Accretion and AGN power

Winds from accretion disks and driving mechanisms

Broad-line regions in AGN and outflows

AGN tori and outflows

Collimated winds: jets

Where is accretion and where is an outflow
OBSERVATIONAL EVIDENCE FOR INFLOWS AND OUTFLOWS IN AGN

- Review of AGN energetics

\[ L = \eta \dot{M}c^2 \sim 6 \times 10^{45} \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{M}}{1 \text{ M}_\odot/\text{yr}} \right) \text{ erg/s} \]

accretion luminosity

\[ L = \frac{4\pi Gcm_p}{\sigma_T} M_\odot \sim 1.3 \times 10^{46} \left( \frac{M}{10^8 \text{ M}_\odot} \right) \text{ erg/s} \]

the Eddington luminosity

\[ T_{bb} \sim \left( \frac{L}{\pi R^2 \sigma} \right)^{1/4} \sim 10^5 \left( \frac{L}{10^{46} \text{ erg/s}} \right)^{1/4} \left( \frac{R}{1 \text{ light−day}} \right)^{-1/2} \text{ K} \]

effective temperature of blackbody accretion disk emission \( \rightarrow \) peaks at \( \sim 10^{16} \text{ Hz} \)
**Observations: Inflows and Outflows in AGN**

- Analogy with hot stars

Optical/UV spectroscopy: blueshifted absorption or P Cygni line profiles

\[
a_{\text{rad}} = \int d\nu \frac{\kappa_{\nu} F_{\nu}}{c}
\]

- \( F_{\nu} \) -- stellar radiation flux
- \( a_{\text{rad}} \) -- radiative acceleration
- \( \kappa_{\nu} \) -- opacity coeff.

Wind from an O star

**Eta Carina**
Observations: Inflows and Outflows in AGN

- Analogy with solar (Parker) wind

What triggers the solar wind:
- waves and turbulence,
- or magnetic reconnection?

\[ \dot{M} \propto F_{\text{heat}} \propto F_X \]

Some stars have disks (T Tauri) and winds

(Matt & Pudritz 2005)
OBSERVATIONS: INFLOWS AND OUTFLOWS IN AGN

- Analogy with hot stars

$T$-range for radiation-driven and coronal stellar winds

$T$-range for geometrically-thin accretion disks in AGN is similar to stellar range!

AGN winds can be radiation-driven!
**Observations: Inflows and Outflows in AGN**

- Evidence for outflows: BAL QSOs

7 BAL QSOs (red throughs), 2 non-BAL QSOs

- Similarity of the CIV line profile of the nova-like variable RW Sex with those of BAL QSOs

*All BALQSOs absorption lines are blueshifted → outflows!*

Trump et al. 2006
Evidence for outflows: high-ionization UV emission lines (HILs) in QSOs

blueshifted CIV emission line in luminous radio-quiet and radio loud QSOs

HILs in QSOs are blueshifted
By ~few x 100 – 1000 km/s → these broad line produced in winds!
Evidences for outflows in AGN:

- Warm absorbers in Seyfert galaxies
- Covering factors can be as high as 0.5

Warm absorber fit to the ASCA satellite spectrum of NGC 3783 → Ne IX absorption line

Fe K line in Fairal 9 from ASCA

Mushotzky (1997)

Reynolds (1997)
**Observations: Inflows and Outflows in AGN**

- Evidence for outflows: ultra-fast X-ray outflows (UFOs)

Very fast outflows of highly ionized material by XMM/Newton in absorption lines of highly ionized Fe, S, Mg → **warm absorbers?**

Fe Kα line normalized by continuum emission:
- Absorption line well defined, but emission line much less defined

$L_{\text{kin}} \sim 0.1 L_{\text{bol}}, \ v \sim 0.13c$ !

The physical implications are:
- Persistent (>6-7 yrs), massive wide-angle wind, covering 0.3-0.6,
- $\dot{M} (\text{wind}) \sim \dot{M} (\text{accretion})$, column density $N_H \sim 8 \times 10^{23} \text{ cm}^{-2}$, **super-Eddington → Compton-thick wind?**

**BUT:**

Often only one line is detected: unsure identification, ionization/column density

Region strongly influenced by:
- background subtraction, continuum modelling, lower effective area/resolution

PG 1211+143; Pounds & Reeves (2009)
Evidence for outflows: jets in radio and other (AGN) galaxies

Jet in M87 ➔ optical emission is synchrotron mechanism (electrons accelerated in B-field)
Uncollimated or partially collimated winds:
- UV resonance lines in QSOs and Seyferts (line-driven winds)
- BAL QSOs
- UV absorbers: warm absorbers, UFOs (X-ray Ultra-Fast Outflows)
- Super-Eddington winds?

Collimated winds (jets)
- Powerful and not so powerful radio galaxies
  (RLQ, FR II, FR I), Seyferts
- LLAGN (XRB hard state compact jets)
THEORY: INFLOWS AND OUTFLOWS IN AGN

Summary: radiation-driven winds

To drive a wind by radiation \( \rightarrow \) need opacity \( \rightarrow F_{\text{rad}} > F_{\text{grav}} \)

- Resonance lines
  - e.g., C IV
- Dust
- Electron scattering

- Wind \( T < 10,000 \text{ K} \)
- Wind \( T < 2,000 \text{ K} \)
- Wind fully ionized \( T > 10,000 \text{ K} \)

- But linewidth \( \sim 10^4 \text{ km/s} \)
- \( T_{\text{gas}} \sim 10^{10} \text{ K} \)!
- No lines! No dust!
- What is the geometry of the wind?

BLR must be clumpy but what about wind?

Super-Eddington wind?
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- Radiation-driven disk winds: driving spherical wind by resonance lines

\[ \frac{v(r)}{v_{\text{max}}} = w_c + (1 - w_c)(r/r_{\text{max}})^\beta \]

- Line profiles similar to stellar line profiles

Drew & Giddings (1982)

Dependence beyond the Lyman limit, down to X-ray wavelengths. In the optically thin approximation, even when the spectral index is increased to \( \alpha = 3 \) in the ultraviolet and X-ray part of the spectrum, the mass-loss rate needs to be of the order of \( \sim 1000 M_\odot \text{yr}^{-1} \), if the visual luminosity of the QSO is comparable with that of 3C 273. It is anticipated that, such mass loss is not achievable in AGN!
Radiation-driven disk winds: driving by resonance lines (Shlosman et al. 1985)

\[ F_{l,\text{tot}} = \sum_l \frac{\mathcal{F}(R; v_l)}{c} k_i \rho \frac{1 - e^{-\tau_l}}{\tau_l} \]

radiation force (Sobolev)

per unit volume summed over lines (C, N, O lines)

\[ \tau_l = \frac{k_i \rho c}{v_l} \left| \frac{dv}{dz} \right|^{-1} \]

optical depth in line \( l \)
depends on \( v \)-gradient!

\[ \rho v_z g = \dot{M} \]

\[ (v_z^2 - v_s^2) \frac{dv_z}{dz} = v_z \left[ \frac{2v_s^2z^2}{gR_0^2} - z \frac{dv_s^2}{dz} - \frac{GM_{\text{BH}}z^2}{g^{3/2}R_0^3} (1 - \Gamma_{\text{es}} - \Gamma_1) \right] \]

\[ \frac{dT}{dz} = \frac{2}{3} v_z \left[ \frac{H - \Lambda}{k_B n} - T \left( \frac{dv_z}{dz} + \frac{2zv_z}{gR_0^2} \right) \right] \]

vertical velocity and line radiation force profiles (normalized by gravity)

Shlosman, Vitello & Shaviv (1985)

disk wind fits, But what about line profiles?
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- Radiation-driven disk winds: driving by resonance lines (Proga et al. 2000)

\[ F_{\text{rad}, i}(r) = \int_{\Omega} M(t) \left[ \hat{n} \frac{\sigma_{\text{e}} I(r, \hat{n}) d\Omega}{c} \right] \]

- Radiation force (Sobolev)
- Per unit mass approximated by force multiplier \( M(t) \)
- Electron scattering force

**Force multiplier has been calculated for stellar case only!**

\[ M(t) = \sum_{\text{lines}} \frac{F_{\text{c}} \Delta \nu_D}{F} \min \left( \frac{1}{\beta}, \frac{1}{t} \right) \]

- \( t \) – Sobolev optical depth

Castor, Abbott & Klein (1973)

Proga et al. (2000)
THEORY: INFLOWS AND OUTFLOWS IN AGN

- Radiation-driven disk winds: driving by resonance lines (Murray et al. 1995)

Continuous wind → no clumps
Radiation force (Sobolev) per unit mass approximated by force multiplier $M(t)$ as in Proga et al. (2000)

Wind streamlines make 5° with the disk surface

CIV line shapes don’t fit…. geometry wrong?
Radiation-driven disk winds: driving by dust

But do dust grains survive both the acceleration and associated temperature? need self-consistent treatment!
THEORY: INFLOWS AND OUTFLOWS IN AGN

- Theory: summary of MHD

Mass conservation

\[ \nabla \cdot (\rho \mathbf{v}) = 0 \]

z-component of momentum conservation (Euler eq.)

\[ \rho (\mathbf{v} \cdot \nabla) v_z = -\frac{\partial p}{\partial z} - \frac{\rho \partial \Phi}{\partial z} - \frac{1}{8\pi} \frac{\partial B^2}{\partial z} + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) B_z \]

Energy

\[ \rho T \frac{dS}{dt} = \rho T \mathbf{v}_p \cdot \nabla S = Q \]

Perfect gas

\[ P = \rho \frac{k_B}{\mu m_p} T \]

Ohm’s law

\[ \eta_m J_\varphi e_\varphi = \mathbf{v}_p \times \mathbf{B}_p \]

Induction

\[ \nabla \cdot \left( \frac{\nu'}{r^2} \nabla r B_\varphi \right) = \nabla \cdot \frac{1}{r} (B_\varphi \mathbf{u}_p - B_p \Omega r) \]
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows**: magneto-centrifugal winds $\Rightarrow$ Blandford & Payne (1982) solution ($\rho_{\text{disk}} \sim r^{-3/2}$)

Include inertia and assume MHD conditions

\[ E + (1/c) \mathbf{v} \times \mathbf{B} = 0 \]

Stationary axisymmetric MHD flow

Euler equation

\[ \rho (\mathbf{v} \cdot \nabla) v_z = -\frac{\partial P}{\partial z} - \rho \frac{\partial \Phi}{\partial z} - \frac{1}{8\pi} \frac{\partial B^2}{\partial z} + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) B_z \]

Self-similar solution

\[ r = \left[ r_0 \xi(\chi), \phi, r_0 \chi \right] \quad \mathbf{v} = \left[ \xi'(\chi) f(\chi), g(\chi), f(\chi) \right] \left( GM / r_0 \right)^{1/2} \]

Solutions scale with spherical radius along a given direction

Centrifugal acceleration (gas clouds on B-lines act as “beads on a wire”): a wind is launched when the inclination angle of magnetic lines to the disk is $< 60^\circ$

After launch the flow is dominated by the toroidal magnetic field imposed by rotation

Collimation along the magnetic axis
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows:** magneto-centrifugal winds $\rightarrow$ Blandford & Payne (1982) solution ($\rho_{disk} \sim r^{-3/2}$)

  Disk winds: 2D $\rightarrow$ remove one degree of freedom $\rightarrow$ 1D ordinary differential equation

  **Self-similarity assumptions:**
  - **cylindrical z:** pre-supposes a collimated vertical jet structure
  - **cylindrical r:** accretion disk structure, not jets
  - **spherical $\theta$:** spherical wind (NO collimation)
  - **spherical $r$:** only choice with equations that allow collimation

  Blandford & Payne (1982): $r$-self-similarity; $\theta$ structure same for every field line
  reduces MHD to only two ordinary differential equations

  $$ r = [r_0 \xi(\chi), \phi, r_0 \chi] $$
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows**: magneto-centrifugal winds $\rightarrow$ merging radiation & MHD winds
  generalized Blandford/Payne model (Emmering, Blandford & Shlosman 1992 solution)

$$\rho_{\text{disk}} \sim r^{-\alpha}$$

$$\dot{M} r_0 \nu_0 \sim K B_A^2 r_A^3$$

- $B$-field extracts angular momentum $\rightarrow$ low $\dot{M}$ wind!

Electron-scattering corona widens the line wings

**Self-similarity of**

$B$-lines and $r$

$$v \perp z \text{ axis} \quad v \parallel z \text{ axis}$$
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows**: magneto-centrifugal winds → merging radiation & MHD winds

  Generalized Blandford/Payne model (Emmering, Blandford & Shlosman 1992 solution)

So, disk winds produce characteristic triangular shapes of emission lines in AGN → match as good as for spherical outflows!

CIV emission line profiles for various gas emissivities

CIV emission line profiles with observed asymmetry

CIV emission line profiles for various inclinations to z-axis
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows**: magneto-centrifugal winds $\rightarrow$ reverberation mapping of BLR

Formation of the broad line region (BLR)

**C IV emission line profile evolution** in Seyfert 1 galaxy NGC5548

$\tau = \frac{r}{c}$

All points on an “isodelay surface” have the same extra light-travel time to the observer, relative to photons from the continuum source.

$M_\odot \approx 3 \times 10^7 M_\odot$ in Seyfert 1 galaxy NGC5548

Bottorff, Korista, Shlosman & Blandford (1997)
THEORY: INFLOWS AND OUTFLOWS IN AGN

- **Outflows**: magneto-centrifugal winds

Formation of the broad line region (BLR)

Bottorff, Korista, Shlosman & Blandford (1997)
Outflows: magneto-centrifugal winds

Multi-component warm absorbers in NGC 5548

observer’s orientation in NGC 5548

Bottorff, Korista & Shlosman (2000)
THEORY: INFLOWS AND OUTFLOWS IN AGN

- Outflows: The end of the torus paradigm (Elitzur & Shlosman 2006; Nenkova, Elitzur & Ivezić 2008)

IR radiation transfer in clumpy wind

Toroidal Obscuration region is an outflow and it disappears at $L \leq 10^{42}$ erg/s!
THEORY: INFLOWS AND OUTFLOWS IN AGN

- **Outflows**: collimated MHD winds \(\rightarrow\) jets

Accretion disk-driven jets

Accretion disk driven jets \(\rightarrow\) velocity distribution at the wind base is that of a Keplerian disk

Blandford & Payne model: inertia \(\rightarrow\) poloidal B \(\rightarrow\) toroidal B
**Theory: Inflows and Outflows in AGN**

- **Outflows:** emission mechanism in jets $\rightarrow$ synchrotron radiation

  If electrons are moving at $v \sim c$ $\rightarrow$ radiation is beamed

  Particle moving with Lorentz factor $\gamma$ toward observer emits into cone of opening angle $\theta \sim \gamma^{-1}$

  We only see radiation from a small portion of the orbit, when the cone points toward us $\rightarrow$ but many electrons!
THEORY: INFLOWS AND OUTFLOWS IN AGN

- **Outflows**: collimated MHD winds → jets

Alternative acceleration mechanisms:

- Twin-exhaust scheme
  (Blandford & Rees 1972)

- Radiation pressure in accretion funnels
  (FRT 1985)

- Electromagnetic effects in accretion funnels and
  Poynting flux jets
  (Lovelace 1976, Blandford 1976)

- Magneto-centrifugal acceleration
  (Blandford & Payne 1982)
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows:** collimated MHD winds → jets

Alternative acceleration mechanisms: tapping the rotational energy of black hole

Blandford and Znajek (1977) found a *stationary solution* for monopole magnetospheres of slowly rotating black holes. It exhibited outflows of energy and angular momentum.

Black hole rotational energy \((a = 1)\): 

\[
E_b = 0.29 M_b c^2 \approx 10^{54} \left( \frac{M_b}{2M_\odot} \right) \text{ erg}
\]

Power of the Blandford-Znajek mechanism:

\[
L_{BZ} \approx 3.6 \times 10^{50} a^2 \left( \frac{M}{2M_\odot} \right)^2 \left( \frac{\Psi}{10^{27}} \right)^2 \text{ erg/s}
\]

- \(a\) - spin parameter of the black hole \((0 < a < 1)\),
- \(\Psi\) - the magnetic flux of black hole.
- \(\Psi = 10^{27}\text{G cm}^2\) is the highest value observed in magnetic stars: Ag, white dwarfs, neutron stars (magnetars).

**Efficiency of Blandford-Znajek mechanism?**
**THEORY: INFLOWS AND OUTFLOWS IN AGN**

- **Outflows**: collimated MHD winds → jets

  Tapping the rotational energy of black hole: Blandford & Znajek (1977)

What is the condition for activation of the BZ-mechanism with finite inertia of plasma?

MHD waves must be able to escape from the black hole ergosphere!?

Alfven speed $v_a > v_{ff}$ free fall

\[
\frac{c_a^2}{v_{ff}^2} = \frac{B^2}{4\pi \rho}, \quad v_{ff}^2 = \frac{2GM}{r} = 2r_s = \frac{2GM}{c^2}
\]

Apply at the ergosphere, $B^2 > 4\pi \rho c$

The energy density of magnetic field must exceed that of matter for the BZ-mechanism to be activated!
OBSERVATIONAL EVIDENCE FOR INFLOWS AND OUTFLOWS IN AGN

Evidense for inflows:

To be discussed on Thursday as a FUELING issue
Active Galactic Nuclei (AGN) are powered by accretion processes, but there are clear and objective difficulties to detect this accretion flow.

On the other hand, UV and some X-ray emission and absorption lines point to powerful and diverse outflows from the accretion disks in AGN.

There is a clear preference, both observationally and theoretically, to the presence of accretion disks in AGN, as opposite to spherical outflows.

MHD winds have preference over radiation-driven winds in AGN, because they are capable of extracting angular momentum, which radiation is inefficient in this process.

MHD is probably collimates some of the wind into powerful jets, sometimes relativistic.