Experimental tests of the no-hair theorems of black holes

Nordita

Thu, Mar 25, 2010

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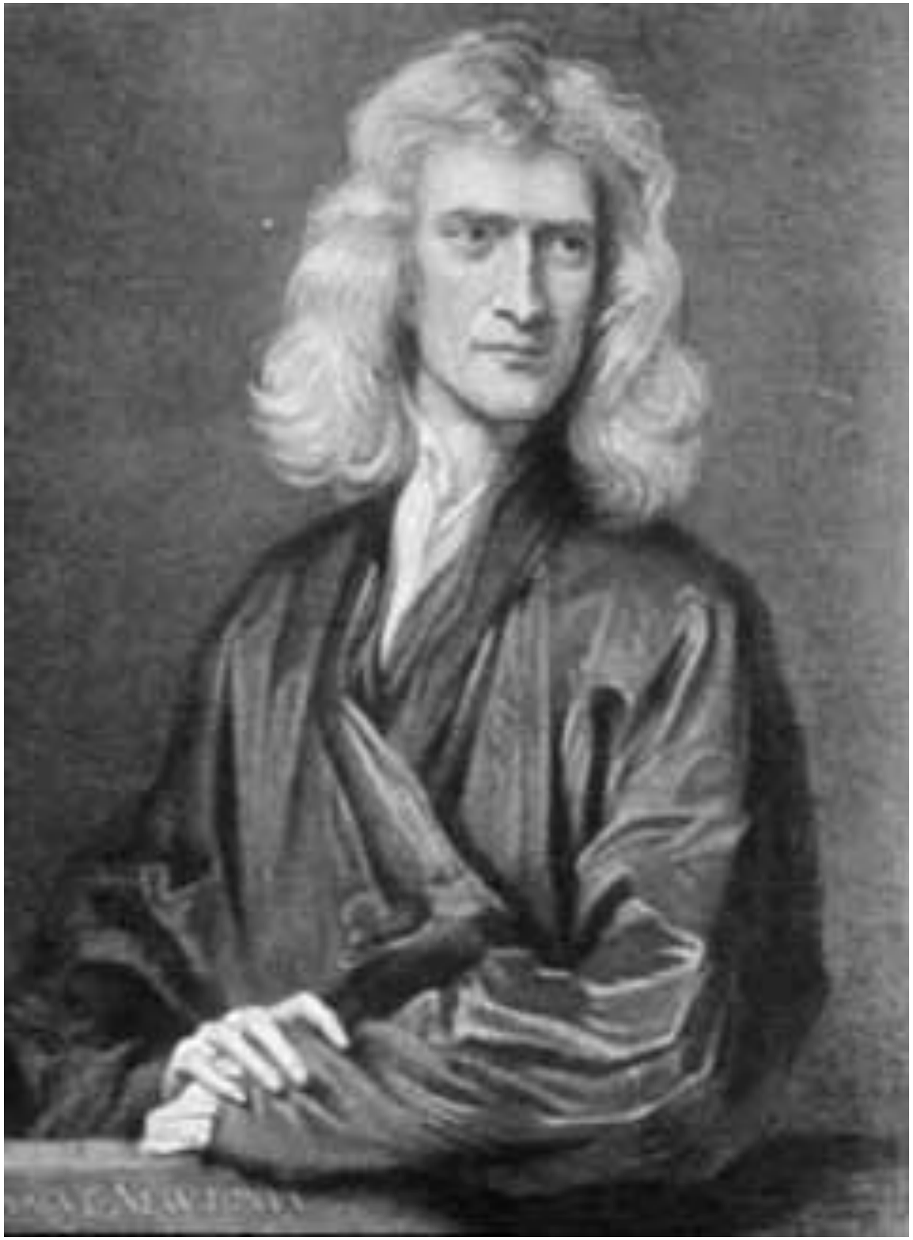


Isaac Newton

Albert Einstein

Proving GR correct
Proving existence of BH

No hair theorem

Israel 1967, 1968
Carter 1970
Hawking 1971, 1972

Thorne (1980)

$$Q = -q\frac{S^2}{Mc^2}$$

black holes $q = 1$,

neutron stars and other structures $q > 2$

Testing no-hair theorem I

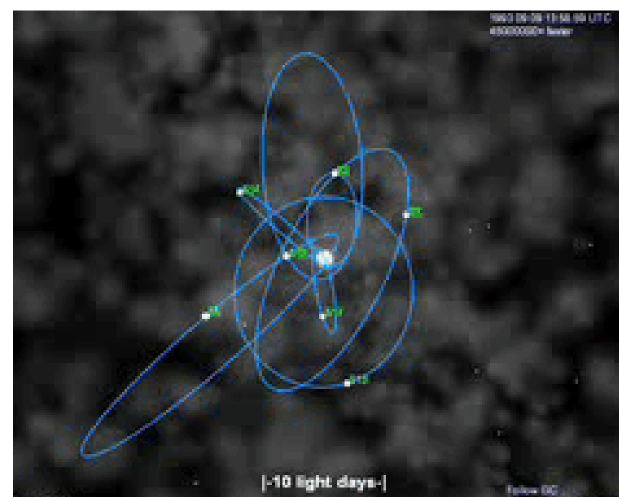
- Observe stars orbiting the Galactic Center

from orbits of stars (period ~ few 10 yr), BH mass ~ 3.6 10^6 solar mass

needed: star orbits with period 0.1 yr, measurement accuracy 10^{-5} arcsec

periastron advance: M
classical spin-orbit coupling: Q
GR spin-orbit coupling: S

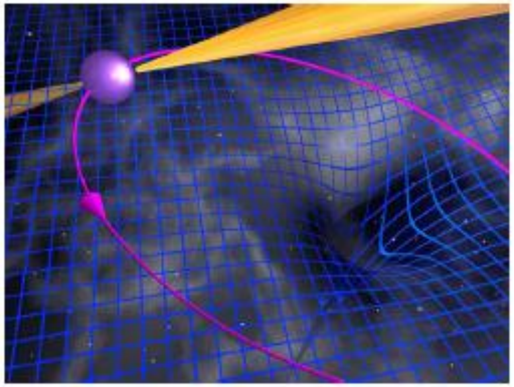
Do such stars exist?
Can we find them?



Testing no-hair theorem II

- Millisecond pulsars

Find a pulsar in ~ 1 hour eccentric orbit around
> 10 solar mass BH



Periastron advance: M and S
Q difficult to measure

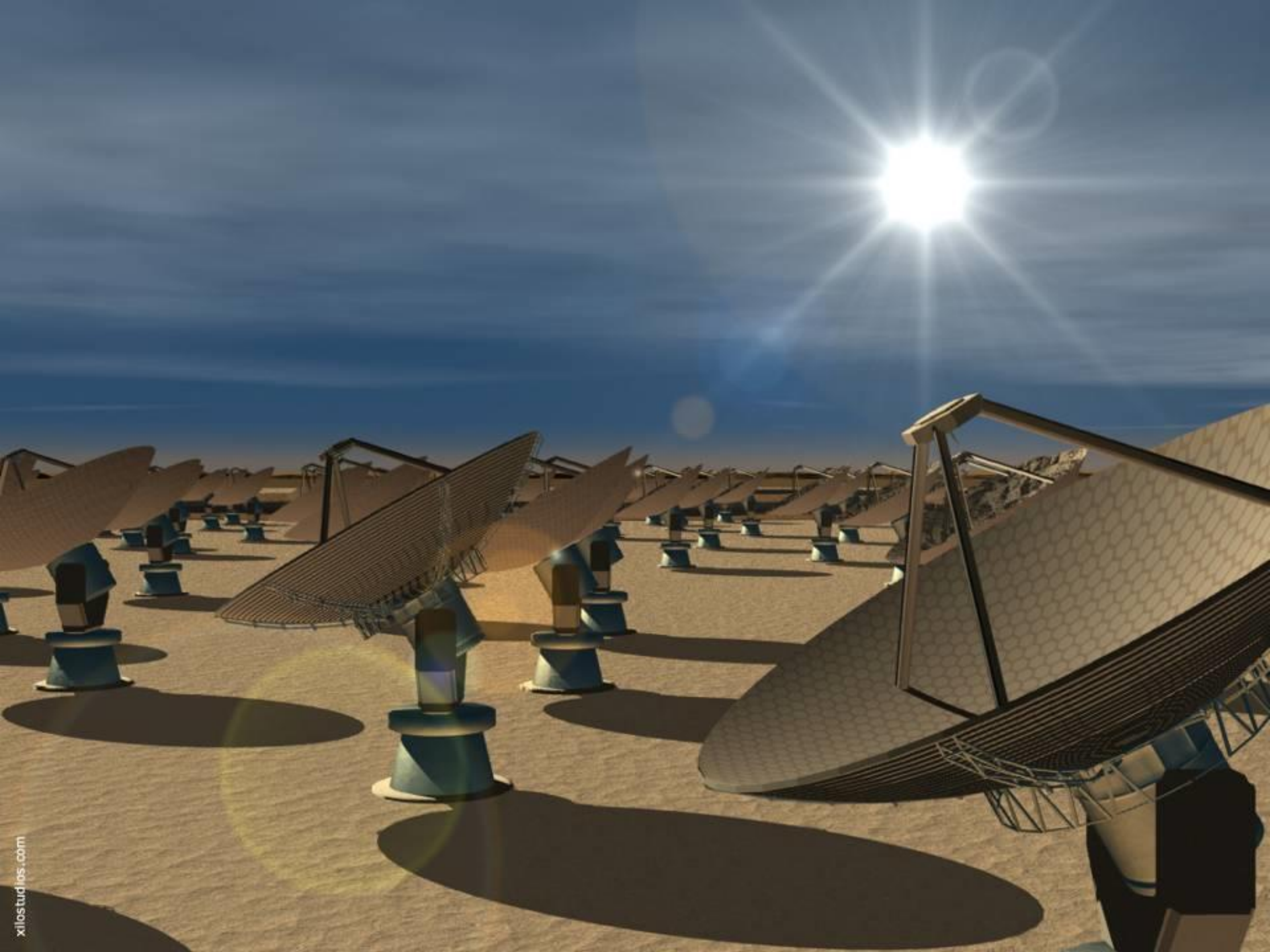
Needed: 10^{-7} second accuracy in pulse timing (SKA)

Do such systems exist? Can we find them?

Square Kilometer Array

...

Most importantly, SKA observations will finally address the fundamental question of whether GR can describe nature in the ultra-strong field limit. One can not only study stellar black holes but also apply the same timing techniques to pulsars around the super-massive black hole in the Galactic Centre. This allows a direct comparison of the properties of these objects: one can determine mass, spin and quadrupole moment of black holes to test their description in Einstein's theory (the "no-hair"-theorem) for the first time obviously a major achievement in the history of physics!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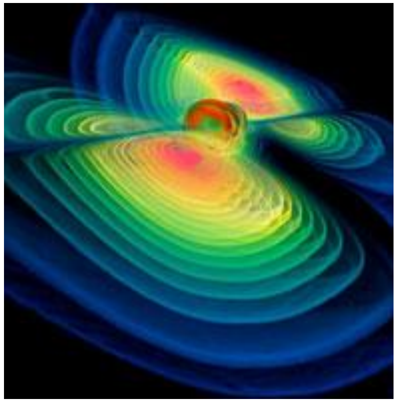
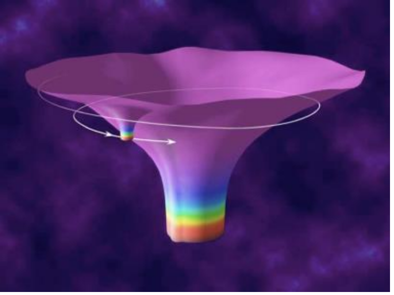
Testing no-hair theorem III

- Gravitational wave antenna LISA

Needed: Observe merger of two black holes

Do we ever see a merger? Do we understand the physics?



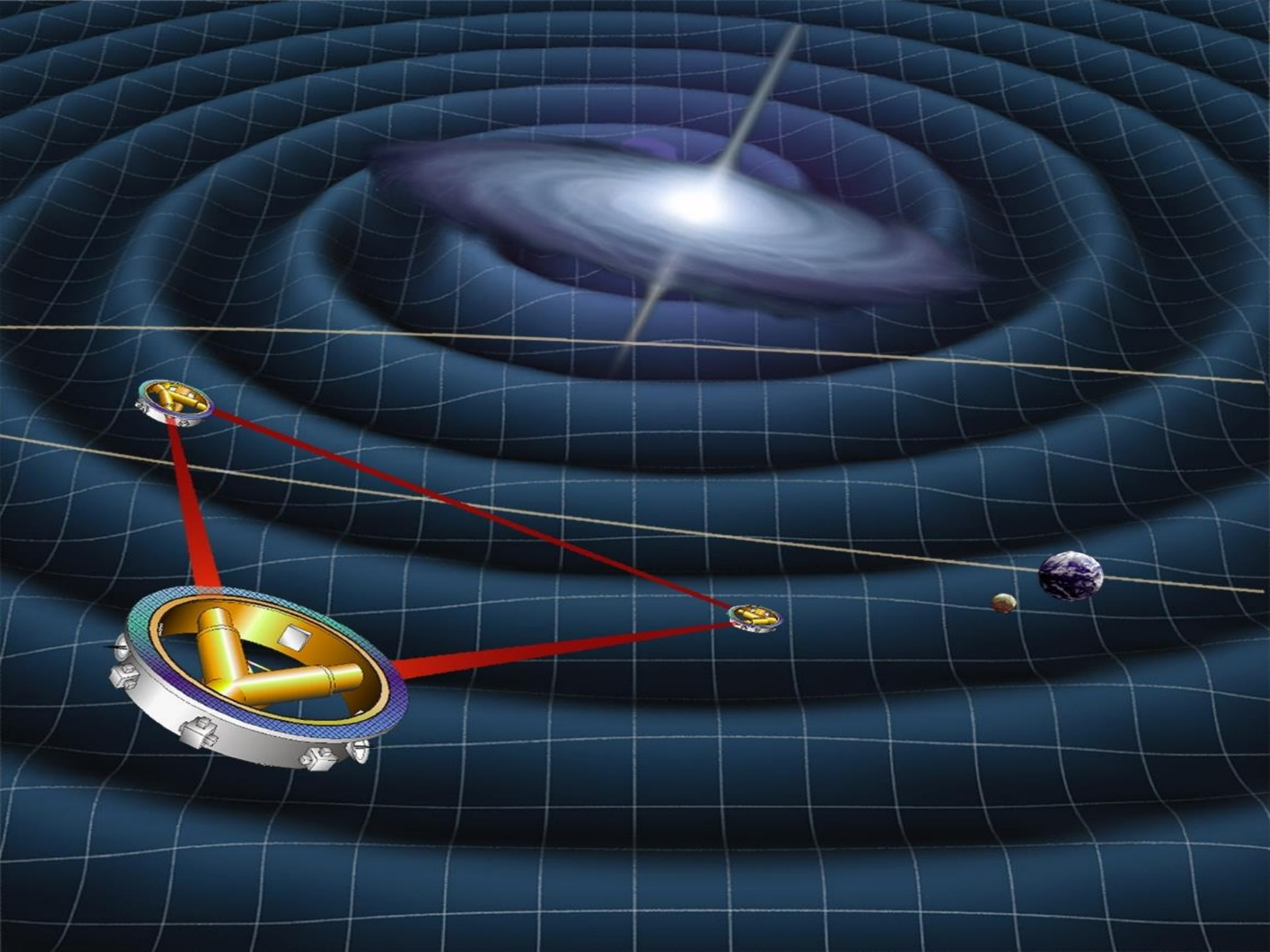


LISA

..

Observing the violent mergers of massive black hole is not the only way to probe their mysteries. Black holes at the center of galaxies are surrounded by **swarms of orbiting stars**, caught in the gravitational grip of the black hole. In our own Milky Way galaxy, we observed the stars close to the Sgr A* black hole for more than a decade, long enough to see the stars trace out entire orbits.

The gravitational waves emitted during the slow inspiral encode a map of the black hole spacetime, precisely revealing the shape and structure of the gravitational field around the black hole. This spacetime map will for the first time allow astronomers to compare the shape, structure and nature of true astrophysical black holes to the mathematical predictions of gravitational theory.



binary black hole system OJ287

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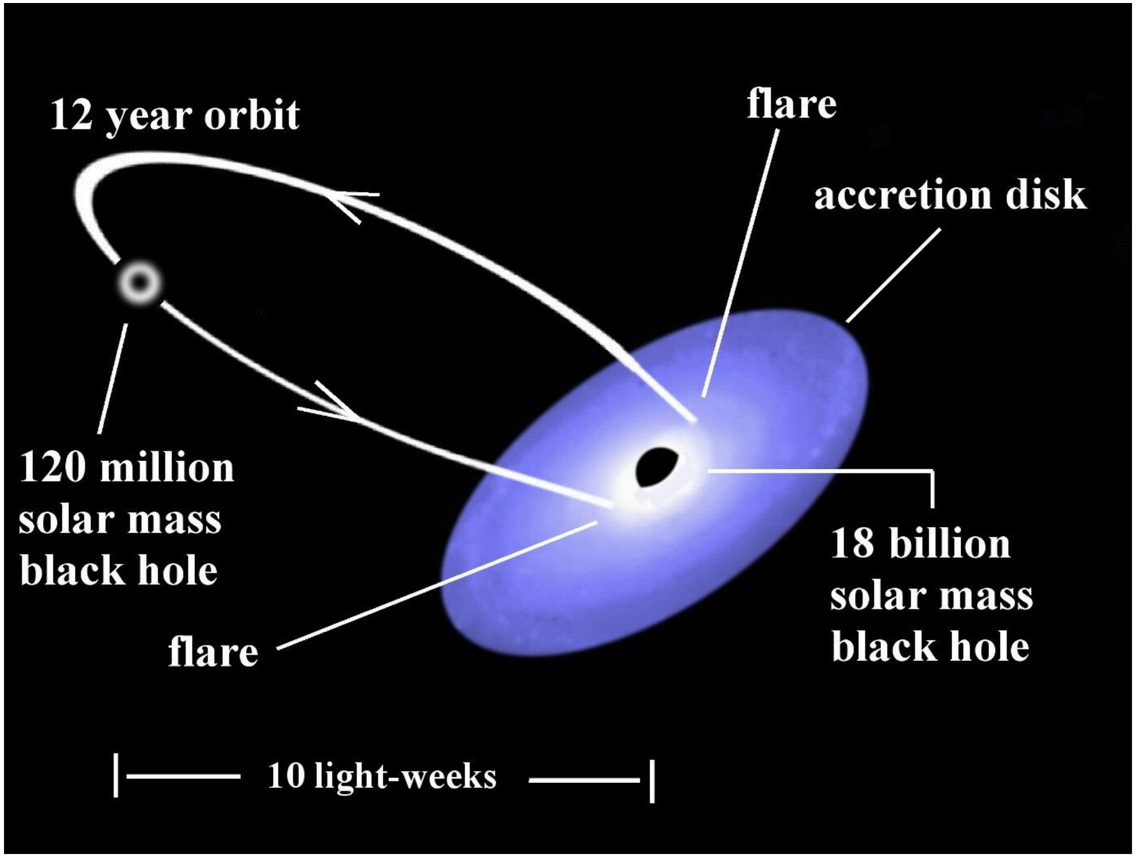
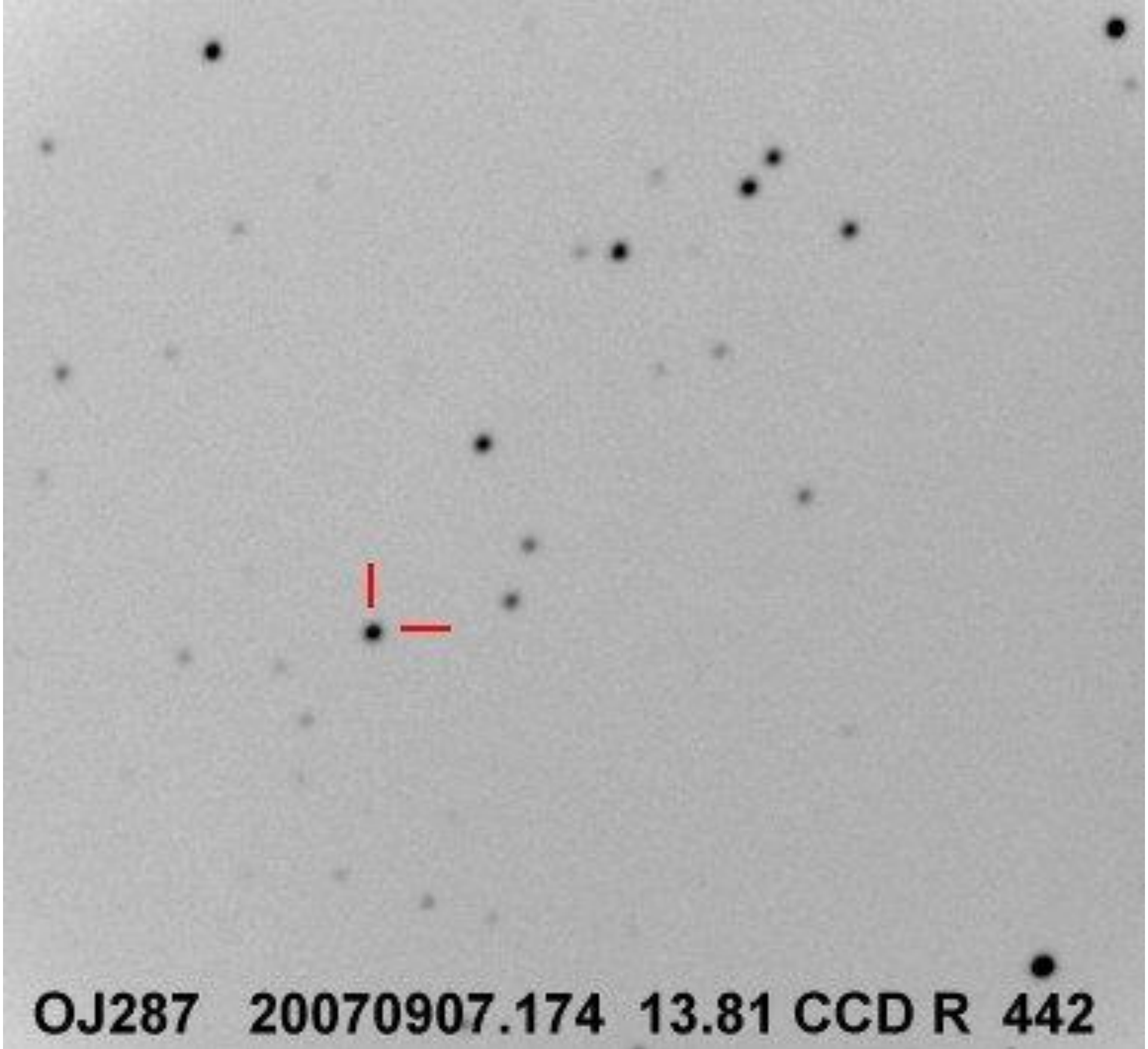
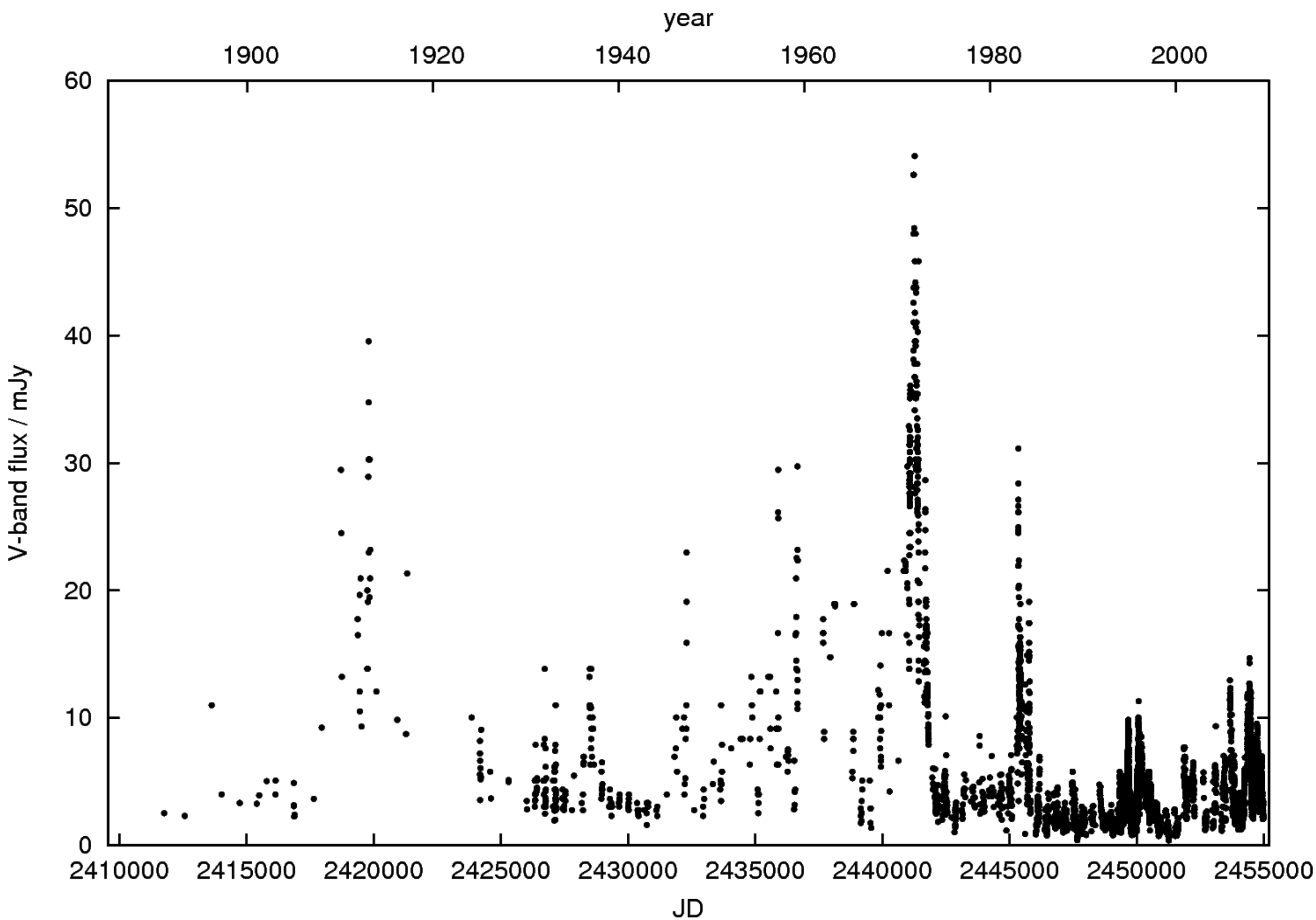
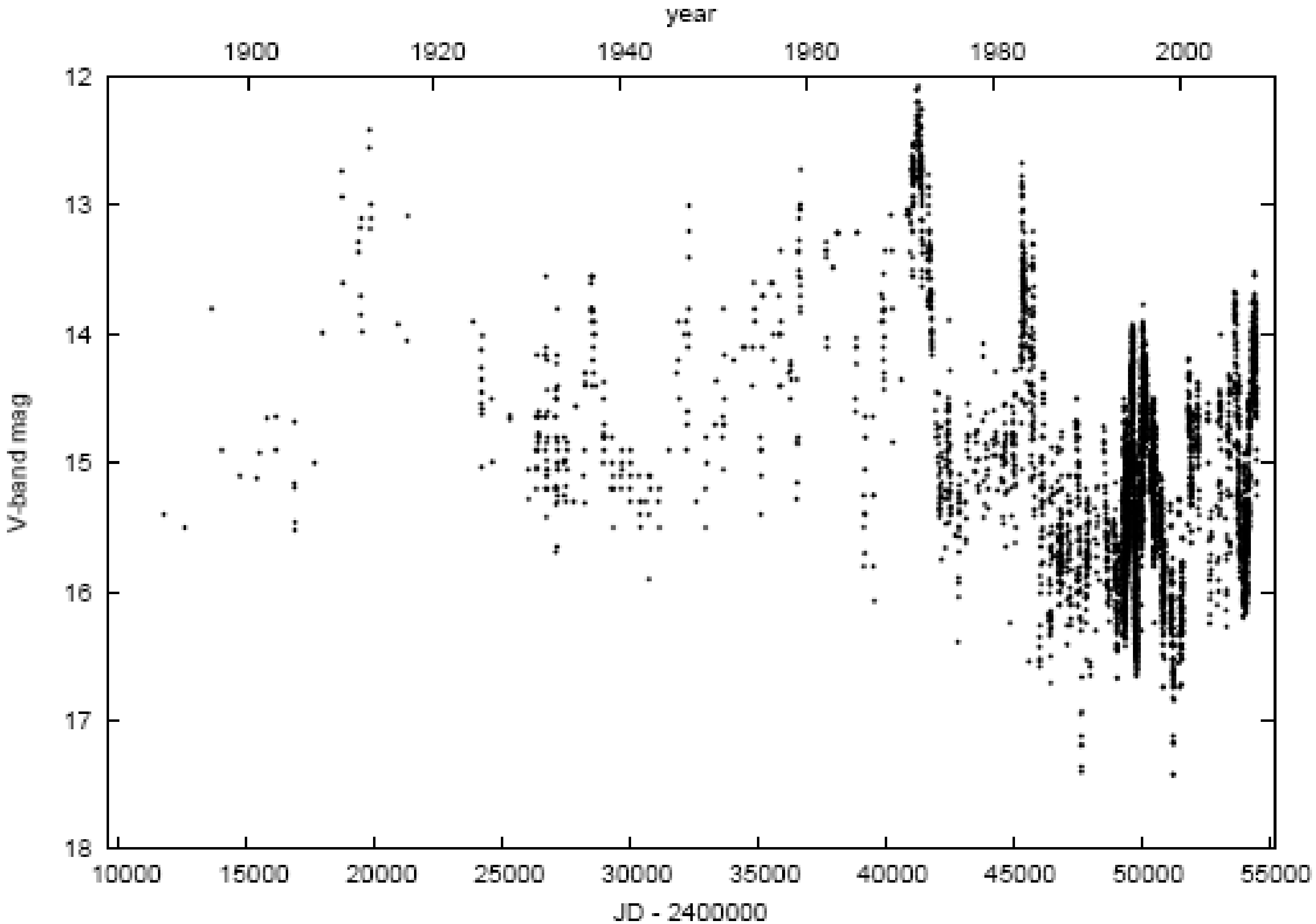


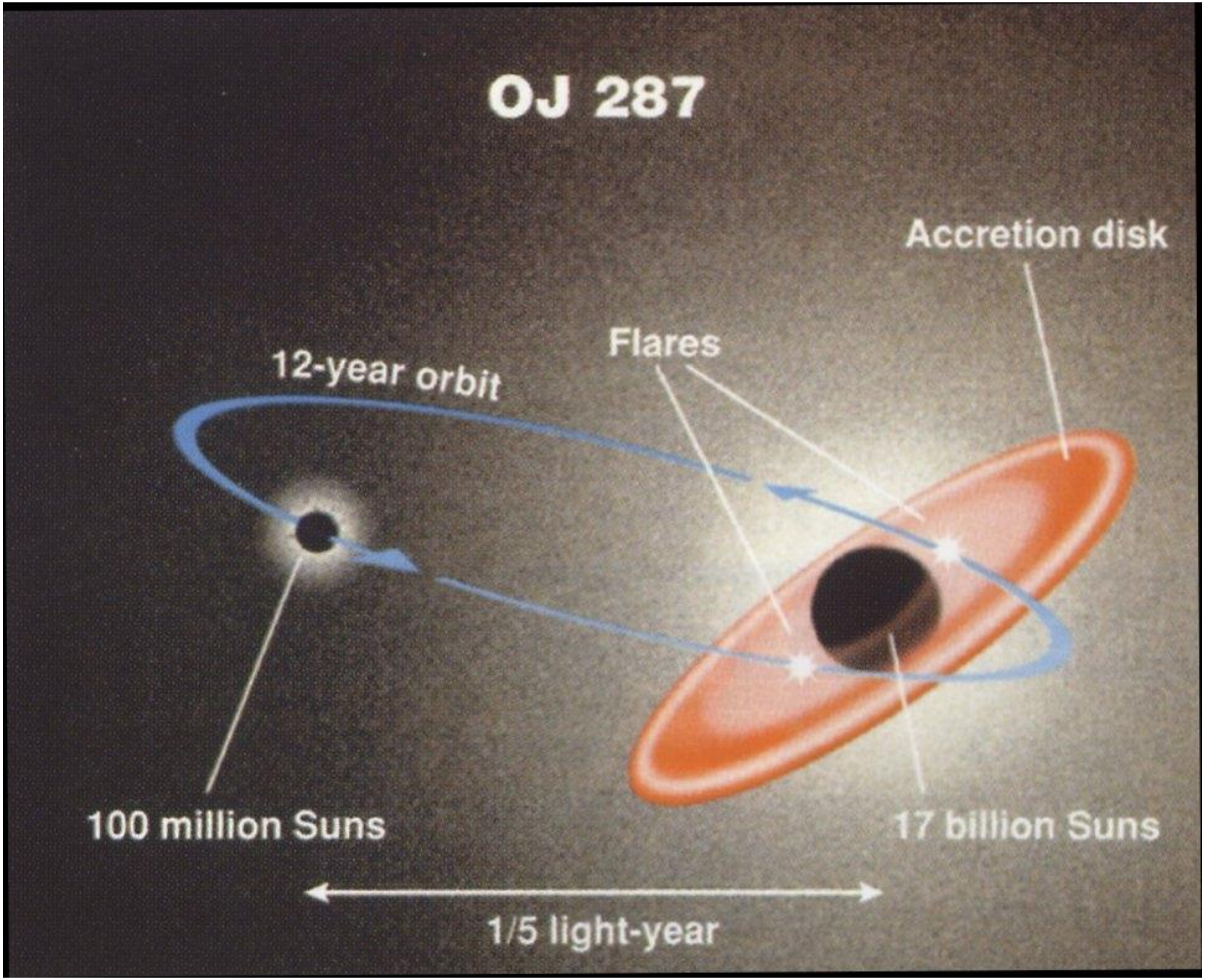

OJ287 20070907.174 13.81 CCD R 442

OJ287 light variations



OJ287 light variations




OJ 287
Accretion disk
Flares
12-year orbit
100 million Suns
17 billion Suns
1/5 light-year

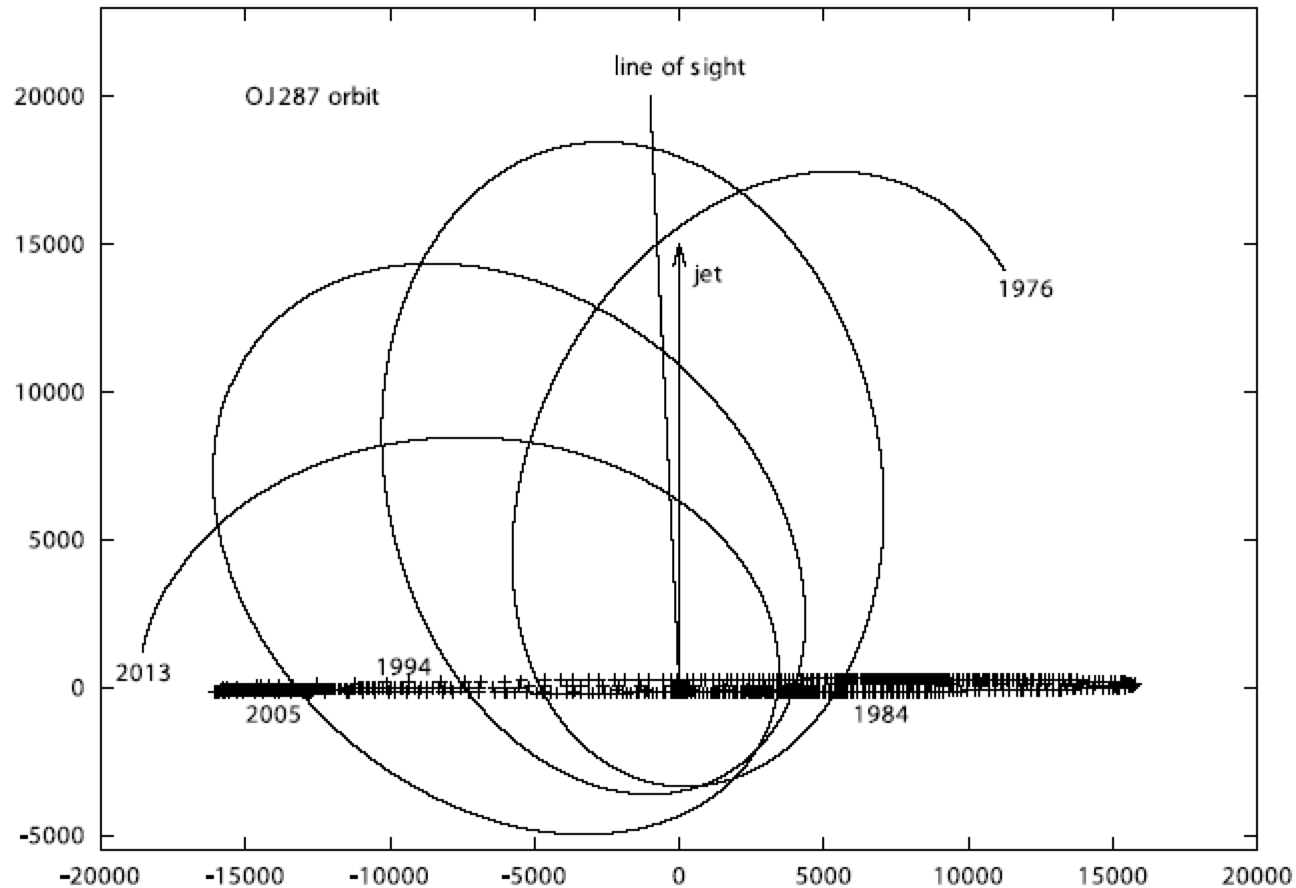


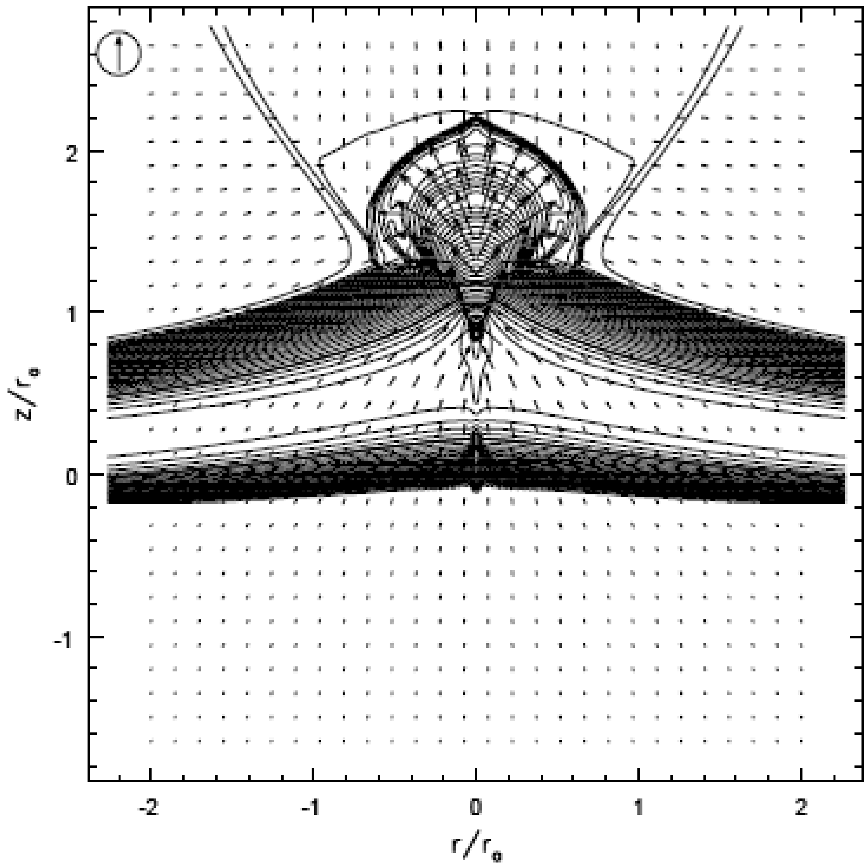
FIG. 1.—Precessing-binary model of OJ 287. The primary black hole is at coordinates (0, 0). The secondary black hole traces out a precessing elliptical orbit counterclockwise around the primary, illustrated here from 1976 to 2013. The secondary crosses the accretion disk of the primary (*horizontal set of points*) at impact sites; the 1984, 1994, and 2005 impacts are labeled. The axis of the accretion disk is labeled "jet." Not far from the jet is the line of sight to the observer. The binary orbit is at right angles to the accretion disk; Sundelius et al. (1997) have shown that this is not a restriction on the generality of the model, i.e., different relative inclinations would produce very similar results.

Solution of the timing problem. Level I

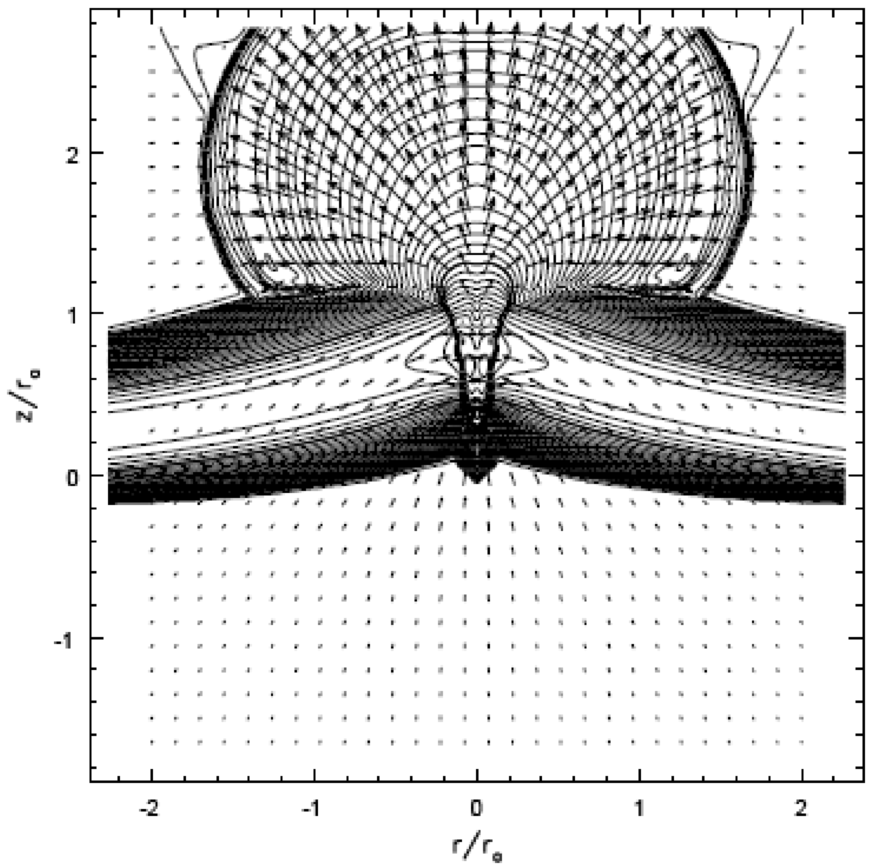
- Six well timed outbursts
- Iterative code
- Astrophysical effects: disk bending, delay of radiation burst

Black hole – Accretion disk collision

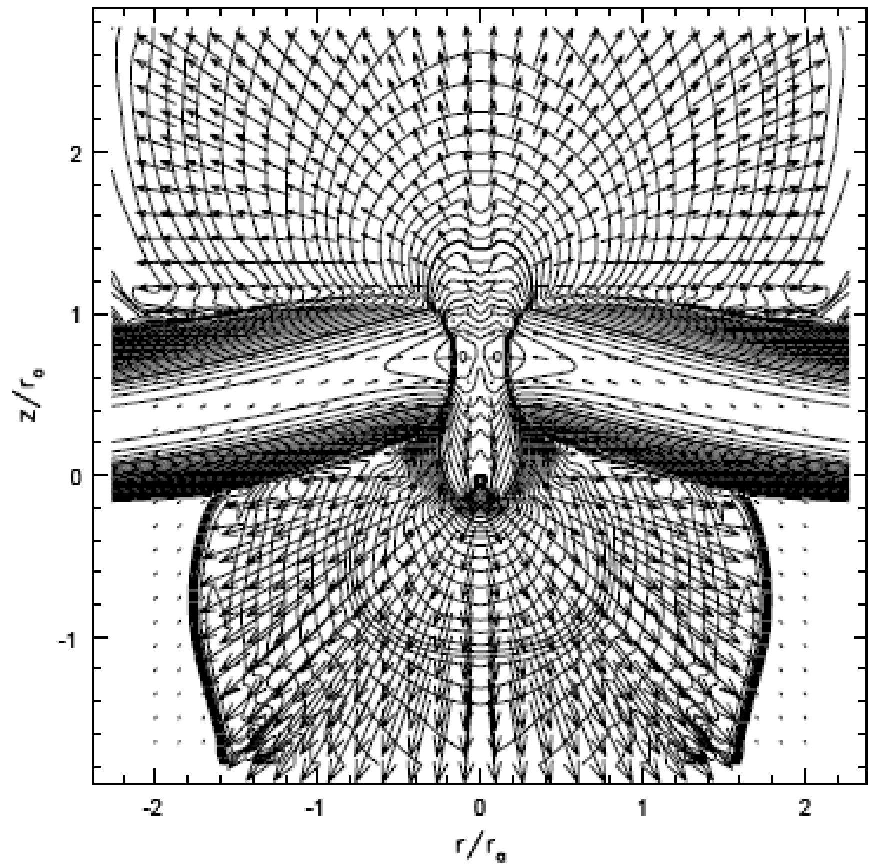
- Ivanov et al. 1998



Collision 2



Collision 3



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OJ 287 OUTBURST STRUCTURE AND A BINARY BLACK HOLE MODEL

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Received 1995 April 17; accepted 1995 October 4

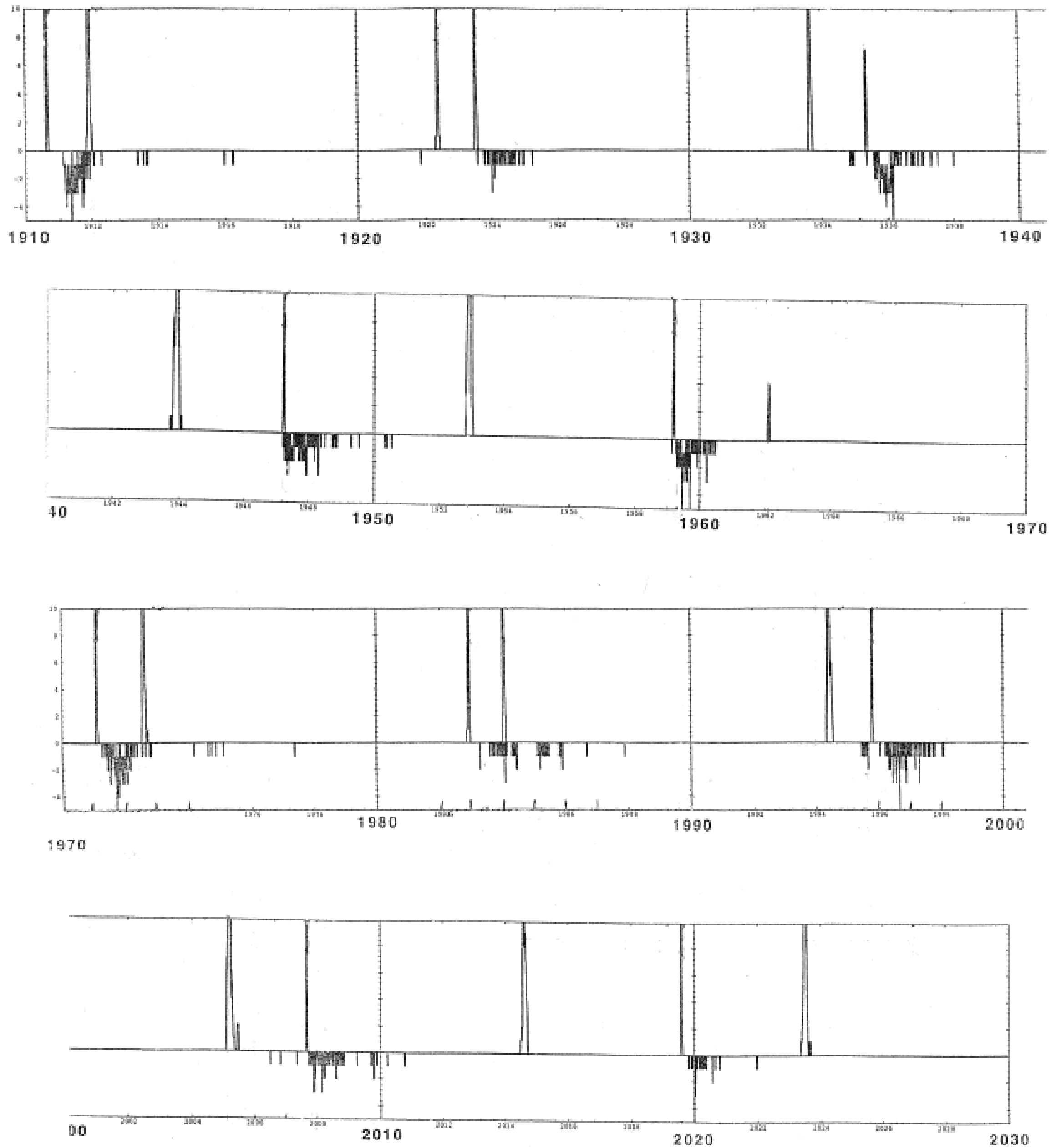
At the time the bubble turns optically thin, the expected flux density is of the order

$$\begin{aligned} S &= \epsilon_\nu^{\rm ff}\, V_{\rm bubble}/[(1+z)4\pi D^2_{\rm OJ\,287}] \\ &= 6.8\times 10^{-38} n^2 T^{-1/2} (4/3)\pi R^3_{\rm bubble}/[(1+z)4\pi D^2_{\rm OJ\,287}] \\ &\sim 8\ {\rm mJy}\ , \end{aligned} \tag{14}$$

where $D = zc/H_0$, and $H_0 = 80\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.

Disk Crossings and Outburst Times in Orbit 1: Precession 39.1°, Time Delay 1.03, Primary Mass $1.825 \times 10^{10}\ M_{\odot}$, Eccentricity 0.661

Disk Crossing	Time Delay (yr)	Time Ahead (yr)	Distance (AU)	Disk Level (AU)	Outburst Time (yr)
1895.59......................	1.19	−0.21	15042	33	1896.57
1898.59......................	0.04	...	3399	...	1898.63
1903.60......................	2.83	−0.21	18572	157	1906.21
1910.57......................	0.05	...	3506	...	1910.62
1912.61......................	0.55	−0.13	11650	41	1913.02
1922.50......................	0.07	...	4247	...	1922.57
1923.67......................	0.16	−0.07	6658	4	1923.77
1934.27......................	0.14	...	6149	15	1934.40
1935.39......................	0.07	−0.04	4470	−6	1935.42
1945.48......................	0.43	...	10555	259	1945.91
1947.28......................	0.05	−0.04	3591	...	1947.30
1954.89......................	2.30	−0.06	17770	72	1957.14
1959.21......................	0.04	−0.03	3376	...	1959.22
1962.69......................	1.58	−0.06	16227	247	1964.20
1971.13......................	0.05	−0.04	3701	...	1971.14
1972.67......................	0.31	+0.01	9217	−73	1972.99
1982.96......................	0.08	−0.04	4801	−53	1983.00
1984.04......................	0.11	...	5547	−30	1984.16
1994.53......................	0.20	−0.09	7469	87	1994.64
1995.80......................	0.06	...	4010	−17	1995.86
2005.19......................	0.81	−0.17	13333	265	2005.82
2007.66......................	0.05	...	3437	−33	2007.71
2013.53......................	3.03	−0.21	18837	148	2016.35
2019.54......................	0.05	...	3434	...	2019.58
2021.94......................	0.76	−0.17	13091	−235	2022.54


1910
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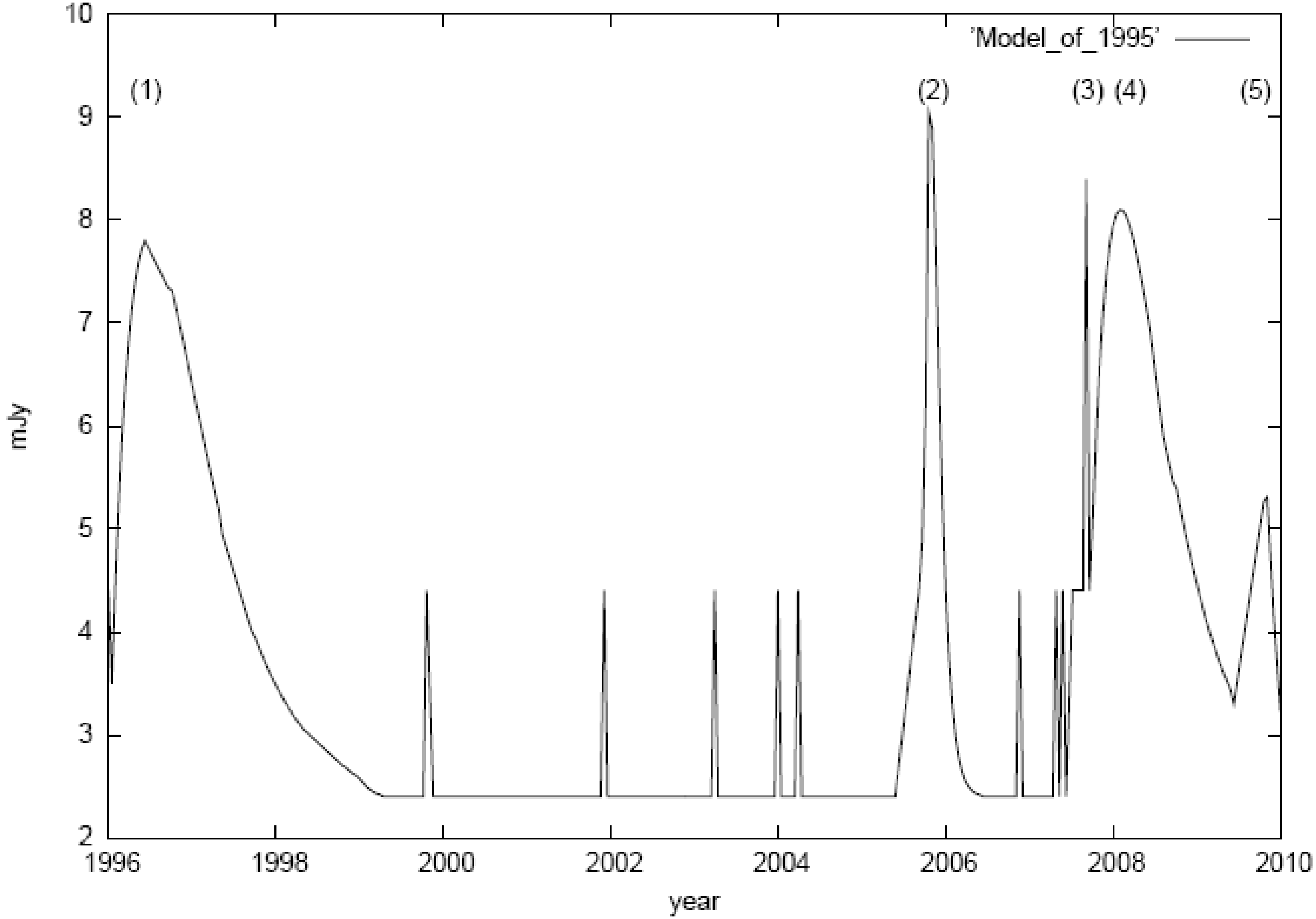

Fig. 1.— The 1995 light curve of OJ287. Five ma-

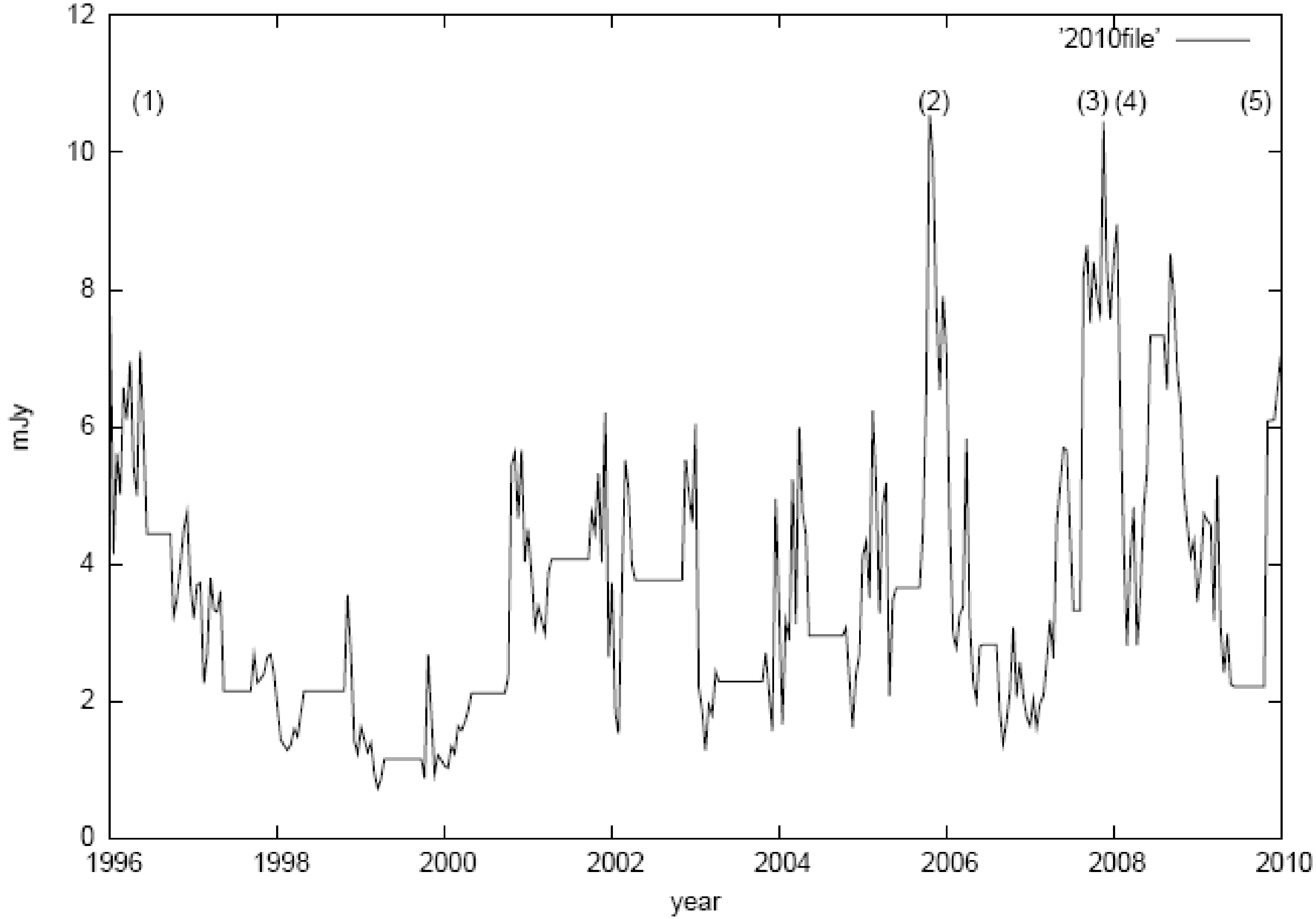

Fig. 2.— The observations of OJ287 during 1996

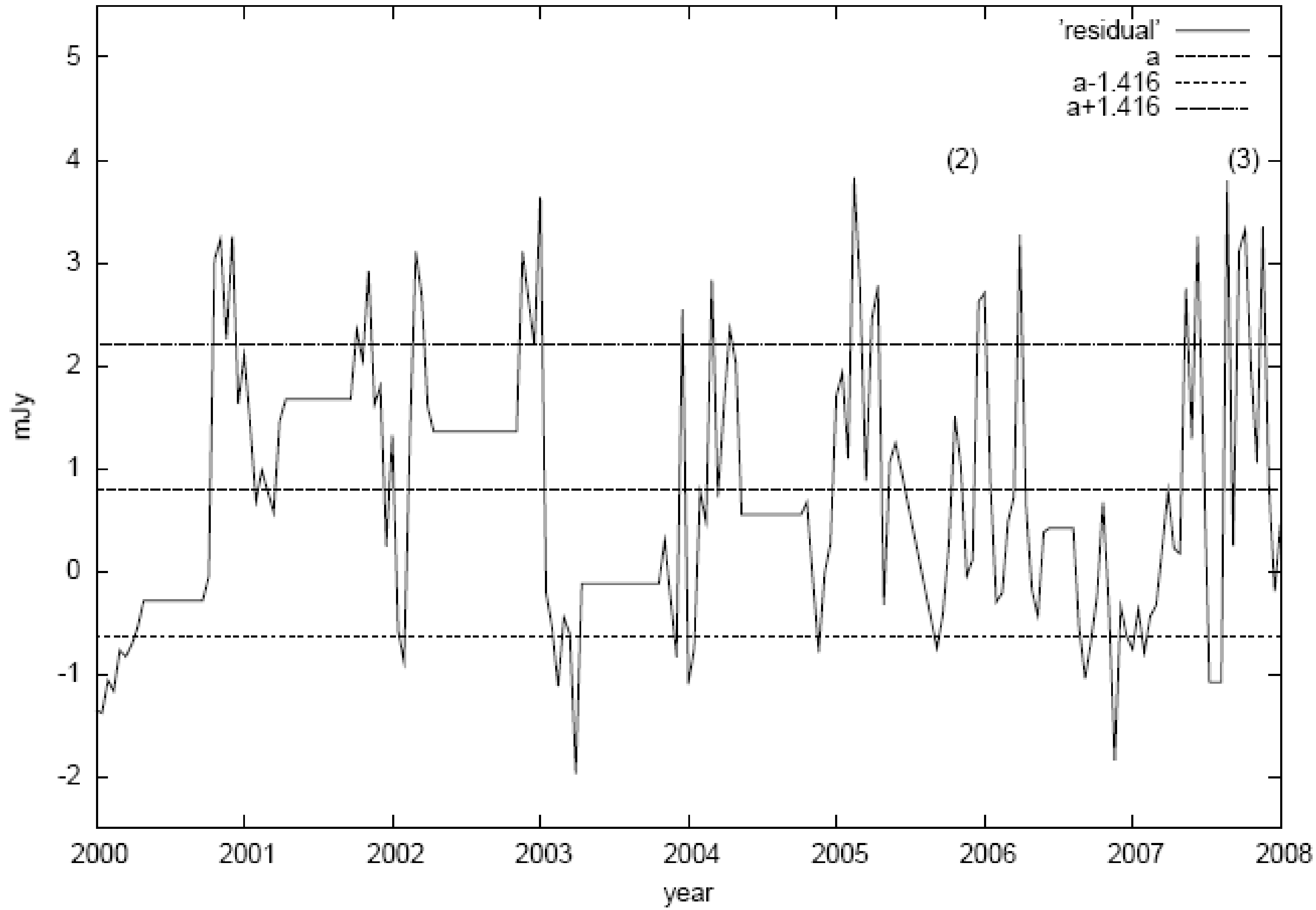

Fig. 3.— The residuals observations minus the model for OJ287 during the 2000 - 2008.

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LETTERS

A massive binary black-hole system in OJ 287 and a test of general relativity

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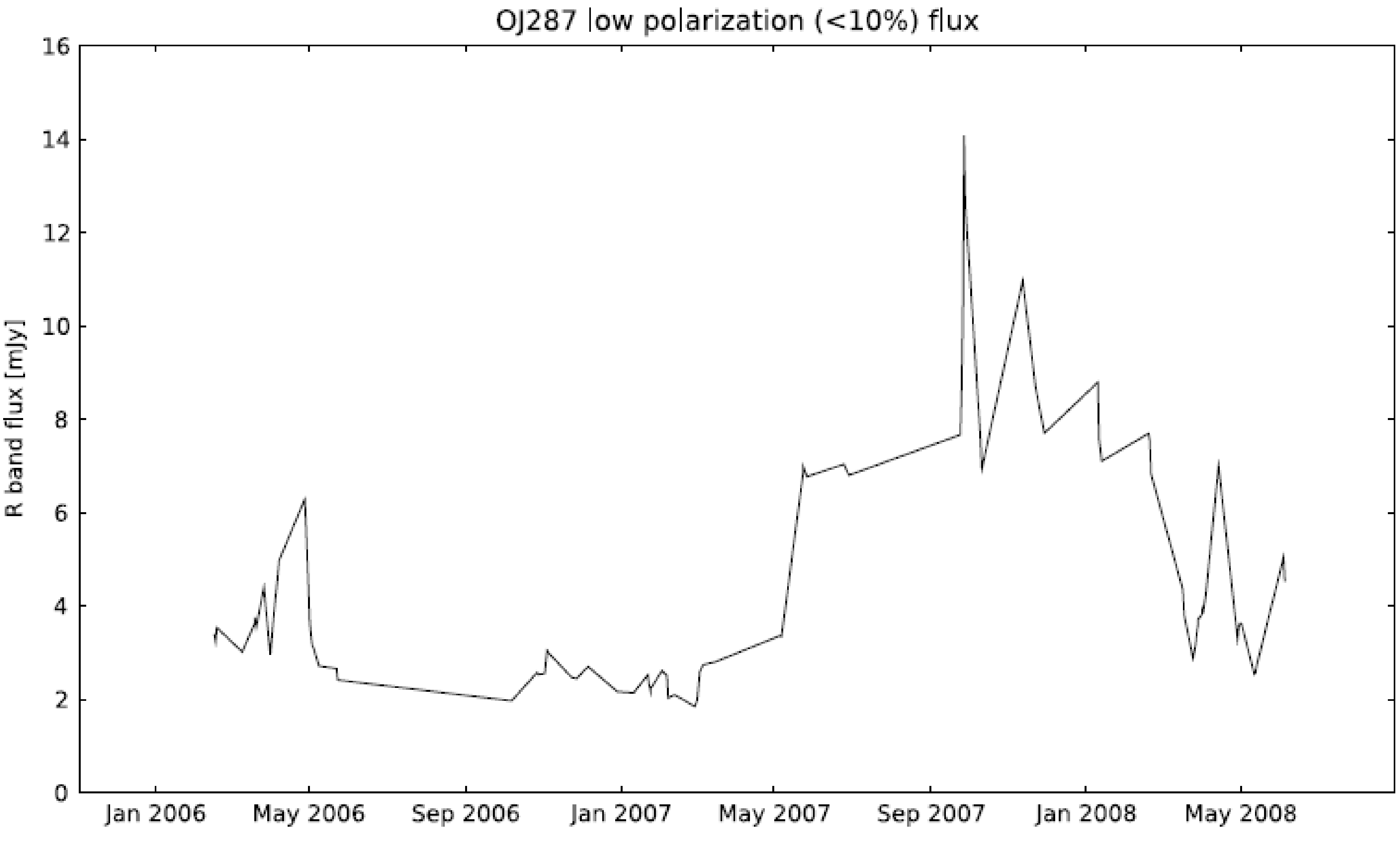
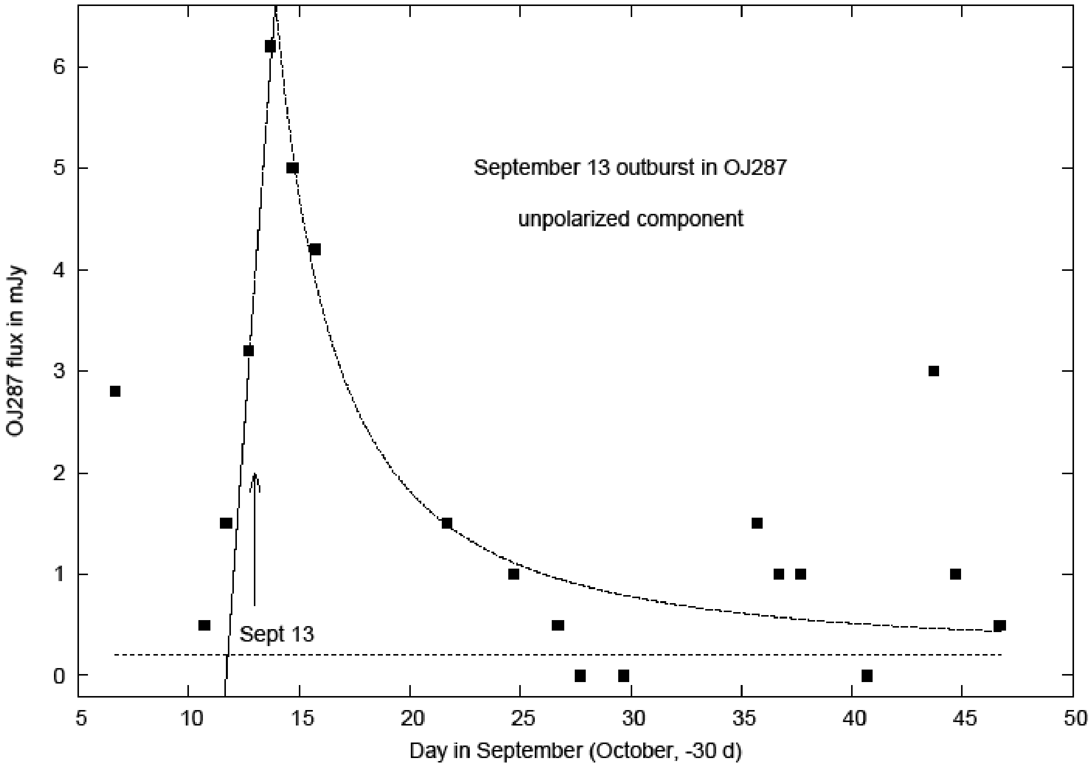
Prediction: 2nd outburst at Sept 13, 2007



September 13 2007, unpolarized



Testing no-hair theorem IV

- Timing OJ287 outbursts

Periastron precession: M

Disk impacts far from periastron: S

Disk impacts close to periastron: Q

Solution of the timing problem. Level II

Measuring the spin of the primary black hole in OJ287

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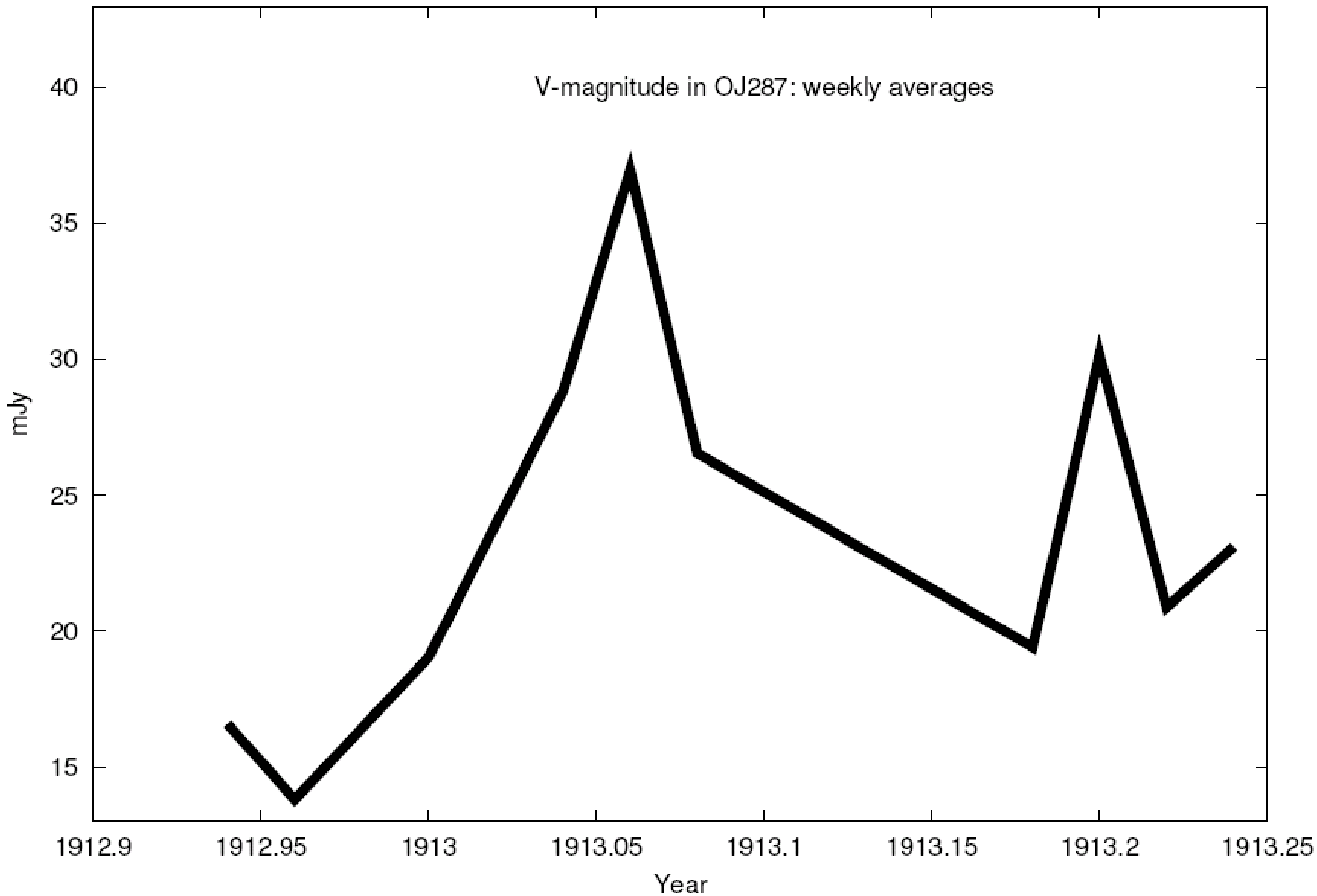
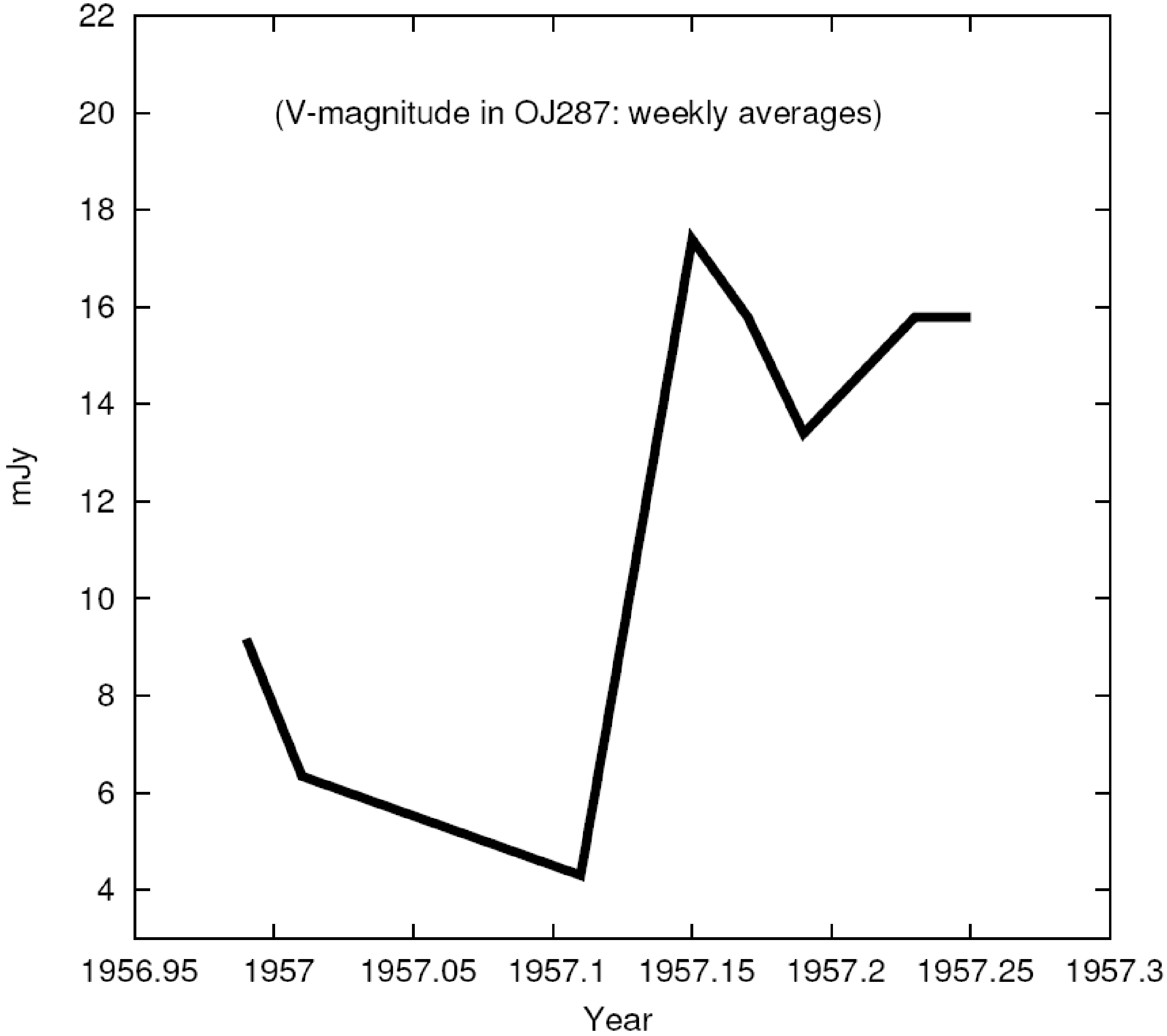
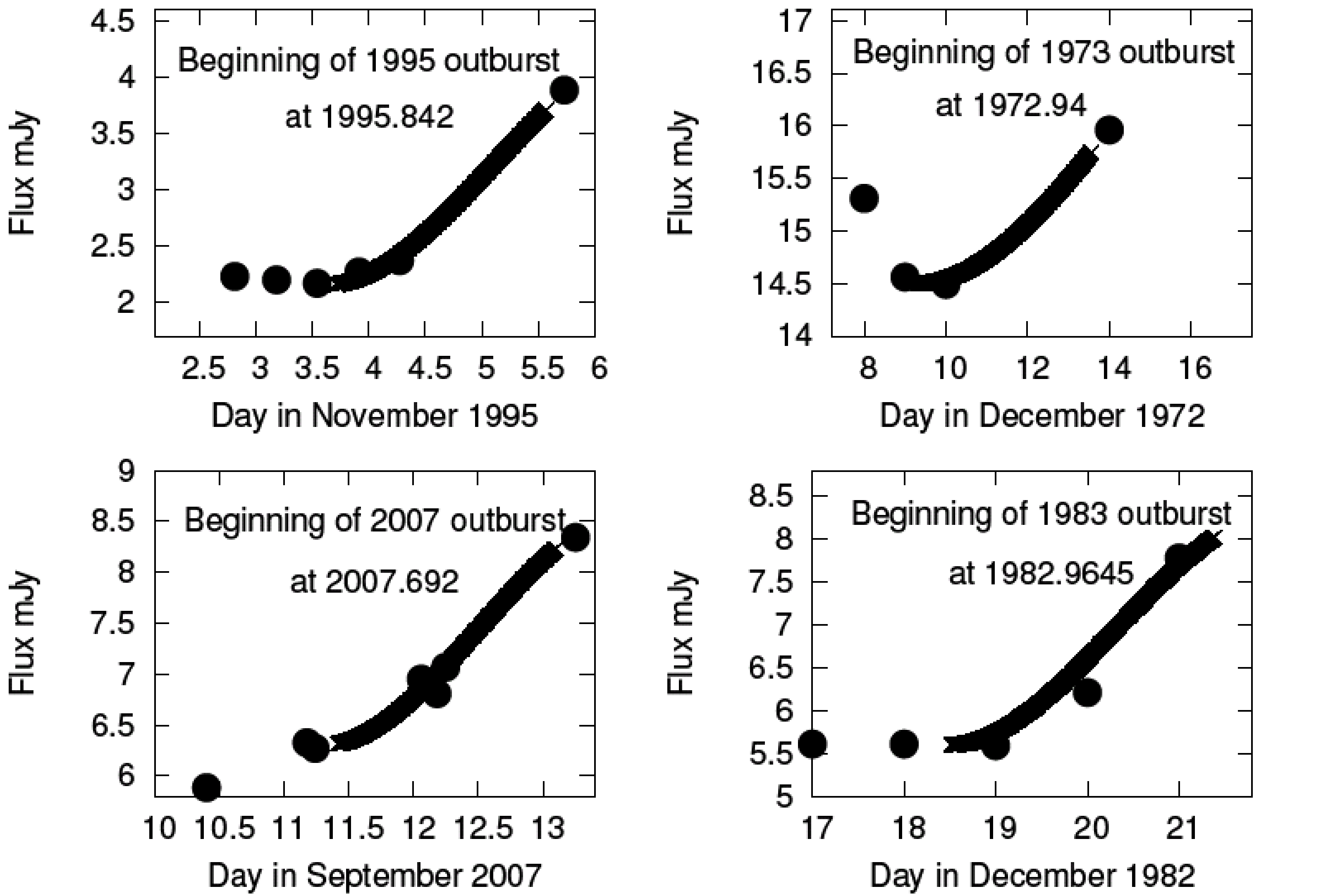
1913 outburst



1957 outburst





Beginning of 1995 outburst
at 1995.842
Flux mJy
Day in November 1995
Beginning of 1973 outburst
at 1972.94
Flux mJy
Day in December 1972
Beginning of 2007 outburst
at 2007.692
Flux mJy
Day in September 2007
Beginning of 1983 outburst
at 1982.9645
Flux mJy
Day in December 1982

Outburst times normalized to 1982.964 ± 0.0005

1912.980	$\pm\ 0.020$
1947.283	$\pm\ 0.002$
1957.080	$\pm\ 0.030$
1972.945	$\pm\ 0.012$
1984.130	$\pm\ 0.005$
1995.842	$\pm\ 0.0015$
2005.745	$\pm\ 0.012$
2007.692	$\pm\ 0.0015$

Post Newtonian terms

$$\ddot{\boldsymbol{x}} \equiv \frac{d^2\boldsymbol{x}}{dt^2} \quad = \quad \ddot{\boldsymbol{x}}_0 + \ddot{\boldsymbol{x}}_{1PN} + \ddot{\boldsymbol{x}}_{SO} + \ddot{\boldsymbol{x}}_Q$$
$$+\ddot{\boldsymbol{x}}_{2PN} + \ddot{\boldsymbol{x}}_{2.5PN} \,,$$

$$\ddot{\boldsymbol{x}}_0 \;=\; -\frac{G\,m}{r^3}\,\boldsymbol{x}$$

where $\boldsymbol{x} = \boldsymbol{x}_1 - \boldsymbol{x}_2$ stands for the center-of-mass relative separation vector between the black holes

$$m \;=\; m_1 + m_2 \;\text{ and }\; r \;=\; |\boldsymbol{x}|.$$

1. order Post Newtonian term

$$\ddot{\boldsymbol{x}}_{1PN} = \quad -G\,\frac{m}{c^2}/r^2\Big\{\boldsymbol{n}\left[-2(2+\eta)\frac{G\,m}{r}\right.$$

$$\left.+(1+3\eta)v^2 - \frac{3}{2}\eta\dot{r}^2\right] - 2(2-\eta)\dot{r}\boldsymbol{v}\Big\},$$

$$\boldsymbol{n} \;\equiv\; \boldsymbol{x}/r \;\text{ and }\; \boldsymbol{v} \;\equiv\; d\boldsymbol{x}/dt,$$

$$\dot{r} \;\equiv\; dr/dt \;=\; \boldsymbol{n}\cdot\boldsymbol{v},\; v \;\equiv\; |\boldsymbol{v}|$$

$$\eta = m_1\,m_2/m^2.$$

2. Order Post Newtonian term

$$
\begin{aligned}
\ddot{\boldsymbol{x}}_{2PN} = \quad & -\frac{G\,m}{c^4\,r^2}\left\{\boldsymbol{n}\left[\frac{3}{4}(12+29\eta)\left(\frac{G\,m}{r}\right)^2\right.\right. \\
& +\eta(3-4\eta)v^4+\frac{15}{8}\eta(1-3\eta)\dot{r}^4 \\
& -\frac{3}{2}\eta(3-4\eta)v^2\dot{r}^2-\frac{1}{2}\eta(13-4\eta)\left(\frac{G\,m}{r}\right)v^2 \\
& \left.-(2+25\eta+2\eta^2)\left(\frac{G\,m}{r}\right)\dot{r}^2\right] \\
& -\frac{1}{2}\dot{r}\boldsymbol{v}\left[\eta(15+4\eta)v^2-(4+41\eta+8\eta^2)\left(\frac{G\,m}{r}\right)\right. \\
& \left.\left.-3\eta(3+2\eta)\dot{r}^2\right]\right\},
\end{aligned}
$$

Radiation term

$$\ddot{\boldsymbol{x}}_{2.5PN} = \frac{8}{15}\frac{G^2m^2\eta}{c^5r^3}\left\{\left[9v^2 + 17\frac{G\,m}{r}\right]\dot{r}\boldsymbol{n} - \left[3v^2 + 9\frac{G\,m}{r}\right]\boldsymbol{v}\right\},$$

Spin – orbit term

$$
\begin{aligned}
\ddot{\boldsymbol{x}}_{SO} \quad &= \frac{G\,m}{r^2}\ \left(\frac{G\,m}{c^3\,r}\right)\ \left(\frac{1+\sqrt{1-4\,\eta}}{4}\right) \\
&\chi\Bigg\{\Bigg[12\ [\boldsymbol{s}_1\cdot(\boldsymbol{n}\times\boldsymbol{v})]\Bigg]\,\boldsymbol{n} \\
&+\Bigg[\left(9+3\sqrt{1-4\,\eta}\right)\ \dot{r}\Bigg]\,(\boldsymbol{n}\times\boldsymbol{s}_1) \\
&-\Bigg[7+\sqrt{1-4\,\eta}\Bigg]\,(\boldsymbol{v}\times\boldsymbol{s}_1)\Bigg\}\,,
\end{aligned}
$$

where the Kerr parameter χ and the unit vector $\boldsymbol{s}_1$ define the spin of the primary black hole by the relation $\boldsymbol{S}_1 = G\,m_1^2\,\chi\,\boldsymbol{s}_1/c$ and χ is allowed to take values between 0 and 1 in general relativity.

Quadrupole term

$$\ddot{\boldsymbol{x}}_Q = -q\frac{3}{2}\chi^2\frac{G^3}{c^4}\frac{m^3}{r^4}[(5(\boldsymbol{n}\cdot\boldsymbol{s}_1)^2-1)\boldsymbol{n}-2(\boldsymbol{n}\cdot\boldsymbol{s}_1)\boldsymbol{s}_1],$$

where the factor q ($= 1$ in GR) is introduced for the possibility of testing the 'no-hair' theorem of black holes, according to the original idea of Will

Parameters

$\Delta\phi^\circ$	39.1 ± 0.1
m_1	$(1.83 \pm 0.01) \cdot 10^{10} M_\odot$
m_2	$(1.4 \pm 0.1) \cdot 10^{8} M_\odot$
χ	0.28 ± 0.08
ϕ_0	$56^\circ.5 \pm 1^\circ.2$
e_0	0.6584 ± 0.001
q	1.0 ± 0.3
t_d	0.75 ± 0.04

$$M_1 = (1.83 \pm 0.01) \cdot 10^{10} M_\odot$$

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DETERMINING QUASAR BLACK HOLE MASS FUNCTIONS FROM THEIR BROAD EMISSION LINES: APPLICATION TO THE BRIGHT QUASAR SURVEY

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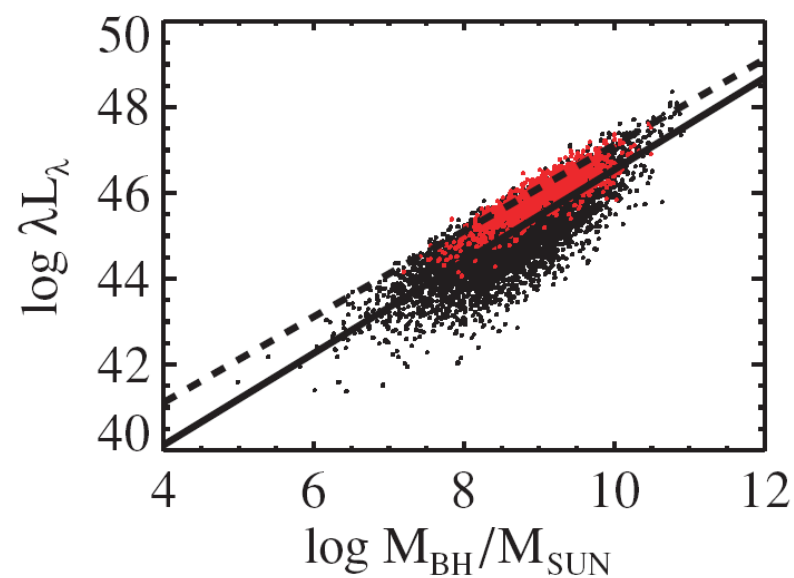
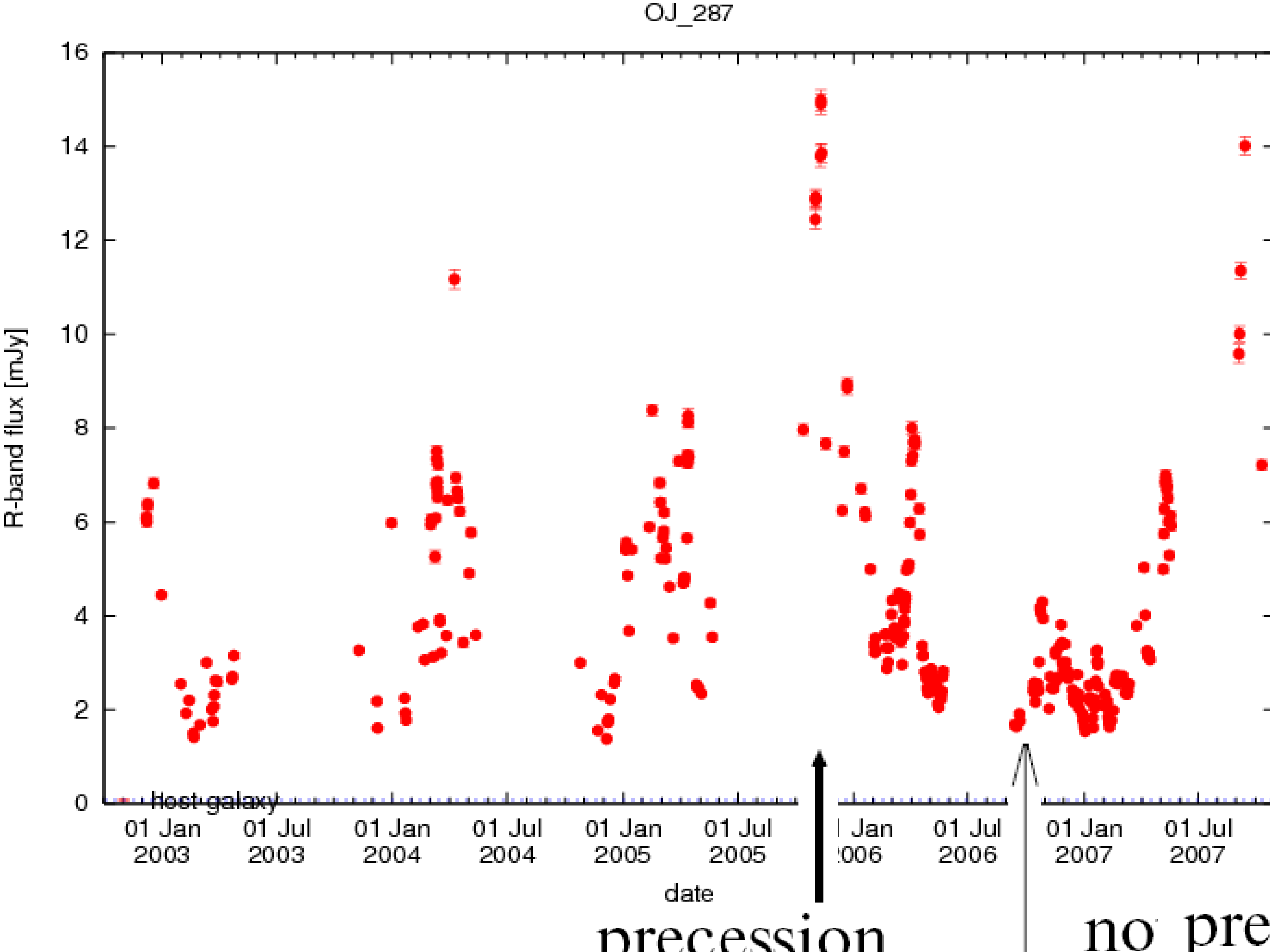
10^{47} ergs/s corresponds to $10^{10.5 \pm 0.5}$ $M_\odot$



$$\Delta\phi = 39.1 \pm 0.1$$



precession

no precession

$$e_0 = 0.6584 \pm 0.001$$

Dancing with black holes

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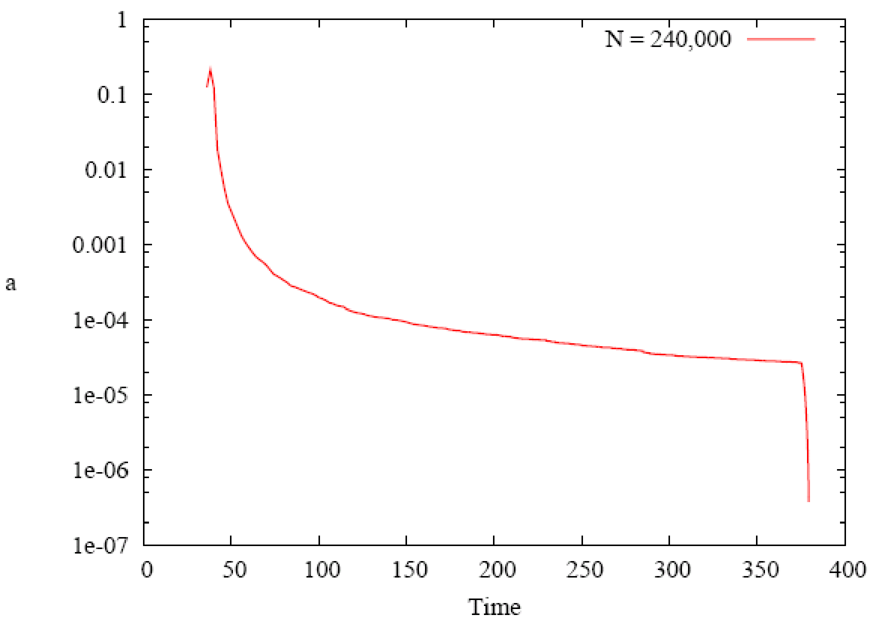
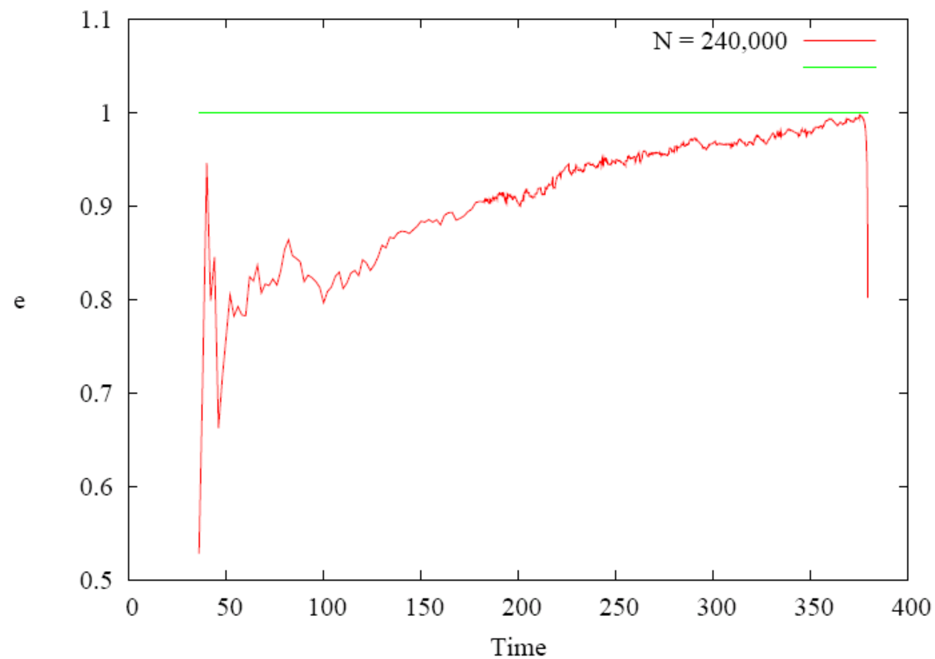
email: sverre@ast.cam.ac.uk





$$t_d = \quad 0.75$$

implies

$$\alpha_g \; / \; \dot{m}/\dot{m}_{\mathbf{edd}} = 14$$

If $\dot{m}/\dot{m}_{\mathbf{edd}} = 0.01$

$$\alpha_g = 0.14$$

$$m_2 = (1.4 \pm 0.1) \cdot 10^8 M_\odot$$

INTERACTION OF SECONDARY WITH THE PRIMARY

R (r_{per})	$\log(\delta E)$ (ergs)	$\log(T_{eq})$ (10^6 K)	$\log(t_{dyn})$ (s)	$\log(\tau)$	S_V (mJy)
1.05……	54.59	5.42	5.63	1.44	5.1

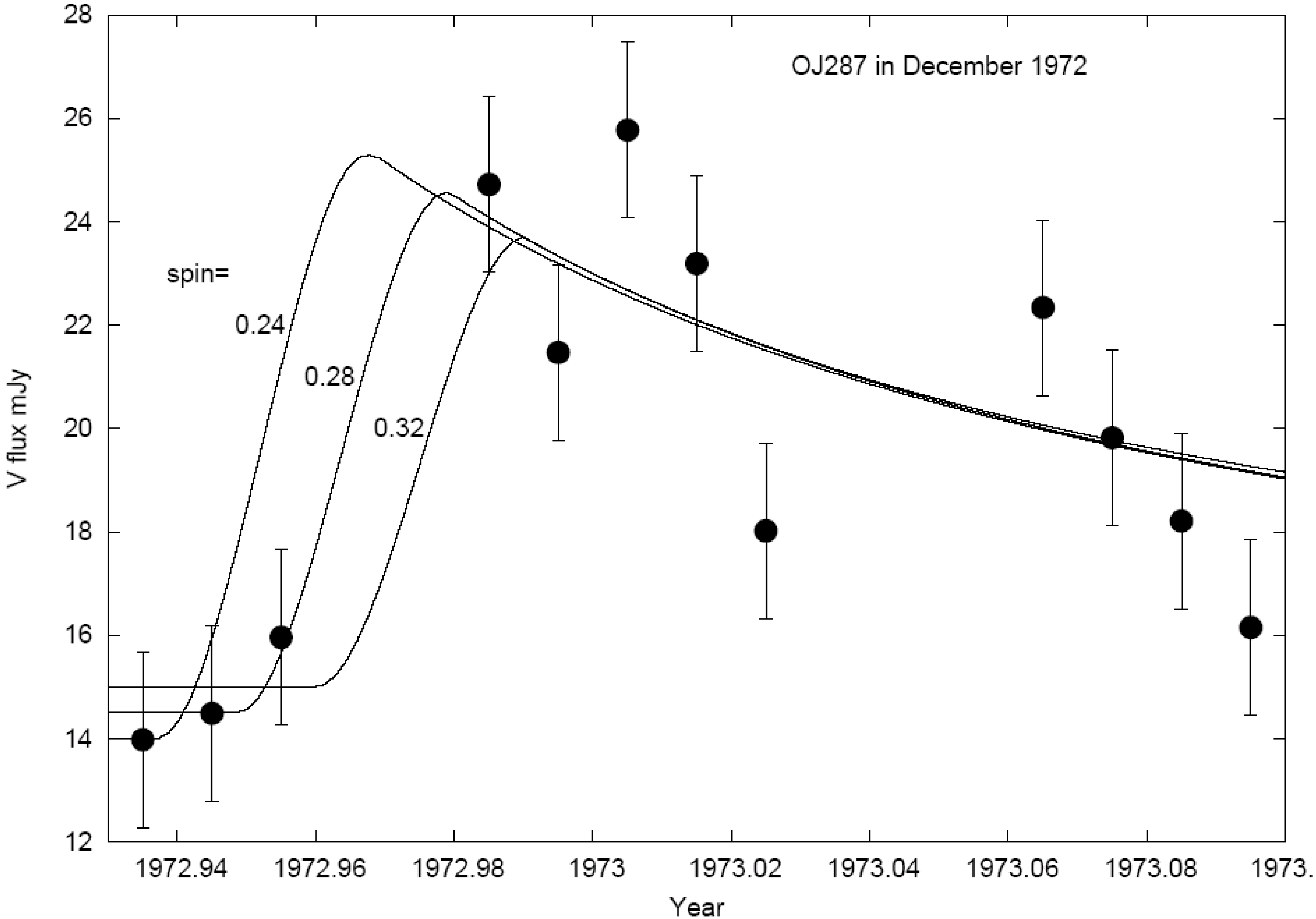
the secondary black hole $10^8\ M_\odot$

$$H_0 = 80\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

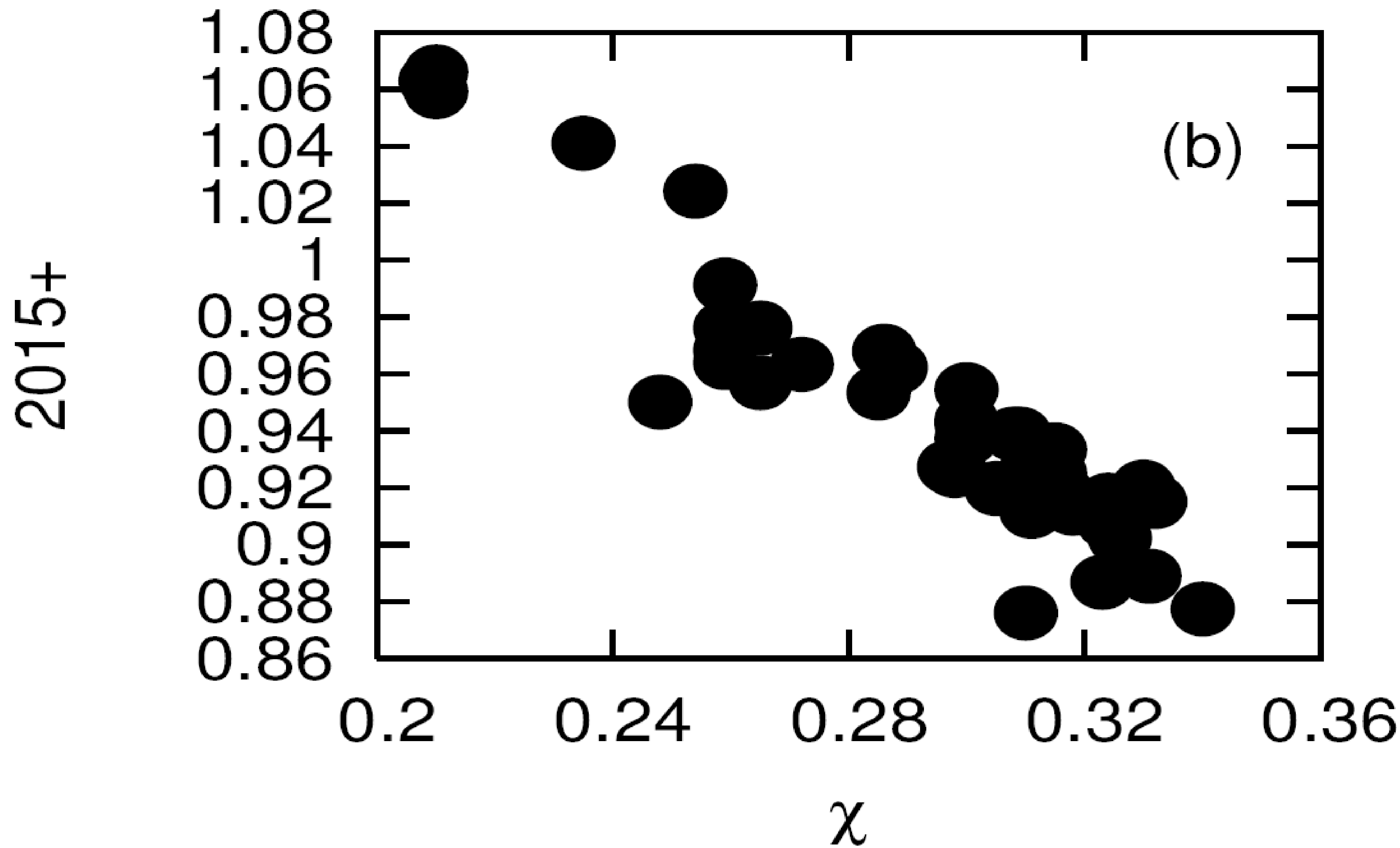
Correct for H_0=72, S_V=6.1

gives m_2=1.4 10^8

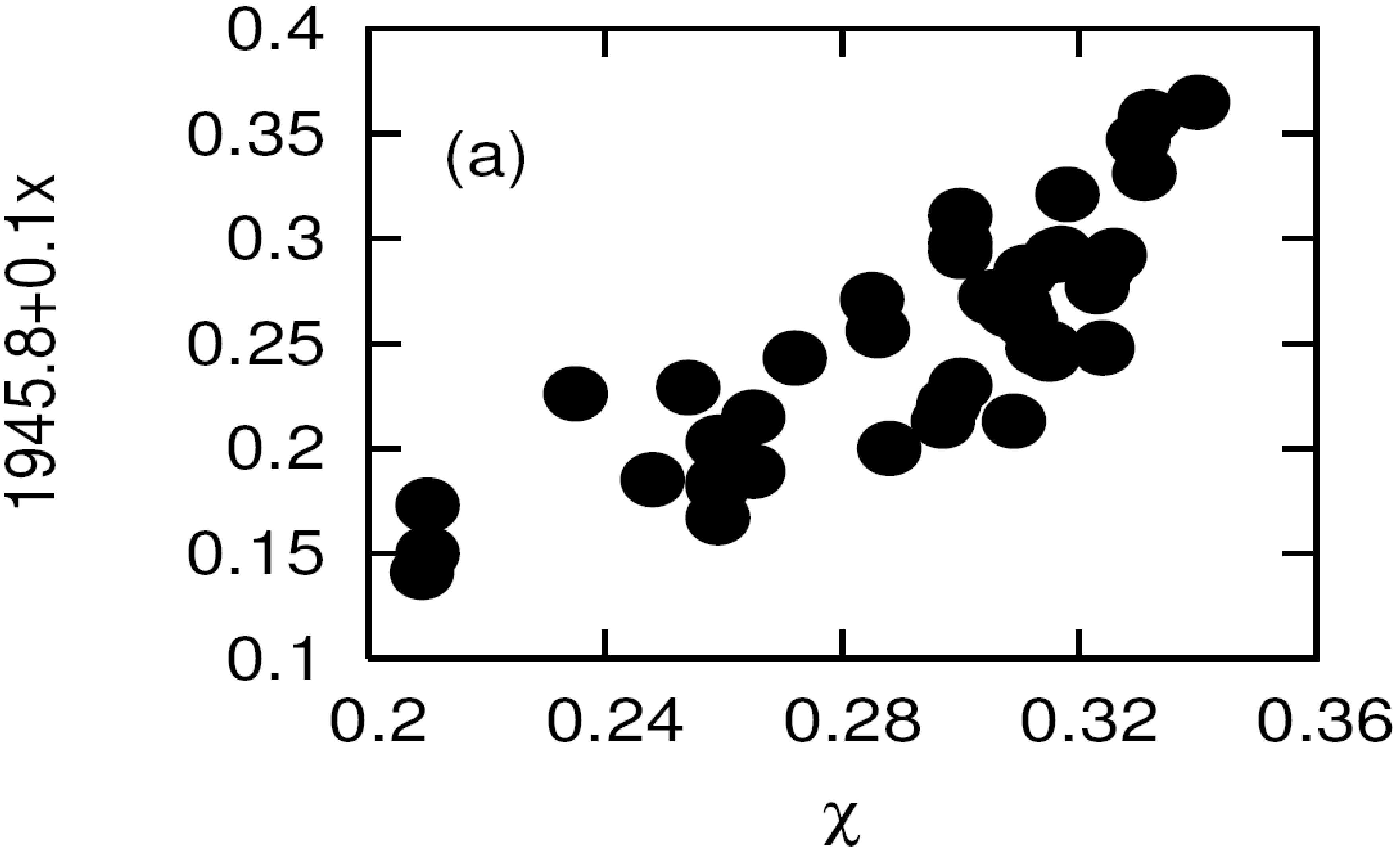
$$\chi = 0.28 \pm 0.08$$



Better value in 2015



...or in 1945



The Astronomical Journal, 132:1256–1266, 2006 September

OPTICAL MONITORING OF BL LACERTAE OBJECT OJ 287: A 40 DAY PERIOD?

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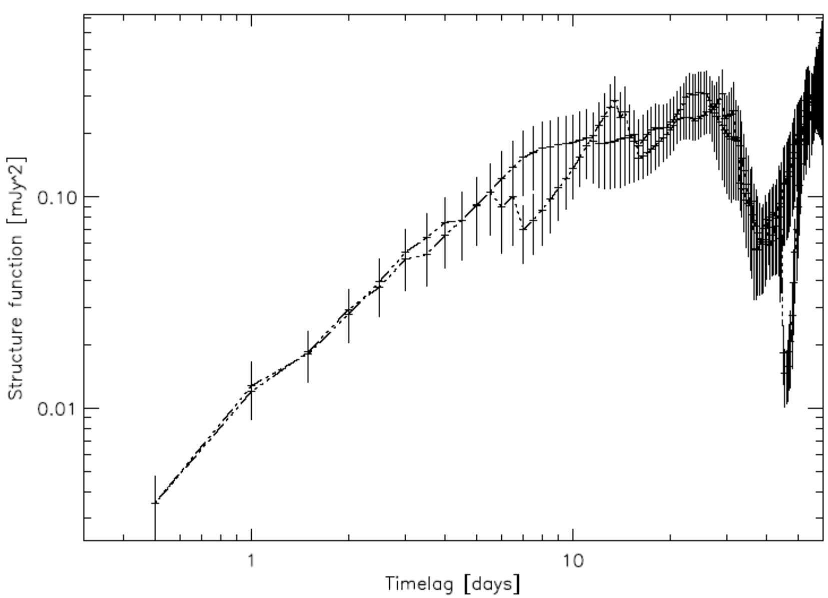


$$\chi = 0.35 \pm 0.06$$

Fig. 2.— Structure function of the light curve in the BATC i band. The minima at 34 and 44 days indicate the periods of the variation. See text for details.

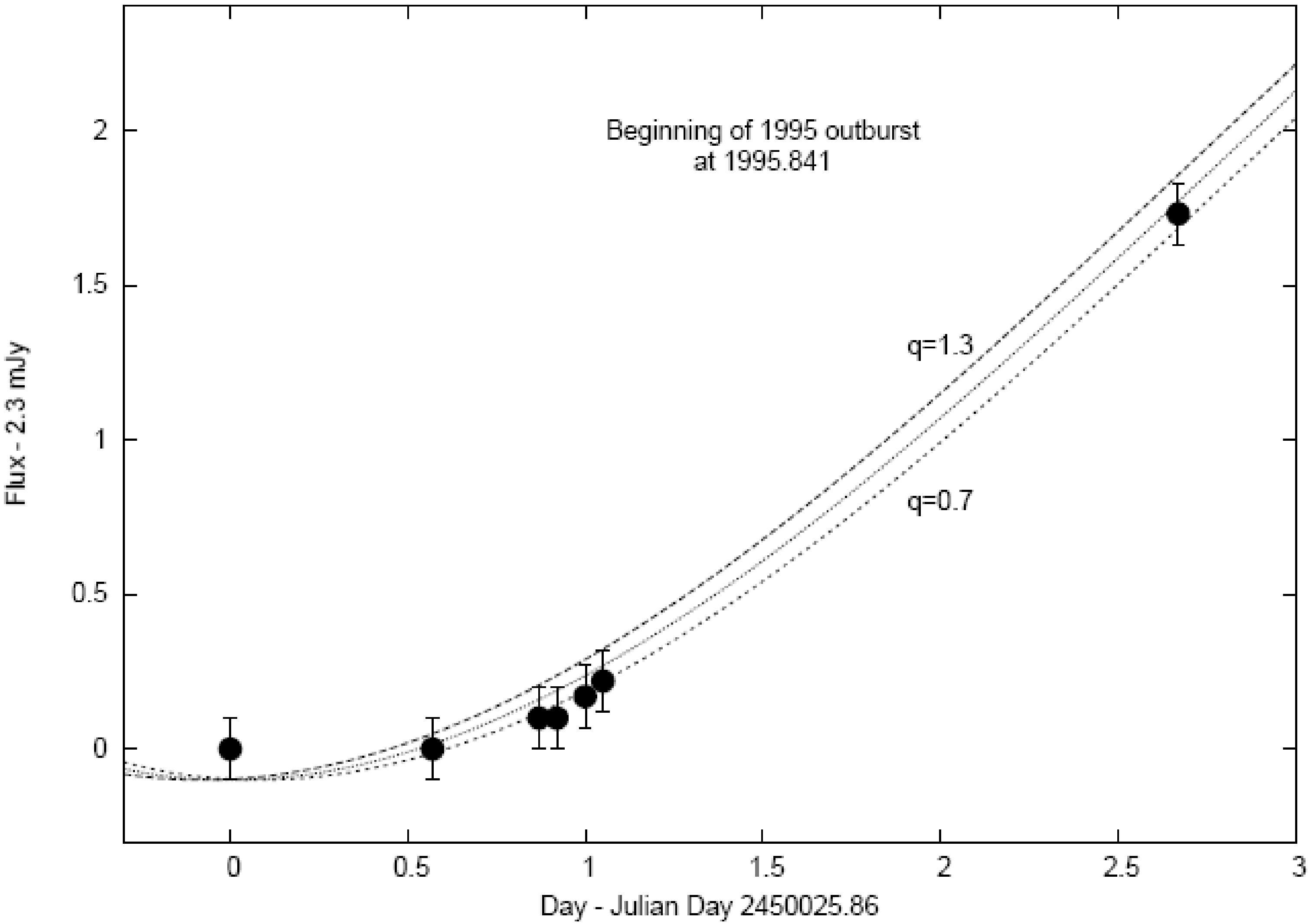


Fig. 3.— The observations of OJ287 at the beginning of November 1995, transformed to optical

New tests of no-hair theorem

- Historical data
- Do more data exist?

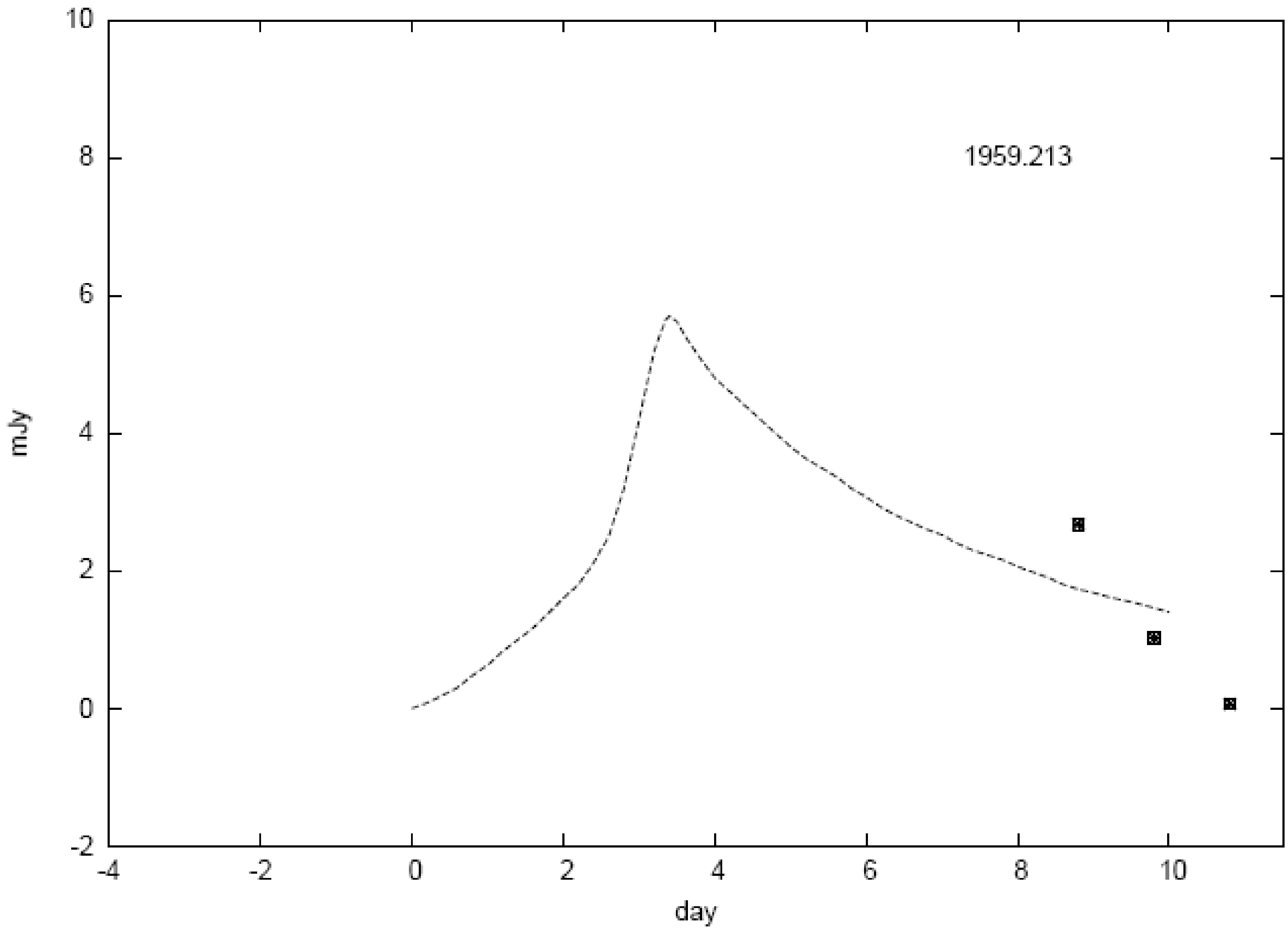


Fig. 1.— The observation of the brightness of OJ287 at the expected 1959 outburst time. The

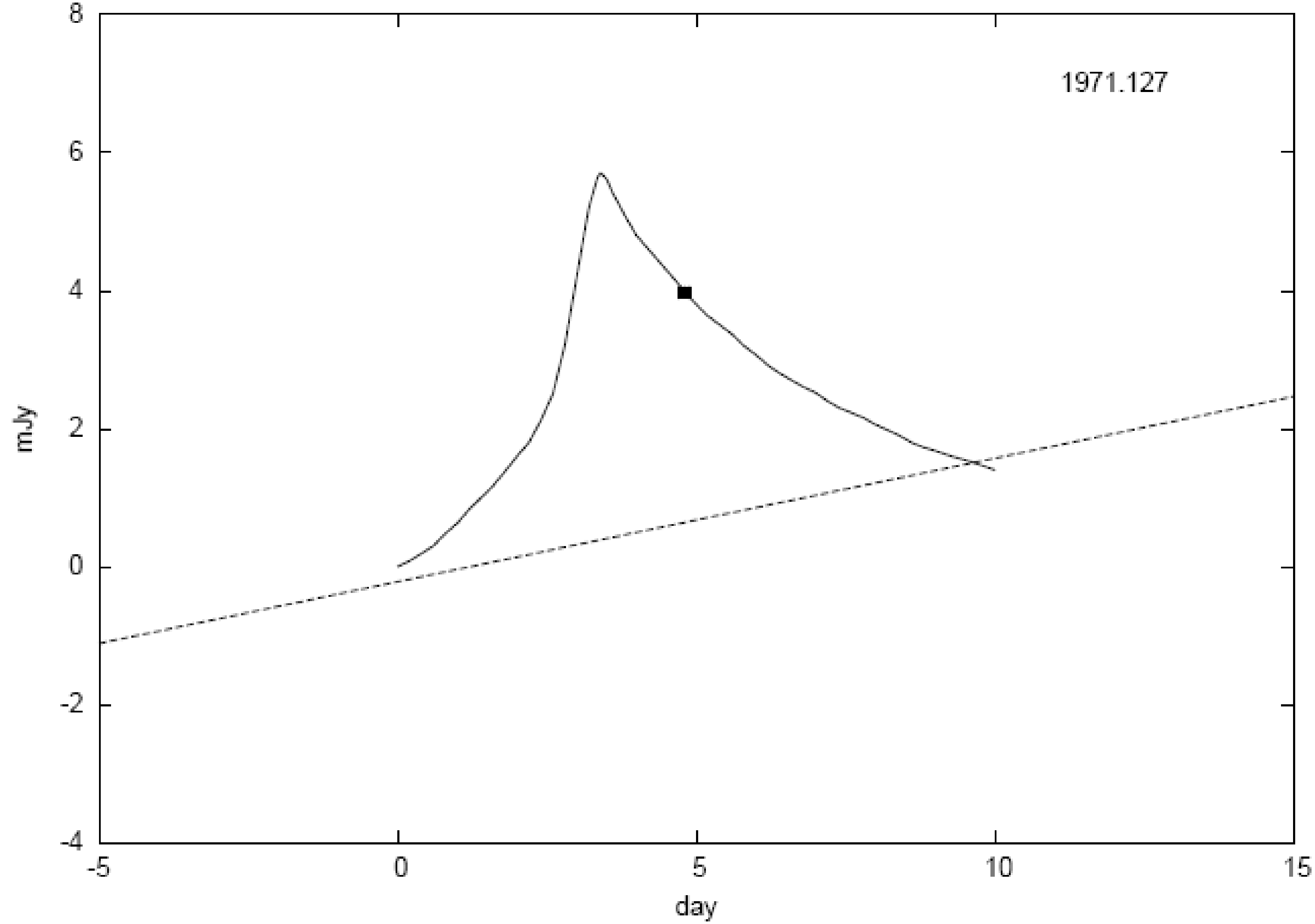


Fig. 2.— The observation of the brightness of OJ287 at the expected 1971 outburst time. The

The 2019 outburst

2019.553 if $q = 1$
2019.5536 if $q = 0.5$
2019.5524 if $q = 1.5$

The range here is 10 hours

July 21

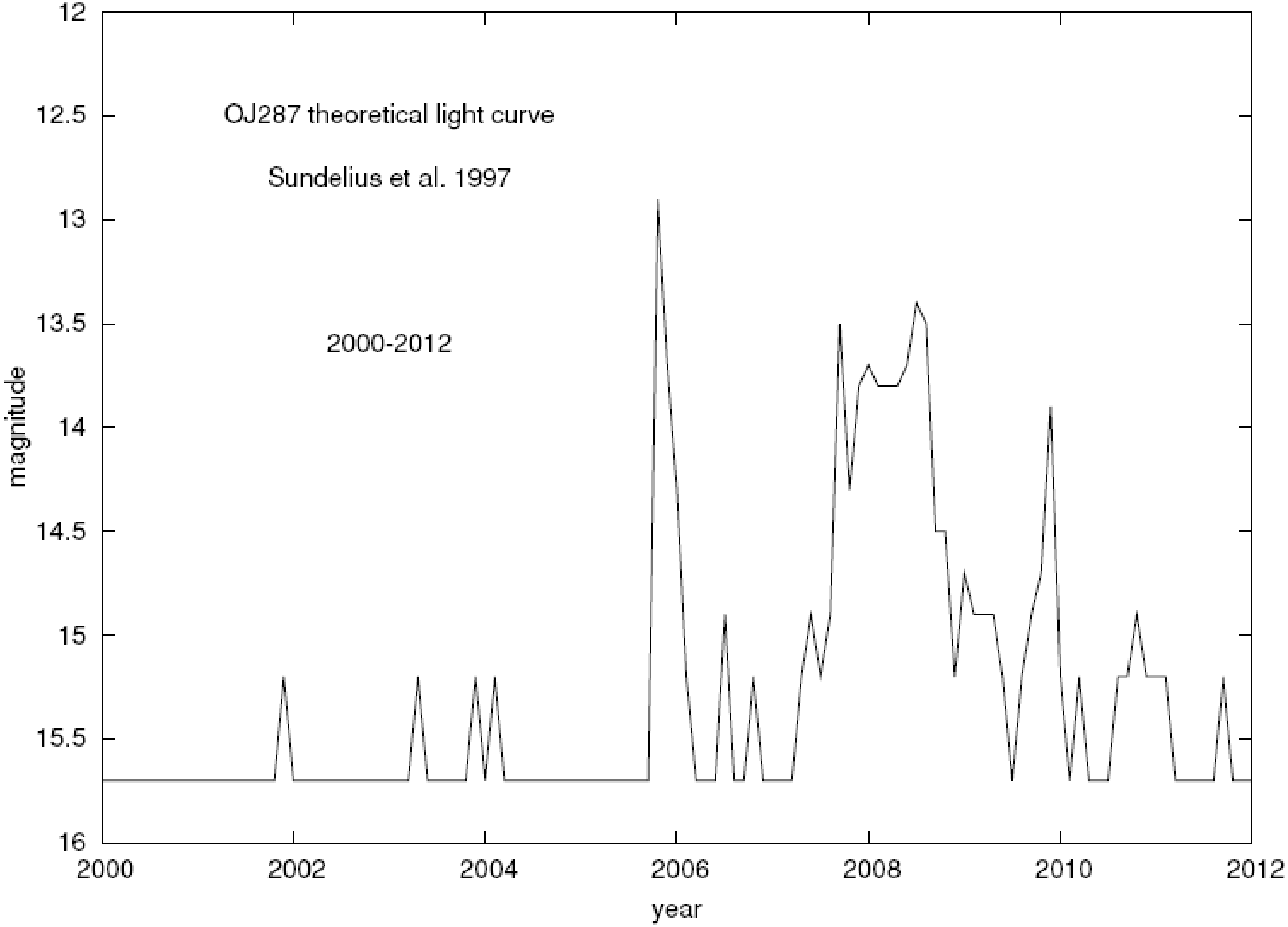
The distance from the Sun

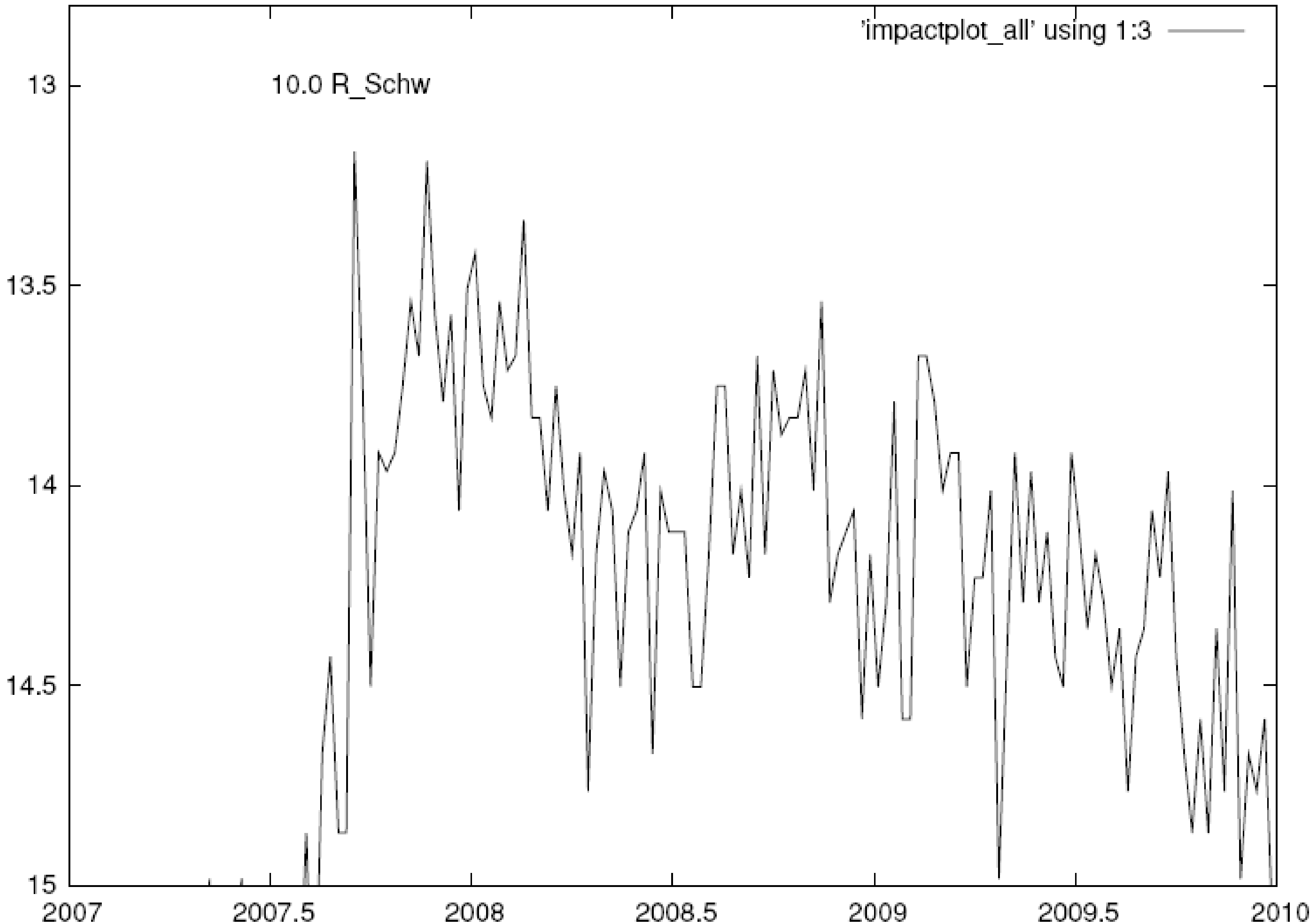
8 degrees

Conclusion

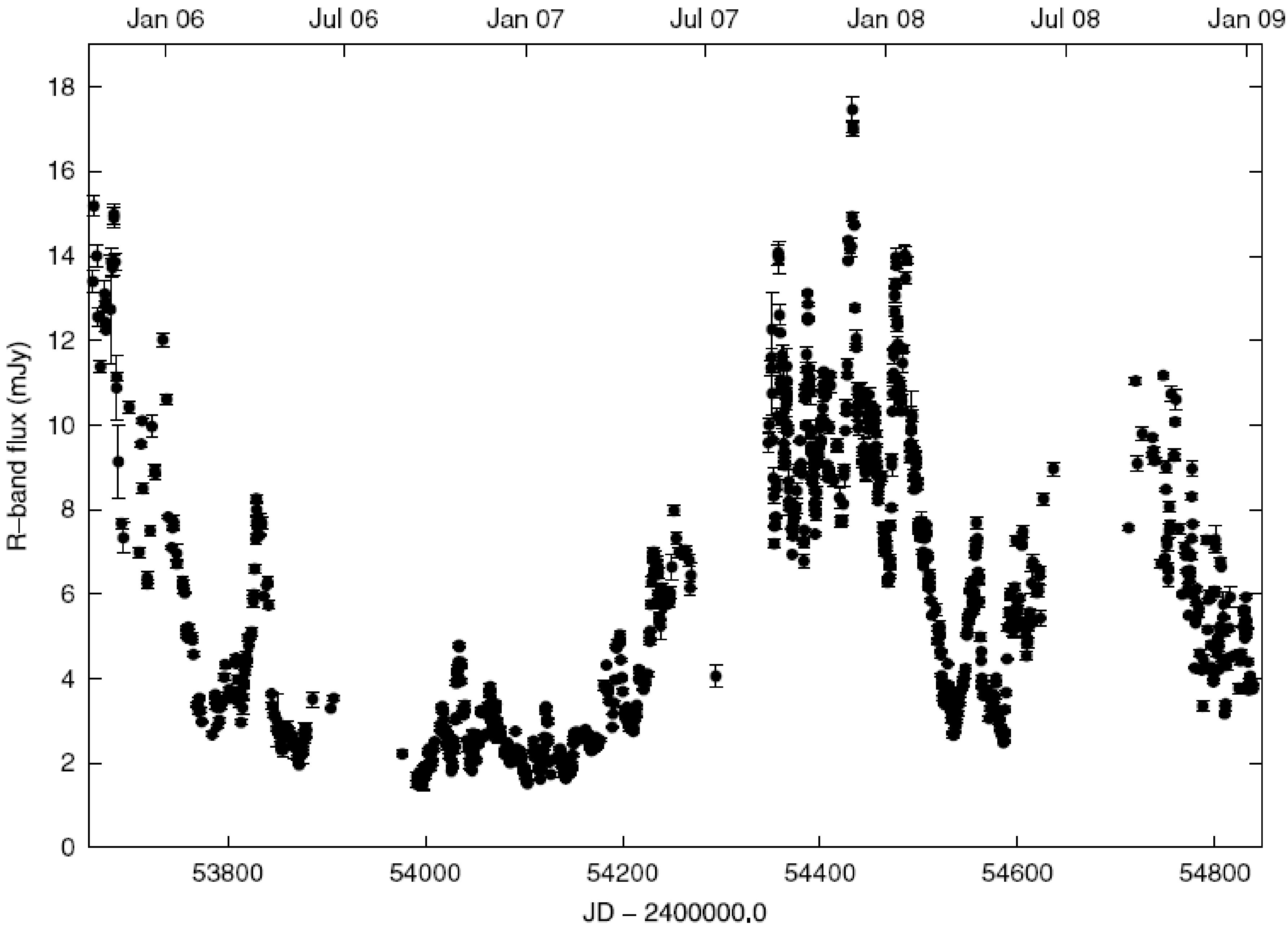
- The no-hair theorem is confirmed at 30% level
- Black holes are (probably) real
- General Relativity is (probably) the correct theory of gravitation
- We know more in 2019, accuracy level down to 10% ?

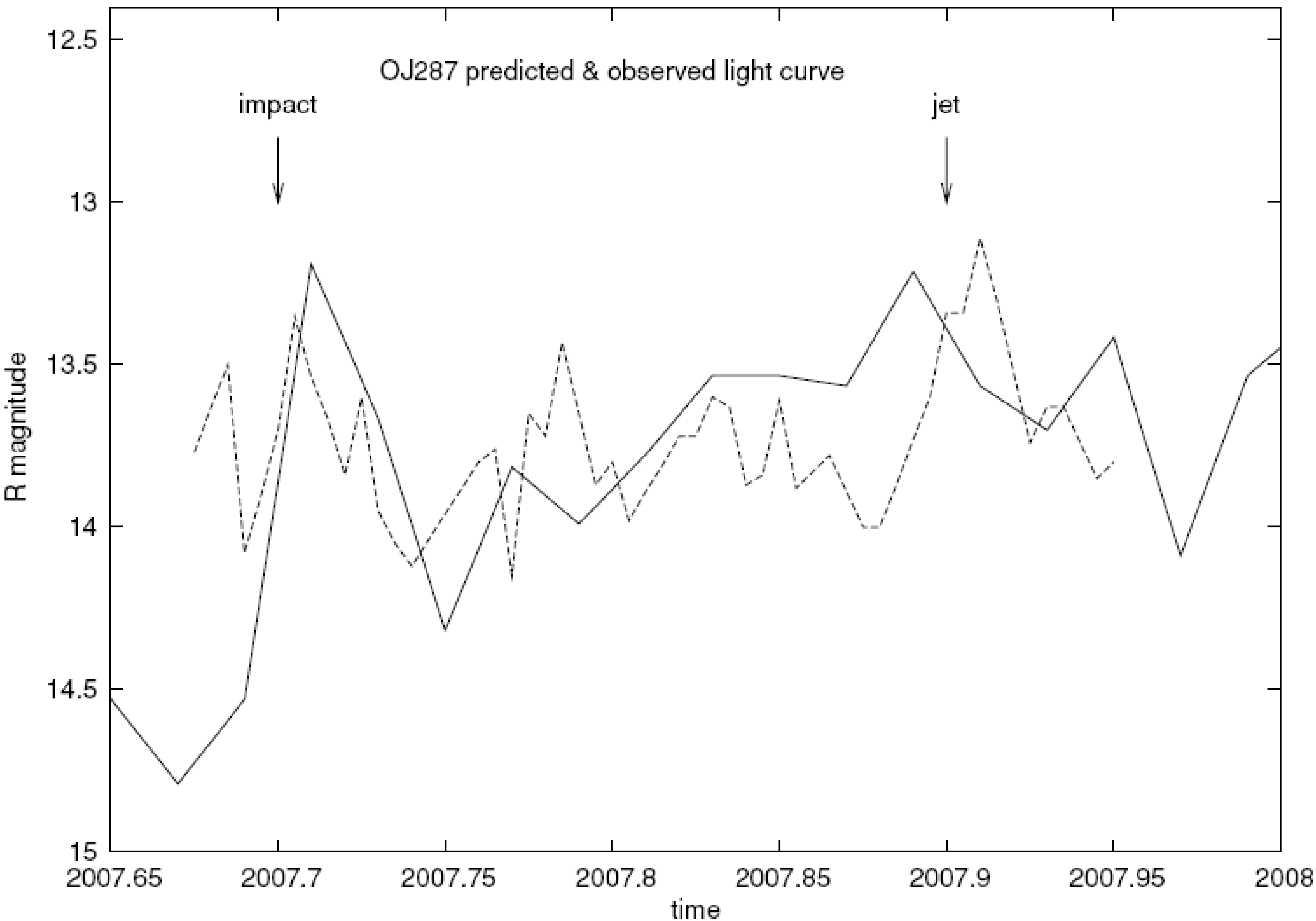
Tidal outbursts



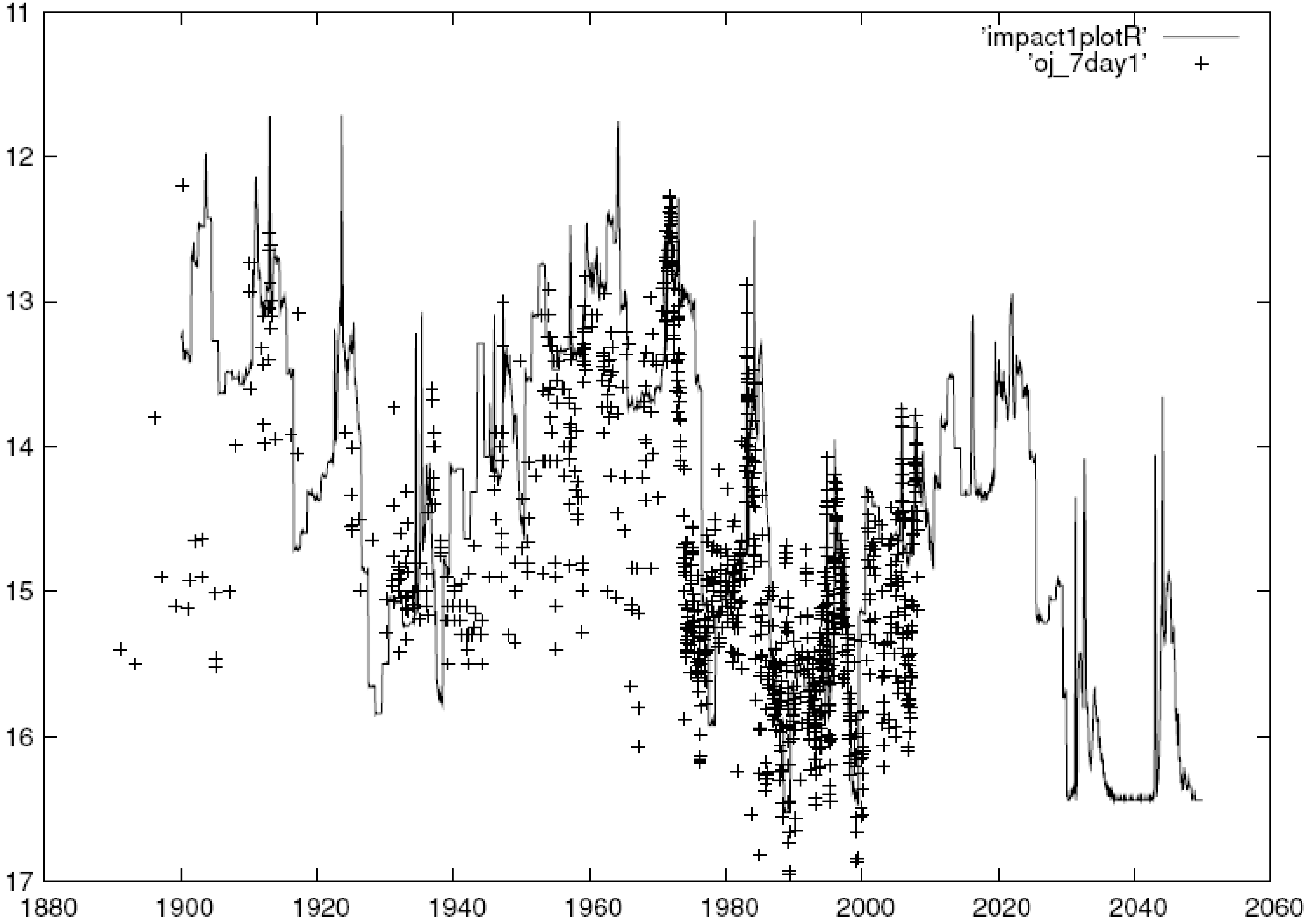


'impactplot_all' using 1:3
10.0 R_Schw
13
13.5
14
14.5
15
2007
2007.5
2008
2008.5
2009
2009.5
2010

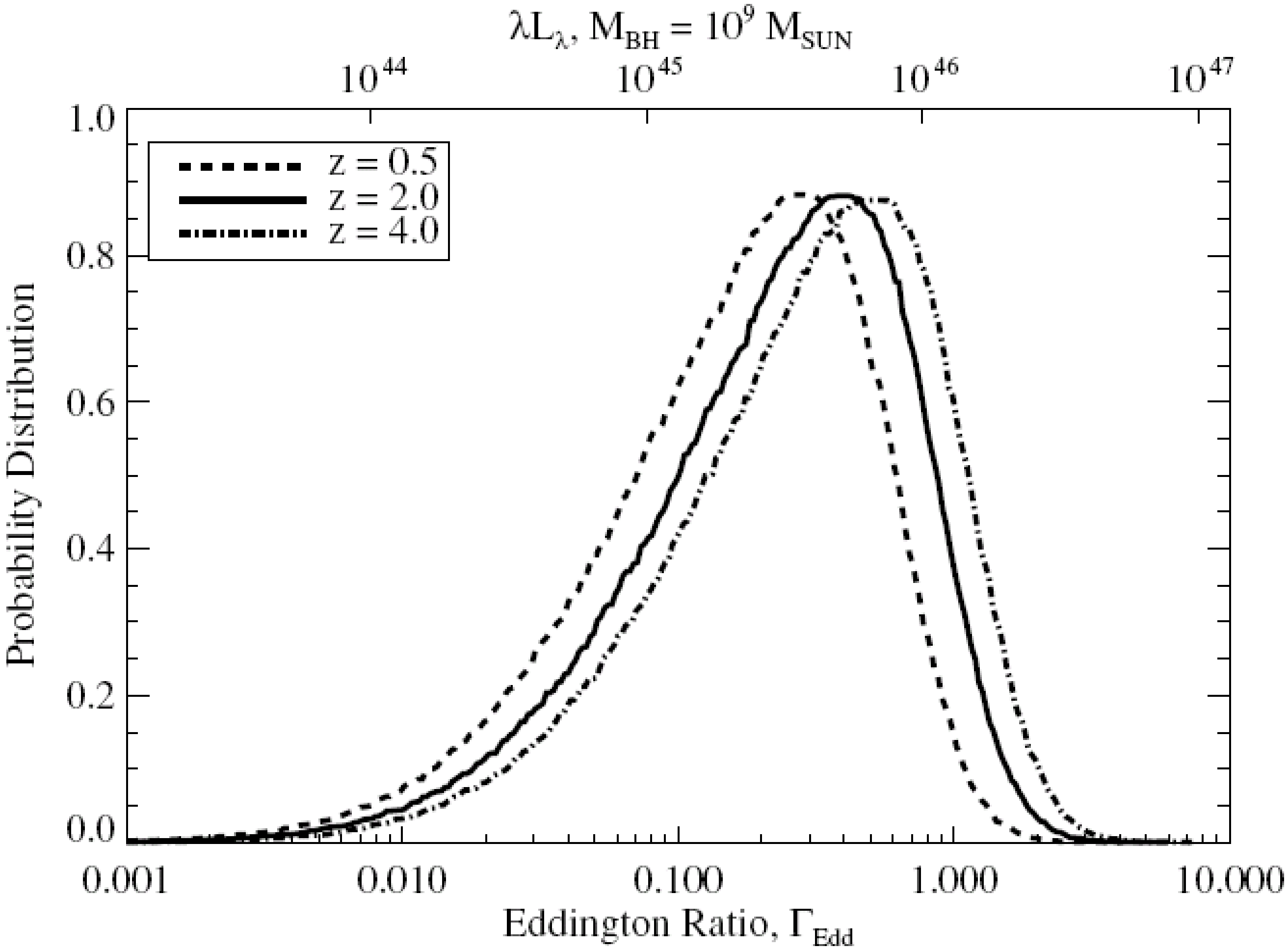

Jan 06
Jul 06
Jan 07
Jul 07
Jan 08
Jul 08
Jan 09
R–band flux (mJy)
0
2
4
6
8
10
12
14
16
18
53800
54000
54200
54400
54600
54800
JD – 2400000.0

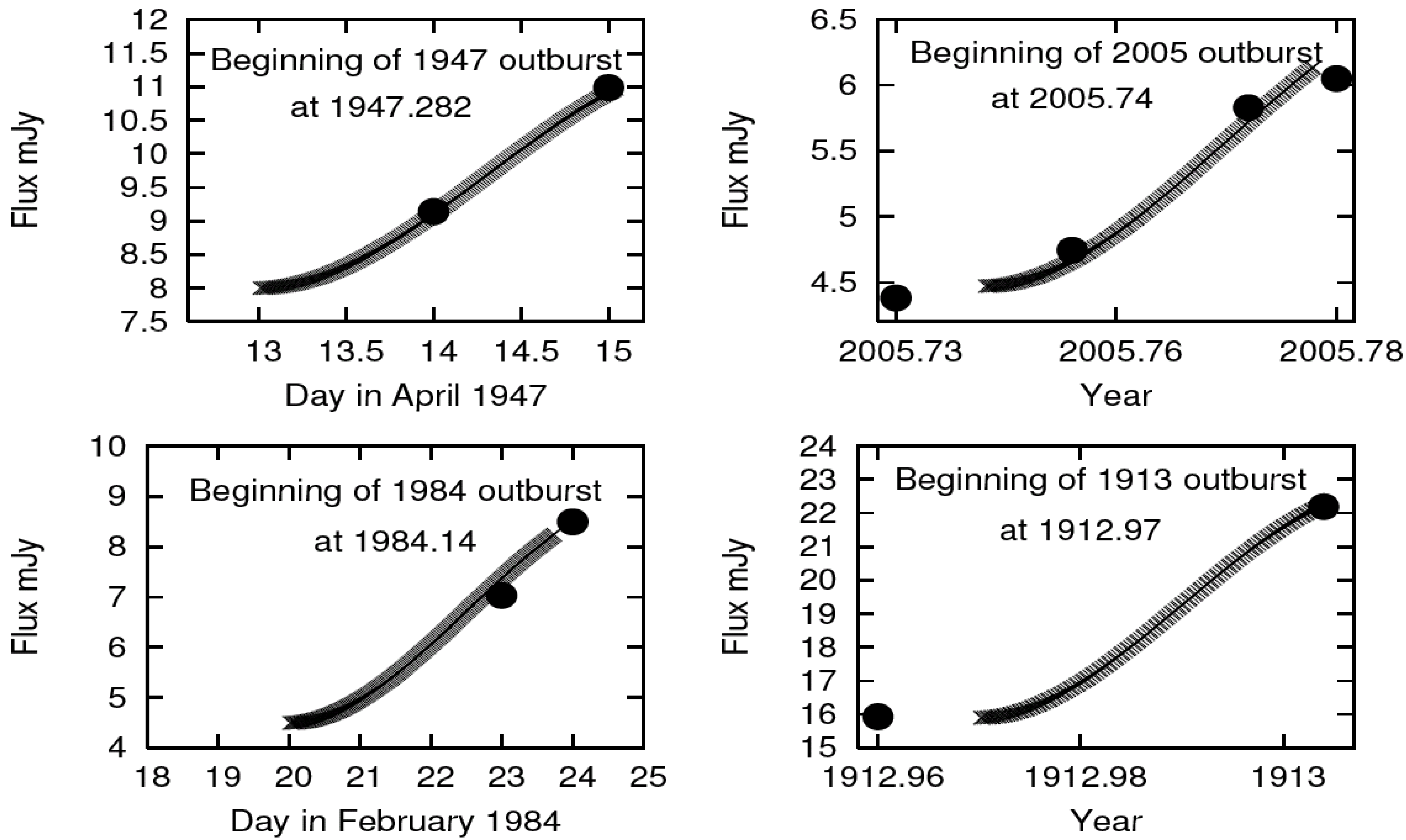


OJ287 predicted & observed light curve
impact
jet
R magnitude
12.5
13
13.5
14
14.5
15
2007.65
2007.7
2007.75
2007.8
2007.85
2007.9
2007.95
2008
time


'impact1plotR'
'oj_7day1'
11
12
13
14
15
16
17
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060

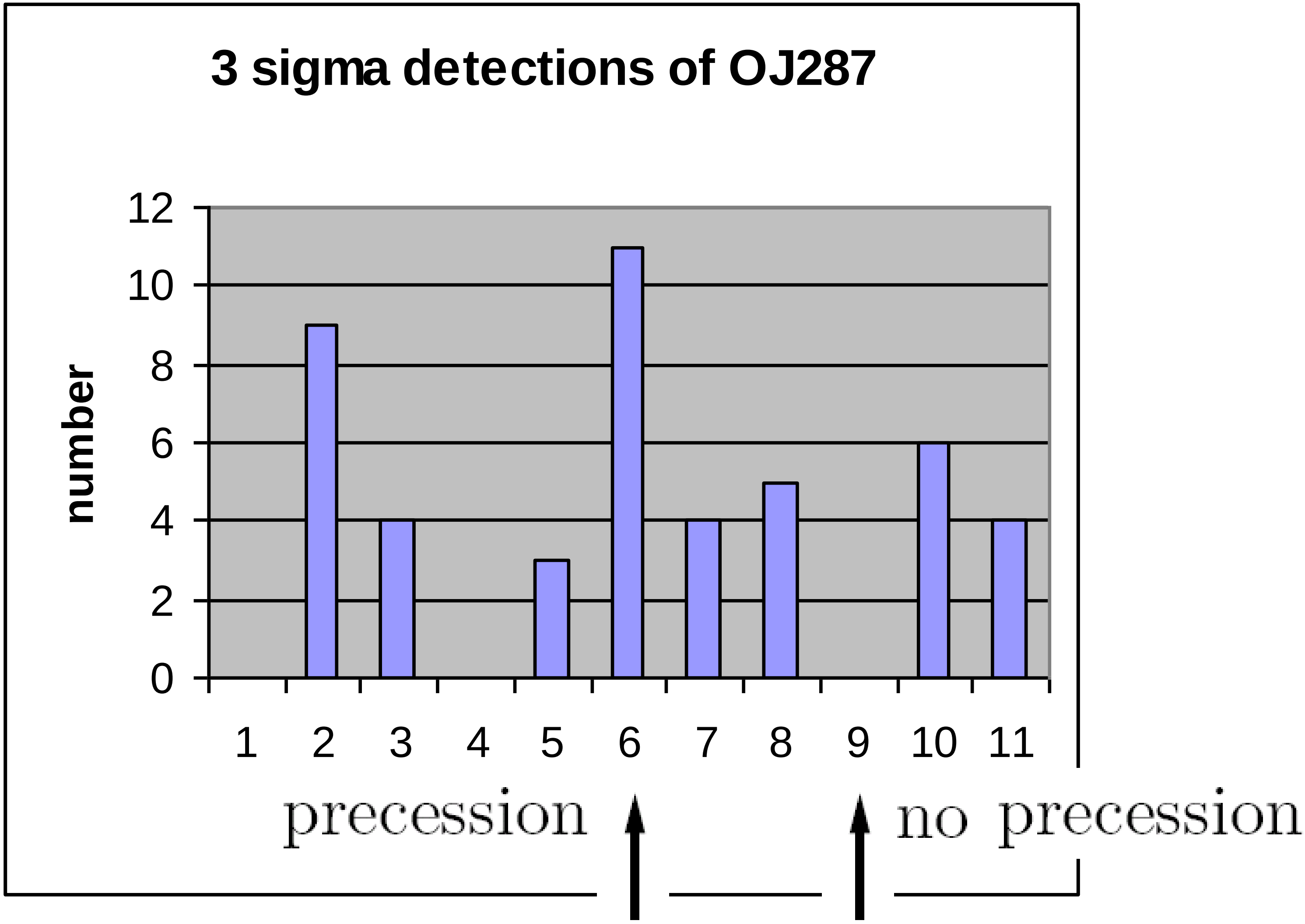
$M_{BH} = 10^9\ M_{SUN}$ unlikely



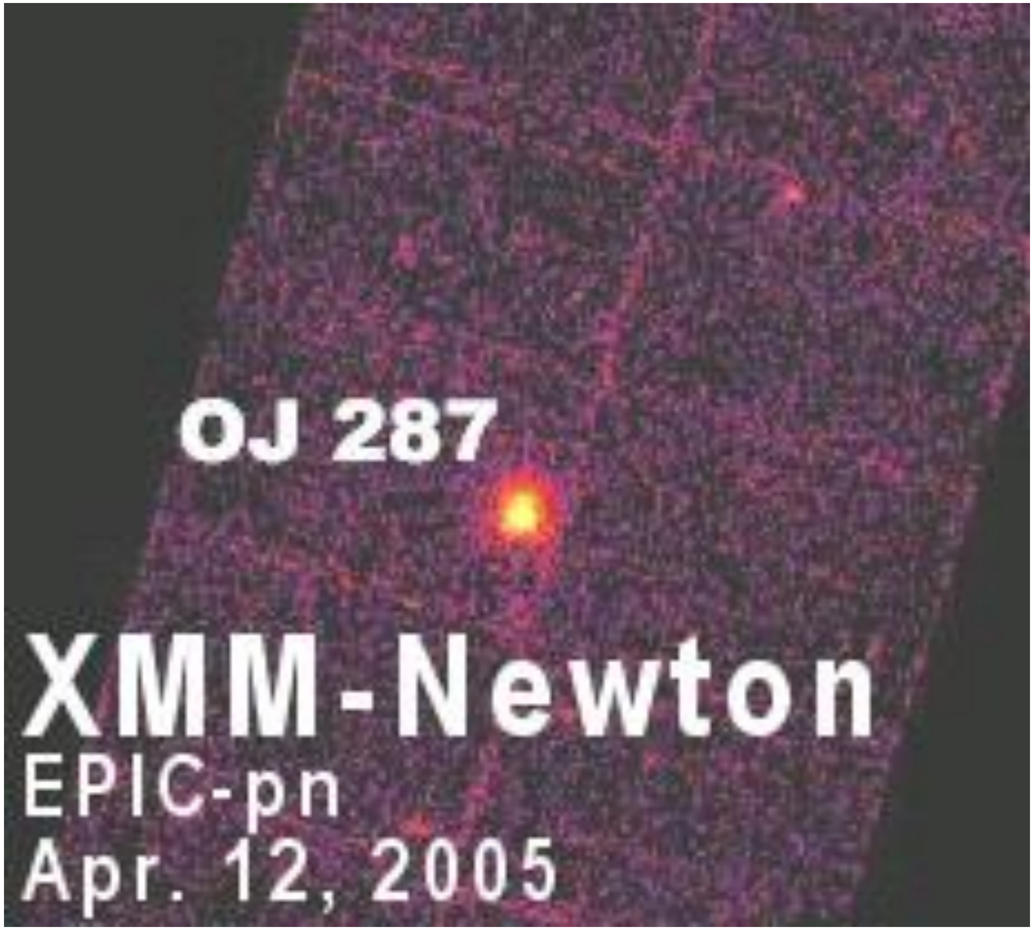


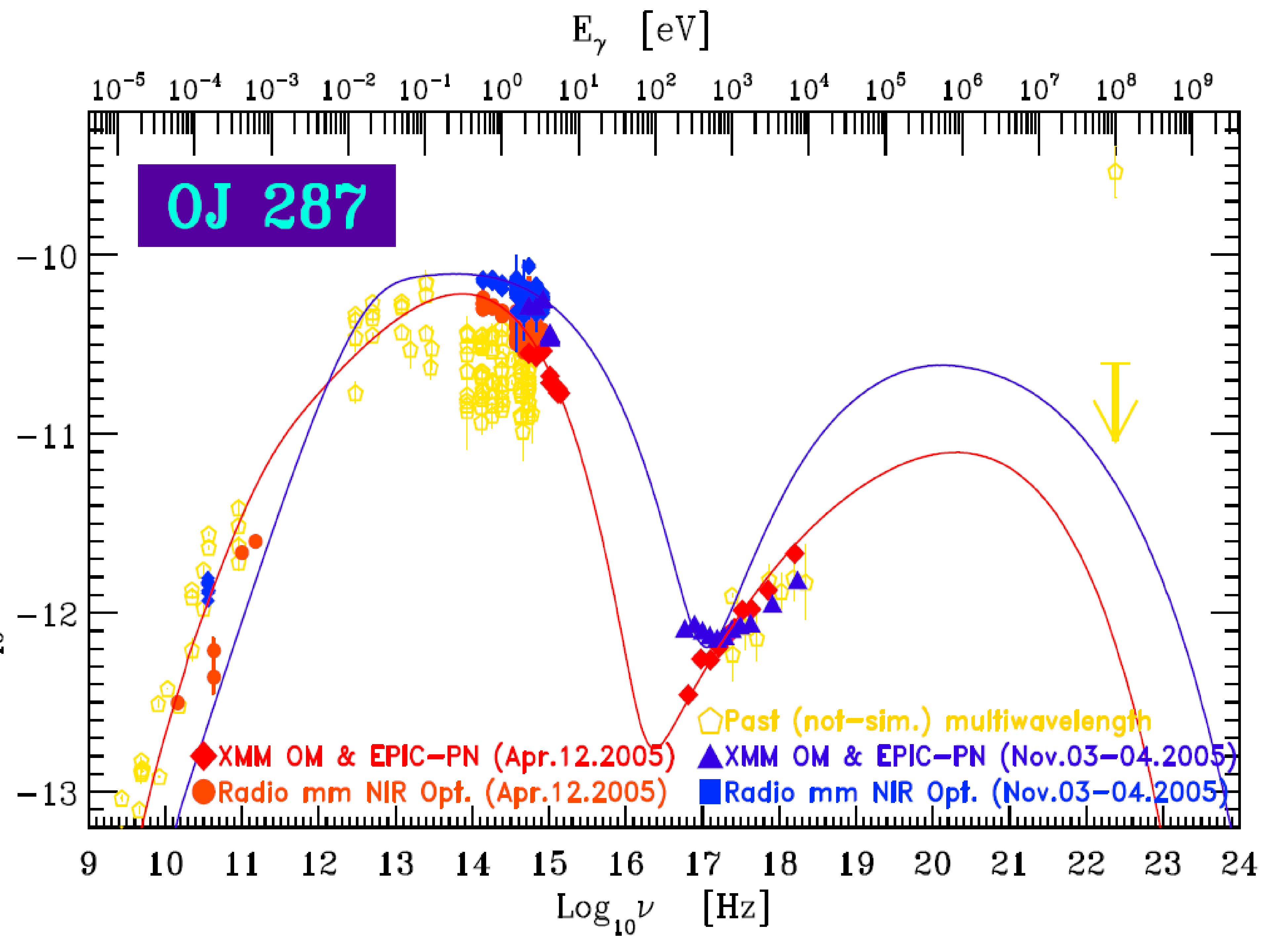
Beginning of 1947 outburst
at 1947.282
Flux mJy
Day in April 1947
Beginning of 2005 outburst
at 2005.74
Flux mJy
Year
Beginning of 1984 outburst
at 1984.14
Flux mJy
Day in February 1984
Beginning of 1913 outburst
at 1912.97
Flux mJy
Year

Rossi X-ray Timing Experiment: detections by quarter year

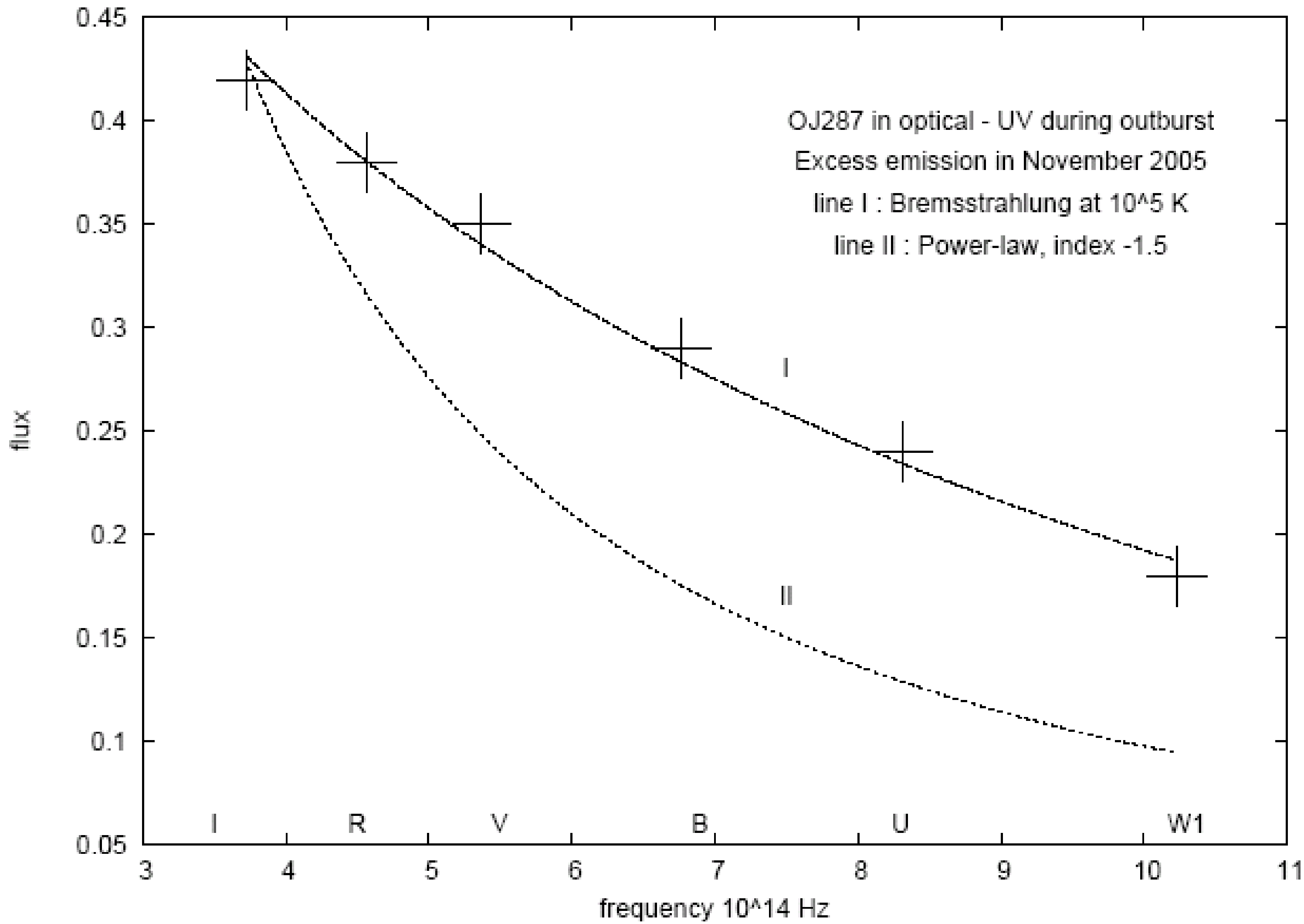


No outburst in hard X-rays; outburst in soft X-rays





E_γ [eV]
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}
OJ 287
−10
−11
−12
−13
Past (not-sim.) multiwavelength
XMM OM & EPIC-PN (Apr.12.2005)
XMM OM & EPIC-PN (Nov.03-04.2005)
Radio mm NIR Opt. (Apr.12.2005)
Radio mm NIR Opt. (Nov.03-04.2005)
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
$\mathrm{Log}_{10}\nu$ [Hz]



OJ287 in optical - UV during outburst
Excess emission in November 2005
line I : Bremsstrahlung at 10^5 K
line II : Power-law, index -1.5
flux
frequency 10^14 Hz
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
3
4
5
6
7
8
9
10
11
I
II
I
R
V
B
U
W1

$$t_d = 0.75 \pm 0.04$$

the time lag from the emergence of the hot gas to the moment at which it becomes transparent is

$$t_d \propto M_{\rm sec}^{26/21} v_{\rm rel}^{-355/84} h^{13/21} n^{102/112} . \qquad (13)$$

PROPERTIES OF ACCRETION DISK

R (pc)	log (T) (K)	log (h) (cm)	log (n) (cm^{-3})
0.01775......	5.46	15.49	14.18

$\alpha_g = 1$ $\dot{m}/\dot{m}_{\rm edd} = 0.1$ $t_d = 1$

Radio position angle

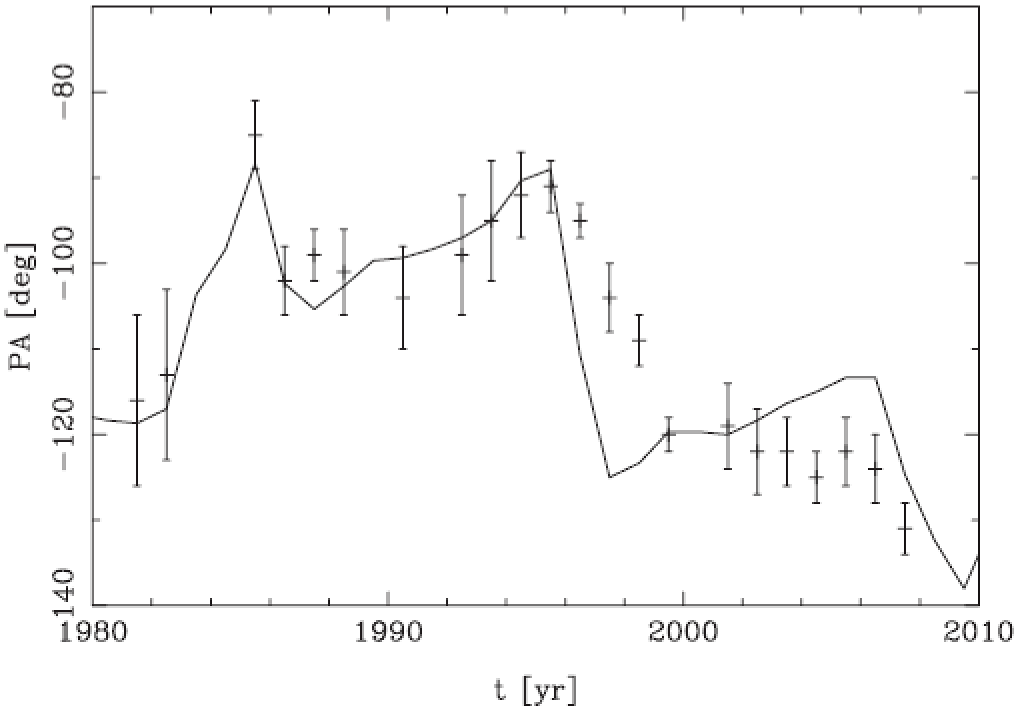
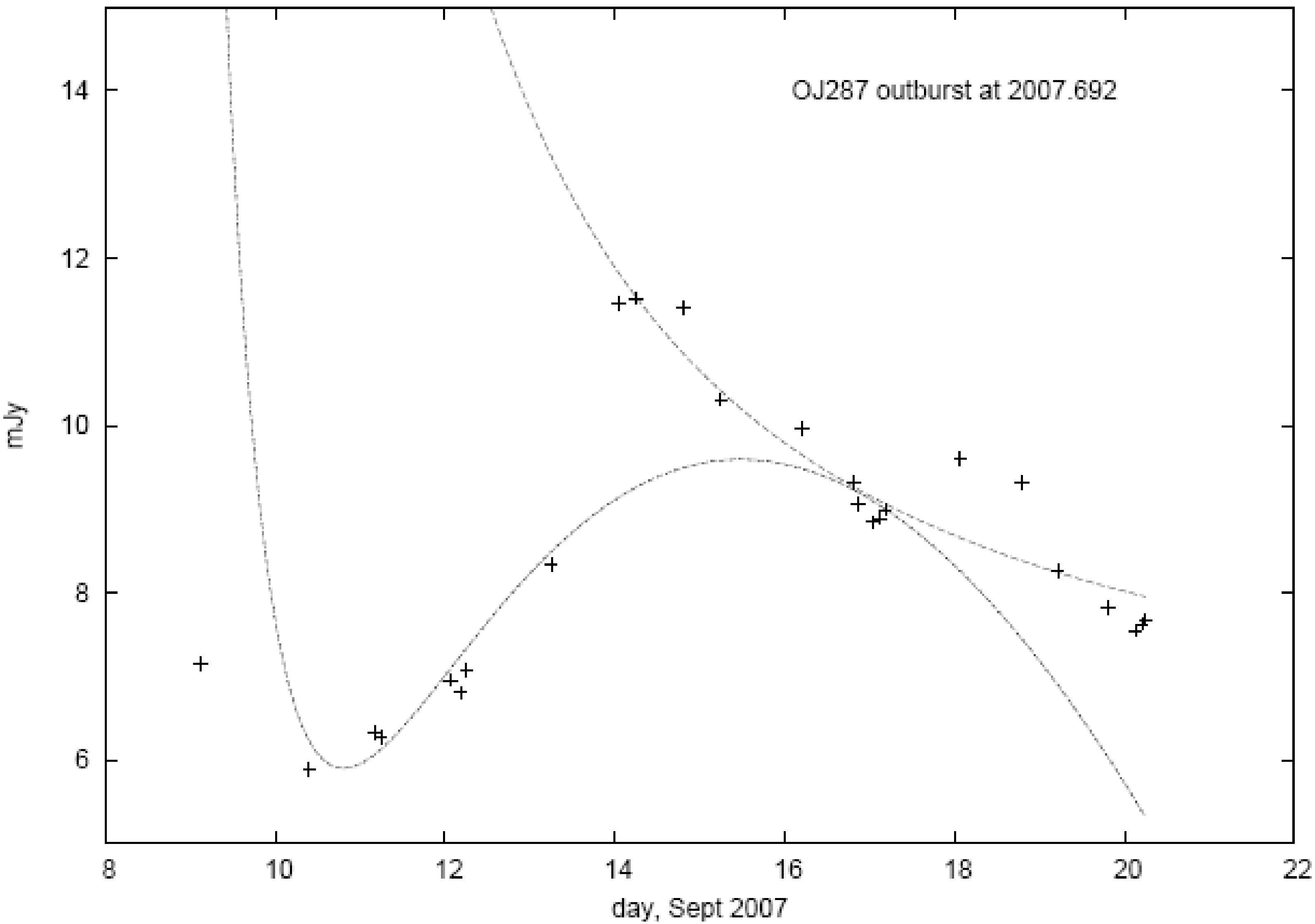


Figure8. The jet of OJ287 has been observed in radio since early 1980s, and its direction in the sky has been found to vary considerably. The figure illustrates the position angle of the radio jet as a function of time (observations) as well as the theoretical position angle calculated from the varying viewing angle. There is a good match with the data when a time delay is applied, and the basic viewing angle is chosen optimally.



OJ287 outburst at 2007.692
mJy
14
12
10
8
6
8
10
12
14
16
18
20
22
day, Sept 2007