Extragalactic Astronomy II

Lecture 9

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- In general one can expect that the gas has non-zero angular momentum. Thus it cannot fall straight onto the SMBH. Through friction with other gas particles and by the resulting momentum transfer, the gas tends to assemble in a disk oriented perpendicular to the direction of the angular momentum vector.
- The frictional forces in the gas are expected to be much smaller than the gravitational force. Hence the disk will locally rotate with approximately the Kepler velocity.

Physical phenomena in the accretion disk

- Since a Kepler disk rotates differentially, in the sense that the angular velocity depends on radius, the gas in the disk will be heated by internal friction. In addition, the same friction causes a slight deceleration of the rotational velocity, whereby the gas will slowly move inwards.
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- potential energy $\rightarrow$ kinetic energy $\rightarrow$ heat (through friction)
- If the virial theorem holds, half of the potential energy released is converted into kinetic energy; in the situation considered here, this is the rotational energy of the disk. The other half of the potential energy can be converted into internal energy.

Temperature profile of a geometrically thin, optically thick accretion disk

Consider a mass m that falls from radius $r + \Delta r$ to r, the loss of potential energy is released

$$\Delta E = \frac{GM_{BH}m}{r} - \frac{GM_{BH}m}{r + \Delta r} \approx \frac{GM_{BH}m}{r}\frac{\Delta r}{r}$$

We neglect the self gravity of the disk, assuming that the SMBH is the dominant contributor to the gravitational potential.
Assuming half of the energy is converted to heat and half to kinetic energy, $E_{heat} = \Delta E/2$. If we assume that this energy is emitted locally, the luminosity will be

$$\Delta L = \frac{GM_{BH}\dot{m}}{2r^2}\Delta r$$

Temperature profile of a geometrically thin, optically thick accretion disk

$\dot{m}$ denotes the accretion rate, which is the mass that falls into the black hole per unit time. In the stationary case, $\dot{m}$ is independent of radius, since otherwise matter would accumulate at some radii. Hence the same amount of matter per unit time flows through any cylindrical radius.

If the disk is optically thick, the local emission corresponds to that of a black body. The ring between r and $r + \Delta r$ then emits a luminosity

$$\Delta L = 2 \times 2\pi r \Delta r \sigma_{SB} T^4(r)$$

Factor 2 comes from the fact that the disk is two sided and its emitting surface area is $2 \times 2\pi r \Delta r$

Temperature profile of a geometrically thin, optically thick accretion disk

$$T(r) = \left(\frac{GM_{BH}\dot{m}}{8\pi\sigma_{SB} r^3} \right)^{1/4}$$

A more exact calculation accounts for the fact that part of the generated energy is used to heat the gas, whose thermal energy is also partially advected inwards. This yields

$$T(r) = \left(\frac{3GM_{BH}\dot{m}}{8\pi\sigma_{SB} r^3} \right)^{1/4}$$

This represents the temperature profile of the accretion disk for $r \gg r_s$.

Temperature profile of a geometrically thin, optically thick accretion disk

Scaling by the Schwarzschild radius,

$$T(r) = \left(\frac{3GM_{BH}\dot{m}}{8\pi\sigma_{SB}r_s^3}\right)^{1/4}\left(\frac{r}{r_S}\right)^{-3/4}$$

$$T(r) = \left(\frac{3c^6}{64\pi\sigma_{SB}G^2}\right)^{1/4}\dot{m}^{1/4}M_{BH}^{-1/2}\left(\frac{r}{r_S}\right)^{-3/4}$$

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- the total emission of the disk is, to a first approximation, a super-position of black bodies consisting of rings with different radii at different temperatures. For this reason, the resulting spectrum does not have a Planck shape but instead shows a much broader energy distribution.
- the lower and upper bound of the frequency interval is determined by the lowest and highest temperature (at the outer and inner radius) of the disk.

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- on how far the disk extends inwards. For a black hole without rotation, this innermost stable orbit is at $r = 3r_S$, whereas it is smaller for a black hole with angular momentum.
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- the efficiency $\epsilon = L/\dot{m}c^2$ depends on the spin of the black hole. It increases from 6% for a non-rotating black hole to 29% for one with maximum rotation.
- For any fixed ratio r/r_S, the temperature increases with the accretion rate. This is exactly as expected because energy emission is $\propto T^4$ and $\propto \dot{m}$. Hence $T \propto \dot{m}^{1/4}$

Temperature profile

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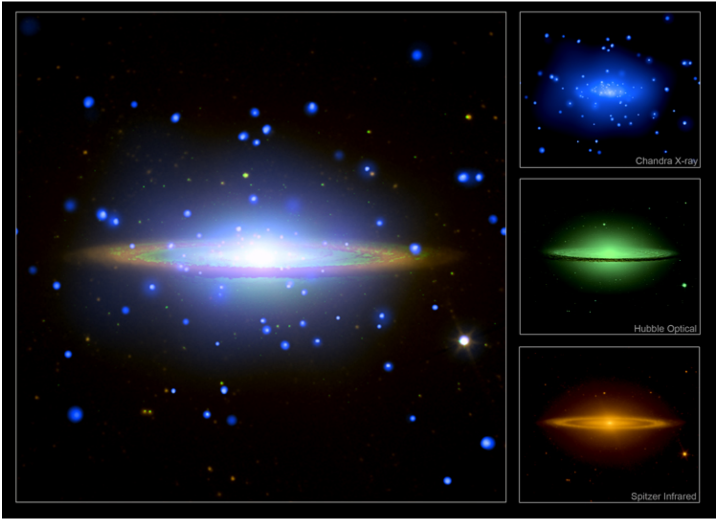
X-ray emission from the Sombrero Hat galaxy

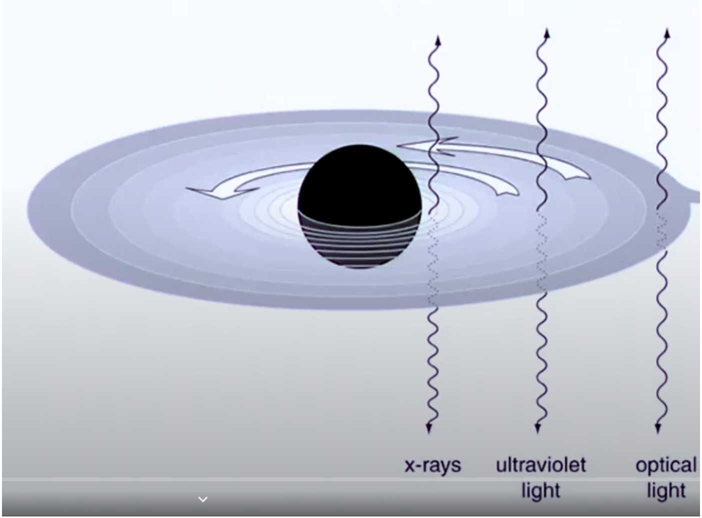


Supermassive black hole in Interstellar

The planet around a SMBH named Gargantua has strong enough gravity that time dilation is very strong - hours on the planet will translate to years in low gravity. This implies that the planet is very close to the SMBH. But it is not getting tidally disrupted.
What can we say about the mass of the SMBH? Would it have a accretion disk? Would it be maximally rotating? Could it have a full-size main sequence star going around it? What would be the source of energy for such a black hole?

Thorne - Science of Interstellar

Thermal emission from the accretion disk



Advection dominated Accretion Flow

So far, we have assumed that the disk is optically thick. The optical depth of the disk depends on its surface density, which in turn depends on the accretion rate. In a system where the accretion rate is low, the disk may be optically thin, and the emission process of the heated gas can become inefficient. In such a case, the gas cannot efficiently cool, and the thermal energy generated by friction in the disk is advected inwards together with the gas. Such a disk (called 'advection-dominated accretion flow', or ADAF) is rather inefficient in converting rest mass into radiation, and so its corresponding ϵ can be quite small.

Outflows in ADAF

However, such an accretion flow may be quite efficient in generating outflows, such that part of the accreted material is ejected in form of jets. Hence, this mode of accretion likely plays an important role for radio galaxies.

So in radio-galaxies, a low accretion rate, inefficient (in mass to energy conversion mode) may likely operate - we call it 'radio-mode' of the AGN. The high efficiency mode is called 'quasar-mode'

Simulations based on the millenium simulations supported by multiband observations of AGN have confirmed this. See Croton et al. (2006) and subsequent papers by the group.

Bondi-Hoyle-Lyttleton accretion

Assume a black hole being immersed into a spherically-symmetric gas distribution which for large radii is homogeneous with density ρ_∞ and sound speed c_s. The gravitational pull by the black hole causes the gas to have an inward-directed velocity. Provided the gas is adiabatic, then the mass accretion rate calculated from the equations of fluid dynamics, yields

$$\dot{m} = \frac{4\pi G^2 M_{BH}^2}{c_s^3} \rho_\infty$$

Spherical accretion

This Bondi–Hoyle–Lyttleton accretion rate yields an indication of the mass influx onto the accretion disk, provided the angular momentum of the surrounding gas is sufficiently small. In this case, it can flow in at the rate $\dot{m}$, until it reaches a radius where the angular momentum becomes important and the gas is forced onto circular orbits, forming an accretion disk. Purely spherical accretion, i.e., where the gas has zero angular momentum and no disk is formed, is very inefficient; only a tiny fraction of the kinetic energy gets dissipated and radiated away. Unlikely, that this scenario operates, except in the most quiescent situations.