Observational tests of the picture of disk accretion

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Abstract In this chapter, I present a summary of observational tests of the basic picture of disk accretion. An emphasis is placed on tests relevant to black holes, but many of the fundamental results are drawn from studies of other classes of systems. Evidence is discussed for the basic structures of accretion flows. The cases of systems with and without accretion disks are discussed, as is the evidence that disks actually form. Also discussed are the hot spots where accretion streams impact the disks, and the boundary layers in the inner parts of systems where the accretors are not black holes. The nature of slow, large amplitude variability is discussed. It is shown that some of the key predictions of the classical thermal-viscous ionization instability model for producing outbursts are in excellent agreement with observational results. It is also show that there are systems whose outbursts are extremely difficult to explain without invoking variations in the rate of mass transfer from the donor star into the outer accretion disk, or tidally induced variations in the mass transfer rates. Finally, I briefly discuss recent quasar microlensing measurements which give truly independent constraints on the inner accretion geometry around black holes.

1 Introduction

Observations which, in hindsight, present evidence for mass transfer have been known about since antiquity (e.g. the system Algol). Evidence for accretion power by black holes can be seen, again, in hindsight, as far back as the discovery of jets from active galactic nuclei (Curtis 1918), and the bright, broad-lined nuclei of the Seyfert galaxies (1943). Theoretical discussion of the possibility of accretion began in the 1940s (Kuiper 1941; Bondi & Hoyle 1944), with the focus on mass transfer in contact binaries, and accretion from the interstellar medium, respectively. Studies of the importance of accretion power in astrophysics first became
prominent about 15 years later (Crawford & Kraft 1956), as it began to become clear that many of the classical, recurrent and dwarf novae were short orbital period spectroscopic binaries, often with photometric modulation at the same period (e.g. Walker 1954; Joy 1954; Joy 1956; Greenstein & Kraft 1959; Kraft 1964). The conclusion was thus drawn that mass transfer must, in some way, be responsible for the unusual phenomenology of the class of objects (see also Kopal 1959 for a synthetic discussion).

The basic elements of accretion disk theory are reviewed in the chapter in this volume by Omer Blaes, while a review of the progress in connecting the “microphysics” of magnetohydrodynamics to the “macrophysics” of classical accretion disk theory is presented in the chapter by Chris Fragile. This article will focus on showing the observational tests that have verified that simple pictures of how accretion disks should work, largely developed in the 1970s, match many of the observational constraints at some broad level. It will also discuss the observational evidence for cases where the simple picture breaks down, and more complicated models must be invoked – even though in some cases it is not clear what those more complicated models are.

A variety of means of testing accretion disk theory can be made – broadband spectroscopic measurements (see e.g. Juri Poutanen’s and Jeff McClintock’s articles in this volume), and measurements of rapid variability (see e.g. the article by Tomaso Belloni & Luigi Stella in this volume) are generally used to understand the processes in the inner accretion flows. In some cases, these methods also provide valuable information about the global accretion process. In this article, I will focus on discussing the observational constraints on accretion disk theory that come from other methodology – chiefly, but not exclusively variability on much longer timescales. Apart from some discussion of quasar microlensing, I will leave aside the discussion of topics such as the detailed structure of inner accretion flows around black holes, as this topic is covered elsewhere in this volume. Accretion disk theory will be discussed in this article in broadbrush strokes, to set the stage for understanding which observations will be interesting, but will be discussed in detail in the other articles in this volume.

2 A basic picture: setting a target for observations to test

In the standard picture of an accretion flow onto a compact object from a binary companion, we have the following structures:

1. An accretion stream which begins at the donor star (see e.g. Albright & Richards 1996 for a discussion of how evidence for streams can be found using Doppler tomography)

2. An accretion disk – a geometrically thin, optically thick flow in Keplerian rotation, with a small inward drift due to either bona fide viscosity, or, as has become increasingly favored in recent years, a magnetic field effect that can be well modelled on a macroscopic scale as acting like viscosity. The accretion disk is generally assumed to extend outward to the “circularization radius” – the radius where the specific angular momentum of the accreted material is the same as that for gas in a circular orbit around the accretor. If the stellar radius is larger than the circularization radius (as can happen for wind-fed systems, and for accretion by “normal” stars, rather than by compact objects), a disk
will fail to form, and the accretion stream will impact the accretor directly. A
disk may also fail to form in the case of a rotating high magnetic field accretor,
where the magnetic field of the central star becomes dynamically important
for a circular disk outside the circularization radius (e.g., Ghosh & Lamb 1979).

3. A “hot spot” where the accretion stream from the donor star collides with the
outer accretion disk, and releases its excess kinetic energy.

4. In systems without black hole accretors, a boundary layer should exist, where
the excess rotational energy of the innermost part of the accretion disk is
dissipated (Lynden-Bell & Pringle 1974). In systems with black hole accretors,
there may be excess rotational energy at the innermost stable circular orbit,
but it should be transported across the event horizon. As the focus of this
volume is black holes, we will not discuss the boundary layers further, except
to say that evidence for them is found in both white dwarf (e.g., Pandel et al.
2003) and neutron star (e.g., Mitsuda et al. 1984) accretors, but that their
spectra can be complicated, and, often, the emission does not show up as an
extra blackbody component added to a disk model fit (e.g., Godon & Sion 2005;
Piraino et al. 1999).

In active galactic nuclei, only the accretion disks are present. Certain types of
deviations from this picture are well-studied, and represent separate topics in their
own right – e.g. spectral state phenomenology (in particular states in which the
accretion disk becomes geometrically thick) and the presence of jets. These topics
are covered in detail in other chapters in this volume and will not be covered here
in detail.

3 Classes of accretors

A wide variety of classes of accreting objects exist in the Universe. While a large
fraction of the literature on accretion involves the study of mass-transferring binary
stars, some accretion takes place onto isolated objects. In particular, active galactic
nuclei are generally presumed to accrete from their local interstellar medium. In
many protostars, the accreting object is a single star.

Since the focus of this volume is on accretion onto black holes, the focus of this
article will be on the black hole accretors themselves. Studies of stellar mass black
holes are often plagued by small number statistics. Studies of active galactic nuclei
suffer from difficulty in making detailed measurements, as well as long timescales
of variability. It is thus useful to supplement studies of black holes with studies
of other classes of accreting objects. Additionally, comparisons between black hole
accretors and other classes of accretors can be excellent ways to determine which
phenomenology is truly unique to black holes, rather than being generic to the
process of accretion.

The classes of mass transferring binaries seen in nature include:

1. Low Mass X-ray Binaries (LMXBs). These are systems in which a neutron
star or black hole accretes from a low mass main sequence star or a low mass

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1 Many other authors decompose neutron star spectra in different ways – White et al. 1986;
Church & Balucinska-Church 2004, and there remains debate about the right spectral models
for accreting low magnetic field neutron stars. There is widespread agreement that neutron
star spectra usually require at least two thermal or quasi-thermal spectral components.
subgiant star through Roche lobe overflow. The mass transfer rates in these systems are determined by the rate at which either the donor star expands (due to nuclear evolution) or the orbit shrinks (due to magnetic braking and/or gravitational radiation).

2. High Mass X-ray Binaries (HMXBs). These are systems in which a neutron star or black hole accretes from a massive star. Many of these objects have Be stars as the donor stars, and the accretion seems to take place from the equatorial wind. Others have supergiant donors, and the accretion takes place through gravitational capture of the stellar wind of the supergiant. For these fast-wind systems, the accretion disk may begin to have a circular orbit very close to the compact object, or, in some cases, a disk may not form at all. Finally, others have much shorter orbital periods, and their donor stars are either Roche-lobe filling or nearly Roche-lobe filling. In these systems the mass transfer takes place through either a focused wind, or actual Roche lobe overflow. See Corbet (1986) for a discussion of the different classes of high mass X-ray binaries.

3. Symbiotic stars. These are systems which, based on their initial definition, show evidence for both hot and cool components in their optical spectra. Since their initial discovery, it has been realized that the cool components are red giants, and the hot components are various forms of accreting objects. Most symbiotic stars have white dwarf accretors, but a small fraction have neutron star accretors (Hynes et al. 2013 and references within). The mass transfer is generally believed to take place through capture of the red giant star wind, although some symbiotic stars are at least very close to being in Roche lobe contact. For a relatively recent review, see Sokoloski (2003).

4. Cataclysmic variables. These are systems in which mass is transferred from a low mass main sequence star or a low mass subgiant star to a white dwarf; they are the analogs of low mass X-ray binaries, for systems where the accretors is a white dwarf. Cataclysmic variables are broken into a large number of subclasses based on different observed phenomenology of variability. These sub-types are often named in terms of the prototype object, as is typical for nomenclature of variable stars. In this article, we will use nomenclature descriptive of the phenomenology, a practice which is thankfully becoming more common in the cataclysmic variable community as well.

5. Ultracompact binaries. These are binaries in which the donor star is degenerate – either a white dwarf, or a low mass degenerate helium star. In the Milky Way, these have been seen only with white dwarf or neutron star companions. When the system is a double white dwarf binary with mass transfer, it is called an AM CVn star, after the prototype object. When the accretor is a neutron star (or, potentially, a black hole) it is called an ultracompact X-ray binary. We refer the reader to Nelemans & Jonker (2010) for a review on the ultracompact X-ray binaries, and to Maccarone et al. (2007) and Zepf et al. (2008) for a discussion of the evidence for an ultracompact black hole X-ray binary in NGC 4472.

6. Various classes of close binaries with two “normal” (i.e. not compact remnant) stars show evidence for accretion. These include, for example, Algol systems (in which mass transfer takes place from an evolved star to a main sequence star) and W UMa systems (contact binaries, in which both stars overflow their Roche lobes simultaneously). We refer the reader to Thomas (1977) for a review of these systems. Accretion disks form rarely in these systems (although see Olson 1991 for evidence of a disk in one Algol, KU Cyg).
While active galactic nuclei represent one of the two major classes of accreting black holes, almost no fundamental tests of accretion theory have been put forth primarily from studies of active galactic nuclei. Such tests would be exceedingly difficult – tests based on spectroscopy would run into the problem that these systems are not fully ionized like the disks of X-ray binaries, making models of the inner accretion disks much more complicated (e.g. Done et al. 2012) – trying to understand the inner accretion disks around black holes using active galactic nuclei is considerably more difficult than trying to understand the inner disks around stellar mass black holes.

A further large part of our understanding of the outer parts of accretion disks comes from studies of variability on timescales long compared with the light crossing time at the Schwarzschild radius. In this case, the problem for using active galactic nuclei as test cases stems from the fact that their viscous timescales, even at the inner edge of the accretion disk, are expected to be much longer than the durations of any light curves assembled by astronomers. As a result, nearly all of our understanding of the outer parts of accretion disks, as well, comes from studies of stellar mass accretors. It should be noted, of course, that many fundamental advances in the studies of outflows from accretion disks have been developed with essential contributions from observations of active galactic nuclei, and in recent years, studies of lensed quasars have started to give some distinctive observational tests of the accretion geometry in active galactic nuclei.

It is thus the case that most of the fundamental constraints on accretion disk theory must come from studies of mass transferring binary systems, because they present accessible timescales, and have disks in an ionization state which is simpler than do active galactic nuclei. Our goals should be to develop fundamental theories of accretion in general, and then to determine which phenomenology is specific to black holes. As a result, it often makes sense to incorporate observational constraints from other classes of accreting objects. The systems with neutron star accretors are the most similar to those with black hole accretors, given that the radiative efficiency for accretion onto a neutron star is very similar to that for a non-rotating black hole, at least in the context of a standard Shakura-Sunyaev accretion flow.

The systems with white dwarf accretors (and particularly the cataclysmic variable stars, rather than the symbiotic binaries) are, however, the class of systems which have often provided the best constraints on accretion theory. Like black hole and neutron star accretors, the cataclysmic variables have the emission from their primary stars dominated by the accretion process rather than by core fusion, so that the radiation from the accretor can be taken as a tracer of the accretion disk’s activity. That nuclear fusion contributes significantly to the emission only in low-duty cycle bursts is a fundamental difference between accreting compact objects and other kinds of accreting stars.

It may seem a bit odd for a volume on black holes to include a substantial discussion of the literature on cataclysmic variables, but in many cases, the CVs provide tighter constraints on the basic physics processes which can be expected to be generalizable to all of accretion physics. The chief advantage of cataclysmic variables

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2 One exception is the surface layer fusion that can take place in supersoft sources. Another exception is in classical nova explosions. Novae can actually dominate the total energy output from accreting white dwarfs, but they have very low duty cycles, and hence are negligible most of the time for most CVs.
variables relative to X-ray binaries for studying accretion is that the CVs are more numerous. About 10 times as many CVs as LMXBs are known, and the nearest CVs are about 10 times as close as the nearest low mass X-ray binaries. While in recent years, there have been a few geometric parallax measurements made of X-ray binaries in the radio (e.g. Miller-Jones et al. 2009; Reid et al. 2011), such measurements have been made for much larger samples of CVs. It also turns out that the outbursting cataclysmic variable stars tend to have shorter recurrence times than the outbursts X-ray binaries, allowing for a large class of systems which have been studied repeatedly. The other advantages of the CVs being closer is that they are brighter optically, and are observed at lower extinction. Furthermore by being more numerous, there are many more eclipsing CVs known than eclipsing neutron star, or, especially, black hole X-ray binaries.

4 Evidence for the basic structures of accretion disks

A variety of observational approaches has been used to establish the basic picture of disk accretion seen in binary systems. These include both spectroscopic observations, and variability studies. Here, we first show that accretion disks really do form in many cases, and discuss the circumstances where accretion takes place without disks. We then discuss techniques that can be used to map out the accretion geometry in binary systems.

4.1 Proof that accretion really happens in disks

Among the first things worth testing are whether accretion really does take place in disks. In fact, the paper with the first association of stellar binarity with the production of classical novae (Walker 1954) presents a key piece of evidence that the accretion process, at least in those systems must take place via a disk. It shows the properties of the eclipse of the system – relatively long ingresses and egresses and short minima for the primary eclipse, while having much weaker secondary eclipses (constrained by Walker & Herbig 1956 to be less than 0.03 magnitudes, with primary eclipses of about 1 magnitude). In hindsight, these eclipse properties clearly indicate that the solid angle subtended by the accretion disk must be a small fraction of what would be subtended by a star of the same maximum radial extent. A second, more direct, but more recent piece of strong evidence that the objects believed to be accretion disks really are disks is that many of them show double-peaked emission lines (see Bailey & Ward 1981; Marsh 1988 for a discussion of cataclysmic variables; Eracleous & Halpern 2003 for a discussion of active galactic nuclei; and Soria 2002 for a discussion of X-ray binaries).

4.1.1 Systems with accretion not happening via disks

At the same time, there are clear examples of systems in which there is accretion which does not take place through a disk. These are systems which have circularization radii smaller than the radius at which a potential accretion disk would be disrupted. The most obvious such radius would be the radius of the accreting star, and indeed for non-compact stars, accretion disks are the exception rather than
the rule. For compact stars, the relevant radius will usually be the magnetospheric radius of the accretor.

The observational data on accreting objects support this theoretical scenario. There are classes of accreting white dwarfs and accreting neutron stars which lack the standard signatures of disk accretion. The accreting white dwarfs in this class are called polars. The name derives from the fact that their accretion light is often strongly polarized and that polarization stems from the fact that the accretion is channelled down the systems’ magnetic poles. These systems release large fractions of their emission in the X-rays relative to other cataclysmic variables, because the emission comes mostly from an accretion column rather than accretion disk. They also frequently show periodic emission, with the modulation taking place on the rotation period of the white dwarf. An analogous class of neutron stars are the accretion-powered X-ray pulsars. In both classes of objects, cyclotron lines have been seen (e.g. Reimers & Hagen 2000 for polars; Hemphill et al. 2013 for X-ray pulsars). It is important to note that there are classes of systems which show magnetically dominated accretion and disk accretion at the same time – the intermediate polars among cataclysmic variables (Warner 1983), and both slow (Jonker & van der Klis 2001; La Barbera et al. 2001) and millisecond (Wijnands & van der Klis 1998) X-ray pulsars among the neutron stars.

4.2 Eclipse mapping of accretion disks

At this point we have established that disks really do form in accreting objects. We also have sound theoretical reasoning, combined with empirical support, to show that the binary systems which do not have accretion disks have accretors which are fundamentally different from black holes – they either have surfaces at large radii, or they have dynamically important magnetic fields. It is thus reasonable to assume that all accretion onto black holes takes place through accretion disks, and, in this volume about black holes, to worry only about disk accretion from this point on.

Now, we can determine whether certain specific predictions of the simplest accretion disk models are in agreement with the observational data. One of the most straightforward predictions is that any disk in a steady state should have $T \propto R^{-3/4}$. This result comes from equating the differential blackbody luminosity in an annulus, $dL = \frac{G M \dot{m}}{R^2} dR$, to the differential power released by gas falling through that annulus, $2 \pi \sigma T^4 R dR$, and solving for $T$ as a function of $R$. In this framework $\dot{m}$, the accretion rate, and $M$, the accretor mass, are constants in a steady state accretion disk, while $T$ is the temperature of the annulus, $R$ is the radial distance of the annulus from the compact object’s center, $dL$ is the luminosity of the annulus, and $G$ and $\sigma$ are the gravitational constant and the Stefan-Boltzmann constant, respectively.

The technique of choice for testing these models has been eclipse mapping of cataclysmic variables (e.g. Horne 1993; Baptista 2001). Eclipse mapping is one of the few means of getting geometric information about continuum emission processes of accretion disks (with quasar microlensing being the other major method). Cataclysmic variables are the system class of choice for this work because there are optically bright eclipsing cataclysmic variables. No eclipsing low mass X-ray binaries with black holes are known, and the few eclipsing neutron star X-ray
binaries are not as bright as the brightest eclipsing CVs. Furthermore, bright accreting neutron stars are likely to have important effects from irradiation of the outer accretion disk by the inner accretion disk, meaning that the implications of a disagreement between the data and the standard theoretical $T \propto R^{-3/4}$ law might be expected, and could be difficult to disentangle from other effects.

It is most convenient to begin by attempting to model the “novalike” (i.e. persistently bright) cataclysmic variables, or the “dwarf nova” cataclysmic variables near the peaks of their outbursts. These are the systems that are expected to have nearly constant mass transfer rates on timescales of order the viscous propagation timescale through the accretion disks. The novalike systems have frequently failed to show $R^{-3/4}$ temperature profiles (Wood et al. 1992a; Baptista et al. 1995 – but see Rutten et al. 1992 for an alternative result); they often typically show much flatter temperature profiles. The quiescent dwarf novae almost universally show temperature profiles that are much flatter than $R^{-3/4}$ (e.g. Wood et al. 1986,1992a). This can be interpreted as a build-up of mass in the outer accretion disk during quiescence, a loss of mass due to winds which take mass away from the inner disk relative to what is in the outer disk, the emission of that optically thin disk wind which emits substantial light, or some combination of the different effects (e.g. Wood et al. 1986; Baptista et al. 1998).

Knigge et al. (1998) showed that the integrated spectra found simply from summing optically thick blackbodies does not describe the integrated spectrum of UX UMa, one of the prototype objects for eclipse mapping studies. Baptista et al. (1998) and Robinson et al. (1999) show that the results of eclipse mapping campaigns can be affected significantly by errors in what had previously been standard treatments – the treatment of brightness temperatures as effective temperatures (implicitly assuming optically thick blackbody emission as the only source of light), and the failure to compute the effects of limb darkening properly. They find that even with careful treatment of limb darkening, the temperature profiles are flatter than $R^{-3/4}$.

Additionally, with a more careful treatment of the radiative transfer in accretion disks, it becomes possible to model the vertical structure of the disks. The standard Shakura-Sunyaev treatment yields a ratio of height $H$ to radius $R$ of $H/R \propto R^{1/8}$. Cataclysmic variable accretion disks typically span a range of a factor of only about 10-100 in radius between the surface of the white dwarf and the outer edge of the accretion disk, meaning that $H/R$ should change by, at most, a factor of 1.8.

Only relatively large values of $H/R$ can be measured using eclipse mapping techniques, so generally, attempts are made only to estimate the scale height of the outer accretion disk. The numerical values of the theoretical scale heights for the Shakura-Sunyaev model indicate that $H/R \sim 0.03$ should be typical for bright CVs. Higher values have generally been found (e.g. $H/R$ of about 0.06 for Z Cha), indicating that some additional process is puffing up the outer disks in these systems, or that some other geometric feature or radiative transfer process is not accounted for in the existing eclipse mapping analysis (Robinson et al. 1999).

A few eclipse mapping studies of X-ray binary accretion disks have been made as well. Here, one expects irrations of the outer disk by the inner X-ray emitter to heat the outer disk, and cause it to have a larger scale height than expected in the context of the Shakura-Sunyaev disk model (e.g. Meyer & Meyer-Hofmeister 1982). At least for the source X 1822-371, the prediction of Meyer & Meyer-
Hofmeister (1982) is verified (Puchnariewicz et al. 1995; Bayless et al. 2010). X-ray eclipse mapping has shown large spatial scale X-ray emission. This is sometimes interpreted in terms of the region in which the X-rays are produced being spatially very large (Church 2004), but may be due to large scale optically thin disk winds which scatter a small fraction of the X-ray emission back into the observer’s line of sight. It is generally true in X-ray binaries that the disk winds seem to be more important in soft states than in hard states (Neilsen & Lee 2009); it is also true that the accretion disk corona sizes from eclipse mapping are larger in bright sources than in fainter sources (Church 2004).

To date, a single strong candidate eclipsing black hole X-ray binary is known (see Pietsch et al. 2006 for evidence of the eclipsing nature of the object and Orosz et al. 2007 for the dynamical evidence that the object is a black hole X-ray binary). This system is a high mass X-ray binary with a luminous 70 $M_\odot$ donor star, (Orosz et al. 2007). The combination of the brightness of the donor star relative to the accretion disk, and the fact that the donor star should have a strong wind, and hence not act as a “sharp edge” for doing eclipsing mean that eclipse mapping of this accretion disk is not particularly promising. Furthermore, the object is in M33, at a distance of about 800 kpc.

4.3 Evidence for hot spots

There are multiple lines of reasoning supporting the existence of hot spots where accretion streams impact the outer circular disks of accreting objects. In general, the hot spots in X-ray binaries can be quite a bit more difficult to detect than those in cataclysmic variables. This can be well understood in terms of the fraction of the total energy released as the material falls inwards. If one sets the expected luminosity of an accretion flow due to a fall through a potential from height $r_{\text{out}}$ to height $r_{\text{in}}$, then $L = -GM\dot{m} \left( \frac{1}{r_{\text{out}}} - \frac{1}{r_{\text{in}}} \right)$. The hot spot luminosity can be obtained by setting $r_{\text{out}}$ to the orbital radius, and $r_{\text{in}}$ to the circularization radius, while the total luminosity can be obtained by setting $r_{\text{in}}$ to the radius of the compact star. For systems with orbital periods of a few hours, the few $\times 10^9$ cm radii of white dwarfs will typically be of order 10% of the circularization radii, so a substantial fraction of the luminosity will be produced at the hot spot. For X-ray binaries, the fraction of the power produced at the hot spot will be a factor of order 1000 smaller. Hot spots can thus be detected in black hole and neutron star accretors only if either the mass transfer rate is extremely low, and hence the radiative efficiency of the inner accretion flow is extremely small, or in the more common case, the systems are transients, and are being observed during a quiescent period, in which the accretion rate into the outer accretion disk far exceeds the accretion rate onto the central compact object (McCintock et al. 1995; Froning et al. 2011). The hot spots tend to have a larger vertical height from the disk midplane than do the other parts of the outer disk, so there are also cases, for specific inclination angles, where the hot spot occults the inner disk when it is in the observers path to the compact object (White & Mason 1985). In quiescent dwarf novae, the hot spot luminosity can be a very large fraction of the total luminosity from the system, leading to strong orbital modulations as the viewing angle of the hot spot changes (e.g. Wood et al. 1989).
4.4 Spiral structure: evidence for deviations from simple disk models

The technique of Doppler tomography (Marsh & Horne 1988) allows a form of indirect imaging of accretion disks by looking at how line profiles change as a function of orbital phase. Steeghs (2000) shows two-armed asymmetries in a several cataclysmic variables in outburst using Doppler tomography. The evidence for such phenomena in X-ray binaries is much weaker, although it has been suggested that spiral density wave may help explain some of the large amplitude variability in GRS 1915+105 (Tagger & Pellat 1999).

5 Large amplitude, long timescale variability

One of the most important facets of the behavior of both cataclysmic variables and X-ray binaries is the presence of large amplitude, relatively smooth variations. These are often called dwarf nova outbursts in cataclysmic variables, and X-ray novae, or soft X-ray transient outbursts, in the X-ray binaries. In the X-ray binaries, these transients can lead to variations in the X-ray luminosities of the accreting systems of factors of $10^4 - 10^6$ or more.

As it became clear that the dwarf novae and classical novae, often seen in the same objects, were fundamentally different phenomena, two models emerged for explaining the dwarf novae. Both involved modulating the accretion rate onto the compact object. In one model, the mass transfer instability model, the rate at which mass enters the accretion disk is variable, while in the other model, the disk instability model, mass is supplied to the accretion disk at a constant rate, but there are instabilities in the way the mass flows through the disk. I will argue in this article that there is evidence supporting, if not demonstrating conclusively, the idea that both of these mechanisms apply at least some of the time.

5.1 Mechanisms for large variations in luminosity

Some mechanisms for producing mass transfer rate variations may be irradiation of the donor star by the accretor (e.g. Hameury et al. 1986; Harpaz & Rappaport 1991), magnetic activity cycles in the donor stars (e.g. Bianchini 1990), or changes in the eccentricity of the orbit of the inner mass transferring binary in a hierarchical triple system (e.g. Hut & Paczynski 1984; Maccarone 2005; Zdziarski et al. 2007). Mass transfer rates depend on the gas density at the inner Lagrange point. The pressure scale height in a stellar atmosphere is typically of order $10^{-4}$ of the orbital separation. Therefore, changes in either the radius of the star or the orbital separation of the binary can lead to large changes in the mass accretion rate of order $10^{-4}$ could lead to factors of a few changes in the mass transfer rate. Thus, the lack of direct evidence that these changes should not be taken as proof that the mass transfer rate is not changing via these mechanisms. Strong evidence for mass transfer variations can come in the form of finding variations in the accretion rate when one averages over timescales much longer than any reasonable timescale for

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3 Classical novae are runaway nuclear fusion episodes on the surface of white dwarfs (Schatzman 1949), and hence have nothing to do with accretion disks, apart from that disks are usually the means by which the gas is transported to the white dwarf.
mass to propagate through the accretion disk. This does not preclude variations in the mass transfer rate which happen faster than this timescale – it is just that such faster variations are likely to be extremely difficult to disentangle from disk instabilities, and as we will show in this article, considerable evidence exists that disk instabilities do explain much of the outburst phenomenology in accretion disks.

The thermal viscous instability is strongly favored as the primary source of disk instability. In this scenario, the viscosity parameter of the accretion disk is a function of the ionization state of the gas, so that when the disk is cold and neutral, the mass flow rate is smaller than when the disk is hot and ionized. Given, also, a temperature-density relationship for the disk, a limit cycle instability will develop for accretion rates within a range commonly seen in binaries with accreting compact objects, so that many of these objects are expected to show outburst cycles as predicted by the limit cycles. The leading alternative, or perhaps complement, to the disk instability model is a model in which the mass transfer rate is varied. An extensive review of the features, successes, and shortcomings of the disk instability model is given by Lasota (2001). I will summarize some of the major points presented in that work, but will focus in this section on the observational developments since that time.

5.2 The thermal-viscous instability and stability criteria

The basic first order predictions of the disk instability model are seen to be followed pretty well by most transient accreting compact objects. By and large, the systems which have accretion rates high enough that one would expect their disks always to be fully ionized are persistent, and the systems which have accretion rates lower than that value are transient (Lasota 2001; see Coriat et al. 2012 for a confirmation that the result still holds with a much larger sample of objects). A particular system near the threshold for stability is persistently accreting, but shows large amplitude variability (Maccarone et al. 2010).

An encouraging recent result came from the measurement of a precise geometric parallax distance for SS Cyg. For quite some time it had simultaneously been held up as the prototype system for studying dwarf nova outbursts, and had been a system which appeared to have too high a mass accretion rate to allow the dwarf nova ionization instability to take place. The VLBI parallax distance found by Miller-Jones et al. (2013) indicates that the source is closer than was previously thought. The change of distance results in a mass transfer rate for SS Cyg sufficiently low that the system is below the threshold for stable accretion in the ionization instability model.

5.3 Disk instabilities and peak outburst luminosities

Warner (1987) first found the relation between peak brightness and orbital period for cataclysmic variables, and that has recently been revisited with a larger sample by Patterson (2011) who finds:

\[ M_{V, \text{peak}} = 5.70 - 0.287 P_{\text{orb, hr}}. \]  (1)
The relation between peak optical luminosity and orbital period for dwarf novae. The data are taken from Patterson (2011). The relation is consistent with the $L \propto P^{4/3}$ relation expected from theory. Data points are plotted without error bars for clarity, but the typical errors are $\sim 10\text{-}20\%$ on the peak luminosity, and negligible on the periods.

A least-squares fit of the data from Patterson (2011) to a power law relationship finds that the peak luminosity scales with $P_{\text{orb}}^{1.2}$. These data are plotted in Figure 1. Given the relatively large scatter in the data, it is in fairly good agreement with the predictions for theoretical models which suggest that the whole accretion disk should be at a constant temperature in dwarf novae outbursts (e.g. Osaki 1996; Cannizzo 1998; Smak 2000), yielding a $L \propto P^{4/3}$ relationship.

Some other indications that favor disk instabilities as a baseline model come from looking at the peak luminosities seen from X-ray binaries and from cataclysmic variables. In both cases, these are well-correlated with orbital period (Shahbaz et al. 1998; Portegies Zwart et al. 2004 – P04; Wu et al. 2010). Wu et al. find:

$$\frac{L_{\text{peak}}}{L_{\text{Edd}}} = -1.80 + 0.64 \log P_{\text{orb, days}}$$  \hspace{1cm} (2)$$

for X-ray binaries, although with a different treatment of the bolometric corrections, P04 found a steeper relationship for short orbital periods and a saturation at about the Eddington luminosity for long orbital periods. These data are plotted in Figure 2. In any event, there is at least rough agreement with the finding of King & Ritter (1998) that outburst peak luminosities should scale with the radius of the accretion disk.
Fig. 2 A replotting of the data presented in Portegies Zwart et al. (2004), which shows that the peak X-ray luminosity for X-ray transients increases with orbital period. Unlike for the cataclysmic variables, irradiation is expected to be important, the distances are in many cases very poorly known, the bolometric corrections can be uncertain, and some systems may remain in radiatively inefficient states, so it is difficult to make quantitative comparisons between theory and data.

5.4 Outburst durations

The durations of outbursts of many, but not all, systems, are relatively well in-line with the expected viscous timescales of the accretion disks for the black hole systems (see e.g. Chen, Shrader & Livio 1997; P04). The outburst durations are shorter than the viscous timescales for the CV accretion disk, where irradiation is not important, and so cooling fronts can truncate the outbursts before the entire disks are accreted (Lasota 2001). Some significant amount of the data which represent exceptions to the basic ionization instability may be explained as the result of tidal effects (see section 5.5.1).

5.5 Phenomena which are hard to explain in terms of disk ionization instabilities

While the ionization instability explains the phenomenology of X-ray binary and CV outbursts in broad brushstrokes, there are phenomena which are clearly not in agreement with that picture. In the cataclysmic variables, where the recurrence times between outbursts tend to be much shorter than in X-ray binaries, it can be clearly seen that there are variations from outburst to outburst in ways that
have been fit, to date, only by adding in truncations of the inner accretion disk and variations of the mass transfer rate (e.g. Schreiber et al. 2003; Lasota 2012). There are a few other cases where strong evidence for mass transfer instabilities are expected. A prime recent example among black hole candidates is the ongoing outburst of Swift J1753.5-0127, which has been in outburst since 2005, and has an orbital period of about 3.2 hours (Zurita et al. 2008). The outburst duration of 8 years (and counting) combined with the short orbital period is something that cannot be explained in terms of an ionization instability model. While the observation of superhumps (see the following section for a discussion of superhumps) in this source (Zurita et al. 2008) should imply that this outburst is a “super-outburst” and hence should be longer than normal outbursts, the super-outbursts in well-studied systems are only a factor of a few longer than the normal outbursts. Several neutron star accretors have also undergone outbursts that lasted far longer than the expected viscous timescales for the systems’ orbital periods (e.g. Wijnands et al. 2001 and references within).

On the flip side, the 1999 transient episode of the accreting black hole XTE J1819-254 showed strong evolution on timescales of a few hours, having reached a flux of about 12 Crab, corresponding to a super-Eddington luminosity for the source (Hjellming et al. 2000; Orosz et al. 2001). The variations were clearly too fast to be the result of some global disk instability, and too strong to have been the result of the normal variability typically seen in X-ray binaries.

An additional line of evidence for variations in the mass transfer rates – perhaps the most direct such evidence – comes from Cantrell et al. (2010). They interpret the blue excess in the light from A 0620-00 in quiescence as coming from the accretion impact spot. In the context of that interpretation, the variability in the quiescent luminosity of the hot spot immediately implies that the rate at which matter is reaching the outer accretion disk is changing strongly as a function of time. The variation in the quiescent ultraviolet flux of the source also supports this interpretation, since the ultraviolet light can be demonstrated even more convincingly than the optical light to come from the hot spot (McClintock et al. 1995; Froning et al. 2011).

5.5.1 Tidal effects

In an X-ray binary, the presence of a donor star means that tidal forces on the accretion disk may be substantial and variable on the orbital period. There are a few observe phenomena which have very well motivated theoretical explanations as coming from tidal effects. There are also a few phenomena which may more speculatively be associated with tidal effects.

One phenomenon which is well-associated with tidal interactions is that of superhumping. Superhumps are oscillations in the light curves of some outbursting dwarf novae and X-ray binaries. There is a critical mass ratio of 0.35 below which CVs in bright states show superhumps, and above which CVs never show superhumps (Patterson et al. 2005). The oscillations occur with a period very close to, but not exactly equal to, the orbital period of the binary. The oscillations are well-explain by a model in which an eccentric instability develops at the 3:1 resonance between the orbital period of the accretion disk and the orbital period of the binary system, and then this disk precesses due to the tidal forces (Whitehurst
Fig. 3 The MAXI data for Swift J1753.5-0127. The system, which had not been observed prior to 2005, has clearly been a bright X-ray source for the duration of the MAXI mission. Given its orbital period of 3.2 hours, its viscous timescale should be much less than a year, and the long outburst cannot be explained in the context of the standard disk instability model.

1988). The limit on the mass ratio is then given by the limit that the accretion disk not be tidally truncated inside the location of the 3:1 resonance region.

The superhumping behavior is associated with “super-outbursts” of these systems. Most of the cataclysmic variables which show superhumps show a sequence of outbursts, in which some small fraction of the outbursts are significantly brighter than the rest of them. For example, in V1504 Cyg, which has been well-studied with Kepler, the superoutbursts happen about once for every 14 normal outbursts (Osaki & Kato 2013).

The prevailing view for these phenomena being so well coupled is that the thermal-tidal disk instability explains both effects (e.g. Osaki 1996). In this model, the outbursts of the disk are caused by the standard thermal instability model, discussed above. The outer edge of the accretion disk moves outwards during each normal outburst. After a series of normal outbursts, the disk is outside the 3:1 resonance radius, and the next normal outburst triggers the tidal instability, which drives in material from far out in the disk, leading to an increased peak accretion rate and outburst duration. A modification of the tidal instability model has been proposed by Truss et al. (2002) to explain the re-brightening in soft X-ray transients. In their model, they suggest that irradiation of the outer accretion disk is uneven. Tidal forces cause the location of the irradiation region to change, allowing for the originally un-irradiated region to become irradiated later, allowing,
at a relatively late time, a new portion of the disk to become hot and enter a high viscosity state.

Superhumps have also been seen in several short period X-ray binaries (e.g. O’Donoghue & Charles 1996; Zurita et al. 2002; Zurita et al. 2008; Wang & Chakrabarty 2010; see also Wachter et al. 2002 for a more tentative result). The emission modulation mechanism in the CVs is thought to be tidal modulation of the viscosity, a mechanism which cannot work in low mass X-ray binaries because such a small fraction of the energy is dissipated in the outer accretion disks of X-ray binaries (e.g. Haswell et al. 2001).

Among the X-ray binaries which have shown some evidence for superhumps are short period black hole X-ray binaries (e.g. Nova Mus 1991, GRO J0422+32, XTE J1118+480 and Swift J1753.5-0127), and a few recurrent transient neutron star X-ray binaries (4U 1608-52 – Wachter et al., 2002; and Aql X-1 – R. Jain, private communication – and see also the discussion in Wachter et al. 2002 ). Interestingly, the two recurrent transient neutron stars are known to show outbursts with different amplitudes – e.g. Aql X-1 seems to show some kind of outburst roughly every 100 days, and a more major outburst every 300 or so days (Maitra & Bailyn 2008). There is also evidence for superhumping in the ultracompact X-ray binary 4U 1820-30 (Wang & Chakrabarty 2010) – this system is persistently bright, and at a short orbital period.

The black holes which have been seen to show prominent superhumps in recent years have not shown outbursts of varied amplitude. It may be, however, that these systems have shown only super-outbursts. This idea has been put forth by Maccarone & Patruno (2013) as part of the reason why some short period black hole X-ray binaries seem to be brighter than one might expect given the Wu et al. (2010) relation, and might then allow for the normal outbursts of the short period black hole X-ray binaries to manifest themselves as very faint X-ray transients (see also Knevitt et al. 2013 who discuss how short period transients may be absent from all-sky surveys). Such a scenario is strongly bolstered by finding superhumps in the bright outbursts from short-period systems. It is worth further noting that the “normal” outbursts from such systems, because of radiative inefficiency for black holes in the low hard state, should be ~ 10 times fainter than their superoutbursts, rather than just the factor of a few difference seen for the CV superoutbursts and the candidate superoutbursts in the neutron star X-ray binaries.

5.6 Large amplitude variability in active galactic nuclei

A much harder question to answer is whether active galactic nuclei are susceptible to the same type of accretion disk instabilities as X-ray binaries. In principle, they should be, as their accretion disks are much cooler than those of X-ray binaries, but theoretical calculations suggest that the outbursts may be quite a bit less dramatic than in X-ray binaries (Hameury et al. 2009). Determining observationally whether they do have outbursts is complicated by the fact that the typical one month timescales for outbursts of X-ray binaries, if scaled up to even the smallest, $10^6 M_\odot$ black holes in AGN, would take place on timescales of several millenia. Evidence for a rather sharp variation in the luminosities of the Galactic Center can be seen by looking at reflection spectra from molecular clouds, which indicate that it was
several orders of magnitude brighter about 100 years ago than it is now (e.g. Ponti et al. 2010) – still, there is no observational means to determine whether this variation was due to changes in the mass transfer rate into the AGN’s accretion disk, or changes in the rate of flow through the disk. Koerding et al. (2006) found that the spectra of active galactic nuclei are consistent with following a hysteresis loop like that followed for black hole and neutron star X-ray binaries (Maccarone & Coppi 2003), which is suggestive of the idea that the AGN pass through similar outburst curves, but this merely suggestive evidence is the strongest evidence to date that AGN actually do have outbursts due to disk instabilities, rather than that they merely should have such outbursts.

6 Mass loss from accretion disks

The evidence for disk winds in active galactic nuclei has been well-reviewed by Ken Pounds in this volume. In X-ray binaries, similar types of evidence for disk winds – the discovery of X-ray absorption lines which appear to be dependent on inclination angle and on source spectral state (e.g. Diaz-Trigo et al. 2006; Neilsen & Lee 2009; Ponti et al. 2012). X-ray binaries provide an additional means of searching for evidence for disk winds. The mass transfer rates can be estimated from both the luminosities of the hot spots in quiescence, and from binary evolution modelling. These can then be compared with the long-term mean luminosities of the system, which provide an independent estimate of the mass accretion rate. If the mean mass transfer rate from the donor star is substantially larger than the mean mass accretion rate by the accretor, then there is additional evidence in support of winds being important. This methodology, too, shows that substantial mass loss is likely to be taking place from accretion disks around black holes (e.g. Froning et al. 2011).

7 Gravitationally lensed quasars

Ideally, one would like to learn about the structures of accretion disks by imaging them, rather than by testing models of their spectral or variability properties. Good prospects exist for making millimeter VLBI images of a very small number of very nearby galactic nuclei (e.g. Doeleman 2008). Relatively little hope exists in the near term for making direct images of a large sample of black hole accretion disks spanning a range of flux levels, and relatively little hope exists for doing small scale direct imaging at frequencies other than in the millimeter through sub-millimeter band.

A technique has been exploited for making indirect imaging measurements of the accretion flows around active galactic nuclei – namely using gravitationally lensed quasars (see e.g. Chen et al. 2012 for an extensive discussion of recent results; Chang & Refsdahl 1979 for the first discussion of the possibility). When 4

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4 In the longer wavelength radio bands, an alternative indirect imaging technique has recently been applied – the examination of the details of interstellar scintillation properties of a source (Macquart et al. 2013). This technique is useful only for very compact radio bright objects – i.e. core dominated active galactic nucleus jets – and since this article is concerned with disks, we do not discuss the technique except to point out that it exists.
a quasar is behind a galaxy or group or cluster of galaxies, two types of lensing take place. The first is that the effect of the “smooth mass” of the lens (i.e. the lens's dark matter halo plus the sum of the stars) leads to the production of multiple images of the background object. The second is that individual stars in the lensing galaxies may microlens the background object. For cases where the lensed background source is much larger than the stars, the effects of the microlensing process are small, since then only a small part of the object is microlensed at a time. As a result, the magnitude of variability due to microlensing can be used to probe the size scale of the background object relative to the sizes of the stars doing the lensing.

By observing the amplification factors due to microlensing at different wavelengths, one can map out the size scale of the accretion disks versus wavelength. The technique of choice for such work is time series analysis of microlensing. In the ideal case, the system will be well enough studied that the time delays due to the different path lengths light travels to form each of the observed multiple images are known. Then one can correct for these time delays, and remove the variability intrinsic to the quasar, so that the variability due to microlensing can be isolated (e.g. Morgan et al. 2008, 2010).

It can be difficult to arrange large numbers of epochs of monitoring data in the X-rays, particularly when arcsecond angular resolution is needed, and only Chandra can provide the necessary data. The optical monitoring data are more readily obtained. As a result, methods which invoke less intensive X-ray coverage are desirable. Pooley et al. (2006) show that optical data can be used to determine the magnitude of the optical microlensing anomalies, and then a single X-ray epoch can be used to estimate the variance in the X-ray magnifications due to microlensing in a statistical sense, from the variance in the X-ray images' brightnesses. This can still often yield important information about the size scale of the X-ray emitting region, while using considerably less time on the most oversubscribed telescopes.

A few key results come from Morgan et al. (2008;2010)'s studies: that the optical continuum comes from regions with spatial scales of $\sim 100r_g$, that the X-ray continuum comes from regions with spatial scales of $\sim 10r_g$, and that the Fe K$\alpha$ emission typically comes from regions even smaller than the X-ray continuum. Microlensing of the broad line regions of quasars – by the sheer fact that any microlensing is detected at all – indicates that the broad line regions are not spherically symmetric (Sluse et al. 2012).

Chen et al. (2013) have shown that the gravitational lensing by the quasar’s own black hole can lead to factor of $\sim 2$ systematic errors on the estimates of the spatial scales. This result applies primarily to the small X-ray emission regions, since for much spatial scales of more than tens of Schwarzschild radii, the effects of light bending by the black hole are very small. Usually, the size of the emission region will be under-estimated, but the direction and magnitude of the effect depend on the inclination angle of the accretion disk, the spin of the black hole, and the emissivity profile of the accretion disk. These errors are of the same order as errors in black hole masses from most techniques used for active galactic nuclei. Chen et al. (2013) also find that subtle differences in the time delays for different images should be detectable with excellent microlensing campaigns. With good enough data, the inclination angles and spins of black holes in quasars might be measurable using microlensing – giving measurements independent of those which come e.g. from iron line measurements.
It is important to note that low luminosity active galactic nuclei have not yet been well-studied using these techniques, and may have different accretion geometries – the systems which have been analyzed are all bright quasars. The finding of very small X-ray emission regions thus does not have any clear implications for the controversy about whether the thin accretion disks around black holes in X-ray binaries are truncated, with an inner advection dominated region emitting most of the hard X-rays (see e.g. Rykoff et al. 2006; Kolehmainen et al. 2013). These data thus do not help to resolve the controversies about whether the inner accretion disks in low/hard states are truncated, or extend into the innermost stable circular orbits – although the technique is, in principle, useful for resolving such controversies in low luminosity AGN, if lensed LLAGN can be discovered which are bright enough to perform such studies. While there has been a recent discovery of a candidate low luminosity AGN with short time delays between the different images and flux ratio anomalies (Anguita et al. 2009), this particular object is extremely faint (the brightest image is seen at magnitude 24.6 in the 606W and 814W filters with the Hubble Space Telescope), and it is unlikely that it will be useful for understanding the X-ray geometry of low luminosity AGN.

8 Summary

Several key pieces of accretion disk theory show good agreement between models and observations – the basic structures of the accretion disks as geometrically thin, and optically thick in their outer parts, and the existence of hot spots and spiral arms are all well established. At the same time, there is much about accretion disks which is of great importance which is not fully understood – particularly the development of a theory of why and how accretion disks vary. A great deal of the observed phenomenology agrees with the basic picture of the hydrogen ionization instability model. Particularly, the accretion rate above which systems becomes stable is in good agreement with the predictions of that model, as is the relationship between outburst peak luminosities and system orbital periods. At the same time, there are observational results, such as the duration of the outbursts of several short period X-ray binaries, that probably require mass transfer variations as well, and the detailed shapes of the outbursts are not always well matched by models.

Acknowledgements The author thanks the conference organizers for having promoted a series of stimulating discussions. He also thanks the Avett Brothers, whose sublime Magpie and the Dandelion made the process of finalizing this manuscript far more enjoyable than it would have been otherwise.

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