ACCRETION DISKS
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Accretion

By accretion one understands in astrophysics the accumulation of matter onto a heavy object, under the influence of its pull of gravity. The object can be, for example, a star, a black hole, or a neutron star. Most of the objects of these types are quite isolated, without much gas around that could be pulled in by their gravity. Accordingly, the vast majority of stars do not show any evidence of accretion, while most neutron stars and probably almost all black holes in our galaxy are unobservable for this reason.

While somewhat exotic compared with normal stars or galaxies, accretion disks attract attention because they are involved in a wide range of highly visible phenomena. These range from the formation of our planetary system and the rings of Saturn to the X-ray binaries in our galaxy and the collimated jets from protostars and accreting black holes.

The observable effects of accretion can range modest to quite dramatic. This depends on the amount of mass accreted per unit time, but even more on the *depth of the potential well* of the gravitational field of the accreter. The simplest model of accretion would be a free particle falling radially to the accreter from a large distance. If its starts from rest at infinity, it arrives at the surface R of an accreter of mass M with the *escape speed* $v_{\rm e} = (GM/R)^{1/2}$. We can also write this as $v_{\rm e}/c = (r_{\rm g}/2R)^{1/2}$, where $r_{\rm g} = 2GM/c^2 = 2.8M/M_\odot$km is the SCHWARZSCHILD RADIUS of the mass M. For a neutron star with $M = 1.4M_\odot$ and $R = 10$km, for example, the particle would arrive at the surface with some 30% of the speed of light. Accretion onto compact objects, in which M/R is large, is therefore accompanied by the release of large amounts of energy.

A free particle attracted to a compact object from a large distance has only a small chance of hitting it. If its initial motion is not directed very precisely to the object, it will just make an orbit around and return to the same large distance. In other words the cross section for accretion by free particles is small. The same effect plays a role when we consider the more realistic case of accretion of a gas, and is then called the 'angular momentum problem', discussed below.

The accreting gas might, for example, be provided by a protostellar cloud, in the case of a growing protostar, or by a companion star in a binary. If the accreting star is a neutron star or black hole, such a binary is called an X-RAY BINARY, if it is a white dwarf, the binary is called a CATACLYSMIC VARIABLE. Finally, accretion of some form of interstellar matter onto a massive black hole in the nucleus of a galaxy produces an ACTIVE GALACTIC NUCLEUS (AGN).

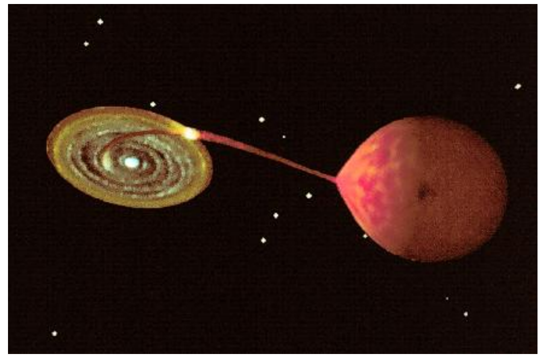

Figure 1: Artist's impression of a binary system consisting of a low-mass main sequence star (red) and a white dwarf. The main sequence star fills its Roche lobe and transfer mass to the white dwarf. Because of the orbital motion of the stars around each other, the mass transfering stream of gas is not directed straight to the white dwarf, and accumulates in an orbiting accretion disk. The impact of the stream on the disk edge causes a bright *hot spot*. (copyright Dana Berry and Keith Horne, Space Telescope Science Institute)

Fig 1 shows an artist's impression of an accretion disk fed by mass overflow from the secondary in a binary. Images like this can not be made with telescopes. Almost all disks are so small, as seen from earth, that their geometry can be inferred only by indirect means. Disks that can be observed directly are our planetary system, the rings of Saturn, and spiral galaxies. None of these, however, is typical for gaseous accretion disks. Our solar system is only the solid residue of an accretion disk that existed during its formation. In the case of Saturn's rings, the particles making up the rings also behave more like free particles than like a gas. The disks in spiral galaxies are much more complicated than gaseous disks. Also, galactic disks are not old enough to have accreted much onto the galactic core since their formation.

The best prospect for directly observing accretion disks is in protostars. They are the largest disks in angular diameter, as seen from earth, and with currently developing high-resolution infrared and mm-wave imaging detailed observations of their structure will be possible (see INFRARED ASTRONOMY). Large 'proplyds' (protoplanetary disks) have been imaged in the optical by the Hubble Space Telescope; examples are shown in xxx (proplyd) and xxx (HH30).

In the case of binary systems like Fig. 1, information on the size, thickness and temperature of the disk is provided by eclipses. If the binary is oriented such that the earth happens to be near its orbital plane, the

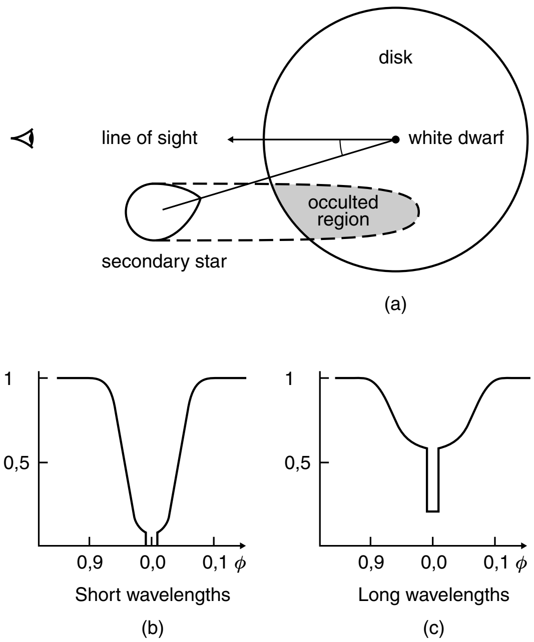

Figure 2: Light curve of an eclipsing binary with an accretion disk around the primary star. The accretion disk widens the eclipse of the primary star. Details of the light curve can be used to infer size and temperature of the disk. (figure modified after Frank, King and Raine, *Accretion power in Astrophysics*, CUP)

disk and the mass-providing secondary star eclipse each other regularly as the components orbit around each other. The shape of the light curve in different wavelengths can then be used to infer the properties of the disk, such as its size and temperature (Fig. 2, see also BINARIES).

Accretion temperatures

A characteristic temperature in accretion problems is the VIRIAL TEMPERATURE,

$$T_{\rm v} = -\Phi/\mathcal{R}, \tag{1}$$

where $\mathcal{R} = 8.314\,10^7$ erg $\rm g^{-1}K^{-1}mole^{-1}$ is the molar gas constant and Φ the depth of the potential well. At a distance r from a point mass in Newtonian gravity, $\Phi = -GM/r$. If all the kinetic energy gained by dropping into the potential well were dissipated into internal energy (heat), the gas would get a temperature of the order $T_{\rm v}$. For a neutron star, $T_{\rm v} \sim 2\,10^{12}$K, corresponding to a mean thermal energy per proton of the order 1GeV. The radiation actually observed from accreting systems indicates much lower temperatures. This is because a thermal plasma at this temperature radiates energy at an enormous rate, much higher than can be supplied by the infalling gas. Instead of $T_{\rm v}$, the gas settles at a lower temperature, such that the dissipated energy is roughly balanced by energy lost by radiation.

A second characteristic temperature is obtained by assuming that the radiation is emitted like a blackbody from the surface of the accreting object. Equating the luminosity $L = 4\pi r^2\sigma T^4$ of a black body of radius R and temperature $T_{\rm B}$ to the energy generated by accretion at a rate $\dot M$ (mass per unit time) yields

$$T_{\rm B} = \left(\frac{GM\dot M}{4\pi R^3\sigma}\right)^{1/4}, \tag{2}$$

where $\sigma = 5.6692\,10^{-5}$ erg $\rm cm^{-2}K^{-4}s^{-1}$ is the constant in Stefan-Boltzmann's law. Actual temperatures differ from this, since the emitted spectrum differs from a black body, the emitting surface is not equal to that of the accreting object, or, in the case of black holes, much of the accretion energy is swallowed by the hole rather than being radiated. Still, $T_{\rm B}$ often provides a good order of magnitude for the observed temperatures. The reason is that in these cases the accreting gas is OPTICALLY THICK, so that by repeated photon emission and absorption processes the accretion energy is reprocessed into something like a black body spectrum. For a cataclysmic variables, protostars and AGN, $T_{\rm B} \sim 10^4 - 10^5$K, for X-ray binaries around 10^7K, corresponding to photon energies of 1–10 eV and 1keV, respectively. Optically thin accretion processes can also occur however (see below under *two-temperature accretion*), producing photons of much higher energies.

Radiation pressure and the Eddington limit

The photons released by an accreting object exert a force on the accreting gas. By scattering (or by absorption and reemission) on an atom, ion or electron, the outward direction of the photon is changed into a more random direction. The outward momentum of the photons is thereby transferred to the gas: the radiation exerts an outward force. If $F = L/(4\pi r^2)$ is the radiative energy flux at distance r, and κ the opacity of the gas (scattering plus absorption), the acceleration due to this force is $g_{\rm rad} = F\kappa/c$. This force is just balanced by the inward acceleration of gravity $g = GM/r^2$ when the luminosity L has a value called the EDDINGTON LIMIT or Eddington luminosity:

$$L_{\rm E} = 4\pi GMc/\kappa. \tag{3}$$

A *steady* photon source, bound by gravity, can not have a luminosity significantly exceeding this limit. At a larger luminosity, the atmosphere of the source is blown off by radiation (this happens, for example in a NOVA EXPLOSION). The value of the Eddington luminosity depends on the opacity of the gas, and thereby on its state of ionization. It depends on the mass of the source but not its size. Close to the compact object in an X-ray binary the gas is nearly fully ionized, usually of normal stellar composition, and electron scattering the dominant radiation process, with opacity $\kappa \sim 0.3\mathrm{cm}^2/\mathrm{g}$. The Eddington limit is then

$$L_{\mathrm{E}} \approx 1.5\,10^{38} M/M_{\odot} \quad \mathrm{erg/s}. \tag{4}$$

For a neutron star of $1.4\mathrm{M}_{\odot}$, this is about 50 000 times the luminosity of the Sun.

If this luminosity is generated by accretion, equating it to the accretion energy defines the EDDINGTON ACCRETION RATE

$$\dot{M}_{\mathrm{E}} = 4\pi c R/\kappa, \tag{5}$$

or about $1.5\,10^{-8}\mathrm{M}_{\odot}/\mathrm{yr}$ for a neutron star of 10 km radius. A neutron star can not accrete much more than this. The radiation pressure building up would prevent further accretion, and the gas would accumulate in an extended atmosphere around the star instead of settling onto the neutron star surface. (This assumes that radiation is only by photons; at sufficiently high temperature and density energy losses by neutrinos become important, see THORNE-ZYTKOW STARS). The accretion rate onto a black hole can be much higher than $\dot{M}_{\mathrm{E}}$. An atmosphere surrounding a hole is not supported at its base, but flows in through the horizon. In the process it takes with it the photons trapped in the gas. Depending on the density of such an atmosphere, the accretion rate can be arbitrarily high. The luminosity as seen from earth does not become much bigger than L_{E}, however.

Disks

Mass transfer in a binary

As an example for the formation of an accretion disk, consider a binary in which one of the stars is large enough to fill its Roche lobe (see CLOSE BINARIES), the other a compact star (white dwarf, neutron star or black hole). The Roche lobe-filling star is called the secondary, since it is the less massive star in such binaries (see CATACLYSMIC VARIABLES). Mass flows off the secondary at the inner Lagrange point L_1. The orbit of a hypothetical free particle from this point is shown in Fig. 4. Except directly at L_1, the orbital velocity is very high compared with the sound speed of the gas. Consequently, its path is almost ballistic, i.e. close to that of a free particle. Since gas clouds can not flow through each other, however, the ballistic flow ceases at the first intersection point of the orbit. The supersonic relative motion of the two parts of the gas stream is dissipated here through shock waves, heating the gas and deflecting the stream.

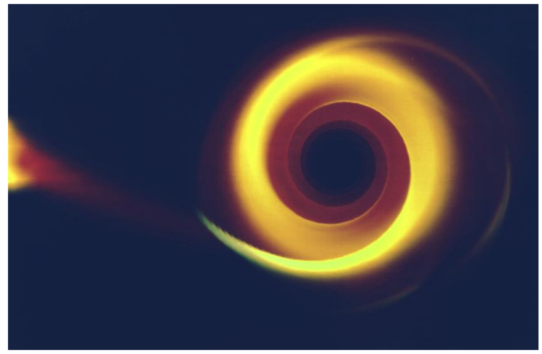

Figure 3: Hydrodynamic simulation of mass transfer in a binary, showing the accumulation of gas in a ring. An additional viscous process has to be added to make the gas accrete onto the primary star (at the center of the ring). Color indicates temperature (red is cool, green is hot).

The further evolution of the stream depends on additional physics such as the rate at which the gas can cool. An example of what the stream might look like after a few orbital periods of the binary is shown in Fig. 3. The orbiting gas has accumulated into a ring; newly arriving gas is incorporated into the ring through a system of shock waves. The strongly non-circular motion of the gas has settled into a more quiet circular orbit; most of the energy dissipated in the process has been radiated away. Leaving aside perturbations by the impacting stream, and in the absence of viscous forces, the gas can orbit indefinitely on such circular orbits.

The 'angular momentum problem'

In the process of settling onto a circular orbit, a great deal of energy is dissipated, but the angular momentum of the gas around the primary has not changed (neglecting corrections due to the gravitational pull of the secondary). Since a circular orbit has the lowest energy for a given angular momentum, the gas can only sink further into the gravitational potential, and accrete onto the primary, if it can lose some angular momentum. Finding the process by which this is done in real systems is called the *angular momentum problem.* We have illustrated it here with the example of mass transfer in a binary, but the same problem arises for the formation of stars from interstellar clouds, or the accretion of gas onto the massive black holes in AGN. In these cases, the initial angular momentum due to random motion of the gas clouds is many orders of magnitude larger than can be accomodated by the accreting object. Rather than accreting directly, the gas forms a disk, acting like a temporary 'parking orbit'. The orientation of the disk is given by the direction of the total angular momentum vector of the clouds, while the time it takes the gas

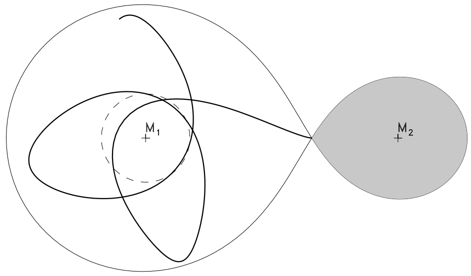

Figure 4: Binary showing Roche lobes, the lobe-filling secondary star (M_2, hatched), and the orbit of a particle released from the inner Lagrange point. The 'rosette'-shape of the orbits around the primary (M_1) is caused by the orbital motion of the binary.

to spiral in through the disk depends on the processes solving the angular momentum problem.

Viscous disks

In many cases (DWARF NOVAE and X-RAY TRANSIENTS) the accretion onto the compact object is episodic, in the form of outbursts. The decay of such an outburst gives some information on the accretion time, that is, the time it takes the gas to spiral in from the secondary star to the accreting primary. For dwarf novae, for example, this time is a few days, showing that the angular momentum transport process allows accretion in a few days or less of the mass that is involved in producing the outburst. Though actual numbers are model-dependent, these observations indicate angular momentum transport 12-15 orders of magnitude more efficient than expected from the natural viscosity of the gas. The process responsible for the angular momentum transport in disks is not known with certainty. In view of this uncertainty, the theory of accretion disks makes an arbitary assumption about the angular momentum transport process. It is assumed that the disk behaves, in effect, like a fluid with a very high viscosity.

Such an enhanced viscosity does indeed solve the angular momentum problem. As a thought experiment, start with a ring of gas orbiting at some distance from the source of the gravitational potential. Viscous stress between neighboring orbits rotating at slightly different velocity makes the ring spread both outward and inward, forming a disk. This spreading has a remarkable property: if sufficient time is available, almost all the mass accretes onto the central object. A small amount of mass in the the outer parts of the disk expands indefinitely, carrying away almost all the angular momentum of the original ring. The time for spreading to a given distance is inversely proportional to the viscosity.

A characteristic velocity in the disk is the isothermal sound speed $c_\mathrm{s} = (\mathcal{R}T)^{1/2}$, where T is the temperature at the midplane of the disk (the surfaces are cooler). A characteristic frequency is the orbital frequency Ω. The unknown disk viscosity ν can then be measured in terms of a dimensionless viscosity α, defined by

$$\nu = \alpha c_\mathrm{s}^2/\Omega. \tag{6}$$

Where observational indications, such as the decay time of an outburst are available, they indicate viscosities in the range $\alpha = 10^{-3}$–1. Such values are then used when making theoretical estimates of the structure of accretion disks. The assumption that the angular momentum transport processes can be represented by (6), with α something of order unity, is called the α-viscosity assumption.

Thin disks

Accretion disks tend to be cool because the accretion times are long and sufficient time is available to radiate away the dissipated gravitational energy. If they are cool, the effects of gas pressure are small. To see this consider the equation of motion for an ideal gas in a gravitational potential of a point mass M, $\Phi = -GM/r$:

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla p - \nabla\Phi, \tag{7}$$

where $\mathbf{v}$ is the velocity, ρ the mass density and p the gas pressure. At a distance r_0, a characteristic time scale t_0 is the inverse of the Kepler frequency, $t_0 = \Omega^{-1} = (r_0^3/GM)^{1/2}$. Introducing dimensionless quantities $t' = t/t_0$, $r' = r/r_0$, $\nabla' = r_0\nabla$, $\mathbf{v}' = \mathbf{v}/(\Omega r_0)$, the equation of motion for an isothermal gas of temperature T becomes

$$\frac{\mathrm{d}\mathbf{v}'}{\mathrm{d}t'} = -\frac{T}{T_\mathrm{v}}\nabla' \ln p - \frac{\hat{\mathbf{r}}}{r'^2}, \tag{8}$$

where $\hat{\mathbf{r}}$ is a unit vector in the radial direction and T_v the virial temperature introduced above. For processes taking place on a length scale r_0 and time scale t_0 the terms in this equation are of order unity, except the pressure term which involves the factor T/T_v. T/T_v is of order unity if all the dissipated energy stays in the gas, but when cooling is effective, it can be very small. The pressure term is then small, and the gas flows ballistically in the potential Φ.

A disk with $T/T_\mathrm{v} \ll 1$ rotates approximately on circular Kepler orbits. The orbital motion is supersonic, with Mach number $\mathcal{M} = \Omega r/c_\mathrm{s} \sim (T_\mathrm{v}/T)^{1/2}$. The thickness of the disk is found by considering the vertical distribution of gas at some distance r_0, assuming it to be in hydrostatic equilibrium in a frame rotating with the Keplerian rate $\Omega(r_0)$. An isothermal gas is then distributed with height z above the orbital plane as $\rho \sim \exp(-\frac{1}{2}(z/H)^2)$, where H is the scale height, $H = r_0(T/T_\mathrm{v})^{1/2} = c_\mathrm{s}/\Omega$. If radiative losses are small, the disk is hot, and the *aspect ratio* H/r_0 is of order unity. Efficiently radiating disks on the other hand are cool and geometrically thin, $H/r \ll 1$.

Under the assumption $H/r \ll 1$ the hydrodynamic equations for an axisymmetric, plane, viscous disk are simple. To lowest order, the radial equation of motion reduces to $v_\phi = \Omega r$. The azimuthal equation of motion can be combined with the continuity equation into a single equation governing the surface density $\Sigma = \int_{-\infty}^{\infty} \rho \mathrm{d}z$:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}[(r^{1/2}\frac{\partial}{\partial r}(\nu \Sigma r^{1/2})]. \quad (9)$$

As expected, this equation is of the diffusion type. It shows that, for a cool disk, all physical factors influencing the evolution of the disk enter only through the viscosity ν. This viscosity, of course, also contains most of the assumptions about unknown processes. Usually, additional equations are needed to determine how radiative cooling affects the temperature structure of the disk, on which ν depends.

For steady accretion, and not too close to the central object, the accretion rate is related to the viscosity by

$$\dot{M} \approx 3\pi\nu\Sigma. \quad (10)$$

A high viscosity implies a low surface density, since the accreting mass spends little time in the disk. The characteristic time t_a for gas orbiting at a distance r to accrete is the viscous time scale,

$$t_\mathrm{a} = r^2/\nu \approx \frac{r^2}{H^2}\frac{1}{\alpha\Omega}. \quad (11)$$

For cool disks, this is long compared with the orbital time scale. On the other hand, a long time scale implies that there is plenty of time for the disk to cool by radiation, so there is a certain circularity in the mechanism that fixes the disk temperature. In a given situation (central mass, distance), the disk temperature is determined by the mass accretion rate and the dominant cooling process. In some cases, disks can exist in either of two stable steadily accreting states, a cool one with long accretion times and a hot one with short accretion times. In other cases, disk models are found to be unstable for certain mass transfer rates, oscillating between states of high and low accretion. The details of the cooling processes determine when such multiple accretion states exist (see *two-temperature accretion* below).

Disk instabilities

The vertical structure of a disk is determined by the need to transport the viscously dissipated energy to the radiating surfaces. For a given surface density Σ, this structure determines the temperature and viscosity of the disk. In conditions where the energy transport process changes rapidly with temperature, the viscous stress $\nu\Sigma$ can depend non-monotically on the surface mass density, in the form of an 'S-curve', as illustrated in Fig. 5. If the mean accretion rate which is imposed (for example, by the mass transfering secondary star) lies in the range where Σ decreases with increasing $\nu\Sigma$ (cf. eq. 10), the disk is unstable. Instead of accreting steadily, it executes a limit cycle alternating between states of high and low accretion. Usually, conditions like in Fig. 5 occur only in limited regions of the disk, for example in the region of partial ionization of Hydrogen. If this region contains enough mass, however, the limit cycle will affect the entire disk. This is believed to be the cause of the dwarf nova outbursts in Cataclysmic Variables.

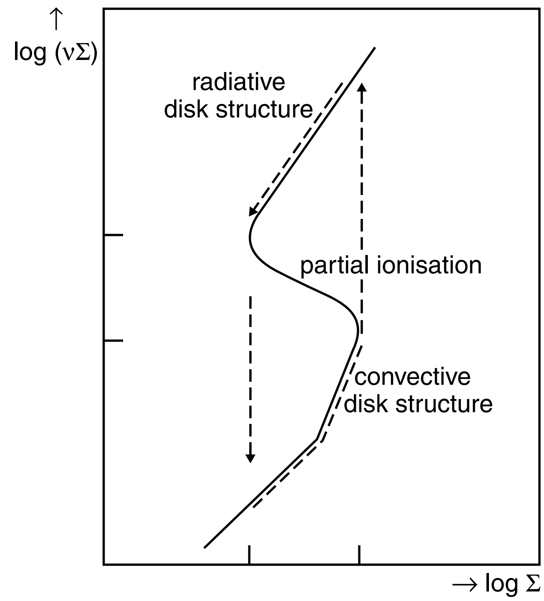

Figure 5: Dependence of the viscous stress $\nu\Sigma$ on surface mass density Σ in a disk where Hydrogen is partially ionized. If the mean accretion rate requires a viscous stress in the range where the slope of the curve is negative, this part of the disk is unstable and executes a limit cycle as sketched by the arrows

Angular momentum transport processes

Historically, the idea that some form of hydrodynamic turbulence exists in disks has played a significant role. It was part already of the ideas of Kant and of Laplace, who proposed that the solar system was formed from an initially gaseous disk-like cloud. If ν_m is the microscopic viscosity of the gas, the Reynolds number $r^2\Omega/\nu_\mathrm{m}$ in an accretion disk is very large, a situation called 'fiercely turbulent' in fluid mechanics (where high

Reynolds numbers and turbulence are considered equivalent). The assumption is that the shear flow in a disk would be unstable and develop into turbulence, as in laboratory shear flows. This has been questioned in the astrophysical community, on account of the fact that the flow in a cool disk is close to Kepler orbits, which are very stable. At the time of this writing, the issue is still controversial, but it seems quite possible that a Keplerian gas flow does not, in fact, produce hydrodynamic turbulence. A closely analogous case is the so-called rotating Couette flow, which has been found to be turbulent in laboratory experiments. The instability appears to be closely associated with the solid boundaries of the experimental container, however. Attempts to demonstrate turbulence for the astrophysical case of an accretion disk where such boundaries are absent, have been inconclusive so far.

Among the processes known to work are *spiral shock waves*. In a large disk (in the sense that the outer radius is much larger than the inner radius), a small compressive perturbation propagating inward steepens into a weak shock wave. Dissipation in the shock damps the wave, but since it also propagates into a flow of increasing velocity, the interaction between wave and mean flow though the shock increases its amplitude. In the absence of other processes damping the wave, a shock of finite strength develops by the balance between shock dissipation and energy extraction from the mean flow. The process produces a modest amount of angular momentum transport, corresponding to $\alpha = 0.01(H/r)^{3/2}$. For protostellar disks, this is in the range of the values inferred from observations, but it is too low for Cataclysmic Variables and X-ray binaries.

If the disk is massive enough that self-gravity is important, angular momentum transport by gravitational instability is possible. The intrinsic growth rate of a gravitational instability is of the order $(2\pi G\rho)^{1/2}$. If this is larger than the shear rate $\sim \Omega$, instability can grow in a disk; if it is smaller, a prospective perturbation is sheared apart before it can grow. In terms of a characteristic disk mass $M_{\rm d} = 2\pi r^2 \rho H$, this condition can be written as $M_{\rm d} > MH/r$. Such disks are called self-gravitating. Self-gravity is more important in cool disks, with small aspect ratio H/r. With the viscosities assumed, the masses of disks in observed systems can be estimated. For X-ray binaries and cataclysmic variables they turn out to be quite small, less than $10^{-8}\mathrm{M}_\odot$, and self-gravity is unimportant.

In the outer parts of disks in AGN, and in particular in protostellar disks, on the other hand, self gravity can be important (see YOUNG STELLAR OBJECTS). In this case, consider a disk cooling by radiation so that H/r decreases with time. As the threshold for instability is reached, non-axisymmetric irregularities with length scales of the order H are formed, which exert forces on each other. The shear flow acting on these forces dissipates energy, which in turn heats the disk. A balance is reached at a temperature just above the threshold for gravitational instability, and angular momentum is transported by the gravitational and pressure forces between the perturbations. This process is likely to be important in young protostellar disks, with inferred masses of the order of a few per cent of a solar mass (see STAR FORMATION).

The currently favorite process for non-self--gravitating disks relies on the fact that most disks are partially or fully ionized, hence support magnetic fields (see MAGNETOHYDRODYNAMICS). The possibility that the actual angular momentum transport in disks is done by some form of small scale magnetic field was already proposed by Shakura and Sunyaev together with their introduction of the α-viscosity assumption. It can be shown that an initially weak magnetic field in an accretion disk is unstable, its energy density growing by extracting energy from the shear flow. The mathematics of the process was computed around 1960 by Velikhov and by Chandrasekhar, its physical interpretation given by Fricke in 1972, and its importance for accretion disks finally realized by Balbus and Hawley in 1992. Numerous 3-dimensional numerical simulations since then have shown how this instability gives rise to the magnetic turbulence postulated earlier. For sufficiently ionized disks the process yields an effective viscosity $\alpha \sim 0.1$. It is a small scale magnetic field, with length scales in the radial direction of the order of the disk thickness H, and appears to behave roughly as expected from a viscous process. The magnetic field appears to break the dynamic constraints that prevent a Keplerian flow to become turbulent by purely hydrodynamic means. In some respects the process resembles the hydrodynamic turbulence proposed earlier, but differs in important aspects as well. The angular momentum transport, for example, is dominated by the magnetic (Maxwell) stresses rather than by fluid motions.

Planets inside disks

Planets grow from a protostellar disk at the same time as the star is formed (see SOLAR SYSTEM: FORMATION). A planet like Jupiter is massive enough to significantly affect the dynamics of this disk. By its tidal effect it clears a gap, a region of low gas density around its orbit, as shown in Fig. 6. The tidal force excites waves in the disk which propagate away from the planet. Through the tidal forces, the planet attracts gas from the sides of the gap which accretes onto it in the form of two streams. On the other hand, the disk also exerts a gravitational torque on the planet. By this force, the planet's angular momentum changes. It moves to a different orbit, usually closer to the star. The planets in our solar system are therefore probably not at the distances where their formation started. An extreme example of

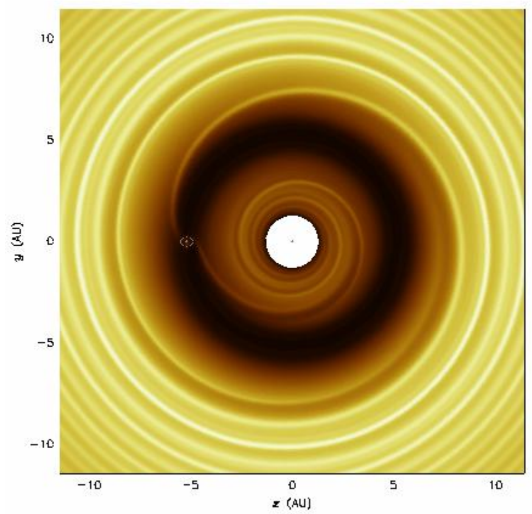

Figure 6: Numerical simulation of a growing gaseous planet inside the protoplanetary disk. The planet has cleared a gap in the disk, and accretes gas from the sides of this gap. W. Kley, Institute for Theoretical Physics, University of Jena.

this 'drifting planet' process may be the massive planets observed in very tight orbits around some nearby stars (see EXTRASOLAR PLANETS).

Radiation processes, two-temperature accretion

The radiation produced by a disk depends on its optical thickness τ. The energy released in the disk by viscous dissipation, per unit surface area and time, at a distance r from the central mass M is approximately $W = \frac{1}{2}GM\dot{M}/r^3$, i.e. half the gravitational energy. (The remaining half stays in the disk in the form of orbital motion.) This heat diffuses out by radiation. If τ (more precisely, the optical thickness for absorption processes, see ELECTRON-PHOTON INTERACTIONS) is large, the radiation emitted at the surface is roughly a black-body spectrum. This yields the approximate surface temperature $T_{\rm s}$ of a cool optically thick disk:

$$T_{\rm s} \approx \left(\frac{GM\dot{M}}{8\pi\sigma r^3}\right)^{1/4}. \qquad (12)$$

If the accretion is steady, so that $\dot{M}$ is independent of r, the predicted temperature varies as $r^{-3/4}$. In the case of protostellar disks and disks in cataclysmic variables, these temperatures are similar to those of normal stellar surfaces, and the same radiation processes determine the details of the emitted spectrum. In accreting black holes and neutron stars, the predicted temperatures are of the order 1keV (10^7K). Indeed, the X-ray spectra of these object often show a component that agrees with the simple prediction (12). Usually, however, there is an additional *hard component* of much more energetic photons, around 100keV. It often dominates the radiated energy (see X-RAY BINARIES). This shows that in these binaries there is an additional component in the accreting plasma that behaves differently from an optically thick disk. The precise nature of this plasma is one of the classical problems of X-ray astronomy, which at the time of this writing has not been solved entirely. From the observed spectrum, it appears to be a thermal plasma of modest optical thickness ($\tau \sim 1$) and a temperature around 100keV, much hotter than the cool disk. The main process producing hard photons under such conditions is inverse Compton scattering of soft photons by hot electrons (see ELECTRON-PHOTON INTERACTIONS).

In the neighborhood of black holes and neutron stars accretion is possible not only via a cool optically thick disk. Theory also predicts the possibility of accretion via a hot state (cf. discussion above under *thin disks*). In this state, the protons are near the virial temperature, while the electrons are much cooler. The accretion flow is geometrically thick ($H/r \sim 1$), but optically thin. Under these conditions, the Coulomb interactions between ions and electrons can be slow compared with the accretion time (depending on accretion rate and viscosity parameter). Since the electrons radiate much more effectively, and are inefficiently heated by the ions, they remain much cooler than the ions: the accretion plasma is not in thermal equilibrium. The Coulomb interaction rate decreases with increasing electron temperature while radiation losses by inverse Compton and synchrotron radiation increase. In a flow of modest optical depth, the inverse Compton losses increase exponentially above about 100keV, so that this a somewhat natural temperature to expect for the emitted radiation. The possibility of such a *two-temperature* accretion flow to explain the hard spectra of X-ray binaries has already been proposed in the beginning of the X-ray astronomy era. The geometry of such a flow, and the nature of its interaction with the cool disk component are still uncertain, however.

Jets from disks

Most systems with accretion disks appear able to produce strongly collimated outflows called jets, at least at some periods in their existence (see ASTROPHYSICAL JETS). Jets with relativistic flow speeds are known from accreting black holes, both the stellar mass holes in X-ray binaries and the massive holes in AGN. Jets at more modest speeds are produced by protostars. They are also known from at least one accreting neutron star (Cir X-1), and an accreting white dwarf (R Aqr). The connection between disks and jets is thus suggestive, but at the same time puzzling. Though jets always seem to be associated with accreting systems in which there is direct or indirect evidence for a disk, not all systems with disks produce jets, or not all the time. A good example are the HERBIG-HARO OBJECTS produced by jets from protostars, which clearly demonstrate that the jets in this case are episodic or highly variable in time (see also YOUNG STELLAR OBJECTS and PRE-MAIN-SEQUENCE STARS).

Summary of types of disk

On a stellar scale, disks are produced in binaries by overflow of gas from one of the components onto the other. The sizes of these disks are as large as normal stars, from a few tenths to a few solar radii. If the primary (the mass receiving star) is a white dwarf, such as in Cataclysmic variables, the inner parts of the disk radiate mostly in the UV, the outer parts in visible light. The mass transfer through these disks are often unstable, causing DWARF NOVA outbursts. If the primary is a neutron star or stellar-mass black hole, the inner disk radiates in X-rays. Mass transfer in these disks is also unstable at low transfer rates, causing the so-called SOFT X-RAY TRANSIENTS. They sometimes produce jets at relativistic speeds. Disks around stars in the process of formation, the PROTOSTELLAR (also called PROTOPLANETARY) disks, are much larger (around 100 AU). Their inner regions radiate in the visible, the outer parts at infrared to radio wavengths. They are probably also unstable, causing the FU Ori outbursts, and are associated with jets and HERBIG-HARO OBJECTS. Disks in AGN rotate around massive (10^6–$10^9 M_\odot$) black holes at the centers of active galaxies. Their central regions radiate both in the UV and in X-rays, and often produce the relativistic jets seen in double-lobed radio sources. Their sizes are somehwat uncertain, but probably of the order of a parsec or larger.

Disks are also seen around BE STARS. The mass in these disks is believed to be slowly expelled by the rapidly rotating star. Some of their properties are similar to those of accretion disks, but with mass drifting away rather than accreting onto the star. They are sometimes called *excretion* or *decretion disks.*

Bibliography

Frank J., King A.R., Raine D.J. 1992 Accretion power in astrophysics, 2nd edition, Cambridge University Press Astrophysics series vol 21, (Cambridge: CUP)

Pringle J.E. 1981 Accretion disks in astrophysics, Annual Review of Astronomy and Astrophysics **19** 137–162

Spruit H.C. 1996 Accretion disks, http://xxx.lanl.gov/astro-ph/9502098