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PROBING GAS RESERVOIRS IN GALAXIES THROUGHOUT THE HISTORY OF THE UNIVERSE

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Abstract. The history of galaxies is marked by a peak of star formation ten billion years ago and a subsequent drop of the star formation rate (SFR) by an order of magnitude. To understand star formation and its winding-down, it is crucial to probe the gas reservoirs from which stars are formed. The IRAM PHIBSS and PHIBSS2 programs survey the molecular gas phase at different redshifts in typical star-forming galaxies, showing that the cosmic evolution of the SFR is mainly driven by that of the molecular gas fraction. We review some of their results, in particular during the winding-down of star formation at $z = 0.5 - 0.8$, and present how such studies on the gas content of galaxies will benefit from the Square Kilometre Array (SKA). If the SKA will allow molecular gas measurements at very high redshift, it will most importantly provide a complete picture of gas in galaxies by probing its atomic phase: it will detect the atomic gas before it cools down to the molecular phase up to $z \sim 1.7$, map environmental effects up to $z \sim 1$ and constrain our understanding of the interplay between baryons and dark matter.

Keywords: Telescopes, Galaxies: evolution, Galaxies: star formation, Galaxies: ISM

1 Introduction

Galaxy formation and evolution are driven by a complex interplay between the hierarchical merging of dark matter haloes, gas accretion, star formation, and outflows driven by stellar winds, supernovae or active galactic nuclei. Galaxy mergers and smooth accretion along the streams of the cosmic web (Dekel et al. 2009) can both account for bringing gas from the intergalactic medium to the centers of galaxies, where it can cool, fragment and form stars. Stars form within cold molecular gas clouds in the interstellar medium (ISM), whose typical density is about hundred particles per cubic centimeter and whose temperature is around 10 K. The densest regions collapse by gravitational attraction until their density and temperature are high enough for deuterium and hydrogen fusion reactions to ignite and for stars be born. Stars emit strong radiation fields and stellar winds throughout their life and can ultimately explode as supernovae, which contribute to heat their surrounding ISM, expel part of the gas and hence hinder subsequent star formation. Together with the radiation, winds and jets from active galactic nuclei, such feedback processes generate powerful outflows of ionized and neutral gas enriched by stellar nucleosynthesis. The material ejected by outflows is not entirely lost, as some of it remains bound and can be recycled when falling back towards the galactic disk. Galaxies thus constantly experience cycles where gas is accreted, used for star formation, ejected and recycled, as notably assumed in the gas-regulated quasi equilibrium "bathtub" model describing typical star-forming galaxies (Bouché et al. 2010; Lilly et al. 2013).

However, star formation is not uniform across cosmic time: while the Milky Way and most nearby spiral galaxies only form a few stars per year, the star formation rate (SFR) could be up to 10-20 times higher ten billion years ago. The evolution of the cosmic SFR averaged over comoving volumes of the Universe displays a peak epoch of star formation between redshifts $z = 1 - 3$ (Madau & Dickinson 2014). Furthermore, at each epoch galaxies are divided between a population of red passive galaxies with low SFR and a population of blue star-forming galaxies following a relatively tight, almost linear relation between their SFR and stellar mass, known as the star-forming main sequence (SFMS; Brinchmann et al. 2004; Noeske et al. 2007). About 90% of the stellar mass assembled since $z \sim 2.5$ was formed in galaxies on and around the SFMS (Rodighiero et al.

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2011; Sargent et al. 2012). Typical star-forming galaxies are expected to progress along the SFMS according to the slowly evolving bathtub model until their star formation is quenched when they enter a denser environment or grow past the Schechter mass $M_{\rm star} \sim 10^{10.8-11}\ M_\odot$ where the accretion stops, and then to rapidly become red and passive (Peng et al. 2010b). Episodes of gas compaction, depletion and replenishment may induce oscillations within the scatter of the SFMS before the final quenching occurs (Tacchella et al. 2016).

Stars being formed within giant molecular clouds, molecular gas and SFR are correlated on both galactic and local scales while atomic and ionized gas extend beyond the star-forming regions of galaxies (Leroy et al. 2008). The Kennicutt-Schmidt (KS) relation (Schmidt 1959; Kennicutt 1998) between the molecular gas and SFR surface densities reflects this correlation and characterizes the star formation efficiency. It has been shown to be near linear on galactic and subgalactic scales at low redshift (Kennicutt & Evans 2012), indicating relatively uniform molecular gas depletion times $t_{\rm depl} = {\rm M_{gas}/SFR}$ around 1-2 Gyr. However, the star formation efficiency may have been higher earlier in the history of the Universe (Combes et al. 2013). Probing molecular and atomic gas reservoirs in typical star-forming galaxies at different epochs is a key ingredient to understand how star and galaxy formation proceeds and evolve across cosmic time.

2 Molecular gas reservoirs across cosmic time

The PHIBSS and PHIBSS2 programs at the IRAM Plateau de Bure/NOEMA interferometer constitute the most comprehensive endeavor so far to survey the molecular gas properties of star-forming galaxies on and around the SFMS at different redshifts from their CO line emission. With a statistically meaningful sample of 52 SFMS galaxies near the peak epoch of star formation, PHIBSS uncovered large molecular gas fractions $f_{\rm gas} = 30-50\%$ at $z = 1-2$ and a near linear KS relation, showing that the evolution of the cosmic SFR is mainly driven by the available gas reservoirs (Tacconi et al. 2013). It further enabled us to obtain the first subgalactic KS relations at high redshift (Freundlich et al. 2013; Genzel et al. 2013). PHIBSS2 significantly extends the sample to cover the build-up ($z \sim 2.5-3$), the peak ($z = 1-1.6$) and the winding-down ($z = 0.5-0.8$) of star formation with more than 120 targets from well-understood parent samples in the GOODS-N, COSMOS and AEGIS fields, aiming at a relatively uniform coverage of the SFMS in the stellar mass - SFR plane. Together with other CO and dust molecular gas measurements between $z = 0-4.5$, Genzel et al. (2015) and Tacconi et al. (2018) use PHIBSS2 data to establish quantitative scaling relations describing how the molecular gas fraction and the depletion time depend on redshift, stellar mass, offset from the SFMS and stellar size. They notably show that these two molecular gas quantities vary smoothly with the offset from the SFMS and confirm that the evolution of the cosmic SFR mostly depends on the evolution of the molecular gas fraction, albeit with a small decrease of the depletion time with redshift.

During the winding-down of star formation at $z = 0.5-0.8$, we report 60 CO(2-1) detections out of 61 targets as part of PHIBSS2 (Freundlich et al. 2018). We obtain molecular gas fractions and depletion times in very good agreement with the scaling relations established by Tacconi et al. (2018). The median depletion time within the PHIBSS2 $z = 0.5-0.8$ sample is indeed 0.84 Gyr, while the corresponding KS relation is strikingly linear. We further carry out single Sérsic and two-component bulge disk fits to the galaxies' HST I-band images with the 2D morphological fitting code `galfit` (Peng et al. 2002, 2010a) to study the influence of morphology through the bulge-to-total luminosity ratio B/T and the stellar surface density $\Sigma_\star$. We find that while the total stellar mass $\rm M_\star$ increases with these morphological indicators, neither the total molecular gas mass $\rm M_{gas}$, the SFR nor the disk stellar mass $\rm M_{disk} = (1-B/T) \times M_\star$ correlate with them. If we assume an evolutionary sequence from small to high B/T, this would suggest a steady supply of molecular gas with an efficient HI to $\rm H_2$ conversion while stars form and the stellar bulge assembles. Alternatively, the resulting absence of correlation for both the molecular gas depletion time and the disk gas fraction $\mu_{\rm disk} = \rm M_{gas}/M_{disk}$ might indicate relatively uniform star formation processes at a given epoch, irrespective of the past star formation history of each galaxy traced by B/T.

PHIBSS2 further includes high-resolution follow-ups with NOEMA and ALMA. These complementary projects will enable us to determine molecular gas spatial distributions and kinematics, to compare them with the stellar and SFR distributions and to characterize the star formation efficiency at subgalactic scales through spatially and kinematically resolved KS relations. We will also be able to test the virialization of the disk and follow the potential evolution of the CO excitation and of the CO flux to molecular gas mass $\alpha_{\rm CO}$ conversion factor. While the PHIBSS and PHIBSS2 samples focus on star-forming galaxies on and around the SFMS, transitional galaxies between the SFMS and the quiescent population contain crucial information about the physical processes at stake during the quenching of star formation. Systematic studies of the molecular gas content of such galaxies are still challenging but will constitute an important step forward towards understanding star formation and gas cycles within galaxies. PHIBSS and PHIBSS2 targets are also predominantly field galaxies in which star formation and the molecular gas content are expected be different from galaxies in denser group and cluster environments, which could be probed by NOEMA and ALMA. Direct detection of more diffuse molecular gas resulting from feedback analogous to the extended ionized gas emission detected by Epinat et al. (2018) in a galaxy group is further conceivable.

3 Perspectives with SKA

The Square Kilometer Array (SKA) is an international radio telescope project consisting of different interferometric arrays in South Africa and Australia to observe metric and centrimetric wavelengths with multiple antenna designs. Its first phase, SKA1, is planned for commissioning in 2024 and will consist in about 10% of the final arrays. It includes an antenna array covering the frequency range from 50 to 350 MHz in Australia (SKA1-LOW) and another one between 350 MHz and 15.5 GHz in South Africa (SKA1-MID). The second phase, SKA2, is envisaged for 2030.

One of the main goals of SKA is to observe the neutral hydrogen gas (HI) at cosmological distances through its 21 cm rest-frame emission, which is currently only detected up to $z \lesssim 0.2$. SKA1 will detect HI in galaxies up to $z \sim 1.7$ and map it up to $z \lesssim 1$ (Blyth et al. 2015), uncovering one of the main missing components of galaxies during the second half of the history of the Universe. SKA1 will enable statistically meaningful surveys of the atomic gas at different epochs (Staveley-Smith & Oosterloo 2015), hence complementing molecular gas surveys such as PHIBSS and PHIBSS2 while providing a more complete picture of gas reservoirs in galaxies and their evolution. In addition to the atomic gas, SKA will also probe molecular gas at very high redshift with the possibility to detect the CO(1-0) line at $z > 7.3$ with SKA1, to detect dense gas tracers such as HCN, HCO$^+$ and CS and to make CO(1-0) surveys at $z > 3.8$ with SKA2 (French SKA White Book 2017). The SKA1 CO(1-0) detections will notably permit to better calibrate the $\alpha_{\rm CO}$ conversion factor and the CO Spectral Energy Distribution (SED) at very high redshift. Furthermore, SKA1 will trace the SFR down to a few M$_\odot$/yr up to $z \sim 10$ from the free-free emission of hot electrons ionized by young stars, which is optically thin, unaffected by dust and hence a more direct tracer of the SFR than UV and IR luminosities (Mancuso et al. 2015).

By mapping the HI atomic gas up to $z \sim 1$, SKA1 will address fundamental issues regarding environmental effects on galaxies and the connection between galaxies and their surroundings. As atomic gas is more extended and more loosely bound to galaxies than molecular gas and stars (as can notably be seen in M81: Yun et al. 1994), it is more easily perturbed, making it a perfect probe of environmental effects such as tidal and ram pressure stripping. By removing part of the gas from galaxies, these processes dramatically affect the quenching of star formation and the subsequent evolution of the perturbed galaxies. SKA1 should further enable the first detection of the brightest parts of the filaments of the cosmic web that feed galaxies and of the diffuse surrounding gas (Vazza et al. 2015), which can currently only be probed in absorption along serendipituous quasar absorption lines (e.g., Schroetter et al. 2016). HI observations will also allow to better understand the evolution of Low Surface Brightness (LSB) and Ultra Diffuse Galaxies (UDG), which harbour large atomic gas masses. In particular, the UDG population first uncovered by van Dokkum et al. (2015) may result from feedback-induced episodes of inflows and outflows in which the atomic gas plays an important role (Di Cintio et al. 2017).

Last but not least, the HI atomic gas reveals the rotation curves of galaxies well outside the optical disk, contrarily to the CO and Hα velocity fields that are confined within the optical radius. From the HI rotation curves, SKA1 will be able determine the dark matter content of galaxies at different epochs and the evolution of the baryonic fraction with redshift (Combes 2015), hence addressing one of the most fundamental issues of cosmology and galaxy formation. Galaxies indeed lack baryons compared to the universal baryon fraction, and it is not clear whether these baryons have been prevented from the beginning to accrete onto galaxies or have been later expelled. Addressing the issue of gas within galaxies hence contributes to better understand our Universe as a whole.

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