Longair - High Energy Astrophysics

Summary Chapter 14

Accretion refers to the process by which diffuse gas or matter falls onto a gravitating object under the influence of gravity. The foundations of accretion theory were laid by Bondi, Hoyle, and Lyttleton, who studied how stars accrete material from the interstellar medium. Although these early studies predicted relatively low accretion rates, the subject gained renewed importance in the 1960s when it was realised that accretion onto compact objects—such as white dwarfs, neutron stars, and black holes—could explain some of the most energetic phenomena in the Universe. In particular, accretion provides a natural explanation for the enormous luminosities of X-ray binaries and active galactic nuclei.

The efficiency of accretion as an energy source depends primarily on how compact the accreting object is. As matter falls into a gravitational potential well, its gravitational potential energy is converted into kinetic energy and, ultimately, into heat and radiation. For a compact object of mass M and radius R, the luminosity produced by accretion is proportional to GMm'/R, where m' is the accretion rate. This means that objects with smaller radii release more energy per unit mass. Accretion onto white dwarfs is moderately efficient, but accretion onto neutron stars is significantly more efficient than nuclear fusion. In the case of black holes, the efficiency can be even higher, particularly if the black hole is rapidly rotating.

Unlike neutron stars, black holes do not possess a solid surface. Matter falling radially into a black hole would, in principle, disappear without releasing energy. In practice, however, infalling matter almost always possesses angular momentum. Conservation of angular momentum prevents direct infall and causes the material to settle into an accretion disc around the black hole. Energy is then released as matter spirals inward through the disc, losing angular momentum and gravitational energy before crossing the event horizon. The maximum energy that can be released depends on how close matter can orbit before becoming unstable, which in turn depends on whether the black hole is rotating. Rotating (Kerr) black holes can release a much larger fraction of the rest-mass energy of accreted matter than non-rotating ones.

Accretion is not unlimited. If the luminosity becomes too large, radiation pressure can oppose gravity and halt further inflow. This balance defines the Eddington luminosity, which depends only on the mass of the accreting object. The Eddington limit provides a natural upper bound on steady accretion and explains why observed X-ray sources and active galactic nuclei rarely exceed certain luminosities. It also explains why accreting neutron stars radiate primarily in X-rays, while accreting white dwarfs emit mainly in the ultraviolet.

Observational evidence strongly supports the role of accretion in both Galactic and extragalactic systems. In X-ray binaries, rapid variability on millisecond to second timescales indicates emission regions comparable in size to neutron stars or black holes. In active galactic nuclei, similar variability is observed on much longer timescales, consistent with accretion onto supermassive black holes. Independent mass estimates based on variability and dynamical measurements of surrounding gas clouds show good agreement, reinforcing the accretion paradigm.

Accretion discs play a central role in these systems. In most astrophysical situations, accretion proceeds through a disc rather than spherically. In a disc, matter moves in nearly Keplerian orbits and slowly drifts inward as it loses angular momentum. For the disc to remain thin, the orbital velocity must be much greater than the local sound speed, ensuring that pressure does not cause the disc to puff up vertically. This "thin disc" approximation works well for many accreting systems, especially at moderate accretion rates.

A crucial question in disc physics is how angular momentum is transported outward. Molecular viscosity is far too weak to explain observed accretion rates, implying that discs must be turbulent. This problem is usually addressed using the phenomenological α-prescription, in which the effective viscosity is assumed to be proportional to the product of the sound speed and the disc thickness. Although this approach does not identify the physical origin of viscosity, it allows analytic models of disc structure to be constructed and compared with observations.

A major breakthrough came with the discovery that weak magnetic fields in differentially rotating discs can give rise to the magnetorotational instability. This instability naturally generates turbulence and provides an efficient mechanism for angular momentum transport. As a result, magnetohydrodynamic turbulence is now widely accepted as the underlying driver of accretion in astrophysical discs.

In a steady thin disc, half of the gravitational energy of the accreted matter is radiated away within the disc itself, while the remaining energy is released very close to the compact object. For neutron stars and white dwarfs, this additional energy is dissipated in a boundary layer near the stellar surface. For black holes, the energy release terminates at the last stable orbit. The temperature of the disc increases toward the centre, leading to a characteristic radial temperature profile and a distinctive emission spectrum. Over a wide frequency range, the predicted spectrum follows a power law, which is broadly consistent with observations of accreting systems.

At high accretion rates, radiation pressure becomes important and the thin disc approximation can break down. The disc may inflate into a geometrically thick structure, leading to more complex flow patterns. In such cases, advective transport of energy becomes important. For black holes, this can result in significantly reduced luminosities, since energy carried inward by the flow may cross the event horizon without being radiated. These ideas are particularly relevant to low-luminosity active galactic nuclei and some states of black hole X-ray binaries.

Accretion in binary systems introduces additional richness. In close binaries, mass transfer often occurs when a star fills its Roche lobe and matter flows through the inner Lagrangian point onto a compact companion. This process efficiently feeds an accretion disc and powers cataclysmic variables, X-ray binaries, and related systems. In contrast, accretion from stellar winds is less efficient but still significant in binaries containing massive stars with strong outflows.

Magnetic fields can strongly influence accretion onto compact stars. In systems with strongly magnetised neutron stars or white dwarfs, the magnetic pressure can dominate close to the star and channel accreting matter along field lines onto the magnetic poles. This produces accretion columns and hot spots, leading to pulsed X-ray emission and rapid spin-up of the compact object. Observations of spin changes in X-ray pulsars provide direct evidence for accretion torques acting on neutron stars.

Accretion also plays a key role in explosive phenomena. In cataclysmic variables, unstable accretion can trigger dwarf nova outbursts, while thermonuclear runaways on the surfaces of white dwarfs lead to classical novae. Continued accretion may eventually push a white dwarf beyond the Chandrasekhar limit, resulting in a Type Ia supernova. In low-mass X-ray binaries, thermonuclear explosions on neutron star surfaces give rise to Type I X-ray bursts, whose properties closely match theoretical expectations.

Finally, accreting black holes in X-ray binaries display a wide range of spectral and timing behaviour. These systems transition between distinct states characterised by thermal disc emission, hard power-law spectra, and strong variability. Observations of quasi-periodic oscillations and relativistically broadened iron lines provide compelling evidence that matter is orbiting extremely close to black holes, allowing tests of gravity in the strong-field regime.