Reverberation mapping and spatial structure of the quasars

Berdina L.A. & Tsvetkova V.S.

INSTITUTE
OF RADIO ASTRONOMY

Institute of Radio Astronomy of NASU, Ukraine

Quasar model

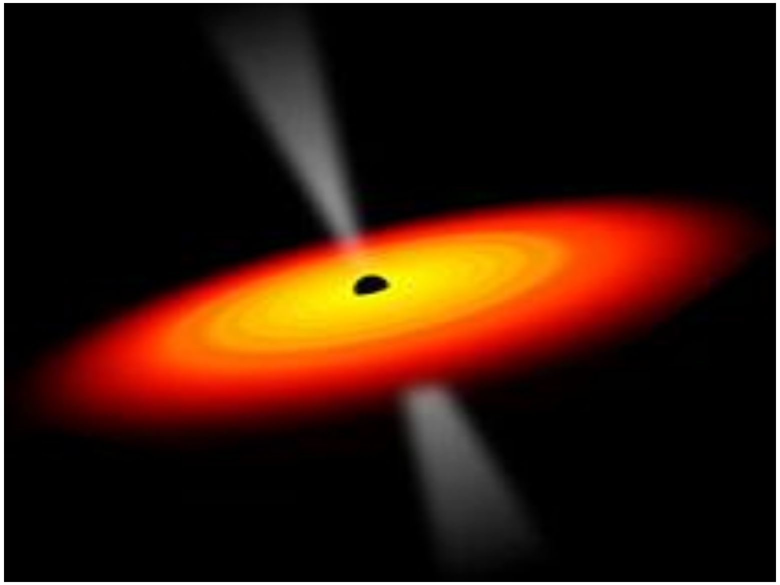
Multilateral studies of quasars and AGNs

but still

- spatial structure,
- spectral features,
- mechanism of variability are not entirely clear

high expectations

projects with synchronous observations of changes in the brightness of quasars and AGNs in several spectral ranges



The **quasar model** (Shakura and Sunyaev, 1973):

- a geometrically thin optically thick accretion disk
- a supermassive black hole in the center

The **accretion disk temperature** along the disk radius (Krolik et al, 1991):

$$T \sim R^{-3/4}$$

Dependence of inter-band **time delays on wavelength**:

$$\tau \sim \lambda^{4/3}$$

for an accretion disk with the temperature $T \sim R^{-3/4}$ (blackbody radiation)

REVERBERATION MAPPING

Measuring the time delays between the brightness fluctuations in different parts of the spectrum

Investigation of the spatial structure of quasars and AGNs with a very high resolution

Gravitational time delays

Depending on the mutual location of a source, lens and observer, and specific spatial distribution of the lens gravitational potential, the observer may see:

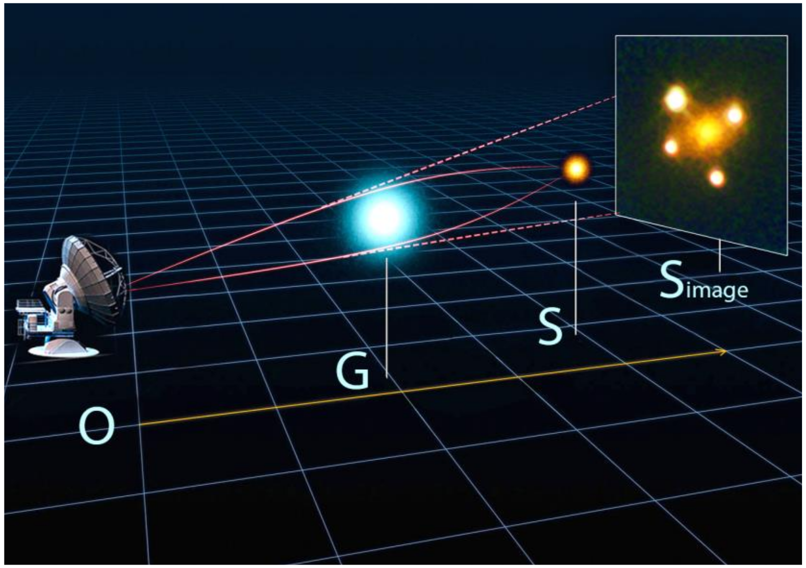
two images of the same quasar

various distortions of the source

four images of the same quasar

light from the images passes different paths to the observer, the fluctuations of quasar's brightness between images is registered shifted in time - the time delays

The RM method allows obtaining **direct estimates of distances** between the quasar regions responsible for radiation in different spectral bands.



International projects on RM:

- **SDSS-RM** (Sloan Digital Sky Survey Reverberation Mapping), Grier C. et al. 2017
- **STORM** (Space Telescope and Optical Reverberation Mapping), Fausnaugh et al. 2018
- **LAMP** (Lick AGN Monitoring Project), Pancoas et al. 2019

Method for determination of the time delays

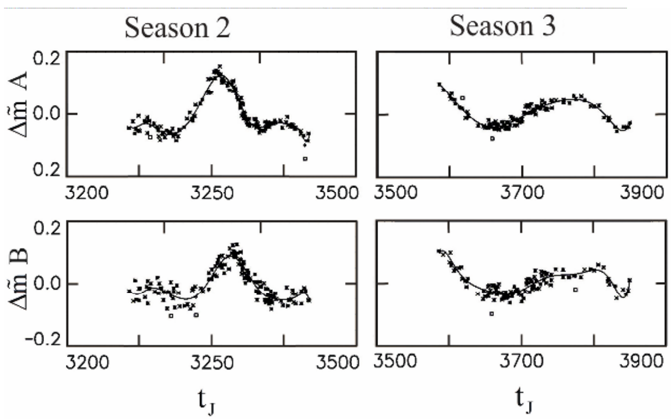
The essence of the proposed method

- Representation of light curves in the form of series expansions in **orthogonal polynomials**.
- Construction of an orthonormal basis specified at a discrete set of unevenly spaced data points (dates of observations) with the use of **Gramm-Schmidt orthogonalization procedure** - for utilizing the useful properties of the orthogonal-polynomial regressions (the Legendre polynomials - for the computational stability).

Advantages of the proposed method

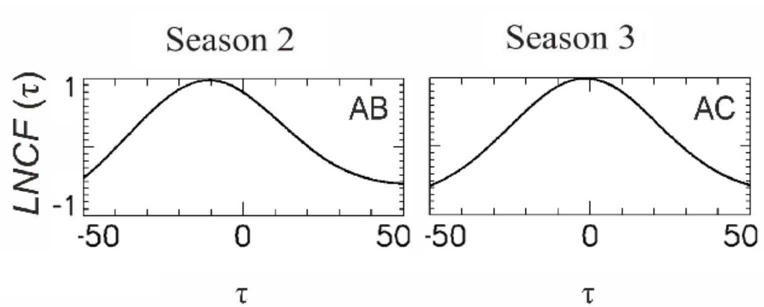
- an opportunity to **eliminate or add any term** of the polynomial approximation of a light curve without a necessity to recalculate the rest of the expansion coefficients.
- a simple way to **release** the light curves from the component of variability resulted from **microlensing effects** in the case of the so-called slow microlensing.

Light curves and approximations



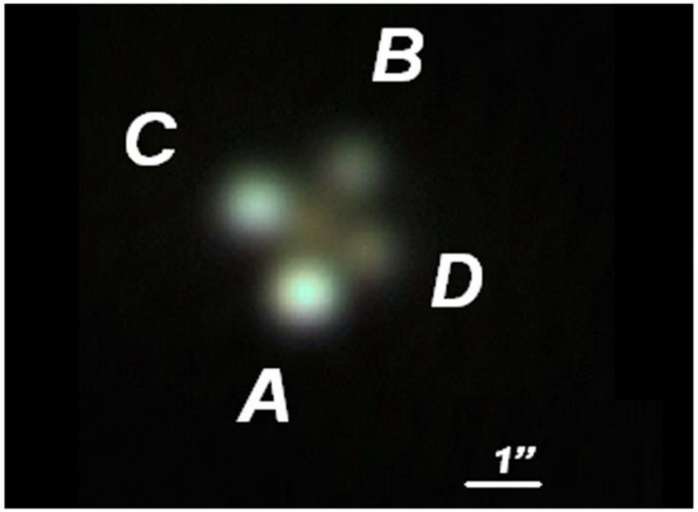
The **initial light curves** and their representations in the form of series expansions in Legendre polynomials

Cross-correlation functions



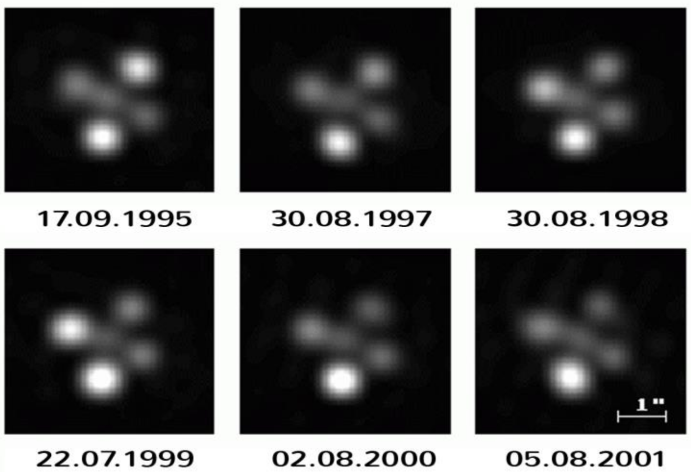
The **cross-correlation functions** for pairs of light curves represented by their approximations. The **time delay** - the time shift between the light curves, where the cross-correlation function reaches its maximum.

QSO 2237+0305 (Einstein Cross)

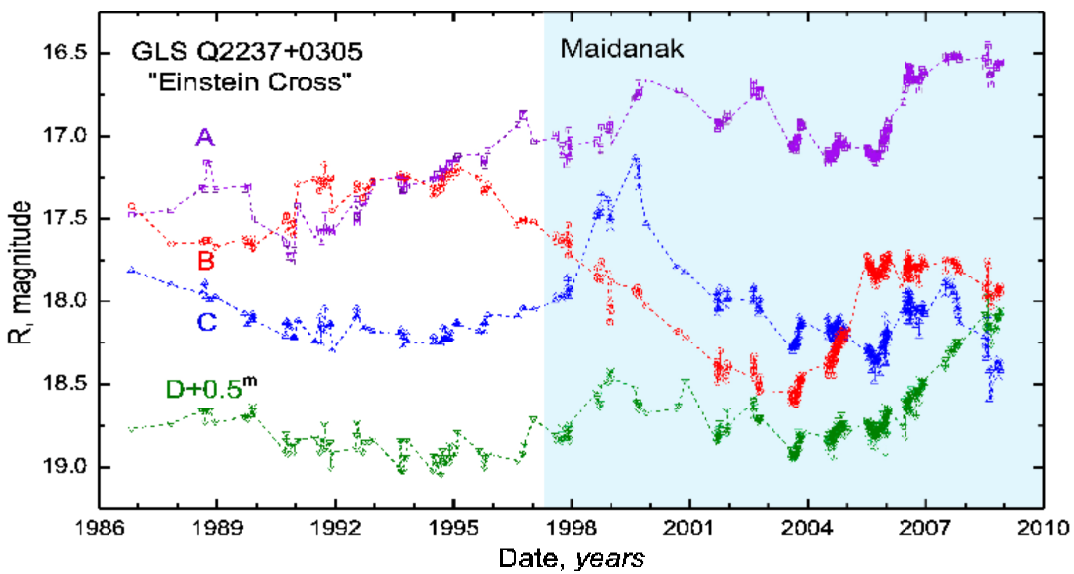


QSO 2237+0305 - a quadruple gravitational lens system with a quasar at z=1.69 seen through the galaxy at z= 0.039.

The **color image** QSO 2237+0305 in 1999 synthesized from three monochrome images of a superb quality taken in **filters V, R and I with** the Maidanak 1.5-meter telescope (obtained by V.Vakulik, Institute of Astronomy of V.N Karazin National University, Kharkov, Uktaine).



Changes of mutual brightness of the quasar components caused by microlensing events (data of monitoring in 1995-2001 from the Maidanak Observatory (A&A 420, 2004).



Light curves of all the four components of QSO 2237+0305. Observations carried out at the 1.5-meter telescope of the Maidanak Observatory are shown at the blue background (Dudinov V. et al. 2011)

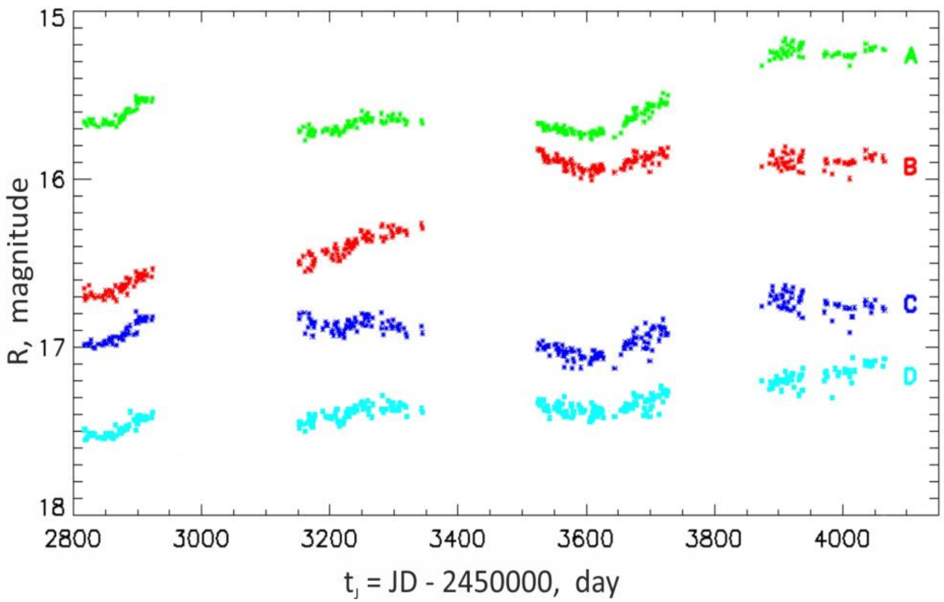
Time delays for Q2237+0305 - R light curves

The new more **accurate** estimates of the **gravitational time delays** between components in Q2237+0305 with our new method (**Tsvetkova et al. 2016**).

Time delays, hours	*R*, our results Dudinov et al., 2011	Bar accounted Schmidt et al., 1998	SIE lens model Wertz & Surdej, 2014	NSIE+γ model Wertz & Surdej, 2014
Δt_{AB}	4.5 ± 1.9	2.0	2.6 ± 0.7	2.51 ± 0.52
Δt_{AC}	- 14.22 ± 1.66	- 16.2	- 17.97 ± 0.7	- 18.01 ± 0.62
Δt_{AD}	- 2.73 ± 4.61	- 4.9	- 5.38 ± 0.7	- 5.41 ± 0.43
Δt_{BC}	- 19.0 ± 1.56	(- 18.27)	(- 20.57)	(- 20.52)
Δt_{BD}	- 2.97 ± 3.96	(- 6.9)	(- 7.98)	(- 7.92)
Δt_{CD}	19.31 ± 2.76	(11.3)	12.59 ± 0.7	12.6 ± 0.58

The obtained results **are consistent with the most recent theoretic predictions** (e.g., Schmidt et al. 1998, Wertz & Surdej 2014).

QSO 2237+0305 – R, I and V light curves

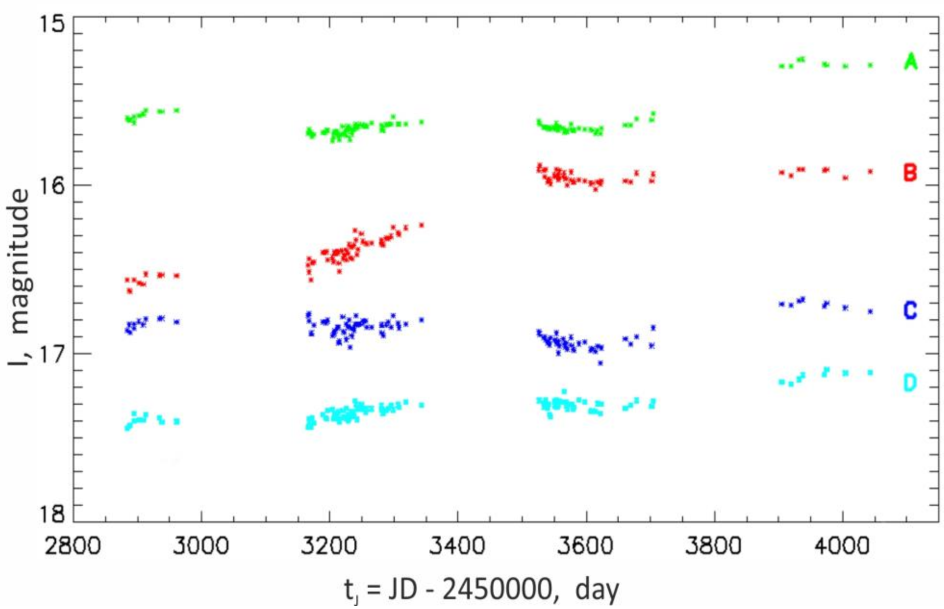


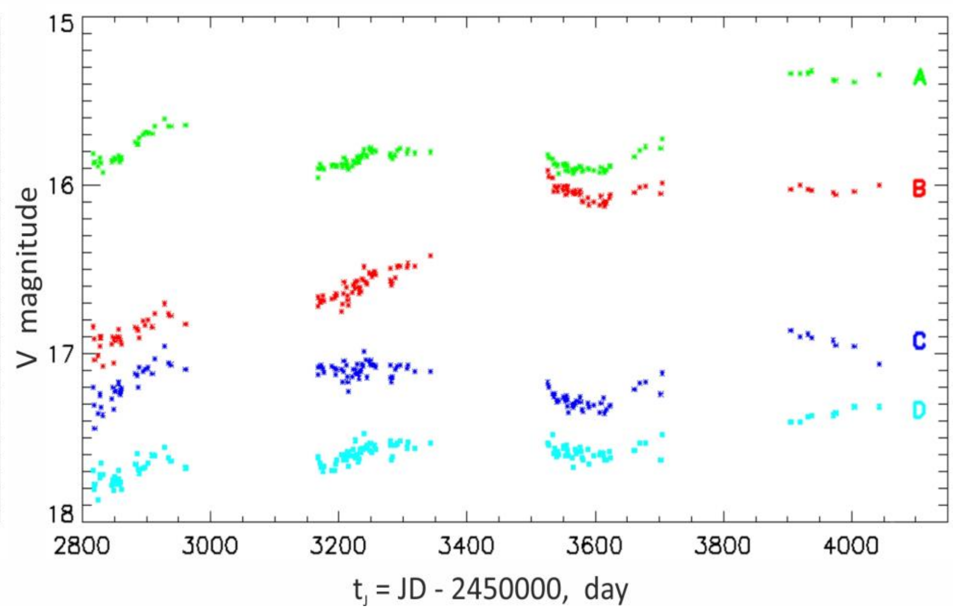
The light curves of the QSO 2237 + 0305 system for **2003–2006 seasons** in filters ***V*, *R* and *I*** of the Johnson-Cousins photometric system as part of the long-term monitoring program at the **1.5-meter telescope of the Maidanak Observatory** from 2001 to 2009 :

I (λ_{eff} = 879.7nm)

V (λ_{eff} = 547.7nm)

R (λ_{eff} = 634.9nm)





The photometry are available on the site: http://www.astron.kharkov.ua/databases/index.html

Time delays between the RV, IR and IV pairs of light curves

Inter-band time delays of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves of the **2004 season**:

Season 2004	Δt_{R-V}	Δt^{ABC}_{R-V}	Δt_{I-R}	Δt^{ABC}_{I-R}	Δt_{I-V}	Δt^{ABC}_{I-V}
Comp A	9.14 ± 2.51	7.18 ± 2.81	2.21 ± 1.07	3.18 ± 1.37	5.67 ± 2.21	6.67 ± 2.34
Comp B	6.68 ± 2.31		3.89 ± 1.08		6.81 ± 1.91	
Comp C	5.61 ± 2.38		4.49 ± 0.53		7.76 ± 2.37	

Inter-band time delays of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves of the **2005 season**:

Season 2005	Δt_{R-V}	Δt^{ABC}_{R-V}	Δt_{I-R}	Δt^{ABC}_{I-R}	Δt_{I-V}	Δt^{ABC}_{I-V}
Comp A	7.31 ± 2.06	6.25 ± 1.97	0.63 ± 0.83	0.63 ± 1.36	7.69 ± 1.39	6.72 ± 2.28
Comp B	5.64 ± 2.35		0.89 ± 1.81		5.83 ± 2.48	
Comp C	5.82 ± 0.62		0.36 ± 1.19		6.57 ± 2.42	

Inter-band time of the Q2237+0305 quasar between the RV, IR and IV pairs of light curves **averaged over components and seasons**:

Season 2004 - 2005	Δt^{ABC}_{R-V}	Δt^{ABC}_{I-R}	Δt^{ABC}_{I-V}
Comp ABC	6.71 ± 2.46	1.71 ± 1.86	6.73 ± 2.31

* time delays in the observer's coordinate system

Reliability of the results

- **excellent agreement** between the time delay estimates obtained **independently** for different macroimages and for two different seasons;

- our estimates of the time delays between filters R and V for seasons 2004 and 2005 are **consistent with the results** obtained by Koptelova et al. (2010) for season 2003:

5.1- 5.6 days for component A and 5.1-5.2 days for component C;

- if the detected proximity of the Δt_{RV} and Δt_{IV} delays is real, the time delay between filters I and R must be short enough - this is just what we see in our results - the **time delay between filters I and R** is **close to the level of errors**.

Season 2004	Δt_{R-V}	Δt_{R-V}^{ABC}	Δt_{I-R}	Δt_{I-R}^{ABC}	Δt_{I-V}	Δt_{I-V}^{ABC}
Comp A	9.14 ± 2.51		2.21 ± 1.07		5.67 ± 2.21	
Comp B	6.68 ± 2.31	7.18 ± 2.81	3.89 ± 1.08	3.18 ± 1.37	6.81 ± 1.91	6.67 ± 2.34
Comp C	5.61 ± 2.38		4.49 ± 0.53		7.76 ± 2.37	

Season 2005	Δt_{R-V}	Δt_{R-V}^{ABC}	Δt_{I-R}	Δt_{I-R}^{ABC}	Δt_{I-V}	Δt_{I-V}^{ABC}
Comp A	7.31 ± 2.06		0.63 ± 0.83		7.69 ± 1.39	
Comp B	5.64 ± 2.35	6.25 ± 1.97	0.89 ± 1.81	0.63 ± 1.36	5.83 ± 2.48	6.72 ± 2.28
Comp C	5.82 ± 0.62		0.36 ± 1.19		6.57 ± 2.42	

The radius R_λ at which the disk temperature matches the wavelength λ_{eff} in the maximum of the blackbody radiation (thin accretion disk model by Shakura & Sunyaev):

$$R_\lambda = \left(\frac{45G\lambda^4 M_{BH}\dot{M}}{16\pi^6 hc^2}\right)^{1/3} \xrightarrow{\text{dimensionless quantities}} R_\lambda = 9.7\cdot 10^{15}\left(\frac{\lambda_{rest}}{1000}\right)^{4/3}\cdot\left(\frac{M_{BH}}{10^9 M_\Theta}\right)^{2/3}\cdot\left(\frac{L}{\eta L_E}\right)^{1/3}$$

$$\tilde{M}_{BH} = M_{BH}/(10^9 M_\odot),\ \tilde{\lambda} = \lambda/1\mu m$$

$$\dot{M} = L/\eta c^2$$

M_{BH} – black hole mass and $\dot{M}$ - accretion rate;
λ - the rest-frame effective wave lengths of the corresponding filters;
L и L_E – luminosity and Eddington luminosity limit;
η – accretion efficiency

Poindexter & Kochanek (2010); Morgan et al. (2010)

Estimation of the time delay for two wavelengths expected from the standard thin accretion disk model by Shakura & Sunyaev (for a **simplified reprocessing model**: annual zones; quasar observed “face-on “):

$$\Delta t_{R-V} = \frac{K}{c}\cdot M_{BH}^{2/3}\left(\frac{L}{\eta L_E}\right)^{1/3}\cdot\left(\tilde{\lambda}_R^{4/3} - \tilde{\lambda}_V^{4/3}\right)$$

The values of the **inter-band time delays predicted by a standard thin accretion disk model** (Shakura & Sunyaev) for $M_{BH} = 9\cdot 10^8 M_\odot$ (Morgan 2010):

$\Delta t_{RV} \approx 0.15$ days $\Delta t_{IR} \approx 0.3$ days $\Delta t_{IV} \approx 0.45$ days

Comparison the measured time delays and predicted theoretically

Rest-frame **time delays** obtained from **observational data**:

Season 2004 – 2005	$\Delta\hat{t}^{ABC}_{R-V}$	$\Delta\hat{t}^{ABC}_{I-R}$	$\Delta\hat{t}^{ABC}_{I-V}$
Comp ABC	2.49 ± 0.92	0.64 ± 0.69	2.51 ± 0.86

$$\Delta\hat{t} = \frac{\Delta t_{R-V}}{1+z_Q}$$

Time delays predicted by a **standard thin accretion disk model** Shakura and Sunyaev :

$\Delta t_{RV} \approx 0.15$ days $\Delta t_{IR} \approx 0.3$ days $\Delta t_{IV} \approx 0.45$ days

$\boldsymbol{M_{BH} = 9 \cdot 10^8 M_\odot}$

(Morgan 2010)

- **project STORM (Space Telescope and Optical Reverberation Mapping)** - Fausnaugh M. et al. (2016) => the measured inter-band time delays are significantly larger than those expected from the standard thin accretion disk model (Shakura & Sunyaev);

- **Morgan et al. (2010)** => to eliminate the observed discrepancy, it's necessary to make changes in the values of the parameters of standard thin accretion disk model: the mass of the black hole M_{BH}, the accretion efficiency η, and/or the ratio of luminosity to the Eddington limit;
- **Jaroszynski et al. (1992)** => were the first to assume the existence of an extended structure in the accretion disk of Q2237+0305 from the microlensing analysis ;

- **Witt & Mao (1994), Vakulik et al. (2007), Shulga et al. (2014)** => similar conclusions (from microlensing events)

Analysis and interpretation of results

In the classic work of Shakura and Sunyaev (1973), the authors admitted a **possibility of a supercritical accretion regime** that leads to formation of an **extended optically thick scattering envelope** on the accretion disk periphery :

Radius of scattering envelope

$$R_{eff} \simeq 3 \cdot 10^2 \dot{m}^{51/22} m^{10/11} \alpha^{-17/11} A^{8/11} \left(cm\right)$$

Effective temperature of scattering envelope

$$T_{eff} \simeq 2 \cdot 10^{10} \dot{m}^{-15/11} m^{-2/11} \alpha^{10/11} A^{-6/11} \left({}^{o}K\right)$$

dimensionless quantities:

mass $m = M/M_{\odot}$ and accretion rate $\dot{m} = \dot{M}/\dot{M}_{cr}$,

A - a ratio of energy losses in the Compton radiation to those in free-free transitions

(10 <A < 300 under physical conditions of interest)

α - efficiency of the angular momentum transport in the accreting matter

In the **optical spectral range** (low-frequency range at the temperature T_{eff}), the **radius** near which the envelope becomes opaque exceeds considerably R_{eff} :

Optical envelope radius

$$R_{opt} \simeq 10^7 \alpha^{-3/4} \left(\frac{10^6\,{}^{o}K}{T}\right)^{3/8} \left(\frac{10^{15}\,Hz}{\nu}\right)^{1/2} \dot{m}^{9/8} m^{3/4} \left(cm\right)$$

Analysis and interpretation of results

R_{opt} (cm)	$R_{opt}V$	$R_{optR}R$	$R_{opt}I$
α=0.015; A=50	$9.56 \cdot 10^{16}$	$1.02 \cdot 10^{17}$	$1.21 \cdot 10^{17}$
α=0.05; A=50	$2.57 \cdot 10^{16}$	$2.77 \cdot 10^{16}$	$3.25 \cdot 10^{16}$
α=0.01; A=100	$1.71 \cdot 10^{17}$	$1.84 \cdot 10^{17}$	$2.17 \cdot 10^{17}$
α=0.05; A=100	$2.97 \cdot 10^{16}$	$3.19 \cdot 10^{16}$	$3.74 \cdot 10^{16}$

The **values of R_{opt},** calculated for sets of **parameters α and A** for the black hole mass **$9 \cdot 10^8$ $M_\odot$** and dimensionless accretion rate **17** (Morgan et al. 2010)

Corresponding **estimates of time delays** for the three pairs of filters **V, R and I**

Δt (days)	T_{eff},(K)	Δt_{RV}	Δt_{IR}	Δt_{IV}
α=0.015; A=50	$0.25 \cdot 10^5$	2.79	6.94	9.74
α=0.05; A=50	$0.77 \cdot 10^5$	0.75	1.87	2.62
α=0.01; A=100	$0.12 \cdot 10^5$	5.07	12.45	17.46
α=0.05; A=100	$0.53 \cdot 10^5$	0.87	2.15	3.02

The **values of time delays** are consistent with the results of this work at the values of parameters α and A:

α = 0.015 and A = 50

α - efficiency of the angular momentum transport in the accreting matter;
A - a ratio of energy losses in the Compton radiation to those in free-free transitions.

Conclusions

- **The method elaborated in our group earlier provided reliable estimates of the inter-band time delays for QSO 2237+0305.**

- **The measured time delays between the flux variations in different filters are an order of magnitude larger than the delays values based on a standard thin accretion disk model (Shakura and Sunyaev , 1973).**

- **The discrepancy between the measured time delays and predicted theoretically can be explained by the fact that the black hole is accreting matter in a moderately super-critical regime. Shakura and Sunyaev showed that such regime may result in creating an extended scattering envelope.**

- **Having used the analytical expressions obtained by Shakura-Sunyaev, we made calculations for quasar QSO 2237+0305 with the black hole mass $M_{BH} = 9 \cdot 10^8 M_{\Theta}$ and show that the inter-band time delay values obtained by us from the data of observations for some parameters of the supercritical regime are consistent with the existence of scattering envelope. The reverberation responses which we observe may arise in quasar's regions located more than 10^{16} cm from the central black hole.**

Thank you for your attention!