Modelling the UV and Optical Emission from Accretion Disks around Supermassive Black Holes – Summary Report

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Extragalactic astronomy, the study of objects outside of our home galaxy (the Milky Way), is an area at the forefront of modern science filled with many unsolved mysteries. One of these mysteries relates to the variation in the amount of light we receive from active galactic nuclei (AGN - defined in the next paragraph) here on Earth. We would expect the total amount of light being emitted, the 'luminosity', from an AGN to be roughly constant. However, when scientists make observations of AGN they find AGN luminosity appears to vary over periods of approximately 2-5 days. For this project, we attempted to help aid in solving this mystery through modelling of an AGN to explain the observed variability.

AGN are the brightest objects in the entire universe, often outshining every star in their host galaxy combined despite being only a tiny fraction of the size of the entire galaxy. AGN emit across the entire electromagnetic spectrum from radio waves to gamma rays so are extremely interesting for astronomers who study all types of light. Fortunately for us here on Earth, their light has diminished to levels undetectable to the human eye by the time it reaches us, so they do not present a danger to Earth's life. This is because they are so far away, millions (or often billions) of light years distant. AGN live in objects known as active galaxies. Active galaxies are divided into many different classes, depending on their observed characteristics and brightnesses across different parts of the electromagnetic spectrum. The brightest active galaxies are known as quasars. These have AGN so bright that they make their host galaxy undetectable. A more common, but less bright, type of AGN live in Seyfert galaxies. Seyfert galaxies are thought to be not too dissimilar to our Milky Way, except they have bright centres harbouring an AGN.

It has been argued, since at least the 1960s, that AGN are powered by gradual continuous matter accumulation from a disk onto supermassive black holes with masses at least a million suns, a process known as *accretion*. This is not necessarily an obvious result, especially given that black holes are the darkest objects in the universe. They are so dense that when even light, the fastest thing in the universe, gets too close it cannot escape. Most AGN are believed to be located at the centre of their host galaxy, a very crowded and chaotic region. The material (mostly hydrogen) located here orbits the central black hole, forming a flat disk shape. The copious amount of frictional and gravitational processes present causes the disk to heat up and lose angular momentum (the rotational analogue of 'linear' momentum which an object moving in a straight line has). The heating causes the disk to be very bright and the loss of angular momentum causes the material to gradually fall towards the black hole. The current leading theory of AGN structure, the *Unified Model*, consists of not just a central black hole and an expansive accretion disk; but a cold, dusty, torus (a doughnut shaped-region) and a blazing x-ray emitter known as a *corona*. There are also broad-line regions (BLR) and narrow-line regions (NLR), both named after the characteristic bright lines which appear if you split their light into its different components. Sometimes jets of material moving at nearly the speed of light are also present. A depiction of a 'typical' AGN can be seen in figure 1.

The timescale it takes for an AGN's luminosity to change appreciably can be used to work out the rough size of the AGN system by imposing that information cannot travel faster than light can, a consequence of Einstein's famous *special relativity*. This fact can be described by applying the simple distance-time equation to the AGN system: Distance = (Speed of Light) $\times$ (Timescale). This technique is known as *reverberation mapping*. Measurements via reverberation mapping tell us that AGN systems are normally many times larger than our solar system. However, this is still a very small fraction of their host galaxy's size.

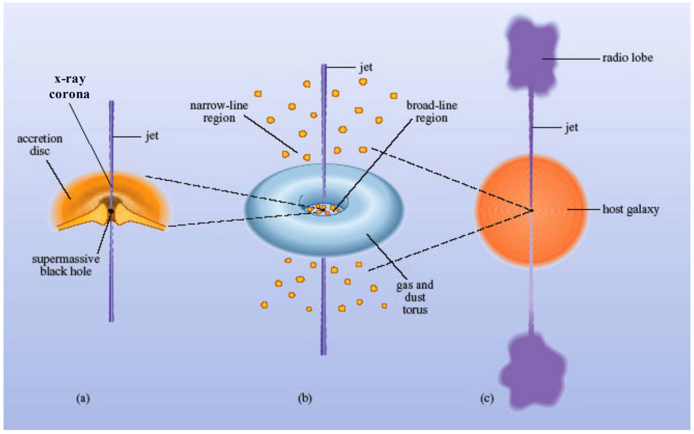

Figure 1: A 'Russian doll' style diagram of a theoretical typical AGN system. (a) The central supermassive black hole is surrounded by an accretion disk and a small but powerful x-ray corona close by. Jets sometimes spew out near the top and bottom of the black hole, a very poorly understood mechanism. (b) The broad-line region is sandwiched by the outer accretion disk and inner dusty torus. A narrow-line region is also present but further out. (c) The jet is very large compared to the host galaxy, often reaching out many times further than the edge of the galaxy forming enormous radio lobes at its ends. Image not created by author. Image credit: Introduction to Active Galaxies. An OpenLearn chunk adapted by permission of The Open University copyright © (2004).

Currently, there are two leading theories that try and explain the observed variability in the UV and optical (light your eye can see) bands. The first suggests that variations in the density of the accretion disk cause variations in its temperature and luminosity. A second, probably more dominant process, is that an x-ray corona situated above the accretion disk shines some of its light onto the disk causing it to heat up and vary in luminosity. This is known as x-ray reprocessing. This process would be similar to heating a piece of metal until it glows and changes colour.

To try and add evidence to the argument, we created a face-on accretion disk-reprocessor model to see if we could explain some light curves from the Seyfert galaxy *NGC 4593*. Light curves are a simple measure of object brightness against time and are commonly used throughout astronomy as an excellent and reliable measuring tool. Due to the distances involved, it is not possible to perform experiments in astronomy; it is an entirely observational science. Therefore, to test our model we had to compare its theoretical light curves with our measured ones. A face-on accretion disk is one where, from Earth, we see a flat side with the black hole in the centre (i.e. looking down one of the jets in figure 1). We expect there to be a rotational symmetry which means if you rotate the system around its centre, it looks identical. Although not realistic, it simplifies the mathematics involved substantially and provides a strong footing for venture into the more general case, known as the inclined accretion disk. The 'reprocessor' part of the name refers to the absorption of x-rays which are then converted into heat.

From analysis of our model, we realised that it was insufficient because it reprocessed the x-rays too quickly and had a timescale of about 1 day as opposed to the measured timescale of 2-3 days. To increase the timescale of our model, we needed an slower reprocessor. The most plausible addition to our model to increase the timescale was the addition of a BLR, theorised to sit between the outer edge of the accretion disk and the inner edge of the dusty torus. By our distance-time equation, we expect its timescale to be longer than the disk's. To test our theory, we compared our model-data discrepancy with some data that other scientists had measured from *NGC 4593*. They measured a timescale of a theoretical BLR region to be about 2-3 days which matched our original model-data discrepancy. We concluded that x-ray reprocessing was the dominant contributor to optical and UV variability but we needed to adapt the 'traditional' accretion disk-reprocessor model by adding a BLR-reprocessor component. In future, we would like to add a BLR to our model so we can perform reverberation mapping allowing us to get an accurate estimate of the size of *NGC 4593*'s AGN.

As an extension to the project, we began creating a more general model for the inclined disk. In doing so, we managed to design a unique algebraic formalism for calculating how an AGN system will reprocess x-rays. This technique has a lot of potential as it allows us to quickly design and test reprocessing models in the future. These tests will enable us to have not only a greater understanding of optical and UV variability, but potentially other currently unsolved mysteries such as how AGN initially form and evolve, and what effects they can have on their host galaxy.