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Mass and spin of the Sgr A* supermassive black hole determined from flare lightcurves and flare start times

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Abstract. The analysis of the Sgr A* X-ray lightcurve of March/April 2007 obtained with *XMM-Newton* reveals periodicities in the start-times of the flares. The same periodicities were reported earlier from brightness modulations of the lightcurves both in the X-rays as well as in the near-infrared. The frequency pattern can consistently be attributed to epicyclic oscillations of matter and the frequency with which light is circling around the black hole. Accordingly, the center of our Galaxy would contain a black hole with a mass of $(4.9\pm0.1)\times10^{6} M_{\odot}$, rotating almost maximally with a spin parameter of a = 0.9959±0.0005. The oscillations arise at a radius, which is 1.13 times larger than the radius of the innermost stable circular orbit.

Key words. black hole physics — Galaxy: center — infrared: general — X-rays: general — X-rays: individual (Sgr A*)

1. Introduction

The center of our Galaxy is suspected to contain a supermassive black hole. Observationally this conjecture is based on the analysis of motions and orbit sizes of stars moving around some central mass (Schödel et al. 2002; Ghez et al. 2005; Gillessen et al. 2009). These observations suggest the presence of a fairly small volume containing a mass of several million solar masses. Mass and spin of the black hole have also been estimated from quasi-periodic oscillations (Abramowicz et al. 2004; Aschenbach et al. 2004; Aschenbach 2004) which have been suggested to be present in the near-infrared (Genzel et al. 2003) and X-ray (Aschenbach et al. 2004) lightcurves of Sgr A*. These candidate periods are suspect because of their enhanced power spectral density in at least three Sgr A* observations, which include the October 26, 2000 (*Chandra*, Baganoff et al. 2001), the October 3, 2002 (*XMM-Newton*, Porquet et al. 2004) and the near-infrared (NIR) observations of June 16, 2003 (Genzel et al. 2003). These observations were particularly important because they showed fairly large outbursts of Sgr A*. I have summarized the results, and I have proposed candidate periods, which are 110 s, 219 s and 1173 s (Aschenbach et al. 2004). Later measurements, both in the NIR and the X-ray band, were not conclusive. Mostly, there was no indication of a period at all, but if a time structured signal was suggested by the data, it happened to

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be close to the candidate period of 1100 s, i.e. 1330 s (Bélanger et al. 2006), ~1500 s (Meyer et al. 2008). However, each one of these observations, taken as a single event, was considered not to be of that significance which would justify an unambiguous claim of the detection of a period. But the fact that these coincidences among the observations exist as far as the putative periods are concerned, is encouraging further study.

The indication of more than one period in the lightcurve data suggests the possibility that the lightcurve is modulated not by just one outstanding period, but that the signal is actually modulated by one ore even more frequencies. So far, the analyses had to deal with lightcurves which were usually subject to a large amount of noise. Therefore I took the opportunity to analyse the starting times of a sequence of flares which were observed with *XMM-Newton* between 31 March and 5 April 2007, which in principle provides an independent access to periodic patterns.

2. Data and analysis

In a recent paper Porquet et al. (2008) reported for the first time a high-level X-ray flaring activity of Sgr A* observed with *XMM-Newton* between 31 March and 5 April 2007. Five flares in a row were detected. Their start-times were assessed quantitatively in a very elegant way by Porquet et al. (2008) and were determined to 291913503, 292051530, 292073530, 202084630, 292092330 in seconds relative to the clock readings on-board of *XMM-Newton*. The shortest separation between any two flares is 7700 s, and 178827 s is the widest interval. Given these times I checked each interval between any two of the flares for accommodating, as closely as possible, a natural number of trains of a trial period covering the range from 10 s to 8000 s with 1 ms spacing, i.e. $\sim 8\times10^6$ periods were checked. The choice of the time intervals is somewhat arbitrary; one can use the time difference between two consecutive events or one can choose the time difference measured against a reference, i.e. the first flare, the second flare, etc. I decided to take all possibilities into account, which for five flares makes 10 measurements. It is obvious that these 10 time interval measurements are not independent of each other, but this procedure tends to reduce any biases in the measurements, e.g. large measurement errors for the one or other start-time. The problem with this approach is that this procedure is likely to produce not only some solutions but also combinations of them, because of the oversampling of the information. But eventual results can be screened for such events and eliminated afterwards.

The algorithm looks for a regular flare start-time pattern keeping in mind that most of the flares have possibly a brightness below the detection limit and are missed in the observations. The quantitative search determines the minimum residual between the observed interval and the time of either n-times or (n+1)-times of the trial period. The values of the residuals are squared and added for the 10 available intervals to the corresponding root-mean-square (rms) value and then divided by the trial period. This is a dimensionless quantity, and this quantity can take values between 0 and 0.5. The inverse of that quantity I call 'goodness of fit' (GOF), which is the ratio of the trial period and the rms deviation from this trial period for the 10 time intervals. The 'goodness of fit' versus the trial period, which I call a periodogram, is shown in Fig. 1

The periodogram shown in Fig. 1 reveals nine prominent peaks which are listed in Table 1. They appear to be grouped in a few period intervals. Most of these frequencies with a fairly high value of the GOF, are linear combinations and harmonics of the frequencies of three trial periods, i.e. P_6, P_7 and P_9 (see column 5 of Table 1). The combinations are not in the period domain, as expected from the algorithm but in the frequency domain. The agreement between the values of the combinations computed from the three frequencies selected as fundamental and the values actually measured is better than 0.6 ms in the period domain. In total, 12 events with periods greater than 100 s are found in the periodogram with GOF>15, out of which nine events are frequency combinations of those three fun-

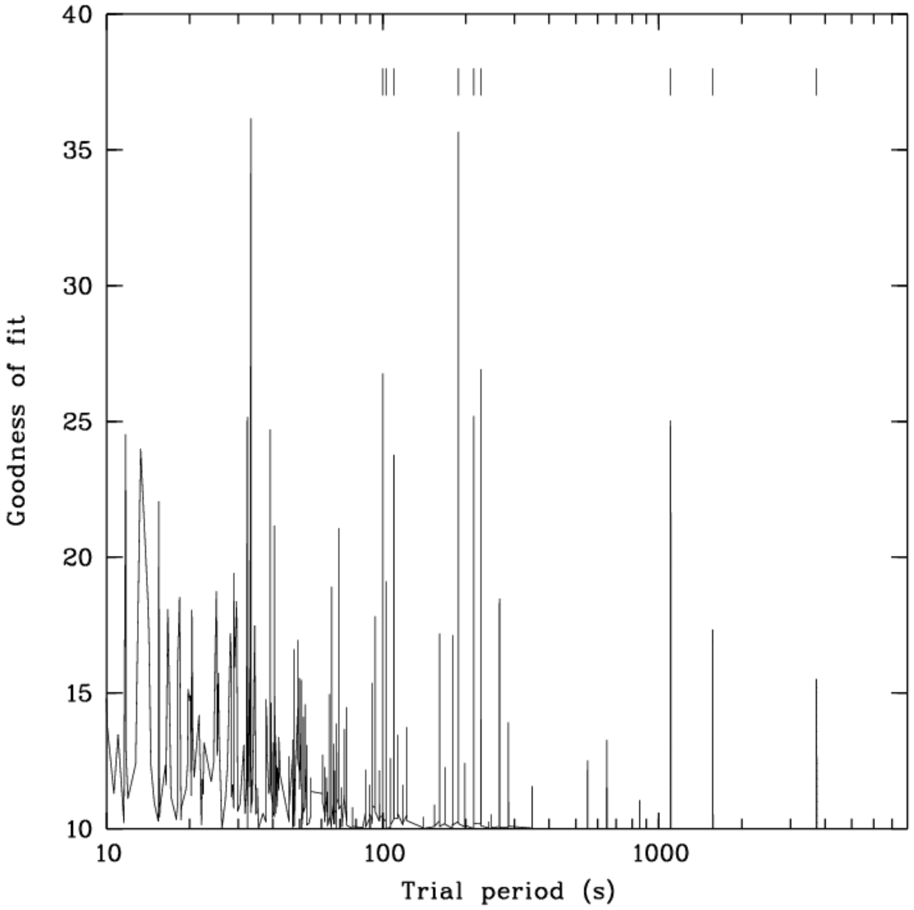

Fig. 1. Periodogram of the trial periods computed from the X-ray flare start-times of the April 2007 *XMM-Newton* observation. The ticmarks in the uppermost part of the graph delineate the positions or periods discussed in the text. Data with a 'goodness of fit' value of less than 10 are not shown. For the definition of 'goodness of fit' see the text.

damental periods, that are P_6 = 226.656 s, P_7 = 1103.893 s and P_9 = 3723.179 s. The set of the three periods between 100 s and 110 s appears to be associated with the first harmonic of P_6 (see Tab. 1). Of course, I have run a number of simulations assuming that five flares happen to occur at random over the entire observation time of 230 ks. GOF values as high as observed are found, for one or another period, quite frequently for periods less than about 100 s, but they tend to occur less frequent with increasing period, so that the periods close to 1000 s and above are somewhat outstanding. On the basis of the simulations I would not claim to have discovered a period. But the simulations also show that the simultaneous occurrence of three periods with GOF values as observed is very rare for a set of five randomly distributed flares. Furthermore I have not found any event that the algorithm I

Table 1. Periods in the X-ray flare start-times of the April 2007 *XMM-Newton* observations.

position	period P (s)	line width ΔP/P (FWHM)	frequency ν (mHz)	mode assign.
1	100.016	1.2×10^{-4}	9.9984	$2\nu_6 + \nu_7 + \nu_9$
2	102.777	1.7×10^{-4}	9.7298	$2\nu_6 + \nu_7$
3	109.980	1.5×10^{-4}	9.0926	$2\nu_6 + \nu_9$
4	188.046	1.7×10^{-4}	5.3178	$\nu_6 + \nu_7$
5	213.650	2.6×10^{-4}	4.6806	$\nu_6 + \nu_9$
6	226.656	2.6×10^{-4}	4.4120	$\underline{\nu_6}$
7	1103.893	1.4×10^{-3}	0.90589	$\underline{\nu_7}$
8	1569.126	2.8×10^{-3}	0.63730	$\nu_7 - \nu_9$
9	3723.179	7.5×10^{-3}	0.26859	$\underline{\nu_9}$

use, which is sorting time intervals in the period domain, actually seemed to have created linear combinations of frequencies in the periodogram.

In view of all that, I have not undertaken the tremendous task of calculating the probability that the observed periods are not random events, because that probability is definitely not zero. Any associated significance number just helps to decide whether to continue or stop the investigations. Because of the astonishing overlap between the periods with those, which show some enhanced power spectral density in the flares of October 26, 2000 (*Chandra*), October 3, 2002 (*XMM-Newton*) and the NIR flare on June 16, 2003 (for a summary see Aschenbach et al. 2004), I am going to continue the investigation. The periods suggested by the flare start times can be compared with the periods suggested by those three flare lightcurves. The periods are 109.980 s (110 s), 226.656 s (219 s) and 1103.893 s (1173 s). The numbers in parenthesis are the periods derived for the October 3, 2002 *XMM-Newton* flare. The numbers without and with parenthesis agree within the error bars of the *XMM-Newton* measurements. In summary, I think that these concincidences of periods justify looking into the possibility that their origin is associated with the Sgr A* black hole.

3. Procedure of frequency assignments

Lacking any alternative model, which invokes more than just one frequency, I restrict the following analysis to an attempt of assigning the observed frequencies to matter oscillations somewhere in the accretion disk. There is matter and fields generating a bright spot somewhere in the accretion disk which is orbiting the central black hole at some radial distance. This motion is described by the Kepler period P_K or Kepler frequency ν_K. The vertical epicyclic frequency (ν_v) represents matter motion perpendicular to the orbit plane, and the radial epicyclic frequency (ν_r) stands for matter motion in the plane along the radius vector. Each frequency is described by an equation (e.g., Aliev & Galtsov 1981; Aschenbach 2004), and each one of the equations contains the mass M and the spin a of the black hole and the radius R of the orbiting bright spot as the only unknowns. If ν_K, ν_v and ν_r were measured, the system parameters can be determined.

A fourth frequency becomes important for a very rapidly rotating black hole and a very tight orbit. This frequency represents the orbit light travel time $P_l = 2\,\pi\,r\,G\,M/c^3$. G stands for the gravitational constant and $r = R/r_g$ is the

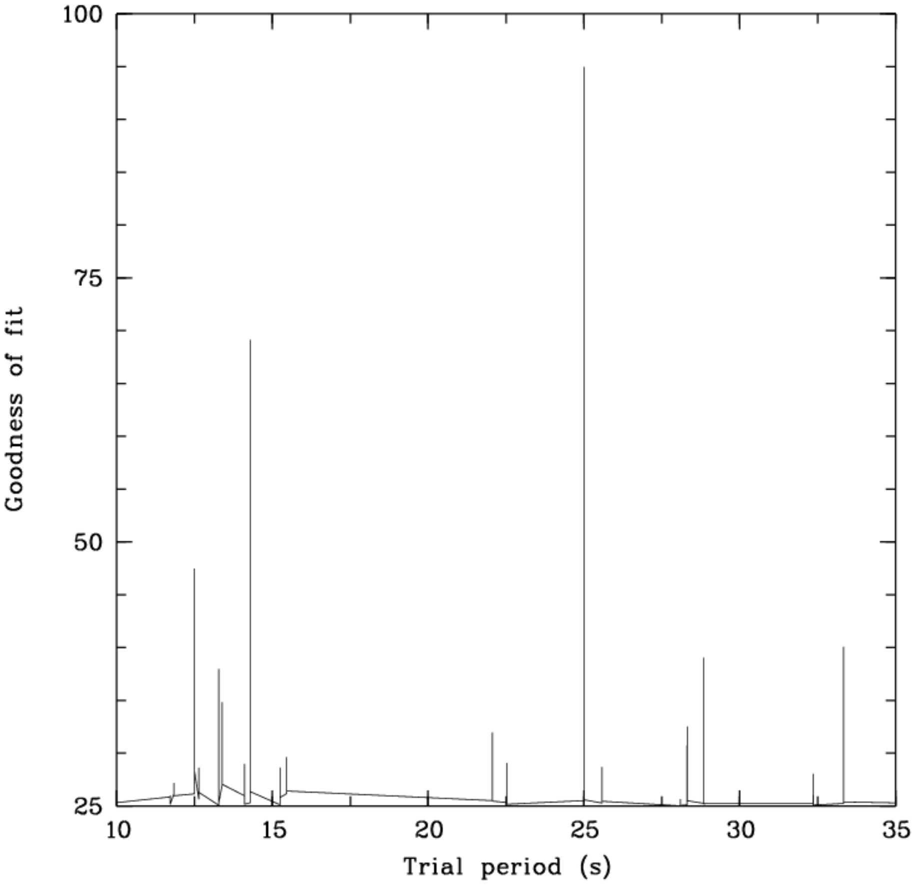

Fig. 2. Periodogram of the trial periods computed from the X-ray flare start-times of the April 2007 *XMM-Newton* observation in the range of 10 s to 35 s using a screening of 10 μs steps. Data with a 'goodness of fit' value of less than 25 are not shown.

orbit radius R expressed in units of the gravitational radius r_g. Because light is bent by gravity it can circle around a black hole once, twice or even more times if the value of a is close to one and the orbit is fairly tight (Cunningham & Bardeen 1973). Under this condition the image of the orbiting bright spot recorded by the infinitely remote observer is a short pulse in time. The observer can see the hot spot only in a very narrow space-time region, from some angular region in azimuth around the orbit. A second pulse is recorded after the next passage of the bright spot through this region. The time separation of the two pulses is the Kepler period. But before that second pulse is seen, some light, emitted at the time of the first passage of the bright spot through the critical space-time region, has completed a full orbit around the black hole, and the observer records a pulse at a time of P_l after the first Kepler passage and P_K-P_l before the bright spot has completed its second orbit around the black hole. The light from the first Kepler passage of the bright spot and that, which has circled the black hole twice, produces a pulse which, in the obervers frame, arrives at a time another 2 P_l-P_K later. For a = 1 and r = 1, P_K = 2 P_l, and there is just one period seen by the observer, which is P_l. There is no periodic time interval at all, which corresponds to the full Kepler period; the shortest period is just half of the Kepler period (Cunningham & Bardeen 1973).

In case that the spin parameter a is slightly less than one and r is slightly larger than one this degeneracy is resolved and there should be three periods available to the observer, i.e. P_l, P_K-P_l and 2 P_l-P_K, out of which 2 P_l-P_K should be very short (=0 for a = 1 and r = 1). In the present case, there appears to be no evidence in the data for a very short period with a high GOF value (c.f. Fig. 1). However, a look at the third column of Table 1 demonstrates that the FWHM of the periods with high peaks are very narrow, so that the original search with a 1 ms spacing might not be precise enough. A search with a spacing of 10 μs is shown in Fig. 2, and there is indeed an exceptionally high peak at a period of P_0 = 25.00030 s. I interprete this as the value of 2 P_l-P_K.

Besides the appearance of three periods instead of just one period, the more moderate case, as far as radius and spin are concerned, delivers individual pulses which are broader in time, have lower peak flux densities, and some halo light from other places around the orbit is being seen by the observer.

The attempts of fitting the observed periods to those which are expected from the model are most successful if the following assignments are made: P_0 is assigned to 2 P_l-P_K, $P_K/2$ to P_5, P_v to P_7 and P_r to P_9. The model contains just three parameters, which are M, a, and r. The fit to the four data points is excellent with residual relative errors of $\Delta P_0/P_0 = 4.\times10^{-7}$, $\Delta P_5/P_5 = 2.7\times10^{-3}$, $\Delta P_7/P_7 = -1.1\times10^{-3}$, and $\Delta P_9/P_9 = 2.3\times10^{-3}$. The best-fit model parameters are M = $4.9\times10^6 M_\odot$, a = 0.9959 and r = 1.487, which is 1.13 times the radius of the innermost stable circular orbit or R = 1.08×10^{12} cm in physical units. The model predicts further periods that might be observationally relevant, and which are P_l = 225.543 s and P_K-P_l = 200.543 s. Despite the excellent fit the choice of assigning $P_K/2$ to P_5 is not unambiguous; it could be assigned to P_4 or P_6, or the choice could be assigning P_l to either P_4, P_5, P_6, or even P_K-P_l, because of the small difference between P_4, P_5, and P_6. The effect of such assignment rotations of P is small on M and a; M can change by $0.1\times10^6 M_\odot$ and the spin a by 0.0005, at most.

4. Conclusions

Given the fit results above it appears that the application of the epicyclic frequency model to a very rapidly spinning black hole with matter oscillations close but outside the innermost stable orbit seems to work for Sgr A*.

The most recent value of M, the mass of the supermassive black hole in the Center of our Galaxy, can be found in the paper by Gillessen et al. (2009). They have determined a mass of M = $4.31\times10^6 M_\odot$ using the orbits of the S-stars around Sgr A* with a 1σ error band of $\pm0.36\times10^6 M_\odot$, which is due to the uncertainty in the distance determination. It should be mentioned that this value of M has grown quite a bit over the past 10 years, though. The value of $(4.9\pm0.1)\times10^6 M_\odot$ derived in this work is higher, but, including the error bars, within their 1σ limit.

The value for the spin of a = 0.9959 is high, but it is not in conflict with the 'Thorne'-limit for an accreting black hole. I note that the value derived in this work is fairly close, possibly slightly above the critical spin of a = 0.9953, above which the anomalous orbit velocity effect or 'Aschenbach' effect (Stuchlík et al. 2005) occurs (Aschenbach 2004).

Despite this apparant success there is a clear need to confirm the periods discussed in this paper, but statistical signifance should not be the ultimate ratio in our efforts but evidence, I think.

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