq$ (2–4) $\times$ 10^{47} erg, was therefore explained as having a gravitational origin.

There is no problem in our lack of information about the amount of energy that was radiated during the lobe-ejection event of NGC 6302. The reason is that in ILOTs the kinetic energy is typically much larger than the radiated energy. For NGC 300OT, for example, estimates of the kinetic energy are on the order of a few $\times 10^{47}$ erg (Kashi & Soker 2010b; Kochanek 2011), much higher than the radiated energy.

We also note that our claim for an ILOT event does not imply that there was only one event. It is possible, as in the case of the LBV in NGC 3432 (also referred to as SN 2000ch), that several short events occurred one after the other. This LBV underwent a major eruption in 2000 which lasted 62 days (Wagner et al. 2004), followed by a series of three eruptions in 2008–2009, lasting for a total of $\sim$531 days (Pastorello et al. 2010).

Just as a plausible example for the PN NGC 6302, there could have been, say, 10 short sub-events, each with an energy of a few $\times 10^{46}$ erg, lasting for $\sim$30–100 day, and repeating periodically, due to an eccentric orbit every $\sim$3–10 yr. Each such sub-event falls well within the OTS. Therefore, in Figure 1 we mark the timescale for the events as we estimate based on our ILOT model, $\sim$0.1–3 yr. This estimate satisfies well the part of the orbit where the companion was close to the primary and could have triggered the events.

We note that the formation of a bipolar nebula via mass loss from an evolved star in a close binary system does not necessarily imply a decrease in eccentricity. This is seen observationally for η Car and the Red Rectangle, a bipolar nebula around a post-AGB star in a binary system with an orbital period of 322 days and an eccentricity of $e = 0.34$. A possible explanation for the high eccentricity of the Red Rectangle was worked out in Soker (2000a). There it was shown that enhanced mass loss rate during periastron passages can overcome tidal effects, and the eccentricity might even increase. In Kashi & Soker (2010a) we found that during the Great Eruption of η Car the eccentricity almost did not change, despite large amounts of mass loss and mass transfer. The eccentricity of the η Car binary system was very high before the Great Eruption. Namely, despite the close approach at periastron, the eccentricity of the system was very large, $e \sim 0.9$, before the Great Eruption, and remained large after the eruption. Overall, both observations and theory support the notion that the binary systems discussed in this study can maintain high eccentricities.

3. OTHER PLANETARY NEBULAE AND PROTO-PNe

There are other bipolar PNe and pre-PNe that might have been formed by ILOTs (in one event or several sub-events). We consider here three pre-PNe as further examples. More pre-PNe were compared to NGC 300OT by Prieto et al. (2009). We end this section by presenting one bipolar PN that was not formed by an ILOT despite having a linear velocity–distance relation.

3.1. The Bipolar Pre-PN OH231.8+4.2

OH231.8+4.2 (The Calabash Nebula, also known as "The Rotten Egg Nebula") is a bipolar pre-PN (e.g., Bujarrabal et al. 2002) that we suggest was formed by an ILOT. The central system of the pre-PN comprises a bright Mira variable star with an estimated zero-age MS (ZAMS) mass of $\sim$3.5 $M_\odot$ (QX Pup; Kastner et al. 1992, 1998) and an A star companion (Sánchez Contreras et al. 2004). According to Alcolea et al. (2001) and Bujarrabal et al. (2002) the lobes reach a velocity of $\gtrsim$400 km s^{-1}, have a momentum of $\sim$3 $\times$ 10^{39} g cm s^{-1}, a total kinetic energy of $\sim$3 $\times$ 10^{46} erg, and were formed over a timescale of $<$125 yr.

Sánchez Contreras et al. (2004) suggest that the lobes were inflated by jets in the velocity range v_j = 500–1000 km s^{-1}. This gives a total jets' mass of $M_j \simeq$ 0.01–0.02 $M_\odot$ and total kinetic energy of $E_j \simeq (0.5\text{–}1) \times 10^{47}$ erg. These jets interacted with the circumbinary gas and inflated the lobes that now contain $\sim$0.3 $M_\odot$ (both lobes contain similar masses in spite of their different extents). This interaction dissipated part of the kinetic energy of the jets.

As with NGC 6302, there are components that were not ejected or were not accelerated during the lobe-ejection event. Most of the nebular mass, $\sim$0.64 $M_\odot$, does not reside in the lobes, but rather resides near the center and expands at low velocities $<$40 km s^{-1} (Alcolea et al. 2001). Some mass is in a torus of radius $\sim$6 AU very close to the center (Sánchez Contreras et al. 2002).

What is most interesting about OH231.8+4.2 is that the primary star is still an AGB star, and that it has an MS companion of spectral type A0 and a mass of $\sim$2 $M_\odot$ (Sánchez Contreras et al. 2004). This is the type of a companion that is required in the binary ILOT model that we have developed over the last several years (Kashi & Soker 2010b). It is very likely (although not necessary) that the companion has an eccentric orbit with an orbital period of $\sim$3–10 yr.

Alcolea et al. (2001) and Sánchez Contreras et al. (2004) considered the active jet phase to have lasted $\sim$100 yr. Sánchez Contreras et al. (2004) proposed that the eruption during these hundred years was like that of FU-Ori-type outbursts of young stars. We instead suggest that this phase, the lobe-ejection event, was much shorter. It was composed of one ILOT event or several close ILOT sub-events, each lasting $\lesssim$100 days. In Figure 1 we mark the timescale we estimate based on our ILOT model, $\sim$0.1–3 yr $\ll$ 100 yr. As the primary of OH231.8+4.2 is still an AGB star, such an event might take place again. Namely, according to our model it is quite possible that OH231.8+4.2 will experience an ILOT event in the near future.

3.2. The Bipolar Pre-PN M1-92

Another example is the dusty (Ueta et al. 2007) bipolar (e.g., Trammell & Goodrich 1996) pre-PN M1-92 (IRAS 19343+2926) that has a general linear velocity–distance relation (Bujarrabal et al. 1998b) and an extra kinetic energy of $\sim$7 $\times$ 10^{45} erg (Bujarrabal et al. 1998a). By extra kinetic energy Bujarrabal et al. (1998a) refer to the energy of the lobes above that of a regular AGB wind. This extra energy, they suggest, comes from the post-AGB jets (Bujarrabal et al. 1998a). The extra energy is calculated from the velocity component along the symmetry axis of the lobes that reaches a maximum velocity of $\sim$70 km s^{-1}.

The kinetic energy in the event could have been higher, but it was dissipated when the ejected jets interacted with the more massive circumbinary gas. The extra momentum along the axis is $\sim$3 $\times$ 10^{39} g cm s^{-1} (Bujarrabal et al. 1998a). If the ejected speed of the jets was $v_j > 70$ km s^{-1}, i.e., more than the maximum observed present speed in the lobes, then the ejected mass was $<0.2\, M_\odot (v_j/70\ {\rm km\ s^{-1}})^{-1}$. The corresponding kinetic energy is $E_j \simeq 10^{46} (v_j/70\ {\rm km\ s^{-1}})$ erg. As a more typical value we take the ejected velocity to be that of an escape speed from a low-mass MS star, $\sim$300–400 km s^{-1}, for which we get $E_j \simeq 5 \times 10^{46}$ erg, and 0.04 $M_\odot$ for the ejected mass in the jets.

The general linear velocity–distance relation, the maximum velocity of the present lobes of $\sim$70 km s^{-1}, and the total energy suggest to us that the lobes were shaped by jets (Bujarrabal et al. 1998a) that were ejected in an ILOT event (or several close sub-events). As we did for the previous objects, we mark in Figure 1 the timescale as we estimate it from our ILOT model, $\sim$0.1–3 yr.

3.3. The Bipolar Pre-PN IRAS 22036+5306

The pre-PN IRAS 22036+5306 (hereafter I22036) shows that the ejection of a bipolar component can last for $\lesssim$1 yr. Sahai et al. (2003) presented *Hubble Space Telescope* (*HST*) observations of this pre-PN, revealing an extended knotty bipolar shape. The structure of I22036 is rather complicated and has many sub-features (Sahai et al. 2003). The total mass of the pre-PN is $\sim$0.065 $M_\odot$ and the velocities of the various components range between 0 and 450 km s^{-1} (Sahai et al. 2006).

Sahai et al. (2006) presented spectra of the object, revealing an interesting fast ($v \lesssim 220$ km s^{-1}) bipolar molecular outflow, which erupted in $\sim$1981. The mass in this component of I22036 was estimated to be $\sim$0.03 $M_\odot$, giving a kinetic energy of $\sim$10^{46} erg. The fast molecular outflow component obeys a linear velocity law up to an outer bow shock region, implying that the ejection event was much shorter than the age at observation, which was $\sim$25 yr. In Figure 1, we mark the timescale as we estimate based on our ILOT model, 0.1–3 yr $\ll$ 25 yr. Another common property of this and NGC 300OT and the two previous pre-PNe is that the AGB progenitor was massive, $M_{\rm ZAMS} \gtrsim 5\,M_\odot$. As we discuss in Section 4, such massive AGB stars are likely to suffer instabilities that can cause them to lose a large portion of their envelope in a very short time.

The short ejection time, the linear velocity–distance relation, the bipolar structure, the massive progenitor, and the outflow velocity range raise the possibility that the ejection event was an ILOT. This leads us to predict that the central star of I22036 has an MS companion of mass $\sim$1 $M_\odot$ with an eccentric orbit with a period of few years.

How is it that an ILOT in the year 1981 was not observed? We note that the central star of I22036 is heavily obscured (Sahai et al. 2003). We therefore suggest that the ILOT heated the circumbinary dust, and most radiation came out in the IR before *IRAS* was launched, and hence avoided detection as an outburst.

It is interesting to mention another indirect evidence for a companion (Sahai et al. 2011b). The very broad Hα wings observed in I22036 (Sahai et al. 2006) can be interpreted as Raman scattering of Lyβ arising in the ionized gas region observed by the Extended Very Large Array (Sahai et al. 2011a), which is surrounded by a neutral region. The required width of Lyβ ($\sim$400 km s^{-1}) might be generated in an accretion disk around a companion (Sahai et al. 2011b).

3.4. A Counterexample

Not all bipolar PNe and pre-PNe were formed/shaped in an ILOT event. A linear velocity–distance relation implies short-period formation event, but not necessarily an ILOT, as is the case with the Hourglass Nebula (MyCn 18). The knots along the polar directions, which are at larger distances than the hourglass structure, have a linear velocity–distance relation. The maximum velocity is $\sim$500 km s^{-1} (O'Connor et al. 2000). Although these properties are as in the other systems discussed here, the total mass of the knots is much smaller and amounts to $\lesssim$10^{-4} $M_\odot$ (Sahai et al. 1999). O'Connor et al. (2000) estimate the total mass in the knots to be $\sim$10^{-5} $M_\odot$ and their velocity in the range of several hundreds to over 600 km s^{-1}. Overall, the kinetic energy of the knots is $\lesssim$10^{44} erg, fitting nova outbursts. Indeed, O'Connor et al. (2000) suggest that the knots were formed from a nova outburst. We agree with this assessment and hence do not consider the knots in the hourglass nebula to have been formed in an ILOT event.

4. A PLAUSIBLE SCENARIO

We propose that the lobes of NGC 6302, OH231.8+4.2, M1-92, I22036, and similar objects with similar bipolar morphologies, a similar lobes' kinetic energy range, and an expansion velocity that shows a linear velocity–distance relation are formed in an ILOT event. Our model for ILOTs (Soker & Kashi 2011; Kashi & Soker 2010b) is a mass transfer onto an MS (or slightly evolved) star. The mass transfer can be in one of two basic processes. In the first process a merger process occurs. A low-mass star is destructed on the MS star, as in the mergerburst model for V838 Mon (Tylenda & Soker 2006; Soker & Tylenda 2006). This is not the case considered here.

In the second process an evolved giant star (LBV, AGB, extreme-AGB) enters an unstable phase. The interaction with a companion causes the star to lose a huge amount of mass in a very short time. Part of this mass is accreted by the MS companion via an accretion disk. The accretion disk launches two jets that form the lobes. The process is accompanied by high luminosity that makes the event an ILOT. An extreme example of such a process is the 20 year long Great Eruption of η Car where the lobes are thought to have been shaped by jets launched by the mass-accreting companion (Soker 2001; Kashi & Soker 2010a). In Kashi et al. (2010) we have already made the connection between the ILOT NGC 300OT and the Great Eruption of η Car. A connection between η Car and a nebula around a post-AGB star—The Red Rectangle—was conducted in Soker (2007). Here we make a direct connection between ILOTs and the formation process of the lobes in some (but not all) bipolar PNe and pre-PNe. An earlier comparison of the NGC 300OT progenitor to pre-PNe was made by Prieto et al. (2009) based on optical and kinematical properties.

There is a question whether the very high mass accretion rate envisioned in our model can lead to the formation of jets. An encouragement for a positive answer is FU Orionis (FU Ori) outbursts. These are Sun-like protostars (young stellar object, YSO) that undergo a rapid accretion episode. The typical mass accretion rate is $\sim$10^{-4} $M_\odot$ yr^{-1} and the mass outflow rate is $\sim$10% the accretion rate (e.g., Reipurth et al. 2002). Hartmann et al. (2011) report on a YSO of 0.3 $M_\odot$ accreting at a rate of $\sim$2 $\times$ 10^{-4} $M_\odot$ yr^{-1}. In their theoretical study Baraffe & Chabrier (2010) take protostars of $\sim$0.1 $M_\odot$ to accrete at a rate of 5×10^{-4} $M_\odot$ yr^{-1}. Therefore, it is quite possible that MS stars of $\sim$1–5 $M_\odot$ can accrete mass at a very high rate as required in our proposed scenario. The physics of jets launching in FU Ori outbursts might be the same as in YSO objects with much lower accretion rates (Königl et al. 2011). Magnetic fields that are required in launching jets can be amplified by a dynamo operating in the accretion disk. In any case, the accreted mass must get rid of most of its angular momentum, and close to the stellar surface jets can efficiently carry the extra angular momentum.

The 20 year long eruption of η Car had four spikes in its light curve. It is also possible that in the systems studied here the interaction occurs over several orbital periods, with mass accretion and jet launching occurring only at periastron passages. In η Car the kinetic energy is $\sim$1000 times larger than in the present systems, and the companion has a mass of $\sim$30–80 $M_\odot$ (e.g., Mehner et al. 2010; Kashi & Soker 2010a, and references therein). The mass accreted onto the companion during the great eruption is several $M_\odot$ (Soker 2001, 2007; Kashi & Soker 2010a). MS stars of mass $\sim$0.3–3 $M_\odot$ have a gravitational potential well similar to that of the Sun. To explain a jets' power of E_j the accreted mass onto a solar like MS star should be

$$M_{\rm acc} \simeq \frac{2E_j R_\odot}{GM_\odot} = 0.05 \left(\frac{E_j}{10^{47}\ {\rm erg}} \right) M_\odot. \quad (1)$$

In the case of NGC 6302 the amount of mass in the lobes is estimated to be 0.1–2.5 $M_\odot$. The upper limit is given in a recent analysis by Wright et al. (2011). However, we suspect that most of this mass is closer to the center and moves at a low velocity. The ejected mass in the lobes that appear in Table 1 is the higher velocity gas that has the linear velocity–distance relation (Szyszka et al. 2011) and for that we take an average velocity of $\sim$200 km s^{-1} (Szyszka et al. 2011). Over all, the kinetic energy in the lobes is highly uncertain, and we take it to be $(0.4–2) \times 10^{47}$ erg. Allowing for $\sim$50% efficiency of the process where the jets accelerated and inflated the lobes requires the jets' energy to be $(1–5) \times 10^{47}$ erg. The companion had to accreted 0.05–0.25 $M_\odot$. If the jets were launched at $\sim$700 km s^{-1}, their mass amounts to 0.02–0.1 $M_\odot$. Namely, the mass lost in the jets is $\sim$20%–40% of the mass transferred to the companion. This is similar to the fraction in the model for the Great Eruption of η Car (Kashi & Soker 2010a).

Based on this discussion, we consider the following scenario. First, we note that the massive ($\sim$2.2 $M_\odot$; Wright et al. 2011) equatorial disk of NGC 6302 was formed over a time period of $\sim$5000 yr that ceased $\sim$650 yr before the lobe-ejection event (Szyszka et al. 2011). We propose that during this time there was a strong tidal interaction that lead to the formation of the equatorial mass loss process. The binary system was stable against the Darwin instability, no Roche lobe overflow took place, and the system avoided a common envelope phase. The orbital separation was about several AU. After losing $\sim$2.2 $M_\odot$ from its envelope, the AGB star entered a more stable phase. For example, its radius decreases.

After another 650 years the AGB entered another unstable phase. For example, a shell helium flash caused its envelope to substantially expand and, a strong magnetic activity, as was suggested for the unstable phase of the primary of η Car during the Great Eruption (Harpaz & Soker 2009), took place. The AGB star has a strong convection, and its envelope is spun-up by the tidal interaction with the companion. With a very strong convection, even a slow rotation can make the AGB star magnetically active, and it might experience a magnetic activity variation, even a cyclical one (Soker 2000b; García-Segura et al. 2001). As a result of the radius increase a very strong tidal interaction took place, and an RLOF occurred. This process is more pronounced if the orbit is highly eccentric, and the process takes place when the companion approaches periastron. This is the case in η Car. During the RLOF an accretion disk was formed and two jets were launched. This leads us to predict that the central star of NGC 6302 has an MS companion of mass of a few $M_\odot$ in an eccentric orbit and an orbital period of several years.

5. DISCUSSION AND SUMMARY

We presented surprising similarities between two seemingly unrelated groups of objects: planetary nebulae (PNe) and eruptive objects with peak luminosity between novae and SNe. The later group is termed ILOT for intermediate-luminosity optical transients (also termed intermediate-luminosity red transients and red novae). The similarities between the ILOT NGC 300OT and the PN NGC 6302 are discussed in Section 2, and similarities with two pre-PNe are discussed in Section 3. They are summarized in Table 1. A connection between the ILOT NGC 300OT and pre-PNe was made by Prieto et al. (2009).

Basically, the lobes of these PNe and protoPNe have kinetic energy similar to that of some ILOTs (Figure 1). They also have a linear velocity–distance relation that points to a short ejection event, and a velocity range that suggests a mass ejection by an MS companion to the AGB progenitor. In the case of low ejected mass and energy, as in the PN MyCn 18 (Section 3.4), a nova outburst rather than an ILOT event launched the jets.

We suggest that the lobes of these PNe and pre-PNe were formed in one event or several sub-events that occurred at periastron passages of the binary system. We emphasize that not all binary progenitors of PNe experience an ILOT. An ILOT event requires that the AGB suffers a major instability. This probably requires a massive AGB star. Also, the orbit should be highly eccentric to prevent a continuous high mass loss rate. These conditions require further study. In our model summarized in Section 4 each such event might last for several months. The AGB enters an unstable phase and loses a large amount of mass. Part of this mass is accreted by the companion, and an accretion disk is formed. The accretion disk launches two jets that inflate the lobes. Our model is compatible with the MS companion of the pre-PN OH231.8+4.2. The primary star in OH231.8+4.2 is still an AGB star (Mira variable), and we predict that another ILOT event is possible in this system. This and some other predictions of our model are listed in Table 1. In particular, we predict that the ejected mass of ILOTs will possess a bipolar structure. We note that a large fraction of the outburst radiation of NGC 300OT was in the IR bands (Prieto et al. 2009) and predict that in many cases ILOTs will be observed from AGB stars with close MS companions.

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