The colours of the extreme universe

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English Summary

The observable Universe

You are probably reading these lines on some spot on Earth, one of the eight planets that orbit our closest star, the Sun. The Sun is, in turn, one element in a structure of a few hundreds of billions of stars[7] bound by gravity and defined as a galaxy, our galaxy, the Milky Way. Such as the Milky Way, trillions of galaxies[8] of different sizes, shapes, and masses, are the building blocks of our vast observable Universe.

The exploration of the observable Universe is an endeavour inherent to the human nature and thus from ancient times human civilizations, from the Babylonians to the Incas, have targeted their skills and imagination to observe and map the skies. However, the scientific study of the observable Universe has seen an unprecedented development only recently, after the telescope constructed by Galileo Galilei evolved, hand in hand with technology, into magnificent machines of exploration. These machines do not only deepen our view to look into inconceivable distances, but also broaden the observable spectrum, allowing us to see and understand the Universe through colours not even humanly perceivable.

Light is the main channel of information to learn about the Universe. The constant speed of light, at $c \sim 3 \times 10^8$ m/s, is of great value since it allows us to look back in time. Due to its constant velocity, light produced at early times of cosmic history would reach us only now, allowing us to witness these early events. This velocity also defines the limits of the Universe observable to our position in space-time. Additionally, light travelling towards us is 'stretched' to longer wavelengths by the expansion of the Universe, in a phenomenon call redshift. The accelerated expansion of the Universe produces a redshift that is always higher at earlier epochs, serving as a tag for the time when an event has occurred. Observing with telescopes is thus sort of travelling in time, and when the redshift of the detected light is available, we can also know the epoch we are travelling back to.

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Crucial information – such as the redshift or the physical origin of the emission – is encoded in the characteristic 'colours'. These colours arise from the different wavelengths of the electromagnetic spectrum that composes light. While the human eye can perceive solely a small part of the spectrum (optical wavelengths), vast information on the physics producing the emission is contained across 'invisible' wavelengths. Lower energy physics usually produce emission at radio, microwave, and infrared wavelengths, while higher energy events produce Ultra-Violet (UV), X-ray and Gamma-ray emission. In this thesis, we have made parallel use of telescopes detecting the emission of galaxies across the electromagnetic spectrum to portray the early Universe in its different colours. We have pushed some of the current frontiers of the multiwavelength study of galaxies and showed how it provides us with a more complete physical understanding of the extreme and distant Universe.

The colours of galaxies and black holes

The physics of galaxies and black holes is one of the most remarkable examples of multiwavelength phenomena in the Universe, since they produce bright and characteristic emission

[7]GAIA DR2 (Gaia Collaboration et al. 2018)
[8]Conselice et al. (2016)

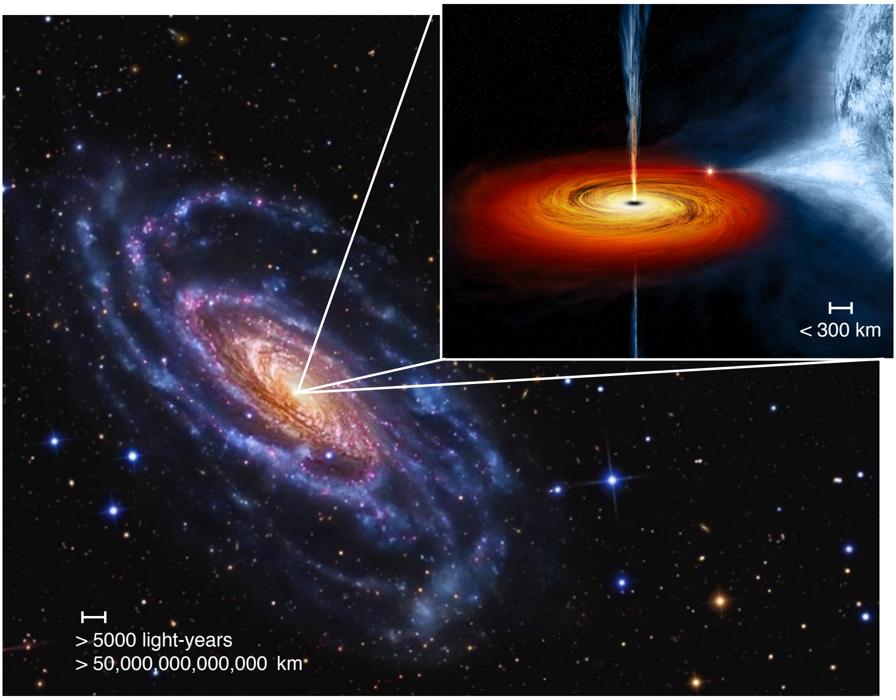

Figure S.11: Comparing the scales of a host galaxy and an accreting black hole. The *larger figure* is a photograph of the optical emission of the nearby galaxy NGC 5033, known to host two supermassive black holes in its center. NGC 5033 is a popular galaxy among amateur astronomers since its characteristic size and brigthness allows it to be easily seen and imaged. The *zoom-in figure* shows an artistic representation of the first source widely accepted to be a black hole (Cygnus X-1). (Credit for NGC 5033: R. Jay GaBany, Cosmotography, and credit for black hole representation: NASA/CXC/M.Weiss)

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across all these wavelengths. The physics of compact objects such as black holes has been recently shown to go even further, and not only produce electromagnetic waves but also gravitational waves, opening the era of multi-messenger Astronomy.

Although galaxies are formed within gravitationally bound structures of a poorly-understood material called dark matter, this main galaxy component does not undergo any other interaction than gravity, and is as suggested by it's name, invisible, producing no electromagnetic wave signature. The multi-wavelength emission in galaxies arise instead from their different baryonic components (atoms of any sort). The baryonic components of galaxies are usually distributed within bulge and disk structures, composed mainly by an interstellar medium and stars. The interstellar medium is a large content of atomic and molecular gas and dust, largely dominated by Hydrogen atoms, and produces emission in the radio, sub-millimeter and infrared regime. The ionized fraction of the interstellar medium can also emit light of optical/UV wavelengths. The molecular phase of the interstellar medium is believed to be the main raw material for the growth of the galaxy, since this gas fuels the production of new stars. The populations of stars within galaxies are the most common sources of the visible optical/UV light in the Universe, as we can witness by looking up to the sky in a clear night.

Additionally, one of the main discoveries in extragalactic astrophysics has been that most (if not all) galaxies host massive black holes in their centres. Indeed, our own Milky Way hosts a black hole in its centre called Sagittarius A*, which has been measured to be 4 million times more massive than our Sun. Black holes are massive compact objects that exhibit such an extremely large gravitational potential, that no matter *or light* within a boundary, called the black hole's event horizon, can escape from it. However, just before matter crosses this horizon, the gravitational pull creates a disk of all matter that is accreted into the black hole. See Figure S.11 for a comparison of the scales of a galaxy and its accreting black hole. The immense kinetic energy of this accretion disk can produce the most (constantly-emitting) luminous and highly energetic events in the Universe, which are called active galactic nuclei (AGN). These galactic nuclei themselves are multi-wavelength phenomena producing emission across the electromagnetic spectrum: the very energetic emission produced in the accretion is exhibited in the UV and X-ray regimes, while the reprocessed and indirect emission originated in the interaction with e.g., dust or magnetic fields, is emitted in infrared and radio wavelengths.

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A new method to characterize the multi-wavelength emission of galaxies and accreting black holes

One of the most efficient methods for extracting the physical properties of galaxies and black holes is modelling this multi-wavelength emission of galaxies, synthesized as their spectral energy distributions (SEDs). In Chapter 2, we have developed a software, AGNFITTER, to consistently model the multi-wavelength emission of galaxies and AGN. AGNFITTER applies Bayesian statistics to fit the observed SEDs, from the UV to the (sub)mm, with semi-empirical and theoretical models of the different physical components. The method we have presented is novel since it recovers the probability density functions of fundamental physical parameters of galaxies and AGN, robustly handling uncertainties and in-homogeneous sampling of the multi-wavelength photometric observations. These parameters include the total masses of the stellar populations, the star formation rates, the total AGN luminosities that correlate with the masses of the black hole and obscuration by dust.. AGNFITTER is a modular and open-source code written in the Python language, and has made compelling contributions to at least 20 different research projects in the last two years, both within and outside our collaboration circles. In Chapter 2, we have also tested and validated this approach by constructing the multi-wavelength SEDs of a sample of ∼ 2000 AGNs, active when the Universe was around one quarter of its current age, selected by their X-ray emission. Our work revealed that modelling the FIR-to-UV SED of AGN can robustly recover the parameters ruling both galaxy and nuclear (AGN) emission, despite the ∼7 orders of magnitude difference in scale.

A new window on the physics of galaxies and black holes

Thanks to the unique combination of the field-of-view, resolution and sensitivity of the LOFAR (Low Frequency ARray) telescope, in the LOFAR-Surveys collaboration we have been taking an important step forward in using the radio regime at low-frequency to trace the growth-properties of galaxies, such as star formation, in the Early Universe. In Chapter 2, we have conducted the first study of the evolution of galaxies and AGN as seen at low radio frequencies. We have characterized the physical properties of star-forming galaxies and AGN selected by their radio emission, back to redshifts of $z \sim 2.5$, when the Universe was one fifth of its current age. We have built the deepest sample of multi-frequency radio spectra, by applying careful source extraction and flux calibration techniques to large radio maps observed by several different radio telescopes, including the LOFAR, VLA, WSRT and GMRT telescopes. Focussing on star forming galaxies with negligible black hole accretion, e.g., whose radio emission is dominated by the emission indirectly arising from new-born stars, we have investigated a characteristic property, the far-infrared-radio correlation, at multiple radio frequencies. The results from Chapter 3 revealed that the FIR-radio correlation at both high and low frequencies is not constant, as suggested by previous literature, but evolves as a function of cosmic time. Most importantly, we have linked the radio emission at low-frequencies (150 MHz) to star formation and black hole accretion activity through the modelling of the FIR-UV SEDs and delivered the first calibration of the radio emission at 150 MHz as a diagnostic of star formation.

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A new high-resolution perspective on the interstellar medium

The interstellar medium in galaxies feeds both the formation of stars and the growth of black holes, making it a key ingredient in the evolution of galaxies. With the advent of the largest sub-millimeter telescope on Earth, the Atacama Large (sub)Millimeter Array (ALMA), we can now probe the interstellar medium in increasingly exquisite detail. Studies of the interstellar medium in the early Universe are most commonly conducted by observing the emission of the rotational transitions of the carbon monoxide molecule (CO), the fine-structure [CII] line, or the emission of the dust continuum (the Rayleigh-Jeans tail). The use of these tracers as a probe of the interstellar medium, however, involve several assumptions on the physical conditions of the gas and dust, such as optical depth, temperature and density of gas and dust-to-gas ratios. These assumptions could introduce large uncertainties to conclusions on the properties of the interstellar medium. In Chapters 4 and 5, we have used the ALMA telescope to make progress settling this issue by characterizing the CO(3-2) molecular emission, and the [CII] emission at high resolution, in a sample of galaxies selected by their sub-millimeter emission (sub-millimeter galaxies, SMGs). We have applied kinematic and dynamical modelling on the data to characterize the velocity fields of these sources, finding that the CO emission in our SMGs are consistent with ordered rotating disk, despite having apparent disrupted optical morphologies. This observation may suggest that molecular gas disks can quickly reform after a merger event. Our parallel study of the [CII] and far-infrared (FIR) dust continuum emission in Chapter 5 showed that galaxies exhibit a strong deficit in the [CII]/FIR ratio compared to the values expected in the literature. Comparing our observations with models of photo-dissociation regions show that this deficit is probably originated in the a thermal saturation of [CII] levels, and a significantly reduced heating of the gas via the photoelectric effect.

A new high-resolution perspective on the multi-wavelength emission of galaxies

An unbiased characterization of the physics of a galaxy requires multiwavelength studies, and this applies as well to high-resolution studies. However, since only a few telescopes provide sub-arcsecond resolution, multi-wavelength resolved studies of galaxies in the early Universe are challenging. In Chapters 4 and 5, we combined our ALMA observation with high-resolution images from the *Hubble Space Telescope* to study the stellar, dust continuum, CO and [CII] gas emission in submillimeter-selected galaxies in the early Universe. After applying robust astrometry corrections based on *GAIA* observations, our work has revealed that the resolved spatial distributions of the dust and molecular gas emission can be *entirely offset* to the stellar emission within these galaxies. This finding challenges common assumptions on energy balance between stellar and cold dust emission, highlighting the potential of combined *HST* and ALMA observations to push forward our understanding of galaxy physics at high redshift. Finally, we have conducted a statistical analysis through stacking of the observed sizes of the dust continuum, molecular gas and stellar emission in our sample of submillimeter galaxies. Our work has revealed that both the cool molecular gas emission and the stellar emission in these sources is clearly more extended than both, the dust continuum, and the [CII] main emission component *by a factor* > 2. To further understand this observation – whether there is a physical difference in the distribution of gas and dust – we have applied a radiative transfer model on the observed average radial profiles of our galaxies. Our work has revealed that this apparent size difference of gas and dust can be produced by large temperature and optical-depth gradients alone.