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What do Quasars Look Like?

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Abstract: Microlensing observations may give us the first nano-arcsecond scale information about the structure of quasars. I review what is currently known about quasars on these scales, highlighting the principal uncertainties. I cover both the continuum emission and the broad line region. I conclude that little is firmly known about the structure of quasars.

Keywords: quasars: general

1 Introduction

Gravitational microlensing has already provided some of the tightest constraints on the structure of quasars (e.g. Rauch & Blandford 1991). Future observations, many of them reviewed at this meeting, should yield considerably more information on the nano-arcsecond scale structure of quasars (e.g. Wambsganss, Paczynski & Schneider 1990; Wyithe, Webster & Turner 2000).

In this review, I summarise what has been learned about the micro-arcsecond structure of quasars by *non-lensing* techniques. I will concentrate on the hypothesised accretion disk surrounding the central black hole (Section 2), and on the broad emission line region (BLR, Section 3). A review of this length must necessarily be incomplete and biased: readers should consult books such as Weedman (1986) and Peterson (1997) for more comprehensive references.

Some scales: at redshifts greater than one, a micro-arcsecond corresponds to a proper scale of around 1600 AU, or 0.01 pc. The Schwarzschild radius of a 10^8 solar mass black hole is 2 AU.

2 The Continuum Source

The optical and UV continuum emission of most quasars is thought to come from an accretion disk, surrounding a massive black hole. In this section, I review the properties of such a disk. I will first discuss the standard Shakura & Sunyaev (1973) disk model, pointing out the observational problems with it. I will then briefly review some recently proposed changes. For more detailed information, see the excellent review by Koratkar & Blaes (1999).

2.1 The Standard Model

The biggest uncertainty with modeling a quasar accretion disk is the nature of the viscosity. Normal gas viscosity is several orders of magnitude too weak too explain the observed luminosities of quasar disks, and until recently no clear alternative had emerged.

Shakura & Sunyaev (1973) showed that if you make three strong assumptions, then you can estimate many of the properties of the disk without knowing anything about the viscosity. The approximations are that the disk is geometrically thin, that there is no significant mass loss in a disk wind, and that all the gravitational potential energy lost by infalling matter is radiated locally (e.g. Blandford 1990).

In this approximation, the luminosity per unit area of the disk surface must be inversely proportional to the distance from the black hole. If the disk radiates as a black body, this means that the inner regions of the disk will be hotter and bluer than the outer regions ($T \propto r^{-1/4}$). The disk will have an inner hole, set by the inner stable orbit around a black hole, which is smaller for Kerr black holes than for Schwarzschild holes (Sun & Malkan 1989).

This simple model clashes with the observations in two serious ways. Firstly, if it is assumed that each section of the disk radiates as a black body, the predicted spectrum has the form $F_\nu \propto \nu^{+0.3}$, where F_ν is the emitted flux per unit frequency and ν is the frequency. This is much bluer that the observed colours of even the bluest quasars, which have $F_\nu \propto \nu^{-0.3}$ (Francis 1996). Secondly, this model predicts that different parts of the continuum spectrum should come from different parts of the disk, blue light from close in and red from further out. Monitoring of some local AGN, however, shows that variations in the blue and red light appear to be simultaneous, with an upper limit on any time lag of less than 0.3 days (e.g. Edelson et al. 2000, and references therein). This is several orders of magnitude less than any plausible sound travel time between the blue- and red-emitting regions of the disk. It is unclear what causes the variability in quasar fluxes, but whatever the cause, it should not propagate faster than the sound speed.

2.2 Refinements to the Standard Model

A great deal of work has been done to refine the standard model. Thick disks, slim disks, ion tori and much more have been added. Unfortunately, the presence or absence of all these features depends crucially on the

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nature of the viscosity, which until recently was unknown. Indeed, more detailed modelling of the emission from the disk surface, and its radiative transfer, have introduced two more predictions that contradict observations (Koratkar & Blaes 1999, and references therein). Firstly, electron scattering should polarise the disk emission, with an E-vector perpendicular to the axis of rotation of the disk. This is the opposite orientation to the weak polarisation sometimes seen. Secondly, the opacity of the disk atmosphere should increase by several orders of magnitude at the Lyman limit, 91.2 nm. This should produce a strong break in the continuum spectrum, but no such break is seen.

General relativistic effects have been added to some models. The gravity of the central black hole deflects the blue light from the inner region of the accretion disk, directing it preferentially close to the surface of the disk (e.g. Sun & Malkan 1989).

X-ray spectroscopy has revealed possible reflection components, and the Fe Kα emission line, both of which may be signatures of X-rays reprocessed by the cold surface of an accretion disk, though other models are also possible (e.g. Nandra et al. 1997). These have led to a model in which the gravitational potential energy of the infalling disk material is emitted as X-rays in a disk corona, not as black body radiation from the disk surface. A feedback cycle applies: the disk is heated by X-rays from the corona, and hence emits UV and optical light. This light is in turn Compton scattered up to high energies by the corona, thus producing the X-rays (e.g. Haardt & Maraschi 1991).

If the X-rays are produced in a small region, perhaps by a magnetic flare, this could explain the observed simultaneity of the variation at different optical and UV wavelengths. In at least one well studied Seyfert galaxy, however, the X-ray and optical variations are uncorrelated (Edelson et al. 2000).

2.3 Recent Developments

Within the last few years, a consensus has at last emerged about the nature of the viscosity in AGN accretion disks. Magnetic instabilities (e.g. Balbus & Hawley 1991) are both inevitable, and provide adequate viscosity. The consequences of this instability have yet to be worked out in detail, though a first few attempts have been made (e.g. Machida, Hayashi & Matsumoto 2000). It is clear, however, that a magnetically unstable disk is a very chaotic, non-axisymmetric system. Its emission is dominated by individual flares, so the peak surface brightness may not lie at the centre. The accretion disk may look like an X-ray picture of the surface of the Sun, rather than the nice uniform circles of most illustrations.

A flaring disk will expose accreting matter to the full intensity of the quasar's radiation field. Radiation pressure will thus drive strong disk winds. These winds may be so strong that the accretion disk is completely concealed in a photosphere of expelled matter. Thus we may not be observing the disk at all, but simply a reprocessing atmosphere (e.g. Barvainis 1993; Dopita 1997).

3 The Broad Emission-Line Region (BLR)

The broad emission lines are characterised by velocity widths of order 5000 km s^{-1}. In this section I review what little is known about the structure of the BLR. For lack of space, I will ignore the important issue of the broad absorption line winds. Once again, I will present the 'standard model', and then point out its flaws.

3.1 The Standard Model

The standard model developed out of photoionisation modelling of HII regions and other galactic nebulae (e.g. Osterbrock 1989). In this model, the BLR consists of a number of discrete small fast-moving clouds. The clouds are all at roughly the same distance from the black hole, and all have roughly the same density. They are photoionised by the UV and X-ray continuum emission from the central regions.

This model suffers from many fatal flaws. Firstly, quasar emission line profiles are extremely smooth (Arav et al. 1998; Dietrich et al. 1999). This either implies that the BLR actually consists of a smooth continuous flow, or that if it consists of individual clouds, there must be at least 10^8 of them.

Secondly, both variability mapping and statistical studies show that the BLR is stratified (e.g. Peterson 1993; Brotherton et al. 1994; Baldwin et al. 1995). The fastest moving parts of the BLR lie only around 0.1 pc from the nucleus, while the slower clouds, which make up the cores of the emission lines, come from around 1 pc out. No two emission lines come from the same region. Some lines may, indeed, be collisionally excited and come from the outer regions of the accretion disk (e.g. Dumont, Collin-Souffrin & Nazarova 1998).

Thirdly, any clouds moving supersonically through the interstellar medium surrounding the quasar will rapidly disintegrate as shocks are driven into them. Some form of confinement, perhaps magnetic, would be needed to keep any small clouds together for even a fraction of a crossing time (e.g. Rees 1987).

3.2 Velocity Structure

How is the line-emitting gas in the BLR moving? In luminous quasars, different emission-lines are offset in velocity from each other (e.g. Marziani et al. 1996), implying some combination of bulk radial motion with obscuration. In the few local AGN with variability mapping data, however, no clear signature of either inflow or outflow is seen (e.g. Peterson 1993). A wide variety of models have been proposed, involving jets, disk winds, orbital motions, line emission from the disk, and much more, but no consensus has emerged. The broad absorption line flows that probably exist in all radio-quiet QSOs probably play a crucial role in this. The velocity offsets between different emission lines differ between radio-loud and radio-quiet quasars (e.g. Corbin & Francis 1994), so the radio jets may also play a part.

4 Conclusions

After three decades of work, it is embarrassing to report that we cannot yet come up with even a rough sketch of the central regions of a quasar. Gravitational microlensing may help in a variety of ways. Examples might include:

- If the accretion disk has a colour gradient (with, for example, the bluer regions nearer the centre) then the quasar should exhibit colour changes during a microlensing event. This is a test of the standard model.
- If the continuum emission comes from individual, off-centre flares, disk rotation may cause each flare to cross a caustic many times during a lensing event.
- If the emission line region has an ordered velocity field, line profiles will change during a microlensing event.

The details are beyond the scope of this review, but any information lensing can provide will be very welcome indeed!

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