Abstract.
In this article we present and discuss the latest results from the observations of stars ("S-stars") orbiting Sgr A*. With improving data quality the number of observed S-stars has increased substantially in the last years. The combination of radial velocity and proper motion information allows an ever more precise determination of orbital parameters and of the mass of and the distance to the supermassive black hole in the centre of the Milky Way. Additionally, the orbital solutions allow us to verify an agreement between the NIR source Sgr A* and the dynamical centre of the stellar orbits to within 2 mas.

1. Introduction
The Galactic Centre (GC) offers due to its proximity the unique opportunity to study the properties of a supermassive black hole (SMBH) in detail. Two parameters of special interest in the last years have been the mass of and the distance to Sgr A*, in direct connection to the question about the nature of the central dark mass. An answer to these questions that was independent of most assumptions became possible, for the first time, in the year 2002, when the star S2 was confirmed to move on a Keplerian orbit around Sgr A* [1]. Follow-up observations covering both radial velocities and proper motions soon made possible the detection of additional stars on orbits. These orbits allow a simultaneous solution for both mass of and distance to the central SMBH.

In the last years those observations have been continued and extended. The rapidly increasing amount of data provides a more and more precise determination of dynamical parameters and thus a more and more precise understanding of the innermost part of our Galaxy ([2], [3], [4], [5], [6]).

2. Instruments and observations
The monitoring of the S-star orbits is necessarily based on diffraction limited imaging and spectroscopy on large telescopes. As the GC is due to strong extinction (AV ≈ 30) not visible in the optical wavelength range, we focused on near-infrared (NIR) observations, mainly in the H and K bands (1.5 to 2.5 μm).

Our observations began in 1992 using the speckle imaging camera SHARP I [7] at the 2.2-m-telescope in La Silla. Since 2002, we have used the detector system NAOS/CONICA (NACO for short), consisting of the adaptive optics system NAOS [8] and the NIR camera CONICA [9] at the 8.2-m-UT4 (Yepun) of the ESO-VLT on Cerro Paranal, Chile. NACO produces high quality images with a spatial resolution of ~40 (H band) resp. ~55 mas (K band).

In order to obtain 3-dimensional information on the GC in general and the S-stars in special, we have additionally collected stellar spectra using the integral field spectrometer SPIFFI ([10], [11]) resp.

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Figure 1. Regularly monitored S-stars. This image is a Lucy-Richardson deconvolved K band NAOS/CONICA image obtained in 2005. At the time of the exposure Sgr A* was active in the NIR and thus can be seen here.

SINFONI, a combination of SPIFFI and the adaptive optics (AO) system MACAO [12, 13]. SINFONI produces diffraction-limited data cubes with 64×32 pixels in the two spatial dimensions and 2048 pixels along the spectral axis, reaching spectral resolutions of ∼3500.

3. More and more S-stars
Since the first reports on stellar orbits, the number of S-stars has always been rather limited, the orbital analyses focused typically on ensembles of 6 to 10 stars. As the very special dynamics of those stars is generally of high interest, we investigated the question, if there are more of such objects. Compared to the situation in 2002/2003, where the analysis of orbits was mainly based on speckle data obtained with SHARP, we now have access to a large number of AO-assisted 8-m-class telescope data, both imaging (NACO) and spectroscopic (SINFONI). So we could expect to detect additional stars (see Fig. 1) for the following reasons:

- We collect more accurate data with lower detection thresholds. Thus it is possible to trace fainter sources with accuracies that allow to detect accelerations within shorter time lines (e.g. S18).
Figure 2. Illustration of stellar motions around Sgr A*. Left: Orbits in the plane of the sky. Sgr A* is located at (0,0), coordinates are given in arcsec. Right: Radial velocities (in km/s) vs. time (in epochs). Figure taken from [6].

- The AO data allow the retrospective detection of sources. Objects, that are too faint or too confused to be identified resp. separated in the elder speckle images alone, can be identified in NACO images and re-found in the SHARP images (e.g. S17).
- High-quality integral field spectroscopy allows the identification of fast sources that appear not to be special in proper motion (e.g. S9).

A good example for this is the identification of the star S18. We noted the fast motion of this object for the first time in a difference map of two NACO images obtained in 2002 and 2005. This quite faint source ($K \approx 17$) showed a remarkably large proper motion. After identifying S18 in NACO images, we were also able to extract radial velocities out of SINFONI cubes and thus could attach a 3-dimensional orbit to it, using the known Sgr A* potential.

Today our ensemble of S-stars has around 30 members. Orbital solutions exist for about 15 of them.

4. Better and better orbital solutions
The permanently increasing time line of observations, which began in 1992 and are being continued until today, in combination with the much better data quality since 2002, allow a more and more accurate determination of the dynamical parameters of the S-star system, especially mass of and distance to Sgr A*.

In order to compute the dynamical properties of the S-star cluster, we fit all available data simultaneously with a proper potential, which is either a purely Keplerian one or includes general relativistic effects and/or an extended component of the central mass. We simultaneously solve for six orbital parameters per star plus (at most) seven parameters for Sgr A* (mass, 3D position, 3D velocity).
Table 1. Reported uncertainties for mass of and distance to Sgr A*. As one can see easily, the accuracies have increased quite dramatically between 2002 and 2006. Masses given by [3] and [5] are scaled with the distance \( R \) to the GC using an assumed distance of 8 kpc, whereas the other mass errors are independent from the distance.

| Analysis      | mass error \([10^6 M_\odot]\) | distance error [kpc] |
|---------------|-------------------------------|----------------------|
| [1]           | 1.5                           | 0.42                 |
| [4]           |                               |                      |
| [3]           | 0.4 \((R/8\text{kpc})^3\)     |                      |
| [5]           | 0.2 \((R/8\text{kpc})^3\)     |                      |
| [6]           | 0.32                          | 0.32                 |
| MPE, April 2006 | 0.22                          | 0.22                 |

Technically this procedure is implemented in the high-level tool Mathematica as a \( \chi^2 \) minimization routine using symplectic integrators. The geometry of the problem is illustrated in Fig. 2.

The mass of and distance to Sgr A*, which have been known to be \( \sim 3.5 \cdot 10^6 M_\odot \) resp. \( \sim 7.5 \) kpc for several years now, have never changed significantly within the reported errors since then. Thus the main effect of the research of the last years was a more and more accurate determination of these values. A major progress in accuracy was made when radial velocities were included into the analysis, thus making assumptions on resp. scaling with the distance to the GC unnecessary. This is illustrated in Table 1, where the reported uncertainties of all main analyses based on the S-star orbits are compared. As one can see, the accuracy in both parameters improved by factors of at least 2 within only three years, which is a quite impressive outcome.

5. Flare position vs. dynamical centre

A welcome side effect of the dynamical analysis described above is the possibility to test whether the dynamical center of the S-star system and the infrared source Sgr A* are in agreement. Sgr A* is generally invisible in the NIR, but shows outbursts (“flares”) on time scales of few events per day [14, 15, 16]. So it is possible to extract a position of the NIR source whenever it is active and to compare this position with the foci of the S-star orbits.

We extracted some 10 flare positions from NACO images and compared them to the dynamic centre of the S-star orbits. The results are presented in Table 2. These positions are attached to an astrometric reference frame set by SiO maser radio stars [17] with an accuracy of few mas, thus Sgr A* is not located exactly at \((0,0)\). As one can see easily, the agreement between the two positions is very good: the upper limit for a deviation NIR source – orbit focus is 2 mas.

Table 2. Flare positions compared with the dynamical centre of the S-star orbits. Obviously, the agreement between the two positions is better than 2 mas.

| RA [mas] | DEC [mas] |
|----------|-----------|
| flares   | +2.24±0.49 | -4.56±0.72 |
| dyn. centre | +2.29±0.67 | -5.52±0.66 |
6. Summary
We presented recent results from the observations of the S-stars orbiting Sgr A*. These results can be summarized as follows:

- The number of S-stars for which an orbital solution can be found is still increasing and has reached a number of $\sim 15$.
- The accuracy of the orbital parameters, especially the mass of and the distance to Sgr A*, has increased substantially within the last three years.
- The position of the NIR source Sgr A* and the dynamical centre of the S-star orbits agree within 2 mas.

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