A Multiwavelength Report on Recent Findings and Ongoing Observations of Sgr A*

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1 Introduction

Einstein's General Theory of Relativity (GR) predicts the existence of blackholes and the closest and best known candidate is Sgr A* at the centre of the Milky Way. It is believed to be a supermassive blackhole (SMBH) and lies at a distance of approximately 8 kpc with an estimated mass of $4 \times 10^6 M_\odot$. Its proximity therefore makes it ideal for the study of blackholes and as a potential testbed for GR, as discussed later in Section 6. It was first identified as a radio source (Balick et al., 1974) back in 1974. It has been studied using the entire electromagnetic spectrum although interstellar extinction makes some wavelengths more problematic than others. Even though, by definition, black-holes are black, they do emit electromagnetic radiation from near the event horizon - as gas and plasma are accreted by the blackhole, this material is heated up and large amounts of energy are emitted and radiated at all wavelengths of the electromagnetic spectrum. However since optical radiation is completely absorbed the best observing bands are radio (including sub-mm), the infrared (from near-infrared, NIR, to far-infrared, FIR) and X-rays.

The scale of a blackhole is set by the size of the Schwarzschild radius $R_s = 2GM_{BH}/c^2 \approx 3km(M_{bh}/M_\odot)$. For Sgr A* this would lead to an angular size of $\theta_{RS} = 10\mu as$ however the angular size is also affected by gravitational lensing due to its own gravitational potential, and is predicted to be $\approx 10\mu as$ making it the largest subtended angle blackhole anywhere in the universe and so is ideal for study. The distance to the Galactic Centre has been determined through high-resolution spectroscopy and the proper motion of stars giving a distance of $D = 8.3(\pm 0.4)kpc$.

Apart from mass the other most important parameter of a blackhole is its accretion rate. This is determined by the distance from which it can accrete, the Bondi radius, given by $R_B = 2GM/v_w^2$ where v is the speed of surrounding gas. Estimates for Sgr A* indicate $R_b \approx 2.5 \times 10^5 R_s \approx 0.1pc$ which was determined by radio polarization measurements. Sgr A* shows suprisingly low levels of activity. Its current accretion rate is about four orders of magnitude lower than that required for a SBMH to grow in a Hubble time (Falke, Markoff, 2013), its radio emission is lower than expected and the amount of gas available as fuel is much lower that required to fuel an SMBH of that size. This has greatly constrained the models of Sgr A*. Conventional models of Sgr A* are based on radiatively inefficient accretion flow (RIAF) where the disk radiates inefficiently due to low particle density (Goddi et al., 2016). However the latest models are based on general relativistic magneto-hydrodynamic (GRMHD) simulations (Goddi et al., 2016), using a stationary rotating torus and the presence of a magnetic field. The BlackHoleCam collaboration (Goddi et al., 2016) has developed a Black Hole Accretion Code to further this area of study. As different models predict different results continued observations are necessary to understand the astrophysics and refine the models.

This report is a short discussion on recent (2016) findings that have been published on Arxiv with an emphasis on multiwavelength comparisions and the potential for future studies. However the report begins with a brief summary of the orbits of stars around Sgr A* surveyed over a number of years using the near infrared (NIR) as this data provides some of the most compelling evidence that Sgr A* is actually a SMBH.

2 Infrared - The Mass of Sgr A* and the Stars Orbiting Sgr A*

The first evidence for a central dark mass was suggested in 1980 through observations from the mid-infrared and radio recombination line observations (Falke, Markoff, 2013). Although it wasn't until the invention of adaptive optics for ground based telescopes that the resolution became sensitive enough to track stars orbiting this mass. Due to the high levels of exinction when viewing the galactic centre in the optical the NIR has been used to view stars orbiting Sgr A* now for decades. There are numerous papers on this subject but this section begins by citing from (Schodel et al., 2002), an early publication on this subject. This survey carried out ten years of high resolution NIR imaging and spectroscopy of the central region of the Milky Way in the vicinity of Sgr A*. They used an 8m ground-based telescope to study the orbits of S1 and S2, the two closest stars to Sgr A*. S2, the star closest to

Sgr A* at the time, was found to be in a highly elliptical Keplerian orbit with a period of 15.2 years and a peri-centre distance of 17 light hours - at peri-centre S2 was found to have a velocity in excess of 5000 km/s. From this data they were able to deduce that this orbit would require an enclosed point mass of $3.7 \pm 1.5 \times 10^6 M_\odot$ at the position of Sgr A*. At this time there were various models that tried to explain Sgr A* e.g. a dark mass (low mass stars, neutron stars or stellar black holes), a ball of heavy fermions, or a ball of bosons. This study effectively ruled out the first two of these models and put constraints on the possibility of the existence of a ball of bosons. The study was a major first step in testing the SMBH model. By 2008, 16 years of stellar orbits of 28 stars had been monitored (Gillessen et al., 2009) using high resolution NIR. This survey combined a long time baseline with high astrometric accuracy using adaptive optics. This further refined the mass of Sgr A* and showed that a single point mass was the best fit model for this system, pointing again to the SMBH model - see Fig. 1 for a plot of the eight closest stars orbiting Sgr A*.

Other evidence that points to the association of a large dark mass with Sgr A* is its own proper motion. Through Very Long Baseline Interferometry (VLBI) it has been possible to track its motion over several years and its motion has been found to be entirely consistent with the motion of the solar system around the Galactic Centre. This implies that the radio source is actually the Galactic Centre.

Today, about 30 stellar orbits have been monitored in the centre of the Milky Way and, combined, this data has yielded the most precise measurement of the mass of Sgr A* as $4.23 \pm 0.14 \times 10^6 M_\odot$ (Goddi et al., 2016) with S2 achieving a velocity of 10000 km/s. In 2016 a new methodology of data reduction was piloted (Boehle et al., 2016). They used the star S0-38, which is an order of magnitude fainter than S2, and so much more difficult to track. The paper illustrates the use of a technique known as speckle holography which allows the speckle imaging data from 1995-2005 to be re-analysed and fainter stars such as S0-38 to be tracked. The study has put further constraints on both the mass and distance of Sgr A* and reduced the uncertainties to a confidence level of 99.7%. The paper hopes that these improved constraints on the gravitational potential in the vicinity of Sgr A*, together with the addition of S0-38, will allow future tests of GR to be carried out when S2 goes through its time of closest approach in 2018.

Observations of these stellar orbits is also ongoing in the radio wavelengths as well. One of the first relatavistic observations for GRAVITY, a second generation instrument on the Very Large Telescope Interferometer (VLTI), an adaptive optics assisted interferometer, will be to observe the peri-astron shift of S2 in 2018. With a precision of about 10μas GRAVITY will push interferometry accuracy way beyond what is possible today. GRAVITY combines the light from four telescopes and measures the interferograms from six baselines simultaneously. It operates in the K-band ($2.2\mu m$). It is hoped that GRAVITY will finally prove that Sgr A* is a SMBH and resolve the debate as to whether NIR flares (discussed in Section 5) are individual hot spots close to the last stable orbit, from statistical fluctuations in the accretion region, or from a jet. GRAVITY is also likely to be included in tests of GR in the strong field limit (Section 6).

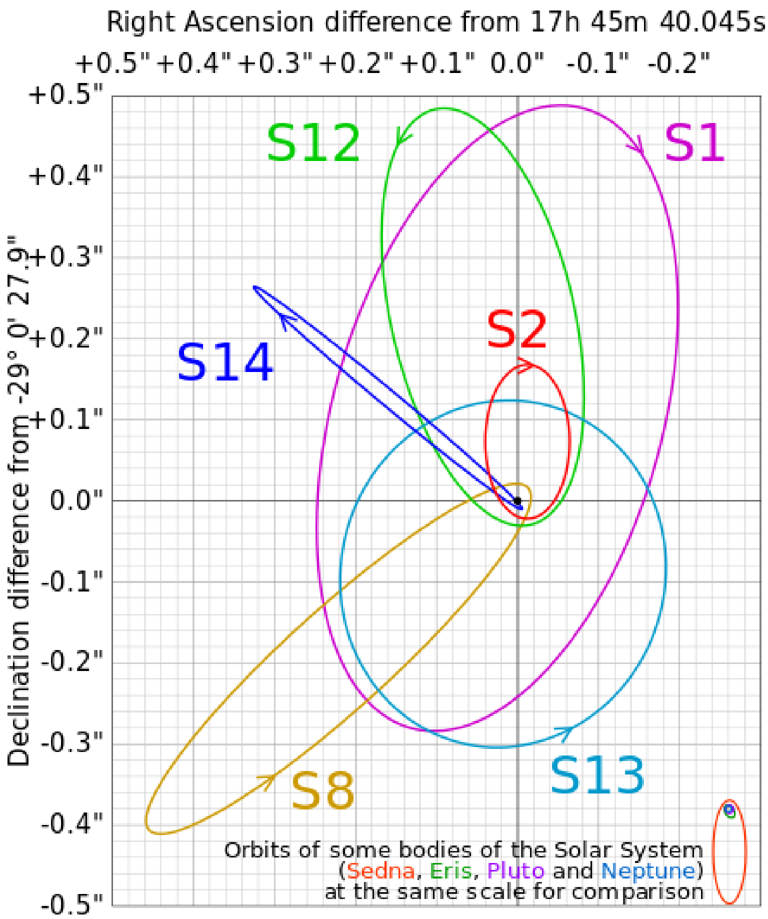

Figure 1: Inferred orbits of 6 stars around SMBH candidate SGR A* (Eisenhauer et al., 2005)

3 Radio including Sub-mm - The Structure of Sgr A*

As mentioned previously blackholes do emit radiation from around the event horizon due to accretion. It has been calculated (Falke et al., 2000) that the visual appearance of a blackhole would appear as a bright photon ring with a dim "shadow" within its interior. Photons orbiting very close to the event horizon will disappear into the blackhole whilst those further away will escape to infinity therefore a clear boundary between light and dark regions is predicted. Gravitational lensing could increase the size of this shadow to bring it to within the limits of Very Long Baseline Interferometry (VLBI) measurements at mm wavelengths. Radio emission from Sgr A* is believed to be produced by the accretion of matter onto the SMBH. At millimetre wavelengths, VLBI can resolve the accretion region of the SMBH. It is believed that this radio emission is either synchotron radiation from a jet outflow, accretion flow onto the SMBH, or an isothermal jet coupled to an accretion flow (Ortiz-Leon et al., 2016). Wavelengths longer than a few centimetres are scattered by the interstellar medium but at smaller wavelengths this scattering is reduced. The scattering obeys a λ^2 dependence (Ortiz-Leon et al., 2016) but at shorter wavelengths this dependence is seen to diminish indicating the structure of Sgr A* may be revealed. The radio spectrum for Sgr A* exhibits a slow rise with frequency until it reaches the submm band where it peaks and then cuts off - this has been termed the "submm bump". It is generally thought that this is due to synchotron emission in transition from being optically thick to optically thin (Falke, Markoff, 2013).

In 2016 a study was carried out to attempt to identify the 2D structure of Sgr A* (Ortiz-Leon et al., 2016). Up until this time existing VLBI baselines were limited in the north-south baselines however this study combined the National Radio Astronomy Observatory Very Long Baseline Array (VLBA) with the Large Millimieter Telescope Alfonso Serrano (LMT) to act as a single VLBI array. This provided good north-south as well as east-west coverage. The study revealed that the image of Sgr A* resembles an elliptical Gaussian. A similar VLBI survery was carried out (Brinkerink et al., 2016) also using the VLBA, LMT and the Robert C. Byrd Green Bank Telescope (GBT) but this time at a 3mm wavelength using closure phase interferometry. Closure amplitudes are formed by combining complex ampltitudes in the correlated data from four different telescopes so that the telescope-based gain errors cancel (Falke, Markoff, 2013). They also managed to account for some structure in the Sgr A* image. The paper describes an Eastern secondary source separate from the primary source, although the authors do note that this asymmetry may potentially be due to interstellar scattering rather than being intrinisic to the source.

The Atacama Large Millimetre Array (ALMA) is the most sensitive (sub)mm-wave telescope ever built and consists of 50 individual antennas of 12m diameter. Joint VLBI observations which include ALMA are planned for 2017 and should provide unprecedented sensitivity due to the improved north-south baseline. Another major development is that sub-mm telescopes are combining around the world, including ALMA, to form the Event Horizon Telescope (EHT) which should provide unrivaled precision for VLBI observations. It is hoped that EHT will have the necessary precision to directly observe the blackhole's "shadow". EHT will also form one of the experiments that tests GR in a strong field (Section 6). EHT aims to improve our understanding of accretion around a blackhole and the physics behind blackhole jets.

4 Gamma Rays and the G2 object

A notable, and widely publicised, event occurred in the vicinity of Sgr A* during 2013-14. It was reported (Gillessen et al., 2012) that a gas cloud, now known as G2, of the order three Earth masses, was on a highly eccentric orbit towards the SMBH and it's predicted pericentre passage would occur late 2013 and would last up to a year. This was again observed using IR. This sparked interest in the scientific community as it was assumed that in-falling matter into the SMBH could accelerate high-energy particles resulting in emission at various wavelengths, including gamma rays. A four year observational campaign was therefore started by using the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes (Ahnen et al., 2016). These two 17m diameter telescopes record flashes of Cherenkov light produced by Extensive Air Showers which occurr in the upper atmosphere and are caused by very high energy γ ray photons with energies $> 50GeV$. The results however were disappointing and the close proximity of G2 to the SMBH had no measureable effect on γ ray emissions, although the authors hope this study will act as a baseline for monitoring any flaring activity in the future. These results, however, are not surpising as it had already been reported (Ghez et al., 2014) that G2 had passed by Sgr A* largely unaffected when monitored using NIR.

5 X-rays, Flares and Multiwavelength Surveys

Since the launch of Chandra in 1999 it was found that Sqr A* is a source of suprisingly weak X-rays (Falke, Markoff, 2013), however Sgr A* does exhibit periods of higher X-ray emission during flaring periods. These occur on a much faster timescale than the steady emission of X-rays. The flaring activity associated with Sgr A* are widely studied and observed phenomena. These can be observed using infrared, X-ray and submillimetre wavelengths. The origin of these flares is still being debated but to understand this activity it is important to compare results from all of these wavelengths. A multiwavelength campaign (Mossoux et al., 2016) was therefore carried out in 2014, also timed to be carried out at G2's closest approach. This ambitious study aimed to make simultaneous observations using X-Ray Multi-Mirror Mission (XMM-Newton) and Wide Field Camera 3 (WFC3) onboard the Hubble Space Telescope (HST) giving observations in X-Ray and NIR respectively. NIR observations were also carried out using the Spectrograph for Integral Field Observations in the Near Infrared (SINFONI) at the VLT in Chile. Radio observations were also carried using the Karl G. Jansky Very Large Array (VLA) in the X band (3.75-2.5cm) and also using the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at 3.2mm. There was no increased flaring activity detected that could be attributed to the passage of G2 however a number of flares were detected at the various wavelengths allowing the data to be analysed and compared using a multiwavelength approach. In total three flares were detected by the WCF3 on board HST plus two more using SINFONIA on the VLT. These were very luminous NIR flares but given that SINFONIA and WFC3 have very high detection limits this is to be expected statistically. Two X-ray flares were detected by XMM-Newton and were two of the brightest flares ever detected by XMM-Newton. Two of the NIR flares had definite X-ray counterparts and the one had the highest NIR-to-X-ray ratio ever observed. It seems that X-ray flares are often accompanied by NIR flares but not necessarily vice versa. Data from CARMA revealed a slight 'bump' but this could not be correlated with any of the NIR/X-ray flares. The three main hypotheses for these flares are: a jet with clumps of ejected material, short-lived "hot spots" orbiting the blackhole or statistical fluctuations in the accretion flow (Goddi et al., 2016). With its 10μas precision GRAVITY may also soon be able to determine the nature of these flares and settle this debate. GRAVITY should also have the precision to detect Lense-Thirring precession for stars orbiting the SMBH and hopefully put constraints on the blackhole spin from these stellar orbits.

In a separate study (Stone et al., 2016) the Herschel Space Observatory's (no longer operational) Spectral and Photometric Imaging Receiver (SPIRE) was used to carry out the longest ever continuous submillimetre survey of Sgr A*. These were observed in three FIR bands: 0.25, 0.35 and 0.5mm. These wavelength are difficult, if not impossible, to observe from the ground. The aim of the study was to test for the variability of luminosity of the accretion flow into the SMBH in order to constrain low-luminosity accretion models. This was then compared with ground-based observations at the Caltech Submillimetre Observatory using 0.85mm and X-ray data from XMM-Newton. Small ($< 1\%$) variations were seen at the three wavelengths used by SPIRE and comparison with 0.85mm ground data support these small variations. However comparison XMM-Newton didn't reveal any corresponding variations.

6 GR Tests and Pulsars

Given the overwhelming evidence that Sgr A* lies in the close vicinity to a SMBH there are a number of ongoing observations which aim to test for the existence of blackholes, test GR and study spacetime around blackholes (Goddi et al., 2016). Some very precise tests of GR have been carried out using pulsars: a pulsar in a binary system can be used to probe the spacetime around that system by comparing the "pulsar clock" with the radio telescope maser. However it is believed that a pulsar orbiting a blackhole could provide an even more accurate test. No such system has yet been found however it is believed that there are many pulsars orbiting Sgr A*. The huge mass of SMBH would provide a very accurate test of GR. Unfortunately only five pulsars (Goddi et al., 2016) within 0.5°of Sgr A* have so far been found, the lack of which has been attributed to interstellar scattering. However in 2013 radio emission from a magnetar (PSR J1745-2900) was detected supporting the hypothesis that many more pulsars may yet still be found. It is hoped that ALMA will help achieve this aim. Rajwade et al. (2016) modelled both canonical pulsars (CPs) and millisecond pulars (MSPs) at the Galactic Centre and found that the optimum frequencies for future studies would be 9 GHz for CPs and 22 GHz for MSPs. They state that it is not surpising current surveys have failed to find many pulsars in the Galactic Centre has they have only probed $< 2\%$ of the population. The authors hope that upcoming telescopes such as the Square Kilometre Array would probe deeper and survey a more sizeable population of the pulsars in the Galactic Centre. Next generation instruments, such as LMT, and ALMA should allow for the first systematic search for pulsars to be carried out at

90 GHz, or even higher (Goddi et al., 2016).

This report has so far mentioned three ongoing projects to test GR: the blackhole shadow using EHT, stars orbiting Sgr A* using GRAVITY and pulsars with ALMA. Each of these techniques utilises different wavelengths and observational techniques: mm-VLBI, astrometry with NIR and pulsar timing with radio. GR has so far only been tested in the weak field limit and in the strong limit using pulsar binary systems. Sgr A* provides a suitable testbed for a comprehensive test of GR in the strong field limit. In order to do this the results from these different observations will need to be combined (Goddi et al., 2016). Each of the above measurements uses a different observational techniques and are therefore subject to different kinds of errors. By combining these results any uncertainties could be reduced. Also measurements of the blackhole mass and spin measured independently using different techniques could be compared to each other increasing the precision of these measurements.

7 Summary

SMBHs provide us with the strongest gravitational fields with which to perform comprehensive GR tests in the strong field limit and Sgr A* is by far the closest SMBH. Three experiments are currently ongoing to test GR. The first is to identify the structure of Sgr A* and obtain an image of the "shadow" of the blackhole. EHT will be an almost Earth sized telescope operating using millimetre VLBI and should have the resolution to obtain an image of this "shadow". The second experiment is continued monitoring of stellar orbits and GRAVITY will have the precision to identify relativistic precession of these orbits. Finally the third ongoing experiment is the continued search for pulsars in the Galactic Centre. It is hoped the combination of these results will test the validity of GR with more accuracy than ever before. The increasing precision of VLBI observations has prompted some authors (Haggard, Rovelli, 2016) to suggest that we are approaching the observational limit to where quantum gravitational effects may be observed. Sgr A* provides us with the most direct evidence of the existence of blackholes and is by far the closest so ongoing observations at all possible wavelengths are essential to provide us with more information on the physics of blackholes and ultimately a test of GR in the strong field limit.

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