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Observation of black holes and extreme gravitational events/Observation des trous noirs et des événements gravitationnels extrêmes

The Galactic Centre at infrared wavelengths: towards the highest spatial resolution

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Abstract

We now know that our Galaxy harbors at its centre a supermassive $3.6 \times 10^6\ M_\odot$ black hole. This result came after more than 2 decades of infrared studies of the Galactic Centre and important instrumental developments in infrared detectors and in high spatial resolution techniques. Adaptive optics, which allows diffraction-limited infrared observations and enhanced sensitivity, was actually the major breakthrough in this respect.

We introduce in the first section of this article what was our knowledge of the Galactic Centre before the advent of adaptive optics. In the second section, after a reminder of the first adaptive optics observations of this region, we highlight the specificities of Galactic Centre adaptive optics observations. In the third and fourth sections, we present the major results obtained from adaptive optics observations of the Galactic Centre: the case of the supermassive black hole and the paradox of youth. In the fifth section, we introduce two main future facilities that will provide even higher spatial resolutions, Gravity—a second generation VLTI instrument—and Extremely Large Telescopes, and the improvements that we expect with these new instruments in our knowledge of the Galactic Centre region. We conclude in the last section. ***To cite this article: Y. Clénet et al., C. R. Physique 8 (2007).***

Résumé

Le Centre Galactique aux ondes infrarouges : vers la plus haute résolution spatiale. Nous savons maintenant que notre Galaxie abrite en son coeur un trou noir supermassif de $3.6 \times 10^6\ M_\odot$. Cette conclusion est le résultat de plus de deux décades d'études infrarouges du Centre Galactique et d'importants développements instrumentaux dans les détecteurs infrarouges et dans les techniques de haute résolution angulaire. L'optique adaptative, qui permet des observations à la limite de diffraction et offre une sensibilité accrue, a en fait été l'avancée majeure dans ce domaine.

Nous introduisons dans la première section de cet article quelle était notre connaissance du Centre Galactique avant l'arrivée de l'optique adaptative. Dans la seconde section, après un rappel des premières observations avec optique adaptive de cette région, nous soulignons les spécificités des observations avec optique adaptative du Centre Galactique. Dans les troisième et quatrième sections, nous présentons les principaux résultats obtenus à partir d'observations avec optique adaptative du Centre Galactique : le cas du trou noir supermassif et le paradoxe de jeunesse. Dans la cinquième section, nous présentons deux futurs principaux instruments qui fourniront des résolutions spatiales encore accrues, Gravity—un instrument de seconde génération du VLTI—et les extrêmement grands télescopes, ainsi que les améliorations que nous en attendons de connaissance de la région du Centre Galactique. Nous concluons dans la dernière section. ***Pour citer cet article : Y. Clénet et al., C. R. Physique 8 (2007).***

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1. Introduction

Since 1974 and the discovery of Sgr A* by Balick and Brown [1], our Galaxy is known to harbor at its centre a bright radio source. Over the last three decades, the exact nature of this source and its putative association with the gravitational centre of the Galaxy have driven many studies, particularly at infrared (IR) wavelengths given the required spatial resolution (better than 1″) and the interstellar extinction in the visible ($A_\mathrm{V} \approx 30$) compared to the IR ($A_\mathrm{K} \approx 3$).

With the advances in IR detector developments in the mid 1980s, observations started to resolve individual sources in the central crowded few arcseconds and the location of the radio source Sgr A* on the IR maps rapidly gained in accuracy (e.g. [2,3]). Together with enclosed mass estimations from gas cloud motions (e.g. [4]) and stellar dynamics (e.g. [5]), the emerging picture at the beginning of the 1990s was the presence of a compact mass of few $10^6\ \mathrm{M}_\odot$ within the few central tenths of parsecs of the Galaxy, perhaps associated to Sgr A*, whose IR counterpart was remaining undetected.

The following breakthrough came with a new imaging technique, speckle imaging [6] conjugated to a ‘shift and add’ data processing [7], allowing a gain in spatial resolution up to the diffraction limit. Employed since 1992 at the ESO 3.6 m NTT telescope by the MPE group [8] and since 1995 at the Keck 10 m telescope by the UCLA group [9], this method has provided the first K-band and H-band diffraction-limited images of the Galactic Centre region. At the end of the 1990s, the surveys of the stars orbiting in the central arcsecond around Sgr A* undergone by these two teams were demonstrating that:

- the radio source Sgr A* was coincident with the dynamical centre of the Galaxy, with a 0.1″ accuracy, but no IR counterpart had been detected down to $K \approx 16$;
- the central compact mass ($2.6 \times 10^6\ \mathrm{M}_\odot$ within 10^{-6} pc) was probably a black hole but alternative exotic solutions, such as clusters of stellar remnants or elementary particles, were still possible.

2. The advent of adaptive optics

Adaptive optics (AO), through a real-time compensation of the atmospheric turbulence with a deformable mirror, allows one to restore the imaging spatial resolution up to the telescope diffraction limit and to gain in sensitivity.

The first AO observations of the Galactic Centre region have been performed on 3.6 m telescopes (Fig. 1): the first H- and K-band images at CFHT in June 1996 with the visible AO system PUEO [10] and the first L-band images at the La Silla 3.6 m telescope in June 1999/May 2000 with the IR/visible wavefront sensors of the ADONIS AO system [11]. The H- and K-band images reached the diffraction limit, a deeper sensitivity than the speckle images obtained at Keck ($K \approx 18.5$ in not too crowded regions) and confirmed the aforementioned conclusions about the IR counterpart of Sgr A* and the mass of the central compact object. The L-band images also remained unsuccessful in detecting the IR counterpart of Sgr A*, putting new constraints, at larger wavelengths, on the IR Sgr A* emission.

These first images have stressed the specificity of AO observations of the Galactic Centre. Visible wavefront sensor AO systems suffer from the paucity of bright visible stars usable for guiding: in this region, the brightest stars in the visible are ∼15th magnitude stars located ∼20″ from Sgr A*. Guiding on one of these stars hence degrades the performance of AO by introducing anisoplanetism. On the other hand, with the presence of a bright IR source ($K = 6.5$) less than 6″ away from Sgr A*, the use of an IR wavefront sensor is therefore well suited for AO observations of the Galactic Centre region. Laser guide star (LGS) AO observations could be at first thought an alternative but their image quality is actually worse than with an IR wavefront sensor: at K, the Strehl ratio reached by the Keck LGS is 30–40% when NACO and its IR wavefront sensor reaches 50–60%.

From the year 2000, AO systems started to equip 8 m class telescopes, feeding imagers first, soon followed by spectrographs and spectro-imagers. The Galactic Centre has been one of the main targets of these new instruments. The following paragraphs present their major results.

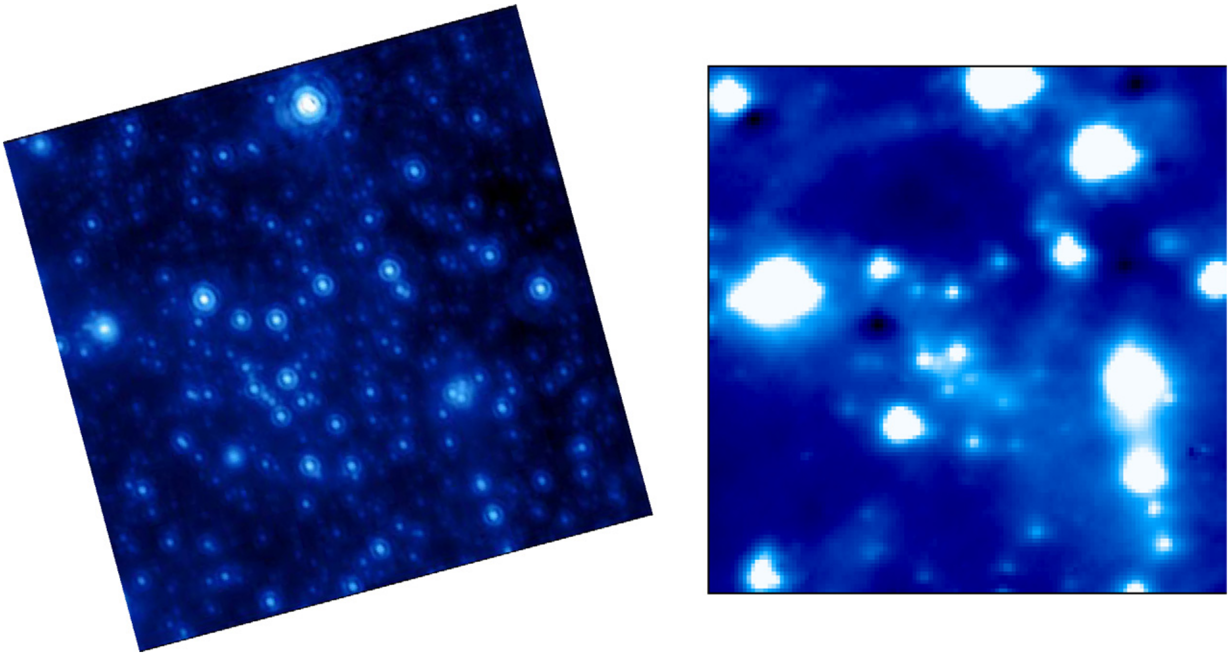

Fig. 1. First AO images of the Galactic Centre region (field of view: ∼13″ × 13″, North is up, East is left). Left, at K with PUEO/CFHT, from Rigaut et al. (1998) [10]. Right, at L with ADONIS/La Silla 3.6 m, from Clénet et al. (2001) [11].

3. The supermassive black hole in the Galaxy

*3.1. The nature of Sgr A**

The stellar orbit surveys that started in the 1990s with speckle imaging have been carried on with adaptive optics assisted imagers at VLT [14] and Keck [15], with a spatial resolution and a sensitivity improved by a factor ∼3 and ∼20 respectively compared to the NTT speckle images (Fig. 2).

These observations have first confirmed that the dynamical compact central mass is located at the inferred infrared position of the radio source Sgr A* within 1σ. Besides, the remaining alternative scenarios to a supermassive black

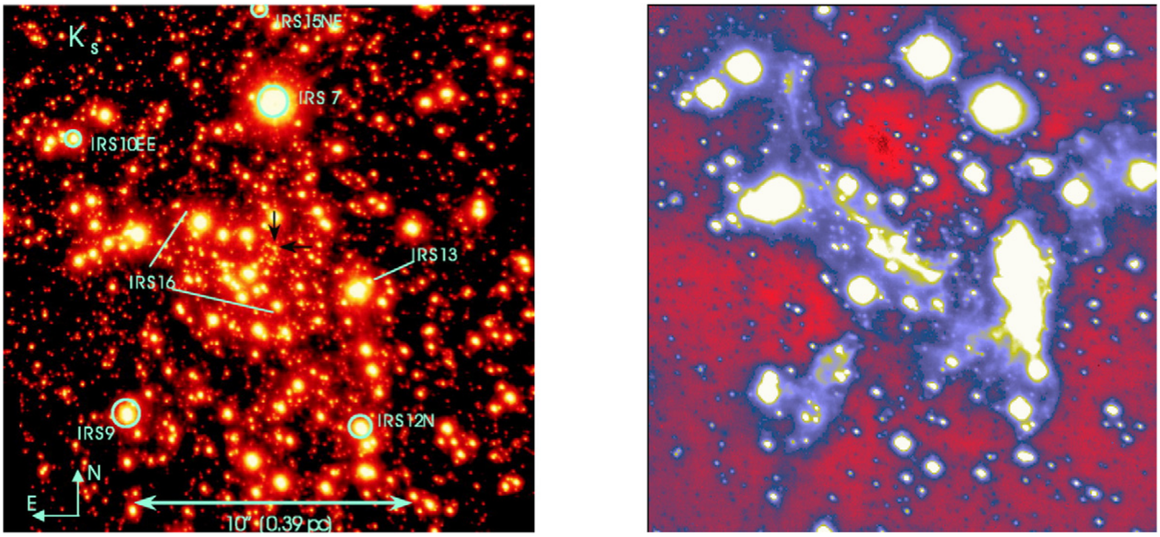

Fig. 2. VLT/NACO images of the Galactic Centre region (North is up, East is left). Left: K-band image (field of view: ∼19″ × 19″), from Genzel et al. (2003) [12], reproduced by permission of the AAS. Right: L′-band image (field of view: ∼16″ × 16″), from Clénet et al. (2004) [13].

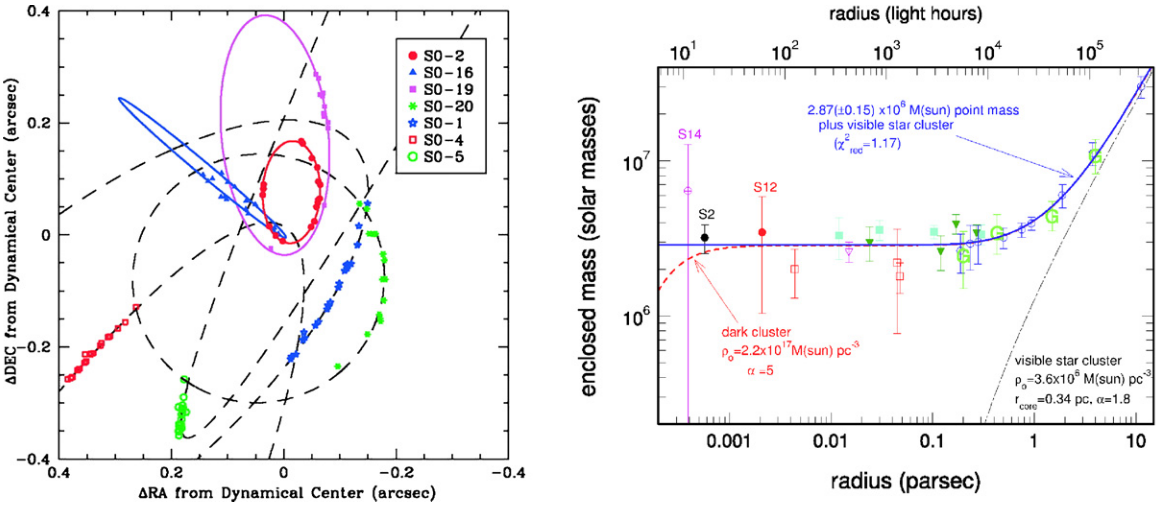

Fig. 3. Left: Orbits of the central stars from AO and speckle observations, from Ghez et al. (2005) [15], reproduced by permission of the AAS. Right: Enclosed mass measurements from AO observations compared to Plummer models, from Schödel et al. (2003) [14], reproduced by permission of the AAS.

hole, a cluster of dark objects (low mass stars, neutron stars, stellar black holes) or balls of dark particles (fermions or bosons) have then been ruled out by the enclosed mass measurements (Fig. 3) derived from these dynamical stellar surveys and performed at a radius down to 45 AU (2.2×10^{-4} pc): at the corresponding density ($\sim 10^{17}$ $M_\odot$ pc^{-3}), the dark cluster would collapse within 10^5 yr, less than the age of the Galaxy, and the required fermion mass in the fermion ball model would be 5 magnitudes beyond the current limit of such particles. A boson ball would comply with the observed density and size of the central dark mass but would also rapidly collapse to a black hole, leaving the supermassive black hole as the only scenario left. The Milky Way is hence the galaxy with the most convincing evidences for the presence of a supermassive black hole.

3.2. The infrared counterpart of Sgr A and the paradox of dimness*

Sgr A* is a very dim source ($L_{\mathrm{IR}} \sim 10^{35}$ erg/s $\sim 3 \times 10^{-10}$ L_{Edd}, $L_X \sim 2 \times 10^{33}$ erg/s $\sim 10^{-11}$ L_{Edd}) and since 1974, no counterpart of Sgr A* had been unambiguously detected at IR, nor at X-ray wavelengths.

With the improved sensitivity provided by AO on 8–10 m class telescopes, IR emission at the location of Sgr A* (within few milliarcseconds) has been detected for the very first time, from 1.6 to 4.8 µm [16–18] (Fig. 4), as outbursts lasting about 1 h and occurring about every few hours. A quiescent emission also seems to have been detected at H and K but is still discussed at larger wavelengths because of the emission of a dusty structure 75 mas south west of Sgr A*, i.e. at the limit of the spatial resolution at these wavelengths [19].

Similarly, the improved sensitivity and spatial resolution of new space observatories (Chandra and XMM) have recently lead to the first detections of X-ray flares from Sgr A* [21,22] and coordinated X-ray and IR observations allowed one to detect simultaneous X-ray and IR flares of Sgr A* [23], suggesting a common origin for both events.

Several models have been proposed to fit the observed spectral energy distribution of Sgr A* and account for the dimness of Sgr A*: radiatively inefficient accretion flow models (RIAF) [24], jet models [25] or a combination of both accretion and jet models [26]. They all attribute the IR flares to the synchrotron emission of accelerated/heated electrons while the X-ray flares would come from either the synchrotron emission of the same population of electrons or the synchrotron self-Compton (SSC) emission of up-scattered sub-millimeter and IR photons. The $\sim 10^2$ s cooling time of the synchrotron model is much larger than the (similar) timescales observed in the simultaneous IR and X-ray flares. The SSC model is also supported by the steep K-band power law slope observed on two rather faint flares with the integral field spectrograph SINFONI [20], which indicates that most probably little X-ray flux has been emitted during these two flares.

However, these arguments hardly favor a particular physical model: the power-law electrons concerned by the aforementioned synchrotron/SSC emissions are involved in both pure RIAF and (RIAF+) jet models. However, the

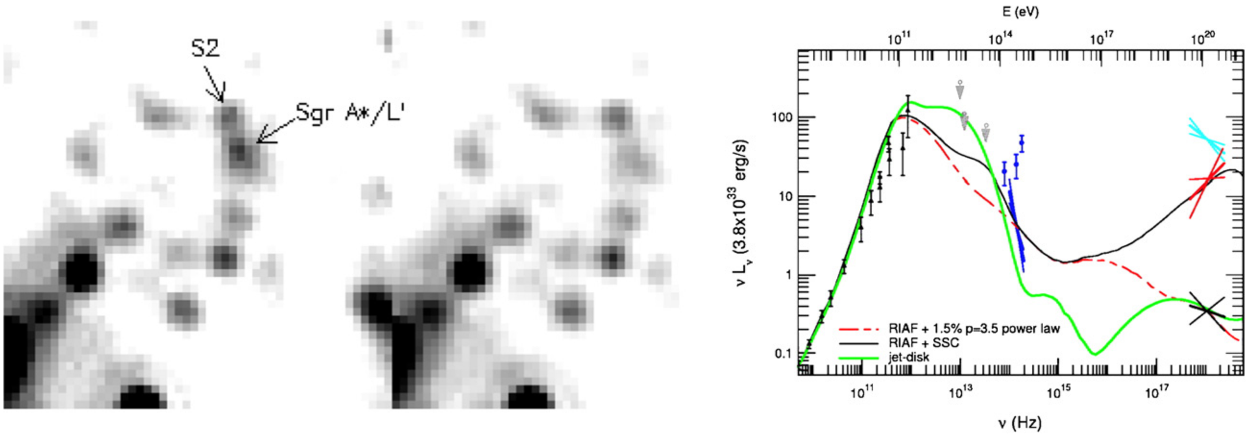

Fig. 4. Left: NACO L′-band images of the central stellar cluster during a flare and ∼1 h later (field of view: ∼1.4″ × 1.4″), from Clénet et al. (2005) [19]. Right: Models of the Sgr A* spectrum during its quiescent and flare states compared to flux measurements, from Eisenhauer et al. (2005) [20], reproduced by permission of the AAS.

periodic modulation observed similarly in the IR [16] and X-ray [27] flare light curves as well as the apparent correlation between the IR power law slope and the IR flux during a flare [28] could sign the accretion of matter close to the last stable orbit around a Kerr black hole.

4. The paradox of youth

4.1. Two young stellar populations

The large number of studies motivated by Sgr A* have also lead to a better knowledge of its environment. AO-assisted long-slit and integral-field spectroscopy has clarified the stellar content of the Galactic Centre region. The picture of the central stellar population is now the following:

- between 0.04 pc (1″) and 0.4 pc (10″) are found numerous emission-line stars, the so-called 'He-stars'. They have been identified from their infrared spectra, in particular their He I lines [29], as blue supergiants between their O and Wolf–Rayet phases. These stars are rotating inside two distinct thin disks (Fig. 5), the inner one rotating clockwise and the outer one counter-clockwise [12].
- inside the central 0.04 pc, the 'central stellar cluster', the so-called 'S-stars', is made only of massive main-sequence stars, typically late O and B stars. Their orbits, unlike the He-stars, are isotropically-distributed and their spin is similar to those of Solar System neighborhood stars.

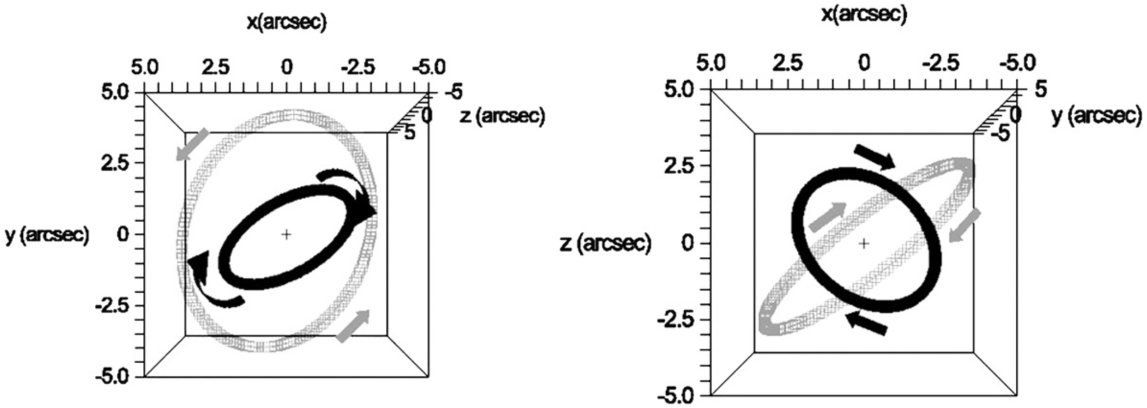

Fig. 5. The two He I star disks, as seen from two different positions. x and y are the plane of the sky coordinates, z is along the line of sight axis, from Genzel et al. (2003) [12], reproduced by permission of the AAS.

The presence of such young stars so close to the central supermassive black hole is know as the 'paradox of youth': the cloud in which would have formed these stars would require unusually high densities to resist the strong tidal forces in the black hole environment and these central stars are too young compared to the duration of a putative migration after a formation outward. Note that the two classes of young stars at the Galactic Centre, namely the He-I stars and the S-stars, have different strong constraints: the He-I stars are more massive, shorter-lived than the S-stars and are distributed in the two aforementioned disks, while the S-stars appear as quite normal stars and are the closest to the supermassive black hole. Hence, each one could be explained by two different kinds of model. Two major classes of models have been proposed to solve this paradox of youth and are presented below.

4.2. Solutions to the paradox

4.2.1. Migration after outward formation

In this scenario, the young stellar population at the Galactic Centre would be brought by a young stellar cluster infalling under dynamical friction [33]. The migration timescale being proportional to the square of the originating distance and inversely proportional to the cluster mass, clusters similar to the Quintuplet or the Arches clusters, whose mass are about $10^4\ M_\odot$, would migrate in $\sim 4 \times 10^7$ yr from a distance of ~ 10 pc.

However, the strong gravitational field of the central supermassive black hole would dissolve this cluster, as it would get closer to the centre. Only the presence of an intermediate mass black hole would overcome this dissolution [34] and allow the cluster to leave early-type stars at about the same location as they are observed now at the Galactic Centre. However, during its infall, the stellar cluster would leave behind him a number of young massive stars that are not observed at large radii at the Galactic Centre. In addition, this scenario would only account for the early-type stars found at a distance of Sgr A* between 0.04 and 0.4 pc and an additional process would be necessary to account for the S-star cluster: during the stellar cluster infall, O-stars could have encountered another star so closely that their envelopes would be stripped and they would finally look like B-stars [35]. But these encounters are not expected to produce stars as 'normal' as the S-stars appear to be from the SINFONI observations [20].

4.2.2. In situ star formation

The major issue in an in situ formation model is the required high density to overcome the high turbulent velocities and strong magnetic fields in the supermassive black hole environment.

The circum-nuclear disk (CND) is a tank of useful gas for star formation and a cycling scenario has been proposed to form the central most massive young stars [30]. The CND has currently an inner unfilled cavity because of the strong radiation pressure of the hot early-type stars. After the death of these stars ($\sim 10^7$ yr), the internal viscosity will make the CND inflow towards Sgr A*, leading to an enhanced accretion that will trigger high compression of the gas and thus star formation. These newly formed stars, and this boosted accretion, will once again empty the central parts of the inflown CND till the cycle starts again.

Another scenario explains the formation of the He I stars by the fragmentation of a disk due to self-gravitation [31]. This model would hence explain the two disks in which these stars are distributed and put constraints on their limit masses (from 10^4 to $10^5_\odot$).

Recent SINFONI observations of the Galactic Centre stellar population [32] have indeed shown that the properties of the two disks (thickness, density profiles, stellar eccentricities, total stellar mass) in which reside the central early-type stars well comply with the in situ formation scenario. Hence, the paradox of youth may partially be resolved, namely for the 'He stars'.

However, this scenario still explains with difficulty the observed properties of the S-stars, in particular the fact that they are only B main sequence stars, not more massive stars and so close to the black hole.

5. Towards milliarcsecond spatial resolutions

5.1. Infrared interferometry

After a recent ESO call for second-generation VLTI instruments, a consortium gathering the MPE (Garching, Germany), the LESIA (Observatoire de Paris, France), the MPIA (Heidelberg, Germany), the Cologne University (Cologne, Germany) have proposed an instrument whose main science driver is the Galactic Centre: Gravity [36].

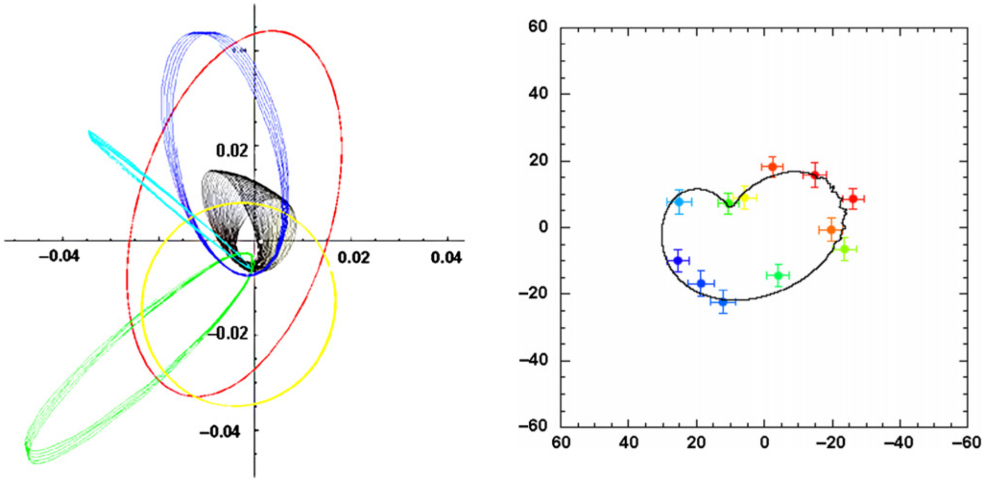

Fig. 6. Left: Simulated relativistic stellar orbits as would be observed with Gravity (axes in mas), from Paumard et al. (2005) [37]. Right: Simulated last stable orbit as would be observed with Gravity during Sgr A* flares (axes in µas) [37].

The first goal of the instrument is to follow up the relativistic orbital motion of stars that are even closer to Sgr A* than the S-stars (Fig. 6). Using up to 6 baselines, Gravity will 'image' these few stars down to a limit magnitude of $K = 19$ in $\sim$1 h with a spatial resolution of about 4 mas. It will then be possible to derive the enclosed mass within these orbits, to compare it with the enclosed mass found from the S-star orbits and thus to constrain the parameters of the putative extended mass around Sgr A*.

The second goal of Gravity is to disentangle between the different Sgr A* flare emission scenarios: within the framework of the 'accretion scenario', Gravity should provide, with an astrometric accuracy of $\sim$10 µas and a limit magnitude of $K = 16$ in $\sim$5 min, the astrometry of the flares by following the hot spots of gas whose emission on the last stable orbit of the black hole is thought to be responsible for the flares (Fig. 6).

Equipped with four infrared wavefront sensors (one for each UT of the VLT) and optimized to increase the instrumental throughput by a factor 20 compared to the present VLTI instrumentation (to reach 40%), Gravity is planned to have its first light in 2012.

5.2. *Extremely Large Telescopes*

Different projects for an Extremely Large Telescope, with prime mirror diameters larger than 30 meters, are now under intensive study phases. Their tentative schedules are already planning a first light between 2015 and 2020 and their first instrumentation will comprise a 'simple' adaptive optics system, such as the current ones on 8–10 m telescopes (e.g., NAOS at VLT, Altair at Gemini North). The spatial resolution will be increased by a factor 3–5, the astrometric accuracy will reach few tenths of milliarcseconds and the sensitivity will gain a factor 10–30.

The potential of such instruments for the study of the Galactic Centre is huge. The dynamical and spectroscopic surveys of the closest stars to Sgr A* (Fig. 7) will bring new and/or more accurate constraints on [38]:

- the black hole mass;
- the distance to the Galactic Centre;
- the extended distribution of matter (parameters of the power-law models);
- the galactic dark matter halo profile (from the galactic shortest to longest axis ratio).

In addition, the 3D orbits and spectra of a greater number of stars will be derived from these surveys, potentially allowing one to better know the two disks in which resides the emission-line stars, to discover the stellar population inside the S-star orbits, and thus to eventually completely resolve the paradox of youth.

6. Conclusion

Sgr A* and the Galactic Centre are perhaps the most striking examples showing the impact of instrumental developments on our scientific knowledge. The highest spatial resolution has been the driver of these developments:

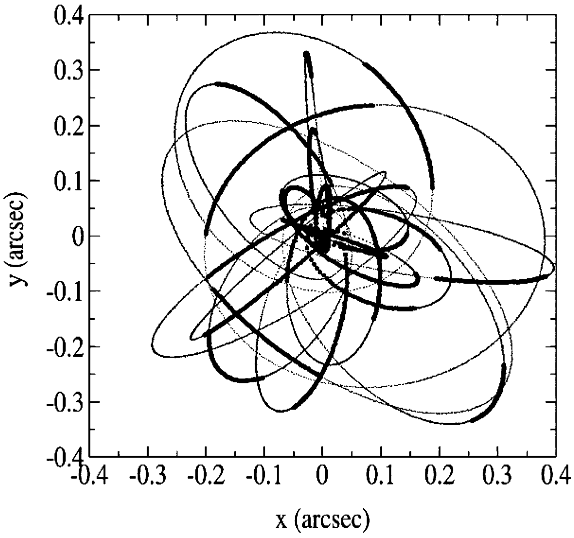

Fig. 7. Simulated positions of 20 stars around Sgr A* as would be observed by a 30 m ELT during 10 years with 10 observations per year (thick points) and their fitted orbits (solid lines), from Weinberg et al. (2005) [38], reproduced by permission of the AAS.

from seeing-limited to speckle, then adaptive optics assisted and, before interferometric images, the gain in angular resolution is about a factor 250! Thirty years after the discovery of Sgr A* and only five years after the installation of adaptive optics on 8–10 m telescopes, the reward has been impressive: the mass and distance of Sgr A* are now known with an unprecedented accuracy, orbital parameters (positions, velocities and even a few accelerations) and physical parameters (temperature, mass, even a few metallicities) can now be derived for several stars. And soon, with Gravity and ELTs, the Galactic Centre will be a unique laboratory to test General Relativity in the poorly know regime of a very strong field!

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