Astronomical Data Analysis Software and Systems VI
ASP Conference Series, Vol. 125, 1997
Gareth Hunt and H. E. Payne, eds.

Determination of Variable Time Delay in Uneven Data Sets

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Abstract. Time delay determinations in astrophysics are used most often to find time delays between flux density variations in different spectral bands and/or lines in AGNs, and different images of gravitationally lensed QSOs. Here we consider a new algorithm for a complex case, when the time delay is itself a linear function of time and the intensity of echo response is exponential function of the delay. We apply this method to the optical-to-radio delay in the lensed double quasar Q0957+561.

Radio-optical variability correlation in Q0957+561 was first reported by Oknyanskij & Beskin (1993, hereafter OB) on the basis of radio observations made in the years 1979 to 1990. OB used an idea to take into account the known gravitational lensing time delay to get combined radio and optical light curves and then to use them for determination of the possible radio-from-optical time delay. It was found this way that radio variations (5 MHz) followed optical ones by about 6.4 years with high level of correlation (≈ 0.87). Using new radio data (Haarsma et al. 1997), for the interval 1979–1994, we find nearly the same value for the optical-to-radio delay as had been found before. Additionally, we suspect that the time delay value is linearly increasing at about 110 days per year while the portion of reradiated flux in the radio response is decreasing.

We conclude that the variable radio source is ejected from the central part of the QSO compact component.

1. Introduction

Time delay determinations in astrophysics are used most often to find time shifts between variations in different spectral bands and/or lines in AGNs, as well as time delays between different images of gravitationally lensed QSOs. In most cases, the task is complicated by uneven spacing of data, so that standard cross-correlation methods become useless. Two different methods are most often used: CCF (Gaskell & Spark 1986) and DCF (Edelson & Krolik 1988), which are based on line interpolation of data sets or binning of correlation coefficients, respectively. We have introduced several simple improvements to CCF (Oknyanskij 1994) and this modernized MCCF combines the best properties of CCF and DCF methods. With MMCF we calculated regression coefficients as functions of time shift. Here, this calculation is generalized for the more complex case where the time delay is a linear function of time, and a portion of the flux density is itself a power-law function of the delay. We apply this method to the optical-to-radio time delay in the gravitationally lensed double quasar Q0957+561. The data sets used here were obtained to determine the gravitational lensing time delay $\tau_\circ$. Our results are nearly identical for values of $\tau_\circ$ in the interval of 410–550 days. In the discussion below, we take $\tau_\circ = 425$ days.

2. Method and Results

Our method includes several steps, which are briefly explained below:

Combined light curves. We take the radio (Haarsma et al. 1997) and optical (Vanderriest et al. 1979; Schild & Thompson 1995) data sets for A and B images and determine (using MCCF) the line regression coefficients k(τ) and m(τ). Then we transform $A(t_i)$ values into the B image scale system for the known value of $\tau_\circ$:

$$B'(t_i - \tau_\circ) = k(\tau_\circ) \cdot A(t_i) + m(\tau_\circ). \qquad (1)$$

We combine these values B' with the usual B ones, sorting by time. The resulting optical light curve was then smoothed by averaging in 200 day intervals with steps of 30 days. This accounts for the physical argument that radio sources should be bigger than optical ones. The value of 200 days for smoothing was taken as about optimal from the autocorrelation analysis of light curves.

Correction for change of time delay and radio flux. Taking the optical-to-radio time delay $\tau_{\rm or}$ to be a linear function of time, let V be the change of optical-to-radio time delay $\tau_{\rm or}$ per year. We fix some moment of time as t_0. It is attractive to choose t_0 so that it falls near a strong maximum in the optical light curve (here J.D. 2445350), which obviously correlates with the high maximum in the radio light curve if take $\tau_{\rm or}(t_0) = 2370$ days. So we can calculate the needed correction:

$$S(t) = \frac{V \cdot (t - t_0)}{365^{\rm d}} \qquad (2)$$

to be added to dates in the optical light curves:

$$t'_i = t_i + S(t_i) \qquad (3)$$

Assuming that a portion of radio flux decreases as a power-law function of time with exponent α. We should also correct the optical flux for that fading before computing the cross-correlation function:

$$I'_{\rm op}(t'_i) = I_{\rm op}(t_i) \cdot (1 + S(t_i)/2370^{\rm d})^{-\alpha} \qquad (4)$$

Computing MCCFs. We compute an array of MCCFs for combined radio and optical light curves, varying V and α.

Map cross-correlation as a function of V and α. For points (V, α) we map the MCCF values (see Figure 1). The best correlation occurs for $V \approx 110$ days/year, and $\alpha \approx 0.7$.

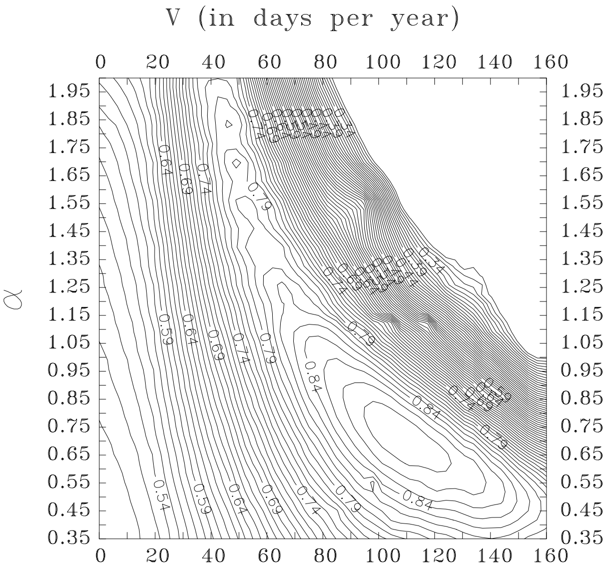

Figure 1. Two-dimensional cross-correlation function (see text).

Comparison of optical and radio light curves. We correct the optical combined light curve using (3) and (4) with the parameters $V = 110^{\mathrm{d}}$ and $\alpha = 0.70$, shift ahead by $\tau_{\mathrm{or}}(t_0) = 2370^{\mathrm{d}}$, and then fit to the radio data by analogy with (1). The corrected optical light curve is shown with with the radio light curves in Figure 2. Most features in both light curves coincide quite well. So the investigation supports our assumption on the lengthening of the optical-to-radio time delay. As a result we can give an expression for the optical-to-radio time delay as a linear function of time:

$$\tau_{\mathrm{or}} = 2370^{\mathrm{d}} + 110^{\mathrm{d}} \cdot \frac{(t - t_0)}{365^{\mathrm{d}}} \tag{5}$$

3. Conclusion

We have calculated the time delay between radio and optical flux variations using a new method. In addition, we have investigated the possibilities that (1) there is a change of the time delay that is a linear function of time, and (2) the radio response has power-law dependence on the time delay value.

Finally, let us stress some additional consequences from our results:

1. For some objects, optical-to-radio time delays were probably not found because they were too long compared to the duration of monitoring program.

2. Optical-radio correlations may not have been recognized in some objects since the time delays as well as response functions probably were variable. This possibility has never been entertained before.

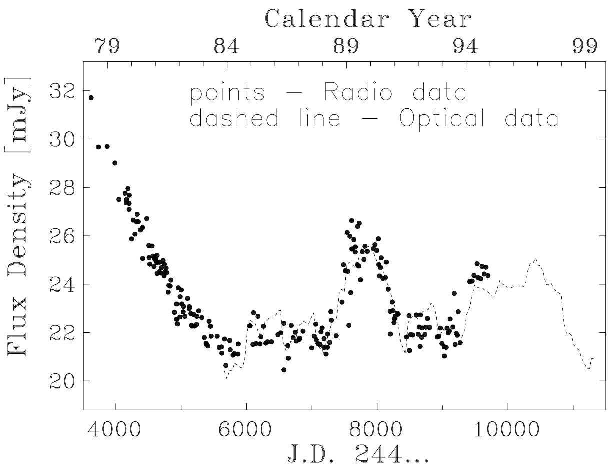

Figure 2. Radio and optical combined light curves. (The optical light curve is corrected as described in the text.)

3. The variable radio flux in Q0957+561 may originate in a very compact jet component moving away from the optical source. Only after another jet component appears (whose time delay value will of course be different) will the QSO again show some optical-radio correlation.

4. If several compact jet components exist simultaneously in a QSO then we may have no chance to find any radio-optical correlation. Only if these jet components move toward the observer closely to the line of sight (as it is probable for Blazars), will radio-optical correlation have a chance to be found, since the time delays for all these variable radio components would be very close to zero.

Acknowledgments. In conclusion, we thank Debborah Haarsma for sending us the preprint with the new radio data for Q0957+561 before publication.

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