Outflows from Accreting Compact Objects

Motivation

- Angular momentum loss
- "Veiling"
- AGN Unification
- AGN Unification
- Feedback
- State Transitions

Disk Winds vs Jets

	Jets	Disks Winds
Key Signature	Radio (sometimes resolved)	**Blueshifted Absorption / P Cygni profiles**
Speed	$v_j \sim c$ (relativistic)	$v_w \sim v_{esc}(R_{w,min})$ $\sim \max\left[v_{esc}(R_0), 0.1c\right]$
Geometry	highly collimated	weakly collimated -- bipolar [e.g. AWDs] -- equatorial [e.g. AGN]
Driving Mechanisms	(i) Blandford-Znajek / Penrose process (ii) MHD/Blandford-Payne (iii) Poynting Flux / Magnetic Tower	(i) MHD/Blandford-Payne (ii) **Irradiation/Thermal Driving** -- $v_{th} \gtrsim v_{esc}$ -- $T_{max} \simeq T_{Comp}$ -- $R_{Comp} = R[v_{th}(T_{Comp}) = v_{esc}]$ -- Effective @ $R \gtrsim 0.1 R_{Comp}$ (iii) Radiation Pressure -- electron scattering ++ continuum driving ++ L/L*Edd ~ 1* -- ***line scattering*** ++ *line-driving* ++ *$L/L*{Edd} \gtrsim 1/2000$
"Preferred" State	Hard State	Soft State
Mass-Loss Rate	?	$\dot{M}_j \sim 0.1\,\dot{M}_{acc}$ (AWDs) $\dot{M}_w \sim 1 - 10\,\dot{M}_{acc}$ (XRBs, AGN)
Kinetic Power	$\dot{M}_j v_j^2 \sim L_{acc} \sim GM\dot{M}_{acc}/R_0$ (bubbles as calorimeters)	$\dot{M}_w v_w^2 \sim 0.1 L_{acc}$ (?)
Angular Momentum Lever Arm	$l_j \sim$???	$l_w \sim$???

Formation of P Cygni Profiles

- Monotonically Accelerating Spherical Outflows from Spherical Objects
  - (strictly) blue-shifted absorption
  - (strictly) symmetric emission
  - $v_{max} \simeq v_{\infty}$
  - F_{max} @ $v = 0$
  - pure scattering: $\int_{\lambda} f_{\lambda} d\lambda = 0$
  - photons encounter exactly **one** resonance
    - $\lambda_{photon} - \lambda_{line} = v/c$
    - defines *Sobolev region* where scattering is possible
    - all parts of the outflow are moving away from each other
- Rotating Disk Winds from Thin Disks
  - foreshortening
  - limb-darkening
  - wind geometry
  - wind kinematics
  - red-shifted absorption possible
  - for bipolar winds:
    - face-on: pure absorption
    - edge-on: pure emission
  - in general:
    - absorption when bright continuum is *behind* the wind
    - emission when it is not
  - pure scattering: $\int_{\Omega} \int_{\lambda} f_{\lambda} d\lambda d\Omega = 0$
  - **But**
    - collisional excitation → radiative de-excitation ("thermal emission")
    - collisional de-excitation ("thermalization")
    - recombination
  - photons may encounter **multiple** resonances

Thermally-Driven Winds

- For sufficiently strong (X-ray) irradiation, there will "alway" be a layer in the disk atmosphere where Compton heating and cooling dominate
- This sets the maximum temperature in the atmosphere, $T_{max} \simeq T_{Comp} \simeq h \langle \nu \rangle / 4k$Depends only on (local) SED
- The corresponding thermal speed is $v_{th}(T_{Comp}) \simeq \sqrt{kT_{Comp}/m_p}$
  - this is independent of radius (it $\tau << 1$)
- The escape velocity from the disk is $v_{esc} = \sqrt{2GM/R}$
- So beyond some critical radius -- the Compton radius -- the thermal speed exceeds v_{esc}
  - $R_{Comp} = R[v_{th}(T_{Comp}) = v_{esc}]$
- Thermal driving is pretty much inevitable at some level
- Solar wind is basically thermally driven
  - although it also has a significant magnetic lever arm, $R_A \simeq 20 R_\odot$
  - **different driving mechanisms can act in concert**
- Properties of thermally driven winds depend critically on
  - *where* (radially and vertically) $v_{th} \simeq v_{esc}$
    - thermal stability
    - $\rightarrow$ heating and cooling
  - local SED
    - optical depth / radiative transfer

Line-Driven Winds

- Eddington limit:
  - luminosity beyond which radiation pressure *on electrons* exceeds gravitational attraction
- But in many situations, $\sigma_e << \sigma_{b-b}$
  - line scattering can dominate the momentun transfer!
- Define "force multiplier" $\mathcal{M}$ so that
  - $P_{rad,tot} = \mathcal{M} P_e$
  - **A magic number**: $\mathcal{M} \lesssim 2000$ (Gayley 1995)
- Line-driving is possible for $L \gtrsim L_{Edd}/2000$
- Driving can be dominated by:
  - a few strong resonance lines
  - many weaker lines
- Single-scattering limit:
  - Momentum carried by photons: L/c
  - Momentum carried by outflow: $\dot{M}_w v_\infty$
  - If each photon scatters once and transfer all of its *momentum* to the flow
    - $\dot{M}_{w,m} v_\infty \simeq L/c$
- Some line-driven flows (e.g. WR stars) violate this!
- Energy limit:
  - Energy carried by photons: L
  - Energy carried by outflow $\frac{1}{2}\dot{M}_w v_\infty^2$
  - If each photon transfers all of its *energy* to the flow
    - $\dot{M}_{w,e} v_\infty^2 \simeq 2L$
  - Requires that photons scatter many times
- Maximum achievable mass-loss rates:
  - $\frac{\dot{M}_{w,e}}{\dot{M}_{w,m}} \simeq 2\frac{c}{v_\infty}$
- Properties depend critically on:
  - ionization structure
  - radiative transfer

Evidence for MHD/Centrifugal Driving in a BH XRB?

Miller+06

- Chandra X-ray spectra of GRO J1644:
  - eclipsing system:
    - $P_{orb} \simeq 2.6\,d$
    - $i \simeq 76^\circ \pm 9^\circ$
    - $M_{BH} \simeq 7\,M_\odot$
    - $M_2 \simeq 2.3\,M_\odot$
  - $L_X \simeq 0.04 L_{Edd}$
    - BB Disk:
      - $kT \simeq 1.3\,keV$
      - $L_{disk} \simeq 0.65 L_X$
    - PL Corona:
      - $\Gamma \simeq 3.5$
      - $L_{cor} \simeq 0.35 L_X$
  - $\simeq 75$ resonance lines showing blue-shifted absorption
    - $v_{shift} \simeq 300 - 1600$ km/s
    - high ionization lines
      - Fe XXIV (IP: 2.0 keV)
      - Si XiV (IP: 2.7 keV)
      - Mg XII (IP: 2.0 keV)
  - Photo-ionization modelling
    - constant density slab
    - $n \simeq 6e15\,cm^3$
    - $\Delta R \simeq 2.5 \times 10^8\,cm$
    - $R_w \simeq 4.8 \times 10^8\,cm \simeq 200\,R_{Schw}$
    - Inferred mass-loss rate
      - $\dot{M}_w \simeq 3.5 \times 10^{17}\,g/s \simeq \dot{M}_{acc}$
        - assumes $\Omega/4\pi \simeq 0.2$
      - $L_w \simeq \frac{1}{2}\dot{M}_w v_w^2 \simeq 4 \times 10^{32}\,erg/s << L_{acc}$
    - Ionization parameter:
      - $\log \xi = \log L_X/nR^2 \simeq 4.5 \pm 0.2$
    - Limits on location
      - $R_{w,min} \simeq 10^{7.5}\,cm$
        - otherwise n high enough to populate metastable FeXXIII levels
        - corresponding lines not observed
      - $R_{w,max} \simeq 10^{9.5}\,cm$
        - otherwise $\Delta R \gtrsim R_w$
        - dilution of radiation field through slab
        - cannot get high enough N at high enough ξ
          - Exclude thermal driving
          - $R_{Comp} \simeq 7 \times 10^{12}\,cm >> R_w$
          - (actually $R_{Comp} \simeq 5 \times 10^{11}\,cm$, see below)
          - Exclude line driving
          - wind is too highly ionized
          - photo-ionization model gives $\mathcal{M} \simeq 2$

Are the Miller+06 arguments robust?

- Netzer06
  - can also fit the spectra with
    - $\log \xi \simeq 3$
    - $n \simeq 10^{13}\ cm^{-3}$
    - $R \simeq 10^5 R_g >> R_{Comp}$
  - thermal driving might work
- Miller+08, Kallman+09
  - Netzer models are a poorer fit than Miller models
  - Netzer models assume/require FeXXIV lines to be optically thick and partially covered
    - data suggests otherwise
  - **BUT** (Kallman+09)
    - $v_w << v_K(R_w)$ [for R_w in Miller's model]
    - $v_w \simeq v_K(R_{Comp})$
    - wide range in v_w
- Luketic+10
  - hydro simulations
  - difficult to produce thermally driven wind matching observations
- **General Point**:
  - **How much should one trust *any* one-zone photo-ionization model for a disk wind?**
    - Is there such a thing as "the" photo-ionization parameter?
    - Is there such a thing as "the" density?
    - ...
  - Luketic+10 models get closer to a realistic test
  - Over to Nick!