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 constants

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 description 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 ways 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 surrounding 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 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 therefore 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 months 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, limited by detector Quantum Efficiency.
- Shot Noise: Poisson 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

This part concerns itself with making an algorithm that can run reverberation mapping analysis on optical- and IR-lightcurves without an initial driving function. A reliable driving function must be made and this is done through 3 methods:

1. The Stochastic model described in Kelly et al. 2009. This model builds on the assumption of AGN variability being described as a Continuous Time First-Order Autoregressive Process (CAR(1)).
2. Modeling the AGN variability as a Power Spectrum with Power Spectral Density slope of a = $-2.3... -3.4$.
3. Using Structure Functions to analyse AGN variability.

3.1. Kelly Method

The stochastic Kelly model is made to model missing data when light curves are sampled unevenly for days/weeks. In the Kelly model the AGN light curve can be modeled as a CAR(1) process, which is consistent with a power spectra with the form $P(f) = \frac{1}{f^2}$, though this assumption is not entirely congruent with observed AGN variability and the model must be modified to obtain an actual AGN light curve. The Kelly model models continuous time as the obscuring of the accretion disk is continuous (it should be noted this is not the same as Fourier analysis). The mode uses 3 parameters to define a light curve:

1. A characteristic time-scale, called the "relaxation time" (t_{Kelly})
2. Amplitude of short time-scale variability
3. Mean value of the Light-Curve

t_{Kelly} is the timescale when the time series becomes uncorrelated and can be related to other relevant timescales for the accretion disk such as the light crossing time, orbital timescale and thermal timescale. In Kelly et al. 2009 they conclude that the orbital and thermal timescale provide good fits, with the thermal one being the best. The differential equation for the Kelly model is

$$dX(t) = -\frac{1}{t_{Kelly}}X(t)dt + \sigma\sqrt{dt}\epsilon(t) + bdt$$

bt_{Kelly} is the mean of the observed light curve and the light curve variance is given by $\frac{t_{Kelly}\sigma^2}{2}$, $\epsilon(t)$ is a white noise function with a mean of zero and variance of one and lastly X(t) is the light curve itself. The Kelly model introduces a bias where there is a axis shift depending on the evolution direction and the direction the light curve is read, a way to account for this is to read the light curve from both directions and then take the mean of those two light curves. The parameters for the Kelly model can be determined by using a maximum likelihood estimate (see equations 3.5 to 3.11 in thesis). The power spectrum for the Kelly model is

$$P(f) = \frac{2\sigma^2 t_{Kelly}^2}{1 + (2\pi t_{Kelly} f)^2}$$

where for short time scales compared to t_{Kelly} the spectrum falls as $\frac{1}{f^2}$ and for long time scales the spectrum is constant.

the main weakness for the Kelly method is its inability to predict areas where there are significant time gaps between data points, here the use of the use the light curves as read from both sides becomes a useful tool to see the range of possible values.

3.2. Power Spectral Density

The Power Spectral Density (PSD) is an expression of the variability of a function as a function of temporal frequency and is determined through a periodogram. For this to work with AGN light curves there is need for an consistent estimator of the PSD, which can be constructed by averaging the periodogram by binning frequencies or averaging over data segments. For the PSD the slope of consistent estimator is useful as it can be used as an indicator of a time dependent variability in the AGN light curve. The PSD can be obtained from evenly and unevenly spaced data. The PSD is obtained from the light curve by first removing the zero frequency power, which is the same as subtracting the mean from the light curve. The modulus squared of the discrete Fourier transform is then calculated and normalized to obtain the power spectra of the relevant function. It is possible to integrate the power spectrum over a frequency range to obtain the rms squared variability of the light curve due to variations over a given time interval. the observed AGN power spectra can have a knee (slope of 0) or a break (slope 1) at low frequencies, in these cases the fitting for the PSD slope is done in loglog space past this knee or break

3.3. Structure function

The structure function is useful for understand long term AGN variability as opposed to short term variability which seems to stem from reletatvistic beaming effects. The reasons for long term variability are suggested to be:
1. Disk Instability
2. Super Novae event bursts close to the AGN
3. Source extrinsic variations due to microlensing events along line-of-sight
The structure function itself is written as follows

$$V(\tau) = \left(\frac{1}{N(\tau)}\sum_{i<j}[m_{opt}(t_i) - m_{opt}(t_j)]^2\right)^{1/2}$$

where $m_{opt}(t_i)$ is the optical magnitude at t_i, $\tau = t_i - t_j$ is the time difference and N(τ) are the number of pairs of $\tau = t_i - t_j$. The structure function can be used on AGN light curves to observe 3 regime:
1. A plateau at time-lags exceeding the longest correlation time-scale, with a value twice the variance of fluctuations in the measurements
2. Plateau at short time-lags with value twice the measurement noise. This plateau arises as the noise has no correlation timescale
3. Power-law increase with time-lag as $[V(\tau)]^{1/2} \propto \tau^{\beta}$ between the two plateau'
The PSD slope (α) is also connected to the structure function slope (β). There seems to be a turnoff point in the structure function for close AGN where the scatter makes the data appear uncorrelated.

4. 4: Reducing the data

this section concern itself with the reduction of observational images of AGN in light curves in the optical SDSS-(g,r,i,z) and infrared Johnson-Cousins J,H,K observational bands. The process of reduction involves sperating the stellar component of the galaxy from the AGN as these are close by Seyfert galaxies where the AGN does not outshine the stellar component. The first task is to locate the center of the AGN in the image and then to determine the angular size of the AGN in the image. A description of detector characteristics is given. The location extraction was done with two methods to compare. One was using existing astrometrical calibration (fine tuned by 3'rd-party software later) and the other was a specific program that looks for abnormal pixels based upon given search criteria, both methods have their advantages and disadvantages. The most reliable of the two mothods is the second (SEXtractor), since using the existing astrometical calibration is unreliable and might miss the AGN/standard stars partially or completely, while the SEXtractor method might include excessive starlight.

The choice of aperture is also important as one too small misses part of the AGN, while one too big will include excessive starlight. Aperture sizes are investigated for different bands to find the size which best reduces scatter from incomplete astrometry, while reducing galactic stellar light pollution.

Subsection 4.3 concerns itself with the SEXtractor algorithm and the code for the error calculation of the AGN light curve, too technical to write neatly in notes, but is useful as a lookup for when i will be working with any code.
subsection 4.4 looks at the standard stars and AGN used to obtain light curves and structure functions and shows the results for the AGN to comment on individual variability. again too specific to write neatly in notes but do take note of how the individual object are analysed for later.

5. 5: MCMC

(Look at the sources on page 84 for intro to MCMC.)
The idea is to use the Markov Chain Monte Carlo (MCMC) algorithm to do a AGN reverberation mapping analysis without the knowledge of the X-ray driving function coming from the central engine beforehand. MCMC is useful for this as the data is sampled sparsly and unevenly and also the equations required to solve the problem would run in the hundreds, as each point in time for the driving function can be seen as an unknown variable if the problem is to be treated analytically.

Taking the entire problem into account when working with the AGN it becomes an impossible task with a huge amount of parameters, so some general assumption must be made to make the problem feasible to solve:

- The Dust Torus is sufficiently uniform, in temperature, as to make the alterations to the Black Body emission, caused by the temperature gradient, fall inside the pre-accepted error.
- It is assumed that any light contribution not originating in the Accretion Disk or dusty Torus can be safely ignored (BLR, NLR, host galaxy light pollution).

Under these assumptions a simplified model can be created, where accretion disk and dusty torus are both governed by a single emission function and both have a single transfer function to describe the response delay to the driving function variations in each filter. With enough observations and computers(or time) this could be solved analytically but we have neither, therefore we use MCMC. The MCMC approach makes a guess for solving a problem and then slowly changes that guess to improve the goodness of fit parameter. MCMC can be used to optimize problems in large dimensional spaces, such as χ^2 minimization.

5.1. 5.1.1: Markoc Chain Monte Carlo Principle

The Monte Carlo part of MCMC is the approach of using randomly sampled data points to determine statistical properties if the random sampling is large enough then the accuracy of the approximated parameters will be high. The Markov Chain part of MCMC is the mechanism by which parameters are changed through each generation of random samples. In total for each random sample the goodness of fit is determined and the best sample is used as a starting point for the next random sample, so each new random sample only depends on the last one in the chain.

5.2. 5.2: Transfer Functions

to obtain the driving function there must be an understanding of how the light curve acts between the AGN and the observer, this would be possible with the transfer function , as knowing the transfer function at all times would make it possible to determine the exact driving function. The problem is the transfer function is not known at all times and the light curve we observe comes as a result of the transfer function where

$$F_l(\tau,\lambda) = \int_{-\inf}^{\inf} \Psi(\tau,\lambda) F_C(t-\tau) d\tau$$

it is not possible to get an accurate estimate of the driving function and the actual shape of the transfer function for the AGN's will be unknown. It is possible to assume that the transfer function is a log normal one

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(ln(x)-\mu)^2}{2\sigma^2}}$$

though this is not entire accurate for the AGN, for the exact shape a combination of the contribution from the BLR and torus must be used

$$f(t,\lambda) = A_T \frac{1}{t\sigma_{Dust}\sqrt{2\pi}} e^{-\frac{(ln(x)-\mu_{dust})^2}{2\sigma^2_{Dust}}} + (1-A_T) N_{AD} BB(T,\lambda) \frac{1}{t\sigma_{AD}\sqrt{2\pi}} e^{-\frac{(ln(x)-\mu_{AD})^2}{2\sigma^2_{AD}}}$$

Where A_T is the fraction of the complete transfer function contribution originating from the Dust Torus, BB(T, λ) the fraction of the Black Body radiation emitted at that wavelength and N_{AD} being the normalisation of the Accretion Disk flux transfer function. The torus is treated as a uniform region of constant temperature and density with a black body spectrum.

The idea is to artificially create a driving function, which can be used for reverberation mapping analysis. There is difficulty in the attempting to generate a reliable driving function based around several unknown transfer functions and unevenly sampled response functions, therefore initial work was done with a fixed transfer function. To create this function a crawler was used initially which would alter one point in the driving function a bit at each step in MCMC algorithm and then move on to the next. This alone had multiple problems that created unphysical and computationally heavy results, to account for this the acceptance criteria would have to be expanded to more than just the standard goodness of fit analysis. The criteria were expanded to include in total:

- χ^2, that is goodness of fit
- The double derivitive of the driving function so as to determine the speed at which the light curve changes, because real light curve have a gradual change and almost no sudden changes.
- The PSD slope for the driving function
- A Kelly fitting to smoothen the driving function.
- Checking for negative light curve values as those would be unphysical.

The specific values for the criteria are listed in the thesis. It should be noted that even with these new criteria a single crawler is still slow computationally.

To account for the crawler slowness we need to be able to generate entire light curves so that we no longer have a fixed, but a varying transfer function. The use of PSD function is assumed to be able to explain AGN light curves. Creating PSD functions with the right slopes was done with a module called "colorednoise" (see link in thesis), which takes the light curves in the various bands as input. The module is incorporated into the MCMC algorithm and the changeable parameters for the algorithm are:

- The dust torus temperature is a single value given by the Planck radiation law and the energy emitted by the torus comes only from what is absorbed by the AGN.
- The natural log of the thermal lag ($\mu_{thermal}$) the natural logarithm of the mean value of the delay in the thermal transfer function and a measure of the Torus radius.
- The natural log of the width of the thermal lag ($\sigma_{thermal}$). A thin, optically thick shell in the Torus would be a delta function and the more physical case of a thick, optically thick Torus has a wider contribution function.
- The thermal fraction of the observed flux (A_T), must be viewed in together with individual normalisation's of the Accretion Disk flux in the differing bands.
- The Accretion Disk transfer function normalisation (N_{AD}) represents the fraction of the driving function energy that becomes re-emitted by the Accretion Disk in the relevant wavelength band.
- The natural log of the Accretion Disk lag (μ_{AD}).
- The natural log of the width of the Accretion Disk lag (σ_{AD})

The rest of chapter 5.2 discusses how the code iterates with a weight given to the changes generated by the colorednoise module or the Kelly smoothing model and the limitations of the code, useful to keep in mind when the code has to be optimized later.