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,

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

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.