MHD Disk Winds in PNe and pPNe

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**Abstract.** Winds from accretion disks have been proposed as the driving source for precessing jets and extreme bipolar morphologies in Planetary Nebulae (PNe) and proto-PNe (pPNe). Here we apply MHD disk wind models to PNe and pPNe by estimating separately the asymptotic MHD wind velocities and mass loss rates. We show that the resulting winds can recover the observed momentum and energy input rates for PNe and pPNe.

**Introduction** While considerable progress has been made in understanding the hydrodynamic shaping of elliptical and bilobed PNe (Balick & Frank 2002), the origin of extreme butterfly nebulae as well as jets in PNe continues to pose a number of problems for theorists.

In particular a formidable problem for pPNe concerns the total momentum and energy in the outflows. A number of observational studies have shown that radiatively accelerated winds in pPNe cannot account for the high momentum and energy implied by CO profiles (Bujarrabal et al. 2001). Thus the total flow momentum \( \Pi \) is such that \( \Pi \gg (L_\ast/c)\Delta t \), where \( L_\ast \) is the stellar luminosity emitted during the pPNe outflow expansion lifetime \( \Delta t \). In light of these results both the launching and collimation of winds in pPNe becomes problematic. Note that while both the dominant hydrodynamic theory for shaping PNe, (the Generalized Interacting Stellar Winds model: Balick 1987; Ike 1988), and models invoking an initially weak toroidal magnetic field (Garcia-Segura et al. 1999) can produce jets neither can account for the momentum excesses in pPNe.

Thus there remains considerable uncertainty about the processes which produce collimated jets/outflows in pPNe and PNe. Other systems which produce jets such as YSOs, AGN and micro-quasars have been modelled via a combination of magnetic and centrifugal forces from accretion disks (Konigl & Pudritz 2000). The success of these *Magneto-centrifugal Launching* (MCL) models is such that it is worthwhile considering if such a scenario can be applied to PNe and pPNe. While models such as Morris 1987, Soker & Livio 1994 and Soker & Rapport 2001 have relied heavily on collimated winds from disks these works did not specify how such winds are launched or collimated. Thus application of MCL disk wind models to PNe and pPNe would close an important gap in building a new MHD disk wind paradigm for these systems (Blackman, Welch & Frank 2001): BFW01, Blackman et al. 2001).

Here we summarize new calculations from Frank & Blackman 2004 who derive scaling relations from the equations for MCL and separately estimate...
MHD disk wind mass outflow rates and asymptotic outflow velocities. These relations are then applied to PNe and pPNe. In these calculations a disk dynamo is invoked to produce the requisite fields.

**Disk Accretion Rate in PNe:** In order to produce a more detailed comparison of MHD disk winds with PNe it is necessary to have a model for PNe accretion disks. It is unlikely that an accretion disk could survive the long main sequence lifetime of a PN central star. Thus, unlike YSOs and AGN, accretion disks in PNe systems must form via binary interactions. Disks may form around secondaries via Roche lobe overflow or accretion of the dense AGB wind (Mastrodemos & Morris 1998). Such systems would be similar to symbiotic stars.

Mastrodemos & Morris (1998) found steady accretion disks could form around a white dwarf companion orbiting a AGB star with \( \dot{M}_{\text{agb}} \approx 10^{-5} \, M_\odot \, \text{yr}^{-1} \). The ratio they found in their models of \( \dot{M}_d/\dot{M}_{\text{agb}} \approx 0.05 - 0.005 \) is consistent with expectations from basic theory.

Accretion disks could also form around the primary after CE evolution and disruption of the secondary star (Reyes-Ruiz & Lopez 1999: RRL99). This model implies a finite lifetime for the disk as the mass reservoir of the disrupted companion is slowly drained onto the primary. A description of disk formation in PNe has been given in RRL99 who found that systems with a primary consisting of an evolved AGB star with mass \( M_* \approx 2.6 - 3.6 \, M_\odot \), a low mass secondary \( \leq 0.08 \, M_\odot \) and an initial binary separation of \(< 200 R_\odot \) may produce disks.

RRL99 also found the disk accretion rate to evolve in time with a power-law manner. \( \dot{M}_d = \dot{M}_{do} (t / \text{yr})^{-5/4} \, M_\odot \, \text{yr}^{-1} \). Typical values of the scale is \( \dot{M}_{do} = 10^{-3} \, M_\odot \, \text{yr}^{-1} \).

**Mass Outflow Rate and Wind Speed from MCL Theory:** The basic physics of magneto-centrifugal launching of winds and jets is well studied when a magnetic field distribution is imposed on the disk. In Frank & Blackman 2004 it was shown how to combine Poynting flux driven outflows with asymptotic wind solutions and mean field dynamo theory to estimate the asymptotic wind speed and the outflow accretion rates.

Magneto-centrifugal launching is a means of converting gravitational binding energy in an accreting source into kinetic energy of an outflowing wind. The magnetic fields act as a drive belt to extract angular momentum from the anchoring rotator and launch the wind. The magnetic luminosity, or equivalently, the maximum magnetic power available for a wind can be obtained from the integrated Poynting flux (BFW01).

\[
L_w = \frac{1}{2} \dot{M}_w u^2 \sim L_{\text{mag}} \quad (1)
\]

\[
\equiv \int (E \times B) \cdot d\mathbf{S}_A \sim \int_{r_i}^{r_A(r_i)} \Omega(r) r B_p B_\phi r dr \sim B_A^2 \Omega \sigma r^3, \quad (2)
\]

where \( r_0 \) is the disk inner radius and \( B_A = B_\phi \sim B_p \) at the Alfvén surface.

More work is required to estimate the mass outflow rate and outflow speed separately. The MCL problem requires the construction of solutions for a steady,
ideal, isothermal magnetohydrodynamic flow. The isothermal assumption eliminates the need for solving the energy equation, but more complex assumptions can be used, e.g. a polytropic law. Blackman & Frank 2004 began with an expression for the magnetic Bernoulli constant which connects the wind at infinity to that at the footpoints of the disk

$$\frac{1}{2}(u_p^2 + \Omega^2 r^2) + \Phi + w + \Omega_o(\Omega_o^2 A - \Omega^2 r^2) = U(a) = \text{const}(a).$$

(3)

where $u_p$ is the polodial speed at infinity, $r_A$ is the Alfven radius where $u_p = u_A$. This equation can then be combined with the momentum equation for the flow with an effective potential for a cold plasma parcel tied to a rotating field line (Blandford & Payne (1982))

$$\mathbf{u} \cdot \nabla u_r = -\partial_r \Phi_{eff} = \left(\frac{GM_*}{r_0^2} \frac{r}{r_0^2} - \frac{rr_0}{(z^2 + r^2)^{3/2}}\right).$$

(4)

Beginning with these two equations one can estimate the properties of the wind at large distances from the disk source if the field strength in the disk can be derived.

Magnetic fields may form in these disks via dynamo processes. The topology of such a field, (the ratio of poloidal $B_p$ and toroidal $B_\phi$ in the disk) and its subsequent value in the coronae remains a subject of considerable discourse. Frank & Blackman 2004 assumed a dynamo driven field in the disk that led to a primarily polodial field in a magneto-hydrostatic disk corona where the wind launches. From the expressions derived for the disk field along with those estimated from the governing MHD equations Frank & Frank 2004 provided estimates for the wind properties. We quote these below,

$$\dot{M}_w \sim 0.1 \alpha_{ss} \frac{r_0}{h_0} \dot{M}_d,$$

(5)

$$u_\infty \sim 2.1 \Omega_0 r_0,$$

(6)

$$L_{mag} \sim 0.22 \alpha_{ss} \frac{r_0}{h_0} \dot{M}_d \Omega^2_0 r^2_0,$$

(7)

$$\dot{\Pi} \sim L_{mag}/u_\infty \sim 0.14 \alpha_{ss} \frac{r_0}{h_0} \dot{M}_d \Omega_0 r_0.$$  

(8)

where $\alpha_{ss}$ is a dimensionless parameter associated with the disk viscosity and $h_0$ is the disk scale height. The third and fourth expressions give estimates of the rate in which energy and momentum are input by the MCL disk wind into the ambient medium.

**Disk Winds Models for PNe and pPNe:** For "classic" PNe, a total mass of $M_{pm} \approx 0.1 M_\odot$ must be accelerated to velocities of $u_{pm} \approx 40$ km/s in a timescale of order $\Delta t_{pm} \approx 10000$ y. This gives $\dot{\Pi} = M_{pm} u_{pm}/\Delta t_{pm} \approx 10^{27}$ g cm/s² and $\dot{E} = M_{pm} u_{pm}^2/\Delta t_{pm} \approx 10^{34}$ erg/s.

For pPNe Bujarrabal et al. (2001) found high total outflow momentum $10^{36} < \Pi/(g$ cm s⁻¹) $< 10^{40}$ and total outflow energy $10^{41} < E/(\text{erg} \text{ s}^{-1}) <
10^{47}. These values can be converted into momentum and energy injection rates using an assumed injection or "acceleration" timescale $\Delta t$, $\Pi = \Pi/\Delta t$, $L = E/\Delta t$.

The question which arises is: can these energy and momentum budgets be met with disk wind models. In what follows we use the relations from Frank & Blackman 2004 quoted above and assume that the inner edge of the disk extends to the stellar surface and use $r_0 = r_i = r_*$. 

**PNe Solutions:** In this case we assume that the star which produces the jet is a proto-WD with an AGB companion (Soker & Rappaport 2001). Thus accretion rates of $\dot{M}_d \approx 10^{-6} M_\odot y^{-1}$ are reasonable. To evaluate the expressions above we choose $M_s = 0.6 M_\odot$ and a disk with $\alpha_{ss} = 0.1$ and $r_0/h_0 = 10$.

For PNe central star parameters ($T_* = 10^5 K$, $L_*$ = 5000 $L_\odot$ such that $r_i = 1.64 \times 10^{10} cm$) we find the following conditions for the wind from the equations above

$$\dot{M}_w = 1 \times 10^{-7} M_\odot yr^{-1} \left( \frac{\dot{M}_d}{10^{-6} M_\odot yr^{-1}} \right)$$

$$u_\infty = 1.25 \times 10^3 km/s \left( \frac{M_s}{0.6 M_\odot} \right)^{1/2} \left( \frac{r_0}{23 R_\odot} \right)^{-1/2}.$$ 

Thus using typical conditions for PNe central stars, the scaling relations derived from the MHD equations yield disk wind parameters well matched with observations.

**pPNe Solutions:** While the mass loss rates and velocities are known for PNe winds the situation for pPNe is not as clear. In general what is observed in pPNe is the total mass in the outflows. Velocities are also uncertain as only properties of swept-up material may be directly determined.

We assume a post-AGB star with mass $M_s = 0.6 M_\odot$, $T_* = 10,000 K$ and $L_* = 5 \times 10^3 L_\odot$ which, assuming a blackbody, yields a radius of $r_* = 1.6 \times 10^{12} cm = 23 R_\odot$. Note that such a star has an escape velocity of $u_{esc} = 98 km/s$.

Achieving the high momentum input rates observed in pPNe via MCL disk wind models will necessitate high accretion rates. We use an accretion rate of $\dot{M}_d = 1 \times 10^{-4} M_\odot yr^{-1}$ which is the 200 year average of that found by RRL99 for their case A. Once again we choose a disk with $\alpha_{ss} = 0.1$ and $r_0/h_0 = 10$.

Assuming $r_0 = r_*$ along with the other parameter values given above, the key wind quantities $\dot{M}_w, u_w, L_m = L_w, E$ are,

$$\dot{M}_w = 1 \times 10^{-5} M_\odot yr^{-1} \left( \frac{\dot{M}_d}{10^{-4} M_\odot yr^{-1}} \right)$$

$$u_\infty \simeq 146 km/s \left( \frac{M_*}{0.6 M_\odot} \right)^{1/2} \left( \frac{R_i}{23 R_\odot} \right)^{-1/2}.$$ 

$$L_m \simeq 6.7 \times 10^{34} erg s^{-1} \left( \frac{\dot{M}_d}{10^{-4} M_\odot yr^{-1}} \right) \left( \frac{M_*}{0.6 M_\odot} \right) \left( \frac{R_i}{23 R_\odot} \right)^{-1}.$$
Note that $L_w \Delta t \approx 10^{44}$, a value in the middle of the range found by Bujarrabal et al. 2001. Note also that the solution above has $u_\infty \approx 1.5 u_{esc}$. Since $u_\infty \approx u_{esc}$ the higher velocity outflows seen in some pPNe would require more disks around more compact central sources.

Given a model for the temporal history of the disk accretion, the total energy and momentum for the outflows can be found. Replacing $\dot{M}_d$ with $\dot{M}_d(t)$ from RRL99 and integrating gives

$$E = \int \frac{1}{2} \dot{M}_w u_\infty^2 dt \approx 1.3 \times 10^{44} \text{ erg} \left[ 1 - \left( \frac{1 \text{ yr}}{t} \right)^{1/4} \right] \quad (15)$$

$$\Pi = \int \dot{M}_w u_\infty dt \approx 1.8 \times 10^{37} \text{ g cm s}^{-1} \left[ 1 - \left( \frac{1 \text{ yr}}{t} \right)^{1/4} \right] \quad (16)$$

These results show that the MCL disk wind models can achieve both energy and momentum injection rates as well as the total energy and momentum required to account for many pPNe described by Bujarrabal et al (2001). The total energy and momenta budgets we find from these solutions fall well within the range of pPNe outflows with momentum excesses. Taken together with our previous calculations for "classic" PNe winds, these results confirm the predictions of BFW01 that magnetized disk winds can account for much of the outflow phenomena associated collimated outflows in the late stage of stellar evolution.

The results above indicate that collimated flows which form from transient disks in the pPNe stage will appear as dense knots in mature PNe flows. This may also serve to explain the presence of so-called FLIERs (Fast Low Ionization Emission Regions) seen in some PNe. The mass loss rate in the winds derived above rapidly decrease with time. Thus the bulk of the jet’s mass will lie near its head. As the material in the disk is accreted onto the star the jet will eventually shut-off leaving the dense knot to continue its propagation through the surrounding slow wind.

When the star makes its transition to a hot central star of a PNe its fast, tenuous spherical wind sweeps up a shell of the slow AGB wind material. The shell’s expansion speed will typically be of order 40 km/s and it will not catch up to the head of the jet. Thus during the PNe phase the jet head will appear as a dense, fast moving knot which should lie outside the PNe wind blown bubble. We note that masses of FLIERs are estimated to be of order $10^{-4} - 10^{-5} M_\odot$ which is reasonable for the models presented above. FLIER velocities can be lower than the $\approx 100$ km/s calculated above but deceleration of the jet head will occur via interaction with the environment. We note also that hydrodynamic simulations of PNe jets in which the jet ram pressure decreases in time (as would occur for our model) show characteristic patterns of backward pointing bow-shocks (apex pointing back towards the star). If such results are robust, the jets produced by disk winds in our scenario above may also yield similar morphologies.

**Discussion and Conclusions** Our results for pPNe show that momentum excesses need not occur for outflows driven by MCL winds. While this is encouraging in terms of finding a mechanism for driving pPNe outflows the solutions require fairly high accretion rates ($> 10^{-5} M_\odot \text{ yr}^{-1}$). It is not clear if such
conditions can be achieved with the frequency required by observations. While solutions of RRL99 yield accretion rates and time dependencies which lead to the correct outflow momenta and energetics, their models place fairly stringent limitations on the nature of the binaries that form disks from disrupted companions. If accretion onto undetected compact orbiting companions is invoked Soker & Rappaport (2001) then higher values of $\dot{M}_d$ may not be required.

We note that a robust prediction of our models is the ratio of wind mass loss rate to accretion rate, i.e. $\dot{M}_w/\dot{M}_a \approx 1$. This is true for most MCL disk wind models and can be seen as a target prediction which can be explored observationally.

This paper comprises a step beyond Blackman Frank Welch (2001) in establishing the efficacy of MHD paradigms for pPNe/PNe in which strong magnetic fields play a role in both launching and collimating the flows. It is also worth noting that recent simulation results by Matt, Blackman & Frank 2004 confirm that the exposed rapidly rotating magnetic core model can produce well collimated outflows.

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