Notes for Lynge R. B. Lauritsen Master Thesis "Dust reverberation mapping of AGN in the local universe"

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1. 1: Introduction

The paper discusses the reduction of data from the REM telescope in La Palma to obtain usable AGN (Active Galactic Nuclei) light curves which is needed for reverberation mapping. AGN observation in different bands (J,H,K,g,r,i,z) can be used to determine optical and thermal lags times in the AGN. This is done by the use of a Markov Chain Monte Carlo algorithm to determine the best fit for the UV-continuum light curve and transfer function for the AGN, which are used to determine lag times. The wavelength range for the bands are listed below for my own reference:

- J- 1.1 to 1.4 μm
- H- 1.5 to 1.8 μm
- K- 2.0 to 2.4 μm
- g- 0.50 to 0.57 μm
- r- 0.65 to 0.74 μm
- i- 0.74 to 1.0 μm
- z- 28 to 48 μm WRONG?

A description of the Hubble relationship/flow is given and the difference between peculiar velocity of galaxies, which comes from the gravitational interaction between the galaxies (especially those locally) and recessional velocity, which comes as a result of the expansion of the universe. The Hubble law lets us determine distances to galaxies where the recessional velocity dominates

$$d \simeq \frac{c}{H_0}\frac{(z+1)^2-1}{(z+1)^2+1}$$

here H_0 is the Hubble constant and the source of trouble. The trouble came historically from accurate distance measurement and Malmquist bias (as the distance increases only objects of increasing absolute flux will be included.) though today the trouble is related to the discrepancy (5σ today) between the H_0 value obtain in the local universe with Cepheids and Type Ia Supernovae (SNe Ia) measurements and the CMB value from the Planck Collaboration, where they are using a flat LCDM cosmology.

A list of the condition for a perfect standard candle/ruler is given, which can be used to determine H_0:

- Has physical properties allowing the identification as a standard candle or ruler
- Can be independently calibrated e.g. does not build upon previous distance or luminosity determinations (a one-step process), as errors stack
- At sufficient distance that error associated with peculiar velocity is small
- Astrophysically simple i.e. distance determination is independent on internal properties of the object
- Determines the Hubble constant independently of other cosmological

an example of a one step method for obtaining H_0 is the megamaser method where interferometry of nearby galaxies with Super Massive Black Holes(SMBH) have gas clumps that are assumed to move with Keplerian motion around the SMBH. Observations of these clumps can be used to determine their velocity and acceleration, which with the assumption of Keplerian motion can give us the gas radius from the SMBH and the SMBH mass. The gas radius can then be used to determine the distance to the galaxy using trigonometry. There are uncertainties for this method related to the disk geometry and inclination.
A distribution of the classical distance ladder is given, i will list the steps in order:

- 1. Parallax approach for close stars
- 2. Open clusters for nearby galaxies
- 3. Cepheids for 20-30 Mpc
- 4. Type Ia Supernovae (SNe Ia) for d>50 Mpc here peculier velocity error drops below 10 %
- 5. other methods (Tully-Fisher/Faber-Jackson relation) also for d>50 Mpc

the main issue here is error propagation through each step in the ladder

AGN/Quasars are not good standard candles since they have a varying luminosity but unchanging SED (Spectral Energy Distribution), though they can be observed at high redshifts and therefore if their inner dimensions are known then they can be used as standard rulers. The internal dimension can be determined using reverberation mapping. These internal measurements could then be used for galaxy distance measurements which can be used to determine H_0.

1.1. 1.2 AGN

AGN are luminous phenomena located in the center of galaxies which are not powered by the galactic stellar population but from gas accretion onto a SMBH. The emission obtained from the accretion is strong in the X-ray bands. Some of the observational criteria for an AGN are:
1. The pointlike representation of an AGN upon an imaging detector
2. Strong emission lines
3. The Continuum Luminosity varies over time
4. Evidence of strong non-stellar emission
5. Strong X-RAY emission
6. Radio emission
7. Non-stellar UV through IR emission
8. Broad emission lines in the UV through IR.
Though not of these are always present in an object.

AGN can be categorized into a couple of different objects for example the Seyfert galaxies which are in spiral galaxies. Seyferts are further split into Seyfert I and Seyfert II galaxies, where the first has Broad Line Region (BLR) emissions and forbidden lines and the second only has Narrow Line Region (NLR) emission. Quasars are Quasi-stellar objects and are the brightest of the AGN, They are in many similar to Seyferts though they have weak stellar absorption features and have less NLR to BLR emission relative to Seyferts. Radio galaxies (galaxies that have sufficiently powerful radio emission) are almost all AGN ellipticals that like the Seyferts can be classified into two groups the Broad-Line Radio Galaxies (BLRG) and Narrow-Line Radio Galaxies (NLRG). Besides being radio load, which the Seyferts are not, these AGN also have radio jets stretching out to kpc or Mpc from the host galaxy.

The way that the spectrum of an AGN differs from the spectrum of a star is its varying luminosity and it non-blackbody radiation (a powerlaw).
For an object like an AGN to emit so much energy over its lifetime (E>3 X 10^{61} erg in some cases) it cannot be from fusion, since fusion has a mass-to-energy conversion efficiency of 0.007, whereas free-falling material onto a black hole has an efficiency of 0.06 and for a rapidly rotating black hole up to 0.42.

Friction due to the viscosity of the gas in the accretion disk results in the gas heating up as it falls into the black hole, resulting in emission (think of concentric rings rotating approx. Keplerian and having friction between each other), said another way potential energy is released from inwards movement and is seen in the form of thermal radiation. The emission of the accretion disk can be shown to be aprrox. a series of concentric black body rings at different temperatures, where temps are higher for higher accretion rate and lower for more massive BH.

The BLR is in a halo surround the accretion disk and has strong line emission with velocity widths from 500 $\frac{km}{s}$ up to 10000$\frac{km}{s}$, this dispersion is Doppler broadening due to the rotation of the BLR. This large Doppler broadening lead to line blending. The BLR absorbs 10% of the emitted AGN energy and as the BLR clouds are optically thick they will cover 10% of the AGN solid angle.

Reverberation mapping of the BLR can be used to determine the structure of the BLR as it will respond to continuum variations from the AGN. Reverberation mapping looks at the delay in variations in the AGN UV-driving function and the BLR response to determine the transfer function. The reverberation mapping technique gives us an independent measure of the BLR geometry without having to make assumptions about the geometry beforehand, though there are still assumptions associated with the method which are described by Peterson 1993 (see thesis for full reference):
1. The Continuum emission originates at a single compact and central source. Thus follows the SMBH model of the AGN.
2. The BLR has a small filling factor (the majority of the volume attributed to the BLR is a vacuum), hence photons are able to propagate freely inside the BLR. This seems to be supported by the low filling factor of the BLR, and no evidence of is observed for an Inter-Cloud Medium scattering the wave fronts.
3. There is a simple relationship between the ionizing continuum and the observable UV/optical continuum flux.
4. The light travel-time t_{LT} = r/c across the BLR is the most important time scale.
(a) The BLR variations, as response to the continuum variations are short compared to t_{LT}.
(b) Significant geometrical changes to the BLR (dynamical time scale) happens over significantly larger time scales than the t_{LT}, t_{dyn} can be estimated as the time taken for cloud of gas to cross the BLR; $t_{dyn} = \frac{r}{\Delta v_{FWHM}}$.
(c) t_{rec}, the time scale for the cloud to reprocess ionizing radiation, is virtually instantaneous
The delay of the BLR response Δt gives the light travel time and there the radius of the BLR, so the physical extend of the BLR can be measured from the time delay in the response function. The technique also allows for analysis of individual iso-delay layers and even the delay in individual lines using spectroscopy. The BLR overall in AGN's seems to be inhomogeneous (clouds) and spans a large radius with different "layers" where atomic transitions with higher ionization energies have smaller radii.

Reverberation mapping is not only relevant for the BLR but also for the accretion disk and dust torus (relevant part for thesis). For a geometrically thin, optically thick accretion disk the theory states we have $T \propto r^{-\frac{3}{4}}$ (though in reality it may be more like $T \propto r^{-1}$ see Fausnaugh et al. 2017 and figure 1.3 in the thesis) for the temperature-radius relation which means the BB emission will be spatially dependant. The inner parts of the disk will radiate in the UV while the outer parts will radiate in the visual and IR. X-ray emission from the corona will undergo variations which the disk being irradiated must respond to and this will produce a time delay between the UV- and IR-emission in the disk. To measure the AGN variations and do reverberation mapping we need data over mounts to years. The modelling of the X-ray driving function can also be used to compensate for more sparse sampling than what is usually used.

The NLR does not lend itself to reverberation mapping analysis, due to the fact that its vast spacial scale does not undergo variations on an observable timescale. The NLR can also be spatially resolved and therefore indirect observational techniques becomes less important.

The dust torus of an AGN surrounds the accretion disk and BH and has a temperature which is affected by the energy released by the accretion disk. The inner part of the torus will at the dust sublimation temperature, thus knowing the thermal lag can be used to determine the dust sublimation radius.
The Torus is important as it can obscure the inner parts of the AGN, depending on the inclination angle. The obscuring affects the driving function and the BLR emission. Observation of dusty tori suggest they are both geometrically and optically thick and in some cases have a high Hydrogen column density. Mid-IR and sub-mm observation indicate a torus size of 0.1-10 pc. The torus is interesting for us since it can be used as a standard ruler like the megamaser disk mentioned earlier, since the torus responds to the variations of the accretion disk and can be probed using reverberation mapping.

The unification theory states that all AGN are ostensibly the same and any difference observed is due to the conditions of the observation i.e. the inclination angle. The difference seen in type I and II Seyferts where there is no broad emission lines and a weaker continuum in type II is because the emission is being blocked by the orientation of the torus. Unification theory also predicts axisymmetrical AGN. Dust is the best candidate for the obscuring that would result in these type difference and the idea is to use this dust to obtain information about the size of AGN and therefore have a standard ruler.

2. 2: Flux and Magnitude

Much of this is the same as what we learned in observational astrophysics.

telluric absorption bands are for partial absorption and can be accounted for, while for total absorption there are transmission windows for a given altitude. Many componenets of the atmosphere lead to absorption like water, ozone, CO2.

the concept of apparent magnitude is presented and the specific observational filters used are shown (see above). The concept of absolute magnitude and its relation to apparent magnitude is also presented.

Flux is the energy received over a given area over a given time, which for a telescope is dependant upon the source luminosity, the distance to the source and for ground-based observations the atmospheric conditions (also any dust in space between the source and observer). to be able to work with absolute fluxes these dependencies must be accounted for when obtaining the apparent fluxes from the AGN and reference stars. the point when using reverberation mapping is not to obtain the absolute fluxes but the time-dependent difference between different observational bands. Good measurements of these time-dependent flux variations can be obtained with the right wavebands and the use of photometric standard stars that do not vary in their energy output so that instrumental magnitudes/fluxes can be calibrated and compared.

For the errors associated with flux measurements there are ones related to atmospheric effects and inter-stellar/-galactic material (A_v), for AGN close by the latter is assumed to be negligible or at least of having the same effect on all objects measured (even material distribution in line of sight). Noise can be split up into technical and fundamental noise. the fundamental noise limit is the physical limit of the observation like the diffraction or seeing limit, while technical noise can be reduced. The SNR parameters are (Hainaut 2005)

- Signal:number of photons detected by detector, lmited by detector Quantum Efficiency.
- Shot Noise: poison distribution and comes in form of signal noise, sky noise (background) and Dark noise (thermal)
- Read-Out-Noise (RON): amplifier adds noise at read out.

SNR is fully given by:

$$SNR = \frac{N_{signal}}{\sqrt{N_{signal} + n_{pixels} \cdot (N_{sky} + N_{dark} \cdot t + RON^2)}}$$

3. 3: Defining a light curve