Black-hole activity feedback across vast scales

Black-hole activity feedback is intensively studied on both galaxy-cluster scales and parsec scales. There are, however, many open questions about how the close surroundings of supermassive black holes affect large-scale structure and vice versa.

Both observational and theoretical studies of black-hole activity or active galactic nucleus (AGN) feedback have been ongoing since the first indication of supermassive black holes powering quasar activity in the 1960s. Although several crucial astrophysical questions have been answered in the following decades, a number of open problems remain, in particular how AGN feedback operates over nearly eight orders of magnitude — from scales of \(10^{-13}\) pc to the galaxy-cluster scales of a few hundred kiloparsecs. At the beginning of June 2022, about 50 junior as well as senior researchers met in Brno for the post-lockdown edition of the Cologne–Prague–Brno meeting (‘Black-hole Brno for the post-lockdown edition of the junior as well as senior researchers met in the beginning of June 2022, about 50 scales of a few hundred kiloparsecs. At scales of \(\sim 10^{-3}\) pc to the galaxy-cluster nearly eight orders of magnitude — from particular how AGN feedback operates over been answered in the following decades, quasar activity in the 1960s. Although of supermassive black holes powering of AGNs. General relativistic magnetohydrodynamic 2D and 3D models of magnetized accretion flows show that ultrafast outflows and jets can be generated within a few tens to a few hundred gravitational radii (Agnieszka Janiuk, Bestin James). Since SMBHs are surrounded by NSCs, accretion flows can frequently be perturbed by a star or a compact remnant, which can address some of the quasi-periodic accretion or outflow phenomena, including quasi-periodic eruptions (QPEs; Petra Suková).

Several blazars exhibit jet morphological changes, which can be linked to flux density variations and outbursts through changes to the viewing angle. A model of bulk jet precession driven by the Lense–Thirring effect or by a secondary black hole can naturally account for the periodic variation of the Doppler-boosting factor, which changes the underlying jet flux density (Silke Britzen). This model has successfully been applied to address recurring radio outbursts of the ‘Rosetta-stone’ BL Lac source OJ287 or to explain the formation of the ring-like temporal pattern in the radio jet structure of the flat-spectrum radio quasar PKS 1502+106, which is a candidate source of high-energy neutrinos. Exciting prospects for novel observational tests of these models are finally enabled by just-emerging X-ray polarimetry thanks to the Imaging X-ray Polarimetry Explorer (IXPE; Giorgio Matt).

Feedback on large scales

Supermassive black holes (SMBHs) are not isolated. On the contrary, they are typically surrounded by the densest stellar systems in galaxies, nuclear star clusters (NSCs), which have comparable sizes to globular clusters but are many times more massive, and, in barred spiral galaxies, nuclear stellar disks, which have scales from a few tens to a few 100 pc (Rainer Schödel, Álvaro Martínez). On the scale of a few 1,000 gravitational radii, accretion flows are present that manifest themselves in the form of broad lines, characteristic continuum emission as well as outflows and jets (Božena Czerny, Ana Müller, Peter Boorman).

The nearest NSC, and the only one that can be resolved observationally into individual stars (Andreas Eckart, Florian Peissker), is the NSC at the centre of the Milky Way (MW NSC) with a half-light radius of \(\sim 4\) pc and a stellar mass of \(\sim 10^7\) \(M_\odot\). The MW NSC is old \((\sim 80\% of the stellar mass formed \(\geq 10\) Gyr ago) and possesses a power-law density cusp of stars around Sgr A*. Past accretion activity of Sgr A* a few million years ago may have affected stars in the surrounding NSC via star–disk and star–jet collisions (Michal Zajaček, Anabella Araudo, Petr Kurfürst), thus stripping away the envelopes of giant stars and rendering them invisible, which may explain the observed dearth of giant stars within about 0.2 pc from Sgr A*.

More generally, black-hole accretion in AGNs can induce outflows. The model of a failed dusty outflow has been invoked to explain the formation of broad-line regions at a few thousand gravitational radii (Božena Czerny, Ana Müller), one of the most important observational characteristics of type I AGNs. General relativistic magnetohydrodynamic 2D and 3D models of magnetized accretion flows show that ultrafast outflows and jets can be generated within a few tens to a few hundred gravitational radii (Agnieszka Janiuk, Bestin James). Since SMBHs are surrounded by NSCs, accretion flows can frequently be perturbed by a star or a compact remnant, which can address some of the quasi-periodic accretion or outflow phenomena, including quasi-periodic eruptions (QPEs; Petra Suková).

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Feedback on small scales

Supermassive black holes (SMBHs) are not isolated. On the contrary, they are typically surrounded by the densest stellar systems in galaxies, nuclear star clusters (NSCs), which have comparable sizes to globular clusters but are many times more massive, and, in barred spiral galaxies, nuclear stellar disks, which have scales from a few tens to a few 100 pc (Rainer Schödel, Álvaro Martínez). On the scale of a few 1,000 gravitational radii, accretion flows are present that manifest themselves in the form of broad lines, characteristic continuum emission as well as outflows and jets (Božena Czerny, Ana Müller, Peter Boorman).

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Eight orders of magnitude

Jets emanating from giant elliptical galaxies provide enough radio-mechanical power to inflate radio lobes and drive weak shocks into the intergalactic medium, which balances the radiative cooling. To drive the jet, an AGN needs to be switched on at a moderate level, hence a certain amount of gas needs to be provided for accretion. In galaxy-cluster or large-scale AGN feedback, the theory of ‘precipitation’ is popular \((\sim)\). It is based on thermal instabilities operating in the hot halo gas, thanks to which gas condenses or ‘precipitates’ onto cold clumps or filaments that ‘rain’ onto the central galaxy, and subsequently ignite or maintain AGN feedback. This mechanism has recently been confirmed by the study of the correlation between jet power and Bondi-accretion power. While giant elliptical galaxies that exhibit cooling flows revealed via \([\text{N}\Pi]+\text{H}\alpha\) emission exhibit a significant correlation between jet power and Bondi-accretion power, those without...
cooling flows lack the same correlation (Tomáš Plšek).

In comparison, from the point of view of small-scale feedback, accretion onto supermassive black holes is driven by channelling cold gas from larger galactic scales, for example through the bar potential and/or cloud–cloud collisions, which probably caused significant past accretion activity of Sgr A*.

Of course, both the large-scale and the small-scale effects of the black-hole activity are causally linked. Accretion from the circumgalactic medium, in the form of precipitation, for example, is a primary source of material for both star-formation as well as accretion and AGN feedback. However, the AGN feeding and feedback act on different timescales, which makes the comprehensive statistical analysis challenging.

Parsec-scale nuclear star clusters can in principle mix up the cards. In the stationary 1D models of the stellar-wind feeding in the NSCs\textsuperscript{4,5}, the radial flow velocity goes through zero at the so-called stagnation radius, which separates inflow and outflow regions. In this sense, NSC can 'isolate' the black hole, which is then mostly fuelled — at a very low level — by the stellar-wind material within the inflow zone while any external cold material is hindered by the collective NSC outflow. The final accretion and feedback state of the galaxy is then modulated by the NSC presence, its stellar brightness profile (core or cusp), and the stellar-wind properties of late-type or early-type stars. This is illustrated in Fig. 1, where we depict the connection between the large-scale feeding and AGN feedback on megaparsec scales, and the processes operating on the scale of a few parsecs within an NSC.

**Ernst Mach and Brno**

The combination of detailed hydrodynamical modelling as well as high-resolution X-ray and optical data is required to understand the complex interplay between the large-scale cold gas inflow and the small-scale distribution of matter within the gravitational sphere of influence of the SMBH. The connection between large-scale and small-scale properties of galaxies was the central theme of the conference. This is related to Mach's principle stating that the local state of inertia is determined by the large-scale distribution of matter\textsuperscript{6}. Like the main theme of feeding and feedback near cosmic black holes, Mach's principle has a continued impact on all scales of the gravitational Universe. Indeed, in general relativity, the effects of frame dragging influence particles along with fields (Vladimír Karas).
It is, therefore, extraordinarily fitting that the meeting happened to take place in Brno, close to Ernst Mach’s birthplace of Chrlice, where he was born in 1838 (Jiří Dušek). Moreover, the meeting held the award ceremony for the Ernst Mach Medal, an honorary award of the Czech Academy of Sciences (Eva Zažimalová). This year, the recipient was Andreas Eckart, in recognition of his life-long contribution to physical sciences, in particular for his important contribution to infrared studies of the Galactic Centre. Eckart has contributed to both observational techniques as well as to the theory of astronomical black holes, additionally using the framework of philosophical discussions besides standard approaches⁷. He contributed to the development of decisive infrared instrumentation, in particular SHARP and GRAVITY, for the European Southern Observatory telescopes. In addition, he conducted the first high-resolution near-infrared imaging observations of the vicinity of Sgr A*, which resulted in the detection of fast-moving stars around Sgr A*, known as S-stars. These are now routinely used for the tests of general relativity, developed by Albert Einstein, who was in turn inspired by Mach’s principle.

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Competing interests
The authors declare no competing interests.