

A massive black hole at the very centre of our galaxy

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It's now almost a dozen years that astronomers have gazed at the centre of the Milky Way—the galaxy our sun belongs to—with instruments which are more and more acute. They suspect that this region harbours a very massive black hole of several million times the mass of our sun. Transforming this guess into a certitude is important because it would have consequences for the related question: what is the engine that powers Quasars, the most luminous objects in the universe?

A black hole to power Quasars?

The idea that the centre of certain galaxies is hosting a monstrous black hole as massive as one billion times the sun's mass (denoted M_{\odot}) is not a new one. In the 70's it became clear that the quasars (Quasi Stellar Objects or QSO) were both compact, as their name indicates, and extremely distant objects, thus of an exceptional luminosity. It has been then necessary to imagine a mechanism able to convert mass into energy in a much more efficient way than the nuclear fusion that was unable to account for the observations. Retrieving the potential energy of matter reaching the horizon of a black hole was then proposed by Rees and Van del Bel as an efficient mechanism: it allows one in principle to extract $1/2 mc^2$, and thus to reach a yield of 50% (see Box), compared to the 1% of nuclear fusion. This mechanism is effective, provided that the matter in question, star or gas, does not fall directly onto the horizon but rather follows some spiralling trajectories, forming an accretion disk, where collisions, friction and tidal forces will cut it into pieces and warm it to extremely high temperatures, thus allowing the conversion of energy into X and UV radiation. Accretion of only $10 M_{\odot}$ per year is then sufficient to produce the 10^{40} W typical of a quasar's luminosity. This model has a fair coherence, based on different considerations about typical lifetime of quasar activity, short term variability, etc. One deduces that the mass of those hypothetical black holes should be of the order of

$10^9 M_{\odot}$, i.e. a significant fraction of the mass of the whole galaxy (a few $10^{11} M_{\odot}$, for the Milky Way).

Because they are so far away—in fact at cosmological distances—studying the host galaxy of a QSO is difficult. However, astronomers have identified a bestiary of analogous objects, but far less violent, called Active Galactic Nuclei (AGN), that are sitting at the centre of closer galaxies. With the improvement of the instruments' capabilities, the end of the 90's brought the confirmation that in all galaxies where an AGN was found, the star's velocity distribution—measured through the Doppler shift of the light—exhibited a dramatic change at the heart of the galaxy, a testimony to the presence of a very high mass, strongly concentrated but not luminous. This was a good indication, but not yet a proof that a black hole was indeed carrying this mass. Within the error bars of the measurements, another hypothesis was still possible: a dark stellar cluster made of low luminosity objects such as white dwarfs, brown dwarfs or even stellar black holes. At the same time it became clearer that a large majority of galaxies, if not all, were featuring a compact massive dark nuclear condensation even if no sign of activity was detected. It also became clear that our own galaxy was a member of the club. Demonstrating that the Galactic Centre was actually harbouring a black hole then became an important quest with consequences far beyond the simple knowledge of our own galaxy: such a discovery could heavily strengthen the hypothesis of QSO powered by monstrous black holes. The hunt for the Galactic Center black hole had begun!

The Galactic Center

A traveller that would make for the constellation of Sagittarius and continue his trip along some 24000 light-years, would arrive in regions very different from that of his departing point, the sun. He would probably be first struck by the density of stars around him: one million times larger than in the sun's neighbourhood. He would also be amazed by the beauty of mixed blue and red luminous ribbons that wrap as some spiral arms around what appears as a dense cluster of particularly bright stars, very blue because they are very hot. All these features, he could not see before his arrival, because an opaque veil of sub-micronic dust grains is indeed totally hiding the heart of the galaxy; despite there being only one grain per thousand cubic meters, distances are so large that the cumulative effect finally builds this veil. In the infrared however, the wavelength becomes large enough with respect to the grain size for the electromagnetic waves to propagate more easily: in other words, the absorption by the veil decreases with wavelength to a point that, while the fraction transmitted at 550nm is only one billionth, about 10% of the light is left to go through it at 2200 nm.

At radio wavelength there is a total transparency and it is while pointing a radio telescope towards this region that Balick and Brown found in 1974 a strong radio source they called SgrA*, the A meaning that it was the most luminous in the Sagittarius constellation. Not only strong in radio signal, SgrA* is also variable, an additional clue that it could belong to the class of AGN. If this hypothesis is correct, the radio emission could then be some indirect trace of the accretion process; however one would deal



◀ **Fig. 1:** An infrared ($\lambda = 3.7 \mu\text{m}$) view of the field, 3.2 light-year wide, around the radio source SgrA*, at the very centre of the Milky Way, our own Galaxy. The image was taken with the tandem instrument NAOS and CONICA on the VLT. NAOS is the adaptive optics system while CONICA is an infrared camera. To have an idea of the crowding, one should note that only one percent of the stars on this image are bright enough to be recorded and that in the region around our Sun, there would be only one star in this field. The diffuse ribbons delineate bubble of ionized gas, seen through radiative recombination of H^+ .

here with an especially low level of activity, since there was no emission detected at other wavelengths. If it's not by its emission, then why not try to hunt the super-massive object through its gravitational signature? The fact is that a big mass should have some effect on the trajectories of stars close enough to it and even some stars could be gravitationally bound to SgrA*. The cluster of bright stars appeared then especially well suited for this quest: at those distances, only the most luminous stars have a chance to be separated from the herd.

The infrared image of Fig. 1, taken at 3700 nm gives an idea of the crowding in a field of only a few light-years around SgrA*. Even this picture is far from fully expressing the reality since only one percent—the brightest members—of the whole stellar population is showing up. However, even restricting our study to those light-houses, confusion is still too high if one uses classical imaging on a telescope, even the largest such as the European Very Large Telescope of ESO in Chile (8m diameter). As long as the sharpness of the images does not reach one tenth of an arcsec ($0.5 \mu\text{radians}$), it's impossible to separate stars in a reliable way and to follow them in their trajectory around a putative black hole. Now it's a fact that a telescope, even in a very good site gives images not much better than $5 \mu\text{radians}$. Gaining this order of magnitude on the sharpness of the images is what adaptive optics has brought. Some obstinacy and some luck were the other ingredients of success.

NAOS, the adaptive optics system of the Very Large Telescope

The light from distant sources that reaches our planet after, sometimes, a journey of millions or billions of years, first meets the atmosphere. It does not have a very good welcome, since within a few micro-seconds, the wavefront will suffer some twisting due to inhomogeneities in the optical medium, that is the air, with the consequence that the image sharpness is severely reduced, by a factor of at least 10 with respect to the diffraction limit of a large telescope. Adaptive optics, whose concept is due to Babcock (who passed away recently) was actually developed during the 90's: in short, this is the art of reshaping in real-time an embossed wavefront to recover the full resolving power of a telescope. For this purpose, a flexible mirror of a dozen centimetres in diameter is subtly distorted at a rate of typically 500 times a second, so that bumps and slumps are compensated on the reflected beam. A wavefront sensor, using the light from a star close to the source of interest, provides at each moment the residual error on the wavefront and feeds a fast real-time computer that builds through some clever algorithm the command to the deformable mirror. Adaptive optics is now becoming a standard equipment of large telescopes.

The Very Large Telescope (VLT) is one of the few European "big science" equipment assemblies. Made of four 8m telescopes, it was built at the top of mount Paranal in the north of Chile (see Fig. 2), under the responsibility of the European Southern



▲ Fig. 2: The four units of the Very Large Telescope. Each telescope features an 8m primary mirror. VLT has been built by European Southern Observatory on Cerro Paranal in the north of Chile.

Observatory (ESO). It is a great success, both on the technical and on the operational sides, producing at a regular pace results that are at the forefront of astronomy.

A French consortium (Onera, Lesia at Observatoire de Paris and Laboratoire d'Astrophysique de Grenoble) provided the adaptive optics system NAOS which equips Yepun, one of the four telescopes [1, 2]. Installed at the end of 2001, NAOS began to produce top quality images for the astronomical community in spring 2002. In brief, NAOS is 2.3 tons of sophisticated optics, mechanics, detectors and electronics (see Fig. 3), built around a deformable mirror comprising 185 actuators, which accepts as an input a perturbed image and provides at its output a quasi-perfect one. Coupled to the infrared camera CONICA built by a German consortium (Max Planck Institutes from Heidelberg and Garching), NAOS must be considered as the best system in the world in several respects: the most sensitive in terms of the star used to servo the system, it also produces diffraction-limited images in the largest wavelength range (1.2 to $5 \mu\text{m}$) and has many specialised features, including a unique infrared wavefront sensor that allows one to servo the correction loop on purely infrared sources. Because the dust grains afore mentioned are found everywhere in the galaxy, such infrared sources are the only ones actually detectable in heavily obscured regions such as the Galactic Centre.

The infrared hunt for the Galactic Centre black hole

For almost ten years, several stars close to the radio source SgrA* have been followed by a German team of the Max Planck Institute

► Fig. 3: NAOS, the adaptive optics system built by a French consortium is the blue cylinder on the right; it is installed on the Nasmyth platform of the Yepun telescope of VLT. One can see the actively supported thin primary mirror of Yepun at the bottom.



in Garching led by Prof. R. Genzel. Part of the French team of NAOS joined the group in 2002 with the goal of benefiting from the unique capabilities of the NAOS / CONICA tandem (later nicknamed NACO) in this peculiar hunt for the black hole. The idea behind those difficult measurements is that the trajectory of the stars orbiting a big mass should reveal differences depending on the way this mass is distributed: either as a cluster of a finite dimension or as a collapsed object. Despite those trajectories being only a fraction of one arcsec wide on the sky, many points along them were recorded over several years, especially using the first ESO adaptive optics system—ADONIS—developed by the same groups that built NAOS. This first set of data indeed revealed extremely large velocities for certain stars, implying effectively that a mass as large as several millions of M_{\odot} should lie in a very small volume practically at the position SgrA*, an important first step. The hypothesis of a dense dark cluster was however not yet excluded at this point.

It was during the spring and summer of 2002, in the course of the science verification phase before final delivery to the community, that a dramatic advance occurred. The Galactic Centre was one of the targets of the program and the infrared wavefront sensor was pointed at a bright infrared star, only 6 arcsec north of SgrA*, thus providing an excellent quality of the correction. Good luck occurred then in a twofold way. First it happened that one of

the monitored stars was passing at its closest approach to the centre of mass during this time (on a 15 years orbital period...) and second, it appeared that this approach was at an especially small distance: only 17 light-hours (Fig. 4). This star (called S2) thus played the role of a probe that sensed the gravitational field at a distance of only three times Pluto's orbit around the sun. The fact that the trajectory remained a pure Keplerian one constrained the mass distribution to a point such that it was no longer possible to consider a mass distributed as a dark cluster of stellar-like objects or even, another plausible hypothesis, as a ball of fermions—neutrinos or the more exotic gravitinos or axinos—sustained by Fermi pressure. The size of all those structures would have been larger than the 17 light-hours and the star trajectory would have been significantly modified. The only acceptable solution remained the black hole [3]. This is certainly the strongest piece of evidence ever produced of the existence of what was until now a purely theoretical object. In turn, this non-ambiguous result gave strong support to the proposal of a very massive black hole at the centre of most of, if not all, galaxies, and in particular of those hosting a quasar whose engine powering it is then most likely to be the accretion mechanism proposed by Rees and Van del Bel.

Since then, NACO and its unique capabilities have confirmed this result with new genuine discoveries: the infrared (1.7 to 5 μm)

Supermassive black holes and accretion

First proposed by Laplace during the 18th century, the black hole concept obtains its full coherent status with Einstein's general relativity. The theory interprets gravitation in terms of the distortion of space-time: the light rays that exhibit its weave, are twisted close to massive objects. The theory associates with any mass a critical radius: if the mass is concentrated within the sphere of critical radius, then no particle, even the photon, can escape. This radius, called the Schwarzschild's radius, or horizon, is defined by equating the potential energy $GmM_{\text{TN}}/R_{\text{H}}$ of a mass m with its maximum kinetic energy $1/2 mc^2$, leading to the relationship: $R_{\text{H}} (\text{Km}) \approx 3 M/M_{\odot}$.

Several types of black holes are predicted by astrophysicists. The collapse of the heart of a star whose initial mass is larger than 45 M_{\odot} leads to the formation of a stellar black hole. When the core is beyond 3 M_{\odot} , even the repulsive forces of the degenerated matter (electrons and neutrons) cannot resist the huge pressure of gravity. One may note that although a black hole of one Earth mass would be extremely compact (1 cubic centimetre!), this is no longer the case for a black hole of several billions of solar masses. Such ultra-massive black holes may have formed from the fusion of stellar black holes, themselves resulting from a very dense stellar cluster such as those found at the centre of galaxies.

This postulate that ultra-massive black holes do exist at the very centre of certain galaxies (indeed probably all) is at the basis of the QSO central engine paradigm.

Quasars, found in 1961, exhibit three characteristics: they are extremely luminous, extremely compact and are intense sources of X-ray and UV radiation. The first characteristic is deduced from comparison between their apparent brightness and their enormous distance—several billions of light-years—measured by the redshift; one then finds that they radiate 10^{40} W typically, i.e. several hundred times the luminosity of the brightest galaxies. Compactness, the second characteristic, is first indicated by their apparent small size on the sky: in fact they look like unresolved stars, hence their name of Quasi-Stellar objects. Even more, the time scale of the variations of their flux is short: from a few hours to a few weeks, so that their linear size, which is expressed in light-days, is far below the size of condensation at the heart of any galaxy. The third characteristic, the X-UV emission, testifies that the emission process is likely the black body emission of a plasma at several millions degrees Kelvin.

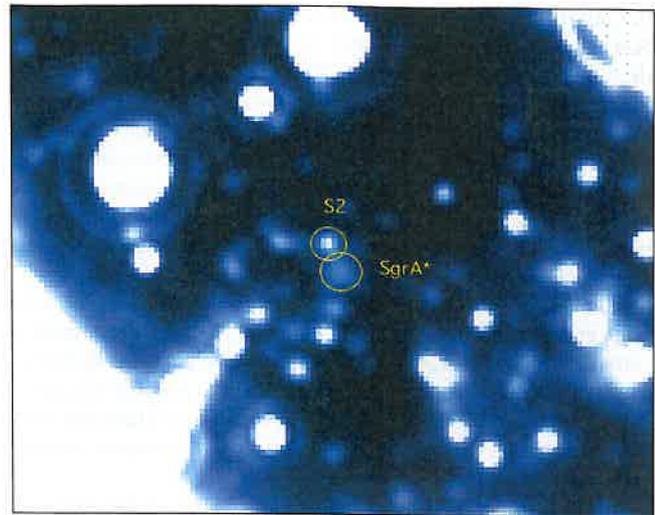
How is it possible to produce such a huge luminosity in so small a volume? Nuclear fusion is unable to do it because its yield when converting mass into energy is only 1% of mc^2 . A much more efficient mechanism consists of bringing a mass m from infinity down to the horizon of a black hole: if the whole potential energy can be retrieved, then by definition of the horizon, 50% of mc^2 becomes available. One condition, however, is that the matter does not cross the horizon following a free fall but rather spends a certain time in an accretion

disk where it will be torn by collisions and tidal forces and will eventually be heated to extremely high temperatures through some viscosity effect and finally will radiate in the X-UV spectral range.

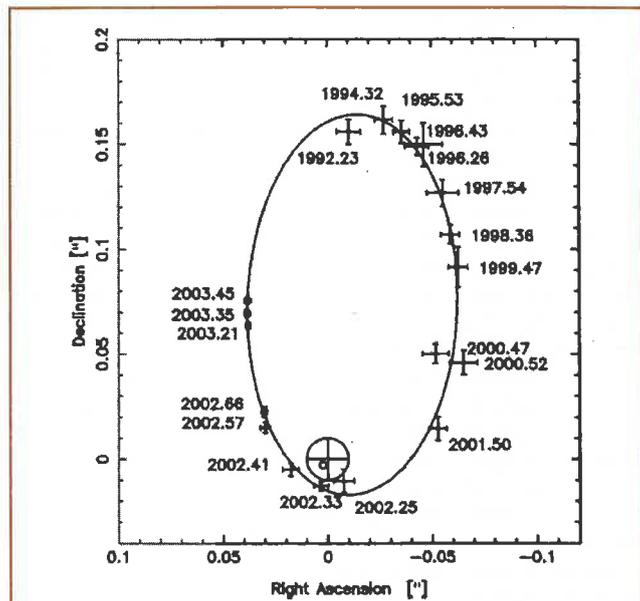
Viscosity is an important ingredient that must be efficient because at the relativistic velocities we are dealing with, differential velocities are indeed extremely large; viscosity provides in addition a good mechanism to loose angular momentum, a required condition for the matter to fall towards the centre. This proposed mechanism is not just a theoretical one: in fact it can explain the X-ray emission of X binaries, a system of two stars where the external layers of one component is accreted by a very compact companion, a neutron star. Applied to a quasar, one finds that this process requires an accretion of only 10 solar masses per year on a black hole of $10^9 M_{\odot}$ to explain the observed luminosity of 10^{40} W.

The next question is then why $10^9 M_{\odot}$? It is the great physicist Eddington who remarked that there should be an upper limit to the luminosity of a black hole of a given mass because the radiation pressure is responsible for a self-limitation of the accretion process. From this simple relationship between luminosity and mass, one may derive that $10^9 M_{\odot}$ is the minimum mass required to provide the observed 10^{40} W. In addition, a $10^9 M_{\odot}$ black hole has a Schwarzschild radius of 3 light-hours, fully consistent with the observed variability time-scale.

counterpart of the radio source which was eagerly looked for has been eventually detected with, here also, an unexpected behaviour that brought a superb bonus. Rather faint and difficult to separate from other sources (especially the star S2 which brought certitude to the existence of the black hole), the quiet emission observed unambiguously [4] at 3.6 and 4.8 μm (see Fig. 5) corresponded precisely to what was expected, i.e. the synchrotron emission of relativistic electrons most likely associated with a stable collimated jet of plasma, indeed the same that is responsible for the radio emission. On the other hand, what came as a real surprise was the observation at several infrared wavelengths of sudden flares lasting for typically 90 minutes, with an estimated frequency of 3 per day [5]. Those bursts would rather be associated with episodic phases of accretion of matter on the horizon of the BH, i.e. the same mechanism that is invoked for the Quasar engine, but here with a much more modest efficiency. This hypothesis is even more attractive since a quasi-periodic modulation of 17 minutes is observed during the flare that could correspond to the period of the Last Stable Orbit (LSO). This is a well defined orbit, predicted by General Relativity, where matter could accumulate for a time but, when it eventually leaves, falls irremediably onto the black hole horizon. Such an orbit is strongly constrained by the theory in the case of a rotating black hole (named a Kerr black hole): if the hypothesis is correct, then the observed period of 17 minutes could correspond to twice the minimum value for a $3.6 \cdot 10^6 M_{\odot}$ black hole. The inferred rotational period of the black hole itself would then be 13 minutes.



▲ Fig. 5: A close-up of the image of Fig. 1. The infrared emission at 3.7 μm of the black-hole direct environment (accretion disk and/or jet) which has been eagerly looked for was detected unambiguously by NACO: it corresponds to the slightly diffuse patch in the circle marked SgrA*. The point source marked S2 is the star whose orbit made certain the presence of a black hole of 4 millions solar mass at the position of SgrA*.



▲ Fig. 4: The orbit of the star S2 around the radio source SgrA*, determined using several years of precise measurements of its relative positions. Note that the projected great axis of the complete orbit is only 0.18 arcsec, i.e. about one third of the size of the spot of a star on the best standard images obtained in the best sites in the world. The data points brought by NACO are those on the bottom left. The cross marks the position of the putative black hole at the location of the radio source SgrA*. The extremely close approach (only 17 hour-lights) to SgrA* during which the orbit remained Keplerian implies a mass concentrated in a quasi point-like object, i.e. a black hole. The figure is taken from Adenhauer 2003.

Black holes are all in all rather simple physical objects: one can show that they are totally described with three parameters only, their mass, their angular momentum, i.e. their spin, and their charge. With the infrared measurements at high angular resolution provided by NACO, the first of those three parameters is well determined. It may well be the case for the second parameter, spin. In any case, the year 2004 with its intensive campaign of measurements should confirm or invalidate this guess. If it is confirmed, as we expect, then the charge will remain the last parameter to measure. We will then be in a position to claim that the era of experimental physics of black holes has indeed begun.

References

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