Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic Centre

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Most galactic nuclei are now believed to harbour supermassive black holes. Studies of stellar motions in the central few light-years of our Milky Way Galaxy indicate the presence of a dark object with a mass of \( \approx 2.6 \times 10^6 \) solar masses (refs 2, 3). This object is spatially coincident with Sagittarius A∗ (Sgr A∗), the unique compact radio source located at the dynamical centre of our Galaxy. By analogy with distant quasars and nearby active galactic nuclei (AGN), Sgr A∗ is thought to be powered by the gravitational potential energy released by matter as it accretes onto a supermassive black hole. However, Sgr A∗ is much fainter than expected in all wavebands, especially in X-rays, casting some doubt on this model. Recently, we reported the first strong evidence of X-ray emission from Sgr A∗ (ref. 6). Here we report the discovery of rapid X-ray flaring from the direction of Sgr A∗. These data provide compelling evidence that the X-ray emission is coming from accretion onto a supermassive black hole at the Galactic Centre, and the nature of the variations provides strong constraints on the astrophysical processes near the event horizon of the black hole.

Our view of Sgr A∗ in the optical and ultraviolet wavebands is blocked by the large visual extinction, \( A_V \approx 30 \) magnitudes, caused by dust and gas along the line of sight. Sgr A∗ has not been detected in the infrared due to its faintness and the bright infrared background from stars and clouds of dust. Detection of X-rays from Sgr A∗ is therefore essential to constrain the spectrum at energies above the radio-to-submillimetre band and to test the supermassive-black-hole accretion-flow paradigm.

We first observed the Galactic Centre on 21 September 1999 with the imaging array of the Advanced CCD Imaging Spectrometer (ACIS-I) aboard the Chandra X-ray Observatory and discovered an X-ray source coincident within \( 0′′.35 \pm 0′′.26 \) (1σ) of the radio source \( \sigma \). The luminosity in 1999 was very weak, \( L_X \approx 2 \times 10^{35} \) erg s\(^{-1}\) in the 2–10 keV band, after correction for the inferred neutral hydrogen absorption column \( N_H \approx 1 \times 10^{23} \) cm\(^{-2}\). This is far fainter than previous X-ray observatories could detect.

We observed the Galactic Centre a second time with Chandra/ACIS-I from 26 October 2000 22:29 through 27 October 2000 08:19 (UT), during which time we saw a source at the position of Sgr A∗ brighten dramatically for a period of \( \approx 10 \) ks. Figure 1 shows surface plots for both epochs of the 2–8 keV counts integrated over time from a \( 20′′ \times 20′′ \) region centred on the radio position of Sgr A∗. The modest peak of the integrated counts at Sgr A∗ in 1999 increased by a factor of \( \approx 7 \) in 2000, despite the 12\% shorter exposure. The peak integrated counts of the fainter features in the field show no evidence of strong variability, demonstrating that the flaring at Sgr A∗ is intrinsic to the source.

Figure 1: Surface plots of the 2–8 keV counts within a \( 20′′ \times 20′′ \) field centred on Sgr A∗ at two epochs. The data were taken with Chandra/ACIS-I on (a) 21 September 1999 and (b) 26–27 October 2000. The effective exposure times were 40.3 ks and 35.4 ks, respectively. The spatial resolution is \( 0′′.5 \) per pixel. An angle of \( 1′′ \) on the sky subtends a projected distance \( \approx 0.04 \) pc at the galactocentric distance of 8.0 kpc (ref. 30). The peak integrated counts per pixel at the position of Sgr A∗ increased by a factor of \( \approx 7 \) from the first epoch to the second, despite the slightly smaller exposure time (\( \approx 12\% \)) in the second epoch. The low-level peak a few arcseconds to the southwest of Sgr A∗ is the infrared source IRS 13, while the ridge of emission to the northwest is from a string of unresolved point sources. The fainter features in the field are reasonably consistent between the two epochs, considering the limited Poisson statistics and the fact that these stellar sources may themselves be variable; this consistency shows that the strong variations at Sgr A∗ are intrinsic to the source.

Figure 2 shows light curves of the photon arrival times from the direction of Sgr A∗ during the observation in 2000. Panels (a) and (b) show hard-band (4.5–8 keV) and soft-band (2–4.5 keV) light curves constructed from counts within an angular radius of \( 1′′.5 \) of Sgr A∗. Both bands exhibit roughly constant, low-level emission for the first \( \approx 14 \) ks, followed by an \( \approx 6\)-ks period of enhanced emission beginning with a 500-s event (4.4σ significance using 150-s bins). At 20 ks, there occurs a large-relative-amplitude flare or flares lasting \( \approx 10 \) ks, and finally a return to the low state for the remaining \( \approx 6 \) ks. About 26 ks into the observation, the hard-band light curve drops abruptly by a factor of \( \approx 5 \) within a span of \( \approx 600 \) s and then partially recovers within a period of \( \approx 1.2 \) ks. The
soft-band light curve shows a similar feature, but it appears to lag the hard-band event by a few hundred seconds and is less sharply defined.

Figure 2: Light curves of the photon arrival times and band ratios from the direction of Sgr A* on 26–27 October 2000. Panels (a) hard-band (HB = 4.5–8 keV) counts, (b) soft-band (SB = 2–4.5 keV) counts, (c) hard/soft band ratio within a circle of radius 1.5" or an annulus of inner and outer radii 0.5" and 2.5", respectively. The x-axis shows the time offset from the start of the observation at 26 October 2000 22:20 (UT). The data are shown with 1σ error bars. The single 2.8-hour period of flaring activity which we have detected so far during a total of 21 hours of observations yields a (poorly determined) duty cycle of ~1/8. Our continuing observations of this source with Chandra will permit us to refine this value. During the quiescent intervals at the beginning and end of this observation, the mean count rate in the 2–8 keV band was (6.4 ± 0.6) × 10⁻³ counts s⁻¹, consistent with the count rate we measured in 1999, which was (5.4 ± 0.4) × 10⁻³ counts s⁻¹. The detected count rate at the peak of the flare was 0.16 ± 0.01 counts s⁻¹ within a 1.5-radius extraction circle, but this is ≈ 30% less than the true incident count rate due to pile-up of X-rays in the detector during the 3.2-s integration time per CCD readout.

The ratio time series in panel (c), defined as the ratio of hard-band counts to soft-band counts, suggests the spectrum hardened during the flare. The difference between the band ratio measured at the peak of the flare and the average of the band ratios during the quiescent periods at the beginning and end of the observation is 0.63 ± 0.21 (i.e., 3σ). The peak-flare band ratio in panel (c) is affected to some extent by the effects of pile-up (see Figure 2 caption), which would tend to harden the spectrum; however, the band ratios in panel (d), which were computed using the non-piled-up data extracted from the wings of the point spread function, also show evidence for spectral hardening with 2.7σ significance. The sizes of dust-scattering halos in the Galactic Centre are typically ≳ 1" (ref. 10), so dust-scattered X-rays from the source contribute a negligible fraction of the emission within the source extraction region that we used; hence it cannot account for the spectral variations. We therefore conclude that the spectral hardening during the flare is likely to be real.

The quiescent-state spectra in 1999 and 2000 and the peak flaring-state spectrum in 2000 are shown in Figure 3. We fit each spectrum individually using a single power-law model with corrections for the effects of photoelectric absorption and dust scattering 10. The best-fit values and 90% confidence limits for the parameters of each fit are presented in the first three lines of Table 1. The column densities for the three spectra are consistent, within the uncertainties, as are the photon indices of both quiescent-state spectra. Next, we fit a double power-law model to the three spectra simultaneously, using a single photon index for both quiescent spectra, a second photon index for the flaring spectrum, and a single column density for all three spectra. The best-fit models for each spectrum from the simultaneous fits are shown as solid lines in Figure 3; the parameter values are given in the last line of Table 1. Using this model, we derive an absorption-corrected 2–10 keV luminosity of $L_X = (2.2^{+0.4}_{-0.3}) \times 10^{35}$ erg s⁻¹ for the quiescent-state emission and $L_X = (1.0^{+0.1}_{-0.1}) \times 10^{35}$ erg s⁻¹ for the peak of the flaring-state emission, or ≈ 45 times the quiescent-state luminosity. We note that previous X-ray observatories did not have the sensitivity to detect such a short-duration, low-luminosity flare in the Galactic Centre 6. The best-fit photon index $\Gamma_t = 1.3^{+0.5}_{-0.6}$ ($N(E) \propto E^{-\Gamma}$) for the flaring-state spectrum is slightly flatter than, but consistent with, systems thought to contain supermassive black holes 11.

If we view the outburst as a single event, the few-hundred-second rise/fall timescales and the 10-ks duration are consistent with the light-crossing and dynamical timescales for the inner $\lesssim 10$ Schwarzschild radii ($R_s \equiv 2GM/c^2$) of the accretion flow around a black hole of $2.6 \times 10^6$ solar masses; here $R_s$ is the radius of the black-hole event horizon (i.e., the boundary at which the escape velocity equals the speed of light), $G$ is the gravitational constant, $M$ is the mass of the black hole, and $c$ is the speed of light. While we cannot strictly rule out an unrelated contaminating source as the origin of the flare (e.g., an X-ray binary, for which little is known about such short-timescale, low-luminosity events as we have detected; W. Lewin, private communication), this explanation seems unlikely since the characteristic angular scales of the young and

| Spectrum | $N_H$ | $\Gamma_q$ | $\Gamma_t$ | $\chi^2/\nu$ |
|----------|-------|------------|------------|--------------|
| 1999 Quiescent | $5.8^{+1.3}_{-1.4}$ | $2.5^{+0.8}_{-0.7}$ | ... | 19/22 |
| 2000 Quiescent | $5.0^{+2.9}_{-2.3}$ | $1.8^{+0.7}_{-0.9}$ | ... | 7.6/12 |
| 2000 Flaring | $4.6^{+2.0}_{-1.6}$ | $1.0^{+0.8}_{-0.7}$ | ... | 12/17 |
| All | $5.3^{+0.9}_{-1.1}$ | $2.2^{+0.5}_{-0.7}$ | $1.3^{+0.5}_{-0.6}$ | 45/55 |

Best-fit parameter values and 90% confidence intervals for power-law models, corrected for photoelectric absorption and dust scattering 10. $N_H$ is the neutral hydrogen absorption column in units of $10^{22}$ H atoms cm⁻². $\Gamma_q$ and $\Gamma_t$ are the photon-number indices of the quiescent-state and peak flaring-state spectra ($N(E) \propto E^{-\Gamma}$). $\chi^2$ is the value of the fit statistic for the best-fit model and $\nu$ is the number of degrees of freedom in the fit. The parameter values for the spectrum marked “All” were derived by fitting an absorbed, dust-scattered, double power-law model to the three spectra simultaneously (see text and Figure 3).
which agrees well with infrared-derived estimates of age and that it would be fortuitously superposed on Sgr A*.

Moreover, it is not clear that X-ray binaries can be easily produced by local dust reprocessing of an iron emission line in the flaring-state spectrum.

Strong, variable X-ray emission is a characteristic property of AGN; factors of ~2–3 variations on timescales ranging from minutes to years are typical for radio-quiet AGN\(^1\). Moderate-to high-luminosity AGN (i.e., Seyfert galaxies and quasars) show a general trend of increasing variability with decreasing luminosity\(^2\). However, this trend does not extend to low-luminosity active galactic nuclei (LLAGN), which show little or no significant variability on timescales less than a day\(^3\).

Assuming the X-ray flare is from Sgr A*, it is remarkable that this source—generally thought to be the nearest and least luminous example of accretion onto a central supermassive black hole—has shown a factor of \(\approx 45\) variation that is an order of magnitude more rapid than the fastest observed variation of similar relative amplitude by a radio-quiet AGN of any luminosity class\(^4\). We note that flares of similar luminosity would be undetectable by Chandra in the nucleus of even the nearest spiral galaxy, M31. LLAGN emit \(L_X \gtrsim 10^{38}\) erg s\(^{-1}\) (ref. 14), so it should be kept in mind that the astrophysics of accretion onto even the LLAGN may differ substantially from that of Sgr A*. This makes Sgr A* a uniquely valuable source for testing the theory of accretion onto supermassive black holes in galactic nuclei.

The faintness of Sgr A* at all wavelengths requires that the supermassive black hole be in an extremely quiet phase, either because the accretion rate is very low, or because the accretion flow is radiatively inefficient, or both\(^5\). A variety of theoretical scenarios, usually based on advective accretion models\(^6\–\(^8\), jet-disk models\(^9\), or Bondi-Hoyle models\(^10\–\(^12\), have developed this idea. An important prediction of the advective accretion models is that the X-ray spectrum in the Chandra energy band should be dominated by thermal bremsstrahlung emission from hot gas in the outer regions of the accretion flow (\(R \gtrsim 10^3 R_\odot\)), but a region this large could not produce the rapid, large-relative-amplitude variations we have seen. Thus, the properties of the X-ray flare are inconsistent with the advective accretion flow models. The low luminosity and short timescales of this event are also inconsistent with tidal disruption of a star by a central supermassive black hole\(^13\).

In all models, the radio-to-submillimetre spectrum of Sgr A* is cyclo-synchrotron emission from a combination of sub-relativistic and relativistic electrons (and perhaps positrons) spiralling around magnetic field lines either in a jet or in a static region within the inner 10 \(R_\odot\) of the accretion flow. The electron Lorentz factor inferred from the radio spectrum of Sgr A* is \(\gamma_e \sim 10^2\). If the X-ray flare were produced via direct synchrotron emission, then the emitting electrons would need \(\gamma_e \gtrsim 10^3\). For the 10–100 G magnetic field strengths predicted by the models, the cooling time of the particles would be \(\sim 1–10^3\) s. Thus, the \(\approx 10\)-ks duration of the flare would require repeated injection of energy to the electrons. On the other hand, if the X-rays were produced via up-scattering of the submillimetre photons of the relativistic electrons, a process called synchrotron self-Comptonization (SSC), then \(\gamma_e \sim 10^2–10^3\) would be required, and the cooling time would be of order hours, which is consistent with the duration of the flare. The rapid turn-off of the X-ray emission might then be attributed to the dilution of both photon and electron densities in an expanding plasma.

The X-ray spectra of radio-quiet quasars and AGN are thought to be produced by thermal Comptonization of infrared-to-ultraviolet seed photons from a cold, optically thick, geometrically thin accretion disk by hot electrons in a patchy corona above the disk\(^13\,14\). The X-ray spectra of these sources generally soften as they brighten\(^15\). In contrast, the extremely low luminosity of Sgr A* precludes the presence of a standard, optically thick accretion disk\(^15\); hence, the dominant source of seed photons would be the millimetre-to-submillimetre synchrotron photons.

The energy released by an instability in the mass accretion rate or by a magnetic reconnection event near the black hole would shock accelerate the electrons, causing the synchrotron spectrum to intensify and to extend farther into the submillimetre band. Consequently, the Compton up-scattered X-ray emission would harden as the X-ray intensity increased, exactly as observed. We note that the millimetre-band spectrum of Sgr A* has been observed to harden during one 3-week flare\(^16\) and one 3-day flare\(^17\), as would be required by the current SSC models for Sgr A* (refs 20, 22).
To test the SSC models, we measured the flux density of Sgr A* at a wavelength of 3 mm with the Millimeter Array at the Owens Valley Radio Observatory, simultaneous with part of the 2000 Chandra measurement. Unfortunately, the available observing window (20:10–02:30 UT) preceded the X-ray flare (04:03–06:50 UT) by a few hours. The observed flux density of Sgr A* was 2.05 ± 0.3 Jy, consistent with previously reported measures 7,22. Recently, a 106-day quasi-periodicity has been reported in the centimetre band from an analysis of 20 years of data taken with the Very Large Array (VLA). A weekly VLA monitoring program detected an ≈30% increase in the radio flux density of Sgr A* beginning around 24 October 2000 and peaking on 5 November 2000. This increase was seen at 2 cm, 1.3 cm, and 7 mm (R. McGary, J.-H. Zhao, W. M. Goss, and G. C. Bower, private communication). The timing of the X-ray flare and the rise in the radio flux density of Sgr A* suggests there is a connection between the two events, providing additional indirect support for the association of the X-ray flare with Sgr A* and further strengthening the case that it was produced via the SSC or direct synchrotron processes. Definitive evidence for these ideas will require detection of correlated variations in the radio-to-submillimetre and X-ray wavebands through future coordinated monitoring projects.

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