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Jet power in pre-planetary nebulae: Observations vs. theory

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Abstract. High velocity jets are among the most prominent features of a wide class of planetary nebulae, but their origins are not understood. Several different types of physical models have been suggested to power the jets, but there is no consensus or preferred scenario. We compare current theoretical ideas on jet formation with observations, using the best studied pre–planetary nebulae in millimeter CO, where the dynamical properties are best defined. In addition to the mass, velocity, momentum, and energy of the jets, the mass and energetics of the equatorial mass-loss that typically accompanies jet formation prove to be important diagnostics. Our integrated approach provides estimates for some key physical quantities – such as the binding energy of the envelope when the jets are launched – and allows testing of model features using correlations between parameters. Even with a relatively small sample of well-observed objects, we find that some specific scenarios for powering jets can be ruled out or rendered implausible, and others are promising at a quantitative level.

Keywords. Stars: AGB and post-AGB, stars: winds, outflows, planetary nebulae: general

1. Introduction

Jets are prominent and common features of planetary nebulae (PNe). They are known to develop in the rapid transition from the asymptotic giant branch (AGB) to the pre-PN phase, but their formation is not well understood. This paper outlines an approach to constrain the origins of the jets by confronting basic jet theory with observations. This is a challenging objective because the regions where the jets form are star-sized, and cannot be resolved by current observations. Thus the formation mechanisms have to be identified using properties that can be observed on much larger size scales.

From the earliest CO surveys of evolved stars, it was recognized that the mass-loss of pre-PNe is different from that of AGB stars (Knapp *et al.* 1982). Broad velocity wings were later discovered in the CO spectra which were identified with optical jets, and over ten years ago, Bujarrabal *et al.* (2001) showed that these could not be powered by the radiation field of the central star.

Since that time, an important development has been the ability to map the CO emission of individual objects in more detail (e.g., Cox *et al.* 2000; Alcolea *et al.* 2007). Together with HST imaging (e.g., Sahai *et al.* 2007) a standard picture has emerged of a typical pre-PN. It consists of an extended remnant AGB envelope, an inner region of enhanced mass-loss which appears as a torus, and jets which consist mainly of entrained material.

The jets and tori together constitute the last major mass-loss in the formation of a PN. Hence their timing, geometry, and dynamics all offer potentially important clues to the ejection process. The timing has recently been studied by Huggins (2007), who finds that jets and tori are quasi-simultaneous, with evidence for a preferred sequence. This paper deals with their dynamical properties.

2. Observations

The approach adopted here is to assemble a sample of the best available CO observations of individual pre-PNe with strong jets to investigate the systematics of the ensemble and to compare them with theoretical expectations.

The sample consists of 12 bona fide pre-PNe for which good estimates can be made of the mass, velocity, momentum, and energy of the jets and tori. The spectral types of the central stars range from M to Be. The objects are: IRAS 04395+3601, 09371+1212, 11385−5517, 17423−1755, 17436+5003 19343+2926, 19475+3119, 19500−1709, 22036 +5306, 23304+6147, 23541+7031, and AFGL 2688. The observations are the combined work of several groups – the main sources include: Alcolea *et al.* (2007), Bujarrabal *et al.* (2001), Castro-Carrizo *et al.* (2002, 2005), Olofsson & Nyman (1999), Sahai *et al.* (2006), Sánchez Contreras *et al.* (2004, 2006).

3. Dynamical properties

We discuss in turn the dynamical properties of the jets and tori that can be derived from the observations. Quantities that involve the mass vary as distance squared. The distance in most cases is not very well known, but the main conclusions do not depend on this uncertainty.

Masses. We first check the observed masses of the jets and tori to assess their contribution to the mass budget. Their combined mass, $m_{\rm tot}$, which is the mass of the AGB envelope at the final ejection phase, ranges from 0.05 to 1.0 $M_\odot$. This is roughly centered on the typical mass of a mature, ionized PN. Hence the jets and tori make a significant contribution to the masses of PNe. The mass fraction in the jets ranges from 0.08 to 1, consistent with the range in solid angle of typical jet structures seen in optical images.

Velocities. The mean velocities of the tori range from 7 to 16 km s^{-1}, and the mean velocities of the jets range from 22 to 150 km s^{-1}. The maximum velocities of the jets are approximately a factor of three higher.

It is found that the jet velocities decrease with increasing envelope mass ($m_{\rm tot}$), in accord with the idea that the outflows are powered by light jets that are mass-loaded by the entrainment of material. It is also found – unexpectedly – that the mean velocities of the tori correlate with the mean velocities of the jets, as shown in Fig. 1 (left). This implies that jets and tori are dynamically coupled. In fact, the relation extrapolates to small or zero torus velocity for zero jet velocity, which suggests that the tori may actually be driven from the vicinity of the central star by the jets.

Kinetic energies. The observed kinetic energies of the outflows are plotted vs. $m_{\rm tot}$ in Fig. 1 (right). The tori and jets are shown separately: it can be seen that the jets dominate the energetics.

Fig. 1 includes curves for two reference energies. The first, labeled $E_{\rm sec}$, is the maximum energy that could be extracted by accretion of the whole AGB envelope onto a main sequence secondary star. This is given by the usual expression for accretion energy $GM_{\rm sec}m_{\rm acc}/2r_{\rm sec}$, with the accretion mass $m_{\rm acc}$ replaced with $m_{\rm tot}$. Note that the ratio $M_{\rm sec}/r_{\rm sec}$ for stars on the lower main sequence is approximately constant, so that $E_{\rm sec}$ is essentially independent of the mass of the companion and depends only on the accreted mass.

The second reference energy, $E_{\rm bin}$, is the binding energy of an AGB star with envelope mass $m_{\rm tot}$, assuming a core mass of 0.6 $M_\odot$, an AGB radius of 350 $R_\odot$, and a binding coefficient $\lambda = 0.25$. If the jets are somehow powered by the infall of a companion, a standard assumption of common envelope calculations is that the infall terminates when

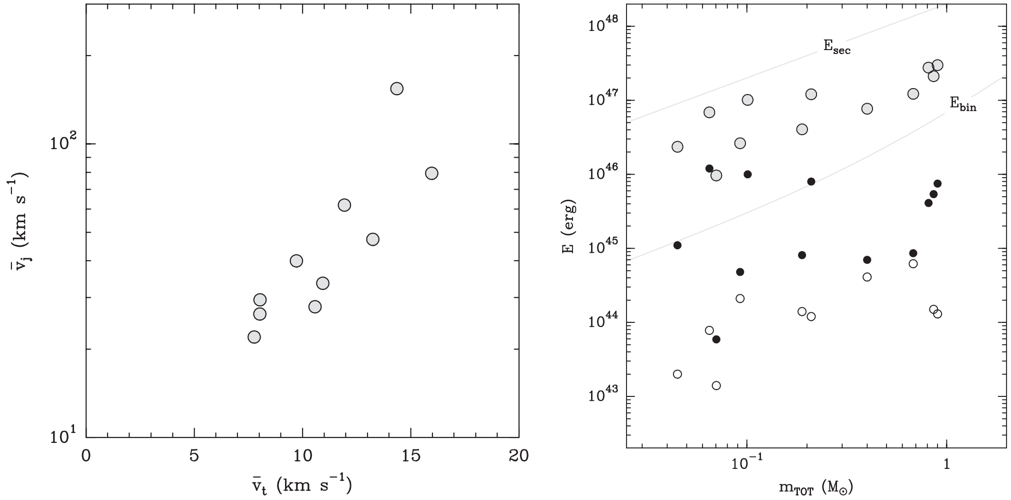

Figure 1. *Left*: Mean velocities of the jets vs. mean velocities of the tori. *Right*: Kinetic energies of the jets (filled circles) and tori (open circles), and estimated input energies (gray-filled circles). The curves labeled $E_{\rm sec}$ and $E_{\rm bin}$ are reference energies described in the text.

enough mechanical energy is generated to unbind the envelope. In this case we expect the observed kinetic energy to be $< E_{\rm bin}$.

From Fig. 1 it can be seen that the energies of the jets and tori are significantly less than $E_{\rm sec}$. The energies of the tori are also significantly less than $E_{\rm bin}$. This is consistent with several possibilities for torus formation (including the standard picture of common envelope ejection) in which the final kinetic energy is small compared with the escape energy.

Input energies. The currently observed kinetic energy in a pre-PN is much less than the initially injected kinetic energy, for two reasons. First the gas has done work against the gravitational field of the central star; and second, the interactions of the initial jets in forming the outflows is highly inelastic, and much of the energy is lost in the form of radiation. We focus on the second effect which is larger.

Because the momentum of the outflows is conserved and is directly observed, we can use the momentum to estimate the initial energy ($E_{\rm o}$) if we know the initial velocity. Fig. 1 shows our estimates of the total energy input as gray-filled circles, based on a nominal initial velocity 1350 km s^{-1} (three times the Keplerian velocity of lower mass main sequence stars). The actual initial velocity is likely to be within a factor of a few of this number; larger for core accretion, and at least several 100 km s^{-1} based directly on the observed jet spectra. It can be seen that $E_{\rm o} > E_{\rm bin}$ and $E_{\rm o} < E_{\rm sec}$.

4. Observations vs. theory

The dynamical properties of the ensemble of pre-PNe described here place useful constraints on possible ejection mechanisms. We consider the three most widely discussed scenarios, all of which involve a companion.

Accretion onto the AGB core. The first is based on accretion of part or all of a companion onto the dense core of the AGB star or its remnant, either during a common envelope phase or later when the envelope has been removed (e.g., Soker & Livio 1994). The energy generated by such a process depends mainly on the accreted mass, which in turn depends on the detailed circumstances of the accretion. It seems unlikely that such a model could inject energy for the sample of pre-PNe at a level that depends on the envelope mass, as found here, and there are no predictions of such an an effect. This scenario must remain doubtful, and a variation with long time-scales has already been ruled out by timing arguments (Huggins 2007).

Infall. The infall of a companion is consistent with the energetics of the tori, but standard common envelope calculations do not produce high velocity jets. Other mechanisms have been suggested to tap the infall energy (e.g., Nordhaus & Blackman 2006), but there are no detailed proposals that produce directed flows with high efficiency and energies in excess of the binding energy. Thus jet scenarios driven by infall remain unproven.

Accretion onto a companion. The observed energetics of the jets and tori are consistent with the third scenario, the accretion onto a companion star (e.g., Morris 1987; Soker & Rappaport 2000). In addition, consideration of the observed momentum in the flows and the efficiency of momentum production based empirically on YSO jets or disk-jet theory demonstrates that the accretion of a few tenths of the ejected envelope can give rise to the observed momentum. This particular scenario is strengthened by the fact that the few known AGB stars with tori and jets follow the same momentum-mass relation. One of these AGB stars (V Hya) is a known, detached binary with spectroscopic evidence for accretion onto a companion, and one of the sample pre-PNe (HD 101584) is a binary, and has evidently passed through a mild common envelope phase. Some of the other sample pre-PNe have observational limits on possible close companions (Hrivnak *et al.* 2011). It will be of considerable interest to see if these observations can be refined, to strengthen or challenge our conclusions.

Acknowledgments

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References

Alcolea, J., Neri, R., & Bujarrabal, V. 2007, *A&A*, 468, L41
Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sánchez Contreras, C. 2001, *A&A*, 377, 868
Castro-Carrizo, A., Bujarrabal, V., Sánchez Contreras, C., Alcolea, J., & Neri, R. 2002, *A&A*, 386, 633
Castro-Carrizo, A., Bujarrabal, V., Sánchez Contreras, C., Sahai, R., & Alcolea, J. 2005, *A&A*, 431, 979
Cox, P., Lucas, R., Huggins, P. J., Forveille, T., Bachiller, R., Guilloteau, S., Maillard, J.-P., & Omont, A. 2000, *A&A*, 353, L25
Hrivnak, B. J., Lu, W., Bohlender, D., Morris, S. C., Woodsworth, A. W., & Scarfe, C. D. 2011, *ApJ*, 734, 25
Huggins, P. J. 2007, *ApJ*, 663, 342
Knapp, G. R., Phillips, T. G., Leighton, R. B., Lo, K. Y., Wannier, P. G., Wootten, H. A., & Huggins, P. J. 1982, *ApJ*, 252, 616
Morris, M. 1987, *PASP*, 99, 1115
Nordhaus, J. & Blackman, E. G. 2006, *MNRAS*, 370, 2004
Olofsson, H. & Nyman, L.-Å. 1999, *A&A* , 347, 194
Sahai, R., Young, K., Patel, N. A., Sánchez Contreras, C., & Morris, M. 2006, *ApJ*, 653, 1241
Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2004, *ApJ*, 617, 1142
Sánchez Contreras, C., Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sargent, A. 2006, *ApJ*, 643, 945
Soker, N. & Livio, M. 1994, *ApJ*, 421, 219
Soker, N. & Rappaport, S. 2000, *ApJ*, 538, 241