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Seminar

Stellar processes in Galactic center

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Abstract

The seminar is about stars orbiting Galactic center. It is focused on dynamics and evolution of so called S-stars, stars orbiting central black hole on distances up to 0.04 pc. Evidences of existence of a massive black hole (MBH) are presented and techniques of observing Galactic center as well.
Contents

1 Introduction 2

2 Evidences of existence of MBH in Galactic center 2
   2.1 Mass function .......................................................... 2
   2.2 Why a Black Hole and not Something Else .......................... 3
   2.3 Double black hole ....................................................... 4

3 Observing Techniques 4
   3.1 Extinction ..................................................................... 5
   3.2 Resolution issues ........................................................... 5
   3.3 Astrometry and spectrometry ......................................... 6
   3.4 Orbits determination ...................................................... 7

4 Dynamics and evolution of stars close to Galactic center 7
   4.1 Characteristic scales [1] .................................................. 7
   4.2 Different stellar density cusp .......................................... 10
   4.3 Evolution of stars in Galactic center ............................... 11
   4.4 Where were the stars born ............................................. 11
   4.5 Star-MBH interactions ................................................... 13

5 Conclusion 13
1 Introduction

In 1974 Balick and Brown detected radio source in the center of our Galaxy\cite{1}. As the telescopes and cameras got better, exploration in infrared bands begun and existence of a massive black hole (MBH) is inescapable conclusion. With the observations of dense stellar cluster the basic properties of MBH can be calculated and soon the effects of special relativity will be observed\cite{1}. Center of Galaxy is therefore extremely interesting for astrophysicists because many different objects and processes, which are not found anywhere else in the Galaxy, take place there. Techniques used for observations and new cameras are developing in hand with observational demands, so observations are getting better and provide fresh data for this field of astronomy.

Figure 1: Left: Laser of a VLT active optics points toward Galactic center. Source: APOD. Right: Galactic center pictured in 3 bands, made during the same observing campaign as picture on the left.\cite{2}

2 Evidences of existence of MBH in Galactic center

It can be concluded from observations made in the past decade that a massive black hole exists in center of our Galaxy.\cite{3} Its position is equivalent to a well known radio source named Sgr A*\cite{5}. This makes Galactic center a unique space in our Galaxy and the nearest massive black hole system we can study.\cite{1} I will show in next few paragraphs that the center is really occupied by black hole.

2.1 Mass function

Mass function describes a distribution of mass. In this case we are interested in mass enclosed in different radii. In noncentral parts of our Galaxy the relation $m(r) \propto r$ is observed\cite{4}. However this relation is not necessary valid close to the Galactic center. If this relation or any other in form $m(r) \propto r^n$, where $n > 0$ is valid, then the mass function decreases to zero in the center. If there is a compact mass the mass function will converge to $m$, where $m$ coresponds to the central mass.

$m(r) \propto r$ relation is observed outside 0.4 pc. Between 0.4 pc and 0.04 pc mass function flattens to $m(r) \propto r^{0.4}$\cite{2}. On approximately the same length-scale there appears a cluster of

\footnotesize{\begin{itemize}
  \item This relation is calculated from orbital velocities and it differs from distribution of observable mass. This paradox is one of the strongest evidences of dark matter existence.
\end{itemize}}
young massive stars. Flattened mass distribution is not yet an evidence of central mass but points out that mass function might converge to nonzero value. With recent technologies it was possible to observe and measure orbits of stars as close as 0.5 mpc to the Galactic center. Figure 2 shows that mass function converges[4].

![Figure 2: Measurements of different groups are presented on same graph. Triangles and circles are measurements of stellar orbits, ”G” marks are measurements of gas kinematics. Solid line is the best fit to all the data. Dash-dot line represents a mass function if only star cluster was present and dash line represents a mass function if a cluster of unknown dark objects existed in the center. [4]](image)

### 2.2 Why a Black Hole and not Something Else

Primary parameters of the dark mass\(^2\) are mass, size, location and velocity. For determination whether the dark mass is MBH only mass and size are relevant. We have already seen how the mass is measured. Size can only be estimated. There are several ways to estimate the size of a MBH. The most accurate measurements can be made trough radio observations.

Gas can be observed with radio telescopes on similar distances from Galactic center like stars. It has the same orbital velocities and same results are acquired for mass of black hole. Beside this, slightly better resolution is achieved with radio telescopes. Sgr A\(^*\) appears as point source and upper limit for it’s size is 20 AU\(^3\).[5]

Despite the radio data is the strictlies criteria it is worth to mention some others.

Central object cannot be larger than smallest periapse\(^4\) observed. The smallest periapse observed is 0.22 mpc.[1]

\(^2\)Term dark mass is widely used for naming unknown mass, not to be confused with dark matter, unknown particles interacting with known matter with gravitational interaction only.

\(^3\)1 AU= 150000000 km. Astronomical unit is mean distance between Earth and Sun.

\(^4\)periapse is the shortest distance between orbiting object and focus of ellipse.
From near infra red observations the size of source can be calculated. The upper limit for it’s size is derived from minimum amount of time required for information to travel across the object. If one side of source begins changing brightness, the other side can only learn about it and contribute to it in time

\[ t = \frac{d}{c_0} \]

\( d \) is diameter of a source and \( c_0 \) is speed of light. Timescale is determined trough observations of brightness fluctuations and diameter is calculated. [1]

In center is also an X-ray source, which is most probably connected to the star cluster[5]. The same method of observing brightness fluctuations can be used as in the infra red bands.

These criteria are plotted on the graph on figure 3.

![Graph showing size and density of dark mass candidates](image)

Figure 3: Squares: candidates for dark mass. Circles: lower limits on the size and density of the dark mass[4]. Only black hole or some exotic objects are small enough (exotic objects like boson stars are not proven to exist not even theoretically).

### 2.3 Double black hole

We have seen on the figure 3 that the estimated size of the central object is \( 10^{-6} \) pc. We know nothing about the object but its mass which tells us that the central object is a black hole. Only presence of black hole can be proved with current observations and not the mass distribution inside \( 10^{-6} \) pc. It is possible that two black holes (or even more) exist in the center. This is plausible, because of the galaxy formation process. Galaxies were formed with merging of more smaller galaxies, each having a black hole in its center.[1] It is thus possible that two central black holes haven’t merged yet like their host galaxies did.
3 Observing Techniques

Observing Galactic center is somewhat different than observing other parts of the Galaxy. Gas and dust prevents visible light to come through and observations in other wavelengths than visible and UV are necessary. This phenomena is called extinction. Beside this we are limited with telescope resolution. Galactic center is 8 kpc away and central star cluster is 0.04pc large. This means that size of cluster on the sky is 1 arc second only. [4]

3.1 Extinction

Stars’ spectra are approximately black-body and extend mostly over visible and near infrared bands. Because the extinction in visible is around 30 magnitudes, observing in infrared is necessary. K band (2.2µm) is widely used, because extinction drops to 3 mag in this band. It drops to zero at longer wavelengths but several problems arise when observing at longer wavelengths; stars are dimmer, resolution of telescope is lower and ambient background is much higher. Observation of stars is impossible in radio-bands where no above problems exist, but stars do not emit light in radio-bands.

![Figure 4: Picture shows Galactic plane in different wavelengths. It is clearly seen that dust absorbs visible wavelengths but not infrared. Stars are visible in visible and near infrared only. Source: http://mwmw.gsfc.nasa.gov](image)

3.2 Resolution isues

Resolution of telescope is determined with diffraction patterns (we neglect effects of the atmosphere here). Because the aperture of a telescope is always a circle a simple formula can be used to calculate resolution:

$$\phi = 1.22 \frac{\lambda}{D},$$

(3.1)

where $D$ is diameter of aperture and $\lambda$ the wavelength. Picture of a point source in a focal plane is a 2 dimensional Airy function. From formula above we can easily calculate that resolution of a telescope is no longer important at diameters of few centimeters if bad seeing is present. Seeing is condition of atmosphere and tells us what the degree of ”star twinkling” is. Twinkling is caused by hot and cold air cells with different densities. When air mixes, light from stars
passes different cells of hot and cold air what causes oscillations in position of a star on the sky and it’s intensity. Time-scale is in order of a second in infra red bands and some ten times shorter in visible bands. If we take picture of stars with exposure times longer than one second, picture won’t be Airy function any more but much larger spot. Seeing is measured in angle. Usual seeing on continents is around 1 arcsec and 0.2 on high islands. In order to resolve tens of stars in one square arc second special techniques are used.[6]

Effects of seeing can be reduced if it is known how a star will twinkle. Because the scintillation is a random process, effect must be measured and picture corrected in real-time. An artificial star is created with a laser in the observed field, so that the optical paths of object’s light and laser are almost identical. Scintilations of artificial star are observed and parameters to correct the optical path are calculated. However the scintilations cannot be totally eliminated.

Another technique frequently used is speckle imaging. Many images of the source are made with exposure times shorter than one second. Because oscillations occur on one second time-scale, short-exposure image is affected in a different way. Each cell of hotter or cooler air slightly changes the optical path and shifts the image. More images of the same objects are created, depending on the number of cells that distracted the light path. If the object is not point-like, images can be interlaced. More pictures are made and images are extracted and summed into one image with higher signal. Only small amount of light is collected on detector in one second so low noise and high sensitivity cameras are used.

Correct image reduction can do further improvements to resolution. Because we can calculate how the telescope pictures a point source, reverse process can be made (deconvolution). Two algorithms are usually used. One is Wiener deconvolution, which works well with images with low signal to noise ratio. We have a system[7]

\[ y(r) = h(r) \ast x(r) + v(r), \]  

(3.2)

where \( \ast \) denotes convolution and \( y, h, x, v \) are observed signal, point spread function (PSF), input function and additive noise respectively. The goal is to find \( g(r) \), so we can estimate \( x(r) \) as follows:

\[ \tilde{x}(r) = g(r) \ast y(r), \]  

(3.3)

where \( \tilde{x}(r) \) is an estimate of \( x(r) \) that minimizes mean square error. \( g(r) \) is found using a Fourier transform.

Another deconvolution frequently used is Richardson-Lucy’s [8]. Pixels in the observed image are represented as

\[ c_i = \sum_j p_{ij} u_j, \]  

(3.4)

where \( p_{ij} \) is point spread function (Airy function in this case), \( c_i \) is the observed value at position \( i \) and \( u_j \) is true value at position \( j \). Idea is to calculate the most likely \( u_j \), given the observed \( c_i \) and known \( p_{ij} \). \( u_j \) is calculated iteratively.

Deconvolution doesn’t improve spatial resolution significantly, but increases strehl ratio. Strehl ratio is amount of energy collected in the central order of Airy function, divided by all of the energy that is collected. Strehl ratio can be close to 1 after processing.

### 3.3 Astrometry and spectrometry

Position of stars is measured by astrometrical methods. It is possible to measure the star positions with accuracy of a few houndreds \( \mu \)arcsec. The position of S stars is compared with brighter nearby stars and these are compared with standard stars with well known positions. From 1992 to 2002 SHARP camera at ESO 3.5 telescope was used. Now the NACO camera
at VLT is used. Measuring spectra of stars in the Galactic center is harder than measuring spectra of other stars. Stars in the center are close to each other and separate spectra can not be observed. Area of 0.8” times 0.8” is covered with SINFONI spectroscope at VLT. However spectral lines of stars can be resolved from each other, because they have high radial velocities and they are resolved even with a low resolution spectroscope (R= 4000 or R=1500 for SINFONI).[3]

### 3.4 Orbits determination

A Keplerian orbit can be described by 6 parameters: semi-major axis $a$, eccentricity $e$, inclination $i$, angle of the line of nodes $\Omega$, angle from ascending node to pericenter $\omega$ and the time of the pericenter passage $t_p$. If the potential is not Keplerian, orbits have more parameters. Cause for non Keplerian potential is extended mass or influence of Schwarzschild metric. Recent measurements have been fitted with these extended parameters, but no difference from Keplerian potential was calculated.[3]

6 Keplerian parameters can not be observed directly and orbits must be described by any other 6 independent parameters. These can be either position (in two dimensions, as distance can not be measured precisely enough to observe any variations), velocity (in 2D), acceleration (in 2D), radial velocity and radial acceleration, because nothing else can be measured.[3]

Measuring the position of the central mass is more simple than determining the orbits. Because all stars orbit the same central mass, the acceleration vectors of all stars point to the position, where the mass is. Result obtained with this method is shown in figure 7 on the left. Pros of this method are that we do not need to know the parameters of the orbit. The other method is fitting an orbit to the observations (figure 7 right). Nowadays the second method is used, because there is enough data to fit the orbits well enough. Process is done by computer with a simple monte-carlo method. Last method will someday give other informations about the central mass like double black hole, Schwarzschild potential and more.[3], [1]

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**Figure 5:** *Bottom left:* Image in H band of central 20 arcsec. *Top left:* Crop of central 2 arcsec. *Top right:* Image processed with Wiener algoritm. *Bottom right:* Image processed with Richardson-Lucy algorithm. Stars are sharper but some ring artifacts appear.[2]
4 Dynamics and evolution of stars close to Galactic center

4.1 Characteristic scales [1]

Several important length and time scales govern the dynamics of stars around a massive black hole. I will list most important ones and calculate their values with assumptions of $M_\star = 1M_\odot$, $R_\star = 1R_\odot$ and the $M = 3.5 \times 10^6 M_\odot$ for black hole mass.[1]

**Event horizon.** The event horizon or Schwarzschild radius (for non-rotating black hole) is

$$r_S = \frac{2GM_{BH}}{c^2} = 3 \cdot 10^{-7} \text{pc} \sim 9\mu\text{arcsec}$$

**Tidal radius.** The tidal radius is the maximum distance, where tidal forces can overwhelm the stellar self-gravity:

$$r_T = R_\star \left(\frac{M_{BH}}{M_\star}\right)^{1/3} = 3 \cdot 10^{-6} \text{pc} \sim 90\mu\text{arcsec}$$

**Relaxation length-scale** is the minimum distance, where large angle deflections by close gravitational encounters are possible. Closer to the black hole, the escape velocity of black hole exceeds the escape velocity from the stellar surface:

$$v_e^2 = \frac{GM}{R}$$

$$r_R = \frac{M_{BH}}{M_\star} R_\star = 0.08 \text{pc} = 2\text{arcsec}$$
Figure 7: Left: Projected average acceleration vectors with 2σ errors. Position of central mass is shown in grey shades. Calculated from data by 2003.[4] Right: Orbit of star S2 fitted with Keplerian model. Central mass is black spot at dec = 0, RA = 0. Central mass has moved in 16 years, so the orbit is not closed (zoomed frame.) Mass is not drawn point-like because of the same reason.[3]

**Age of Galactic center.** It is assumed that Galactic center is of the same age as Galaxy. This is similar to Hubble time\(^5\).

\[ t_H = 10 \text{Gyears} \]

**Dynamical timescale** or orbital time is the time it takes a star to cross the system.

\[ t_D = s\pi \frac{r}{v} = 2\pi \sqrt{\frac{r^3}{GM}} = 2 \cdot 10^5 \text{ years (at } r = 3 \text{ pc) = 300 years (at } r = 0.03 \text{ pc)} \]

**Relaxation time-scale.** Relaxation time is a measure of the time it takes for one object to be significantly perturbed or ejected from a system. Relaxation time can be approximately derived from the rate for large angle deflections, because mostly these can eject the stars from the cluster due to high energy exchange. Time scale for large angle deflections is

\[ t_L = \frac{1}{n\sigma\Sigma}, \]  

(4.1)

where \( \sigma \) is one dimensional velocity dispersion and \( \Sigma \) is a cross-section:

\[ \Sigma \sim \pi \left( \frac{G(M_\star)}{\sigma^2} \right)^2 \]

\(^5\)Hubble time is age of the universe; 13.7 billion years.
The actual rate is larger due to the addition of many weaker interactions, so timescale is of the order
$$t_l \sim \frac{\sigma^3}{G^2(M_*)^2 \pi n_*} \sim 1 \text{Gyres}$$

**Segregation timescale.** Segregation is process, where massive stars ”sink” into the center of a cluster and less massive ones take place in outer parts of a cluster. Time-scale is same as relaxation time-scale and scales with $M_*$:
$$t_s \sim t_l \frac{\langle M_* \rangle}{M_*}$$

**Collision time-scale** Because there is a high density of stars in the Galactic center, collisions can occur. It can be derived, that the rate of collisions between star of mass $M_\alpha^a$, radius of $R_\alpha^a$ and another star with mass $M_\beta^b$ an radius $R_\beta^b$ is:
$$t_{c}^{-1} = 4\sqrt{\pi n_* \sigma (R_\alpha^a + R_\beta^b)^2 \left[1 + \frac{G(M_\alpha^a + M_\beta^b)}{2\sigma^2(R_\alpha^a + R_\beta^b)}\right]} = 10^{-9} \text{year}^{-1} \text{ at } 0.02 \text{ pc}$$

### 4.2 Different stellar density cusp

Simulations of stellar systems around the black hole indicate that a wide range of scenarios all lead to the formation of a stellar density cusp, a region of diverging density around massive black hole. We do not know how the stellar cusps are formed. Only observations in present time are possible and no comparisons with other galaxy centers can be made. If we want to study the evolution of the Galaxy center we have to make models and compare model results with observational data.

**Simple models**

Let us assume that the stellar population is spherically symmetric. Distribution of stars is described with a distribution function of form[9]
$$f(r,v) = KE^p, \quad E = \frac{GM}{r} + \frac{1}{2}v^2,$$
where $K$ and $p$ are constants. For this distribution function star density satisfies
$$n_\star(r) = \int f d^3v \propto r^{-(p+3/2)},$$

The simplest distribution is isothermal ($p = 0$). Such a distribution will give rise to a $n_\star \propto r^{-3/2}$.[1] If relaxation time is short enough, the initial distribution will be erased and final configuration will depend only on boundary conditions and the stellar mass function. If all stars have the same masses, the solution is called Bahcall-Wolf. Stars relaxed from a system represent a mass flux. Flux of mass can be expressed in units of energy [10]:
$$F \sim \frac{n_\star r^3 v^2}{t_r},$$
where $t_r$ is relaxation time. If 4.1 is inserted, flux can be expressed with $n_\star$ and radius:
$$F \sim \frac{G^{3/2}m_M^2 r^{7/2}}{M_{BH}^{1/2}}.$$

In a steady-state condition $F$ must be constant and relation $n_\star \propto r^{-7/4}$ is obtained from the last equation. If the star population consist of stars with masses $0 < M_\star < M_2$, it can be shown [1] that distribution function scales with $r^{p_M}$, where $p_M = \frac{M}{4M_2}$.

Stellar distribution around adiabatically growing black hole can also be solved analitically[13].
Complex models

Figure 8: Top: Top view of orbits at time $t = 0$ and $t = 10^6$ years. Bottom: Side view of the same orbits.[11]

In the era of computers the problems are solved numerically with n-body simulations. Complex star-star interactions can be taken into account and general theory of gravity is obeyed. Many simulations were made and the latest results show, that characteristics of observed system around the central black hole can be reproduced with stars initially concentrated in a disk, where stars have slightly eccentric orbits (figure 8).[11].

4.3 Evolution of stars in Galactic center

Evolution of stars at such extreme conditions is different from evolution of isolated stars.[1] This can be concluded from the most basic observations, which revealed that star density is about 10 000 times higher than in Sun’s neighborhood. When colors of stars are measured abundance of red stars is observed and many Wolf-Rayed stars⁶ are found.

Star formation at extreme conditions is not yet well understood and it is not clear yet wether the stars were born in central cluster or were they born outside and imported into the cluster later. Star-black hole and star-accretion disk interactions are also interesting to study.

4.4 Where were the stars born

Two different populations of stars are found in the inner 0.4pc. In the inner 0.04 pc mostly B stars are present and OB and Wolf-Rayet stars are observed between 0.04 and 0.4 pc. This distinction is important, because B stars are more numerous, less massive and longer lived (by 1 or 2 orders than OB and Wolf-Rayet stars). There may actually be two separate issues: how to explain OB and WR stars at 0.04-0.4 pc and how to explain stars (with designation S followed by number and often caled S stars) within 0.04 pc. Some scenarios proposed focus on both issues and some on one or another. I will focus mostly on S star formation. Any explanation of the S stars should account for three principal properties[1]:

1. The stellar population is entirely normal main sequence stars population. They have normal luminosities, normal absorption lines in their spectra and they rotate with velocities similar to those of nearby Galactic disk B stars.

⁶Wolf-Rayet stars are massive, hot stars with strong helium emission lines.
2. The relative fraction of the young stars increases toward center, where no giant old stars exist (in the inner 0.02 pc).

3. The orientations of the stellar orbits appear overall random in contrast to the ordered planar rotation observed farther out.

Problems arise, because the minimal proto-stellar cloud density that can resist the MBH tide is much higher compared to clouds elsewhere in the Galaxy[1] \( n_{\text{min}} \sim 10^4 \text{cm}^{-3} \):

\[
n_{\text{min}} \sim \frac{m_{\text{MBH}}/m_{\text{Hydrogen}}}{r^3} \sim 10^8 \text{cm}^{-3}.
\] (4.6)

The young stars are also too short-lived to migrate to the inner parts of Galaxy center by dynamical friction. There are some proposed solutions but none is quite satisfactory.

\textit{In-situ} star formation models include external pressure to trigger cloud collapse. Cloud-cloud collision could initiate cloud fragmentation and star formation. However it is not clear if high enough compression can be achieved for cloud becoming unstable. Such a cloud would be Jeans-unstable already at 2 pc and stars would form at those distances[1].

Another in-situ theory suggests that stars were formed in a gaseous disk around MBH. Such a disk is not observed in our Galaxy but has been observed in some others. A fragmentation due to self gravity has to occur in the disk if stars are supposed to form. The criterion for disk fragmentation due to self gravity can be estimated. Jeans mass \( M_J \) and Jeans radius \( R_J \) must be such that free fall time \( t_{\text{ff}} \) is shorter than the sound crossing time. Criterion for Jeans radius is simple:

\[
R_J > c_s t_{\text{ff}},
\] (4.7)

what can be rewritten to a similar condition for \( M_J \):

\[
M_J > \rho c_s^3 t_{\text{ff}}^3.
\] (4.8)

If exact numbers for a disk around black hole are calculated, the \( M_J \) gives few Solar masses. Proto stellar cloud then begins accreting gas from disk and grows. This theory explains well the formation of stars but not why there are only B stars in the cluster[1].

Rejuvenation model assumes that stars are older than it appears. They were somehow imported to the Galactic center, where they were affected by envelope stripping collisions, tidal heating... Stars could be formed by lower mass mergers. Problem is, that none of these processes would create a cluster of B stars or a cluster of any similar stars in general.

Dynamical friction might be responsible for importing stars close to the black hole. Dynamical friction is a process, where a star penetrates through a cluster of other stars or gas. Star exchanges some of its kinetic energy with stars in a cluster so stars gain some speed and star looses it. If they are all orbiting a black hole, star can exchange enough energy to change its orbit into a much tighter one. The derivation of an expression for dynamical friction is beyond the scope of this seminar, but it is easy to show, that force of dynamical friction can be expressed with 3 physical quantities mass \( M \), speed \( v_M \) and mass density of surrounding media \( \rho \). Expression for force always contains gravitational constant and there is only one combination of these variables that has the units of force[5]:

\[
f_{\text{d}} \propto \frac{G^2 M^2 \rho}{v_M^3}.
\] (4.9)

In line with this theory are two star clusters 10 pc from the center but again this theory can not explain excess of B stars.
Another class of dynamical scenarios are those that invoke 3-body interactions. The exchange scenario postulates that B stars once had a very massive binary companion. They were born in a massive cluster and an orbit developed that brought them close to the central black hole. B star exchanged companion there and is orbiting black hole then. Simulations show that exchange rate is high enough if there are enough pairs around. The weakness of this scenario is having a cluster where lot of massive stars are born and again it can not explain B star cluster. Other 3-body scenarios include small black hole interactions and high eccentricities in the orbits of B stars.

4.5 Star-MBH interactions

Tidal disruption, tidal heating, gravitational wave emission are some of the effects of star-MBH interaction concerning evolution. I will only discuss tidal disruption here.

The interaction is characterized by three length-scales: the stellar radius $R_\star$, the Schwarzschild radius $r_S$ and the tidal radius $r_t$. The different regimes of tidal disruption can be classified:

$r_S \ll r_t \ll R_\star$ The tidal disruption is weak and star processes are dominated by star’s gravity and pressure.

$r_S \ll r_t \sim R_\star$ A strong Newtonian interaction will occur which would result significant mass loss and possible disruption, depending on the central concentration of stellar density profile.

$R_\star \sim r_S < r_t$ The disruption is complete, star debrieses fall into the black hole and the disruption must be treated relativistic.

$R_\star \ll r_S < r_t$ This is the usual case in Galactic center. The disruption can be treated as Newtonian.

$R_\star \ll r_t \ll r_S$ Star falls into the black hole as a point particle without being significantly perturbated.

It is clear that disruption occurs if black hole is small enough so that $r_t < r_S$ and if star’s angular momentum is small enough so that the minimal distance between star and black hole is smaller than tidal radius.

There is yet no clear evidence of tidal disruption, but debries would form supernova remnant-like structures, a long term signatures of tidal disruption[1]. It was suggested that Sgr A East radio source originates from tidal disruption processes, but it is not proven yet that it is not supernova remnant.

5 Conclusion

The following table shows progress achieved to date. Galactic center is studied through observations and theoretically. If conclusions in a particular category were made, the field is marked with a tick.
Galactic center position and BH properties

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<th>Theory</th>
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<tr>
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</tr>
<tr>
<td>Nature of BH(^5)</td>
<td>in near future</td>
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Properties of stellar system

<table>
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<th>Observation</th>
<th>Theory</th>
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<td>✓</td>
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<tr>
<td>Dynamical properties(^6)</td>
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<td>Some models give results comparable with observations</td>
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<tr>
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<td>Theories are not even close to explain strange population in GC</td>
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<tr>
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Post Newtonian physics

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There are no dramatic discoveries expected in next few years. Stellar tracks of fainter stars will be observed and accuracy will get better. Goal of the next years is a detection of effects of general theory of relativity and characterization of central mass. With observation of fainter stars more will be known about dynamical processes and stellar evolution.

References


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\(^5\)binary black hole, spin . . .  
\(^6\)eccentricity, inclination of orbits  
\(^7\)Important for studying central mass properties
[10] www.maths.ed.ac.uk/ douglas/