Photo-Reverberation Mapping

Tutorial #5

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The goal of this tutorial was to learn photo-reverberation mapping (photo-RM) methods and techniques, and to get introduce to tools that simulate active galactic nuclei (AGN) light-curves and perform photo-RM. And then, to apply these methods to real observational data.

Task 1

1. Simulating Light-Curves

In the `photRM.py` module, there are functions implemented to generate artificial AGN light curves. The `lc_two_bands` function generates them and returns light-curves that are ready for photo-RM. There are two main components for these light-curves [?, ?]:

- The X band, which covers only the continuum. This one is generated with a Damped random walk (DRW) process , which is able to describe optical thermal emission of the accretion disk.
- The Y band, which covers emission lines and its surrounding continuum. It is modeled as described in [?, ?]. The emission line response curve is obtained by convolving the X band light curve with a Gaussian kernel, which mean and standard deviation depend on the radius of the broad line region. Then this is summed up with another pure continuum curve with appropiate realistic weights.

I generated three pairs of light curves with $\log L = 43$, 44 and 45 $L_\odot$ respectively. They are 5000 data points long, have redshift $z = 0.1$, have an oscillatory signal with an amplitude of 0.14 magnitudes, noise of a factor of 0.00005, and a random time-lag. In Figures 2, 3 and 4, I plotted the first 1000 detections of these light-curves. The time-lags printed by the `lc_two_bands` function are 9.86, 33.65 and 114.82 days respectively.

2. Estimating Time-Lags

Then, I estimated the time-lags of each pair of light-curves. For this, I used `pyzdcf` [?], a python implementation of a simpler version of `PLIKE`, a Fortran code [?, ?].

The method used here is a cross-correlation function (CCF) [?]:

$$CCF(\tau) = CCF_{YX}(\tau) - ACF_X(\tau), \tag{1}$$

where CCF is the cross-correlation function between the X and Y light curves, and ACF is the auto-correlation function, i.e. the cross-correlation of X with itself. The method implements a discrete CF (DCF) [?], which does not need to fill in the gaps to obtain uniformly sampled light curves. Instead, it creates time bins of an appropiate size, and calculates a discrete correlation. Then, the z-DCF method uses a z-transformed DCF [?] over equally populated bins.

The results are plotted in Figures 5, 6 and 7. The estimations closely match the time-lag posted by the `lc_two_bands` function. They are 9.0, 33.0 and 115.0 days respectively. Thus, these are very good results. However, the accuracies and errors are lost in the `pyzdcf` code.

I note that the more luminous AGN have a larger time-lag (see Figure 1). This can be explained with the size or supermassive black hole (SMBH) mass versus luminosity relation [?, ?]:

$$R_{BLR} \propto L^{\alpha} \tag{2}$$

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Different authors have estimated α. For example, [?] obtained an estimate of 0.665 ± 0.069 and [?] obtained one equal to $0.519 + 0.063 - 0.066$. I plotted this relation to see how it looks like for these artificial light-curves in Figure 1. None of these slopes fit the artificial light curves, so by trial and error I found that a slope of 0.340 somewhat fits them. The difference might be due to the fact that these light-curves are artificial, or perhaps a redshift correction should be done first.

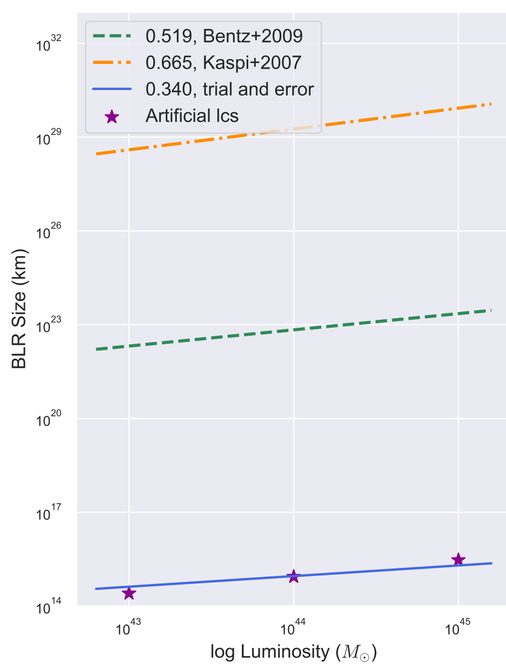

Figure 1: Luminosity versus time-lags for the artificial light-curves.

3. Gapped Light-Curves

Then, I created three pairs of gapped light curves based on the artificial one with $\log L = 43L_{\odot}$. They have three different cadences:

1. One detection every five days.
2. A pattern of a month with detections everyday and then a month of no detections.
3. A pattern of three months of observations eveyrday, then six months of observations once a month and a gap of three months.

The correct time-lag for this light curve is 9 days. However, the lag estimated for the one with the first cadence was $15.0(+0.0-0.0)$ days, for the second cadence it was $9.0(+2.0-0.0)$, and for the last one it was $135.4(+36.0-10.0)$. I initially expected the first cadence to produce a correct estimate, but even though it is wuite close to the correct lag, it is not fully precise. I think this happens because since the frequency of the detections is more sparse, the flares that occur in the light curve can fit into one of the gaps, artificially producing a larger value of the CCF function.

The second cadence did produce the expected 9 days of time-lag, but this estimate now has

Task 2: NGC 4395

References

[1] H. Edri, S. E. Rafter, D. Chelouche, S. Kaspi, and E. Behar, "Broadband Photometric Reverberation Mapping of NGC 4395," , vol. 756, p. 73, Sept. 2012.

Figures

3.1. Artificial Light Curves

3.2. CCF of Artificial Light Curves

3.3. CCF of Gapped Light Curves

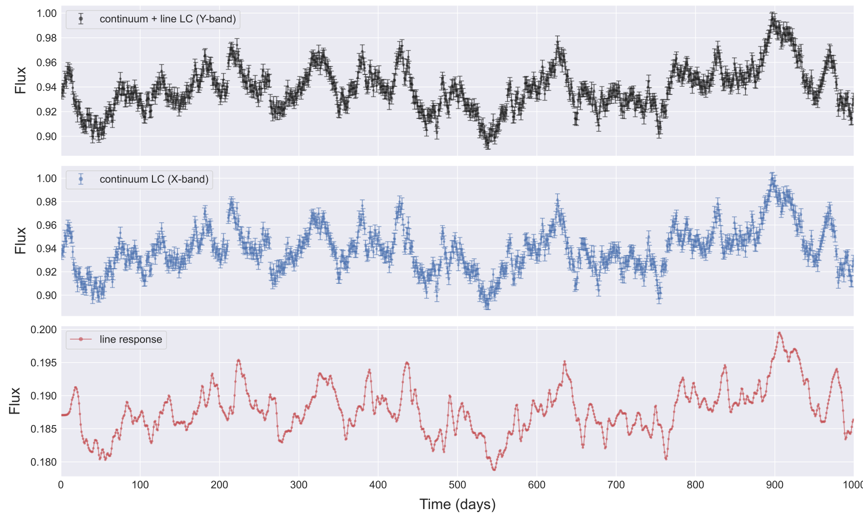

Figure 2: Artificial light-curve of an AGN with $\log L = 43L_{\odot}$ and a time-lasg of 9.86 days.

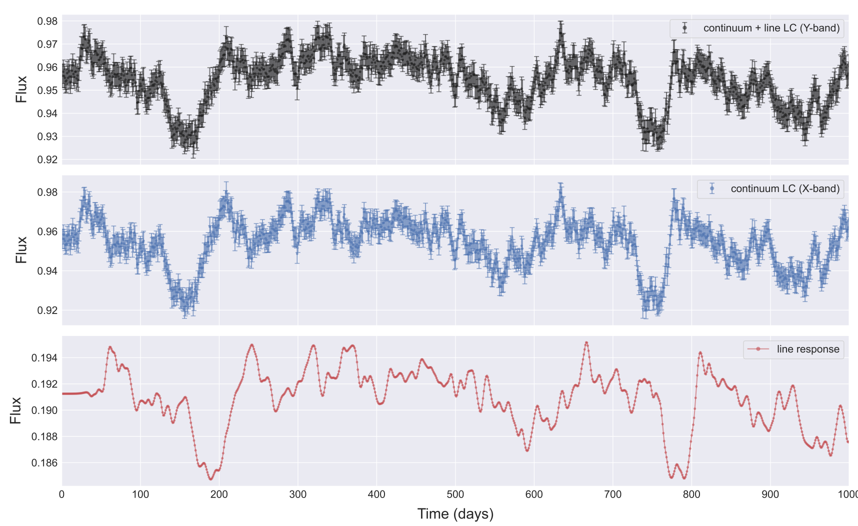

Figure 3: Artificial light-curve of an AGN with $\log L = 44L_{\odot}$ and a time-lag of 33.65 days.

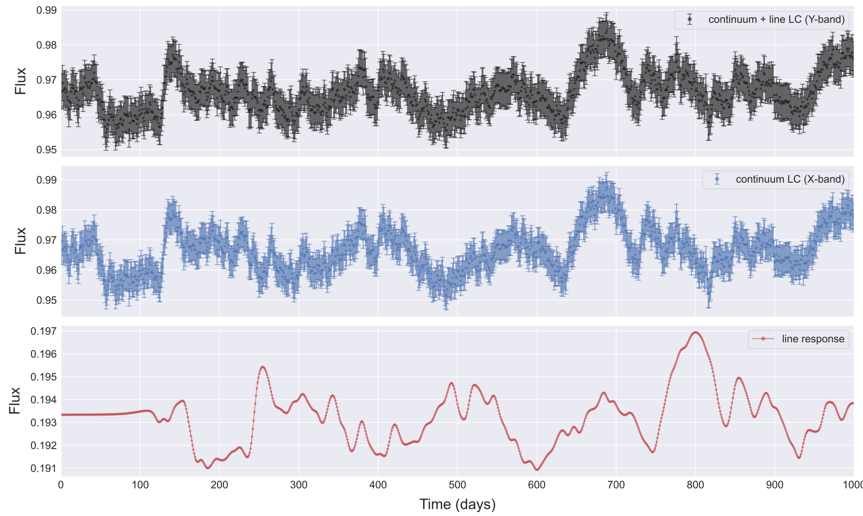

Figure 4: Artificial light-curve of an AGN with $\log L = 45 L_{\odot}$ and a time-lag of 114.82 days.

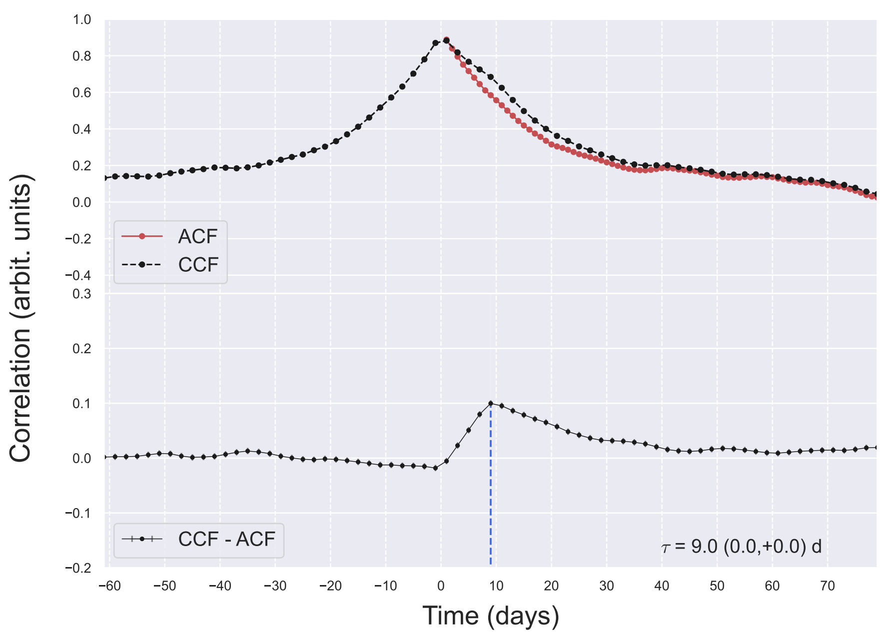

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Figure 5: CCF of the artificial light-curve with $\log L = 43 L_{\odot}$

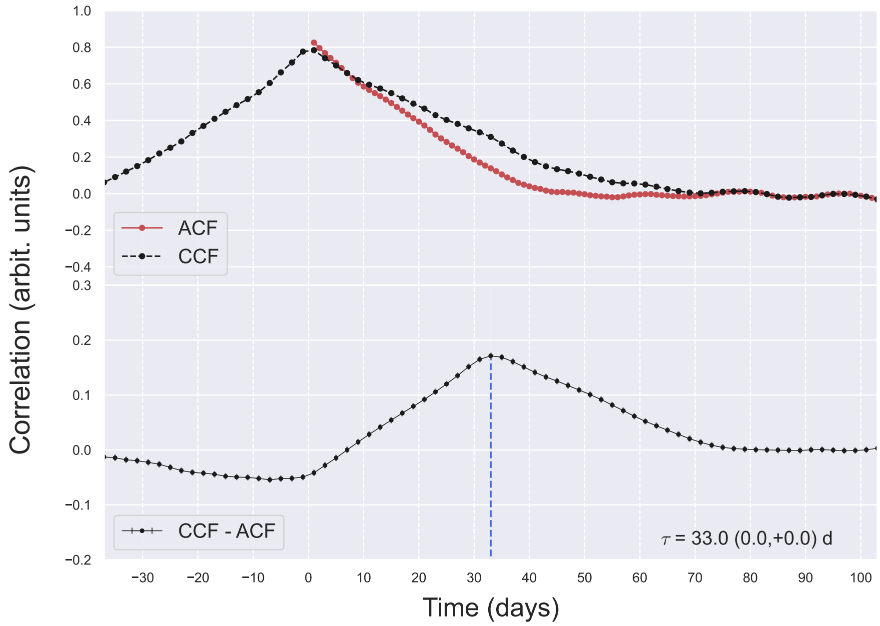

Figure 6: CCF of the artificial light-curve with $\log L = 44 L_{\odot}$.

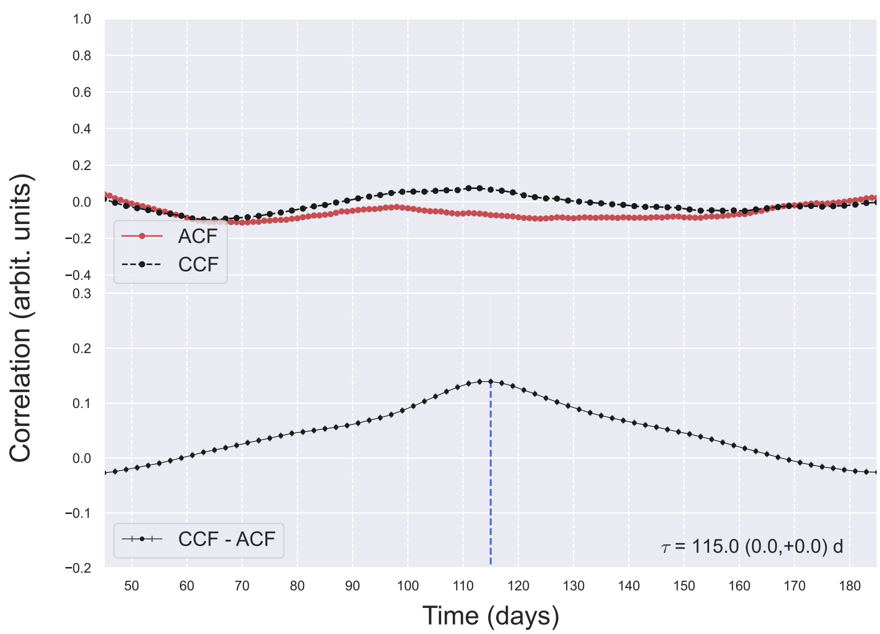

Figure 7: CCF of the artificial light-curve with $\log L = 45 L_{\odot}$.

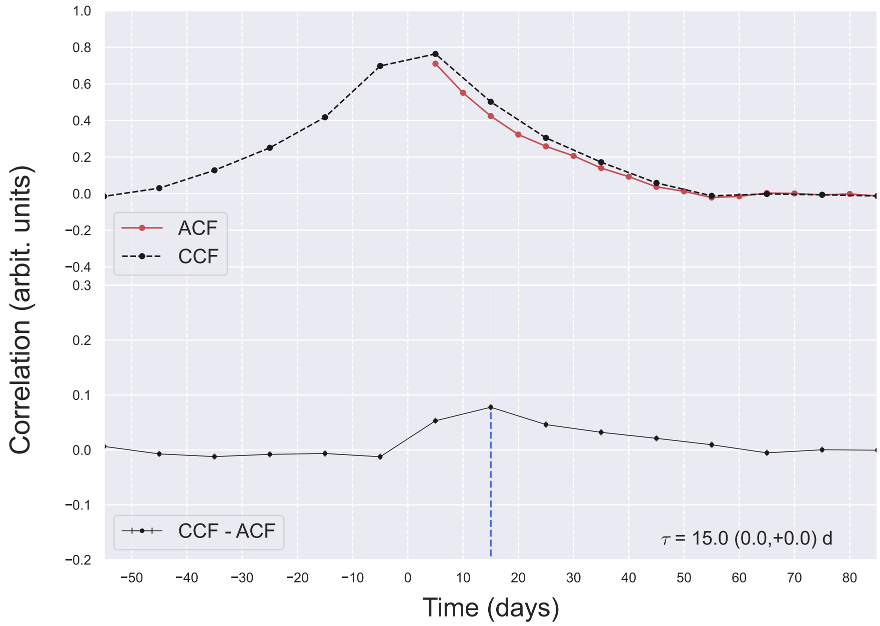

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Figure 8: CCF of the artificial light-curve with $\log L = 43 L_\odot$ with detections every five days.

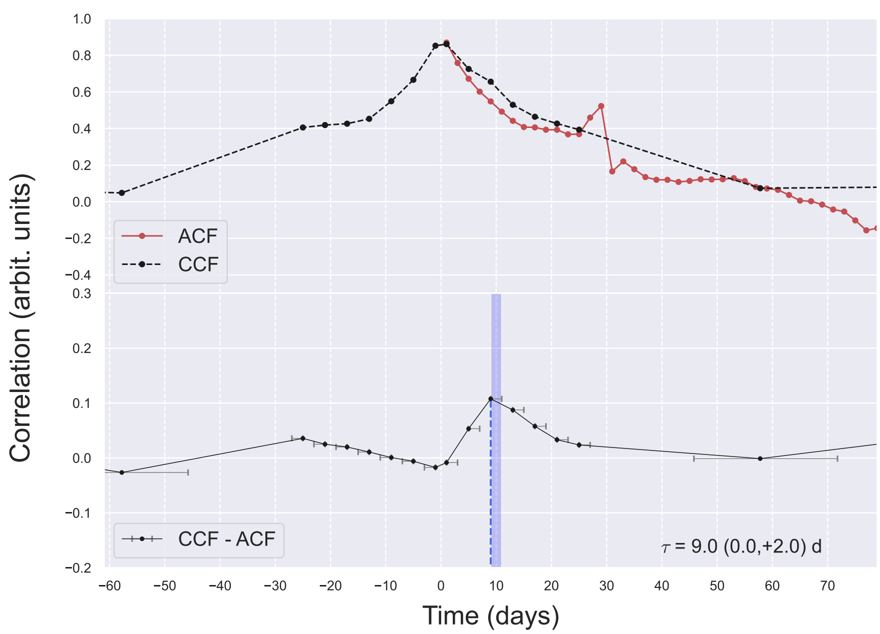

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Figure 9: CCF of the artificial light-curve with $\log L = 43 L_\odot$ with detections in a pattern of every day for one month and then a gap of a month.

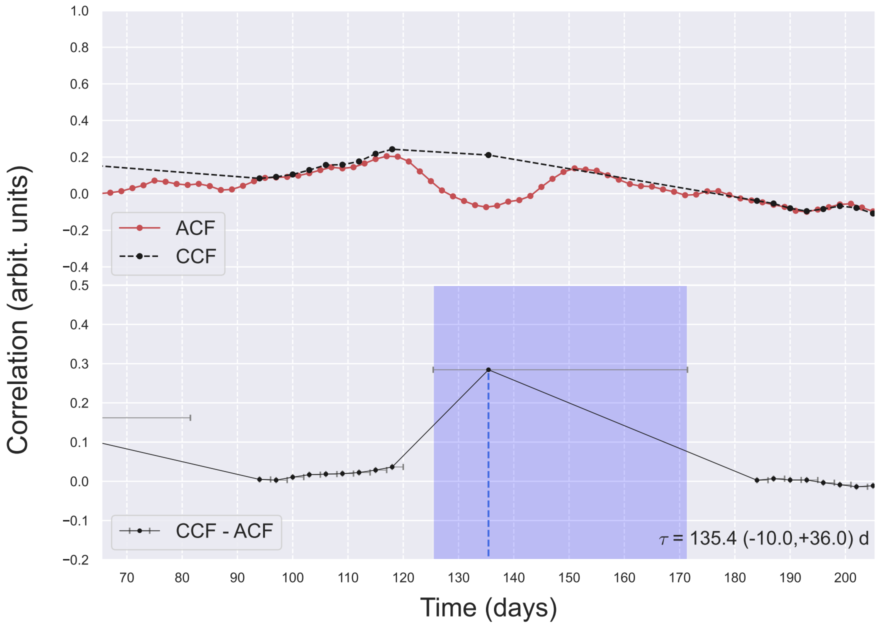

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Figure 10: CCF of the artificial light-curve with $\log L = 43 L_{\odot}$ with detections in a pattern of three month of observations every day, followed by six months of observations with a frequency of once per month and then a gap of three months.