AstroTalk: Behind the news headlines; June 2023

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Monster black holes lurking in our cosmic backyard

Black holes are the most extreme objects in the Universe. Supermassive versions of these unimaginably dense objects likely reside at the centres of all large galaxies. Stellar-mass black holes—which weigh approximately five to 100 times the mass of the Sun—are much more common, with an estimated 100 million in the Milky Way alone.

Only a handful have been confirmed to date, however, and nearly all of these are 'active'—meaning they shine brightly in X-rays as they consume material from a nearby stellar companion, unlike dormant black holes, which do not.

Last year, astronomers using the Gemini North telescope on Hawai'i discovered the closest black hole to Earth, which they dubbed *Gaia* BH1. This dormant black hole weighs about 10 times as much as the Sun and is located 1,560 light-years away in the direction of the constellation Ophiuchus, making it three times closer to Earth than the previous record holder, an X-ray binary system in the constellation of Monoceros.

This discovery was made possible based on exquisite observations of the motion of the black hole's companion, a sun-like star that orbits the black hole at about the same distance as the Earth orbits our Sun.

> "*Take the solar system, put a black hole where the Sun is, and the Sun where the Earth is, and you get this system*," explained Kareem El-Badry, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics in the U.S.A. and the Max-Planck Institute for Astronomy in Heidelberg, Germany. "*While there have been many claimed detections of systems like this, almost all these discoveries have subsequently been refuted. This is the first unambiguous detection of a sun-like star in a wide orbit around a stellar-mass black hole in our galaxy*."

Although there are likely millions of stellar-mass black holes roaming the Milky Way galaxy, the few that have been detected were uncovered by their energetic interactions with a companion star. As material from a nearby star spirals in towards the black hole, it becomes superheated and generates powerful X-rays and jets of material. If a black hole is not actively feeding (i.e., it is 'dormant') it simply blends in with its surroundings.

> "*I've been searching for dormant black holes for the last four years using a wide range of data sets and methods*," said El-Badry. "*My previous attempts—as well as those of others—turned up a menagerie of binary systems that masquerade as black holes, but this is the first time the search has borne fruit*."

The team originally identified the system as potentially hosting a black hole by analysing data from the European Space Agency's *Gaia* spacecraft. *Gaia* accurately measures the positions and motions of billions of stars. The spacecraft is capable of capturing the minute irregularities in a star's motion caused by the gravity of an unseen massive object. The movement of stars against the sky can give essential clues about objects that gravitationally influence these stars. These objects can include other stars, exoplanets and also black holes.

> "*The accuracy of Gaia's data was essential for this discovery. The black holes were found by spotting the tiny wobble of their companion stars while orbiting around them. No other instrument is capable of such measurements*," says Timo Prusti, ESA's *Gaia* project scientist.

Gaia provided accurate measurements of the movement in three directions, but to understand more precisely how the stars moved away and towards us, additional radial velocity measurements were needed. Ground-based observatories provided these for the newly found black holes, and this gave the final clue to conclude that the astronomers had detected black holes. And so, to explore the system in more detail, El-Badry and his team turned to the Gemini Multi-Object Spectrograph instrument on Gemini North, which measured the velocity of the companion star as it orbited the black hole and provided precise measurement of its orbital period.

The Gemini follow-up observations were crucial to constraining the orbital motion and, hence, the masses of the two components in the binary system, allowing the team to identify the central body as a black hole roughly 10 times as massive as our Sun.

> "*Our Gemini follow-up observations confirmed beyond reasonable doubt that the binary contains a normal star and at least one dormant black hole*," elaborated El-Badry. "*We could find no plausible astrophysical scenario that can explain the observed orbit of the system that doesn't involve at least one black hole*."

The team relied not only on Gemini North's superb observational capabilities but also on Gemini's ability to provide data on a tight deadline, as the team had only a short window in which to perform their follow-up observations.

> "*When we had the first indications that the system contained a black hole, we only had one week before the two objects were at the closest separation in their orbits. Measurements at this point are essential to make accurate mass estimates in a binary system*," said El-Badry. "*Gemini's ability to provide fast-turnaround observations was critical to the project's success. If we'd missed that narrow window, we would have had to wait another year*."

Astronomers' current models of the evolution of binary systems are hard-pressed to explain how the peculiar configuration of *Gaia* BH1 system could have arisen. Specifically, the progenitor star that later turned into the newly detected black hole would have been at least 20 times as massive as our Sun.

This means it would have lived only a few million years. If both stars formed at the same time, this massive star would have quickly turned into a supergiant, puffing up and engulfing the other star before it had time to become a proper, hydrogen-burning star like our Sun.

It is not at all clear how the solar-mass star could have survived that episode, ending up as an apparently normal star, as the observations of the black hole binary indicate. Theoretical models that allow for survival all predict that the solar-mass star should have ended up on a much closer orbit than what is actually observed.

This could indicate that there are important gaps in our understanding of how black holes form and evolve in binary systems, and also suggests the existence of an as-yet-unexplored population of dormant black holes in binaries.

> "*It is interesting that this system is not easily accommodated by standard binary evolution models*," concluded El-Badry. "*It poses many questions about how this binary system was formed, as well as how many of these dormant black holes there are out there*."

> "*As part of a network of space- and ground-based observatories, Gemini North has not only provided strong evidence for the nearest black hole to date but also the first pristine black hole system, uncluttered by the usual hot gas interacting with the black hole*," said his colleague, Gemini Program Officer Martin Still. "*While this potentially augurs future discoveries of the predicted dormant black hole population in our Galaxy, the observations also leave a mystery to be solved—despite a shared history with its exotic neighbour, why is the companion star in this binary system so normal?*"

More recently, once again using data from the *Gaia* mission, the same astronomers have now also discovered the second closest black hole to Earth, dubbed *Gaia* BH2. *Gaia* BH2 was found 3,800 light-years away, in the constellation Centaurus. In galactic terms, *Gaia* BH1 and *Gaia* BH2 reside in our cosmic backyard.

The new black hole was also discovered by studying the movement of its companion star. A strange 'wobble' in the movement of that star, compared with the apparently stationary stars in the background, indicated that it must be orbiting a very massive object, approximately ten times more massive than our own Sun. Other explanations for these massive companions, like double-star systems, were ruled out since they do not seem to emit any light.

Until recently, all the black holes astronomers knew of were discovered by emission of light—usually at X-ray or radio wavelengths—produced by material falling under the influence of their massive gravitational pull. *Gaia* BH1 and *Gaia* BH2 are truly black and can only be detected by their gravitational effects. The distance of the companion stars to their parent black holes, and the orbits of the stars around them, are much longer than for other known binary systems composed of black holes and stars. Those closer star–black hole pairs, commonly referred to as 'X-ray binaries', tend to be very bright in X-ray and radio emission, and thus easier to find. But these new discoveries suggest that black holes in wider binaries are more common.

> "*What sets this new group of black holes apart from the ones we already knew about is their wide separation from their companion stars. These black holes likely have a completely different formation history than X-ray binaries*," explained El-Badry.

Black holes are often not completely invisible. When material falls onto them, they may emit radiation in radio and X-rays. For *Gaia* BH2, NASA's Chandra X-ray Observatory and the South African MeerKAT radio telescope (on the ground) looked for this emission, but they were not able to spot any signal.

> "*Even though we detected nothing, this information is incredibly valuable because it tells us a lot about the environment around a black hole. There are a lot of particles coming off the companion star in the form of a stellar wind. But because we didn't see any radio light, that tells us the black hole isn't a great eater and not many particles are crossing its event horizon. We don't know why that is, but we want to find out*," says Yvette Cendes who helped discover the second black hole and is an astronomer at the Harvard–Smithsonian Center for Astrophysics.

The new type of black hole does not emit any light, making them practically invisible, probably because they are much further away from their companion stars. *Gaia* BH1 and *Gaia* BH2 have the most widely separated orbits of all known black holes. The fact that they are also the closest known black holes to Earth suggests that many more similar black holes in wide binaries are still waiting to be discovered.

> "*This is very exciting because it now implies that these black holes in wide orbits are actually common in space—more common than binaries where the black hole and star are closer. But the trouble is detecting them. The good news is that Gaia is still taking data, and its next data release (in 2025) will contain many more of these stars with mystery black hole companions in it*," Yvette explains.

Gaia's next data release will be based on 66 months of observations and will contain improved information on the orbits of stars. In the meantime, astronomers will be busy figuring out where these black holes in wide orbits come from.

> El-Badry points out, "*We suspected that there could exist black holes in wider systems, but we were not sure how they would have formed. Their discovery means that we must adapt our theories about the evolution of binary star systems as it is not clear yet how these systems form*."

Independently of El-Badry's team, other astronomers recently also found a dormant 'monster' black hole in the solar neighbourhood, coming in at about 12 times the mass of our Sun.

> "*It is closer to the Sun than any other known black hole, at a distance of 1,550 light years*," said Dr. Sukanya Chakrabarti of the University of Alabama (USA). "*So, it's practically in our back yard. In some cases, like for supermassive black holes at the centres of galaxies, they can drive galaxy formation and evolution. It is not yet clear how these non-interacting black holes affect galactic dynamics in the Milky Way. If they are numerous, they may well affect the formation of our galaxy and its internal dynamics*."

To find the black hole, Dr. Chakrabarti and her team analysed data of nearly 200,000 binary stars released last year from the *Gaia* mission.

> "*We searched for objects that were reported to have large companion masses but whose brightness could be attributed to a single visible star*," she says. "*Thus, you have a good reason to think that the companion is dark*."

Non-interacting black holes don't typically have a doughnut-shaped ring of accretion dust and material that accompanies black holes that are interacting with another object. Accretion makes the interacting type relatively easier to observe optically, which is why far more of that type have been found.

> "*The majority of black holes in binary systems are in X-ray binaries—in other words, they are bright in X-rays due to some interaction with the black hole, often due to the black hole devouring the other star*," said Dr. Chakrabarti. "*As the stuff from the other star falls down this deep gravitational potential well, we can see X-rays*."

These interacting systems tend to be on short-period orbits, she said.

> *"In this case we're looking at a monster black hole but it's on a long-period orbit of 185 days, or about half a year,"* Dr. Chakrabarti said. *"It's pretty far from the visible star and not making any advances toward it."*

Simple estimates suggest that there are about a million visible stars that have massive black hole companions in our Galaxy, but there are a hundred billion stars in our Galaxy, so it is like looking for a needle in a haystack.

Scientists are trying to understand the formation pathways of non-interacting black holes. There are currently several different routes that have been proposed by theorists, but non-interacting black holes around luminous stars are a very new type of population. So, it will likely take some time to understand their demographics, and how they form, and how these channels are different—or if they're similar—to the more well-known population of interacting, merging black holes.

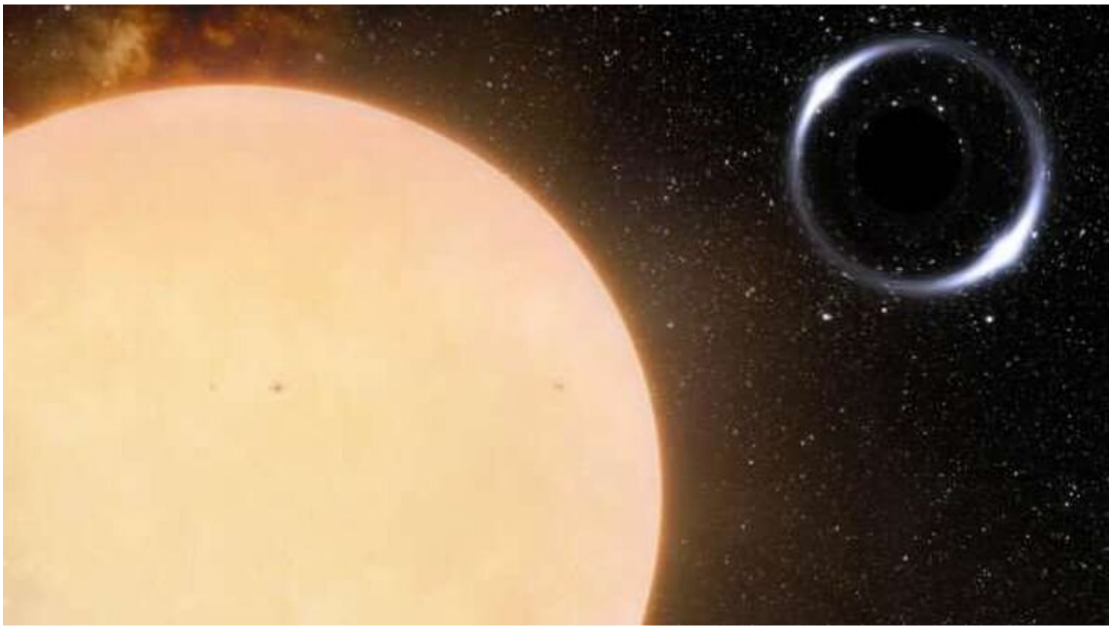

Fig. 1. Astronomers using the International Gemini Observatory have discovered the closest-known black hole to Earth. Credit: International Gemini Observatory/NOIRLab/NSF/AURA/J. da Silva/Spaceengine/M. Zamani

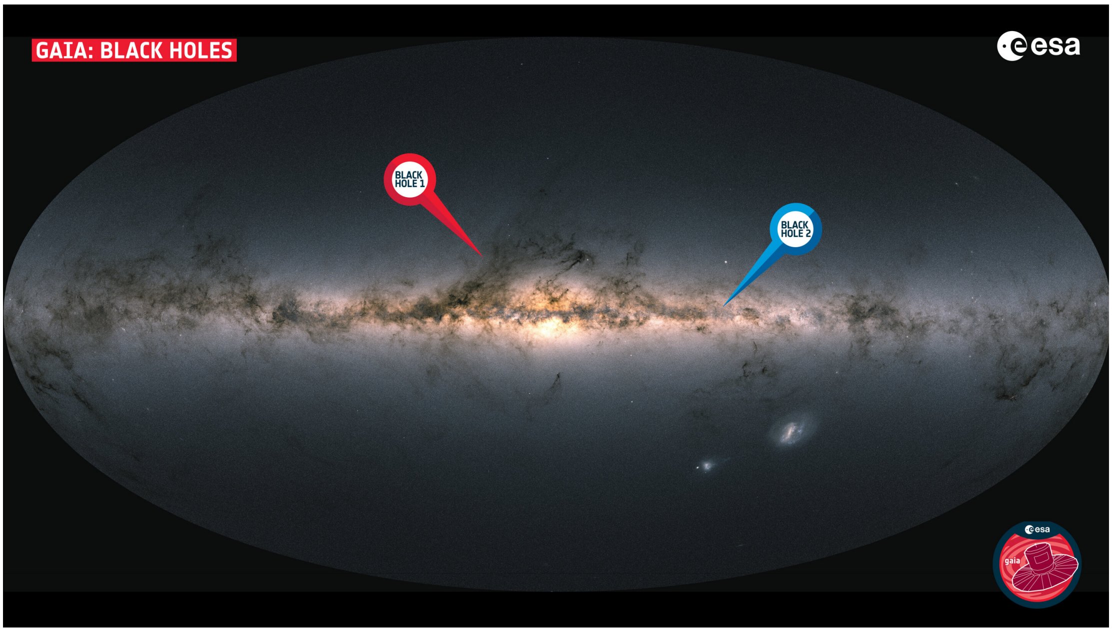

Fig. 2. The location of the first two black holes discovered by the *Gaia* mission in the Milky Way. This map of our Galaxy was also made by the *Gaia* mission. *Gaia* BH1 is located just 1560 light-years away from us in the direction of the constellation Ophiuchus and *Gaia* BH2 is 3800 light-years away in the constellation Centaurus. Credit: ESA/Gaia/DPAC; CC BY-SA 3.0 IGO, CC BY-SA 3.0 IGO

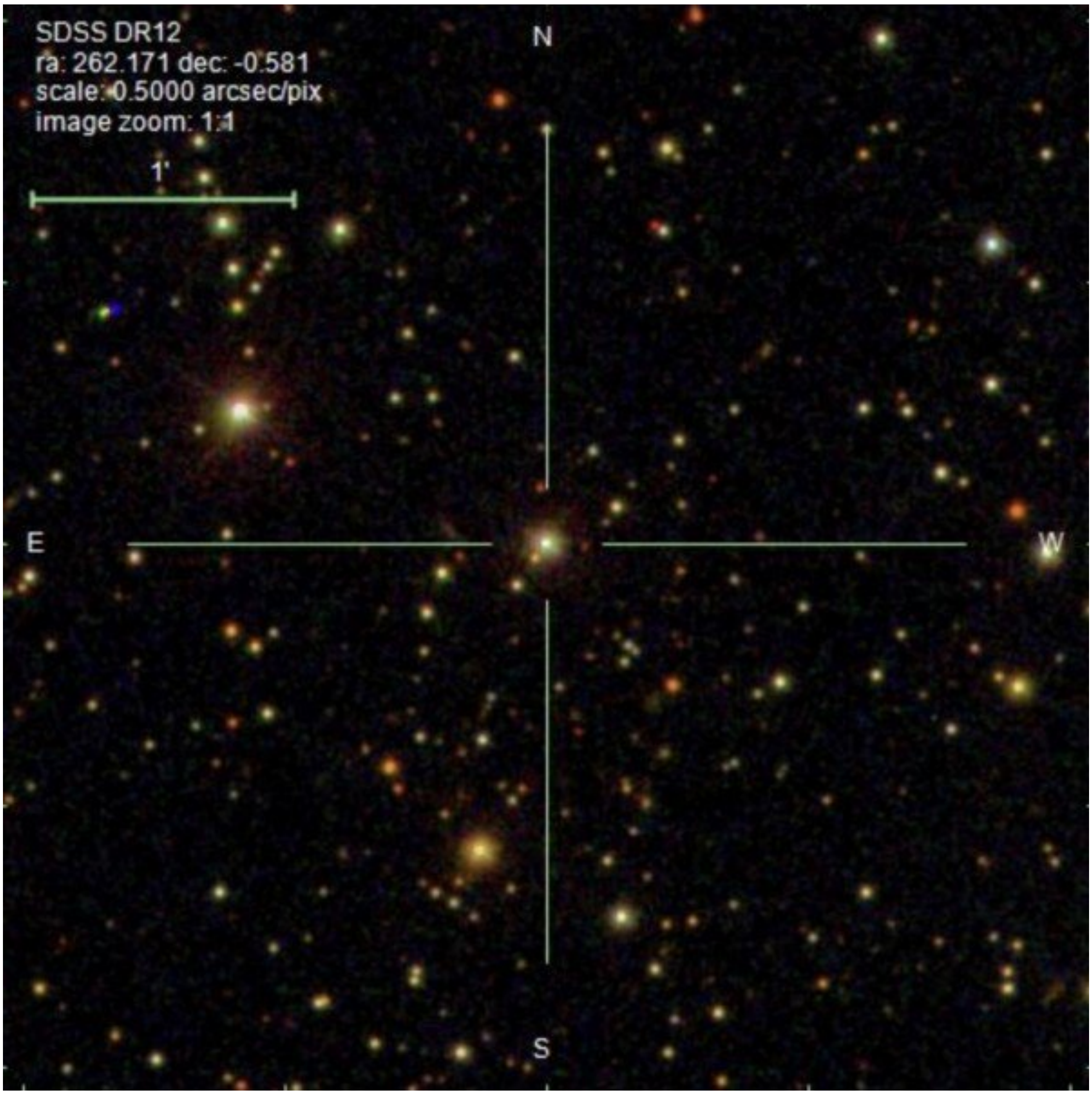

Fig. 3. The cross-hairs mark the location of the monster black hole newly discovered by Dr. Chakrabarti's team. Credit: Sloan Digital Sky Survey / S. Chakrabarti et al.

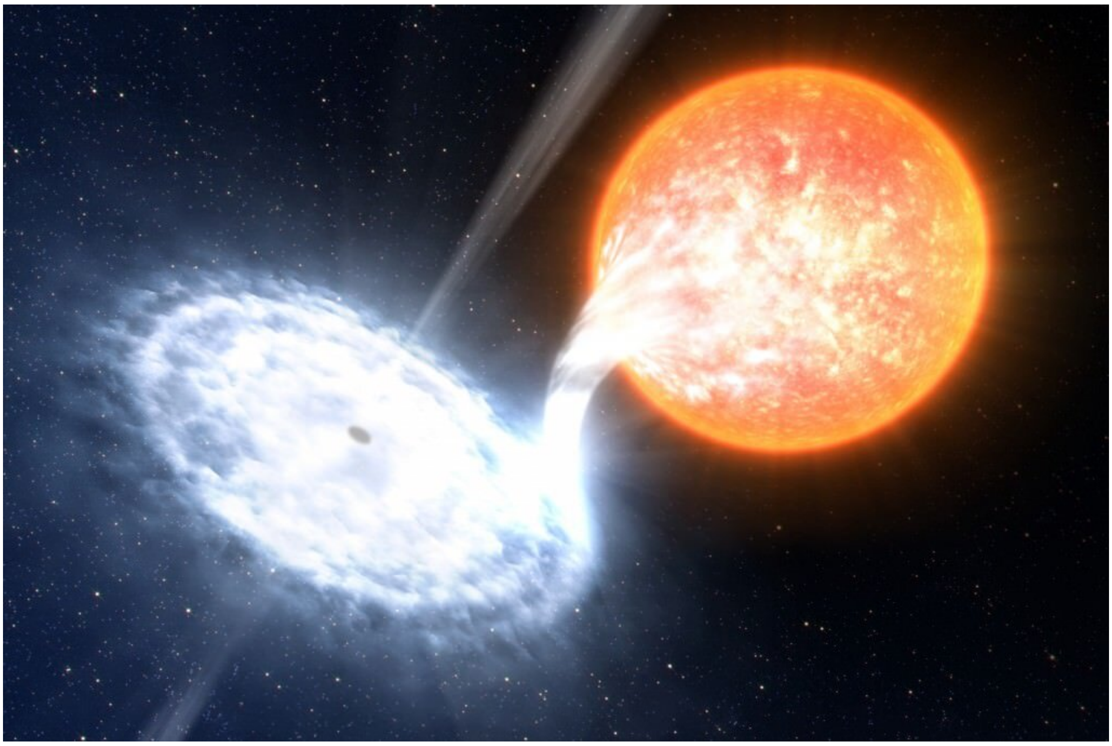

Fig. 4. *Gaia* BH1 is a Sun-like star co-orbiting with a black hole estimated at 10 times the Sun's mass. Credit: ESO/L. Calcada