Stars Orbiting Black Hole in the Galactic Center

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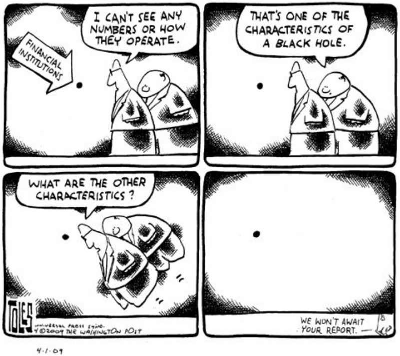
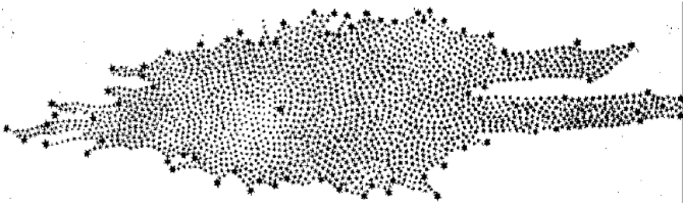


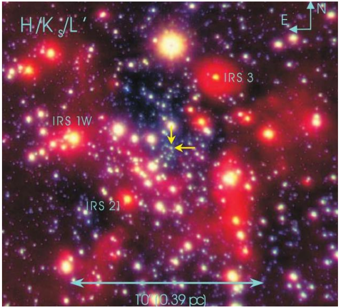
History

- In 1785 Herschel atempted to map our Galaxy. Sun was close to the center.
- Harlow Shapley calculates coordinates of the Galactic center in 1918 in his study of distribution of globular clusters.
- In 1974 Sgr A*, a point-like radio source in the center of the Galaxy is discovered.
- In early 90s He emission stars and source known as IRS 16 are discovered.
- In 2002 ten years observational data of star S2 were published. 15.2-year orbit was fitted to the data.



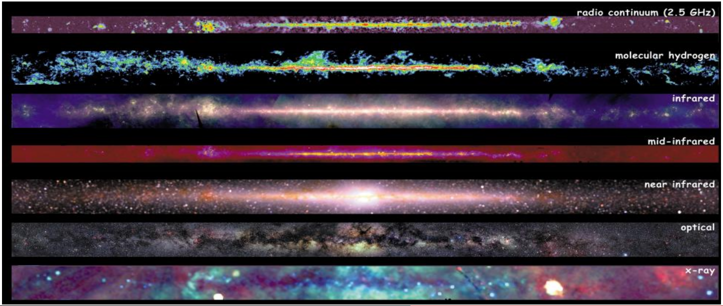
Facts about GC

- Distance to the Galactic center is 7.6 kpc. pc is parsec = 3.26 ly = $3{\cdot}10^{13}$ km.
- One pc long line at a distance of GC is 27 arcsec large on our sky.
- There are tens of stars around the MBH in a region of diameter of 0.04 pc.



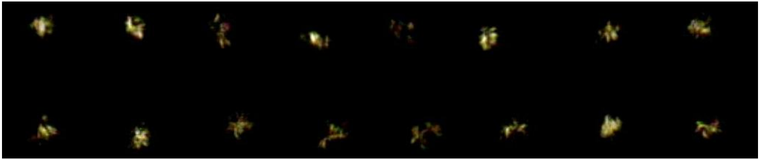
Extinction

- Extinction in visible wavelengths is around 30 magnitudes.
- Extinction drops to 2 magnitudes in near IR.
- Observations are made in K band (2.2 μm), where extinction is 3 magnitudes.
- Problems at longer wavelengths:
  - dimmer stars
  - lower telescope resolution
  - higher ambient background noise



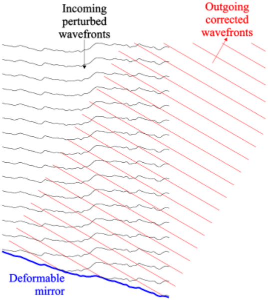
Resolution and seeing

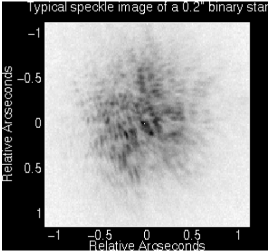
- $\Phi = 1.22\frac{\lambda}{D}$
- Seeing tells us what the degree of "star twinkling" is. Cells of hot and cold air cause oscilations in position and brightnes of a star.
- Seeing is measured in arcseconds it equals FWHM of a star image.
- Resolution of a 8 m telescope is $0.01 \cdot 10^{-3}$ arcsec at $\lambda = 2.2\mu$m and 0.2 arcsec is considered a good seeing.
- Effect of seeing must be reduced to sucsessfuly observe star cluster in a 1 arcsec region.

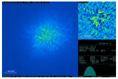


Adaptive optics and specle imaging

- Disturbed wavefronts can be corrected with adaptive optics. Laser excites sodium atoms in mesosphere, which then apear to glow like a star. Such an artifficial star is observed, wavefront disturbtion is calculated and a small mirror is properly deformed.
- Effect of seeing can be avoided with specle imaging. Short exposures are affected in a different way. Each cell of hotter or cooler air produces a separate image. These images are than sumed into one.

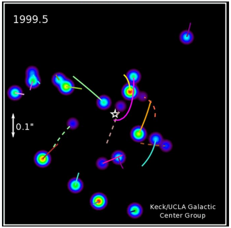


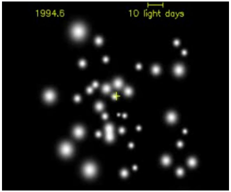


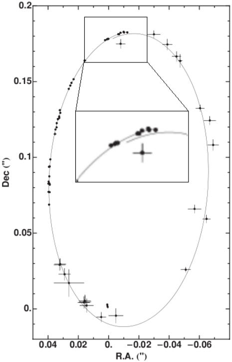


Astrometry

- Astrometrical measurements are made on VLT and Keck.
- Accuracy of VLT is around 0.02 marcsec in last years of observations.
- Position is compared to brighter stars in the observed field and these stars are compared to standard stars with well known position.

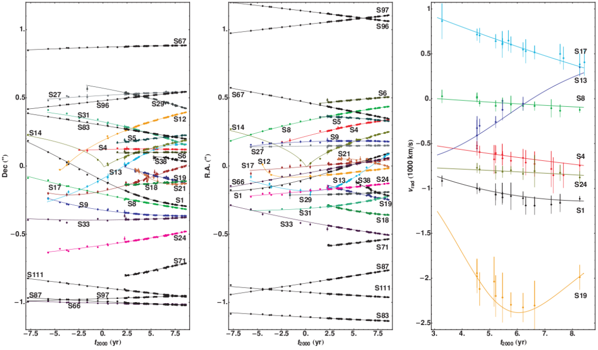






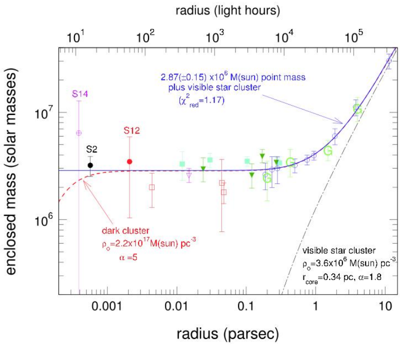
Spectrometry

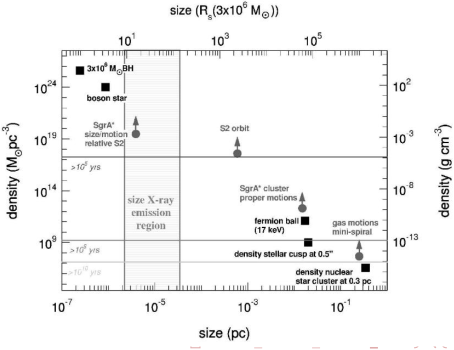
- Spectra are taken on VLT with spectroscopes of resolution of 4000 or 1500.
- Area of 0.8" is covered. Because stars have high velocities, spectral lines of different stars are separated.
- Orbital parameters are calculated from positions and radial velocities.



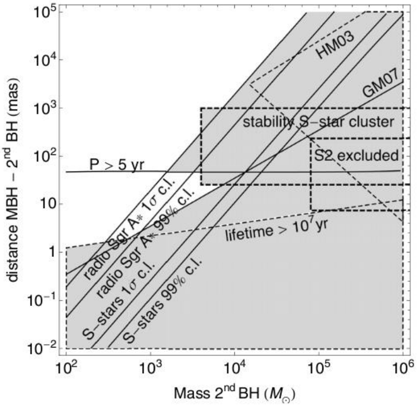
Determination of BH mass

- Mass function of $m(r) \propto r$ is observed outside the 0.4 pc.
- Between 0.4 and 0.04 pc mass function flattenes to $m(r) \propto r^{0.4}$.
- Following graph shows that m(r) converges to nonzero value in the center.
- Flare





Dvojna črna luknja



Characteristic scales

Several important time and length scales govern the dynamics in the GC.

- **Event horizon** or Schwarzschild radius:

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

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

$$r_T = R_* \frac{M_{BH}^{1/3}}{M_*} = 3 \cdot 10^{-6}\mathrm{pc} \sim 90\mu\mathrm{arcsec}.$$

- **Age of galactic center.** It is assumed that the GC is the same age as Galaxy.
- **Dynamical timescale** or orbital time:

$$t_D = 2\pi\sqrt{\frac{r^3}{GM_{BH}}} = 2{\cdot}10^5 \text{ years } (\text{at } r = 3 \text{ pc}) = 300 \text{ years } (\text{at } r = 0.03 \text{ pc}).$$

Characteristic scales

- **Relaxation time-scale** measures time it takes for one object to be significantly perturbated or ejected from a system. Time scale for large angle deflections is:

$$t_L = \frac{1}{n_* \sigma \Sigma}, \quad \Sigma \sim \pi \left(\frac{G \langle M_* \rangle}{\sigma^2} \right)^2$$

$$t_R \sim \frac{\sigma^3}{G^2 \langle M_* \rangle^2 \pi n_*} \sim 1\mathrm{Gyears}$$

- **Segregation time-scale** is the same as relaxation time-scale but scales with M_*:

$$t_s \sim t_R \frac{\langle M_* \rangle}{M_*}$$

- **Collision time-scale.** It can be derived, that the rate of collisions between star of mass $M_\star^a$, radius of $R_\star^a$ and another star with mass $M_\star^b$ and radius $R_\star^b$ is:

$$t_c^{-1} = 4\sqrt{\pi} n_\star \sigma (R_\star^a + R_\star^b)^2 \left[1 + \frac{G(M_\star^a + M_\star^b)}{2\sigma^2 (R_\star^a + R_\star^b)} \right] = 10^{-9} year^{-1} \text{ at } 0.02 \text{ pc}$$

Two simple solutions

- Spherically simetric distribution of stars is described with

$$f(r,v) = KE^p, \qquad E = \frac{GM}{r} + \frac{1}{2}v^2$$

Star density for this distribution equals:

$$n_*(r) = \int f \mathrm{d}^3 v \propto r^{-(p+3/2)}$$

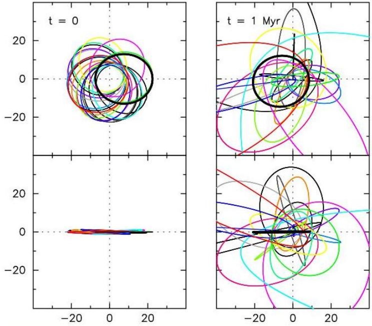
- Isothermal distribution ($p = 0$) gives $n_*(r) \propto r^{-3/2}$
- Bechall-Wolfs are steady-state solutions that depend only on boundary conditions. Stars relaxed from a system represent constant mass flux:

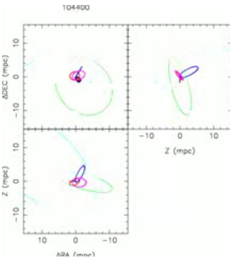
$$F \sim \frac{n_* r^3 v^2}{t_R} \sim \frac{G^{3/2} m n_*^2 r^{7/2}}{M_B H^{1/2}} \Rightarrow n_* \propto r^{-7/4}$$

Computer simulations

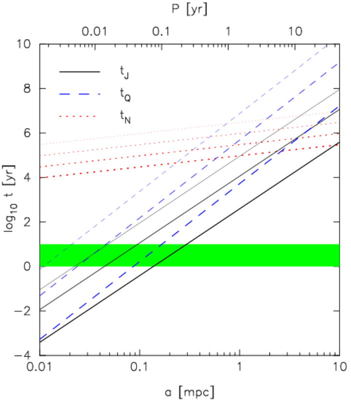
Numerical N body simulations give satisfactory results of GC dynamics.

- Star-star interactions are taken into account,
- General theory of relativity is obeyed,
- Dynamical properties can be correctly simulated,
- Simulations of evolution history haven't been sucsessful yet.





Frame-dragging, kvadrupolni moment, vpliv drugih zvezd



debela črta: $e = 0.99$
srednje debela črta: $e = 0.9$
tanka črta: $e = 0.5$

Stellar population in GC

- Population outside the 0.4 pc limit is normal Galactic population,
- Space between 0.4 and 0.04 pc has excess of B stars,
- In the inner 0.04 OB and Wolf-Rayet stars dominate.

Strange population in GC and extreme conditions suggest that yet unknown processes take place.

The paradox

- Stars can form from an external trigered cloud colapse at 2 pc. Cloud at smaller distances would be Jeans unstable.
- Stars can be born in a fragmented disk around black hole. This theory cannot explain excess of blue stars around MBH.
- Stars could be formed trough violent processes like merging smaller stars, stripping older stars to appear younger etc. This theory cannot explain cluster of simmilar stars.
- Dynamical friction coud import stars to the center faster than expected otherwise. Other star clusters around BH talk in advance to this theory but again cannot explain symilarity of stars.
- 3 Body interactions could import stars to the center but many pairs of blue giants and smaller stars should exist in the neighbourhood.

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