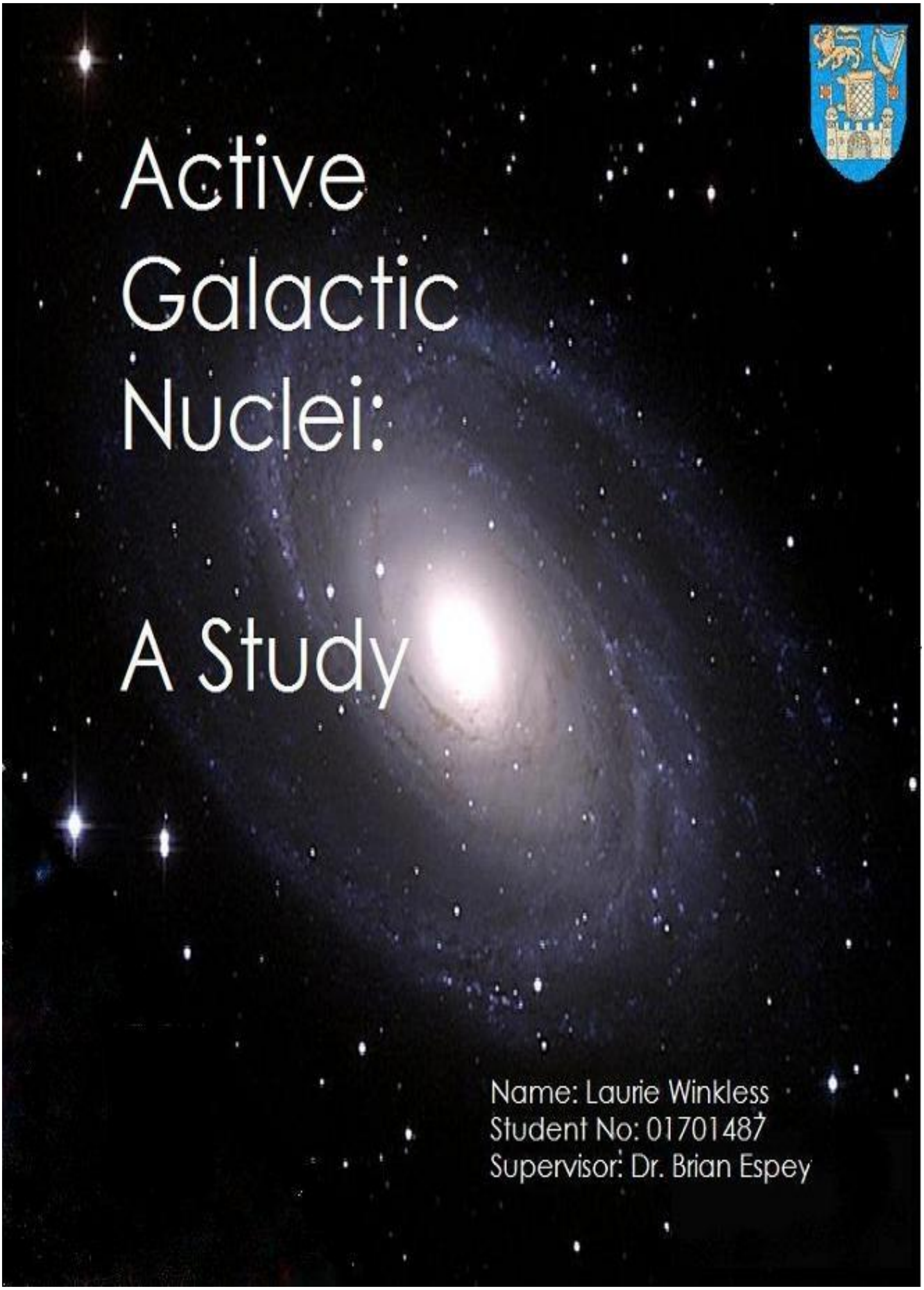

Active Galactic Nuclei:

A Study

Name: Laurie Winkless
Student No: 01701487
Supervisor: Dr. Brian Espey

Abstract

The aim of this project was to analyse a number of AGN in relation to their taxonomy, their properties, their prominent emission lines and other key parameters. To minimise the inherent ambiguities in the data, I used comparative methods to analyse the sources. This involved comparison between a number of independent observations of a particular set of active sources, and a comparison of three telescopes used to observe them. I looked at the accuracy of curve fitting in relation to the CIV line, and the effect of a decreasing resolution on the 'see-ability' of an AGN. I also looked at the effect of different cosmologies on the calculated age of the Universe. This, I found to be 13.65Byrs.

Acknowledgements

I'd like to thank the Physics Department for constant use of its many facilities.

I'd also like to thank Dr. Rassoul from Florida Institute of Technology, who fed me a lot of information, even before I started researching my project, and who was always there if I was really stuck.

And last, but certainly not least, I want to send my warmest thanks to my supervisor, Dr. Brian Espey, for all his support, and seemingly unending patience throughout the process.

Contents

1. Introduction

The study of such high-redshift objects as Active Galactic Nuclei can, by its very nature, result in ambiguous data, as there is all too often no way to absolutely prove or disprove an idea. It is these ambiguities which make this area a highly-debatable and ever-changing one. And it is these ambiguities which lie at the very heart of this analysis.
The aim of this project was to familiarise myself with the most recent and accepted models of AGN taxonomy, their methods of energy production, and any related phenomena.
I analysed spectral data from three telescopes, the HST, IUE and Tytler. Each of these scopes observed a different set of active sources, in relation to their redshift, continuum flux and emission-line strengths, to name but a few of the parameters. For each set of objects, I looked at the measurements of each of these parameters taken by three independent observers. This allowed me to minimise the ambiguities and errors in the data, as much as possible. In those instances in which less data was available, the errors are much more pronounced, and the possible implications much more ambiguous.
Next, I looked at the accuracy of curve fitting in AGN spectra analysis. I compared the asymmetry of the fit of the CIV line for all three of the scopes, and then compared the normalised values of the continuum flux (from each observer) to this asymmetry.
I also looked at one object at varying resolutions, to gain further insight into the possible ambiguities of spectrum analysis.
I finally looked at the effect of imposing a different cosmology on my data, and how this could alter the measured age of the Universe.

I feel the first thing which should be addressed is defining what an active galactic nuclei actually is. According to the Encyclopaedia of Astronomy and Astrophysics, the term **Active Galaxy** is one which refers to any galaxy that produces significant emission in addition to that from its constituent stars, stellar remnants and interstellar medium. From spectral analysis, we see that the emission is non-stellar in origin, and that it seems to originate in the very centre of the galaxy. This, therefore, is where the term **Active Galactic Nuclei** (**AGN**) originates**.** **AGN** are the most luminous, long-lived sources in the universe. They emit strongly over the entire observable wavelength range, from x-rays and γ- rays through to radio. The most powerful examples can radiate a thousand times as much energy as the galaxies in which they are embedded. Many AGN vary in brightness by substantial amounts over timescales as short as years, months, days, or even hours. Because a light source cannot vary over a timescale shorter than the time taken for light to cross the diameter of the source, the energy source in an AGN must be very compact. The nature and implications of this 'central engine' will be discussed in the next section of this report.

2. Theory

2.1 The Central Engine

At optical wavelengths, the emission from most galaxies is dominated by that from the stars. However in at least 10% of galaxies, additional intense emission is also detected from the centre (nucleus) of the galaxy. This emission often far out-shines that from the surrounding stars (often by factors >10^2).
In such galaxies, observations in other wavebands (radio, IR, UV, X-rays & Gamma-rays) often also reveal emissions indicating a variety of non-stellar processes are present. Furthermore the emission from the nucleus invariably has temporal and spectral characteristics which indicate the source of the emission is **not** the result of stellar processes.

- the emission varies too fast to be due to a collection of stars
- the overall spectral energy distribution of the emission is very different to that for stars
- the spectral contain features not observed in stars

Such galaxies are called **"active galactic nuclei"** (**AGN**), or sometimes simply "active galaxies". The more distant (highly luminous) objects are usually referred to as quasars.

As stated above, in other wavebands, the difference between "normal galaxies" and AGN is often far more obvious.

- In the **radio band** a subset of AGN exhibit jets, often ending in lobes far outside the galaxy. These jets emanate from the centre of the galaxy, which is often visible, a point source of emission.
- In the **optical & UV bands**, spectral emission lines are usually present with characteristic shapes and intensity ratios (along with absorption lines and/or jets in some sources).

- In the **X-ray band** the emission from "classic" AGN is totally dominated by a point source at the centre of the galaxy (although diffuse, extended emission and jets are sometimes visible, along with a number of low-luminosity X-ray sources within the galaxy itself).

Traditionally AGN are divided into numerous (often overlapping) sub-classes based on various differences in their observed characteristics. However the current paradigm is that the ultimate energy source in all AGN is similar, and that the observed characteristics are secondary effects of their environment and our viewing angle. (See Figure 2.1)

Some AGN can radiate up to a thousand times as much energy as a conventional galaxy (typical luminosity of 10^9 - 10^{13} $L_\odot$). Not only that, but the region of space the energy is emitted from is comparable in size to our own Solar System!
How can this phenomenon be explained? The current working model is one of a **'central engine'**, consisting of a supermassive black hole, surrounded by a hot accretion disk.
The formation of this 'central engine' would have begun when the host galaxy was young, and the stars in its core were tightly packed. Star collisions and mergers occurred, giving rise to a single massive black hole (10^6 - 10^9 M_o). Gas from the galaxy's interstellar medium, from a 'cannibalized' galaxy, or from a star that strays too close, falls onto the black hole. As in X-ray binary star system, an accretion disk forms, emitting huge amounts of light across the electromagnetic spectrum (infrared to gamma-rays).

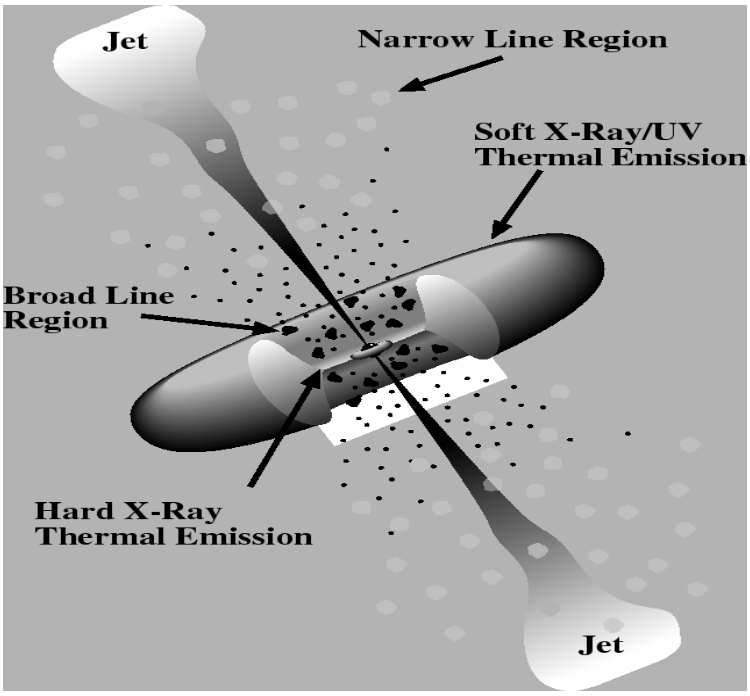

Figure 2.1
Model of a
radio-loud AGN

(From Urry &
Padovani, 1995)

A number of discoveries have led to the widespread acceptance of this **"Black Hole Paradigm"**:

- One of the earliest identified AGN was discovered in M87, which is an E0 galaxy. It was found to have two oppositely directed jets that protrude perpendicular to the plane of the disk. These jets seemed to originate at the central compact source and lead out to the extended lobes. The appearance of jets suggested that there is a transport of energy and particles from the compact source to these extended regions.
- The light curve of M87 showed a sharp rise in luminosity towards its nucleus. It was proposed, that maybe there was an 'attractor' at the centre which pulled a large population of stars towards it, thereby increasing luminosity?
- The detection of very broad, gravitationally redshifted x-ray emission lines in MCG 6-30-15 pointed toward the existence of supermassive ($M>10^7M_\odot$) object in the centre of the galaxy.
- Dynamical studies of the gas in M106 and M87 also advocated the occurrence of a central massive object.

- Velocity dispersion of stars in the nuclear region of a number of galaxies was also shown to rise rapidly inwards. This also suggested the presence of a massive object in the nucleus.

The mass of this central source can be estimated by assuming it is isotropic and stable, and, for simplicity, look at the case of completely ionized hydrogen. Full analysis of this can be found in Appendix One.

2.2 Active Galactic Nuclei: Observations

Variability studies have been essential in understanding the physics of AGN, because the size of the region emitting the enormous amount of energy characteristic of AGN is too small to be resolved. At higher photon energies, more rapid (and higher amplitude) variability is observed. Therefore, we see that x-rays vary more than the optical. AGN emit a continuum radiation from the vicinity of the central black hole. However, they also emit intense, broad emission lines originating in fast moving dust clouds located in a small region around the continuum source.[1]

As was briefly mentioned in the Introduction, the flux level of the continuum and the intensity of the spectral emission lines emitted by AGN can undergo variations on timescales as short as hours. The variability timescales tend to be longer in intrinsically brighter object. When the flux emitted by a source of energy varies significantly with a timescale t, this flux variation sets a limit to the size, R of the emitting region such that $R \leq ct$.

The correlations and delays between the variations of the continuum flux provide information on the nature of the physical processes which produce the continuum. The same could be said for the timescales themselves, the various spectral line intensities, and the regions from which they originate.

[1] This region is known as the **Broad Line Region, see Appendix Two.**

The electro-magnetic spectrum of radio-quiet AGN, after subtraction of the stellar continuum emitted by the host galaxy, extends from ~1mm to ~100keV with a prominent broad peak in the UV-extreme UV (EUV) range, with a secondary peak in the infra-red. The x-ray emission is dominated by a power-law component ($f_\nu \propto \nu^{-\alpha}$) which steepens in the hard x-ray range (>50keV) possibly with a cut-off around 100keV. The observed spectral shape of the continuum of AGN from 1200-5000Å is roughly consistent with thermal emission from an accretion disk. However, the variations of the UV continuum flux occur on timescales of days, weeks or months, which are shorter, by many orders of magnitude, than the timescales expected from variations in the accretion rate. Observations of NGC 4151 and NGC5548 showed a correlation between x-rays and UV emission on short timescales. This suggested a model where the surface of the disk is irradiated by the central variable x-ray source.

The variability of the x-ray source is due to **explosive reconnections** of magnetic field lines permeating the accretion disk and the corona. This corona is heated using accretion energy. The hot photons from this process transfer some of their energy to UV photons (emitted by the disk) and soft x-ray photons. They, in turn, produce medium and hard energy x-ray photons via inverse Compton emission. This **Comptonization and Reprocessing model** explains the observed correlation between x-ray and UV emission in NCG4151 and NGC5548.

This model does not hold true for all AGN, but a close look at the data reveals a striking similarity of the variations in the two energy ranges. Thus, we can say that the basic link between the two is provided by Comptonization.

2.3 Emission Lines

Much of our understanding of AGN is due to their emission lines.

Emission line intensities and emission line ratios supply information on the physical conditions in the line emitting gas. The electron density and temperature, the degree of ionisation and excitation, and the chemical composition, can all be deduced from line ratio analysis. An example of a typical AGN spectrum can be seen in Figure 2.3.

The first question which must be asked is how do we explain the observed emission lines? There have been two models offered to do just this:

The first of these models centres on the **BLR** and the **NLR.** The most obvious feature of spectral observations is the division into broad and narrow emission lines, which seem to emanate from two distinct regions in the nucleus. The first is called the 'Broad Line Region' (BLR) and the second is the 'Narrow Line Region' (NLR). The physical properties of each of these regions are listed in Appendix Two. The division into these two regions works well for modelling AGN.

The second of these models is called the **Photoionisation Model**. Photoionisation is the most likely source of excitation for the emission line gas in AGN. The evidence for this is provided by the correlations between the variations of the continuum (See section 2.2), of, for example, Seyfert 1 galaxies, where changes in the luminosity of a line clearly relates to changes in the continuum luminosity. An important concept in this model is that of a 'cloud', introduced to distinguish entities in the emission line region. The presence of MgII and FeII shows that the broad-line gas is optically thick. Also, in many cases, the low and the high ionisation lines have similar profiles. Thus, it is reasonable to assume that there are many optically thick clouds, each one producing the emission lines in approximately equal proportions. A related, but somewhat alternative picture is that of a spherical shell around the ionising source, which produces high excitation lines from its inner part and low excitation lines from its outer part.

Other models have also been proposed. For an overview of these, please turn to Appendix Three.

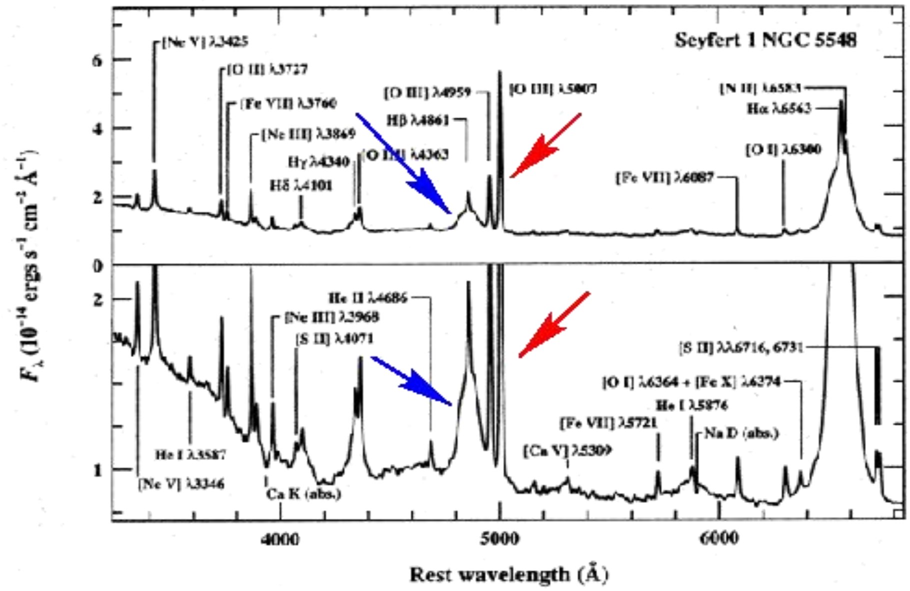

Figure 2.3
Example of broad and narrow emission lines. Blue arrows indicate broadened lines, while red indicate narrow lines. Spectrum is from the Seyfert I galaxy NGC 5548 (Adapted from [Peterson, 1997)](#)

Whichever model turns out to be correct, there are standard ways in which to analyse the emission lines, there are three types of primary observations, and three corresponding ways of analysis, which can be used. They are related to the **line intensities**, the **line variability** and the **line profiles**. These three methods are outlined in Appendix Four.

2.4 Spectral Energy Distributions

The SEDs of normal stars (and galaxies) are well approximated as blackbodies in the temperature range of 2000-50000K, and thus, their emission is strongly concentrated in the UV through IR parts of the spectrum. In contrast, the continuum spectra of AGN are quite complex. They emit comparable energy (per unit log bandwidth) over most of the observable spectrum.[3]

[3] One exception is the radio region, in which radio-loud AGN are three orders of magnitude brighter than their radio-quiet counterparts.

As mentioned earlier, the SEDs of AGN can be approximated to a power-law of the form $f_\nu \propto \nu^{-\alpha}$ where α is found to be between zero and unity. This power-law format is what led to the idea that this continuum is **non-thermal** in origin. Relativistic electrons in a magnetic field can produce a synchrotron spectrum, over many decades of frequency, if given a power-law distribution of energies.

So, the temptation to attribute the bulk of AGN spectrum to synchrotron emission is an understandable one, primarily because of the broad-band energy characteristics of the emission. There is also a similarity between AGN spectra and those of synchrotron sources, such as supernovae. What sort of model could be used to describe this broad-band continuum of AGN?

By the end of the 1970's, the accepted model was called the **synchrotron self-Compton (SSC) mechanism**. Via this process, it is possible, in principle, to produce the required higher-energy emission, all the way to X-rays.

Let us look at some of the features of the spectral energy distributions of AGN by looking at a sample of AGN (See Figure 2.4 below):

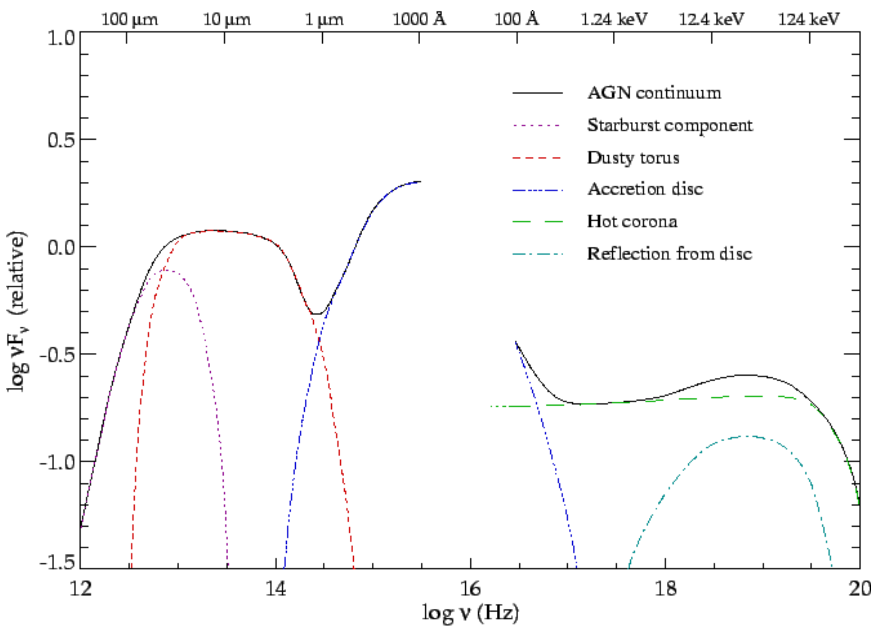

Figure 2.4
Mean SEDs (Spectral Energy Distributions) for a sample of AGN. (Courtesy of Elvis, et al, 1994)

Note the absence of observations at high energies (γ-rays). This is due to technical limitations.

1. The Extreme Ultra-Violet gap (912Å -0.1keV) is due to the large opacity (absorption by neutral hydrogen) of the ISM in our own galaxy. The photons which cause this large opacity are the cause of the strong emission lines seen through the UV and optical spectrum of the AGN.
2. The gap between the submillimeter and short-wavelength radio is due to the opacity of the Earth's atmosphere on account of water vapour absorption at certain wavelengths.
3. The most prominent feature of AGN SEDs is the strong peak in the UV spectrum. This feature is known as the 'Big Blue Bump' (BBB) and it begins in the near-IR and can extend all the way to soft x-ray energies. It arises from the morphology of the AGN. The BBB peaks in the extreme UV which is consistent with the expected emission from an accretion disk around a ≈$10^8 M_\Theta$ black hole that is accreting material at the Eddington Rate (see Appendix One).

So, we can see that although the spectrum can be approximated by a power-law, it is the often overlooked features, such as broad depressions and bumps, which provide important clues to the origin of the emission.

And the fundamental question about AGN spectra is how much of the spectrum is thermal emission, and how much is non-thermal? That is, how much of the emission is due to particles which have attained a Maxwellian velocity distribution by collisions, rather than those whose velocities are not described by a Maxwell-Boltzmann distribution. A closely related question is how much of the emission is **primary,** i.e., due to particles powered directly by the central engine (synchrotron-emitting particles) or thermal emission from the accretion disk. From that, we can then determine how much is **secondary**, i.e., emitted by gas which receives its energy from the primary processes, but then re-radiates the emission (free-free emission from an ionised gas).

2.5 Spectral Variability

One of the most remarkable characteristics of AGN is their strong flux variability. As was mentioned briefly earlier, the very existence of intra-day continuum variability puts an upper limit (set by light travel time) on the size of the continuum source. This provides one of the strongest arguments for identifying an accretion disk around a supermassive black hole as the source of continuum radiation. The cause of continuum variability is not understood, although accretion disk instabilities are sometimes invoked as a driving mechanism.

The most rapid and highest amplitude variations are seen at the highest photon energies. X-ray flux variations have been detected in Seyferts on timescales as short as minutes.

We can distinguish the magnitude of the variations as a function of frequency *f* by their 'power density spectra', which are conventionally modelled as a power law i.e. $P(f) \propto f^{-\alpha}$ where α is typically in the range 1-2 for most AGN (where α =0$\cong$white noise).α =1 corresponds to variations that can be described as a random walk. Larger values of α correspond to increased amplitudes of variability over longer timescales (lower frequencies *f*).

In some cases (NGC 4151), the most prominent variation seem to occur almost simultaneously from x-rays through to optical wavebands. The smaller amplitude structures in the light curves differ across the spectrum, with lower amplitude and less structure seen at lower photon energies.

The near simultaneity of the variations requires that the variations are driven by radiation rather than, for example, by propagation of disturbances through the accretion disk. These observations, along with detection of the x-ray hard-tail and the FeKα emission line, point to the aforementioned '**reprocessing'** model, in which a variable x-ray source illuminates the accretion disk from above, with the absorbed x-ray energy driving variations absorbed at the lower photon energies.

2.6 A Unified Model?

Although our understanding of the AGN phenomenon has increased dramatically, major fundamental issues remain unsettled. These include the precise mechanisms involved in feeding the central black hole, the relationship between AGN activity and ultra-luminous starbursts, and the reason why some AGN in elliptical galaxies are radio loud (but not those in spirals). It is believed that a **Unified Model** can account for all kinds of active galaxy. According to this model, the supermassive black hole and its inner accretion disk is surrounded by a thick dusty torus. (See Figure 2.6) The type of active galaxy that is seen depends on the orientation of the torus and (the often present) jets relative to the observer's line-of-sight.

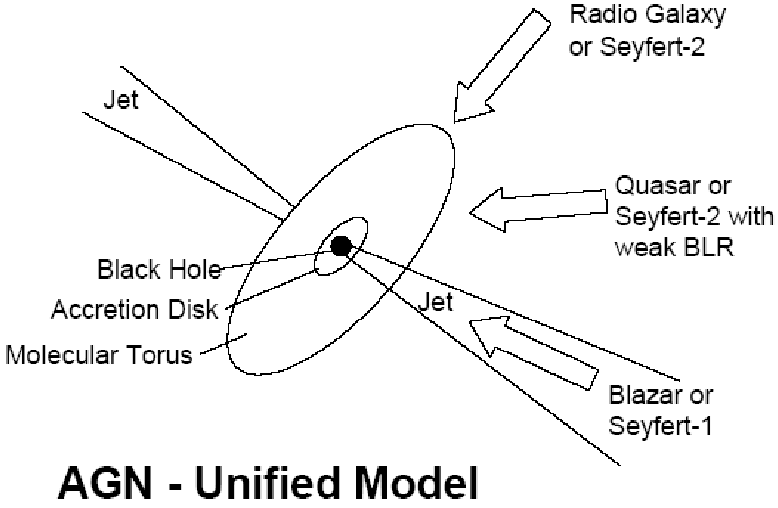

Figure 2.6
A schematic of a general AGN and the effect of viewing angle on observations made (Heisler, 1998)

- Jets radiate most strongly along it axis. Anyone looking along, or very close to, the axis will see a violently variable source with no spectral lines. This is referred to as a **BL Lac** object or **Blazar**.
- Looking at an acute angle to the jet, one will see an unobscured compact source: **Quasar**.
- From a viewpoint closer to the plane of the torus, we see only the jets and the extended radio-emitting clouds of a **Radio Galaxy**.
- A **Seyfert 1** will be seen when the observer's line-of-sight looks over the rim of the torus and toward the innermost regions of the AGN.
- A **Seyfert 2** will be seen when the central engine and the gas clouds in its vicinity are hidden.

So we have now established that some of the differences we see between various types of AGN are due more to the way we observe them than to fundamental differences between the various types.
But, some fundamental differences between the types to exist; not all of the subclasses display the identical features. To show this, I will now review each of the subclasses with reference to their luminosity, absorption/emission features and any other physical characteristics they might display.
The most luminous, and most well-known, of the subclasses are the **Quasars**. Their name is simply the abbreviation for *quasi-stellar radio sources*. They are very powerful AGN that outshine their host galaxies. They appear point-like and belong to the most distant AGN. They have nuclear magnitudes of $M_B < -21.5 + 5\log h_o$. They are the most distant objects we know in the universe, and many observed quasars have redshifts > 4 (Schneider, Schmidt and Gunn 1989). They are still the only discrete objects which can be observed, with relative ease, at $z \cong 1$, and thus, are potentially important for use as a cosmological probe. The detection of very high redshift quasars remains of great interest because their existence provides an important constraint on the

formation of large-scale structures in the very early universe, as well as on the formation of heavy elements, which are clearly seen in the spectra of all quasars. Observations of high redshift quasars show considerable steepening of the continuum below 1000Å. This is likely to be due to the large number of neutral hydrogen absorption systems on the line-of-sight.

Next come **Seyfert galaxies**. They are of lower luminosity than quasars, with $M_B > -21.5 + 5\log h_o$.[4] A Seyfert galaxy has a quasar-like nucleus, but the host galaxy is clearly detectable.
The Seyfert class can be sub-divided again:
Seyfert 1s (Sy1s) display two sets of **emission** lines. One set is characteristic of a low-density ($n_e \approx 10^3 - 10^6 cm^{-3}$) ionized gas, with widths corresponding to several hundred kilometres per second, and are referred to as the **narrow lines.** A second set of **broad lines** is also seen, but in the **permitted** lines only.
They display widths of up to 10^4 kms^{-1}. The absence of broad **forbidden** line emission indicates that the broad-line gas is of high density ($n_e \approx 10^9 cm^{-3}$ or higher). **Seyfert 2s (Sy2s)** differ from Sy1s in that only the narrow emission lines are present in its spectra. As well as the strong emission lines, weak absorption lines due to the late-type giant stars in the host galaxy are also observed in both types of Seyferts. These lines are weak because the starlight is diluted by the non stellar continuum.

Another subclass of the Seyferts is **NLXGs (Narrow-Line X-ray Galaxies)**. They have high-excitation emission lines, like Seyferts, but with lower luminosities than those typical of Seyferts. Their optical spectra are heavily reddened and extinguished by dust within the galaxy.

[4] This method of differentiating between Quasars and Seyferts was first used by Schmidt and Green, 1983.

Radio galaxies have dominant radio spectra (i.e. they are *radio-loud*). Their morphology strongly resembles that of Quasars, but on a smaller scale. The radio jets are very distinct and they emit synchrotron radiation. Radio loud galaxies are sometimes referred to as Fanaroff and Riley (FR) galaxies, and they can be subdivided into two classes [Fanaroff & Riley1974].

Type I FR galaxies are generally less luminous than their type II counterparts, and have a weaker optical emission as well. The radio emission of FR I galaxies is classified as "core dominated," as opposed to the "lobe dominated" emission regions of FR II galaxies.

The other subclasses of AGN and their properties can be found in Appendix Three.

2.7 Standard Candles and Cosmology

Astronomers cannot use the methods such as trigonometric parallax or Cepheid variables at distances to galaxies beyond the local group, because the parallax shift becomes too small, and at sufficiently large distances we can no longer even see individual stars in galaxies. Distances between galaxies are typically measured in Megaparsecs. One Megaparsec (Mpc) is equal to 1,000,000 parsecs, or 3,260,000 light years. At these distances, Astronomers turn to a series of methods that use **standard candles**; objects whose absolute magnitude is very well known. Then, by comparing the relative intensity of light observed from the object with that expected based on its assumed absolute magnitude, the inverse square law for light intensity can be used to infer the distance. [5]

[5] The intensity of light observed from a source of constant intrinsic luminosity falls off as the square of the distance from the object.

One example of a standard candle is a **Cepheid variable star**. They are effective standard candles. Firstly, their luminosity is quite high (the most luminous Cepheids are 40,000 times more luminous than the Sun), so they can be seen to large distances. Secondly, their luminosities can be computed from the Period-Luminosity Relation. [6]

Beyond 30 Mpc, however, Cepheids are too dim to be detected. At larger distances, we need brighter standard candles. **Type Ia supernovae** (SNe) are superb standard candles. Branch & Tamman (1992) studied many such SNe and found that they all had a peak absolute magnitude of $M_B = -19.6 \pm 0.2$ magnitudes, suggesting their use as a standard candle. Because type Ia supernovae are so bright, it is possible to see them at very large distances. Cepheid variables, which are super-giant stars, can be seen at distances out to about 10-20 Mpc; supernovae are about 100,000 times more luminous than Cepheid variables, which means that they can be seen about 500 times further away. Thus, type Ia supernovae can measure distances out to around 1000 Mpc, which is a significant fraction of the radius of the known Universe.

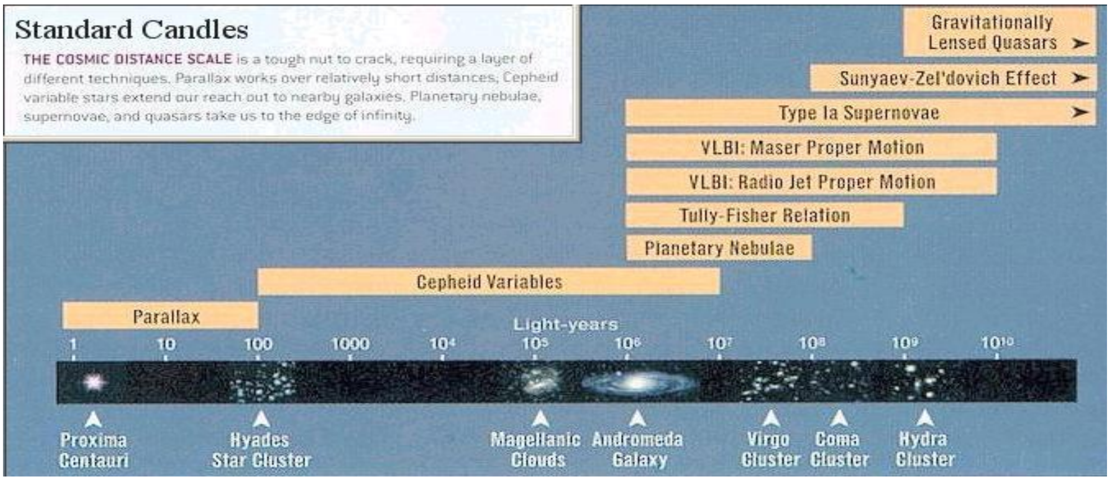

Figure 5
The Cosmic Distance Scale, showing how Quasars may be used as a Cosmological probe (From Ryden, 1998)

[6] Every light appears fainter the farther away it is. The apparent brightness fades in proportion to the square of the distance. If we know its luminosity, we can compare that to how bright it appears to be, and calculate its distance.

The question is, can **Quasars** and other AGN be used to probe even further back in time than Supernovae? (See Figure 5 above)

Like any field of science, **Cosmology** involves the formation of hypotheses about the nature of the universe. Depending on the outcome of observations, the theories will need to be abandoned, revised or extended to 'accommodate' the data. The most widely-accepted theory on the origin and evolution of our Universe is the Big Bang theory. Closely associated with this theory is the notion of the Hubble Constant.

The Hubble constant (H_o) is a measure of the current expansion rate of the universe. Cosmologists use it to extrapolate back to the Big Bang. This depends on the history of the expansion rate. This, in turn, depends on the current density and the composition of the universe. The best estimate for the value of H_o is **71kms^{-1}mpc^{-1}.**

If the universe is flat and composed mostly of matter, then the age of the universe as inferred from the Hubble constant would be about 9 billion years. The age of the universe would be **shorter** than the age of oldest stars!! If the universe contains a form of matter similar to the **cosmological constant**[7] then the inferred age would be larger.
This contradiction implies that either

- Our measurement of the Hubble constant is incorrect
- The Big Bang theory is incorrect or
- That we need a form of matter like a cosmological constant that implies an older age for a given observed expansion rate.

I propose that it is this third possibility which is the most likely.

[7] The notion of a Cosmological Constant was first introduced by Einstein. He subsequently described it as the "biggest blunder of my life"

3. Experimental Method

The aim of this project was to conduct an investigation into the properties and characteristics of every type of AGN, by a number of means. The methods I used are outlined below:

I had access to three databases, each from a different telescope, to compare and contrast AGN properties over a large frequency range. This analysis also gave me an insight into the effectiveness of each of scopes.

I analysed the data, including redshift and line ratios, from 24 different active sources. To minimise the ambiguities, and for comparative purposes, I then looked at the same sources again, but from two other observers.

Next, I looked at the accuracy of curve fitting in AGN spectra analysis. I compared the measurements of different linewidths for each of the three telescopes. This was achieved by comparing the asymmetry of the fit of the CIV line for the scopes, and then comparing the normalised values of the continuum flux (from each observer) to this asymmetry. A clear correlation would show that the telescope is effective over a large range of linewidths.

Next, by looking at one object at varying resolutions, I gained a further insight on the possible ambiguities of spectrum analysis.

I finally looked at the effect of imposing a different cosmology on my data, and how this could alter the measured age of the Universe.

The three telescopes from which I obtained my data were:

- The **Hubble Space Telescope** (HST), which works in the Ultraviolet region (1150-25000Å).
- The **International Ultraviolet Explorer** satellite (IUE), which also works in the Ultraviolet band (1150-3350Å)

- And the **Tytler** telescope, which is a ground-based optical telescope.

I looked at the properties of a number of objects with each scope, paying special attention to the values of redshift, the continuum flux, the flux of the CIV line, the ratios of some other prominent lines, and the linewidths.

All three observers looked at the same objects with each telescope, and took measurements of all of the parameters I have mentioned. I then carried out some comparative analysis, in which I looked at the similarities, and the deviations, between the measured values of each parameter.

Although each observer looked at (most of) the same sources as each other, each telescope looked at different set of sources. This is due to the fact that each one operates in a different waveband. Thus, the number of sources I had to analyse, for comparison purposes, was relatively small. I feel a larger database may have been more beneficial, and would most certainly have lessened the errors inherent in the observations.

As I mentioned earlier, this type of analysis can be very ambiguous. As we will see, the values calculated for each parameter can vary greatly between observers. Thus, I feel that more data, from different observers, would definitely have refined the data I processed and therefore increased the accuracy of the results obtained.

The asymmetry fits were the next thing I looked at. The values were intrinsic to each telescope, regardless of observer. This gave me a good insight into the accuracy of each telescope and how each fit correlates to the fit of the continuum flux.

To analyse the effect of a varying resolution, I looked at the continuum flux of one object in, and then looked at 'binned' versions of that same object. 'Binning' is a process by which an object can be made to look lower in resolution. I looked at the values taken by a number of observers. And again, the potential for ambiguity could be seen in this analysis; logged measurements varied significantly between observers. I have already discussed the idea that different cosmologies (or models) can have a huge impact on the measured age of the Universe. To demonstrate this, I inputted all of the data I had used for the rest of my analysis into the on-line Cosmological Calculator™, which calculates the age of the Universe based on a number of parameters. I varied 'the cosmology', by alternating the values of H_o, the Hubble Constant, Λ, the Cosmological Constant and Ω_m, which is the generic term for all types of matter.

The values of these parameters come under scrutiny, but, so far, only slight disagreements seem to exist between researchers. Constraints on cosmological parameters from MAXIMA 1 by Balbi et al. show a likely range of Ω_m of 0.25 to 0.50, Λ from 0.45 to 0.75. Durrer and Novosyadlij propose similar parameters: Ω_m of 0.37 and Λ of 0.69. However, the best estimates at the moment are from Wilkinson Multiple Anistropy Probe (WMAP). They are H_o=71kms^{-1}mpc^{-1}, Ω=0.27 and Λ=0.73.

I also carried out error analysis using the Sign Test (see Appendix Six) and more quantitative analysis which are included in the Results section.

4. Results

Much of the analysis I carried out to process the data uses comparative methods. The reason for this stems from the fact that, in this field, there are often significant deviations between measurements of the same object from different telescopes and from different observers. Each of the telescopes viewed a discrete set of objects, so unfortunately, a direct comparison between the accuracy of the scopes was impossible. To demonstrate the possible ambiguities, I compared the key measurements taken by each observer (Alyson, Steve, Jay) by a particular telescope. A sample of the type of analysis is shown below. **It should be noted that all of the analyses listed here was carried out for all three telescopes**:

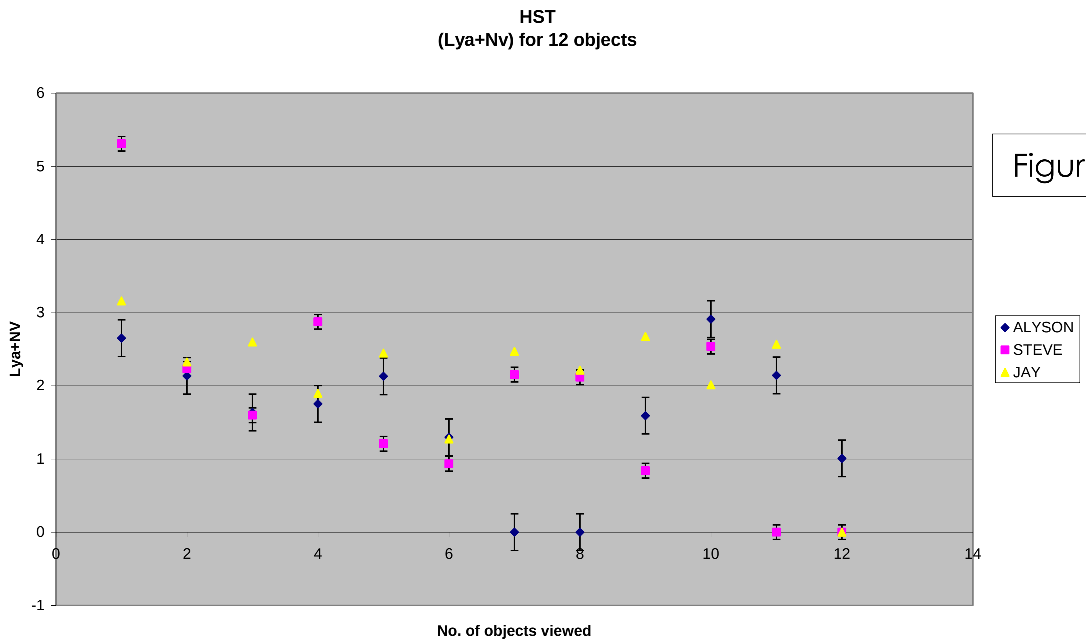

Figure 4.1

Figure 4.1 (above) shows a plot of Hubble Space Telescope data. The purpose of this plot is to show how different observers can measure different values for parameters of the same object. In this case, the measured parameter is an **addition of the fluxes of the Lya line and the NV line**. These two lines are the most prominent in AGN spectra, and by adding them together, we get an idea of the resolution of he telescope. The variation between these values, over the course of 12observations, demonstrates that even with the same telescope pointed at the same object, there will always be a variation of results. As we can see, all three observers are in relative agreement, and if we carry out analysis like the Sign Test, these variations can be put down to scatter, rather than systematic error.

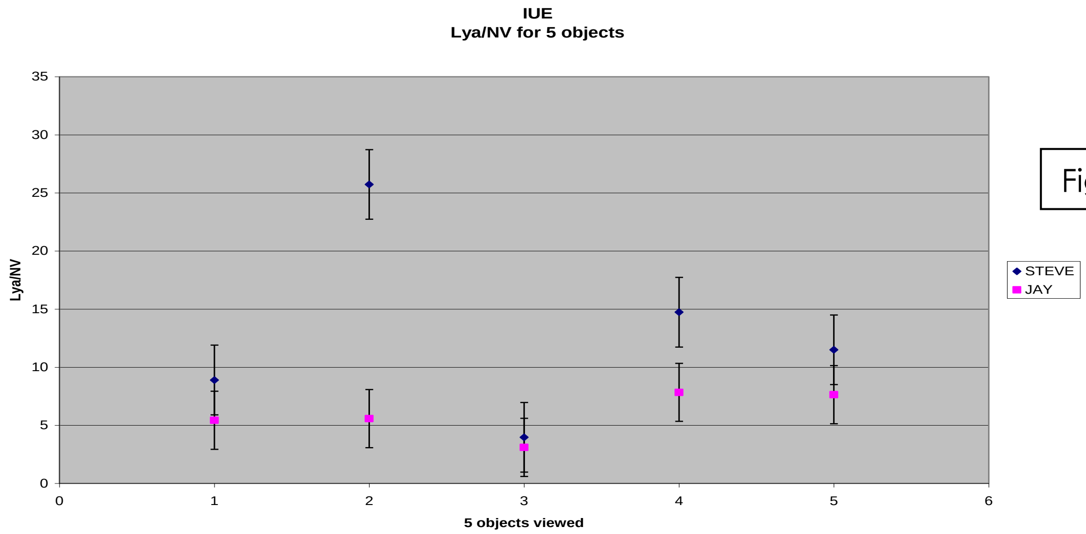

Figure 4.2

I have included Figure 4.2 to show how a low number of observed objects, with a small number of observers can affect the outcome of analysis. The parameter being measured this time is the **ratio between the Lya and the NV line**, which also provides information on the telescope. As can be clearly seen, the 'scatter' of this dataset is much greater, and it is more difficult to see even a slight correlation between the data. I believe that there would be a much lower error if there was a third set of observations for the same set of objects.

Figure 4.3 (below) has been included to show an intermediate dataset. This time, the focus is on the measurement of the **continuum flux**. As can be seen from the plot, the third and the fifth objects were measured by all three observers, and there, the correlation between the data is at its greatest.

Statistically, these deviations can be considered as scatter, rather than real differences between measurements.

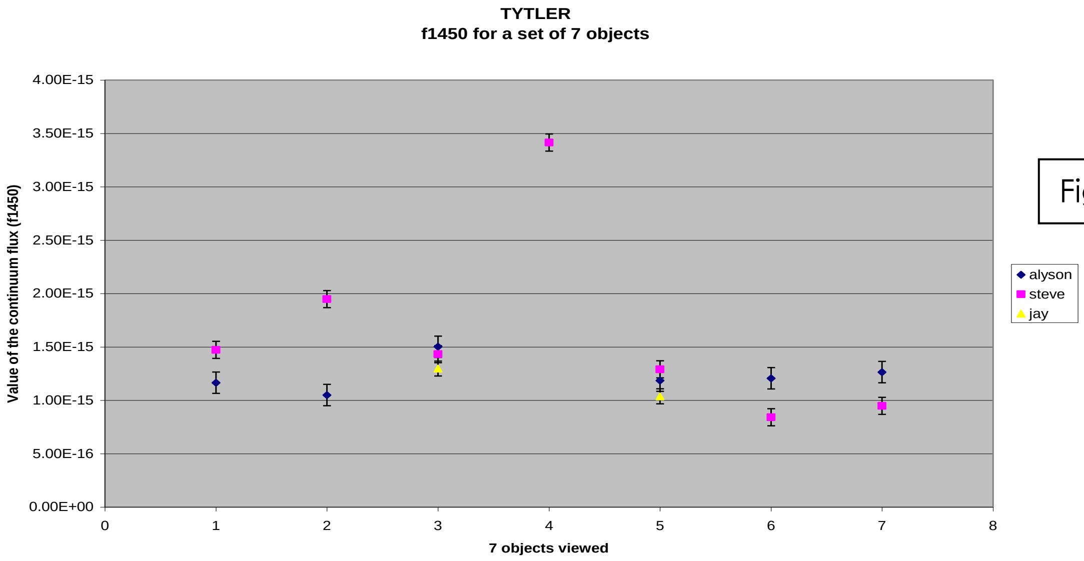

Figure 4.3

Some Error Calculations

I looked at the deviations between measurements taken of each object by a number of different observers. I focussed on a number of main parameters. A table of the calculated deviations between these parameters can be seen below.

	Tytler			HST			IUE		
	Lya+NV Δ= %	Lya/NV Δ= %	f(1450) Δ= %	Lya+NV Δ= %	Lya/NV Δ= %	f(1450) Δ= %	Lya+NV Δ= %	Lya/NV Δ= %	f(1450) Δ= %
Alyson .vs. Steve	30.73	33.1	2.39	8.92	8.41	9.53	n/a	n/a	n/a
Steve .vs. Jay	n/a	n/a	n/a	12.06	3.98	1.42	11.31	21.95	20.56
Alyson .vs. Jay	n/a	n/a	n/a	14.31	3.193	1.05	n/a	n/a	n/a

Curve-fitting (CIV line) analysis of data from each scope and observer then followed. In this first example (Figure 4.4), we see a clear correlation between the value of the line centre when the asymmetry term is **unity,** and when it is variable. The higher the asymmetry term is, the more shifted toward the blue it is. As the variable asymmetry terms are all below unity, we can say that the CIV line is redshifted.

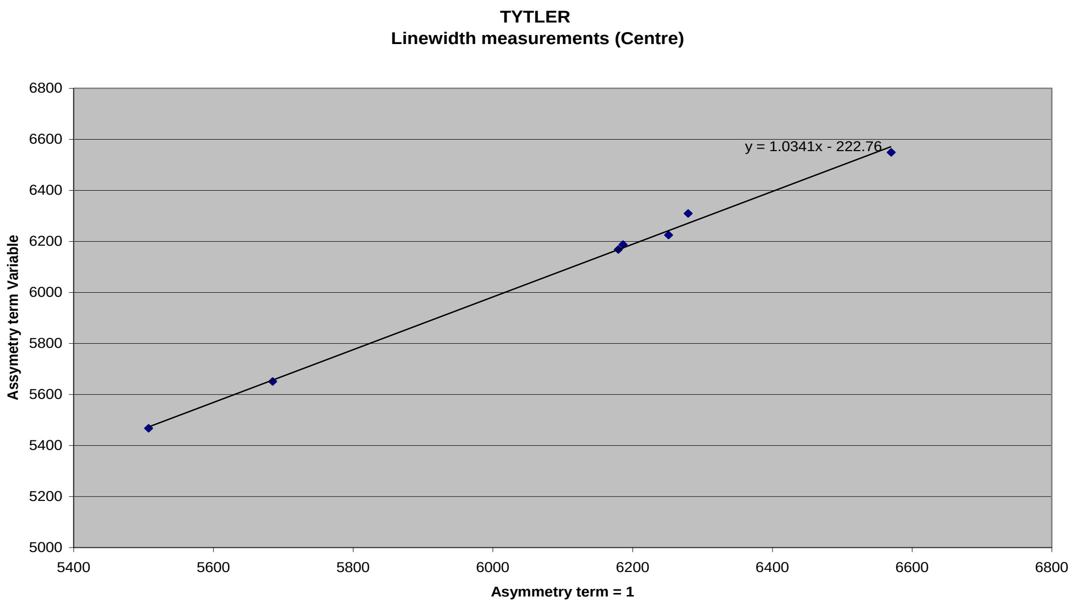

Figure 4.4

Another sample of the type of linewidth/asymmetry analysis I carried out was a comparison between the values of continuum flux measured by each of the three observers and the values of the asymmetry from the CIV fit assigned to each object (Figure 4.5). Note the values of the continuum flux have been normalised, so as to fit on the same scale.

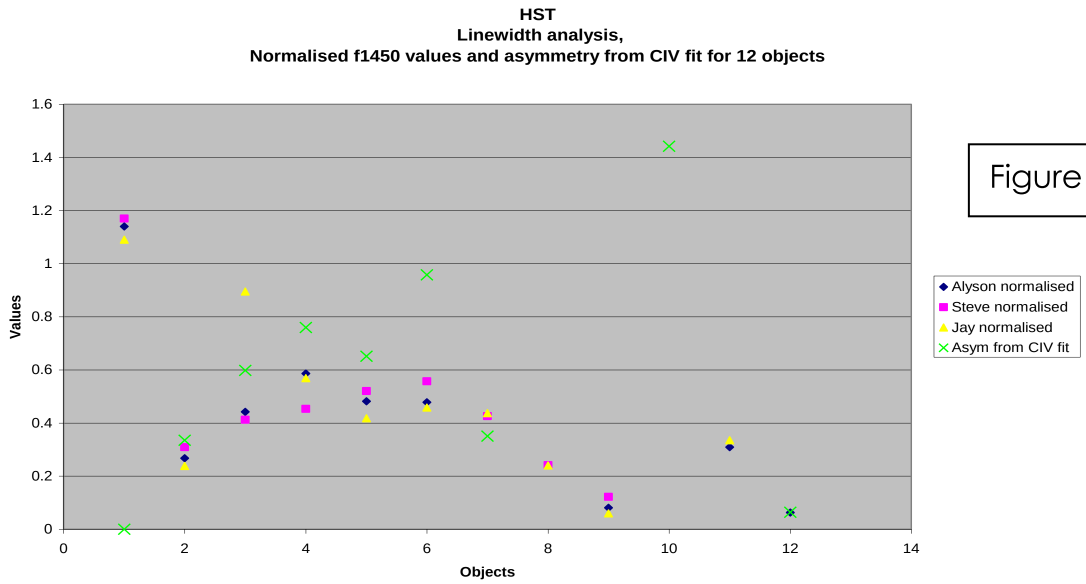

Figure 4.5

There is clearly a level of agreement amongst the observers as to the value of the continuum flux. To a large extent, the value of the asymmetry from the fit of the CIV line also correlates with the data. This shows that the different methods of curve-fitting used by each of the observers are accurate to assign to the entire spectrum.

The final method I used to analyse the implications of curve fitting was to plot the flux of a single object (400 pixels) against the measured wavelengths. This was carried out with only one observer and can be seen in Figure 4.6 below. This plot is that of the CIV line of active source **pks2251p11**, whose maximum is usually found at 1549Å. It can be seen here at a wavelength of 1613 Å. This shows that the CIV line is indeed redshifted

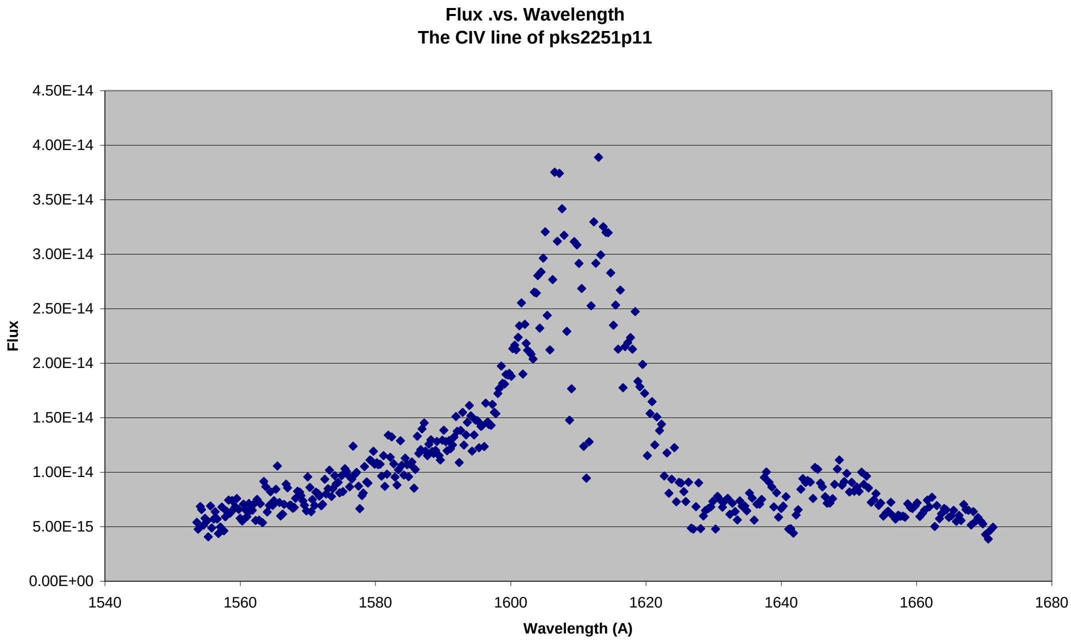

Figure 4.6

Next, the focus of my analysis was on a single object, and the effect of a varying resolution on the accuracy of any measurements taken. Here, I also compared the effect from three observers (Figure 4.7 below).

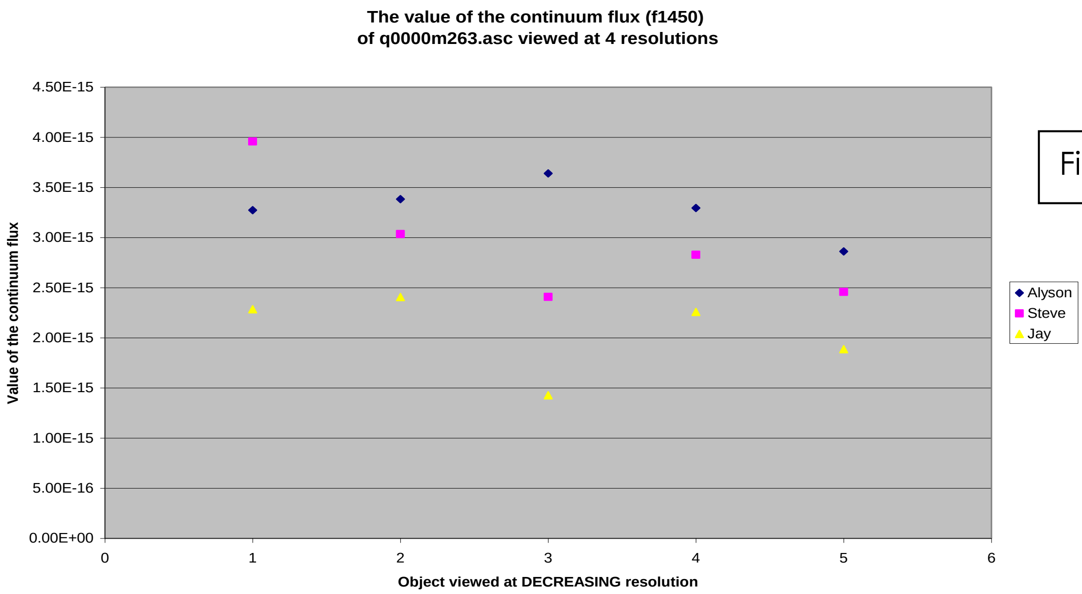

Figure 4.7

The first point is the 'unbinned' version of the object; an even scatter can be seen, with Steve measuring the highest value, followed by Alyson and Jay respectively. As the resolution decreases, of the level of binning increases, we see that Alyson always measures highest, followed by Steve. Jay always measures lower than the others. This is yet another example of the inherent bias nature of such analysis. However, we can also see that, in general, **the value of the continuum flux measured by each observer decreases as the resolution decreases.**

The final set of analyses which I carried out was concerned with the effect of imposing different 'cosmologies' on my data (Figure 8 below). I have already discussed the notion that applying a different model to the Universe will alter the calculated age of the Universe (See Section 2.7, pages 20-21). To show that this is indeed the case, I used the Cosmos Calculator™ to calculate the age for three different cosmologies.

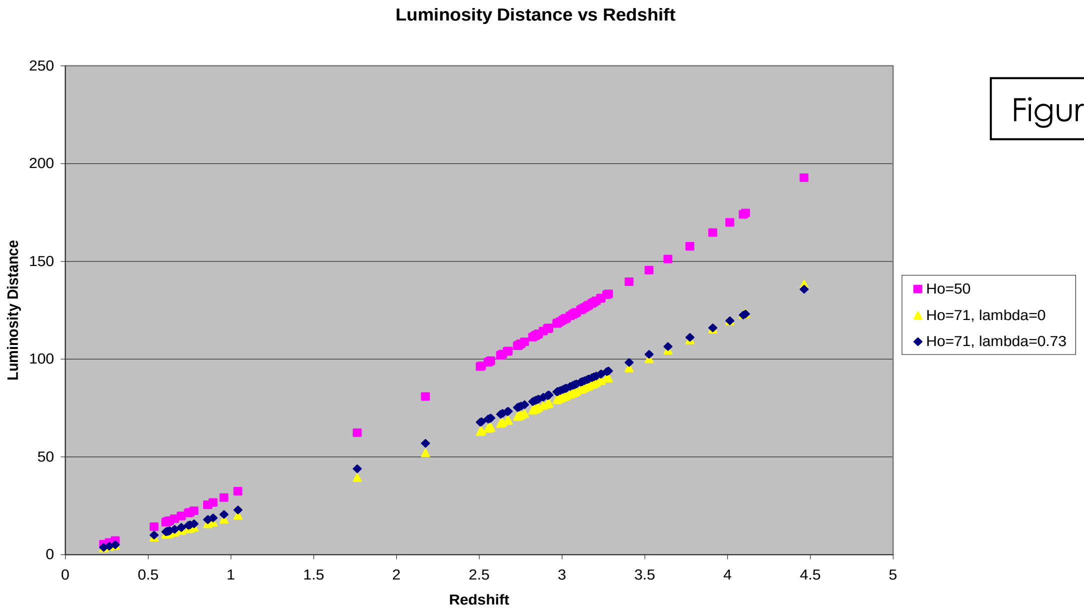

Figure 4.8

The pink curve indicates the cosmology in which H_o= 50kms^{-1}mpc^{-1}, Ω=0.27 and Λ=0.73. It results in a calculated age of the Universe of 19.39Byrs.

The yellow curve has parameters H_o= 71kms^{-1}mpc^{-1}, Ω=0.27 and Λ=0. These parameters give an age of 11.27Byrs.

The blue curve demonstrates the cosmology which has parameters H_o= 71kms^{-1}mpc^{-1}, Ω=0.27 and Λ=0.73 (WMAP data). This gives an age of 13.65Byrs.

5. Conclusions

My analyses of the various properties lead me to a number of interesting conclusions about the various forms of AGN, and of the methods we use to analyse them. From looking at the different parameters of a number of different sources, I familiarised myself with the properties and features of some of the most prominent emission lines found in the spectrum of all AGN.

I saw that measurements made of the same source can vary between observers and telescopes, sometimes to a large degree. These deviations, in my opinion could be all but eradicated if there were more data available for each active source, and from each scope. The method of curve-fitting to spectra, and other related methods of analysis, are ambiguous by their very nature, and often result in very vague and indistinct data. If such uncertainties continue to exist, I do not believe we will ever fully unify AGN models with those of galactic evolution. Gebhardt et al (2000) suggest that AGN activity seems to relate to a phase in the life cycle of a galaxy. According to him, and others, the great goal of AGN studies is to obtain a "grand unifying scheme" which will offer the "global connections" between AGN and Galaxy formation. If we manage to unify our AGN models with those we have successfully offered for galactic evolution, we will have answered a number of fundamental questions on the nature of Universe, which, as yet, have evaded us.

I also do not believe that we have exhausted all of the information the emission lines we observe in AGN spectra can offer us. The crude model of a Broad-Line Region and a Narrow-Line region works, but as yet there have been no studies into the existence of a 'transition region' between the two, displaying intermediate density etc. In semiconductors, without the depletion layer, all we have is a metal. Without an understanding of the transition zone, I feel we may be missing out on a central piece of the AGN puzzle. We will never know if this is indeed the case if we continue to do what has been done before; ignoring it.

I feel very strongly that the use of AGN as standard candles should be extended, but with caution. Previous attempts at producing a Hubble diagram for quasars were not very enlightening for two reasons:

1. The luminosity function for quasars is very broad
2. It evolves with time (there are more luminous quasars at higher redshifts).

However, our ability to look further back into our past has vastly improved since those early attempts, and, new technology makes our results become more defined. The barriers which once stood are being lifted as we speak, and accurate measurement of the luminosity function of quasars is almost within our reach. My analysis of the effect of imposing different cosmologies to our Universe, demonstrates the importance of full understanding of quasars. Using the WMAP parameters and my data, I obtained a value for the age of the Universe of 13.65Byrs, which agrees with the WMAP estimate of 13.666 ± 0.1 Byrs. This has been accepted as the most accurate measurement of the Universe's age to date, and it is believed that further analysis into the usefulness of AGN as standard candles may refine this even more. It should be noted here, that in WMAP cosmology, they introduce a Cosmological Constant, with a value of 0.73. So Einstein's "biggest blunder" has turned out to be correct after all!

The quest to understand AGN is part of a grander quest to understand the early Universe. Although many successes have been recorded, there is still room for improvement in relation to data accuracy. The ambiguities within the study of this field must be removed. According to Sir Martin Rees "*Our present satisfaction [with our state of understanding] may reflect the paucity of the data rather than the excellence of the theory*".

6. References and Bibliography

- *Encyclopaedia of Astronomy and Astrophysics,* 2000 (IOP Publishing)
- Branch, D., and Tamman, G.A. 1992, ARA&A, **30**, 359.
- Elvis, M., Wilkes, B.J., McDowell, J.C., Green, R.F., Bechtold, J., Willner, S.P., Oey, M.S., Polomski, E., and Cutri, R. 1994, ApJ, **95**, 1.
- Fanaroff, B.L., and Riley, J.M. 1974, MNRAS, **167**, 31P.
- Gebhardt, K., et al. 2000, ApJ, **539,** L13.
- Gunn, J.E. 1979, in *Active Galactic Nuclei* (Cambridge University Press: Cambridge) p. 213.
- Gunn, J.E., and Peterson, B.A. 1965, ApJ, **142**, 1633.
- Heisler, C.A. 1998, Astron. Soc. Aust., **15**, 167-75
- Kembhavi and Narlika 1985, 'Active Galactic Nuclei: An Introduction' (Cambridge University Press: Cambridge).
- Lawrence, A., and Elvis, M. 1982, ApJ, **256**, 410.
- MacAlpine, G.M. 1985, in *Astrophysics of Active Galaxies and Quasi-Stellar Objects*, ed. J.S. Miller (University Science Books: Mill Valley), p. 259.
- Miller, J.S., editor. 1985, *Astrophysics of Active Galaxies and Quasi- Stellar Objects* (University Science Books: Mill Valley).
- Netzer, H., and Laor, A. 1993, ApJ, **404**, L51.
- Osterbrock, D.E. 1984, 'Active Galactic Nuclei', QJRAS, **25**, 1.
- Osterbrock, D.E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (University Science Books: Mill Valley).
- Osterbrock, D.E., and Miller, J.S., editors1989, *Active Galactic Nuclei* (Kluwer: Dordrecht).
- Padovani, P., Burg, R., Edelson, R.A. 1990, ApJ, **353**, 438.
- Padovani, P., and Urry, C.M. 1992, ApJ, **387**, 449.
- Peterson, B.M., et al. 1991, ApJ, **368**, 119.

- Peterson, B.M. 1997. *An Introduction to Active Galactic Nuclei'* (Cambridge University Press: Cambridge).
- Rees, M.J. 1984, 'Black Hole Models for Active Galactic Nuclei', in *Annual Reviews of Astronomy and Astrophysics*, Vol. 22, p. 471.
- Schmidt, M., and Green, R.F. 1983, ApJ, **269**, 352.
- Schneider, D.P., Schmidt, M., and Gunn, J.E. 1989, AJ, **98**, 1507.
- Seyfert, C. 1943, ApJ, **97**, 28.
- Siegel, S. and Castellan, N., *Non-parametric Statistics for the Behavioural Science,* second edition. (McGraw-Hill, 1988).
- Smith, E.P., Heckman, T.M., Bothun, G.D., Romanishin, W., and Balick, B. 1986, ApJ, **306**, 64.
- Urry, C.M., Padovani, P., and Stickel, M. 1991, ApJ, **382**, 501.
- Urry, C.M., and Padovani, P. 1995, 'University Schemes for Radio-Loud Active Galactic Nuclei', PASP, **107**, 803.
- Weedman, D.W. 1986, *Quasar Astronomy* (Cambridge University Press: Cambridge).
- www.edu-observatory.org/eo/cosmology.html (WMAP)
- www.earth.edu/~morgan/ajjar/Cosmology/cosmos.html (Cosmological Calculator)

7. Appendices

Appendix One

Mass of the Central Object

- The outward force of radiation pressure must counterbalance the inward force of gravity, in order to ensure a stable environment. The outward **energy** flux at some distance *r* from the centre can be expressed as

$$F = L/4\pi r^2 \qquad (1)$$

Where L is luminosity (ergs^{-1}) of the source.

- Noting that the momentum f a photon is E/c (as $E = h\nu$), the outward **momentum** flux, or pressure, is

$$P_{rad} = \frac{F}{c} = \frac{L}{4\pi r^2 c} \qquad (2)$$

- The outward radiation force on a single electron is thus obtained by multiplying by the cross section for interaction with a photon:

$$\vec{F}_{rad} = \sigma_e \frac{L}{4\pi r^2}\hat{r} \qquad (3)$$

Where σ_e is the Thompson scattering cross-section and $\hat{r}$ is a dimensionless unit vector in the radial direction.

- The gravitational force acting on an electron-proton pair (masses of m_e and m_p respectively) by a central mass M is

$$F_{grav} = -GM(m_p + m_e)\,\hat{r}/r^2 \approx -GMm_p\,\hat{r}/r^2 \qquad (4)$$

- The inward gravitational force acting on the gas must balance or exceed the outward radiation force if the source is to remain intact, so it is required that

$$
\begin{aligned}
&|F_{rad}| \le |F_{grav}| \\
&\frac{\sigma_e L}{4\pi c r^2} \le \frac{GMm_p}{r^2} \\
&L \le \frac{4\pi G c m_p}{\sigma_e} M \\
&\approx 6.31\times10^4 M ergs/s \\
&\approx 1.26\times10^{38}(M / M_\Theta) ergs/s \qquad (5)
\end{aligned}
$$

Equation 5 is known as the Eddington Limit, and can be used to establish a minimum mass, the Eddington Mass M_E, for a source of luminosity L. in units appropriate for AGN, we write this

$$\boldsymbol{M_E = 8\times10^5 L_{44} M_\Theta}$$

Where L_{44} is the central source (bolometric) luminosity in units of 10^{44} ergs s^{-1}.

Appendix Two

Narrow and Broad line Regions: Physical Characteristics

NLR	BLR
• Velocity field ranges up to a few hundreds of kms^{-1}	• Velocity field ranges up to as high as 10-15 thousand kms^{-1}
• Includes both permitted and forbidden lines	• Almost complete absence of forbidden line emission
• $T_e \cong 15000K$	• $T_e \cong 15000K$ (estimated)
• $N_e \approx 3\times10^3 cm^{-3}$	• $N_e \approx 10^9 cm^{-3}$ **
• Sy2 NLRs have apparent radii of ≈ 50pc	• R ≈ 0.07pc
• Ionisation extends to such high stages as O^{++} and Ne^{++} Main energy input mechanism must be Photoionisation	• Although Photoionisation is the most likely energy input mechanism, it has yet to be proven definitively.

**The electron density is higher than the critical densities for collisional de-excitation of all the strong forbidden lines observed from NLR.

Appendix Three

Two alternative models to emission line occurrence in AGN

The first alternative model proposed is called the **Shock-Wave model.** It is based on the assumption that shock waves in the broad-line gas can cause excitation in the gas. This model cannot provide a full description of the observations in the broad-line spectrum (From the BLR), as evidence for Photoionisation can be seen in any variability study. However, in LINERs, this model has shown potential, as some shock-wave models have successfully predicted some processes in the NLR.

A parallel view of the line excitation phenomenon can be found in **Warmers model** of AGN. In this offering, the nuclear activity is due to a burst of star formation, and the so-called 'non-stellar continuum' is just the spectrum of a young, metal-rich cluster containing extremely hot, Wolf-Rayet stars. This model also suggests that the broad emission lines and the observed variability are due to supernovae in the nuclear cluster, and that there is, in fact, no massive object at the centre. This model has broadly been rejected.

Appendix Four

Three standard forms of analysis of emission lines

1. **Line Intensity**

A characteristic feature of all broad line objects which can be seen in their spectra is the presence of both high and low excitation lines. The low excitation lines indicate regions of low ionisation and suggest that at least part of the gas is neutral and thus optically thick to Lyman continuum photons. The high excitation lines indicate highly ionised material.[2]

There is, interestingly, a great similarity of line ratios in objects of very different luminosities. This must indicate that the physical conditions in the line emitting gas are similar in bright and faint objects.

2. **Line Variability**

Over long enough timescales, all broad-line AGN show continuum variability. Spectrophotometric observations show variable broad emission lines in most, perhaps all Seyfert 1 galaxies. Some quasars show variable emission lines too, but there have been very few systematic observations of this kind. The observed line and continuum variability in Seyfert galaxies are clearly correlated. The emission lines respond to the continuum variability after a certain lag (which seems to be longer in more luminous objects).

Assuming that the observed line variability is driven by changes in the continuum luminosity, the emission line light curve depends on the gas distribution in the nucleus and the continuum light curve. There has been no evidence found for narrow line variability in AGN.

[2] A fundamental issue though, is whether the high and low excitation lines originate in the same part of the emission line regions.

3. Line Profiles

There are two distinct classes of line profiles, narrow (200-1000kms^{-1}) and broad (1500-10,000kms^{-1}), which appear to originate from two distinct emission line regions. They are present, in different proportion, in different AGN. Even the narrow emission lines are too broad to be interpreted as due to purely thermal motion. The gas producing the lines must be moving at high speed. The velocity which the gas travels at can be related back to a wavelength in a given profile. Thus studying the line profiles can be used to understand the gas motion in the nucleus.

Appendix Five

Unified model: Some lesser-known subclasses

The least luminous AGN are **LINERs (Low Ionisation Nuclear Emission Line Regions).** Spectroscopically, they resemble Sy2s, except that their low-ionisation lines are relatively strong. They are very common, and are believed be detectable in up to half of all spiral galaxies.
Some models indicate that the emission-line spectra of LINERs are consistent with photo-ionisation by a Seyfert-like continuum which is very dilute.
The relationship between LINERS and AGN is not completely clear. Some, but by no means all, LINERs appear to be simply very low-luminosity Seyfert galaxies. LINER-type spectra can also be produced in cooling flows, in starburst driven winds and in shock-heated gas.

AGN show continuum variability at all wavelengths at which they have been observed, from x-ray to radio. However, there is a small subset of AGN which show short-timescale variations that are abnormally large: $\Delta m \geq 0.1$mag in the visible wavelengths on timescales as short as a day. In addition to their large variations in flux, these objects also tend to have high polarisation relative to most AGN, which also varies, both in magnitude and position angle. These sources are also always radio-loud. These AGN are called **optically violent variables** or **OVVs.**
Some of the properties of OVVs are shared by **BL Lac Objects,** including its tendency toward radio emission. Some of these objects were originally identified as highly-variable stars. BL Lacs do not show emission lines, and are identified by their highly variable non-thermal continuum.
It is thought that both OVVs and BL Lacs are those AGN which have a strong relativistically beamed component close to the line-of-sight. Collectively, OVVs and BL Lacs are referred to as **Blazars**.

Appendix Six

<u>The Sign Test</u>

The details of this test may be found in the textbook "Non-parametric Statistics for the Behavioural Sciences". It gets its name from the fact that it is based on the **direction** of differences between two measurements, rather than **quantitative** measurement of the data.

The procedure, in short, is as follows:

- Determine the sign of the difference between the members of each pair.
- By counting, determine the value of N equal to he number of pairs whose differences show a sign (ties are ignored)
- If N is larger than 35, the value of z is determined from

$$z = \frac{2x \pm 1 - N}{\sqrt{N}}$$

- If N is smaller than 35, the author gives us a table of probabilities associated with that value of N in Appendix Table D (pg 324) of the text.