Erik Zackrisson
Department of Physics and Astronomy
Uppsala University

Mass Bends Light – The First Detection of a Black Hole Through Gravitational Lensing

1. Abstract

Astronomical observations have shown that black holes exist at two different mass scales – stellar-mass black holes formed from the collapse of dying stars, and so-called supermassive black holes fed by the accretion of gas into the central regions of galaxies. While theoretical mechanisms for the formation of black holes at intermediate mass scales have been proposed, the empirical evidence for such objects has remained scant. However, the potential of exploiting effects due to gravitational lensing – the bending of light by strong gravitational fields – to hunt these objects down has so far been largely unexplored. Gravitational lensing has already allowed astronomers to find planets outside our solar system, to estimate the masses of galaxies and probe the dark matter of the Universe. By searching for such effects in archives of high-resolution data from radio telescopes, we have recently uncovered what may be the smallest gravitational lens ever detected. Our numerical models suggest that if the peculiar appearance of this radio source is indeed due to gravitational lensing by a foreground object, then that object must have properties very similar to an intermediate-mass black hole. If confirmed, this would not only be the smallest gravitational lens ever discovered, but also the first case of a black hole discovered through gravitational lensing, at any mass scale.

2. Gravitational lensing and black holes

Rays of light do not always follow straight paths. Gravitational lensing is a well-known effect in astronomy, by which overdensities of matter along the line of sight cause a bending in the light from distant light sources. The size of this effect was accurately predicted by Einstein in 1915, and has in the last few decades helped astronomers to detect free-floating exoplanets, to estimate the masses of galaxies and galaxy clusters, to measure cosmological parameters and constrain the nature of dark matter (for a review, see Bartelmann 2010). Figure 1 features a schematic example of a gravitational lensing effect, in which two galaxies happen to lie along the same line of sight. The foreground object causes a curvature of spacetime, which allows light from the background object to reach the observer along multiple paths. This distorts the image of the background galaxy and makes it appear as a ring-like structrure – a so-called Einstein ring.

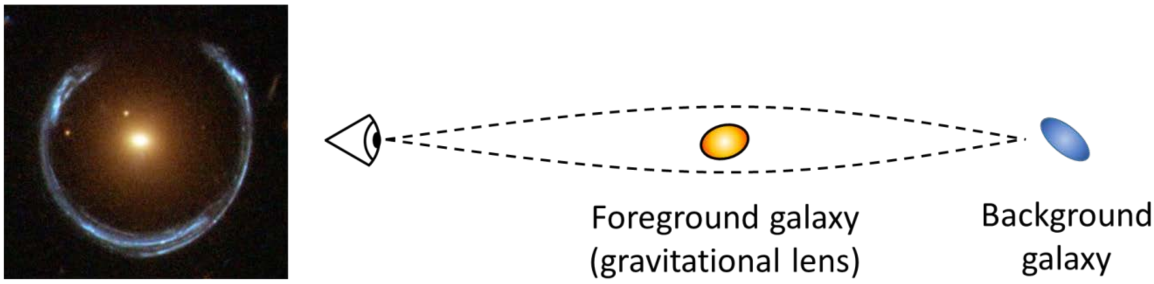

Figure 1. Schematic illustration of the principle behind Einstein rings. The light from a blue background galaxy is curved due to a second, yellow galaxy along the line of sight, making light from the blue galaxy reach the observer along multiple paths. As a result, the observer sees the blue galaxy distorted into a partial ring surrounding the yellow object. The image to the left is a real-life example of the astronomical image of LRG 3-757 ("the cosmic horseshoe"), featuring this type of galaxy-galaxy alignment. In this case, where the gravitational lens is a galaxy, the angle subtended by the Einstein ring in the sky is about one arcsecond (1/3600 of a degree). A lens of lower mass would produce a similar effect but with a much smaller angular diameter of the ring.

The angular scale of the Einstein ring depicted in Figure 1 is primarily determined by the mass of the foreground object (the gravitational lens). A galaxy-mass lens gives rise to a ring with a radius of order one arcsecond (1/3600 of a degree). Objects at subgalactic mass scales are expected to give rise to smaller angular separations between the sides of the ring, and current radio interferometers are in principle able to detect resolved ring structures down to 0.1-1 milliarcsecond scales. Even so, Einstein rings of the type depicted in Figure 1 have – until now – not been reported on scales below 0.1 arcseconds.

The proposed project revolves around a potential detection of an Einstein ring with an angular radius of just $\approx$0.5 milliarcseconds – the very first case of its kind. Lensing effects at this scale can be produced either by dark matter structures in the dwarf-galaxy mass range or by intermediate-mass black holes (e.g. Zackrisson & Riehm 2010), but only objects in the latter category are sufficiently compact to produce distinct ring-like features (Zackrisson et al. 2013). If our interpretation is correct, this would then make our target the first-ever detection of a black hole through gravitational lensing.

Astronomers already have strong observational evidence for the existence of black holes at two different mass scales (for a review, see Narayan & McClintock 2013): Stellar-mass black holes (5-30 times the mass of the Sun) and supermassive black holes ($\sim 10^6$—10^9 times the mass of the Sun). It has been postulated that intermediate-mass black holes ($\sim 10^2$—10^6 times the mass of the Sun) could form from the collapse of the central regions of star clusters (e.g. Portegies Zwart et al. 2004), from the collapse of very massive stars (e.g. Freese et al. 2010) or from direct collapse of gas clouds in the early Universe (e.g. Yue et al. 2014), but the empirical evidence for such black holes remains controversial (see Kormendy & Ho 2013 for a review). If the mass of the object responsible for the lensing in our target object can be accurately pinned down to lie in the $\sim 10^2$—10^6 Solar mass range, this would hence have important implications for our understanding of the cosmic mass distribution of black holes.

3. The first case of gravitational lensing at milliarcsecond scales

Our team has had a long-vested interest in hunting down cases of gravitational lensing on milliarcsecond scales (Zackrisson et al. 2008, Riehm, Zackrisson et al. 2009, Zackrisson & Riehm 2010, Zackrisson et al. 2013). By going through archival data from various high-resolution radio interferometers, we have come across a previously overlooked candidate for such small-scale gravitational lensing. The object in question, J0626+82, was observed by the international VSOP (Very-long baseline interferometry Space Observatory Programme) project which collected data between 1997-2003 and used the Japanese HALCA satellite hooked up to radio telescopes on the ground to achive submilliarcsecond resolution (down to 0.2 milliarceconds under optimal conditions). The VSOP 5 GHz radio map of this object is shown in Figure 2, and features a ring-like structure with a radius of only $\approx$0.5 milliarcseconds, which would be consistent with an Einstein ring produced by an intermediate mass black hole in the $\sim 10^4$ solar mass range (Zackrisson et al. 2013).

A crude VSOP radio map of J0626+82 was shown already in a VSOP survey catalog presented by Dodson et al. (2008), but has never – due to severe underfunding on the analysis side within the VSOP collaboration, and close-down of all VSOP operations already in 2005 – been subject to any detailed analysis (The Dodson et al. paper simply states “This source shows very interesting submilliarcsecond structure” in a brief catalog entry). While the Dodson et al. map also displays the ring-like structure, the map presented in Figure 2 is of much better quality and has been processed by our team member Kaj Wiik (Tuorla Observatory, Finland), who worked for the VSOP project before it was closed down.

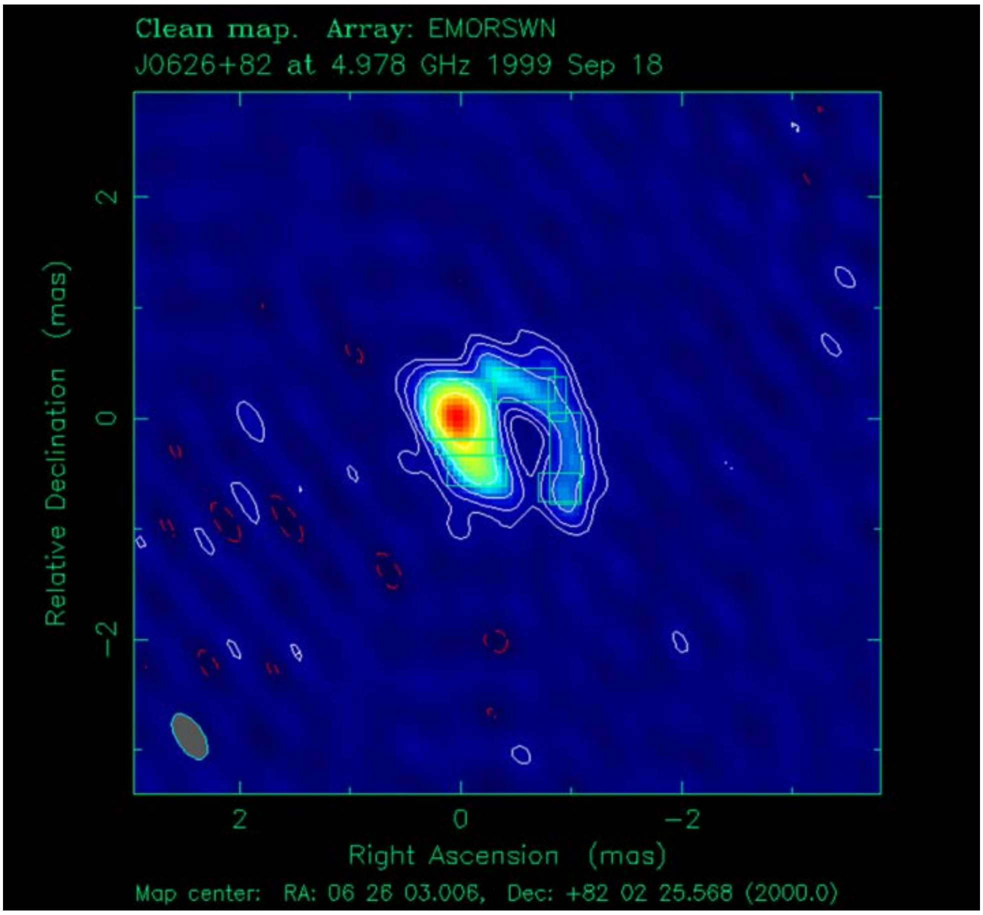

Figure 2. Milliarcsecond-scale map of the J0626+82 radio source, observed by the VSOP project at a frequency of 4.978 GHz. The object appears extremely curved – potentially due to gravitaional lensing by a very compact object (an intermediate-mass black hole) along the line of sight. The resolution (about 0.3 milliarcseconds, mas) is indicated by the grey ellipse in the lower left corner.

4. Project description

4.1. Scientific impact

If J0626+82 could be established as the first case of milli-arcsecond scale gravitational lensing, this would by itself be Nature/Science material. The fact that this could also be the first-ever case of an intermediate-mass black hole detected through gravitational lensing makes the case even more tantalizing. However, to make the case that the ring-like structure of this object is indeed caused by the bending of light by a massive foreground object requires dedicated gravational lens modelling, which we are hereby attempting to secure funding for.

4.2. Data and interpretation

The J0626+82 radio source belongs to a class of objects known as active galactic nuclei, which at radio frequencies – in the absence of gravitaional lensing – typically appear as bright cores with one or two jets emerging from their central regions. This object has also been observed by powerful radio arrays from the ground at both 15 GHz and 42 GHz as part of the MOJAVE project (Lister & Homan 2005). Despite being of somewhat lower quality than the VSOP data, the MOJAVE maps – which our team member Tuomas Savolainen at Mätsehovi Radio Observatory has access to – also show an extremely curved structure. A successful gravitational lens model for J0626+82 would have to simultanteously explain the structures seen in all of the three radio maps at 5 GHz (VSOP), 15 GHz (MOJAVE) and 42 GHz (MOJAVE). This requires fitting a numerical model for gravitational lensing to all three data sets, to establish whether a self-consistent gravitaional lens can explain all the features seen (location of bright spots an curved elongated structures). The alternative explanation would be that the curved shape of J0626+82 is due to intrinsic jet bending. Intrinsic jet curvature is for instance possible if the jet hits a layer of very dense gas, which makes it deviate from its otherwise straight path. While jet bending of this type has been observed many times before in active galactic nuclei, J0626+82 would be the most extreme case ever encountered (featuring a ≈300 degree turn of the jet) and would be worthy of a high-profile publication even if the gravitational lens interpretation should turn out to be falsified as a result of our numerical modeling.

4.3. Project timeline

We estimate that it would take about three months of full-time work to apply our computer-based model of gravitational lensing (Zackrisson et al. 2013) to confirm or falsify the gravitational lensing interpretation of J0626+82. Since none of our team members are able drop our current commitments and complete this task on a reasonable timescale, we are hereby applying for funding to hire somebody with a PhD in astronomy to work 100% on a 3-month contract at Uppsala University under the supervision of Erik Zackrisson. If funding is granted, we should be able complete the project early in 2016. There is no shortage of suitable candidates in the astronomical community in Sweden, where many highly qualified researchers are struggling to get by at the postdoc level.

4.4. Team

Our team consists of:

- Erik Zackrisson (Associate Professor at Uppsala University), with ample experience in the field of gravitational lens modelling. Erik Zackrisson was recruited by Uppsala University in 2015 to take over leadership of the Galaxies and Cosmology research group at the Department of Physics and Astronomy after the recent retirement of Professor Nils Bergvall.

- Kaj Wiik (PhD at Tuorla Observatory, Finland, member of the VSOP project), with expertise in the processing of space-based very long baseline interferometry data.

- Tuomas Savolainen (Associate Professor at Mätsehovi Radio Observatory, Finland, member of the MOJAVE collaboration), with expertise in the processing of both space-based and ground-based very long baseline interferometry data

5. References

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