# A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way

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**Many galaxies are thought to have supermassive black holes at their centres[1]—more than a million times the mass of the Sun. Measurements of stellar velocities[2–7] and the discovery of variable X-ray emission[8] have provided strong evidence in favour of such a black hole at the centre of the Milky Way, but have hitherto been unable to rule out conclusively the presence of alternative concentrations of mass. Here we report ten years of high-resolution astrometric imaging that allows us to trace two-thirds of the orbit of the star currently closest to the compact radio source (and massive black-hole candidate) Sagittarius A*. The observations, which include both pericentre and apocentre passages, show that the star is on a bound, highly elliptical keplerian orbit around Sgr A*, with an orbital period of 15.2 years and a pericentre distance of only 17 light hours. The orbit with the best fit to the observations requires a central point mass of $(3.7 \pm 1.5) \times 10^6$ solar masses ($M_\odot$). The data no longer allow for a central mass composed of a dense cluster of dark stellar objects or a ball of massive, degenerate fermions.**

For the past ten years we have been carrying out high-resolution near-infrared imaging and spectroscopy of the central few light years of our Milky Way for a detailed study of the stellar dynamics in the vicinity of the compact radio source SgrA* (refs 2, 3, 5, 7), the most likely counterpart of the putative black hole[9,10]. From a statistical analysis of the stellar proper motions (velocities on the plane of the sky derived from multi-epoch imaging data) and line-of-sight velocities (Doppler motions derived from spectral lines) we deduced the presence of a mass of about 2.6 to 3.3 million $M_\odot$ concentrated within ten light days of SgrA* (refs 2, 3, 5). To further improve the sensitivity (by about 20) and the angular resolution/astrometric precision of our study (by about 3), we began this year to use the new COudé near-infrared camera (CONICA)/Nasmyth adaptive optics system (NAOS) imager/spectrometer on the 8-m UT4 (Yepun) of the European Southern Observatory (ESO) Very Large Telescope (VLT)[11–13]. Figure 1 shows a diffraction-limited (56 milli-arcseconds (mas) full-width at half-maximum, FWHM) $K_s$-band (2.18 μm) image of the central 40″ of the Milky Way taken with NAOS/CONICA in May 2002. A key factor in constraining the mass distribution is the alignment of the infrared images, where the stars are observed, with the astrometrically accurate radio images,

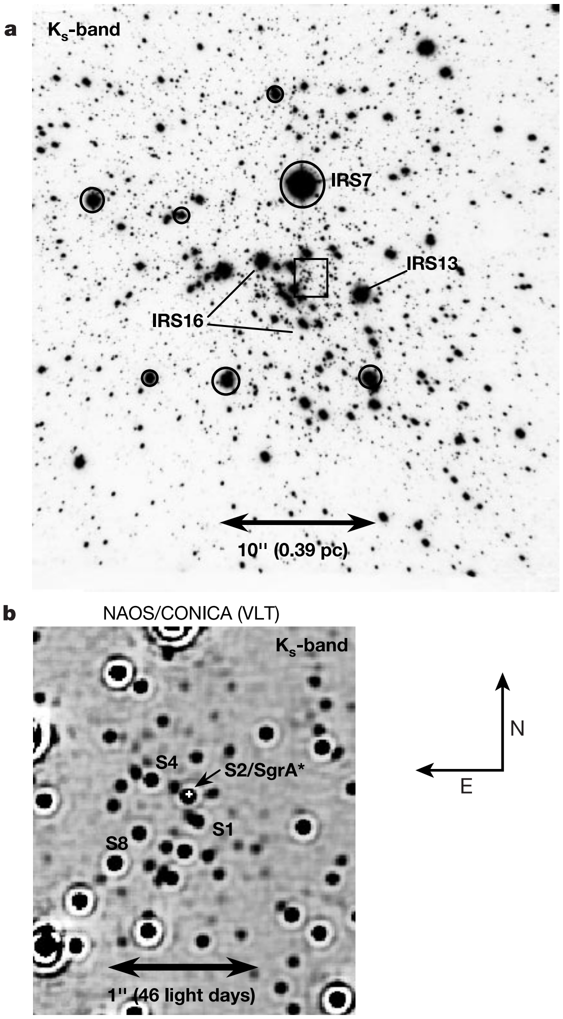

**Figure 1** $K_s$-band image of the centre of the Milky Way. **a**, Diffraction-limited (56-mas FWHM) $K_s$-band (2.18 μm) image of the central 40″ of the Milky Way, obtained with the NAOS/CONICA adaptive optics imager on UT4 (Yepun) of the VLT on 3 May 2002. The prominent infrared sources IRS7, IRS13 and IRS16 are indicated. The scale bars are for an assumed distance of 8 kpc (26,000 light years)[5,21]. The unique infrared wavefront sensor was used to close the loop of the adaptive optics system on the bright supergiant IRS 7, about 6″ north of SgrA*. The Strehl ratio is over 40%. The radio positions of seven SiO maser stars (open circles) were used to align the infrared image with the radio astrometry frame[23]. The SiO masers originate in the central ~1 mas of the circumstellar envelopes of infrared bright, red giants/supergiants. The radio-to-infrared registration is accurate to ±10 mas (including the effect of variation of the point spread function across the field), a factor-of-three improvement over ref. 14. There we could only use two SiO sources, giving the centre position, rotation angle and a single pixel scale for the infrared images. Our new analysis allows solving, in addition, for second-order imaging terms (small for NAOS/CONICA, but significant for the earlier SHARP/NTT data). **b**, The central ~2″ region (rectangle in **a**) around the compact radio source SgrA* (cross). This image is a sum of images taken in May 2002 and has been deconvolved with a linear Wiener filter method to remove the seeing halos. The ring structures around the brighter stars are artefacts of the linear deconvolution algorithm that arise because information on the point spread function in Fourier space is not known up to infinite frequencies. Several of the stars near SgrA* are marked, including the closest star at present (S2) (ref. 5).

where SgrA* is observed. For this purpose we aligned our NAOS/CONICA images with the astrometric grid using seven SiO maser sources in the field of view (circles in Fig. 1) whose positions are known through measurements with the Very Large Array (VLA) and the Very Long Baseline Array (VLBA) to accuracies of a few mas[23]. Having thus derived astrometric infrared positions for 2002, we were then able to compute exact stellar positions relative to SgrA* (in right ascension and declination) for all epochs (including data taken with the SHARP camera at the ESO New Technology Telescope, NTT) between 1992 and 2002. The resulting position of the radio source SgrA* on the infrared image has a $1\sigma$ uncertainty of $\pm 10$ mas, or about a factor of three better than previously[14]. The new position of SgrA* is around 50 mas east of the position given in ref. 14. In spring 2002 the orbiting star S2 had approached SgrA* to within 10–20 mas, thus providing a unique opportunity to determine the mass a factor of 10–20 times more closely in than in previous work.

The first measurements of orbital accelerations for S2 and S1, the two stars closest to SgrA*, were consistent with orbits bound to a central object of about 3 million $M_\odot$, but still allowed a wide range of possible orbital parameters[6,7]. Specifically, possible orbital periods for S2 ranged from 15 to 500 yr (ref. 6). With our new data, we are now able to determine a unique orbit for S2 from astrometric proper motions and provide strong constraints on the mass distribution on distances less than one light day. Figure 2 shows the measured 1992–2002 positions of S2 relative to SgrA*. In spring 2002 we happened to catch the pericentre passage of the star, at which point the measured velocity exceeded 5,000 km s$^{-1}$, about eight times greater than 7.6 yr ago[2,3] when S2 was at apocentre. The S2 data points trace two-thirds of a closed orbit and are robustly fit by a bound keplerian orbit around a central point mass located at the position of SgrA*. The parameters of the best-fitting orbit, along with their fit and astrometric errors, are given in Table 1. They were derived using the publicly available Binary Star Combined Solution Package[15]. For the nominal SgrA* position, the uncertainties of the fit parameters are generally less than 10%. The additional uncertainty introduced by the astrometric errors is of similar size. The semimajor axis ($a = 5.5$ light days) and orbital period (15.2 yr) imply a mass of $(3.7 \pm 1.5) \times 10^6 M_\odot$ within the pericentre radius of 124 AU, or 17 light hours. The pericentre passage of S2 in April/May 2002 thus probes the mass concentration at around 2,100 times the Schwarzschild radius of a $3 \times 10^6 M_\odot$ black hole. The pericentre distance radius of S2 is 70 times greater than the distance from the black hole, where the star would be disrupted by tidal forces (about 16 light minutes for a $\sim 15 M_\odot$, $7 R_\odot$ star like S2; ref. 3). Because tidal energy deposition falls faster than the sixth power of the ratio of tidal radius to orbital radius, tidal effects near the perinigricon of S2 are expected to be negligible, consistent with its lack of infrared variability.

The remarkable consequence of the orbital technique is that the mass can be determined from a single stellar orbit, in comparison to the statistical techniques that use several tens to hundreds of stellar velocities at 10 to 300 light days from SgrA* (Fig. 3). In addition, the orbital technique requires fewer assumptions than the other estimates (for example, equilibrium and isotropy of orbits), and thus is less vulnerable to systematic effects.

The Galactic Centre mass distribution resulting from all available data is well fitted by the combination of a $(2.6 \pm 0.2) \times 10^6 M_\odot$ point mass (the supermassive black hole), plus the visible stellar cluster of core radius 0.34 pc, an outer power-law density distribution with exponent $\alpha = 1.8$ and central density $3.9 \times 10^6 M_\odot\,\mathrm{pc}^{-3}$ (Fig. 3). If the central point mass is replaced by a Plummer mass distribution, which is the most compact one expected realistically (with a power-law index of $\alpha = 5$, in order to mimic the flatness of the observed mass distribution over three orders of magnitude in radius[5]), its central density would have to exceed $10^{17} M_\odot\,\mathrm{pc}^{-3}$, more than four orders of magnitude greater than previous estimates[5–7]. Such a Plummer distribution would be appropriate if the dark mass consisted of a dark cluster of low-mass stars, neutron stars or stellar black holes. The maximum lifetime of such a cluster mass against collapse (to a black hole) or evaporation would be less than a few $10^5$ yr (ref. 16), clearly a highly implausible configuration. Further, theoretical simulations of very dense, core-collapsed clusters predict much shallower, near-isothermal density distributions ($\alpha \approx 2$, see discussion in ref. 3). We conclude that such a dark cluster model can now be safely rejected. Our new data also robustly exclude one of two remaining 'dark particle matter' models as alternatives to a supermassive black hole, namely a ball of heavy (10–17 keV $c^{-2}$) fermions (sterile neutrinos, gravitinos or axinos) held up by degeneracy pressure[17,18], which in principle could account for the entire range of dark mass concentrations in galactic

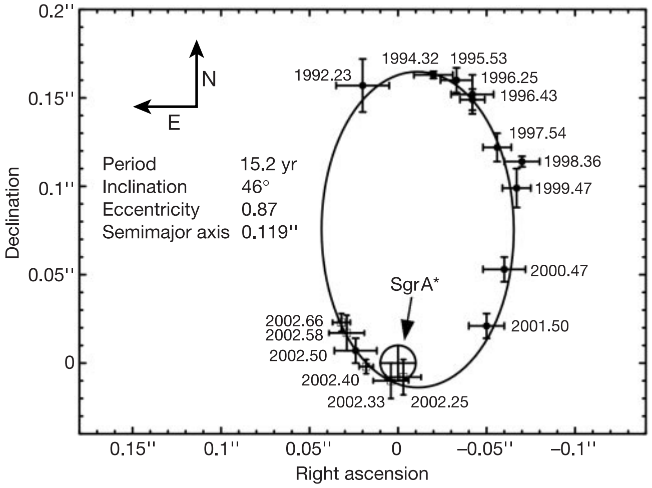

**Figure 2** Orbit of S2 around SgrA*. Orbit of S2, relative to the position of SgrA* (large cross and circle, denoting the ±10 mas uncertainties of the infrared-radio astrometry). The filled small circles (with $1\sigma$ errors) between 1992 and 2001, and at 2002.50, denote the results of our speckle imaging with the SHARP camera on the ESO NTT[5,7]. The five open rectangles are the NAOS/CONICA data points on 2002.25, 2002.33, 2002.40, 2002.58 and 2002.66. The projection of the best-fitting Kepler orbit is shown as a continuous curve, with its main parameters listed adjacent to the orbit (see also Table 1). For determination of the orbital elements (Table 1) we used the publicly available Binary Star Combined Solution Package[15], which computes best-fit orbits from position–time series (including their errors). Uncertainties in the derived parameters are determined from a covariance matrix analysis. The additional uncertainty introduced by the astrometric errors is of similar size and was estimated by letting the position of SgrA* vary randomly within its $1\sigma$ astrometric uncertainty limits and examining the change in the resulting orbital parameters. Because we do not know the line-of-sight velocity of the star, the sign of the inclination given in Table 1 is undetermined. The angle of the line of nodes (36°) is counted east of north. The angle from node to pericentre is counted from the node in the northeast quadrant in the direction of the motion of S2.

Table 1 **Derived orbital parameters for S2**

| Parameter | Value | Formal error* | Astrometric error† |
|---|---|---|---|
| Black hole mass ($10^6 \times M_\odot$) | 3.7 | 1.0 | 1.1 |
| Period (years) | 15.2 | 0.6 | 0.8 |
| Time of pericentre passage (years) | 2002.30 | 0.01 | 0.05 |
| Eccentricity | 0.87 | 0.01 | 0.03 |
| Angle of line of nodes (degrees) | 36 | 5 | 8 |
| Inclination (degrees) | ±46 | 3 | 3 |
| Angle of node to pericentre (degrees) | 250 | 4 | 3 |
| Semi-major axis (mpc) | 4.62 | 0.39 | 0.43 |
| Separation of pericentre (mpc) | 0.60 | 0.07 | 0.15 |

*The $1\sigma$ errors result from the orbital fit.
†The errors due to the 10-mas astrometric uncertainty. See Fig. 2 legend for a description of the angles and of the errors.

nuclei with a single physical model. Because of the finite size ($\sim 0.9''$ diameter) of a non-relativistic, $3 \times 10^6 M_\odot$ ball of around 16 keV fermions, the maximum (escape) velocity is about 1,700 km s$^{-1}$ and the shortest possible orbital period for S2 in such a fermion ball model would be about 37 yr (ref. 18), clearly inconsistent with the orbit of S2. The enclosed mass at perinigricon would require a neutrino mass of over 50 keV, a value which can safely be excluded for neutrino ball models trying to explain the entire range of observed masses in galactic nuclei[17,18]. The only 'dark particle matter' explanation that cannot be ruled out by the present data is a ball of bosons, because such a configuration would have a radius only a few times greater than the Schwarzschild radius of a black hole[16,19]. However, it would be very hard to understand how the bosons first manage to reach such a high concentration, and then avoid forming a black hole by baryonic accretion[16,19]. The data on the Galactic Centre thus show that the central mass distribution is remarkably well described by the potential of a point mass over three orders in magnitude in spatial scale, from 0.8 light days to 2 light years. The contribution of the extended stellar cluster around SgrA* to the total mass cannot be more than a few hundred solar masses within the pericentre distance of the orbit of S2.

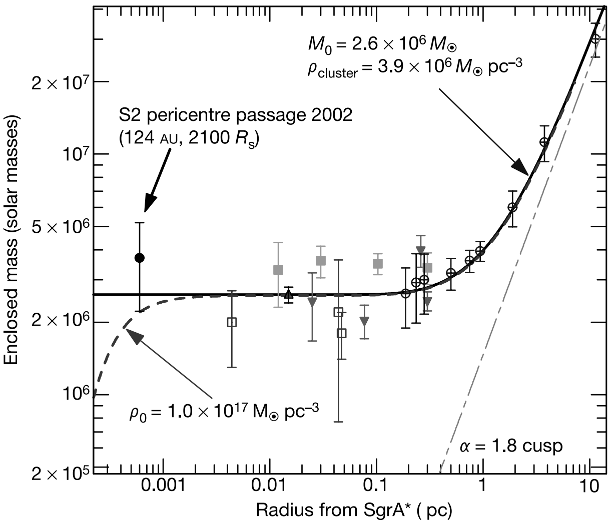

**Figure 3** Mass distribution in the Galactic Centre. Mass distribution in the Galactic Centre (for an 8 kpc distance[21]). The filled circle denotes the mass derived from the orbit of S2. The error bar combines the orbital fit and astrometry errors (Table 1). Filled downward-pointing triangles denote Leonard–Merritt projected mass estimators from a new NTT proper motion data set (T.O., R.S., R.G. and A.E., manuscript in preparation), separating late and early type stars, and correcting for the volume bias in those mass estimators by scaling with correction factors (0.88–0.95) determined from Monte Carlo modelling of theoretical clusters[5]. An upward-pointing rectangle denotes the Bahcall–Tremaine mass estimate obtained from Keck proper motions[4]. Grey filled rectangles are mass estimates from a parameterized Jeans-equation model from ref. 5, including anisotropy and differentiating between late and early type stars. Open circles are mass estimates from a parameterized Jeans-equation model of the radial velocities of late type stars, assuming isotropy[5]. Open rectangles denote mass estimates from a non-parametric, maximum likelihood model, assuming isotropy and combining late and early type stars[22]. The different statistical estimates (in part using the same or similar data) agree within their uncertainties but the variations show the sensitivity to the input assumptions. In contrast, the new orbital technique for S2 is much simpler and less affected by the assumptions. The continuous curve is the overall best-fit model to all data. It is a sum of a $(2.6 \pm 0.2) \times 10^6 M_\odot$ point mass, plus a stellar cluster of central density $3.9 \times 10^6 M_\odot\,\mathrm{pc}^{-3}$, core radius 0.34 pc and power-law index $\alpha = 1.8$. The 'long dash, short dash' curve shows the same stellar cluster separately, but for an infinitely small core (that is, a 'cusp'). The thick dashed curve is the sum of the visible cluster, plus a Plummer model of a hypothetical concentrated ($\alpha = 5$), very compact ($R_0 = 0.00019$ pc) dark cluster of central density $1 \times 10^{17} M_\odot\,\mathrm{pc}^{-3}$.

Thus we have presented the first step in a new phase of near-infrared observations of the immediate surroundings of the central dark mass in the centre of the Milky Way. The observation of orbits of stars surrounding the central dark object offers a clean new way of constraining its mass distribution and testing the supermassive black hole model with the simple assumption of keplerian orbits. Within the next years we hope to observe the accelerations and orbits of several faint stars near SgrA* that have become observable with the increased resolution and sensitivity of the NAOS/CONICA camera/adaptive optics system at the VLT. Even more detailed observations of the SgrA* environment will become possible with infrared interferometry at the Large Binocular Telescope, the ESO Very Large Telescope Interferometer and the Keck interferometer, which will provide resolution of a few to 10 mas (a few light hours). These offer exciting prospects for the exploration of relativistic motions at 10–100 Schwarzschild radii from the central black hole[20]. ☐

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