Models of Accretion Disks

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Abstract.
An accretion flow onto a supermassive black hole is the primary process powering quasars. However, a geometry of this flow is not well constrained. Both global MHD simulations and observations suggest that there are several emission components present in the nucleus: an accretion disk, hot plasma (corona or sphere) with electrons scattering the optical and UV photons, and an outflow (wind/jet). The relative location and size of these emission components, as well as their “interplay” affect the emerging quasar spectrum. I review briefly standard accretion disk models and the recent progress, point out discrepancies between the predicted and observed spectra and discuss some issues in fitting these models to the broad-band spectral energy distribution of quasars. I present examples of models fitted simultaneously to the optical-UV-X-ray data and possible constraints on the parameters.

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IDEA OF AN ACCRETION DISK

Images posted on many Astronomical Web Sites\(^1\) present artist’s views of the central engine of quasars, active galactic nuclei (AGN), and binary systems (XRB). They usually contain a black dot, representing a black hole, surrounded by a disk-like structure “showing” a circular motion of matter flowing towards the black hole potential. There is also a perpendicular to the disk funnel representing a jet. Such artists views of the central engines are not exactly the images astronomers can see in the real observations. Usually, even the highest resolution images show simply a diffuse or in most cases a point-like emission. The incredibly high luminosity (\(> 10^{12}L_\odot\) for quasars) emitted by such an unresolved point source is the main indication of the powerful physical processes involved in generating this energy.

The idea of an accretion disk is almost 50 years old. After the discovery of quasars as luminous radio sources the obvious question to ask was how they are powered? Salpeter (1964) [46] suggested that an accretion onto a massive black hole and a release of the gravitational energy associated with that process can provide this power. Lynden-Bell (1969) [32] gave an idea of “a matter swirling down the Schwarzschild mouth” and presented a concept of an accretion process (and a picture!) that might be at work. In the following years, several papers describing physics of an accretion onto a massive black hole have been published (for example [33, 38, 39]) It is remarkable to read these papers

\(^1\) for example http://chandra.harvard.edu/photo/
http://hubblesite.org/newscenter/archive/releases/
today and reflect on the way they have defined one of the most important processes in astrophysics in our times.

In 1973 Shakura & Sunyaev [47] considered the physics of accretion in great detail including a discussion of energy dissipation, an angular momentum transport by both viscosity and outflow, an origin of turbulence as magnetic or convective. They presented a parameterization of viscosity (\(\alpha\)-viscosity) in terms of efficiency of the angular momentum transfer. The nature of the viscosity has been the key problem in the accretion disk theory, while this convenient parameterization allowed for progress in both analytical modeling and applications to the observations. Twenty years later, Balbus & Hawley (1991) [2] show that the magnetic turbulence associated with MRI (magnetorotational instability) is the best candidate for the viscosity.\(^2\) Now, we understand that accretion flows are magnetohydrodynamical and the magnetic fields play crucial role in the driving the accretion. However, the main difficulty in the analytical description of such disks means that we need to develop simulations to understand the accretion process. While the huge progress in numerical simulations has been made over the last decade there is still no full 3D global accretion flow model available. The accretion phenomenon is still not well understood and there are many remaining questions still waiting for an answer.

Here, I consider issues related to the application of accretion disk models to quasar spectra and constraints on the accretion flow geometry based on the spectral fitting of quasar data.

**OBSERVATIONAL TESTS**

Testing accretion models in quasars has been challenging. We cannot directly image the accretion flow because the central 1 pc region of a galaxy remains unresolved. Therefore in understanding the accretion process we mainly depend on observations of the spectral energy distribution (SED) and variability, and indirectly on large scale signatures of the quasar activity such as jets and outflows. Modeling the observed spectra from the accretion flow however is non-trivial because the disk broadband optical-UV and X-ray emission has to be taken into account, while the interstellar absorption affects the bulk of this emission and hides the peak of the emission, the key feature for the disk temperature determination in quasars and AGN. Thus the both ends of the spectral energy distribution needs to be taken into account to constrain the model parameters in a meaningful way.

**Geometry of Accretion Flow**

The geometry of accretion flow is not well understood and there is no critical observational constraints available at this time. In particular, we do not understand whether the flow becomes spherical, how and where the corona forms above the disk, whether the corona covers the disk at all times, etc. Global MHD simulations (with MRI but no radiation) indicate that several distinct regions form within an accretion flow onto

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\(^2\) An excellent review of the angular momentum transport and MRI is given by Balbus (2003) [3]
a supermassive black hole [22, 40]: a Keplerian turbulent disk enveloped by a hot and unconstrained corona, a hot inner torus, a magnetically confined unbound jet and a centrifugal tunnel. However, these global simulations do not account for radiation. Note that to calculate the spectrum emerging from an accretion flow one needs to take into account emission from each region as well as irradiation and self-illumination of these regions. Thus the global models needs to be developed. Some progress is being made and results of local MHD simulations, which include radiation effects have been recently reported (see [23, 6, 28]).

Elvis (2000) [15] considered observational information to derive an empirical model of a quasar structure. He describes physical location of the regions associated with different spectral components (in particular emission lines). The centrifugal funnel and the outflow are the key features in this model.

**FIGURE 1.** Two types of accretion flow geometry [51]: (1) The hot sphere surrounds the central black hole and the accretion disk covered by a tenuous uniform corona extends outside the sphere. The cold disk photons are inverse Compton scattered in the hot sphere and the corona. Model parameters: size of the sphere, energy dissipation and temperature of the corona, mass and accretion rate.

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**Emission from an Accretion Disk.**

In 1978 Shields [48] suggested that the excess emission (a “bump”) observed above a powerlaw extrapolation between the radio and optical continuum in 3C 273 might be a result of a thermal emission from the disk around a supermassive black hole. Malkan & Sargent (1982) [36] tested this idea with better data and considered several emission components including the disk blackbody emission. The standard disk blackbody emission model is conveniently independent on the energy dissipation process, thus it is independent on the viscosity. The disk effective temperature is proportional to the radius, so \( T(r) \sim T_0 r^{-3/4} \) with the normalization scaling with black hole mass and accretion rate (see [19] for detailed equations). This spectral peak is located in X-rays for stellar mass black hole systems with \( \sim 10 M_\odot \), and it is shifted to UV for a supermassive black hole in AGN. The emitted flux increases with the mass. A direct application of this
FIGURE 2. Two types of accretion flow geometry [52]: (2) Geometrically think disk extends down to the innermost stable orbit of a central black hole. The patchy corona is located above the disk with hot clouds representing flare regions. The cold photons are Compton scattered in the clouds. Model parameters: mass, accretion rate, clouds geometry and velocity, fraction of energy dissipated in the corona.

model to the spectra of many quasars and local active galaxies has been possible with general constraints on the mass and accretion rates.

However, as shown by Czerny & Elvis [8] and Hardt & Maraschi [21] the opacities of the disk atmosphere and effects of a tenuous corona above the disk have to be taken into account when calculating the quasar spectra. Thompson and Compton scattering of the UV photons on the electrons in the disk atmosphere or corona, as well as the bound-free opacities significantly modify the emission. The “modified” blackbody disk models show a change in the spectral shape in the optical-UV and an additional contribution to the emission in the soft X-rays (e.g. [43, 37, 41, 16, 17, 7]). In addition inclination and GR effects shift the spectra towards higher frequencies [56, 29, 49, 50]. Recently more sophisticated models have been developed to treat properly the disk structure and effects of the corona [44, 45], radiative transfer in accretion disk atmosphere [24, 5, 25], and irradiation of the atmosphere [34, 35] in the disk around a supermassive black hole.

SPECTRAL COMPONENTS

The observed broad-band spectra must originate in different parts of the accretion flow. This is because the optical-UV spectra usually associated with a thermal disk emission require much lower temperatures than the thermal X-ray emission. Thus, at least a range of temperatures between $10^4 - 10^6$K is required for the entire optical-to-X-ray range emission. However, the temperature of the standard thermal disk is not high enough to contribute significantly to a typical energy range between 0.1 keV and $\sim 40$ keV (rest frame). On the other hand, the Compton effect becomes important at these energies and the X-ray emission is usually associated with the inverse Compton scattering of low frequency photons (optical and UV) on electrons in a hot medium. The amplification of
the effective boost of the photon energy towards X-rays requires electron temperatures between a few to hundreds keV. Depending on the nature of the hot plasma, the electrons can have thermal or non-thermal distributions. The main idea is that we should have a source of cold optical-UV photons and a hot plasma to create the observed spectra. The geometry of these two medium has not been constrained so far.

Recently Sobolewska et al [51, 52] attempted to constrain a parameter space of accretion models for quasars [4]. They considered two types of geometries: (1) an ionized sphere surrounded by an accretion disk covered by a hot tenuous corona (Fig. 1); (2) an accretion disk extending to the last stable orbit covered by a patchy corona with magnetic flares (Fig. 2). Given the observed spectra of high redshift quasars ($z > 4$) the patchy corona model was more favorable, although one cannot rule-out either possibility. A consistent modeling of large quasar samples with accretion models is needed.

Historically, many studies of large samples used a parameterized form of $\alpha_{\text{ox}}$ [57] which describes the relative optical and X-ray emission. $\alpha_{\text{ox}}$ is defined as a ratio of optical to UV luminosity thus this parameterization avoids the difficulty related to modeling different types of data obtained by optical and X-ray telescopes. This parameterization is convenient for studies of evolution and redshift dependence or general properties of the sample (e.g. [4, 55, 26, 54]). It also shows the significance of the disk emission in respect to the hot Comptonizing medium. However, $\alpha_{\text{ox}}$ alone is not good enough for analysis of properties of accretion flow. This is clearly visible from analysis of the theoretical spectral shape in the optical-UV band. To calculate $\alpha_{\text{ox}}$ one usually needs to extrapolate the flux at 2500Å or 1450Å and assume the optical-UV slope. However, the slope in the optical-UV is very sensitive to the properties of the accretion flow. Observational results of large quasar samples rarely give an observed optical-UV spectral slope. The quasars SED compiled by Elvis et al [14] for only about 100 quasars has been widely used in many studies of AGN samples. The new SED for a large SDSS sample gives a wider scatter around the mean of the optical-UV slope described by Richards et al [42].

**FITTING DISK MODELS TO THE DATA**

For meaningful tests of accretion models one then needs to consider the full optical-UV-X-ray spectral range. A lack of a general fitting package for simultaneous X-ray and optical spectral analysis is a major hurdle in the wide application of the accretion models to the data. XSPEC [1] contains several models, however they are mainly designed for XRB systems [30, 12, 13]. Sherpa [20] in CIAO software allows for easy use of both optical and X-ray data, but it does not have a model applicable to AGN and quasars. Here, we use Sherpa to demonstrate a possible approach to model fitting and argue that good accretion models should be developed for general use by the community, since this is the best way to learn about accretion.

Figure 3 shows the high redshift quasar spectrum fit in Sherpa with two separate power law models in the optical-UV and X-rays. The two ends of the spectrum have been treated independently giving a parameterized description of the spectrum that is not related to accretion models. Figure 4 shows an example of the quasar SED fit with a range of accretion flow models. Note that many models fit quite well the X-ray data, while the optical-UV slope is missed by most of the models. In this case the model
FIGURE 3. Fitting the optical and X-ray spectra. Left: The optical and X-ray spectra of $z=1.86$ quasars are fit by different power law models. Top panel shows the typical X-ray data marked by squares with the error bars over-plotted with a power law model indicated by a solid line. The X-ray photon index $\Gamma = 1.94 \pm 0.11$ and optical slope $\alpha_{UV} = 1.05 \pm 0.01$. Right: the same data on $\log \nu$ vs $\log F_\nu$ plane with the power law models.

FIGURE 4. Fitting accretion disk models of Sobolewska et al to the broad-band spectral energy distribution of a $z=1.86$ quasar. Left: The broad-band optical-X-ray data plotted with a solid yellow line in the optical (emission lines are visible above the continuum) and squares with $1 \sigma$ error bars in the X-rays. The solid colored curves indicate different model parameter fits to the data. Notice that the models have the same $\alpha_{OX}$ and the X-ray slope, but differ a lot in the optical-UV slopes. Right: The zoom into the optical band to show the differences between the models. Model parameters: $M_{BH} = 10^9 M_\odot$ with $\dot{M} = 0.4 \dot{M}_{Edd}$ and $0.5 \dot{M}_{Edd}$; $M_{BH} = 4 \times 10^8 M_\odot$ and $\dot{M} = 0.09 \dot{M}_{Edd}$; $M_{BH} = 5.7 \times 10^8 M_\odot$ and $\dot{M} = 1 \dot{M}_{Edd}$. The red line shows the power law fit to the data.

included a modified blackbody component to account for the accretion disk emission in the optical-UV and the Comptonization in the patchy corona contributing to the X-rays. Clearly theoretical improvement in optical-UV model is needed. One can argue that the optical-UV part of the spectral model is critical to understanding the geometry
of accretion flows as well as the accretion physics.

Koratkar and Blaes [27] considered application limits of the standard accretion models to the quasar spectra. They compare the optical-UV slope predicted by the standard disk blackbody model to the observed median slope of the quasar combined spectrum in LBQS sample [18]. Czerny et al [9] considered an universal shape of quasars and NLS1 spectra in comparison to the simple disk-blackbody shape to illustrate the need for additional processes to account for the observed flattening in the optical spectrum with respect to the blackbody emission. They considered irradiation and outflow as possible processes responsible for the observed flattening of the slope (e.g. [11]). Dust may also lead to observed flattening of the continuum [10, 31]. Modeling a large sample of quasars in the broad-band spectral domain is needed in order to constrain the parameters of the accretion process.

SUMMARY

We considered only the steady state accretion flow spectra and did not really talk about the short and long term variability in theoretical models and observations. Future global simulations should provide us with an evolution of an accretion disk which is clearly needed. Observations show AGN and quasar variability on different timescales. Long term changes in the accretion state may affect our understanding of black hole growth and evolution of structures in the universe.

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