Physics 521 - Astrophysics

Topics today: Supermassive Black Holes, Compact Binaries & Accretion

This week’s reading: Chapters 17 & 18
Peer Review - Due Today Thursday, Nov 1

Homework #5 - Due Thursday, Nov 8, in class
Supermassive BH

Topics covered in last lecture:

- death of massive stars
- formation of compact objects
- neutron stars and stellar mass black holes
Supermassive BHs

- QSOs were first observed in the 1960s and are found in the cores of massive galaxies.

- Their emission is powered by disk accretion. In accreting state SMBHs are referred to as **AGN** or **Quasars**.

Chandra X-ray image of Quasar PKS 1127-145 (NASA)
SMBH Formation

- Several theories exist on how SMBHs could be formed:
  - ‘Lumps’ in early Universe
  - ‘Stellar BH seeds’
  - Collapse of star clusters
Early-Universe ‘Lumps’

- Shortly after the **Big Bang** the Universe might have been **dense enough** for matter to form BHs.
- These seeds subsequently grow.
- **Enough matter** present for **galaxies** to grow around seeds.
‘Stellar BH Seeds’

- A SMBH could form from a stellar mass black hole of \(~10\) solar masses, which was produced by a supernova.

- This requires the surrounding environment to be sufficiently rich in matter.
Star Cluster Collapse

- If stars within a **tight** cluster were of similar size (above the Chandrasekhar limit), BH would form simultaneously.

- These BHs would absorb smaller stars and eventually combine to a SMBH.
Jet Formation

- Quasars show giant jets at multiple wavelengths.
- Particles from the disc fall towards the SMBH and are propelled outwards by the magnetic field.
- The particles move at almost the speed of light and emit synchrotron radiation.
Cannibalism

- Quasars are only active for ~100 million years, but ‘dead’ **quasars** could be revived with a **new food source**, i.e. by colliding with another galaxy.

- We observe colliding spiral galaxies. Milky Way and Andromeda have the same fate.
Our view of the galactic centre is obscured by a lot of dust/gas.

Sgr A* is a compact/bright radio source at the Milky Way’s centre.

The emission is likely coming from close to a SMBH.
Our Galactic Centre

- **Estimate the mass** of our SMBH by following paths of surrounding stars and using Kepler’s law.
- **Provides indirect evidence** for a ~3 million solar mass black hole.
- **We are waiting for a direct image** from the Event Horizon Telescope.

13 year time lapse of stars around Sgr A* (ESO)
Our Galactic Centre

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Compact Binaries
Close Binaries

- A large fraction of stars are not isolated but systems of multiple objects. The majority are far apart and do not influence each other.

- If two stars in a binary are close enough, orbital and rotational energy is dissipated by tidal interactions until the system rotates rigidly (same sides keep facing each other).
Corotating Coordinates

- Consider a **corotating coordinate system** following the stars about their centre of mass.

- In the **rotating frame**, both stars are at rest and the **gravitational attraction** is balanced by a **centrifugal force**.
Gravity in Close Binaries

- The **effective potential energy** for a small **test mass** $m$, located in the orbital plane is

$$U = -G \left( \frac{M_1 m}{s_1} + \frac{M_2 m}{s_2} \right) - \frac{1}{2} m \omega^2 r^2.$$ 

- Corresponding effective gravitational **potential**: 

$$\Phi = -G \left( \frac{M_1}{s_1} + \frac{M_2}{s_2} \right) - \frac{1}{2} \omega^2 r^2.$$
Lagrange Points

- Use the *geometry* to determine $\Phi$ at any point in the orbital plane. Force on $m$ in x-direction is

$$F_x = -\frac{dU}{dx} = -m \frac{d\Phi}{dx}$$

- At the **Lagrange points** $L_1$, $L_2$ and $L_3$, the force on $m$ vanishes. Points are **unstable** equilibria.
Equipotential Surfaces

- Plot points in space that have the same $\Phi$ values (equipotential surfaces).

- Expanding stars fill regions of successively larger $\Phi$.

- Region through $L_1$ is called Roche lobe. Mass transfer in binaries occurs at $L_1$. 
Binary Classification

- **Appearance** of a binary depends on which equipotential surfaces are filled.
Accretion Disks

- **Orbital motion** keeps matter from falling directly onto star but leads to formation of a **thin disk**.

- **Viscosity** (internal friction in the gas) converts kinetic energy (*somehow*) into thermal radiation, leading to **energy loss**. Gas **spirals** slowly towards the primary.
Disk Luminosity I

• An optically thick disk emits like a black body of local temperature $T$ at each radial distance $r$.

• Neglect radial inward motion (and thus viscous disk processes) and assume that disk mass is much smaller than primary’s mass.

• Orbiting gas of mass $m$ has total energy (from Virial theorem):

$$E = -G \frac{M_1 m}{2r}.$$
Disk Luminosity II

- As the gas spirals inward it loses energy, which causes $T$ and powers its black body radiation.

- Consider a **ring** of mass $m$.

- In the **steady state** no mass builds up in the ring, so that a mass $t \cdot dM/dt$ has to pass it.
Disk Luminosity III

- **Energy conservation** dictates that radiated energy is equal to energy passing through ring:

\[ dE = \frac{dE}{dr} \, dr = \frac{d}{dr} \left( -G \frac{M_1 m}{2r} \right) \, dr = G \frac{M_1 \dot{M} t}{2r^2} \, dr, \]

- The corresponding **luminosity** of the ring is

\[ dL_{\text{ring}} = dE = G \frac{M_1 \dot{M} t}{2r^2} \, dr. \]
The surface area of the ring (considering top and bottom) is

\[ A = 2(2\pi r \, dr) \]

Using the Stefan-Boltzmann law gives

\[ dL_{\text{ring}} = 4\pi r \sigma T^4 \, dr = G \frac{M_1 \dot{M}}{2r^2} \, dr \]

\( \sigma \) is the Stefan-Boltzmann constant.
• Solving for the **disk temperature** $T$ gives

$$T = \left( \frac{G M \dot{M}}{8\pi \sigma R^3} \right)^{1/4} \left( \frac{R}{r} \right)^{3/4}$$

$M, R$ are mass and radius of the primary star.

• **Integrating** the equation from $r=R$ to $r=\infty$ gives finally for the **accretion disk luminosity**

$$L_{\text{disk}} = G \frac{M \dot{M}}{2R}$$

$d\dot{M}/dt$ is mass accretion rate due to the secondary.
Disk Luminosity VI

- In absence of a disk, the accretion luminosity (rate at which kinetic energy is given to star) is

\[ L_{\text{acc}} = G \frac{M \dot{M}}{R} \]

- Half of the available energy budget is radiated by the disk, the other half will be deposited on the surface of the star (or in boundary layer).

Used to calculate Eddington luminosity.
Observational Evidence

- Light curves from **eclipsing, semi-detached binaries** provide evidence that picture is correct.
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![Diagram of a binary system with labels for the secondary star, mass stream, primary star, accretion disk, hot spot, and orbit of the secondary about the center of mass. The diagram shows asymmetry providing evidence for a hot spot.](image)

![Graph showing normalized intensity vs. phase with a clear dip at LX Ser.](image)

**Asymmetry provides evidence for a hot spot.**
Different Kinds of Binaries

- Close binaries can evolve in very different ways depending on masses and separation forming e.g.
  - Cataclysmic variables (CVs)
  - X-ray binaries
  - Double (merging) compact binaries
Cataclysmic Variables I

CVs are systems with short orbital periods (typically hours) where a **White Dwarf** (primary) is combined with a cool **normal star** (secondary).

- The **donor star** fills its Roche lobe and mass is transferred to WD via accretion disk.
Cataclysmic Variables II

- CVs show **irregular outbursts** alternating with quiescent states. Bursts are bright enough to be seen by eye - alternative name: **classical novae**.

- Outbursts occur when density/temperature of material accumulating on the WD surface exceeds the **threshold** for **hydrogen fusion** reactions.
Cataclysmic Variables III

- Once burning layer is ejected and **fuel gone**, WD can cool. The whole process eventually restarts.

Nova Cygni 1975 (AAVSO)
Type-Ia Supernovae I

- If accretion lasts long enough to bring WD to the Chandrasekhar limit, runaway carbon fusion can be ignited, triggering a type-Ia supernova.

- Due to the characteristic mass limit, the explosion mechanism is very uniform, leading to very similar peak luminosities.
Type-Ia Supernovae II

- Due to stability, type-Ia supernovae are used as **standard candles** to measure distances to host galaxies (luminosity mainly depends on distance).

Kim et al. (1997)
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Kim et al. (1997)
X-ray Binaries

- If one of the binary stars is sufficiently massive to explode in core-collapse SN, a NS or BH forms.
- If the system survives the explosion, the compact object accretes matter from its companion.
- Deep gravitational potential causes strong gas acceleration and strong X-ray emission.
Scorpius X-1

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- It was the first extrasolar source detected.

- Radio pulsations are very weak.

The sun is the brightest X-ray source.
Low-Mass X-ray Binaries I

- Donor is **less massive** than the compact object.
- Compact object accretes from its companion via **disk accretion**, causing strong X-ray but little optical emission.

LMXBs are very compact with short orbital periods.

Low-Mass X-ray Binaries II

- LMXBs formation involves an **asymmetric SN**.

Millisecond Pulsars

- MSPs have periods between 1-10ms (located in the lower left of P-Pdot diagram).
- MSPs are old and recycled objects, spun up by accreting matter (angular momentum) from a companion (in LMXB).
High-Mass X-ray Binaries I

- Donor is a very massive star, usually easily detected in the optical.
- Compact object accretes matter from the stellar wind of its companion, causing X-ray emission.

Cyg X-1 is a HMXB.

High-Mass X-ray Binaries II

- HMXBs from two massive stars, leading to \(2\) SN.

Double NS Binaries

- Double NS systems are highly relativistic systems, making them **excellent laboratories** to test GR.

- Hulse-Taylor pulsar (PSR B1913+16) provided first **indirect** detection of GWs.

Weisberg & Taylor (2004)
GW Detection

- First **direct detection** from two merging NSs was made last year by LIGO - GW170817.
- Source was localised due to counterparts in γ-ray, X-ray, radio, optical and IR.
- **Multi-messenger** astronomy!!

Abbott et al. (2017)