ACCRETION POWER IN ASTROPHYSICS

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ac·cre·tion \a-ˈkrē-shən\: noun

the process of growth or enlargement typically by the gradual accumulation of additional layers or matter
ACCRETION

• **Accretion**: process by which an object gains/accumulates mass

• Extremely important process throughout the Universe from young stars to supermassive black holes at the centers of galaxies

• Understanding how accretion works is vital in our understanding of the Universe
A SOURCE OF ENERGY

• Extraction of gravitational potential energy as material accretes onto a massive object
  ➡ gravitational potential energy converted to radiation through (magneto-hydrodynamical) friction

• Due to conservation of angular momentum, accreting material usually forms a rotating thin disk
MORE EFFICIENT THAN FUSION!

• Nuclear fusion, which powers stars, is less than 1% efficient for $H \rightarrow He$:

$$E_{\text{nucl}} = 0.007 \text{ mc}^2$$

• Energy from accretion is given by:

$$E_{\text{acc}} = \frac{GMm}{R}$$

• For compact objects (neutron star or black hole) accretion is greater than 20 times more efficient than fusion!
MAXIMUM ACCRETION RATE

• As $E_{\text{acc}} = \frac{GMm}{R}$ the more massive an object and the smaller it is, the greater the energy released through accretion.

• But, there is a limit to how much energy is radiated away, the **Eddington Limit**: inward gravitational force on matter must be greater than the outward radiation pressure otherwise it would blow itself apart.

Einstein & Eddington at the University of Cambridge
COMPACT OBJECTS

• Accretion most powerful onto compact objects

• **Black hole**: a massive object whose gravitational force is so strong that not even light can escape

• **Neutron star**: a star about 1.5 times the mass of the Sun, but with a radius of only \(~10\) km - a star the size of a city!

Light near a black hole gets bent by the strong gravity there.
BLACK HOLES

Come in several ‘flavors’:

- **stellar-mass black holes**
  \( \sim 10 \, M_{\text{sun}} \)
  - formed in supernovae

- **supermassive black holes**
  \( 10^6 \text{ - } 10^9 \, M_{\text{sun}} \)
  - found at the centers of galaxies

Stars orbiting around the black hole at the center of the Milky Way
QUASARS

• aka ‘Active Galactic Nuclei’

• Light from the central region outshines the entire galaxy!

• Only way to power is by accretion of gas onto a black hole

• Using the ‘Eddington Limit’ can estimate that black holes at the centers of galaxies must be typically between $10^6 - 10^9 \ M_{\text{Sun}}$

A nearby Active Galactic Nucleus shoots a high-speed jet of gas
POWERED BY WHAT?

• Nuclear fusion?  
  No

• Dense star cluster?  
  No

• Accretion onto a massive black hole?  
  Yes

Rees (1984)

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**Diagram:**

- GAS CLOUD → star formation → DENSE STAR CLUSTER → stellar coalescence → CLUSTER OF \( \geq 100 M_\odot \) STARS
  - supernovae
  - CLUSTER OF NEUTRON STARS OR STELLAR-MASS BLACK HOLES
  - N-body evolution
  - TIGHTLY-BOUND SYSTEM OF FEW BODIES
    - contraction catalyzed by gas in system that radiates binding energy
    - RELATIVISTIC CLUSTER
      - relativistic instability or gravitational radiation

- SUPERMASSIVE STAR
  - contraction
  - collisional disruption of stars
  - new stars form
  - nuclear explosion
  - post-Newtonian instability
  - black-hole binary
    - \( \geq 3 \) massive black holes
      - slingshot ejection

- contraction and/or accretion
  - collapse and/or accretion
  - nuclear explosion
  - bar-mode instability

- gas cloud
  - spiral together via gravitational radiation
BLACK HOLE - GALAXY CONNECTION

- BHs in the center of all major galaxies
- Do galaxies know about the BH at the center?
- How do they form?
- How does the evolution of one affect the other? (BH feedback)
- How are they fed and how do they grow?

Gultekin et al. (2009)
STELLAR-MASS BLACK HOLES

- Can be formed in a supernova explosion at the end of a massive star’s life
- Often found in binary systems
- Black hole can accrete matter from the companion star!

Matter can be pulled from the companion star to the black hole
NEUTRON STARS

- Also can be formed in supernovae
- About 1.5 $M_{\text{Sun}}$ in 10 km radius
- Average density greater than atomic nuclei
- Densest observable matter in Universe
- Made mostly of neutrons, but may contain exotic matter at the center

Where ? could be: hyperon condensate, kaon condensate, strange quark matter.........
NEUTRON STARS

• Like stellar-mass black holes, can often be found in binary systems

• Can also accrete matter from the companion star

Accretion onto a neutron star
HOW DO WE SEE ACCRETING BLACK HOLES/NEUTRON STARS?

Gas accreting onto black holes and neutron stars gets extremely hot (millions of degrees), so the gas therefore emits thermally in X-rays.
The X-ray Sky

An all-sky X-ray image: the brightest X-ray sources in the sky come from accretion onto black holes and neutron stars

From MAXI onboard the ISS
OBSERVING X-RAYS

Radio & Microwave | Infrared | Visible | UV | X-rays | Gamma Rays

SPACE-BASED

GROUND-BASED

How Light is Absorbed in Our Atmosphere
OBSERVING X-RAYS

Chandra

XMM-Newton
OBSERVING X-RAYS

- X-rays will pass through most materials
- So, how can you focus X-rays?
- Regular optical reflecting telescopes you may be familiar with won’t work!

Normal optical reflectors No good for X-rays
OBSERVING X-RAYS

THE CHANDRA MIRRORS

Field of View ±5 Deg

Focal Surface

10 meters

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter
• I use **X-ray observations** with major observatories such as Chandra, XMM, Suzaku and Swift to study the process of accretion in **X-ray binaries** (stellar-mass black holes and neutron stars) and **Active Galactic Nuclei** (AGN, supermassive black holes).
X-RAY REVERBERATION MAPPING

- Use echoes of light to ‘map’ the inner regions around supermassive black holes
- Analogy: sound echoes in a big cavern, Doppler tomography, sonar off the ocean floor
FIRST IRON LINE REVERBERATION

Zoghbi, Fabian, Reynolds & Cackett (2012)

NGC 4151

Lag (ks)

Energy (keV)

Red wing

Blue horn

long

short