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—more than a million times the mass of the Sun. Measurements of stellar velocities and the discovery of variable X-ray emission 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 Sagittarius 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 \((3.7 \pm 1.3) \times 10^6\) 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 Sagittarius A* (refs 2, 3, 5, 7), the most likely counterpart of the putative black hole.\(^{10}\) 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 Sagittarius A* (refs 2, 3, 5, 7). 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 CONICA near-infrared camera (CONICA/NaSyMy) 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-mas FWHM) K\(_\text{s}\)-band (2.18 \(\mu\)m) 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.
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\(^2\). 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 1σ uncertainty of \(\pm 10\) mas, or about a factor of three better than previously\(^3\). 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 of 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\(^1,3\) 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\(^8\). 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 \(\pm 1.5\) x \(10^6\) \(M_\odot\)) within the pericentre radius of 124 \(\alpha_0\), 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 \(\approx 15M_\odot\), 7R\(_\odot\) 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 perigiricon of S2 are expected to be negligible, consistent with their 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 core of radius 0.34 pc an outer power-law density distribution with exponent \(\alpha = 1.8\) and central density \(3.9 \times 10^{17}\) \(M_\odot\) 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\(^3\)), its central density would have to exceed \(10^{17}\) \(M_\odot\) 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\(^8\) yr (ref. 16), clearly a highly implausible configuration. Further, theoretical simulations of very dense, core-collapsed clusters predict much shallower, near-isothermal density distributions (\(\alpha = 2\), 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\(^11,12\), which in principle could account for the entire range of dark mass concentrations in galactic

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**Table 1** Derived orbital parameters for S2

| Parameter | Value | Formal error | Astrometric error |
|-----------|-------|--------------|------------------|
| Black hole mass (10\(^6\) x \(M_\odot\)) | 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) | \(\leq 46\) | 4 | 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 |

1. \(^1\) The 1σ errors result from the orbital fit.
2. \(^*\) 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 (~0.9° diameter) of a non-relativistic, $3 \times 10^9 M_\odot$ 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 perigiricon 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.\(^3\)\(^,\)\(^4\)

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\(^5\).

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