Accretion Processes

Accretion is important in many aspects of astrophysics:

• Formation of stars and planets. Proto-planetary disks are observed - planets probably form out of the disks.

• Accretion in binary star systems: X-ray binaries, cataclysmic variables, etc.

• Accretion in Active Galactic Nuclei (AGN).

Based partly on the lectures by Koji Mukai (GSFC), Liz Puchnarewicz (MSSL), and Marek Grabowski (UCCS), as well as the text book, Accretion Power in Astrophysics, EXU, and HEA
Accretion onto a compact object

- Principal mechanism for producing high-energy radiation
- Most efficient of energy production known in the Universe.
- Gravitational potential energy released for an object with mass $M$ and radius $R$ when mass $m$ is accreted:
  \[ E_{\text{acc}} = \frac{GMm}{R} = \left(\frac{R_{\text{sch}}}{2R}\right)mc^2 \]
  where $R_{\text{sch}} = 3 \ M_{\text{sun}} \ \text{km}$
  - For a Neutron star, $R \sim 10 \ \text{km} \Rightarrow E_{\text{acc}} \sim 0.15 \ mc^2$
    - Or $\sim 20 \times$ more efficient than nuclear fusion
    - (H $\Rightarrow$ He) $\sim 0.007 \ mc^2$.
  - For a white dwarf, $R \sim 10^4 \ \text{km} \Rightarrow E_{\text{acc}} \sim 1.5 \times 10^{-4} \ mc^2$
    - Or $\sim 50 \times$ less efficient than nuclear fusion.
Origin of accreted matter

- Given $M/R$, luminosity produced depends on accretion rate, $\frac{dm}{dt}$:
  $$L_{\text{acc}} = \frac{dE_{\text{acc}}}{dt} = GM \left(\frac{dm}{dt}\right)/R = \left(\frac{R_{\text{sch}}}{R}\right)(dm/dt)c^2$$

- Consider a neutron star with an observed X-ray luminosity of $10^{38}$ ergs/s, the required mass accretion rate $\frac{dm}{dt} = 10^{-8} M_{\text{sun}}$/year.

- Where does accreted matter come from?
  - Companion? Yes.
  - ISM? Too small to explain observed accreting compact objects of stellar masses. But enough for AGNs --- accreting supermassive black holes with masses $10^6-10^{10} M_{\text{sun}}$. 

The Eddington Luminosity

• A limit to which luminosity can be produced by a given object, assuming a steady accretion state.
• The inward gravitational force on matter is balanced by the outward transfer of momentum by radiation.
• At this point accretion stops, effectively imposing a 'limit' on the luminosity of a given body.

\[ F_{\text{grav}} = \frac{GMm}{r^2} \text{ where } m = m_p + m_e \sim m_p \]
\[ F_{\text{rad}} = \frac{L}{(4\pi r^2 h\nu)} \sigma_T (h\nu/c) \]
\[ = \frac{L\sigma_T}{(4\pi r^2 c)} \]
\[ F_{\text{grav}} = F_{\text{rad}} \Rightarrow \text{the Eddington luminosity} \]
\[ L = 4\pi cGMm/\sigma_T \]
\[ = 1.3 \times 10^{38} \left( \frac{M}{M_{\odot}} \right) \text{ ergs/s} \]
Emitted Spectrum

- Define temperature $T_{\text{rad}}$ such that $h\nu \sim kT_{\text{rad}}$
- Define ‘effective’ BB temp $T_{b} = [L_{\text{acc}}/(4\pi R^{2}\sigma)]^{1/4}$
- Thermal temperature, $T_{\text{th}}$ such that:
  
  $GMm/R = 2 \times 3/2 \ kT_{\text{th}} \Rightarrow T_{\text{th}} = GMm/(3kR)$

Flow optically-thick: $T_{\text{rad}} \sim T_{b}$
Flow optically-thin: $T_{\text{rad}} \sim T_{\text{th}}$
Spectrum

In general, $T_b < T_{rad} < T_{th}$

- For a neutron star with $L_{acc} \sim 1.3 \times 10^{38} (M/M_{\odot})$ ergs/s
  - $T_{th} \sim 5 \times 10^{11} \text{ K} \sim 50 \text{ MeV}$
  - $T_b \sim 2 \times 10^7 \text{ K} \sim 1 \text{ keV}$

Therefore, $1 \text{ keV} < h \nu < 50 \text{ MeV}$

$\Rightarrow$ X-ray and $\gamma$-ray sources

- Similarly for a stellar mass black hole

- For white dwarf, $L \sim 10^{33}$ ergs/s, $M \sim M_{\odot}$, $R=5 \times 10^3$ km,
  - $6 \text{ eV} < h \nu < 100 \text{ keV}$

$\Rightarrow$ optical, UV, X-ray sources
Accretion modes in binaries

Consider binary systems which contain a compact star, either white dwarf, neutron star or black hole.

(1) Roche Lobe overflow
(2) Stellar wind
- correspond to different types of X-ray binaries
Roche Lobe Overflow

• normal star expanded or binary separation decreased => normal star feeds compact

Compact star \( M_2 \) and normal star \( M_1 \)
\( M_2 > M_1 \)

Sections in the orbital plane of Roche equipotentials
Accretion disk formation

Matter circulates around the compact object:

- **ang mom outwards**
- **matter inwards**
• Material transferred has high angular momentum so must lose it before accreting => disk forms

• Gas loses ang mom through collisions, shocks, viscosity and magnetic fields: kinetic energy converted into heat and radiated.

• Matter sinks deeper into gravity of compact object
Magnetic fields in ADs

Magnetic “flux tube”
Mag field characteristics

- Magnetic loops rise out of the plane of the disk at any angle - the global field geometry is “tangled”
- The field lines confine and carry plasma across the disk
- Reconnection and snapping of the loops releases energy into the disk atmosphere - mostly in X-rays
- The magnetic field also transfers angular momentum out of the disk system
The accretion disk (AD) can be considered as rings or annuli of blackbody emission.
Consider a cylinder of an inner radius \( r \) and outer radius \( r + \Delta r \) and a surface mass density of \( \Sigma \).

The torque on the inner cylindrical surface is
\[
G(r) = -2\pi r^2 \nu \Sigma r (d\Omega/dr)
\]
On the outer surface \( G(r+\Delta r) \) in the opposite direction

The net torque on the cylinder is then \( \Delta G(r) = G(r+\Delta r) - G(r) \)
\[
\Delta G(r) = \Delta (dL/dt) \text{ where } dL/dt = r^2 \Omega (dm/dt)
\]
Integration gives
\[
-2\pi r^2 \nu \Sigma r (d\Omega/dr) = dL/dt(r) - dL/dt(r_{in})
\]
Since \( \Omega \propto r^{-3/2} \) for a Keplerian disk,
\[
\nu \Sigma = (dm/dt)/(3\pi)[1-(r_{in}/r)^{1/2}]
\]
Accretion disk structure (cont.)

Energy loss per unit area:
\[ \frac{dE}{dt} = \nu \Sigma r^2 \frac{(d\Omega/dr)^2}{2} \]
\[ = \frac{3GM_* dm/dt}{8\pi r^3} [1 - (r_{in}/r)^{1/2}] \]
where 2 is due to the two sides of a disk.

The luminosity of the disk
\[ L = \int (\frac{dE}{dt})^4 \pi r dr = \frac{GM(dm/dt)}{2r_{in}} = 1/2L_{acc} \]

Another half of the potential energy is kinetic, ie.
\[ 1/2mv^2 = 1/2m(\frac{GM}{r_{in}}) = 1/2L_{acc} \]

Assuming BB,
\[ \frac{dE}{dt} = \sigma T^4(r) \]
\[ \Rightarrow T(r) = \left( \frac{3GM_* dm/dt}{8\pi r^3 \sigma} [1 - \beta (r_{in}/r)^{1/2}] \right)^{1/4} \]
\[ = T_{in} \left( \frac{(r_{in}/r)^3 [1 - \beta (r_{in}/r)^{1/2}]}{1/4} \right) \]
where \( \beta \) is due to the inner boundary cond.
Disk spectrum

Flux as a function of frequency, $\nu$

Log $\nu \cdot F_\nu$

Total disk spectrum

Annular BB emission

Log $\nu$
Complications

- Hot, optically-thin inner region; emits bremsstrahlung
- Outer regions are cool, optically-thick and emit blackbody radiation

- The other half of the accretion luminosity is released at the inner boundary and may partly be used to spin-up the compact star. Emission is often from optical thin, high temperature corona.
- Nuclear burning of matter accumulated on the surface can provide additional luminosity.
Stellar Wind Model

Early-type stars have intense and highly supersonic winds. Mass loss rates - $10^{-6}$ to $10^{-5}$ M\(_{\text{sun}}/\text{year}$.

For compact star - early-type star binary, compact star accretes if $GMm/r > 1/2m v_{\text{rel}}^2$, where $v_{\text{rel}}^2 = (v_w^2 + v_{\text{ns}}^2)$

Therefore, $r_{\text{acc}} = 2GM/v_{\text{rel}}^2$

This process (Bondi-Holye accretion) is much less efficient than Roche lobe overflow, but mass loss rates high enough to explain observed luminosities.
Accretion onto a magnetic star

White Dwarfs and Neutron Stars can possess strong magnetic field. Assuming spherical accretion and a dipole-like B field, \( B \sim \mu/r^3 \), where the magnetic moment \( \mu = B R^3 \) is a const.

- Magnetic pressure \( P_m = B^2/8\pi \)
- Ram-pressure of the accretion flow
  \[ P_r = (\rho v)v = \frac{[dm/dt/(4\pi r^2)](2GM*/r)^{1/2}}{4} \]
- \( P_m = P_r \Rightarrow \text{Alfven Radius} r_m = \frac{(5.1 \times 10^3 \text{ km})[\frac{[dm/dt]/10^{16})^{-2/7} (M*/M_{\odot})^{-1/7} (\mu/10^{30})^{4/7}]}{\frac{GM*(dm/dt)/R*}{\text{Lacc}} = GM*(dm/dt)/R*.} \)

- Alfven Radius characterizes the inner radius of the accretion disk, if there is any.
• Gas captured from companion falls toward the compact star
• The gas may spin around as an accretion disk before falling onto the star
• Material is channeled along field lines and falls onto star at magnetic poles, where most radiation is produced → X-ray or even γ-ray pulsators, X-bursters, etc.
Strong B field neutron Stars in binary systems

Magnetic field channels gas to small area near poles. Gas heated by impact, making hot spot.

As star rotates, hotspot appears and disappears.

Brightness

Time
# X-ray Binaries

<table>
<thead>
<tr>
<th>Type</th>
<th>Donor star</th>
<th>Compact object</th>
<th>Accretion disk</th>
<th>Examples</th>
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<td>MXBR</td>
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<td>K-M V</td>
<td>Mag WD</td>
<td>Ring</td>
<td>DQ Her</td>
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</tbody>
</table>

EXU Section 7.2
Black Holes in General Relativity

- The spherically symmetric solution for a single mass (Schwarzschild metric in natural units; $G = c = 1$):
  \[ ds^2 = -(1-2M/r) \, dt^2 + (1-2M/r)^{-1} \, dr^2 + r^2 \, d\theta^2 + r^2 \sin^2 \theta \, d\phi^2 \]

- The Schwarzschild radius,
  \[ R_s = \frac{2GM}{c^2} \sim 3 \left[ \frac{M}{M_{\text{sun}}} \right] \text{ km} \]
defines the event horizon.
  - Once inside the event horizon, no light nor particle can escape to the outside: thus, J.C. Wheeler coined the term, black hole.
  - Objects just outside an event horizon are seen to experience severe time dilation by an observer at infinity.
• A singularity at the center of a black hole -- a point of infinite density, where the known laws of physics break down.
• Black holes can have only three measurable properties: mass, spin, and charge.
• Real black holes are unlikely to accumulate a significant charge, but spinning black holes (described by the Kerr metric) are highly likely.
• By definition, black holes emit no radiation, except for the probably tiny Hawking radiation due to a quantum process that converts some of their mass into radiation (splitting virtual particle-antiparticle pairs)
• They may be inferred from gravitational waves from double compact stars, binary systems with missing companion, X-ray emission from hot gas ($10^6$ K) in accretion disk
Origin of Stellar-mass Black Holes

• Still very uncertain, but generally expected from \( E=mc^2 \) and the attraction of the gravity.
• No neutron stars can be more massive than \( 3M_{\text{sun}} \). Indeed, the masses of neutron stars as measured in binaries are all consistent with this prediction.
• Thus for a star with a more massive core, one may expect them to collapse into a BH. The star, if single, must start off as a very massive star (\( > 10-20 \ M_{\text{sun}} \)).
• We do not know the exact mass limits for stellar mass black holes.
• For black holes in compact binaries:
  - They need to survive the supernova explosion.
  - Binary evolution involves mass exchanges which can produce unusual stars and change binary separations.
  - A common envelope stage can cause spiraling in of the buried star.
BH vs. Neutron Star

- No hard surface
  - Softer spectrum
- Smaller for BHs
  - Fast variability
- Greater GR effects
  - Last stable orbit
  - $R \sim 3r_s$
Mass Function

• Kepler's third law

\[ P^2 = \frac{4\pi^2a^3}{G(M_1+M_2)} \]
- the orbital period \( P \); binary separation \( a \); the total mass of the binary \( M_1 + M_2 \) (the "primary" + the "secondary")

• If the radial velocities of the secondary (for example) can be measured (single-lined spectroscopic binary), for a circular orbit, the observed velocity follows

\[ V_2 = V_0 + K_2 \sin\left(\frac{2\pi}{P} (\phi - \phi_0)\right) \]
- Where \( V_0 \) is the systemic radial velocity and \( \phi \) is the orbital phase
- \( K_2 = \sin i a 2\pi \frac{M_1}{(M_1+M_2)P} \) is the semi-amplitude of the secondary (true orbital velocity times \( \sin i \), where \( i \) is the binary inclination angle (0 if pole-on)).

• The mass function:

\[ f(M) = \frac{(M_1 \sin i)^3}{(M_1+M_2)^2} = \frac{P K_2^3}{2\pi G} \]
- The right side: only the measurable quantities.
- The left side: several unknown quantities, which may be estimated using other methods (e.g., star classification, eclipsing)
Black Hole Example: Cygnus X-1

- Large X-ray luminosity? \(\rightarrow\) an accreting compact object.
- No pulse or burst \(\rightarrow\) a black hole accretor with no hard surface and strongly misaligned B.
- "ultrasoft" X-ray spectral shape \(\rightarrow\) a lack of hard surface, which would contribute an additional hard X-ray component.
- Identified with an optical star, HDE 226868, in 1971:
  - presumably the mass donor of the compact object, undetected in visual light
  - a radial velocity variation with \(P=5.6\) days and \(K_2 \sim 50\) km s\(^{-1}\)
  - a blue supergiant expected to have \(M_2 \sim 30\) M\(_{\odot}\) if normal(?)
  - Then the unseen compact object probably has a mass of 15 M\(_{\odot}\)

Therefore Cyg X-1 contains a stellar-mass black hole.
Soft X-ray Transients

• Also known as X-ray Novae - a class of X-ray binaries:
  - Typically brighten by many orders of magnitude quickly
  - Then decay exponentially over the next several months.
  - Probably experience such outbursts once every few decades.
• In quiescence, the mass-donor can be studied in detail
• Typical orbital period of 5-20 hrs
• Often low mass main sequence stars.
• Seven so far seen to have $K_2$ of $\sim 500 \text{ km s}^{-1} \Rightarrow$ a mass function $> 3 \, M_{\odot}$: they must contain a black hole primary, regardless of what the secondary is - i.e., dynamically confirmed.
• A higher fraction of soft X-ray transients appear to contain a black hole than X-ray binaries in general.
Other evidence for black holes

- Evidence for frame dragging?
  - A rotating (Kerr) black hole causes precession of orbit around it.
  - Certain properties of Quasi-Periodic Oscillations (QPOs) seen in a black hole transient can be explained by such frame dragging.

- Evidence for event horizon?
  - At low accretion rate, infalling gas may form an Advection Dominated Accretion Flow (ADAF), which is very inefficient at radiating the thermal energy and carries the heat with it.
  - This may explain the low X-ray luminosity of SXTs in quiescence and of Sgr A*.
Micro-Quasar GRS1915

- Radio images show one plasma bubble coming almost directly toward us at 90 percent the speed of light, and another moving away. Each of the four frames marks the passage of one day.
Light Bending

A simulated view of the constellation Orion with a black hole in front.

Because of bending of light, the event horizon will cast a large shadow with an apparent diameter of ~ 5 Schwarzschild radii; next generation radio VLBI may be able to see this for Sgr A*.

Robert Nemiroff (MTU)
Our Galactic Center

• more than 5000 km/s at a mere 17 light hours distance (S2) -- about 3x the size of our solar system -- through the periastron.

• $3.7 \pm 1.5$ million solar masses within this distance.

• Not possible to explain this mass with a neutrino ball model because the required neutrino masses would be too large, or with a dense cluster of dark objects because it would have the lifetime of at most a few $10^5$ years.

MPE: www.mpe.mpg.de/www_ir/GC/gc.html
Sagittarius A*

• A compact radio source
• believed to be at the dynamical center of our Galaxy
• consistent with a super-massive black hole (SMBH) accreting at a modest rate
• proper motions (projected motion on the plane of the sky) of stars within a light year of Sgr A*.
• an unusually weak X-ray source