Correlation between emission-line luminosity and gamma-ray dominance in the blazar 3C 279

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Abstract

The nature of blazar γ-ray emission is still debated, in particular whether it is of a leptonic or hadronic origin. In our study, we are testing the hypothesis that the γ-ray emission of the Flat Spectrum Radio Quasar (FSRQ) 3C 279 (z=0.5362) is generated in a leptonic scenario by inverse Compton scattering of soft photons from the Broad Line Region (BLR). We use a 10-year data set of the source including optical spectra and *Fermi*-LAT data, and search for a possible correlation between the Compton dominance and the emission line luminosity. We find that the simultaneous measurements of these quantities display no correlation. The discrete correlation function (DCF) analysis shows a positive correlation at a time lag of 25 d and an anti-correlation at 60 d, indicating that the changes in the Compton dominance lag behind the changes in emission line luminosity. We consider the positive correlation to arise due to light travel effects and derive constraints on the location of the γ-ray emitting zone in the jet. We propose also a tentative interpretation of the observed anti-correlation as due to a characteristic time-scale of accretion disk activity.

Introduction

3C 279 is one of the best studied FSRQs, monitored nearly in all spectral bands (e.g. [1]).

Tested hypothesis: *leptonic scenario* – γ-ray emission arises from inverse Compton (IC) upscattering of soft photons from BLR by high energy electrons (the IC-BLR scenario) in a compact region of the jet (blob) (e.g. [2])

Expectation: under this scenario, we should observe a correlation between the luminosity of optical emission lines (originating in the BLR) and the Compton dominance.

$$CD = \frac{F_{\rm IC}}{F_{\rm syn}} \propto \frac{N_e U_{\rm rad,BLR}}{N_e U_B} \propto \frac{U_{\rm rad,BLR}}{U_B}$$

Goal: test the IC-BLR scenario for 3C 279 by applying a correlation analysis to long-term optical spectroscopy and γ-ray data of the object.

Data

We use a combined optical and γ-ray data set of 3C 279 spanning from 2008 till 2018:

- ***Fermi*-LAT**: information about γ-ray flux vs time. We extract long-term γ-ray light curve.
- **Optical data**: information about emission line luminosity and non-thermal synchrotron continuum vs time. A set comprises ∼400 optical spectra from the Steward Observatory blazar monitoring program[1] in the wavelength range 4000 – 7550 Å.

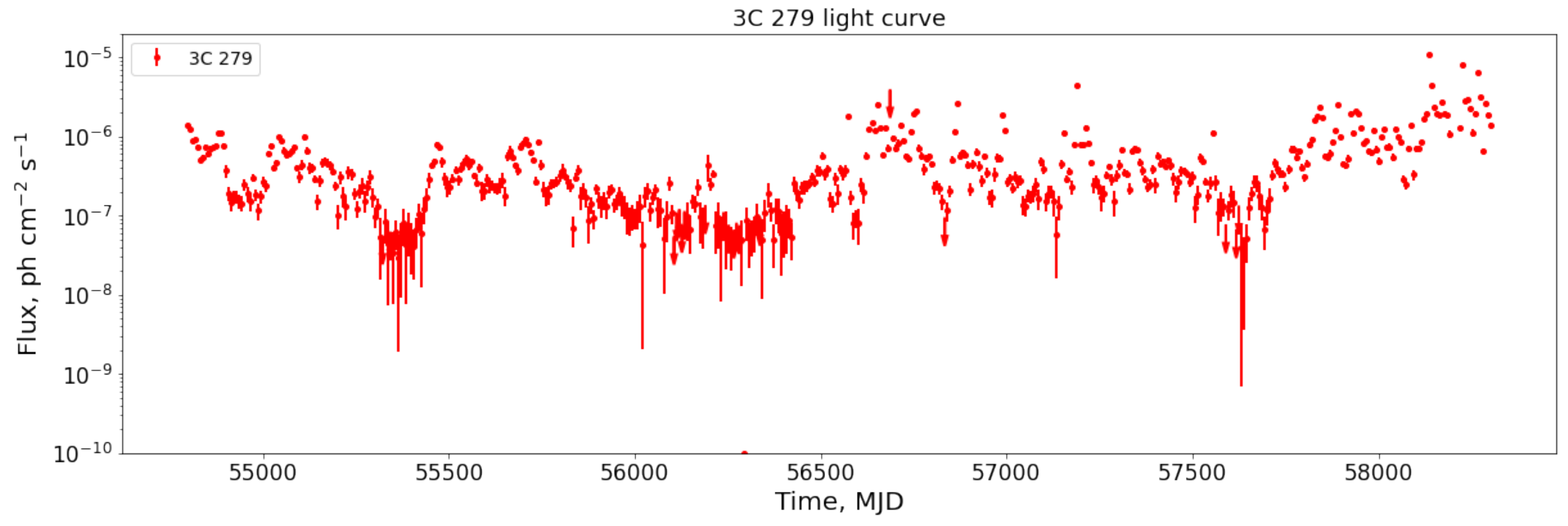

Figure 1. 10-year *Fermi*-LAT light curve of 3C 279 in the range 0.1 - 100 GeV (2008 – 2018)

Analysis

Fermi-LAT γ-ray data

To extract the long-term γ-ray light curve of the source, we perform the maximum likelihood analysis using the *Fermitools* package. The data is selected within a time range November 24, 2008 – July 7, 2018, which corresponds to the time span of the optical data set. We chose "SOURCE" class events in the 0.1 – 100 GeV energy range from a 15° radius region of interest (ROI) centered on the source location, as well as impose a zenith angle cut of $90°$. We use the latest instrument response functions (IRFs) `P8R3_SOURCE_V3`. The composite model of the ROI includes the source of interest 3C 279 and the nearby point source 3C 273 (with a power law spectral model chosen for both), as well as the Galactic diffuse and the isotropic diffuse backgrounds, modeled with the latest templates `gll_iem_v07` and `iso_P8R3_SOURCE_V3_v1` respectively. We choose a 1 week time step for the light curve time binning. The resulting long-term *Fermi*-LAT γ-ray light curve is depicted in Fig. 1.

Optical data

The optical spectra of the source were found to typically represent a power-law continuum (synchrotron component) with a set of emission lines on top of it (originating from the BLR). The most prominent emission line appears to be **Mg II** (source frame: 2798 Å, laboratory frame: 4298 Å). Ignoring the other emission lines which are substantially weaker, we model each spectrum with a sum of a **power law continuum** and a **Gaussian emission line**.

$$F_\lambda(\lambda) = A_c \left(\frac{\lambda}{\lambda_0}\right)^{-p} + \frac{A_g}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\lambda-\lambda_\mu)^2}{2\sigma^2}\right)$$

We fit each spectrum with this model (keeping the central position of the Gaussian constant at $\lambda_\mu = 4298$ Å) and retrieve the emission line energy flux A_g as a function of time (see left panel of Fig. 2). In case the line is not detected (e.g. due to a very high level of continuum), we estimate an upper limit for the line flux based on the magnitude of continuum fluctuations around the expected line position.

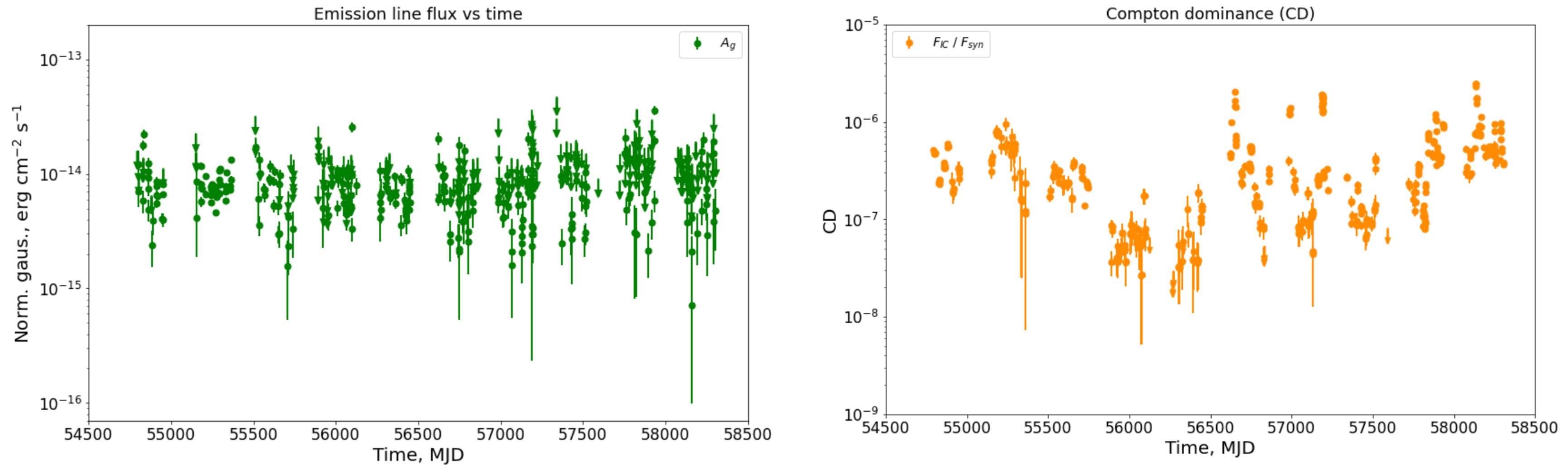

Figure 2. *Left*: Energy flux of the Mg II emission line in 3C 279 spectrum versus time. *Right*: Compton dominance of the source as a function of time. Both light curves span from 2008 to 2018.

Now we proceed to the Compton dominance calculation. We approximate the Compton dominance parameter as a ratio of the *Fermi*-LAT γ-ray flux to the optical synchrotron flux, assuming that the latter is roughly proportional to the total synchrotron flux. We perform the integration of the power law continuum model over the total wavelength range 4000 – 7550 Åfor each optical spectrum, and obtain the optical synchrotron flux as a function of time, which we then use to compute the Compton dominance light curve (presented in the right panel of Fig. 2).

Results

Simultaneous correlation

Now we search for a correlation between the **emission line flux** and **Compton dominance**. We produce a scatter plot of their simultaneous measurements by pairing these two quantities associated to each run of optical observations (left panel of Fig. 3). As one can see, simultaneous measurements of these two quantities display *no correlation*. Hence, we test for the presence of a correlation with a time lag between the changes in one quantity and response in another one.

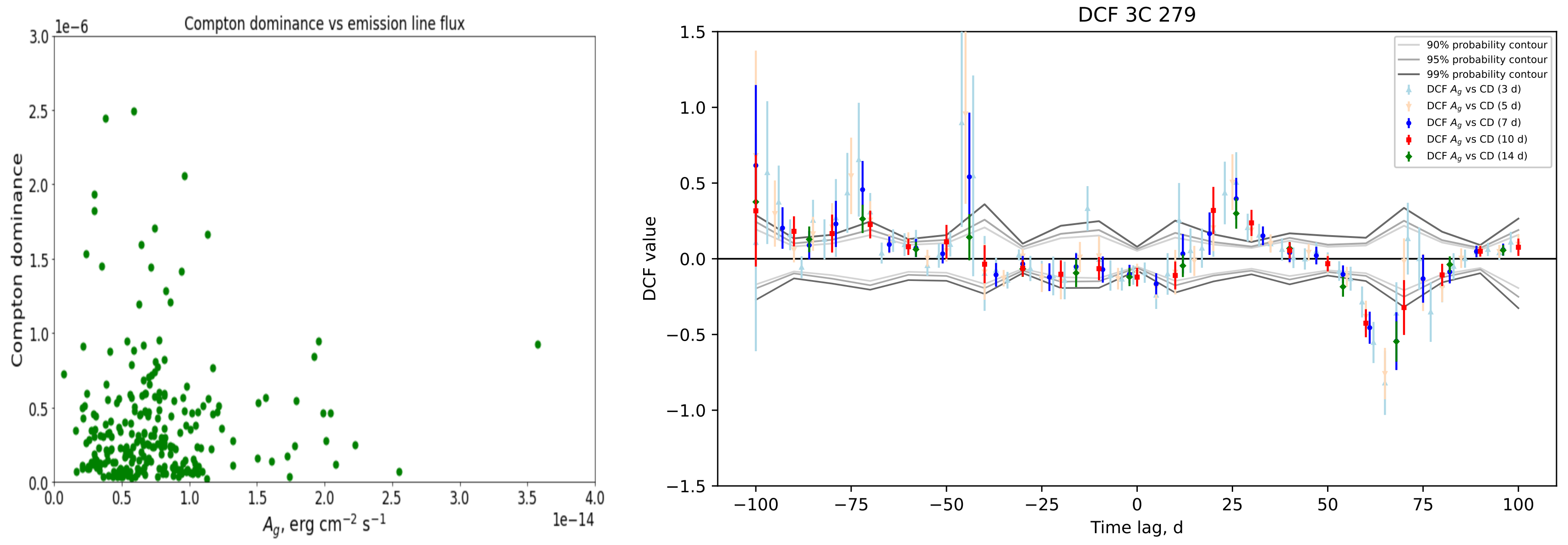

Figure 3. *Left*: Scatter plot of simultaneous measurements of emission line luminosity vs Compton dominance. *Right*: DCF for the light curves of emission line flux and Compton dominance with different time lag binning. The gray contours represent (from lightest to darkest shades) a 90%, 95% and 99.7% (3σ) probability contours.

Discrete correlation function (DCF) analysis

We cross-correlate the light curve of emission line luminosity with that of Compton dominance using the DCF method [3]. The resulting DCF as a function of a time lag is shown in the right panel of Fig. 3. We also compute the significance contours using Monte-Carlo (MC) simulations: in each run one of the light curves is randomly shuffled and cross-correlated with another one, and the resulting DCFs from all runs are stacked. One can see two statistically significant ($> 3\sigma$) peaks in the DCF at positive time lags $\Delta t \sim 25$ d and $\Delta t \sim 60$ d, meaning Compton dominance response follows changes in emission line luminosity with a time lag.

Discussion and conclusions

- Our results are consistent with a leptonic IC-BLR interpretation
- Positive correlation at **25 d** (DCF $\sim$ 0.5):
  - we consider it arising due to the light travel time from BLR to the γ-ray production site
  - γ-ray emitting zone is located $\sim 2 \times 10^{16}$ cm inside the BLR's inner boundary
- Anti-correlation at **60 d** (DCF $\sim$ 0.7):
  - cannot be explained with light travel effects
  - tentative interpretation: related to accretion disk duty cycle

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