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CENTRAL SUPERMASSIVE BLACK HOLE OF THE MILKY WAY

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Abstract. An overview of some important aspects of the supermassive black hole at the Galactic Center, such as evidences for its existence, its main features, effects on stellar kinematics, gas dynamics and distributions of dark and visible matter in its neighborhood, is given here. The possibilities to use the observations of these phenomena as a tool for testing some of the predictions of General relativity and alternative theories of gravity in such extreme conditions is also considered, and some of our recently obtained results in this field are presented. Besides, the influence of the central supermassive black hole on the evolution of the Milky Way is discussed, as well as whether it could trigger the activity of our Galaxy in the future, by starting to accrete the surrounding matter with much higher rate. Taking into account that the Milky Way is on a collision course with M31 Andromeda galaxy, and that their central supermassive black holes will become gravitationally bound and form a binary system of these objects at some stage in the evolution of the resulting merger, some properties and possible consequences of this supermassive black hole binary are also considered here.

1. INTRODUCTION

It is now widely accepted that the supermassive black holes (SMBHs) are located in the centers of most galaxies, including the Milky Way, and that they have fundamental influence on evolution of their host galaxies. Central SMBH of our Galaxy is located in a compact radio source Sgr A* at Galactic Center (GC), and here we will present the main observational evidences for its existence, its properties, effects on stellar kinematics, gas dynamics, distributions of dark and visible matter, structure and evolution of the Milky Way, including some possible future scenarios, such as potential activity of our Galaxy and formation of a binary system of SMBHs during the Milky Way and M31 merger. We will also give a short overview of our main investigations related to the above aspects of the SMBH in Sgr A*, such as: using the observed stellar orbits around GC for testing some predictions of General Relativity (GR) and alternative theories of gravity, studying the accretion physics and space-time geometry in vicinity of SMBHs and observational signatures of their binary systems.

2. OBSERVATIONAL EVIDENCES AND PROPERTIES

Compact radio source Sgr A* at GC was discovered in 1974 by Bruce Balick and Robert L. Brown using the Green Bank 35 km radio interferometer in West Virginia

(Balick and Brown 1974). As it can be seen from a wide-field radio image of the Galactic Center at 90 cm presented in the left panel of Fig 1 (LaRosa et al. 2000), Sgr A* is part of a more complex radio source known as Sgr A.

The first indication that Sgr A* may harbor a SMBH of $\sim 3\times10^6$ $M_\odot$ was obtained by virial analysis of the ionized gas in the central parsec of the Milky Way by Lacy et al. (1982). All successive estimates, although obtained by different techniques, suggested that there was a large mass of $\propto 10^6$ $M_\odot$, enclosed in a very small volume at GC (see the right panel of Fig. 1). For instance, $M_{BH} - \sigma$ relationship resulted with $M_{BH} \approx 9.4 \times 10^6$ $M_\odot$ for the Milky Way bulge velocity dispersion of $\sigma = 103$ km/s (Tremaine et al. 2002).

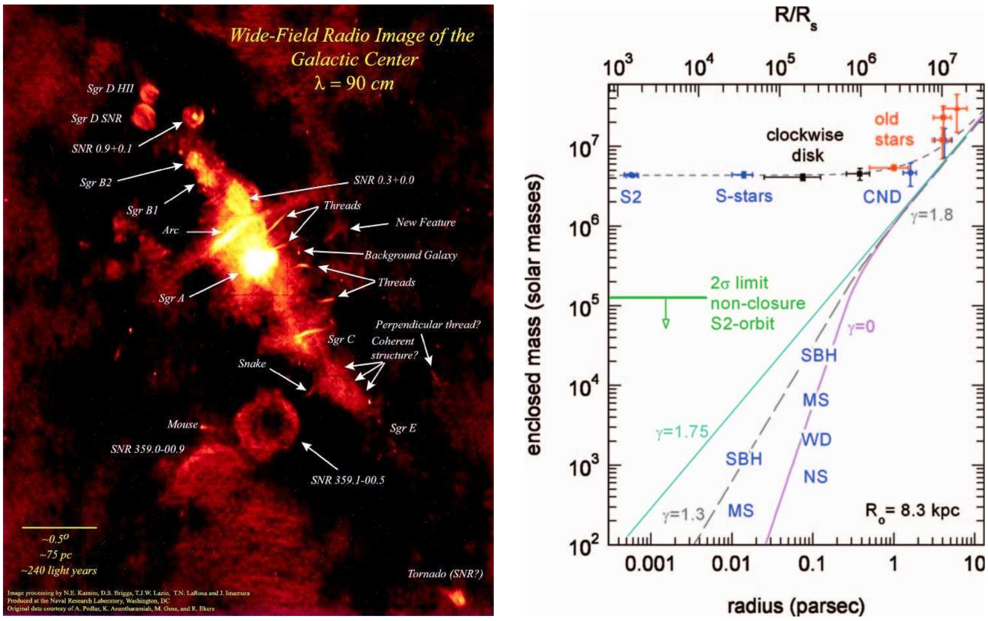

Figure 1: *Left:* a wide-field radio image of the Galactic Center at 90 cm (figure taken from LaRosa et al. 2000). *Right:* mass distribution in the central few parsecs of the Milky Way (figure taken from Genzel et al. 2010). These estimations are based on: the orbits of S-stars (filled blue symbols), clock-wise rotating disk of O/WR stars (filled black squares), proper motions, radial velocities and the light of the old stars (red symbols), and the rotation of the molecular gas in the circum-nuclear disk (open blue circles).

The most direct evidence for the existence of the SMBH at GC would be a detection of its "shadow". Namely, event horizon of a black hole located in front of a planar-emitting source casts a relatively large "shadow" to a distant observer due to the bending of light (see e.g. Falcke et al. 2000 and references therein). Apparent diameter of "shadow" for Sgr A* is 52 $\mu as \approx 5$ R_{Sch} (Doeleman et al. 2008), and it should be observable by direct (Falcke et al. 2000) and/or polarimetric (Bromley et al. 2001) imaging (see the top and bottom panels of Fig. 2). In principle, such imaging should be feasible by the big triangle of submm VLBI (see e.g. Inoue et al. 2012), or by a larger array called Event Horizon Telescope, capable of angular resolutions approaching 20 μas (see e.g. Doeleman 2010).

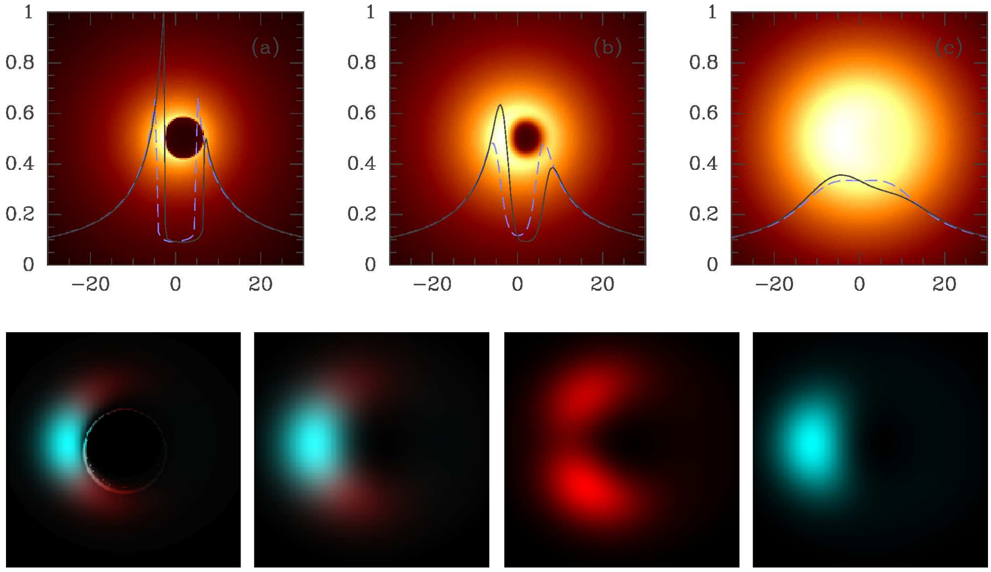

Figure 2: *Top:* GR ray-tracing simulations of "shadow" cast by the event horizon of a black hole with the characteristics of Sgr A* (figure taken from Falcke et al. 2000). The left to right panels show raw ray-tracing image and images seen by an idealized VLBI array at 0.6 and 1.3 mm wavelengths, respectively. *Bottom:* simulated polarization maps at 0.67 mm emission from Sgr A* (figure taken from Bromley et al. 2001). The left to right panels show: raw ray-tracing image, an image blurred to account for finite VLBI resolution and interstellar scattering, vertical and horizontal components of the polarized emission, respectively.

However, until this happens in the near future, the most reliable current evidences for the central SMBH of the Milky Way and estimates for its mass were obtained from Keplerian orbits of fast-moving ($v > 1000$ km/s) stars within $0''.3$ (0.01 pc) at GC. These, so called S-stars, have been monitored since 1995 by Keck 10 m telescopes (Ghez et al. 2008) and by New Technology Telescope/Very Large Telescope (NTT/VLT) (Gillessen et al. 2009a), yielding the following values for the black hole mass and distance to the GC, respectively: $M_{BH} = 4.5 \times 10^6$ $M_\odot, R_0 = 8.4$ kpc (Ghez et al. 2008) and $M_{BH} = 4.3 \times 10^6$ $M_\odot, R_0 = 8.3$ kpc (Gillessen et al. 2009a). These values indicated that Schwarzschild radius of SMBH at GC is $R_{Sch} \approx 10$ μas (0.1 AU) at a distance of ≈ 8 kpc.

S-stars could be used as test particles to probe the gravitational potential in which they move. Two of them are of a special interest: S2 with mass of 15 $M_\odot$ and a highly elliptical Keplerian orbit around Sgr A* (although there are some indications that the observed orbit deviates from the Keplerian one) with a period of 15.6 yr (Schödel et al. 2002), and S0-102 with the shortest orbital period of 11.5 yr (Meyer et al. 2012). Therefore, these stars represent an ideal laboratory for studying the gravity under the extreme conditions, close to the central SMBH of the Milky Way. Especially, different theories of modified gravity which have been proposed as alternative approaches to Newtonian gravity, could be tested using the observed orbits of S-stars.

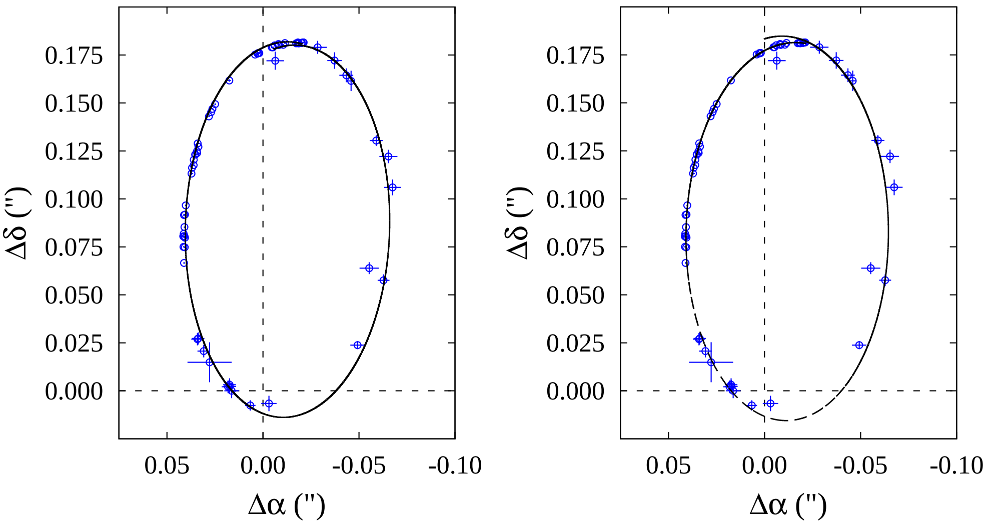

Figure 3: *Left:* fit of S2 star orbit around SMBH at GC in R^n gravity (black solid line) to the NTT/VLT astrometric observations (blue open circles) (figure taken from Borka et al. 2012). *Right:* The same as in the left panel, but for Yukawa gravity (figure taken from Borka et al. 2013).

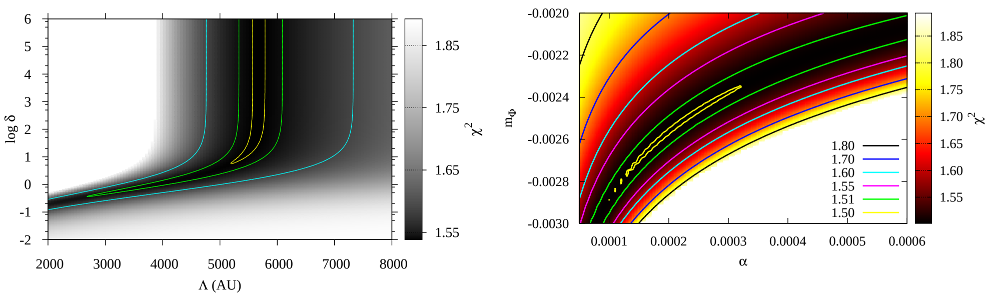

Figure 4: *Left:* χ^2 map over the parameter space of Yukawa gravity for the fits of S2 star orbit to the NTT/VLT observations (figure taken from Borka et al. 2013). *Right:* The same as in the left panel, but for $f(R, \phi)$ gravity (figure taken from Capozziello et al. 2014).

We studied whether the following three such theories: R^n, Yukawa and $f(R, \phi)$ gravity, as well as a bulk distribution of mass, are able to provide reasonable explanations for the deviations in the observed orbit of S2 star, and whether these observations could be used for constraining such modified gravity theories (see Borka et. al. 2012, 2013; Capozziello et al. 2014; Zakharov et al. 2014). Two examples of simulated orbits of S2 star in R^n and Yukawa gravity which give the best fit to the NTT/VLT astrometric observations (Gillessen et al. 2009b) are presented in Fig. 3, while Fig. 4 shows two corresponding χ^2 maps over the parameter spaces of Yukawa and $f(R, \phi)$ gravities.

Recently, a dense, ~ 3 Earth mass gas cloud on its way towards the SMBH at GC was discovered (Gillessen et al. 2012). This gas cloud, labeled as G2, was falling into accretion zone of Sgr A*, and an increase of the keV X-ray emission of Sgr A* and giant radiation flare were expected due to cloud disruption by SMBH. However, G2 was still intact during its closest approach to SMBH in March 2014, in contrast to a simple gas cloud hypothesis, so most likely it hosts a central star (Ghez et al. 2014).

Besides, dark matter (DM) might contribute to the extended mass in GC, and in that case DM evolution would be driven by the scattering of its particles by bulge stars, their accretion into SMBH and self-annihilation (Genzel et al. 2010). Recently, an excess in gamma-ray emission from GC was detected, most likely due to annihilations of DM particles, indicating that DM distribution around the SMBH could strongly affect this annihilation signal (Daylan et al. 2014).

It is also worth to mention that several alternative explanations for the massive compact object at GC, such as a dark cluster of faint stars (neutron stars, white or brown dwarfs), "fermion ball" and "boson star" were disproved, leaving the central SMBH as the most plausible explanation (Genzel et al. 2010).

3. POSSIBLE ACTIVITY OF THE CENTRAL SMBH AT GC

Despite the rich gas reservoir in its surroundings, Sgr A* is faint, with luminosity which is several orders of magnitude lower than the Eddington luminosity. This is due to decrease of accretion rate toward the SMBH, which falls from ~ 0.01 $M_\odot$/yr at several tens pc to $\sim 10^{-9} - 10^{-7}$ $M_\odot$/yr at several hundreds R_{Sch} (Genzel et al. 2010).

However, occasional rapid X-ray flares from Sgr A* were observed, providing evidences for activity of Sgr A* close to its event horizon (Porquet et al. 2008). Besides, Li et al. (2013) recently found an evidence for a parsec-scale jet from Sgr A* and a shock front along the jet (see the left panel of Fig. 5). Also, several echoes of multiple outbursts of Sgr A* in the past were recently detected by Chandra in the observed Fe Kα line emission from molecular clouds near GC (Clavel et al. 2013). The rapid variability of this emission indicated that it originated from the reflection of X-rays generated by SMBH which was much more luminous in the past, causing a highly variable active phase of Sgr A* which occurred sometime within the past few hundred years. This active phase was characterized by at least two luminous outbursts with typical time scales of a few years, during which the Sgr A* luminosity went up to at least 10^{39} erg/s (Clavel et al. 2013).

The observational studies of this sort motivated the corresponding theoretical investigations of Sgr A* activity, such as e.g. MHD simulations of its accretion disk (see e.g. Chan et al. 2009, as well as the right panel of Fig. 5). Moreover, they also indicate that the speculations about the potential future activity of Sgr A* are reasonable.

Our studies of SMBHs activity were mostly concentrated to the investigations of the broad Fe Kα spectral line which originates from the innermost regions of relativistic accretion disks around central SMBHs of active galaxies and quasars. For

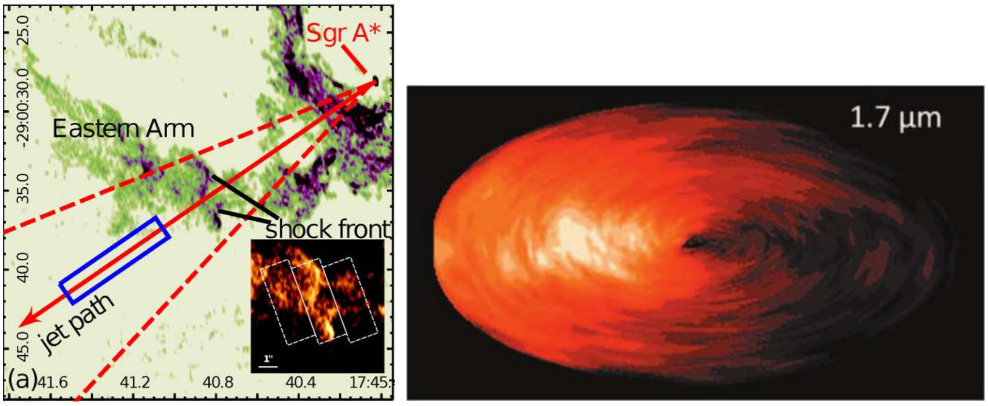

Figure 5: *Left:* evidence for a parsec-scale jet from Sgr A* and a shock front along the jet path (figure taken from Li et al. 2013). *Right:* Ray-tracing simulation of the accretion disk in Sgr A* observed at 1.7 μm (figure taken from Chan et al. 2009).

that purpose we developed a code to perform numerical simulations of radiation from such disks, based on ray-tracing method in Kerr metric and used it for studying the black hole masses and spins, space-time geometry (metric) in their vicinity (Jovanović et al. 2011), their accretion physics (Jovanović et al. 2010, Popović et al. 2012), probing the effects of their strong gravitational fields, and for testing the certain predictions of General Relativity (see e.g. Jovanović and Popović 2008, Jovanović

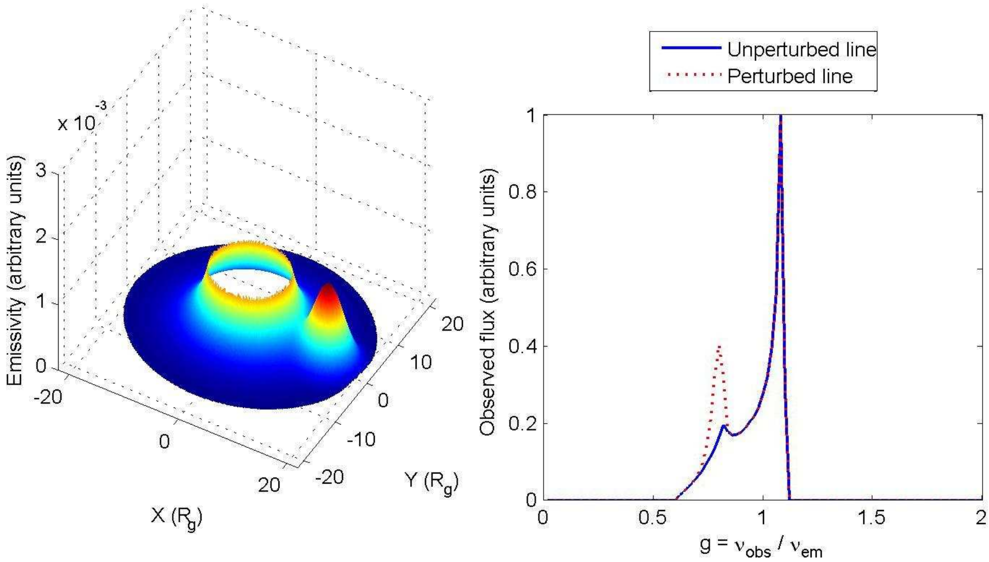

Figure 6: *Left:* emissivity of a relativistic accretion disk around a SMBH perturbed by a bright spot on the disk's receding side (Jovanović et al. 2010). *Right:* the corresponding perturbed (dashed line) and unperturbed (solid line) Fe Kα line profiles.

2012). An example of our investigations in this field is presented in Fig. 6, where we introduced a model of a bright spot (or flare) orbiting in an accretion disk, and used it for studying the variability of double peaked line profiles, emitted from accretion disk of active galaxies and quasars (see Jovanović et al. 2010 for more details). Besides, gravitational microlensing turned out to be very helpful in these studies (see e.g. Jovanović et al. 2008, 2009; Popović et al. 2003ab, 2005, 2006). For reviews of our previous investigations of emission lines emitted from accretion disks around central SMBHs of AGN see e.g. Jovanović 2012, Jovanović and Popović 2009.

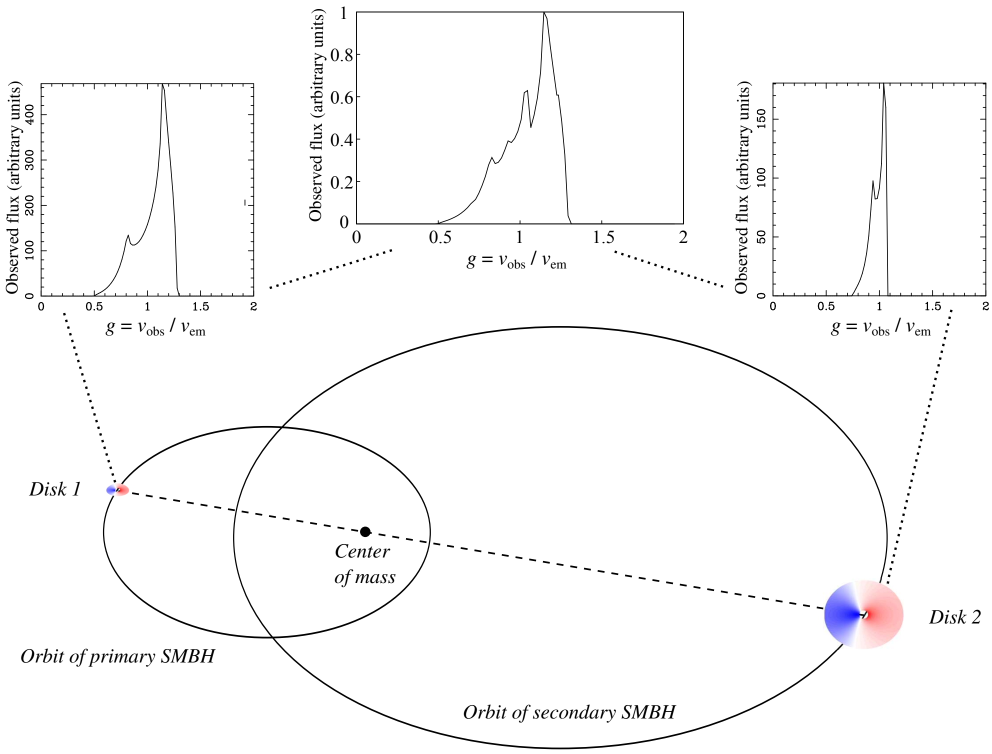

Figure 7: Illustration of two accretion disks around the components of a binary system of SMBHs rotating along a Keplerian orbit, and the corresponding simulated "constituent" and "composite" profiles of the Fe Kα line (see Jovanović et al. 2014 for more details).

4. THE MILKY WAY AND M31 MERGER: SMBH BINARY

It is well known that the Milky Way and Andromeda (M31), the two largest members of the Local Group of galaxies, are moving towards each other at ~ 120 km/s and will collide in a few billion years - within the Sun's lifetime (see e.g. Cox and Loeb 2008; van der Marel et al. 2012). During their merger, the Sun will be most likely scattered to the outer halo and reside at radii larger than 30 kpc (Cox and Loeb 2008), while their central SMBHs will form a binary system, and according to some speculations, they could also produce a luminous quasar (Cox and Loeb 2008). Theory predicts that binary systems of SMBHs should spend a substantial amount of time orbiting along Keplerian orbits, and if they are surrounded by gas, accretion onto one or both SMBHs could occur, resulting with certain observational effects.

We used our model of relativistic accretion disk to study the variations of a composite line emitted from two accretion disks around SMBHs in a binary system (see illustration in Fig. 7), and found that such variations could be used as observational signatures of SMBH binaries (Jovanović et al. 2014). An important result of ours in this field was a recently found observational evidence for the first spectroscopically resolved sub-parsec orbit of a SMBH binary in the core of active galaxy NGC 4151 (Bon et al. 2012). We used a method similar to those typically applied for the spectroscopic binary stars to obtain radial velocity curves, from which we then calculated orbital elements and estimated masses of the components in this SMBH binary.

5. CONCLUSIONS

According to the results of the presented observational and theoretical studies of the Milky Way's central SMBH, one can derive the following conclusions:

1. Central SMBH of the Milky Way has a fundamental influence on the structure and evolution of our Galaxy;
2. In future it could trigger the activity of our Galaxy and form a binary system of SMBHs together with central SMBH of M31;
3. It represents a unique laboratory for testing some of the predictions of GR and alternative theories of gravity in such extreme conditions;
4. We developed a model of a relativistic accretion disk around a SMBH using numerical simulations based on a ray-tracing method in Kerr metric and applied it for investigation of the properties and accretion physics of SMBHs, space-time geometry and strong gravity effects in their vicinity, as well as the properties of their binary systems.

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