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Asymmetric Planetary Nebulae *VI*: the Conference Summary

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Abstract. The *Asymmetric Planetary Nebulae* conference series, now in its sixth edition, aims to resolve the shaping mechanism of PN. Eighty per cent of PN have non spherical shapes and there is no self-consistent single star model to explain them. During this conference the last nails in the coffin of single stars models for non spherical PN have been put. Binary theories abound but observational tests are lagging. The highlight of *APN6* has been the arrival of *ALMA* which allowed us to measure magnetic fields on AGB stars systematically. AGB star halos, some with the imprint of spiral patterns, are now connected to PPN and PN halos. New models give us hope that binary parameters may be decoded from these images. In the post-AGB and pre-PN evolutionary phase the naked post-AGB stars present us with an increasingly curious puzzle as complexity is added to the phenomenologies of objects in transition between the AGB and the central star regimes. Binary central stars continue to be detected, including the first detection of binaries with periods longer than a few days. However the PN binary fraction is still at large. Hydro models of binary interactions still fail to give us results, if we make an exception for the wider types of binary interactions. More promise is shown by analytical considerations and models driven by simpler, 1D simulations such as those carried out with the code MESA. Large community efforts have given us more homogeneous datasets which will yield results for years to come. Examples are the ChanPlaN and HerPlaNe collaborations that have been working with the *Chandra* and *Herschel* space telescopes, respectively. Finally, the new kid in town is the intermediate-luminosity optical transient, a new class of events that may have contributed to forming several peculiar PN and pre-PN.

1. Introduction

The focus of the *Asymmetrical Planetary Nebula* conference series is the physical mechanisms responsible to impart planetary nebulae (PN) their various shapes. The stellar evolutionary phases typically under scrutiny are the mass-losing asymptotic giant branch (AGB) phase, the post-AGB phase where the stars are hotter and more compact, and the white dwarf (WD) phase where the stars reach Earth-sized radii and decrease in luminosity. During these phases stars can be surrounded by circumstellar structures composed of neutral atoms, molecules and dust grains, or ionised gas, often permeated by magnetic fields. Companions to the primary stars are sometimes observed.

Because of the broad range of size and time scales involved in this phase of stellar evolution it is paramount to be clear about what is being discussed, something that was not always clear during the meeting. Without this clarity it is more difficult to draw connections between these evolutionary stages. Speakers often made many tacit assumptions about what the scales being discussed were and as such may have jeopardised the message as members of the audience, more familiar with different size and timescales, may have assumed that the discussed object was something different. A typical source of confusion, which nomenclature does not help, is what is meant when discussing disks (also called rings, tori, skirts, among other names). Some may assume an accretion disk, a rather small and hot structure comprising gas usually in the act of accreting onto a central object. Others may assume a disk is a much larger structure in orbit around a star or binary, or sometime not even in orbit but rather expanding away. These are very distinct structures which bear witness to distinct phenomena.

In the PN field I have witnessed many times the attempt to tidy up nomenclature. I recall the attempt of Sun Kwok to stop the community from baptising every other PN "the butterfly nebula", or Raghvendra Sahai's fight to stop people from calling pre-PN pre-PN. I am all for deregulation in this context, but I would follow this with a plea to characterise with a sentence exactly what is meant every time or as often as possible in any paper where a name for a structure with a hole in the middle is adopted. Along the same lines, I would suggest to give a good and thorough definition of any term used, by listing how large this structure is, or is thought to be. How hot it is. Is it likely to be in Keplerian rotation or is it just being ejected from the system. What is its presumed life time. Such clarity will naturally obviate to the communication barrier both at conferences and in the literature.

After this admonishment, I will talk about topics that were discussed at the conference, ordered, somewhat arbitrarily, along themes. Names within brackets refer to the speakers within this meeting. AGB and post-AGB stars are followed by a general take on magnetic fields. The search for binary companions follows, primarily orbiting central stars of PN. I single out accretion as a likely important concept that should be kept in mind when looking at several of the outflow phenomena at the heart of this meeting. There follows models of shaping. Finally I discuss separately [WC] and other hydrogen-deficient central stars as well as intermediate luminosity optical transients as topics of special interest, at least for me! Eventually I conclude.

2. AGB stars

Twenty-to-thirty per cent of all AGB stars show elongation or asymmetries at scales of $100 \times$ au at millimetre and optical wavelengths (Sahai), while not much asphericity is found at smaller scales of a few $\times$ 10 AU in the midIR (originating from dust; Paladini).

A handful of AGB binaries are known, including for example the sequence E stars (periodic variables in the Large Magellanic Clouds (LMC); Wood). Some heavy planets have been discovered around AGB stars at approximately 1 au, but a census or indeed any statistical inference is still far from possible (Niedzielski).

Masers provide extremely accurate information about the layers where they originate from. Their study has shown the sloshing around of the surface layers of AGB stars produced by pulsations (Gonidakis).

Ionised halos around PN have been known for a while (Corradi 2003). These are revealed when the heating star's ionising radiation leaks out of the PN proper. *Herschel* observations of AGB stars (at wavelengths of 70 and 160 μm) show us the very same halos, but before they become ionised and reveal the diverse morphologies of

Figure 1. Disks can vary in size, composition, angular momentum and ... name. Irrespective of the name we are using for it, it is fundamental to describe carefully the disk structure we are discussing so as to avoid confusion

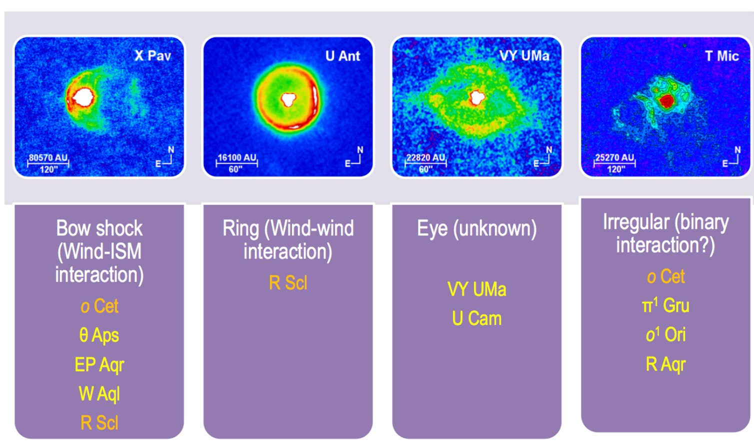

Figure 2. AGB star halos observed by *Herschel*. Talk by Mayer and the MESS collaboration.

AGB envelopes at the few × 1000 and few × 10,000 au scales (Mayer and the MESS collaboration, Fig. 2, (van Hoof et al. 2012; Mayer et al. 2013)). Some of them are spherical or ring-like, like the halo of R Scl. Occasionally interaction with the interstellar medium is evident (e.g., *o* Cet), and has been modelled (Mohamed, Villaver). Others have a lenticular shape (nicknamed "eyes", e.g., VY UMa or U Cam). Others still have irregular morphologies (e.g., R Aqr).

Halos have the interesting characteristic that they can carry the imprint of a binary companion in the form of a spiral pattern. This was observed by *ALMA* in the AGB stars R Scl (Ramstedt; Vlemmings et al. 2013). But radio observations of similar objects already existed, such as those of AFGL 3068 (Morris et al. 2006) and IRC+10216 (Leão et al. 2006). Simulations by Kim (Kim & Taam 2012) show that the spiral patterns encode information about parameters such as the companion mass and orbital period. What remains to be determined is whether similar models can uncover the binary nature of objects, where the spiral patterns are observed during the PN phase, for example in NGC 7027, NGC 6543 (the Cat's Eye nebula), or the Egg Nebula. The case of the Cat's Eye is particularly interesting because no companion has ever been found, despite the fact that this very nearby PN with a hot and faint central star would be a prime candidate for an easy companion detection.

3. Post-AGB stars with and without a pre-PN

The almost unanimous aspherical nature of pre-PN and young PN has long been established (Sahai et al. 2007). What was news to this conference is that "nascent" pre-PN are collimated only 60% of the times, clearly indicating a transition phase between the AGB and the pre-PN phases. These structures are of the same size scale as the AGB halos discussed in § 2. The production of these collimated structures is at the very centre of this conference, particularly because of the suddenness of the onset of collimation. Several pre-PN morphologies have been reproduced by the assumptions that a jet is launched which sculpts the circumstellar envelope (e.g., Sahai & Trauger 1998; Raga et al. 2009), which is then permeated by the ionisation front and illuminated. However, the engine that creates these jets is still unidentified.

We have known for a while about the existence of post-AGB stars that have no nebulosity around them. They were first reported by van Winckel (2003, see also van Winckel et al. 2009) and I like to refer to them as "van Winckel objects". These objects were initially detected because of a double peaked spectral energy distribution (SED), in which the second peak denounced a detached dusty disk or shell structure. The disks were directly detected by the Very Large Telescope Interferometer and have sizes of the order of ~10 au (Deroo et al. 2006). When the stars are observed, a single-lined spectroscopic binary seems to be always present with a period between 100 and a couple of thousands days. About a third of all post-AGB stars with no nebula appear to be such objects. It has long been hypothesised that the reason for these objects not harbouring a pre-PN is that they probably did in the past, but re-accretion of material has stalled the blue-ward evolution of the post-AGB star and the circumstellar material has had time to disperse before it cam be ionised. These objects are likely never to produce an ionised PN. The Red Rectangle pre-PN, could be a rare example of a "van Winckel" object, caught in a phase when it still had a pre-PN. In the future the nebula will disperse, while the star will not heat at first. Eventually, like all post-AGB stars, they will either heat up and become white dwarfs which will eventually cool, or maybe cool directly.

During the conference a couple of things came to light about these objects, which unfortunately make things more complicated. Many post-AGB stars of this nature have been detected in the LMC. However, there we have the benefit of a common, known distance and it appears that about half of the detected post-AGB stars are actually post-RGB (Kumath). How to read this possible mix of objects is not clear.

Additionally, while we tend to state that all post-AGB binaries have Keplerian disks, this is actually known only for the Red Rectangle from radio observations that detect the presence of the CO molecule within the disk's dusty environment (Bujarrabal et al. 2013). Disks with similar characteristics to the Red Rectangle have been detected around other pos-AGB stars, but their kinematics are not known (Bujarrabal).

Tim Gledhill talked about a class of objects whose existence I had not appreciated. Post-AGB stars with no pre-PN (which I would have called "van Winckle" objects), which however had the signature of a detached shell of material, rathe than a disk. Integral field spectroscopy revealed that some of these objects with B spectral type show the initial signs of circumstellar ionised gas. However, no dust is readily observed around these objects. An example is IRAS 18062+2410, a star heating at the rate of 200 K per year, where the ionisation front is observed to be propagating at 120 km/s (the scale of this is a few thousands of AU).

4. Magnetic Fields

We want to know everything about magnetic fields: their presence in AGB, post-AGB and central stars as well as in WDs. We want to know their intensity, geometry and time variability for a sizeable sample, so as to relate these properties to mass, accretion rates, binary status, circumstellar structures, etc.. The questions are of course what generates the fields, what sustains them, and how they manipulate the flow.

Vlemmings, Tafoya, Leal-Ferreira, Sabin, Perez-Sanchez and Todt discussed magnetic fields. *ALMA* results are starting to consolidate a promising picture. For now, we have a much better idea of the relationship between field strength and radius/distance from the centre in AGB stars where an r^{-2} or even steeper dependence is measured. Gauss-scale magnetic fields are measured at the surface of AGB stars, while within the gas of pre-PN, milli-Gauss fields have been measured. No detections have so far been reported of magnetic fields in central stars of PN (but see contribution by Helge Todt), and in fact even the fields reported by Jordan et al. (2005) have proven to be false detections (Jordan et al. 2012).

White dwarfs are known to have weak magnetic fields most of the time. Those that have strong ones (approximately 10% of the sample) are suspected of a merger origin (Nordhaus; Nordhaus et al. 2011). I do wonder what the story is for those CVs known to have a strong magnetic field. The story of WD and magnetic fields appears to be complex. Magnetic fields are likely to be promoted by a common envelope interaction Nordhaus et al. (2007); Regos & Tout (1995); Tocknell et al. (2013) but whether this field would then remain strong after the common envelope has departed is an open question.

5. Binaries

In the PN population the only established binary fraction is the 15-20% of the population that have periods are of the order of a couple of days or less. This is no news (Bond 2000; Miszalski et al. 2009). The question is whether this number is lower than, in line with, or higher than it should be. My personal answer to these questions has been changing over the years, as data has (slowly) accumulated. Currently, I would say that this fraction is high, if we compare it to the fraction of main sequence binaries (with the correct mass range of PN progenitors; Raghavan et al. 2010) with orbital separations that will lead to a common envelope on the AGB (a few per cent).

In addition, the observed fraction is likely to rise once the space satellite *Kepler* is done looking at PN. In our own contribution to this conference (poster by Joseph Long) we have shown that out of the six PN in the Kepler field, two are binaries with variability amplitudes below the ground-based threshold. An additional two are likely to be or have been binaries (the central star of NGC2668 is a likely a fast rotator and the variable central star of Kn 61, with an approximate period of 6.4 days, is possibly, though not conclusively, related to disk outbursts and dwarf novae). The last two objects, both round PN, appear to have no variability. So if I had to guess how many of the central stars already monitored from the ground would, if monitored with Kepler, reveal to be binaries, I would say likely about 10 per cent, making the post-CE PN binary fraction $\sim$30%. But that is my guess now and only time will tell. What is sure is that the current post-CE binary fraction of PN is a lower limit.

What was news at *APN6* is the detection of the first binary PN with periods longer than a few days, but still short enough to insure that an interaction must have happened: BD+33 2642 and LoTr5. The former has a period of 1105±24 days and has an orbital plane aligned with the waist of the bipolar nebula. For the latter the orbital period has not yet been covered by the 1807 days of monitoring. This object was already known to have a fast rotating G type secondary and a hot primary, but the separation was not known (Van Winckel et al. 2014). This is a terrific result because these objects must exist but despite substantial efforts they have eluded detection (De Marco et al. 2004, 2007).

An interesting discrepancy with these numbers was explained by Peter Wood. With his work (Nie et al. 2012) he showed that the fraction of LMC RGB stars that are in close binaries (known as the sequence E stars) is consistent with a population of central star in post-CE binaries of only 7-9 per cent. This is low for the Galaxy but may be in line with a lower metallicity population of the LMC.

Finally, the PN community is becoming wiser as to the usefulness of post-CE binary central stars in the broader context of constraining the CE evolution phase (Ivanova et al. 2013). Work on the kinematic structure of PN around post-CE binaries is revealing a wealth of information about this phase (Jones and Santander). The binaries themselves have been systematically analysed by Hillwig and collaborators and are likely to reveal additional information of the final phase of the CE interaction, such as accretion onto the secondary.

5.1. The Accretion “Genome”

The presence of collimated structures in pre-PN and PN bears witness to the likely action of jets which, if launched by traditionally recognised mechanisms (e.g., Blandford & Payne 1982) need an accretion disk either around the companion or the core of the giant, either during the AGB phase or after. The opportunity for the companion to accrete are many: before Roche lobe contact, during a phase of wind accretion (Huarte-Espinosa) or wind Roche lobe overflow (Mohamed). Whether a CE starts or stable mass transfer takes place is still a question for debate. After the CE dynamical infall phase a fallback disk could form that may lead to one or two accretion disks and of course the small post-CE separation may lead to one or both stars filling their Roche lobes and starting CV activity. We know that this is possible since the explosion of a nova in a PN (Rodríguez-Gil et al. 2010).

Jets however have a broad range of kinematic signatures with those around post-AGB stars (pre-PN) carrying a lot more momentum than those around post-CE (and presumably other) PN. The analyses of Tocknell et al. (2013) and Blackman (Blackman & Lucchini 2014), show good promise for a way forward to fingerprint the launch engine of these jets.

6. The Shaping Engine: Hydrodynamic Simulations and Analytical Models

The engine of these binary interactions is likely gravitational. It is possible that some of this gravitational energy is stored into a magnetic field, which may return it to the gas generating explosive phenomena. Analytical or semi-analytical models are a hopeful way forward (see contributions to *APN3* and *APN4* by Blackman - Blackman 2004; Blackman & Nordhaus 2007), because of the ability to break the problem into sizeable pieces. Comprehensive numerical simulations of the entire interaction are not yet possible, though we should continue to work in this arena. The reason is that the complexity of the problem is mind boggling and including all the necessary physical mechanisms would render the problem too complex to compute: for example this is inherently a 3D problem, but simulating even single stars in 3D is outside our abilities at the moment. We can map 1D stellar structure from stellar evolution codes such as *MESA* (Paxton et al. 2010) into 3D computational domains, but the stellar response becomes extremely non-physical if timescales much longer than a few dynamical times have to be simulated. Results have to be taken with a grain of salt while code validation takes place.

Magneto hydrodynamic (MHD) models, in which the magnetic field does not receive a feedback from the gas (e.g., García-Segura et al. 1999) are very useful, but more as guidelines on shaping than as ways to establish the launch engine. One of the highlights of this meeting for me has been the contribution of Guillermo Garcia-Segura who, using MESA, showed that single stars cannot rotate at rates to provide the magnetic field to impart bipolar shapes to PN (García-Segura et al. 2014). Quite aside from the scientific interest of this result, this is an example of scientific integrity of a researcher who, in light of new information and with the help of new tools revisits his own conclusions.

Binary simulations are also not generating the outflow engine, but they too provide insight on shaping. We have for example seen the ring forming, wide binary models of Kim and Mohamed, and the models of wind Robe lobe overflow of Mohamed, and the disk forming models of Huarte-Espinosa, but none of these models can actually launch gas. However, they can start to inform us about the accretion rates that drive the launch. One step at a time!

6.1. A "Millennium Simulation"?

In cosmology, the Millennium Simulation was a large, billion-particle, N-body simulation of large scale structure formation (Springel et al. 2005), which has been mined by many people. We could wish for a similar simulation in our field: a massive simulation obtained after collating codes, adding physics, attempting massive parallelisation to run on the best supercomputers. Tempting as this may sound, it is not clear to me whether we are ready for a "Millennium simulation". We may be in a similar predicament to the star formation community, where numerical models that attack the problem from a particular angle get different results from alternative attempts. Results are extremely sensitive to set up choices. Clearly stopping the simulation effort just because it is difficult is not a good approach! However, I think we must stop and determine a viable approach to numerical simulations of these events.

Adam Frank gave details of the many improvements and additions to his group's code, *AstroBEAR*, including a user-friendly interface and user support. *AstroBEAR* is a 3D, adaptive mesh refimenent, MHD Eulerian code, with self-gravity (e.g., Huarte-Espinosa et al. 2013). It is clear to me that this type of code is not like, for example, *Cloudy* where the dedicated researcher can learn to use it as a "grey box". Either the new user is already experienced in running 3D hydro codes, or they must be ready to dedicate the necessary time to understand the issues with such runs.

After witnessing the success of community efforts such as the *ChanPlaN* and *HerPlaNe* collaborations I have been wondering if it would be profitable to start a community effort centred around theory. Can the binary interaction problem be dissected and tackled with multiple codes on parallel runs, not only to verify the codes, but also to cover more ground? And how would such effort be coordinated? Rather than being a "broadcasting" collaboration, with one PI and multiple co-Is, it should be more like a point-to-point collaboration where each node performs a separate task and communicates with each node independently. We should gather a consortium of people who would start by dissecting the general problem into a network of tests, which can be carried out by one or more analytical or numerical techniques in parallel. Identifying the task force, the computer needs and the funding sources, would be part of the exercise. As tests are designed, verification and validation would be embedded from the start, avoiding all too common lack of rigorous controls in simulation techniques.

6.2. Intermediate Luminosity Optical Transients

Intermediate luminosity optical transfers, or ILOTs, are outbursts with luminosities between those of novae and those of supernovae (Fig. 3). Detections of these rare events have become more common thanks to the advent of a number of time-resolved astronomical surveys, such as the Catalina Real time Transient Survey (Drake et al. 2009) or the Palomar Transient Factory (Law et al. 2009). What causes these outbursts is still unclear although at least one was a merger of a solar-mass sub giant with, likely a low mass main sequence star (V 1309 Sco; Tylenda et al. 2011). Another was *likely* a merger of a more massive star (V 838 Mon; Bond et al. 2003). Yet others are thought to derive from interaction in asymmetric binaries (Akashi & Soker 2013). It has even been proposed that luminous blue variable events, such as the Great Eruption in η Car was triggered by periastron passages of the eccentric binary (Kashi & Soker 2010).

Some nebulae, which are classified as pre-PN or PN but which are known to be mimics are possibly left behind by such outbursting events (Akashi & Soker 2013). An example is OH231.8+4.3 which is classified as a pre-PN but which does not contain a post-AGB star. It contains, in fact, a Mira and an A star in a wide binary. What exactly caused the nebula is unclear, but we wonder whether it could have been an ILOT event.

ILOTs have been brought to the attention of the APN6 community by Noam Soker and are likely to play a huge role in our understanding of binary-interaction promoted outflows because current and future transient surveys (e.g. the *Large Synoptic Survey Telescope*; Ivezic et al. 2008) will discover them in real time and in large numbers.

7. [WR] Central Stars of PN and Other Oddballs

Contributions by Guerrero, Lagadec, Guzman-Ramirez, Szczerba, Clayton and Blanco-Cardenas reminded us the incredibly messy situation in the hydrogen-deficient central star camp. Hydrogen-deficiency has been for years attributed to a late thermal pulse scenario, but the situation may be far more complicated than that. R Coronae Borealis have recently been attributed to WD-WD mergers (Clayton et al. 2007), although it is not impossible that they may also have a late thermal pulse channel, as shown by the born-again central star Sakurai's object. Yet other born-again central stars, such as V605 Aql and Abell 30 have had their hydrogen-deficient ejecta analysed and found to be oxygen and neon rich, completely at odds with late thermal pulse scenarios (Wesson et al. 2003, 2008). The dual-dust chemistry which initially seemed associated with late [WC] central stars is today known to have a more complex origin: first of all it does appear that dissociation of CO may lead to the formation of PAH, rather than PAH forming from extra carbon left over after all oxygen is locked into CO molecules. Second, the dual-chemistry seem to associate itself with select populations such as the Bulge's. One has to wonder whether there is something extremely obvious we are missing: is there an elephant in the room?

8. Tools, Techniques, Databases and Community Efforts

	Name	Presenter	Function	Reference
Tool	SHAPE	Steffen, Santander	3D reconstruction of PN shapes	Steffen & López 2006
Tool	pyCloudy	Morissette	interface to photoionisation code *Cloudy*	Morisset 2013
Tool/ Database	TMAP, Theossa	Rauch	Stellar atmosphere code and database	Rauch et al. 2013
Tool	AstroBEAR	Frank	3D hydro code	Huarte-Espinosa et al. 2013
Tool	MESA	Sumner	1D stellar structure and evolution code	Paxton et al. 2010
Tool	YT for MOCASSIN 3D	Gesicki	interface to photoionisation code	mocassin.world-traveller.org
Technique	Angular differential imaging	Rattray	high contrast/resolution imaging	pos.sissa.it/ archive/conferences/207/101/ LCDU%202013_101.pdf
Technique	CRIRES	Blanco	High Resolution imaging	Blanco et al. 2013
Database	GAIA	Manteiga	Accurate distances to PN and related objects	–
Database	MASPN	Parker	multi wavelength PN database	–
Consortium	ChanPlaN	Chandra survey of PN	Kastner	Kastner et al. 2012
Consortium	HerPlaNe	Herschel survey of PN	Ueta	Ueta et al. 2014
Consortium	MESS	Herschel survey	van Hoof	van Hoof et al. 2012

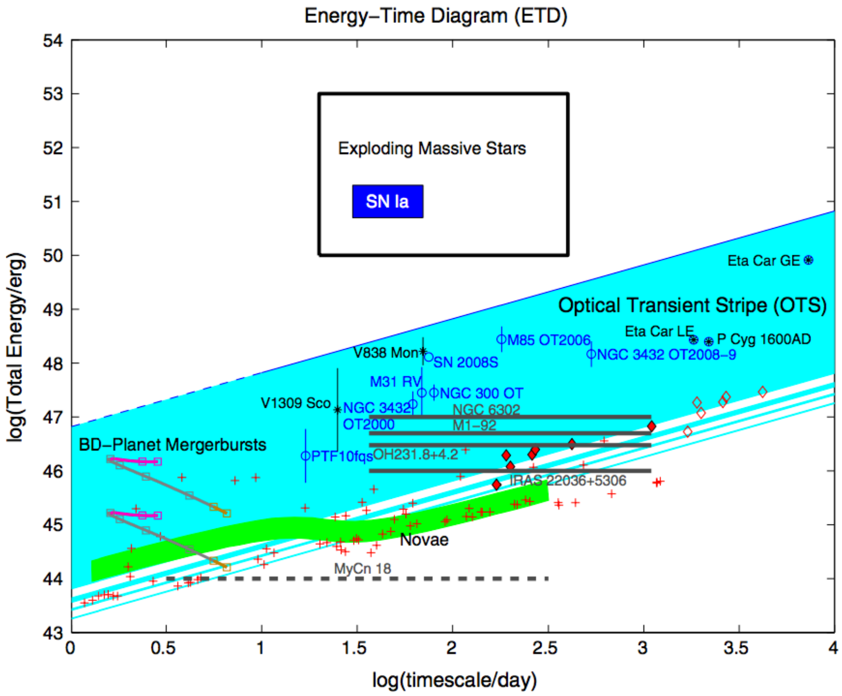

Figure 3. The energy-timescale diagram for intermediate luminosity optical transients. Figure from Soker & Kashi (2012).

Figure 4. The problem with [WC] central stars of PN as well as all hydrogen deficient classes of post-AGB stars has been around for a long time. Clear issues with the theory are easily identifiable but no attempt at putting all the evidence together has succeeded in generating a better scenario for these stars. Is there an elephant in the room? There certainly was one in mine when I returned to my hotel room one evening during the conference!

9. Conclusion

These are exciting times for the scientific community that concerns itself with outflows. *ALMA* and time-domain surveys will no doubt reveal many detail of binary interactions and mass-loss in the next few years, likely in time for the next edition of this APN meeting. Theory efforts, I personally feel, are lagging, but the prospect to intensify them are good.

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