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The Black Hole in the Galactic Center

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Abstract. The Galactic Center harbors the closest MBH and enables therefore unique observations of a resolved stellar system around a MBH. In two ways, the Galactic Center is directly tied to gravitational wave observatories: (i) For extreme mass ratio inspirals, the GC system serves as a template. While it is very unikely that one will witness such an inspiral from our own Milky Way center, the detailed views of the stellar system are an anchor for the overall event rate estimates. (ii) Future infrared and submm observations will allow testing general relativity at Sgr A* - in a regime of field curvature in which also a future space-based gravitational wave observatory will measure.

1. Introduction

The Galactic Center (GC) is a unique laboratory for observing a stellar system around a massive black hole (MBH). Due to the high extinction this needs infrared instrumentation, and the small spatial scales combined with the extremely high stellar density make the use of adaptive optics at an 8m-telescope very rewarding: The GC stars are fully resolved. One can distinguish at least three stellar populations: (i) The so-called S-stars, famous for the detection of individual stellar orbits in the central arcsecond. (ii) The disk stars, a population of young, massive stars, revolving around the MBH in a disk-like configuration at radii between 1" and 10". (iii) The underlying population of old stars (i.e. giants) all over the sphere of influence of the MBH (roughly 25") and beyond. The uninterrupted monitoring of the GC has led to constant progress in our understanding of this stellar system, which will also continue in future. A huge step forward will be possible due to near-infrared interferometry, namely the instrument GRAVITY, which will be able to combine the light from the four unit telescopes on Paranal to a virtual aperture of 120 m. As a complete surprise came during 2011 the discovey of an infalling gas cloud - an object of $\approx$ 3 Earth masses that is on a near-radial orbit currently falling towards Sgr A*, and which will reach the pericenter of its orbit around mid 2013. This proceedings article cannot cover all aspects of astrophysics around the MBH in the Galactic Center. For a recent, comprehensive review please see Genzel et al. (2010).

2. The stellar system

Figure 1 shows a cartoon version of the stellar system. The S-stars in the central arcsecond, a disk-like configuration further out, and the underlying population of giants.

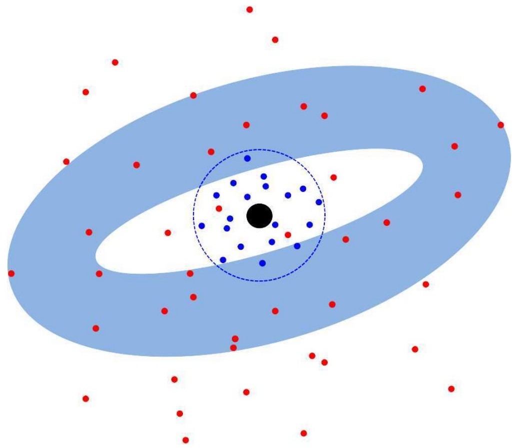

Figure 1. Cartoon version of the stellar system: Blue dots represent the S-stars, red dots the underlying population of old stars. The bighter blue ring stands for the disk of O/WR-stars.

2.1. The S-stars

The S-stars are a population of young stars, spectroscopically identfied as B-dwarfs (Eisenhauer et al. 2005), which reside so close to the black hole that their velocities reach several 100 km/s. From 20 years of uninterrupted monitoring of the motions more than 30 individual orbits have been determined (Gillessen et al. 2009b).

In particular the orbit the star S2 is astonishing, since it revolves in 16 years only, and more than one full recolution has been followed (Gillessen et al. 2009a). Since also the radial velocities can be measured for these stars, the combination of astromety and radial velocites yields a geometric distance estimate to the GC, R_0 (Eisenhauer et al. 2003). The mass of the black M hole is determined from the same fit, yielding a statistical uncertainty of 1.5% only. The systematic unertainty, however, is significant, since R_0 and M are highly correlated parameters. In a purely astrometric data set, $M \propto R^3$, if only radial velocities are present $M \propto R^0$. For our mixed dataset, we find roughly $M \propto R^2$, sucht that the 5% distance uncertainty yields a 10% uncertainty on M.

The spectroscopic identification as B-dwarfs came as a surprise: Such stars are typically around 10^8 years old, and cannot have an age comparable to the relaxation time of the GC system, which is a few 10^9 years (Alexander 2005). However, at the distances at which they are found, star formation is impossible, because of the tidal forces of the MBH. The puzzle was named the 'paradox of youth' (Ghez et al. 2003).

For the solution of this paradox several ideas have been proposed. One contender is the Hills mechanism (Hills 1988): Field binaries get scattered into near loss-cone orbits - for example by massive perturbers like molecular clouds (Perets et al. 2007). During the fly-by at the MBH, the binary gets broken up, and one star leaves the GC as a hypervelocity star, while the other remains bound on a tight, highly eccentric orbit around the MBH. An alternative scenario is that the S-stars have formed from former disks and migrated inwards (Merritt et al. 2009), maybe aided by the dynamical effects on an intermediate mass black hole. A basic difference between the two scenarios is the expected eccentricity distribution. In the Hills-picture, the thermal distribution

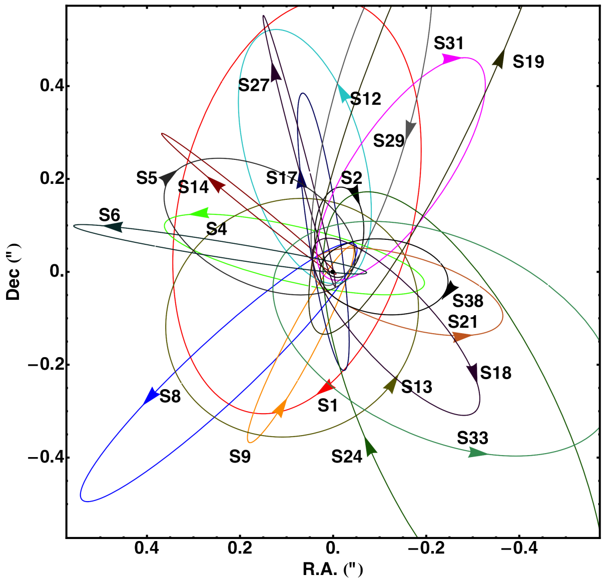

Figure 2. Ilustration of 20 of the more than 30 orbits around the MBH in the Galactic Center.

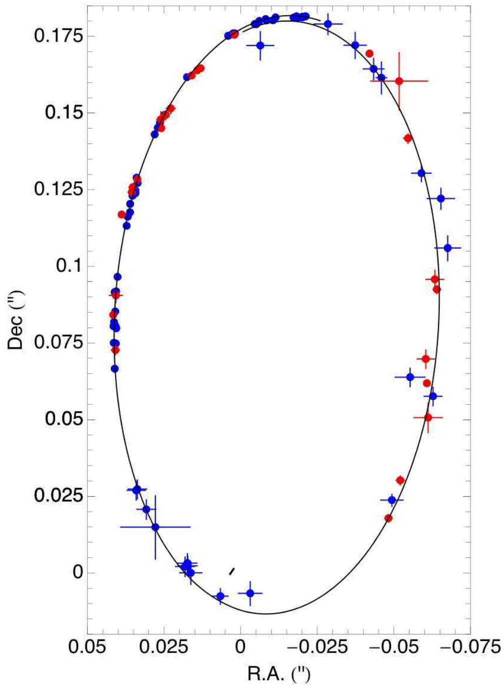

Figure 3. The orbit of the star S2, from Gillessen et al. (2009a). The blue data are VLT measurements, the red from Keck (Ghez et al. 2008). The black line is the combined best fit.

is reached from the 'hot' side, while in the migration scenario from the 'cool' side. Since the currently measured eccentricity distribution is slightly hotter than thermal, the Hills mechanism seems to be the preferred solution. Determining more orbits will help clarifying this point.

The fact that the S2-orbit is a Keplerian ellipse can be used to put constraints on unseen, dark mass components. From the data we can derive that 98% of the mass of the MBH have to be enclosed within the pericenter distance of S2, i.e. around 100 AU. The expected amount of unseen mass, however, is considerably smaller. Various estimates all yield values around 10^{-3} to 10^{-4} of the MBH mass:

- The so-called drain limit is the maximum number of stellar black holes that can reside in the GC in an equilibrium situation. The number is around 10^{-3}.
- Extrapolating the known KLF (Bartko et al. 2010) to fainter luminosities and the density profile (Genzel et al. 2003b; Sch
"odel et al. 2007) to smaller radii yields 10^{-4}.
- The dynamical model of Hopman & Alexander (2006), including stellar remnants, yields 5×10^{-4}.
- Muno et al. (2005) found an overabundance of X-ray binaries close to MBH, and argued that this might be a hint towards the cusp of stellar black holes. The density derived from that yields 1.5×10^{-4}, and the uncertainty in this estimate is dominated by the small number of sources found, namely four.

These limits are particularly interesting for estimating the rates of extreme mass ratio inspirals, a class of events that should be detectable from a space-based gravitational wave detector.

Similarly, one can exclude the presence of a second MBH in the GC. A potential second MBH would need to be relatively light and far away from Sgr A*. Gualandris et al. (2010) showed that one would also have a fair chance of $\approx 50\%$ to detect such an object from the perturbations it has on the stellar orbits. The tightest constraints come from the apparent non-motion of Sgr A* as obtained from VLBA measurements (Reid & Brunthaler 2004).

2.2. The disk stars

Further out resides a population of O/WR-stars. Most of these stars with ages of only $6 \pm 2 \times 10^6$ yrs (Martins et al. 2007) revolve in a disk-like configuration around the MBH (Paumard et al. 2006; Bartko et al. 2009). This population has a top-heavy IMF (unlike the S-stars) and also differs in the eccentricity distribution: The mean eccentricity is rather low ($e \approx 0.4$) compared to the S-stars, where the orbits on average have $e \approx 0.9$.

Also the presence of these stars is surprising. However, their formation can be explained in-situ by the infall of a massive gas cloud (Bonnell & Rice 2008; Hobbs & Nayakshin 2009) that circularized and then formed stars. The competing idea of an inspiraling cluster (Gerhard 2001) is disfavored, since it would overpredict the number of B-stars in the radial regime of the disk by far.

2.3. The old stellar population

Most of the GC stars belong to the old population. Several 1000 proper motions have been determined by now, plus several hundred radial velocities (Trippe et al. 2008; Sch

”odel et al. 2009). This allows setting up dynamical models of the cluster, yielding the mass distribution out to few parsecs.

As a complete surprise came the finding that the radial distribution of the old giants inside the central 5” does not raise anymore - it flattens or even has a hole towards the center. (Buchholz et al. 2009; Do et al. 2009; Bartko et al. 2010). This challenges basic stellar dynamics: A multi-mass stellar population around a MBH should arrange itself in a steeply rising cusp (Bahcall & Wolf 1976) with profiles between $r^{-7/4}$ and $r^{-3/2}$ for the various components.

Merritt (2010) proposed that the GC system has not yet reached a relaxed state to explain the missing cusp. Davies et al. (2011) showed that for a flat IMF (as observed in the stellar disk) stellar collisions can destroy enough giants to explain the lack of these stars in the central 0.4 pc. Also a substantial cusp of stellar black holes ($\approx 10\,M_\odot$) could deplete the centre from the lighter giants that have $\approx 3\,M_\odot$ (L
”ockmann et al. 2010). The issue is of particular relevance for the extreme mass ratio inspiral rates, since the GC system due to its closeness is thought to be a template. For example, it would be very interesting to know whether indeed the missing giants indicate a higher density of stellar mass black holes in the central region, or whether also these objects follow the distribution as observed in the giants. Observationally, one can expect progress by determining orbits for more giants - and thereby constrain their three-dimensional distribution and their eccentricities.

3. Future perspectives

Zooming in further into the GC, beyond what is possible with current instrumention would be very interesting. For example, having access to spatial scales a factor of 10 smaller than what is feasible now, should show stars on orbits with periods as short as one year. These stars would precess due to general relativity by roughly 1° per revolution. The next step in angular resolution will come from near-infrared interferometry, namely the VLTI. Combining the four 8m telescopes on Paranal to an interferometer will allow increasing the spatial resolution by roughly a factor 15. The data are more difficult to interpret, due to the limited number of baselines, but simulations show that it is possible to obtain an image of a moderately complex stellar field in the course of one night, with a positional precision better than 100 μas (Vincent et al. 2011).

Probably the most exciting new possibility with such an instrument concerns Sgr A* itself. The apparent size of the event horizon is 10μas, and the last stable orbit should therefore have a diameter of $\approx$ 60μas. The VLTI will not be able to resolve this, since the resolution of the VLTI in K-band is around 3 mas. However, the foreseeable astrometric precision of 10μas should be sufficient to follow the motion of a localized, bright spot at the last stable orbit. The flares from Sgr A*, as observed since a decade (Genzel et al. 2003a), probably constitute such small emission regions. The observable motions would be suspect to strong gravity, and thus potentially would allow testing relativity around a MBH. Also, the spin of the MBH should be measurable with such an experiment.

Currently, the VLTI is not yet ready to achieve this ambitious goals. The technical prerequisites are:

- Near-infrared wavefront sensing for the adaptive optics: The GC field is crowded and one needs to be able to isolate sources well enough. Also, only the diffraction limited part of the point spread function can be used for interference.

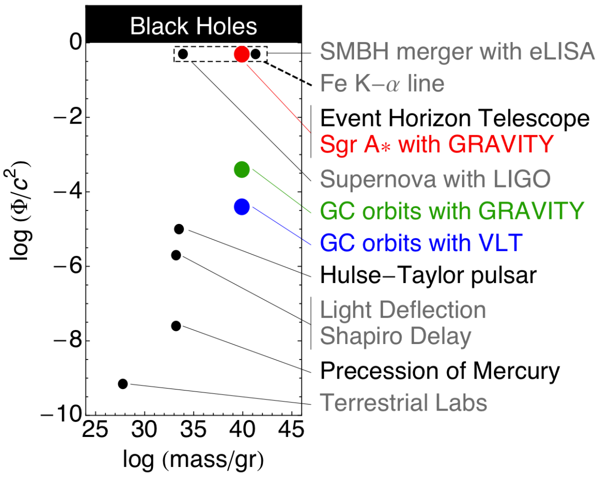

Figure 4. Comparison of various tests of general relativity as a function of mass of the source of gravity and the field strength. Adapted from (Psaltis 2004).

- Fringe-tracking: The atmosphere introduces differential piston, which one needs to measure on a phase reference star nearby - and correct for in real-time.
- Differential astrometry: Measuring the vector between two objects within 1” field of view is the key to get to the highest accuracy.
- The relative faintness of the GC sources implies the use of the four 8m telescopes; the smaller auxiliary telescopes would not be sensitive enough.

While all the technical aspects seem feasible, it still is a major development, and a dedicated instrument is being built currently: GRAVITY (Eisenhauer et al. 2011). It is interesting to see GRAVITY in perspective with other tests of general relativity (figure 3). All current tests are limited to stellar masses, and moderate field strengths. The stellar orbits would extend the regime to the MBH mass scale at a moderate field. The detection of a supernova with LIGO would bring one to the most extreme field strengths, for stellar masses. High fields and high mass are testable with a few experiments: MBH mergers as observed with a space-based gravitational wave observatory, the event horizon telescope aiming at resolving Sgr A* with intercontinental submm-VLBI (Falcke et al. 2000; Doeleman et al. 2009), the relativistic shape of the iron K-α line as observed in X-ray spectra of AGN (Fabian et al. 1995), or flares at the las stable orbit with GRAVITY.

4. Infalling gas cloud

In 2011, we have discovered a very peculiar object: A gas cloud falling on a highly eccentric orbit toward Sgr A* (Gillessen et al. 2011). Due to its dust component, it

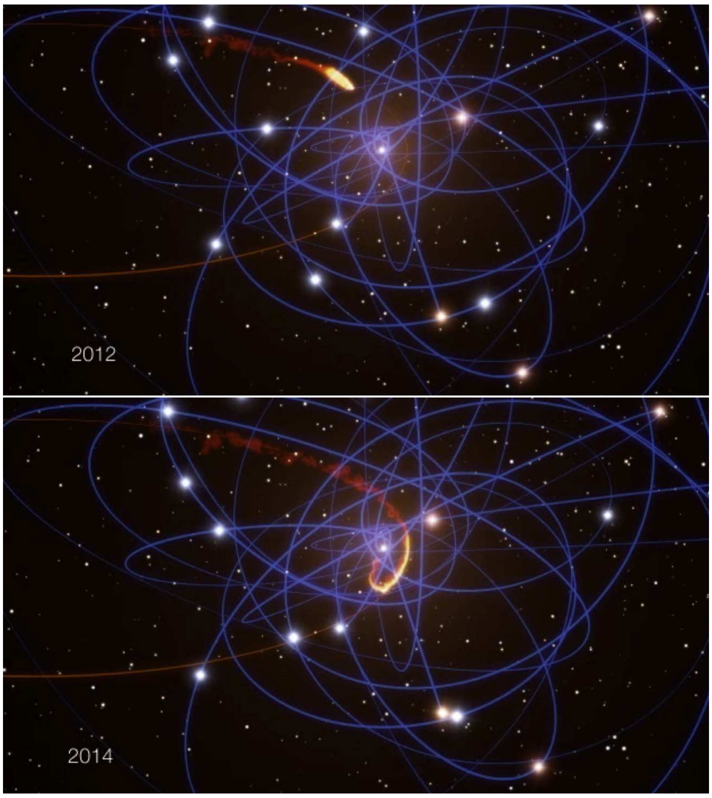

Figure 5. Hydrodynamic simulation of the evolution of the gas cloud. Top: In 2012, it is mainly stretched along its orbit, due to the tidal forces of the MBH. Bottom: In 2014, it is much more disrupted, the level of disruption depends on the density of the hot ambient gas. Simulations from (Schartmann et al. 2012).

shows up as relatively cool source ($T \approx 600\,\mathrm{K}$) in L-band images ($4\,\mu$m), but not in K-band. Furthermore, it can be seen in recombination lines of hydrogen and helium. The cloud is plausibly fully ionized by the hard radiation field of the surrounding stars, and the Brackett-γ recombination luminosity leads to a mass estimate of 3 Earth masses. The orbit is well constrained, since we not only measure an astrometric acceleration and a radial velocity, but also an increase of the radial velocity consistent with this orbit. The epoch of pericenter for the orbit is mid 2013 with a nominal distance of 3000 Schwarzschild radii only. The orbit also is coplanar with the stellar disk, and the apocenter of the cloud orbit is at the inner edge of the disk.

Clearly, a gas cloud cannot survive such a close encounter with a MBH. The tidal forces will tear it apart. Interestingly, our spectroscopy data show that the cloud indeed has developed from 2004 (when it was unresolved) to 2011 a velocity gradient along the orbit - we see the tidal forces acting on the gas cloud already. The amount of tidal shearing observed can be explained with a simple test particle model.

However, Sgr A* is known to be surrounded by a hot accretion flow (Baganoff et al. 2003; Yuan et al. 2003), with a density profile that is rising roughly like r^{-1}

towards the center. At some point, the cloud's material will also feel this gas, and hydrodynamics should add to the disruptive forces of the MBH itself (figure 4).

Ultimately, the gas will feed the MBH. The time scale for circularization is unsure, but for the time when the material has reached the innermost accretion, estimates for the radiative response of Sgr A* exist. Yuan et al. (2004) calculated the broad-band spectral energy distribution for the accretion flow under the assumption of different levels for the accretion rate. Schartmann et al. (2012) assumed that a geometrically thin, optically thick accretion disk would develop to estimate the radiation. In both cases, the luminosity of Sgr A* increases considerably.

The source of energy of this expected increase in radiation is different from what powers the currently observed flares. These are most likely magnetic weather on the accretion disk around Sgr A*, and magnetic reconnection would be a natural source of energy for the flares (Dodds-Eden et al. 2010).

What is the origin of the gas cloud? (Burkert et al. 2012) noted that if the cloud was created at the apocenter of its orbit, in the stellar disk, it should have transformed into an almost linear feature by now. If it formed more recently, the compactness is not as surprising, but then the connection to the stellar disk is hard to understand. The model of a disrupting protoplanetary disk overcomes this weakness (Murray-Clay & Loeb 2011), at the cost of needing to explain how such an object can reach a high-eccentricity orbit. A marked difference between the two models is the flux evolution. The protoplanetary disk scenario constitues a 'tidally triggered comet', that ejects more and more gas, the closer G2 gets to the MBH. Hence, the flux evolution might yield the clue to solving the riddle how such a cloud can exist so close to a MBH.

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