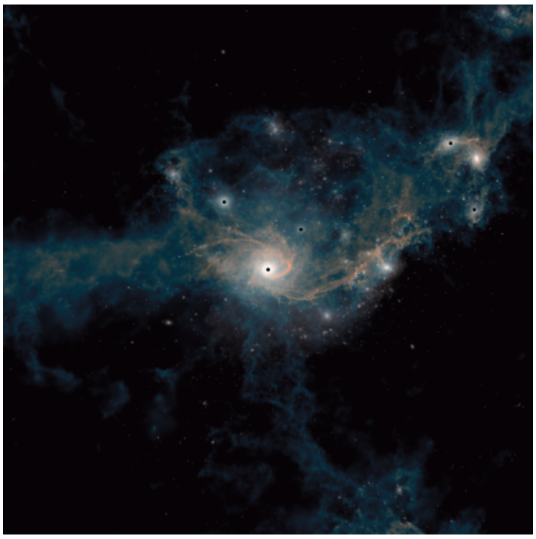
PHYSICS OF THE OUTER ATMOSPHERES OF EXOPLANETS

Since the first identifications of exoplanets in the early 1990s, the pace of discovery skyrocketed with the launch of NASA's Kepler Space Telescope in 2009. As a matter of fact, at the time of writing more than 5,000 exoplanets have been identified, and thousands more await confirmation. It is now believed that, on average, every star in our Galaxy has at least one planet in orbit around it. Furthermore, a sizeable fraction of these trillion+ worlds are likely within their star's habitable zone, i.e., the range of orbital distances within which surface liquid water can exist, possibly supporting lifeforms. To first order, the extension of the habitable zone depends on the luminosity of the host star, which in turn determines the planet's equilibrium temperature. The hot, outer envelopes of stars, however, display a large range of cycling and/or flaring behavior, and the associated UV and X-ray stellar irradiation could severely impact planetary atmospheric composition, causing severe heating, evaporation and possibly desiccation.

At Insubria University we set up an international team, including INAF and University of Michigan, working on the effects of high energy radiation on planetary atmospheres. A number of MSc and PhD thesis, both on theory and observations, can be carried out on these subjects by interested and motivated students.

Astrophysical black holes across space and time



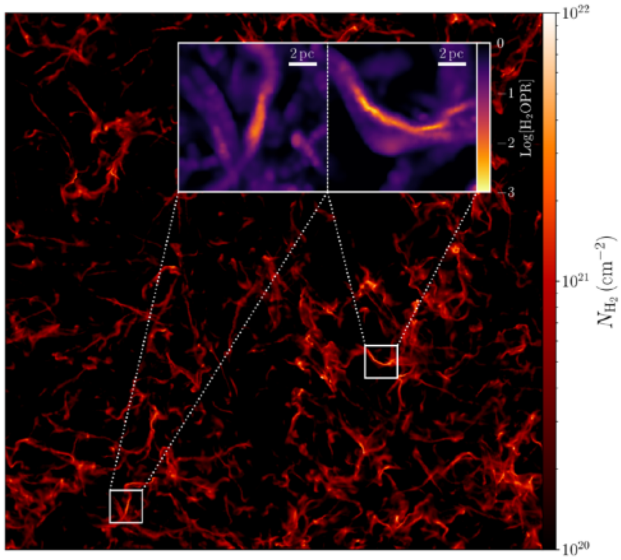
Massive black holes (MBHs) are nowadays observed in all massive galaxies up to very high redshift (z>6), when the Universe was less than 1 Gyr old. Understanding how these objects formed and grew to the observed masses is one of the crucial open questions in astrophysics. On one side, current models suffer many limitations and are still unable to make unique predictions that could be tested by observations. On the other side, observations struggle to measure accurately the MBH and its host properties at sufficient resolution to inform theoretical models. Moreover, MBHs are found to be tightly connected to their host, and this directly links them to the study of how galaxies form and evolve in the Universe, including galaxy mergers, when MBHs can pair into a bound binary system which then shrinks and finally coalesces emitting gravitational waves (GW) potentially observables by the next generation GW detectors as LISA and Einstein Telescope.

The research activity in this field is extremely active and at University of Insubria covers most of these aspects. In particular:

a) MBH formation mechanisms: using semi-analytical and numerical simulations, we study the relative importance of different MBH formation channels, e.g. the remnants of the first generation of stars, or the direct collapse of massive gas clouds (Lupi, Haiman and Volonteri 2021)
b) MBH growth and feedback across cosmic time and the MBH-host interplay: using state-of-the-art cosmological zoom-in simulations, we assess how the accretion process proceeds on MBHs in massive high-redshift galaxies and the impact of the accretion-powered feedback on the galaxy evolution (Lupi et al. 2019, 2022; see Figure above). We also aim at addressing how processes commonly neglected as the accretion above the Eddington limit (Regan et al. 2019) or the capture of stars and compact objects can alter the MBH evolution at early cosmic times
c) MBH binary pairing and evolution: we study how efficient the MBH pairing process during galaxy mergers is, in particular addressing the interaction with the surrounding gas (in circum-nuclear and circum-binary discs) and also the MBH spin evolution (Cenci, Sala, Lupi et al. 2021; Franchini, Lupi and Sesana 2022; Bollati, Lupi et al. 2023)
d) MBH and gas evolution in the relativistic regime: thanks to a general-relativistic extension of the cosmological N-body code GIZMO (Lupi 2023), we aim to build a self-consistent model of gas accretion onto MBHs all the scales from Mpc down to the horizon.

The physics of the interstellar medium

Stars form out of the interstellar gas, in the densest and colder regions called molecular clouds. During their evolution, stars affect this gas, shaping the next generation of stars and the global evolution of galaxies themselves. Properly understanding the evolution of the interstellar medium is the only was to fully characterise galaxies and the star formation within them. The study of how galaxies form and evolve is challenging, as it is requires a detailed modelling of many physical processes that are still poorly understood. Among them, the chemical evolution of the gas is fundamental, as it affects the thermodynamics of the gas, the star formation, and is also responsible for the electromagnetic emission we observe. At University of Insubria, we are at the forefront of this research, with the first studies including a detailed modelling of infrared emission tracers in the cosmological evolution of galaxies (Lupi & Bovino 2020; Lupi et al. 2020). Currently, we are also working on a self-consistent modelling of the chemical evolution of the interstellar medium in simulations, that accounts for the impact of X-rays (which are emitted by accreting MBHs), complex molecules (as CO) and dust evolution.



On smaller scales (AU and less), chemistry becomes even more important, as it strongly characterise the properties of gaseous filaments and clumps collapsing into stars. In particular, the abundance of different molecular tracers is used in observations to constrain the speed of the gravitational collapse, the stellar properties, and the formation of proto-planetary discs and planets in them. At University of Insubria, we work on the most accurate 3D simulations of the formation of molecular clouds and filaments, which include the effect of magnetic fields, cosmic rays, and an extremely complex chemistry, which must be evolved alongside to obtain a reliable description of the physical evolution (see Lupi, Bovino, and Grassi 2022, see Figure).

References:

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