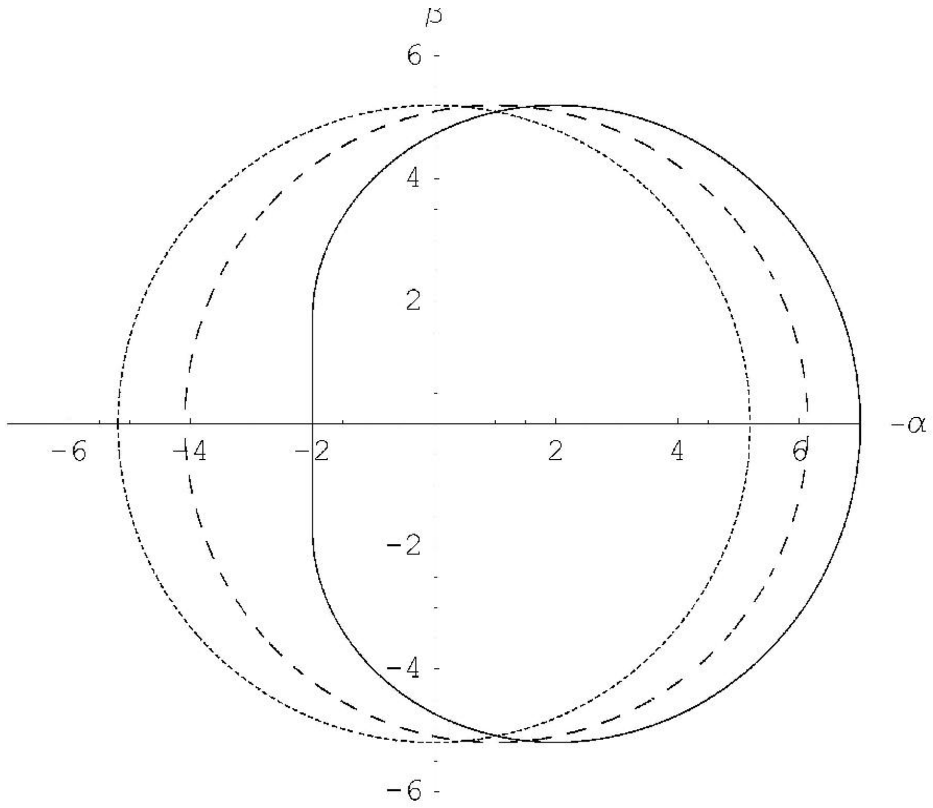

Fig. 2. Mirages around black hole for equatorial position of distant observer and different spin parameters. The solid line, the dashed line and the dotted line correspond to $a = 1, a = 0.5, a = 0$ correspondingly

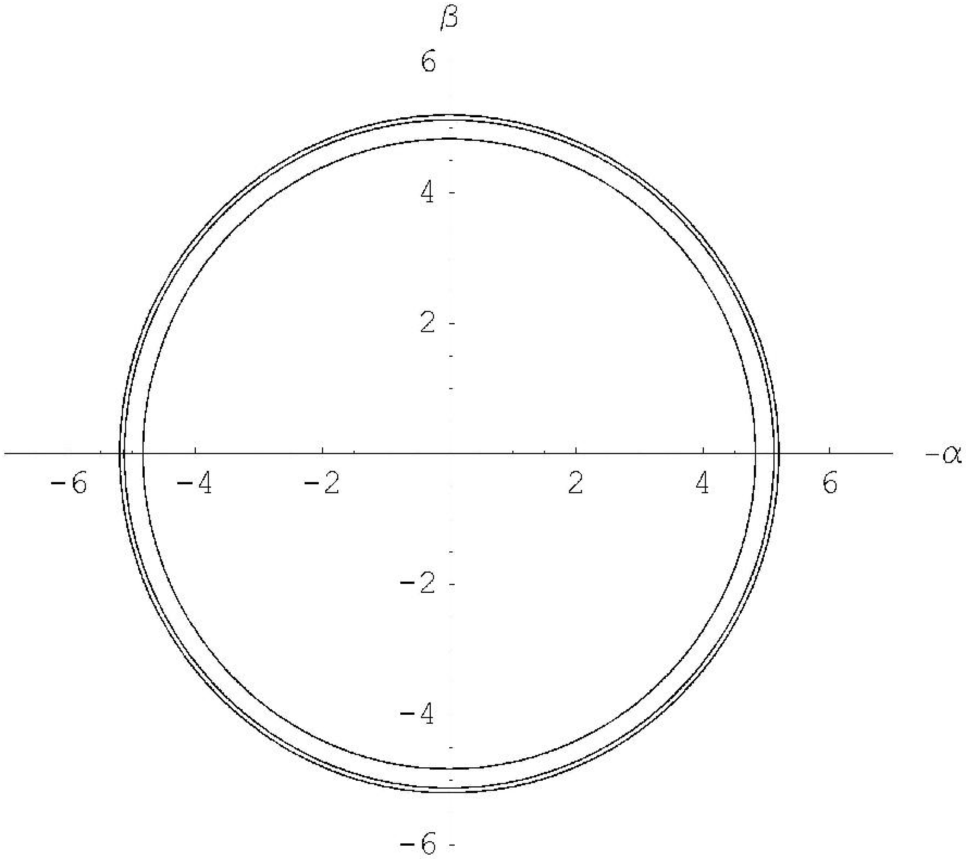

Fig. 3. Mirages around a black hole for the polar axis position of distant observer and different spin parameters ($a = 0, a = 0.5, a = 1$). Smaller radii correspond to greater spin parameters.

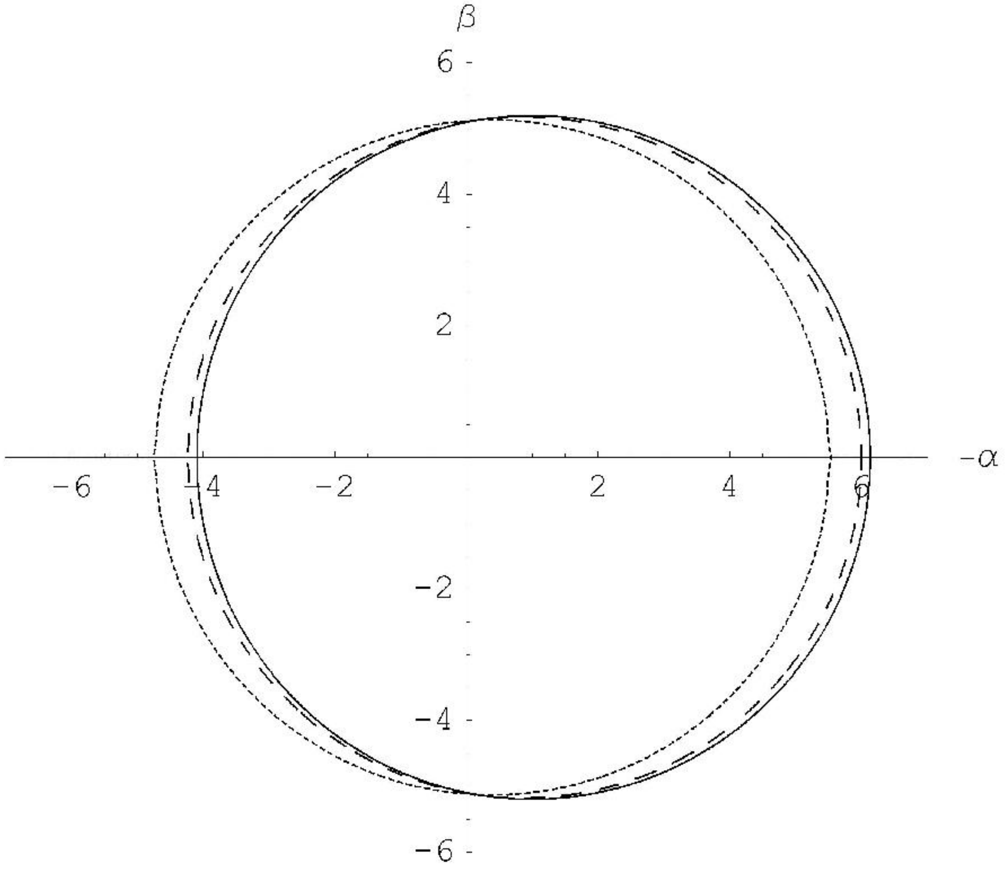

Fig. 4. Mirages around black hole for different angular positions of a distant observer and the spin $a = 0.5$. Solid, dashed and dotted lines correspond to $\theta_0 = \pi/2, \pi/3$ and $\pi/8$, respectively.

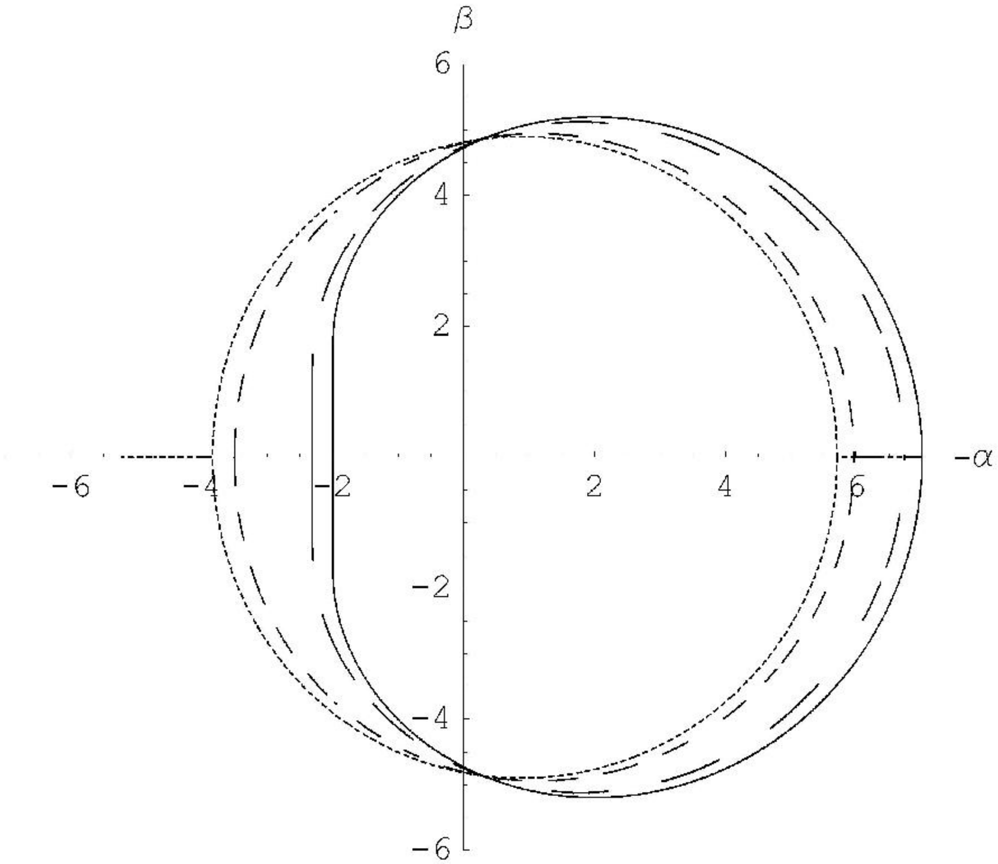

Fig. 5. Mirages around black hole for different angular positions of a distant observer and the spin $a = 1$. Solid, long dashed, short dashed and dotted lines correspond to $\theta_0 = \pi/2, \pi/3, \pi/6$ and $\pi/8$, respectively.

Direct Measurements of Black Hole Charge with Future Astrometrical Missions

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Abstract. Recently, Zakharov et al. (2005a) considered the possibility of evaluating the spin parameter and the inclination angle for Kerr black holes in nearby galactic centers by using future advanced astrometrical instruments. A similar approach which uses the characteristic properties of gravitational retro-lensing images can be followed to measure the charge of Reissner-Nordström black hole. Indeed, in spite of the fact that their formation might be problematic, charged black holes are objects of intensive investigations. From the theoretical point of view it is well-known that a black hole is described by only three parameters, namely, its mass M, angular momentum J and charge Q. Therefore, it would be important to have a method for measuring all these parameters, preferably by model independent way. In this paper, we propose a procedure to measure the black hole charge by using the size of the retro-lensing images that can be revealed by future astrometrical missions. A discussion of the Kerr-Newmann black hole case is also offered.

In this paper we focus on the possibility to measure the black hole charge as well and we present an analytical dependence of mirage size on the black hole charge. Indeed, future space missions like Radioastron in radio band or MAXIM in X-ray band have angular resolution close to the shadow size for massive black holes in the center of our and nearby galaxies.

2. Basic Definitions and Equations

The expression for the Reissner - Nordström metric in natural units ($G = c = 1$) has the form

$$ds^2 = -(1 - 2M/r + Q^2/r^2)dt^2 + (1 - 2M/r + Q^2/r^2)^{-1}dr^2 + r^2(d\theta^2 + sin^2\theta d\phi^2). \quad (1)$$

$$R(r_{max}) = 0, \qquad \frac{\partial R}{\partial r}(r_{max}) = 0, \tag{6}$$

as it was done, for example, by Chandrasekhar (1983) to solve similar problems.

Introducing the notation $\xi^2 = l, Q^2 = q$, we obtain

$$R(r) = r^4 - lr^2 + 2lr - qr. \tag{7}$$

The discriminant Δ of the polynomial $R(r)$ has the form (as it was shown by Zakharov (1991a,b, 1994a)):

$$\Delta = 16l^3[l^2(1-q) + l(-8q^2 + 36q - 27) - 16q^3]. \tag{8}$$

The polynomial $R(r)$ thus has a multiple root if and only if

$$l^3[l^2(1-q) + l(-8q^2 + 36q - 27) - 16q^3] = 0. \tag{9}$$

Excluding the case $l = 0$, which corresponds to a multiple root at $r = 0$, we find that the polynomial $R(r)$ has a multiple root for $r \geq r_+$ if and only if

$$l^2(1-q) + l(-8q^2 + 36q - 27) - 16q^3 = 0. \tag{10}$$

If $q = 0$, we obtain the well-known result for a Schwarzschild black hole (Misner, Thorne and Wheeler 1973; Wald 1984; Lightman et al. 1975), $l = 27$, or $L_{cr} = 3\sqrt{3}$. If $q = 1$, then $l = 16$, or $L_{cr} = 4$, which also corresponds to numerical results given by Young (1976).

The photon capture cross section for an extreme charged black hole turns out to be considerably smaller than the capture cross section of a Schwarzschild black hole. The critical value of the impact parameter, characterizing the capture cross section for a Reissner - Nordström black hole, is determined by the equation (Zakharov 1991a,b, 1994a)

$$l = \frac{(8q^2 - 36q + 27) + \sqrt{(8q^2 - 36q + 27)^2 + 64q^3(1-q)}}{2(1-q)}. \tag{11}$$

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As it was explained by Zakharov et al. (2005a,b) this leads to the formation of shadows described by the critical value of L_{cr} or, in other words, in the spherically symmetric case, shadows are circles with radii L_{cr}. Therefore, measuring the shadow size, one could evaluate the black hole charge in black hole mass units M.

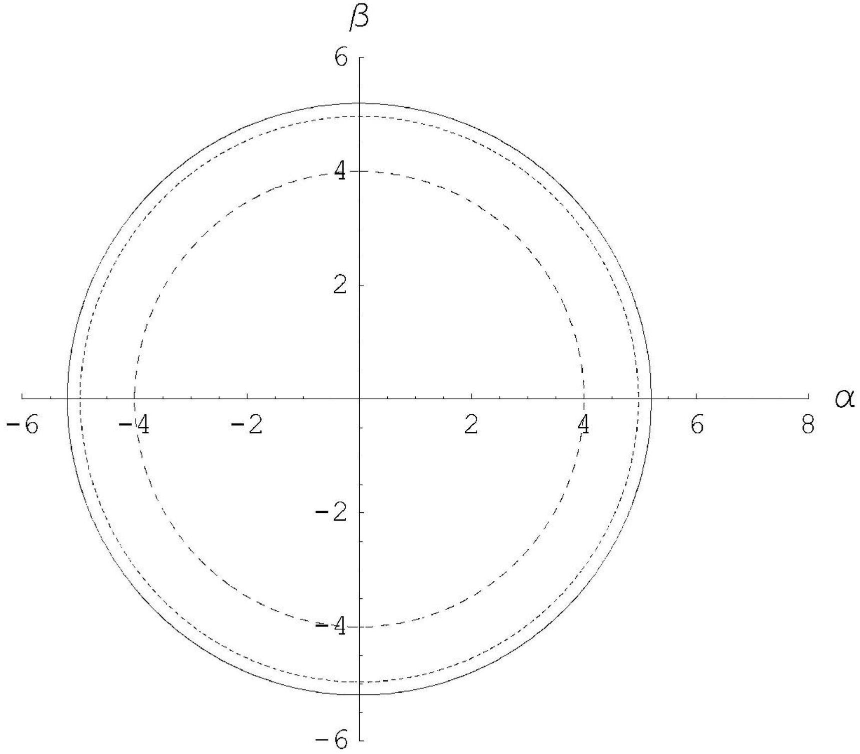

Fig. 1. Shadow (mirage) sizes are shown for selected charges of black holes $Q = 0$ (solid line), $Q = 0.5$ (short dashed line) and $Q = 1$ (long dashed line).

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LETTERS

A size of ~1 AU for the radio source Sgr A* at the centre of the Milky Way

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Although it is widely accepted that most galaxies have supermassive black holes at their centres[1–3], concrete proof has proved elusive. Sagittarius A* (Sgr A*)[4], an extremely compact radio source at the centre of our Galaxy, is the best candidate for proof[5–7], because it is the closest. Previous very-long-baseline interferometry observations (at 7 mm wavelength) reported that Sgr A* is ~2 astronomical units (AU) in size[8], but this is still larger than the 'shadow' (a remarkably dim inner region encircled by a bright ring) that should arise from general relativistic effects near the event horizon of the black hole[9]. Moreover, the measured size is wavelength dependent[10]. Here we report a radio image of Sgr A* at a wavelength of 3.5 mm, demonstrating that its size is ~1 AU. When combined with the lower limit on its mass[11], the lower limit on the mass density is $6.5 \times 10^{21} M_\odot \, \mathrm{pc}^{-3}$ (where $M_\odot$ is the solar mass), which provides strong evidence that Sgr A* is a supermassive black hole. The power-law relationship between wavelength and intrinsic size (size ∝ wavelength$^{1.09}$) explicitly rules out explanations other than those emission models with stratified structure, which predict a smaller emitting region observed at a shorter radio wavelength.

Past very-long-baseline interferometry (VLBI) observations[12–16] of Sgr A* have revealed an east–west elongated structure whose apparent angular size at longer wavelengths is dominated by the interstellar scattering angle, that is, $\Theta_{\mathrm{obs}} = \Theta_{\mathrm{obs}}^{1\,\mathrm{cm}} \lambda^2$, where Θ_{obs} is the observed size in milliarcseconds (mas) at wavelength λ in cm, and equals $\Theta_{\mathrm{obs}}^{1\,\mathrm{cm}}$ at 1 cm. Thus, VLBI observations at shorter millimetre wavelengths, where the intrinsic structure of Sgr A* could become comparable to the pure scattering size, are expected to show deviations of the observed size from the scattering law. This has been demonstrated by the recent detection of the intrinsic size at 7 mm (ref. 8). On 20 November 2002, we successfully carried out an observation of Sgr A* with the Very Long Baseline Array (VLBA) at its shortest wavelength of 3.5 mm (ref. 10). Our observation, with the steadily improved performance of the VLBA system, has produced the first (to our knowledge) high-resolution image of Sgr A* made at 3.5 mm (Fig. 1), which exhibits an elongated structure too.

To yield a quantitative description of the observed structure, we tried a model fitting procedure[17] in which the amplitude closure relation is applied. Compared to the conventional VLBI

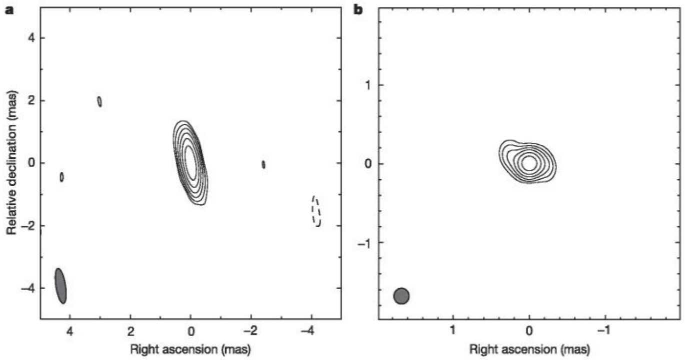

Figure 1 | High-resolution VLBI image of Sgr A* at 3.5 mm obtained with the VLBA on 20 November 2002. The observations were flexibly scheduled to ensure good weather conditions at most sites, and the data were recorded at the highest possible recording rate of 512 Mbit s^{-1}. Standard visibility amplitude calibration including the elevation-dependent opacity correction was done, and the final image was obtained after several iterations of the self-calibration and cleaning procedures. The calibrated total flux density is about 1.2 Jy. **a**, A uniformly weighted image with the restoring beam (indicated at the lower left corner) of 1.13 mas × 0.32 mas at 9°. The peak flux density is 1.08 Jy beam^{-1}. Contour levels are drawn at $3\sigma \times (-1, 1, 2, 4, 8, 16, 32)$; $3\sigma = 17.5$ mJy beam^{-1}. **b**, A super-resolution image with a circular beam of 0.20 mas from which an east–west elongated structure can be seen (see Table 1). Note the different scales. The contour levels are the same as that in **a** with the corresponding peak flux density of 1.01 Jy beam^{-1}.

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LETTERS

Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

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The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation[1]. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun[2,3]. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering[4–7]. Here we report observations at a wavelength of 1.3 mm that set a size of 37^{+16}_{-10} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A* emission may not be centred on the black hole, but arises in the surrounding accretion flow.

The proximity of Sgr A* makes the characteristic angular size scale of the Schwarzschild radius ($R_{\mathrm{Sch}} = 2GM/c^2$) larger than for any other black hole candidate. At a distance of ~8 kpc (ref. 8), the Sgr A* Schwarzschild radius is 10 μas, or 0.1 astronomical unit (AU). Multi-wavelength monitoring campaigns[9–11] indicate that activity on scales of a few R_{Sch} in Sgr A* is responsible for observed short-term variability and flaring from radio to X-rays, but direct observations of structure on these scales by any astronomical technique has not been possible. Very-long-baseline interferometry (VLBI) at 7 mm and 3.5 mm wavelength shows the intrinsic size of Sgr A* to have a wavelength dependence, which yields an extrapolated size at 1.3 mm of 20–40 μas (refs 6, 7). VLBI images at wavelengths longer than 1.3 mm, however, are dominated by interstellar scattering effects that broaden images of Sgr A*. Our group has been working to extend VLBI arrays to 1.3 mm wavelength, to reduce the effects of interstellar scattering, and to utilize long baselines to increase angular resolution with a goal of studying the structure of Sgr A* on scales commensurate with the putative event horizon of the black hole. Previous pioneering VLBI work at 1.4 mm wavelength

uncertainties resulted in a range for the derived size of 50–170 μas (ref. 12).

On 10 and 11 April 2007, we observed Sgr A* at 1.3 mm wavelength with a three-station VLBI array consisting of the Arizona Radio Observatory 10-m Submillimetre Telescope (ARO/SMT) on Mount Graham in Arizona, one 10-m element of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in Eastern California, and the 15-m James Clerk Maxwell Telescope (JCMT) near the summit of Mauna Kea in Hawaii. A hydrogen maser time standard and high-speed VLBI recording system were installed at both the ARO/SMT and CARMA sites to support the observation. The JCMT partnered with the Submillimetre Array (SMA) on Mauna Kea, which housed the maser and the VLBI recording system and provided a maser-locked receiver reference to the JCMT. Two 480-MHz passbands sampled to two-bit precision were recorded at each site, an aggregate recording rate of 3.84×10^9 bits per second ($\mathrm{Gbit\,s^{-1}}$). Standard VLBI practice is to search for detections over a range of interferometer delay and delay rate. Six bright quasars were detected with high signal to noise on all three baselines allowing array geometry, instrumental delays and frequency offsets to be accurately calibrated. This calibration greatly reduced the search space for detections of Sgr A*. All data were processed on the Mark4 correlator at the MIT Haystack Observatory in Massachusetts.

On both 10 and 11 April 2007, Sgr A* was robustly detected on the short ARO/SMT–CARMA baseline and the long ARO/SMT–JCMT baseline. On neither day was Sgr A* detected on the CARMA–JCMT baseline, which is attributable to the sensitivity of the CARMA station being about a third that of the ARO/SMT (owing to weather, receiver temperature and aperture efficiency). Table 1 lists the Sgr A* detections on the ARO/SMT–JCMT baseline. The high signal to noise ratio, coupled with the tight grouping of residual delays and delay rates, makes the detections robust and unambiguous.

There are too few visibility measurements to form an image by the usual Fourier transform techniques; hence, we fit models to the visibilities (shown in Fig. 1). We first modelled Sgr A* as a circular Gaussian brightness distribution, for which one expects a Gaussian relationship between correlated flux density and projected baseline length. The weighted least-squares best-fit model (Fig. 1) corre-

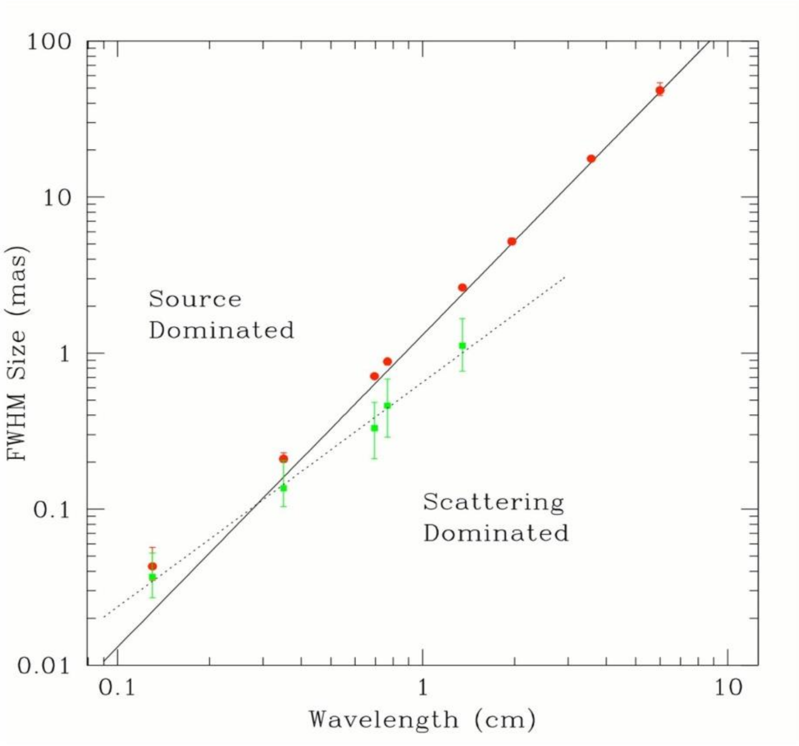
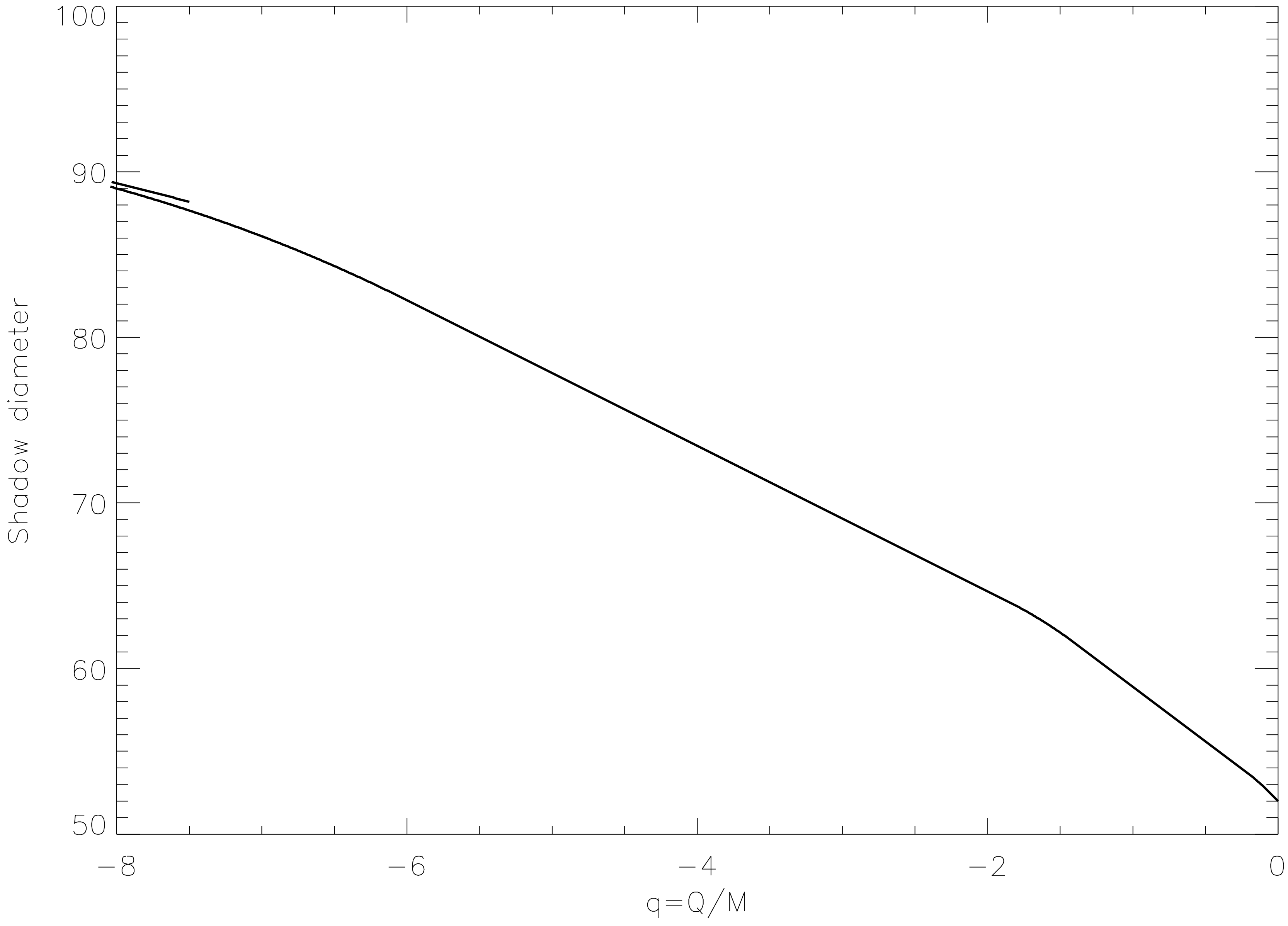
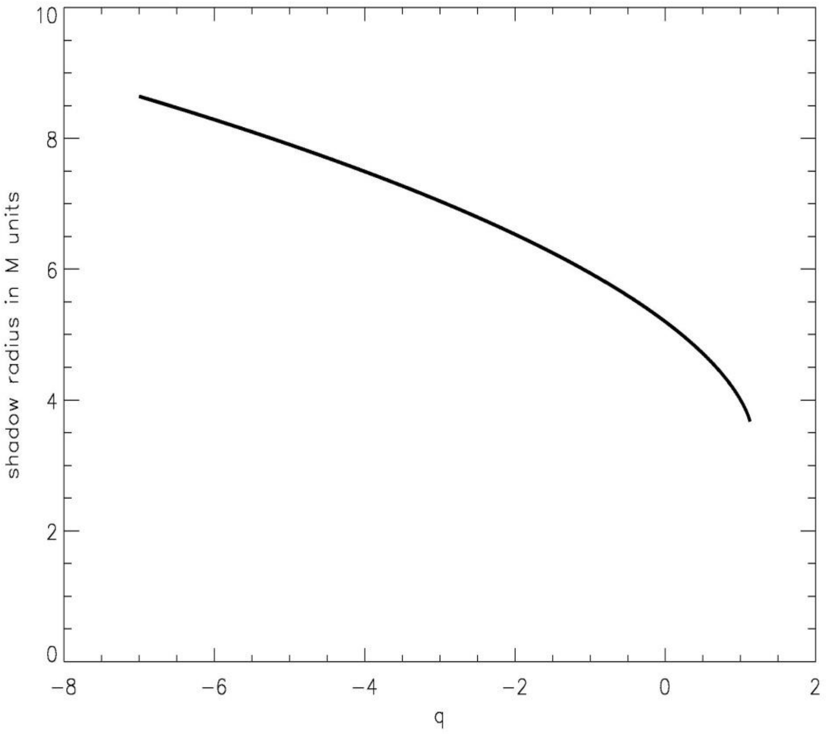
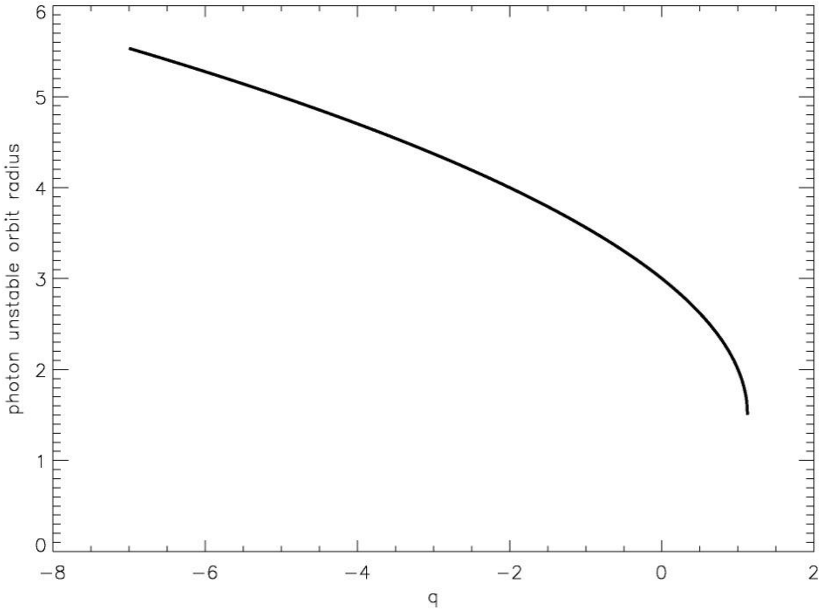


Fig 2

Figure 2 Observed and intrinsic size of Sgr A* as a function of wavelength. Red circles show major-axis observed sizes of Sgr A* from VLBI observations (all errors 3σ). Data from wavelengths of 6 cm to 7 mm are from ref. 13, data at 3.5 mm are from ref. 7, and data at 1.3 mm are from the observations reported here. The solid line is the best-fit λ^2 scattering law from ref. 13, and is derived from measurements made at $\lambda > 17$ cm. Below this line, measurements of the intrinsic size of Sgr A* are dominated by scattering effects, while measurements that fall above the line indicate intrinsic structures that are larger than the scattering size (a 'source-dominated' regime). Green points show derived major-axis intrinsic sizes from 2 cm $< \lambda <$ 1.3 mm and are fitted with a λ^α power law ($\alpha = 1.44 \pm 0.07$, 1σ) shown as a dotted line. When the 1.3-mm point is removed from the fit, the power-law exponent becomes $\alpha = 1.56 \pm 0.11$ (1σ).


Shadow diameter
100
90
80
70
60
50
−8
−6
−4
−2
0
q=Q/M


shadow radius in M units
10
8
6
4
2
0
−8
−6
−4
−2
0
2
q


photon unstable orbit radius
0
1
2
3
4
5
6
−8
−6
−4
−2
0
2
q

Recently,Bin-Nun (2010) discussed an opportunity that the black hole at the Galactic Center is described by the tidal Reissner-- Nordstrom metric which may be admitted by the Randall--Sundrum II braneworld scenario. Bin-Nun suggested an opportunity of evaluating the black hole metric analyzing (retro-)lensing of bright stars around the black hole in the Galactic Center. Doeleman et al. (2008) evaluated a shadow size
for the black hole at the Galactic Center. Measurements of the shadow size around the black hole may help to evaluate parameters of black hole metric Zakharov et al (2005). We derive an analytic expression for the black hole shadow size as a function of charge for the tidal Reissner-- Nordstrom metric. We conclude that observational data concerning shadow size measurements are not consistent with significant negative charges, in particular, the significant negative charge Q/(4M^2)=-1.6 (discussed by Bin-Nun (2010) is practically ruled out with a very probability (the charge is roughly speaking is beyond
9 σ confidence level, but a negative charge is beyond
3 σ confidence level).

RADIO INTERFEROMETER MUCH LARGER THE EARTH

"SPECTR-R" (Mission "RadioAstron")

Main scientific tasks of the mission –

syntheses of high-precision images of various Universe objects, its coordinates measurements and search their variability with the time. A fringe width of the system is up to 7 micro arc seconds.

Main characteristics of the space radio telescope

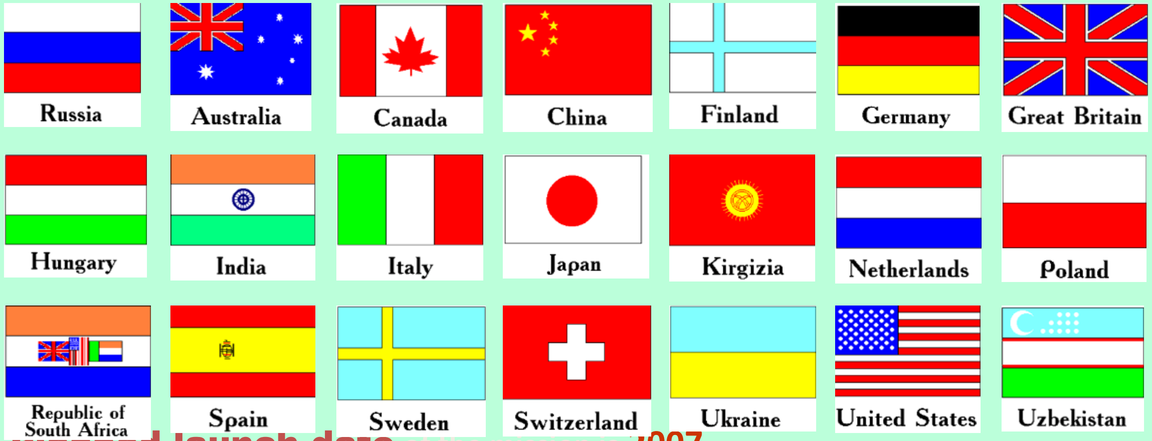
Spectral band:

wavelength (cm) -	92;	18;	6.2;	1.19-1.63
frequency (GHz) -	0.327;	1.66;	4.83;	18-26

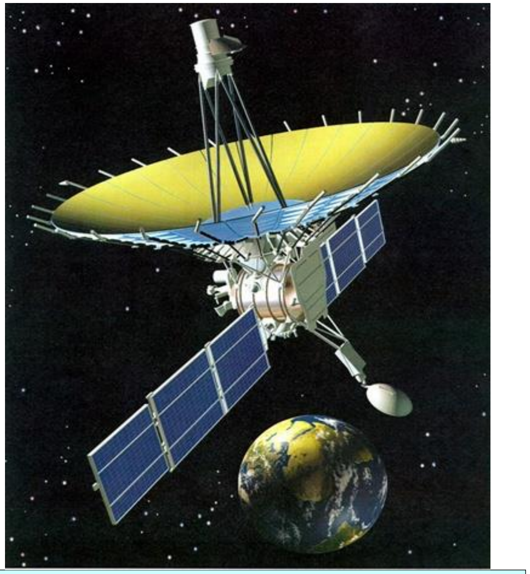
Main organizations:

on scientific complex - Astro Space Center of Lebedev Physical Institute of Russian Academy of Science;

of spacecraft - Lavochkin Research Production Association of Russian Space Agency.

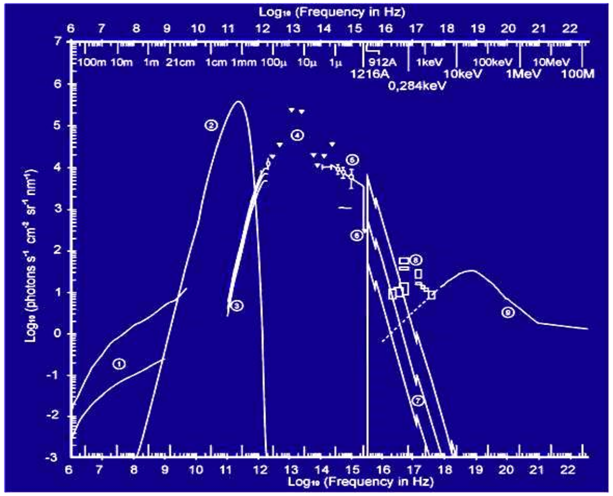


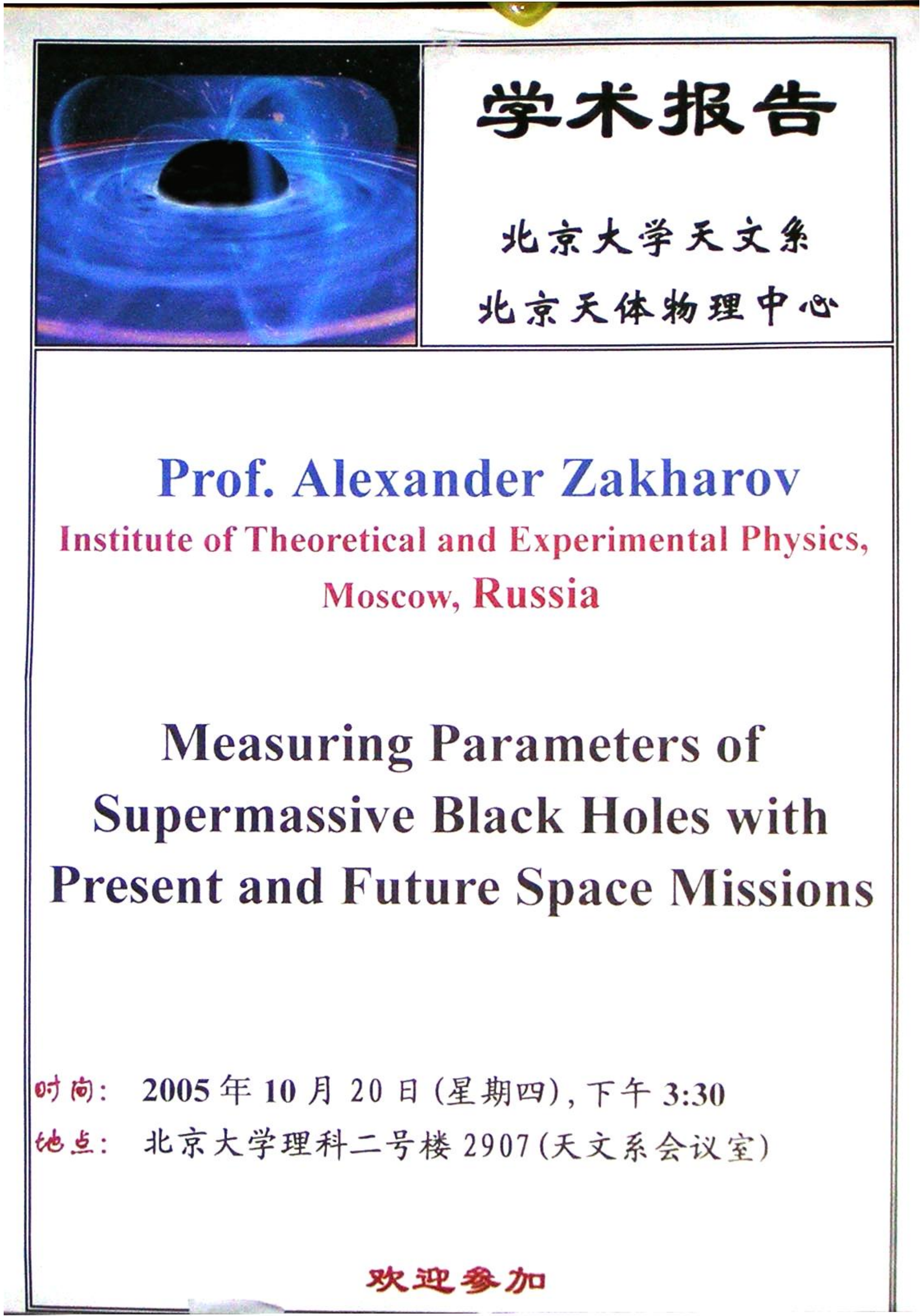
Planned launch date of the mission is 2007.



The orbit of the mission :

apogee -	310 000 - 370 000 km
perigee -	10 000 - 70 000 km
declination -	51.6 °
period variation -	7 - 10 days
Guarantied time of activity -	5 years
Scientific payload mass -	2100 kg
Pointing accuracy of radio telescope -	35"





学术报告

北京大学天文系

北京天体物理中心

Prof. Alexander Zakharov

Institute of Theoretical and Experimental Physics,
Moscow, Russia

Measuring Parameters of Supermassive Black Holes with Present and Future Space Missions

时间: 2005年10月20日(星期四),下午3:30

地点: 北京大学理科二号楼2907(天文系会议室)

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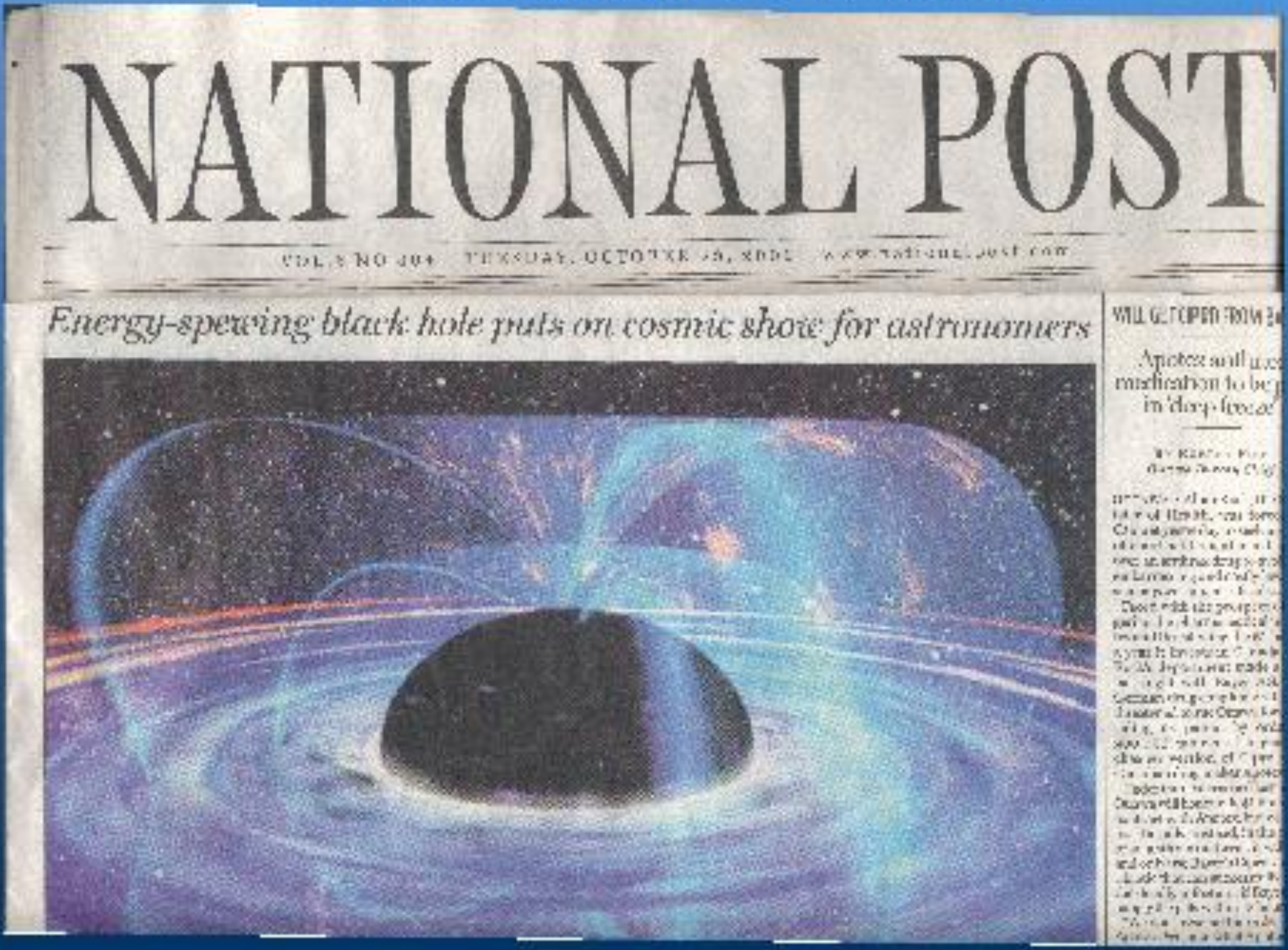
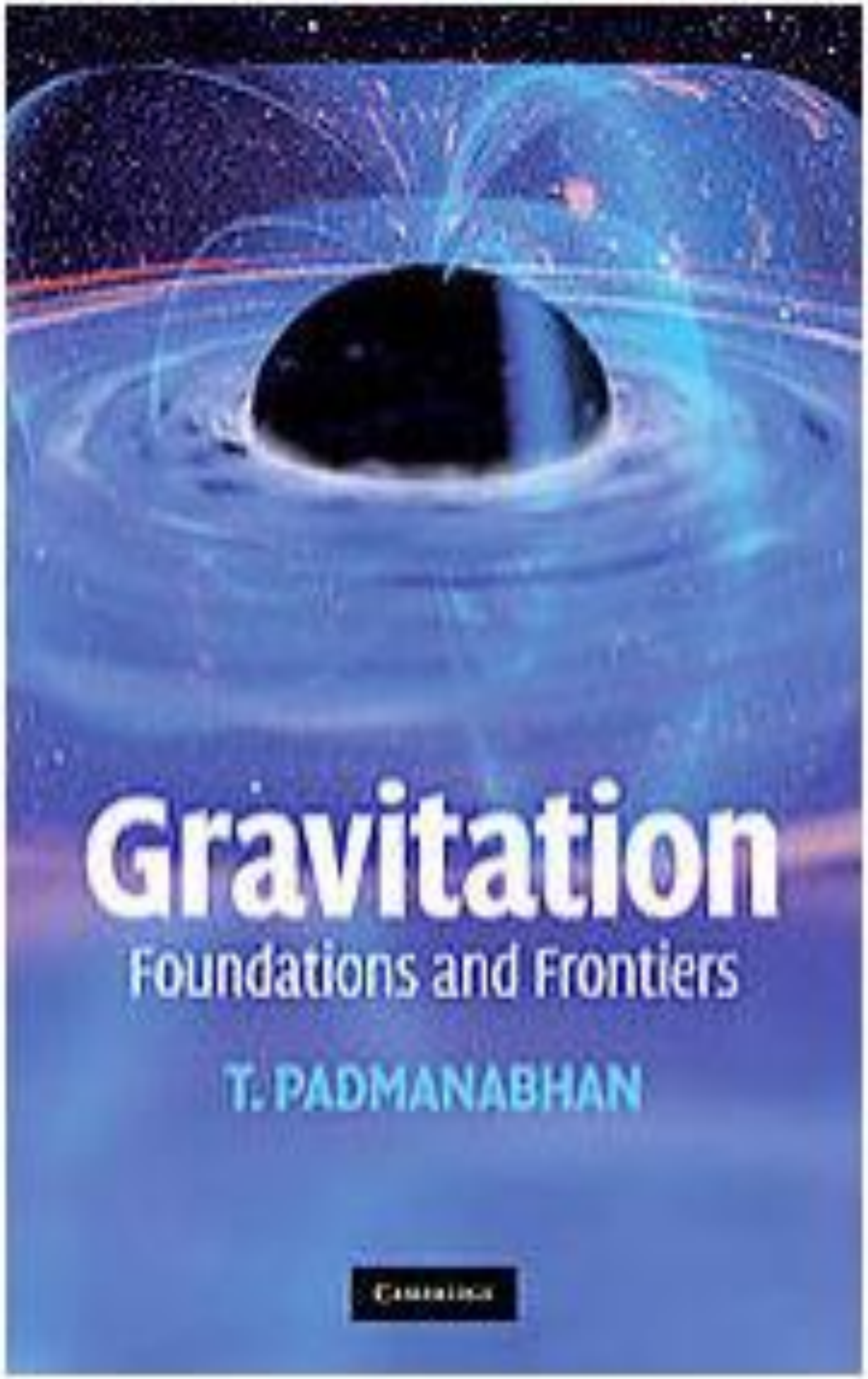
What is a black hole?

Everyone already seems to know!



NATIONAL POST

Energy-spewing black hole puts on cosmic show for astronomers



Gravitation

Foundations and Frontiers

T. PADMANABHAN

CAMBRIDGE