Using Kinematic Properties of PPN to Constrain Engine Paradigms

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- PPN are more kinematically demanding than PN based on CO observations of PPN: (Bujarrabal et al. 01) :
  - 28/32 objects have both fast outflows (>~50km/s) with momenta injection rates $d(M_j v_j)/dt > L_{rad}/c$; cannot be driven by radiation
- constraining accretion rates is of particular interest if PPN evolve to PN; then PPN constraints are also PN constraints.
- what fraction of PPN does high momentum population characterize? need more data
- high power PPN jets plausibly facilitated by binaries, which produce accretion, magnetic field amplifcaton and MHD jets. Which specific accretion engines are viable?
- measured energies in outflows and tori help constrain paradigms (Huggins 12) BUT really need to constrain power ("power" is not actually constrained in Huggins 12)
- Here: show framework to constrain accretion modes AND already rule out some

A few points about magnetic fields

- Magnetic fields are the "drive belt" not the "motor": energy source is diff. rotation and turbulence. Dynamo theory describes the field amplification
- Dynamically important fields are thus *consequences* of binary interactions as the interactions supply the free energy via conversion of gravitational potential energy to kinetic energy, and then to magnetic energy
- Dynamo theory is a subtle subject because it requires modeling turbulence. "Applied" dynamo theory "tunes" parameters to match solar field cycle. "Fundamental" dynamo theory seeks to identify the physics behind these parameters.
- Dynamos amplify both large and small scale fields.
- MHD angular momentum transport in disks leads to both local and large scale contributions. Jets are evidence for large scale angular mom. transf.
- Magnetic Tower vs. Magneto-centrifugal MHD Jets two classes of models

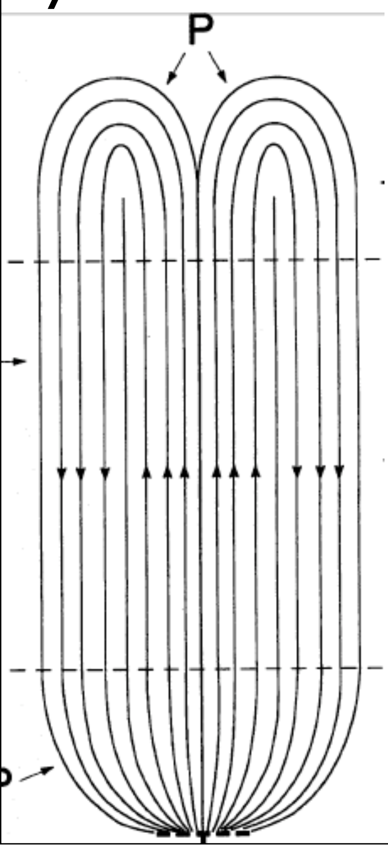
Magnetic Tower

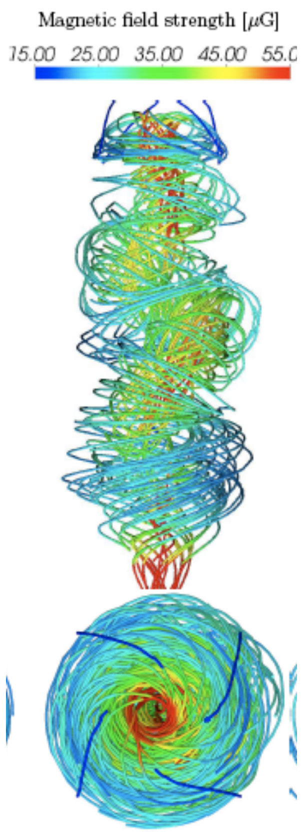
-low density magnetically dominated "cavity" grows with time
-toroidal magnetic pressure pushes flow ahead of the rising tower
-Field || to flow on axis, changing to toroidal field at edge.
-in principle, remains magnetically dominated out to observable scales, so flow is still slaved to magnetic field there
-field primarily toroidal at large r

Magneto-centrifugal Launch

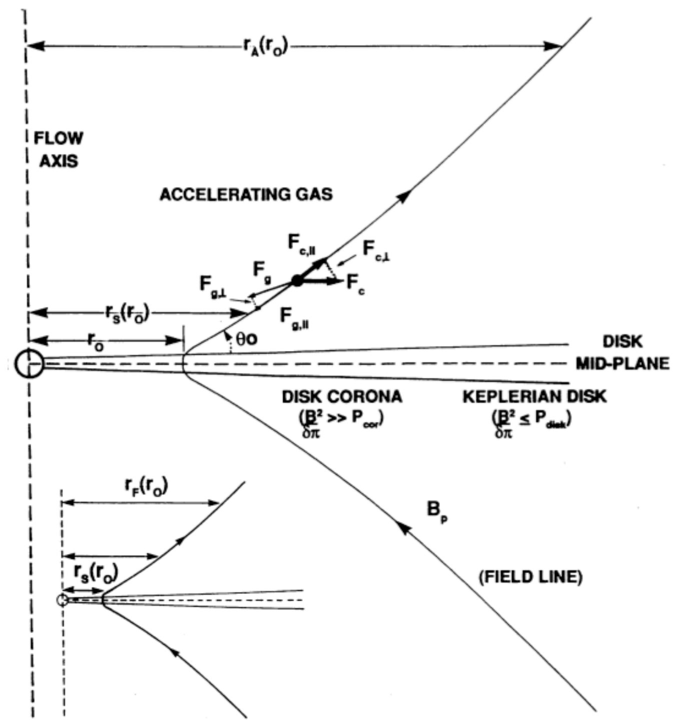
-magnetically dominated at base (and thus resembles magnetic tower there) base but becomes flow dominated at observable scales
-flow is centrifugally launched onto field lines from disk, then pressure from toroidal magnetic pressure accelerates flow
-field at large scales is slaved to flow on observed scales: e.g. if jet has nonuniform outflow speed, field can be stretched along jet direction, so field could be less dominantly toroidal than for magnetic tower

Lynden-Bell 96,03





Huarte-Espinosa



Blandford Payne (82); Pellitier & Pudritz (92)

But ALL Jets Must Obey some Basic Kinematic Constraints:

$$L_{mec} = \frac{1}{2}\dot{M}_{j,N} v_{j,N}{}^2 \leq \frac{1}{2}\frac{GM_a\dot{M}_{ac}}{r_{in}} = \frac{1}{2}\dot{M}_{ac} v_k{}^2 (r_{in})$$

$$v_j \equiv Q v_k (r_{in}),$$

$$\text{so the inequality implies}: \dot{M}_{ac} \geq Q^2 \dot{M}_j$$

Use momentum conservation to constrain $\dot{M}_{ac}$

$$\dot{M}_{ac} \geq Q^2 \dot{M}_{\mathrm{j}} \simeq Q^2 \frac{M_{\mathrm{j}}}{t_{\mathrm{ac}}} \simeq Q^2 \frac{M_{j,\mathrm{obs}} v_{j,\mathrm{obs}}}{Q v_{\mathrm{kep}}} \frac{1}{t_{\mathrm{ac}}}$$

$$= 1.4 \times 10^{-4} \frac{M_\odot}{\mathrm{yr}} \left(\frac{Q}{3}\right) \left(\frac{M_a}{M_\odot}\right)^{-1/2} \left(\frac{R_{ac}}{R_\odot}\right)^{1/2} \left(\frac{M_{j,\mathrm{obs}}}{0.1 M_\odot}\right) \left(\frac{v_{j,obs}}{100\mathrm{km/s}}\right) \left(\frac{t_{\mathrm{ac}}}{500\mathrm{yr}}\right)^{-1}$$

$M_{j,\mathrm{obs}}, v_{j,\mathrm{obs}}, t_{\mathrm{ac}}$ from observations

$5 \gtrsim Q \gtrsim 1$ from standard MHD jet models

v_{kep} from assumed accretor (e.g. MS or WD)

Which Modes of accretion have high enough acc. rates?

Accretion onto Primary?

- PPN jet momentum demands can be accommodated by super-Eddington (SE) accretion onto primary WD from shredded low mass companion (e.g. Nordhaus and Blackman 2006; Nordhaus et al. 2010; also Blackman, Frank, Welch 2001; Reyes-Ruiz & Lopez 1999) which would likely have thick disk and bipolar outflow with SE mechanical luminosities.

- embedded novae/dwarf novae as signatures(?)

- distinguish jets that unbind envelope from jets that don't: some models may be relevant for latter but not former (e.g. Matt et al; B. et al. 2001)

Accretion onto secondary?

- Bondi-Hoyle-Lyttleton onto companion, ion acceleration region: (Huarte-Espinosa et al '13):

  $\dot{M}_{BH} = 1.1 \times 10^{6} M_{\odot}$ / yr, for primary wind $\dot{M}_{w} = 8 \times 10^{-5} M_{\odot}$ / yr; wind speed $\mathrm{v}_{w} = 10$km/s

  primary mass $M_{s} = 1.5 M_{p}$ secondary mass $M_{s} = 1 M_{\odot}$

- WRLOF (Mohamed & Podsiadlowski 12) separation, (a=20AU), dust accel. radius ($R_{dust} = 6R_p$ =10AU) primary Roche Lobe =8.5 AU)

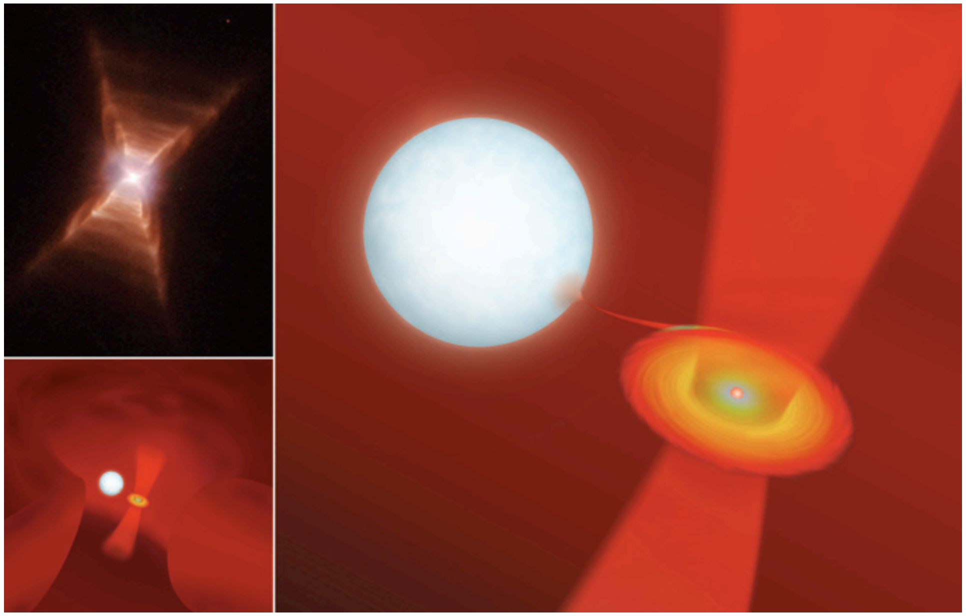
  $\dot{M}_{WR} = 2 \times 10^{-5} M_{\odot}$ / yr; primary mass $\mathrm{M}_{p} = 1 M_{\odot}$; secondary $\mathrm{M}_{s} = 0.6 M_{\odot}$

- CE (Ricker & Tamm 12) on companion: (super-Eddington)

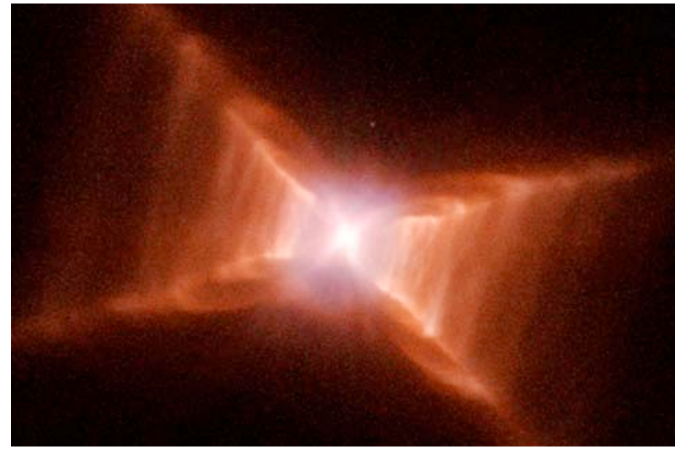
  $\dot{M}_{CE} = 10^{-2} M_{\odot}$ / yr for primary mass $\mathrm{M}_{p} = 1 M_{\odot}$; secondary $\mathrm{M}_{s} = 0.6 M_{\odot}$

- Red- Rectangle special case (Witt et al. 2009; special case) $\dot{M}_{RR} = 2 - 5 \times 10^{-5} M_{\odot}$ / yr

PPN Scenario for Red Rec. (Witt et al. 09)



HD 44179: Red Rectangle



Carbon-rich outflows with
oxygen-rich contamination.
(NASA, ESA, Van Winckel Cohen)

from Witt et al. (2009,11):

-**Upper left**: HST composite from Cohen et al. (2004). bipolar axis length ~15,000 AU.

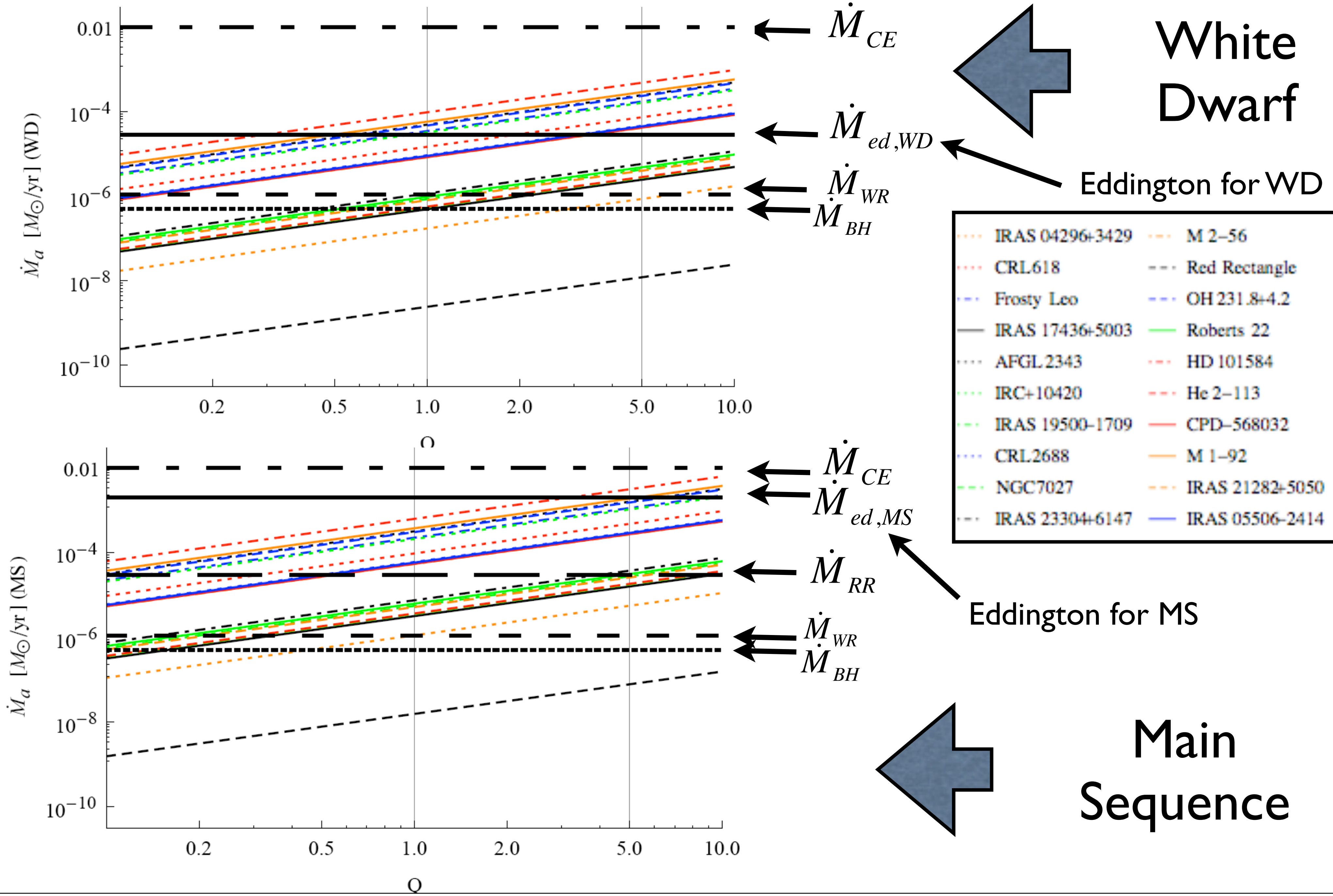
-**Main**: artist (S. Lane) depiction of of basic paradigm, scale ~ 1 AU. Accretion onto secondary via Roche lobe overflow

-**lower left**: HD 44179 may be embedded in the central cavity of a circumbinary disk of thickness 90 AU and cavity diameter 30 AU.

-Accretion rate constraint comes from needed Luminosity to maintain Lyman continuum that sustais ionization of the HII region in RR of Jura 1997 (assume 710pc distance)need 2 -5 x 10^{-5} M_{sun}/yr, gives maximum disk temp of 17,000K

-jet produces blue shift in Hα emmission, modulating primary envelope

Accretion Rate Constraints for Sample that includes 19 objects (18 from Bujarrabal 01 &1 from Sahai et al. 08) (Blackman & Lucchini 2013 http://arxiv.org/abs/1312.5372)



Additional Implications of Momentum Conservation

In principle: the observed evolution of outflow speeds from PPNe to PNe can be predicted/simulated as function of age for each accretion scenario, keeping the primary and jet physics the same, and focusing only on different accretion rate evolutions for different accretion scenarios, and locus of jet origin.

Lower powers, but FASTER outflow speeds are likely to be observable for PN compared to PPN as one sees deeper into the core for PN and thus jet flow that is not as slowed by mass loading. We can estimate the maximum observable jet speed:

$$v_{j,N} = Qv_k = 520\ \text{km/s}\left(\frac{Q}{\sqrt{2}}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{R}{R_\odot}\right)^{-1}$$

$$\text{Max}(v_{j,obs}) = \frac{M_{j,N}v_{j,N}}{fM_{env}(1-e^{-\tau(R_N)}) + M_{j,N}} \sim \frac{M_{j,N}v_{j,N}}{fM_{env}} \sim 100\ \text{km/s for PPN}$$

$$\sim \frac{M_{j,N}v_{j,N}}{M_{j,N}} \sim 1000\ \text{km/s for PN}$$

$f \sim 0.1$ (solid angle of envelope intercepted)

$\tau(R_N)$ is optical depth with respect to obsever at radius where jet speed equals naked launch speed.

Scaling of Accretion Rates with Accretor Mass

- mass radius relation for low mass MS (Demircan & Kahraman 91):

$$R_a \sim 0.99 R_* \simeq R_\odot \left(\frac{M_a}{M_\odot}\right)^{0.89} \text{,for zero age MS and}$$

$$R_a \sim 2 R_* \simeq R_\odot \left(\frac{M_a}{M_\odot}\right)^{0.75} \text{,for terminal age MS.}$$

- empirical mass radius relation for planets (Torres 2012)

$$r = \begin{cases} m^{0.3} & m < 1 \\ m^{0.5} & 1 \le m < 200 \\ (22.6) m^{-0.0886} & m \ge 200 \end{cases}$$

m= M/M_e

- thus $\frac{dL_{mech}}{dM_a} > 0$ for all cases, and only weakly dependent on mass for the MS case

- correlation between jet and tori (>100AU) outflow power (Huggins 12) might be explained if torus depends on either equatorial ejection and jet from accretion, or if both depend on accretion.

- (Huggins 2007: Jets lag tori by ~250 yr)

Conclusions

- Constraining accretion rates from both theory and observations is fundamental to pinning down engine paradigms; mechanical outflows give minimum constraint (note also Red Rec. where independent constraints are available) (see Blackman & Lucchini 2013)
- All jet models powered by accretion obey kinematic constraints; e.g. magnetic fields draw their energy from gravity ultimately (gravity->kinetic -> magnetic-> kinetic); though observed magnetic geometry might distinguish specific MHD models
- PPN outflows provide more demanding constraints than those of PN; particularly important if PN are merely evolved stages of PPN
- Likely to be multiple classes of engines, not single scenario (accretion onto primary, as well as various modes of accretion onto secondary)
- Bondi-Hoyle Lyttleton (BHL) wind accretion and wind Roche lobe overflow (M-WRLOF, based on Mira parameters) are too feeble for all 19/19 objects that we looked at (from Bujarrabal 01 and Sahai et al. 08) for a MS accretor. For a WD accretor, BHL is ruled out for 18/19 objects and M-WRLOF for 15/19 objects. Roche lobe overflow from the primary can seemingly accommodate 7/19 objects but only accretion modes operating from within common envelope evolution seem to be able to accommodate all 19 objects. Sub-Eddington rates for a MS accretor are acceptable but 8/19 would require super-Eddington rates for a WD.
- More data and theory/simulation needed to refine constraints in the plots of $\dot{M}_a$ vs Q
- Would be nice to include companion separation as a third dimension on plots