Notes for Andreas Skielboe "Colossal creations of gravity From clusters of galaxies to active galactic nuclei""

Malte Brinch
University of Copenhagen
Septemper 2019

1. Chapter 3: Probing the structure of active galactic nuclei

To first order, the problem of reverberation mapping can be formulated as a deconvolution problem in which the flux in the emission-line light curve, at a given wavelength λ, $F_l(t,\lambda)$ is given by a convolution of the AGN continuum light curve, over some wavelength range, F_c(t) with a transfer function $\Psi(t,\lambda)$ that encodes the physics and geometry of the BLR,

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

the transfer function is assumed to be linear. Multiple approaches for determining BLR size and transfer function are presented

- directly using the convolution theorem of Fourier transforms, requires very high data quality
- maximum entropy method that finds the solution for the transfer function that has the highest entropy, while still providing a good fit, computationally expensive, relies on assumptions about transfer function shape, hard to do extensive error analysis and model comparisons.
- The Subtractive Optimally-Localized Averages (SOLA) method, estimates the 2D response as a weighted average of the emission line light curve data points.
- Dynamical modelling in which a simplified physical model of the BLR is constructed, and its parameters are inferred within the framework of Bayesian statistics, requires long computation time and flexibility for good BLR description.
- regularized linear inversion (RLI), very few assumptions about transfer function shape, fast method

RLI does chi-squared minimization together with a minimiztion of the first order drivitive of the obtained solution, such that the solution is smoothed at the level of the noise. the advantages of RLI are:

1) makes no assumption about the shape or positivity of the transfer function,
2) can be solved analytically, and
3) has very few free parameters (the regularization scale as well as the transfer function window and resolution).

Since the data we are working with is always decrete we can rewrite the transfer equation into a linear matrix equation

$$L_{\Delta\lambda} = \Psi_{\Delta\lambda} C$$

where $L_{\Delta\lambda}$ is the emission line light curve integrated over the wavelength range (spectral bin) $\Delta\lambda$, C is a matrix of continuum light curves (see below), and $\Psi_{\Delta\lambda}$ is the transfer function corresponding to the given wavelength range. For perfect noise free data solving the discrete transfer equation would just involve inverting C to obtain the transfer function Ψ. Because of noise it is not possible to determine an exact solution to the linear inversion problem. Instead the χ^2 is minimized (goodness of fit) together with a smoothing condition so as to not fit the noise.
To be able to state anything about the BLR structure from the transfer function we need to make some assumptions

- That the variations in the AGN continuum bands are correlated with the AGN ionizing continuum
- That the continuum emission originates from a region negligible in size compared to the BLR.
- That the continuum ionizing radiation is emitted isotropically.
- The BLR structure is constant and the response linear for the duration of the campaign, such that a single linear transfer function can be calculated from the full light curves.

Chapter 3.4.1 shows how to solve the response function. Responds functions are calculated in a time delay of 0-30 days as that seem to be sufficient for the Seyferts, significant response power happens at 0-15 days.

The continuum light curve is fitted using Gaussian processes since studies of AGN variability, using sampling intervals of days, have suggested that AGN continuum variability is well modelled by a damped random walk or Ornstein–Uhlenbeck (O–U) process. This is called a CAR(1) or continuous-time first-order autoregressive process, which is a stationary Gaussian process with a power spectral density (PSD) slope of -2. Recent high cadence observations have shown that have steeper PSD slopes less than -2, which would mean small scale variability would be suppressed in the light curve. The slope of the PSD and therefore the continuum model PSD seem to have only a small effect on the response function.

Look up DNEST4 code by Brendon J. Brewer for MCMC code to obtain best fit Gaussian process parameters, multiple realizations of the best fit Gaussian parameters can also be made (1000 of them) to estimate the statistical error on the response function.

The assumption of a constant linear response might not be true as there seem to be long time-scale non-linearities and also high variability features that are inconsistent with models that suggest that the BLR emission comes from an extended region. There might be a time delay between the UV and optical continuum. There is a possibility for negative response values due to a number of reasons, though not any conclusive evidence.

2. Chapter 4: Photometric reverberation mapping

many parts here are taken directly from the PHD, always remember to rewrite stuff like that in your own words. Large chunks of text have ""

This chapter concerns itself with photometric reverberation mapping using the JAVELIN code. Properties of AGN have been found to correlate with large scale properties of their host galaxies, indicating a link between AGN activity and galaxy evolution. Their luminosity is good for probing the early universe and SMBH evolution. Reverberation mapping of different continuum bands can furthermore put constraints on the accretion disk (Edelson et al., 2015). (Hönig et al., 2014, use reverberation mapping of the dust torus together with an interferometric size measurement to determine absolute distances). High efficiency reverberation mapping can use photometric observations to measure an average time delay for a given emission line, several AGN can be observed simultaneously this way and can be done without spectral flux and wavelength calibrations.

For the aperture try using 5 pixels to avoid contribution from galaxy as much as possible maybe??? (remember not same telescope.)

The standard stars are selected to be non-variable and away from the edge of the field and any bad pixels on the CCD.

"Another way to measure R_{BLR} is to assume a parametric form for Ψ and determine the best fit parameters by convolving the continuum light curve with the transfer function to obtain a model emission line light curve that can then be compared to the data. If a transfer function is selected that is unimodal and symmetric, its position, defined as the median of the distribution, should be a good estimate for the median time delay, also found in CFF methods. Because this method provides a complete, albeit simple, model for the reverberation mapping problem, it has the benefit of providing well defined error estimates for the model parameters." This is what we want to do and this is what JAVELIN does by using to top-hat model for the transfer function and includes modeling of the continuum light curve to determine a likelihood distribution for the time delay (Zu et al., 2011).""
JAVELIN work by modeling the broad band continuum light curve as

$$F_c(t) = C(t) + n_c$$

Where $F_c(t)$ is the observed continuum band flux as a function of time, C(t) is the intrinsic continuum light curve and n_c is the noise in the continuum band. Note that we assume that the continuum flux contains random noise, but no contribution from emission lines. On the other hand we have the narrow-band emission line light curve, which is a combination of line emission and continuum,

$$F_l(t) = \alpha C(t) + L(t) + n_l$$

where $F_l(t)$ is the observed narrow-band flux as a function of time, L(t) is the intrinsic, uncontaminated and noise free emission line light curve, n_l is the noise in the narrow band and α controls the contribution of continuum emission to the observed narrow-band flux.

"It is worth noting that the model used by JAVELIN is a phenomenological, rather than physical, model. This means that the JAVELIN time delay is difficult to interpret outside of the context of the method used to derive it (as is the case for CCF time delays)."

There is evidence for a time delay between the UV and optical continuum the measured time delay is not from the black hole to the BLR but from the region of the accretion disk emitting the optical continuum to the broad emission line region

JAVELIN assumes that the continuum light curve is uncontaminated by variable broad line flux which if not entirely true depending on the filters used.

"Studies of large samples of light curves in SDSS have revealed that AGN light curves are well approximated by a Gaussian process with a particular type of covariance function called Ornstein–Uhlenbeck (OU; Gillespie, 1996; MacLeod et al., 2010; Zu et al., 2013). A Gaussian process with an OU covariance function is also known as a damped random walk (DRW). The DRW has the advantage that it is easy to calculate, and allows for fast generation of a large number of light curve realizations, required in Monte Carlo sampling procedures when fitting light curve models (Kelly et al., 2014)"
"The light curves generated by a DRW has a power spectral density (PSD) function with a constant slope of -2. Recent studies using high signal-to-noise and high-cadence observations from Kepler have indeed found evidence for a steeper PSD power-law slope of up to -4.51, at time scales shorter than a few days (Mushotzky et al., 2011; Edelson et al., 2014). A steeper PSD slope means that the light curve has less structure on small scales, compared to what is predicted by the DRW model. modeling noisy light curves using a DRW may overfit the light curves resulting in the following:
1. If the additional noise is due to flux calibration issues affecting both the continuum and emission line light curves in a single epoch, overfitting the light curves can introduce excess power in the time delay distribution at $\tau = 0$ (e.g. Gaskell & Peterson, 1987; Edelson & Krolik, 1988).
2. If the noise is independent between the two light curves, overfitting the continuum may still produce accurate time delay measurements, but the error on the time delay will be underestimated. This is due high frequency noise being propagated to the likelihood distribution, resulting in error estimation being done on small scale noise, rather than on the underlying likelihood signal."

Error bars can be multiplied by a factor to make them dominate over the variability's on the smallest scales for the light curves. This effectively removes the effect of high frequency noise and makes the likelihood distribution smoother. This preserves large scale behavior, which is what we need to determine the time delay.