Simulations and modelling of the interstellar medium in galaxies

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Abstract. The latest observations of molecular gas and the atomic hydrogen content of local and high-redshift galaxies, coupled with how these correlate with star formation activity, have revolutionized our ideas about how to model star formation in a galactic context. A successful theory of galaxy formation has to explain some key facts: (i) high-redshift galaxies have higher molecular gas fractions and star formation rates than local galaxies, (ii) scaling relations show that the atomic-to-stellar mass ratio decreases with stellar mass in the local Universe, and (iii) the global abundance of atomic hydrogen evolves very weakly with time. We review how modern cosmological simulations of galaxy formation attempt to put these pieces together and highlight how approaches simultaneously solving dark matter and gas physics, and approaches first solving the dark matter $N$-body problem and then dealing with gas physics using semi-analytic models, differ and complement each other. We review the observable predictions, what we think we have learned so far and what still needs to be done in the simulations to allow robust testing by the new observations expected from telescopes such as ALMA, PdBI, LMT, JVLA, ASKAP, MeerKAT, SKA.

1. Introduction

A fundamental challenge in astrophysics is to understand the connection between a very homogeneous early Universe, as probed by the Cosmic Microwave Background (CMB) radiation and its temperature fluctuations (e.g. Komatsu et al. 2011), and the density contrasts observed today on large scales, such as the galaxy clustering (Tegmark et al. 2004), and the small scales, such as stars. The wide range of scales associated with this problem, from a few astronomical units to Gpc, is also connected to several orders of magnitude in temperature and density. The computational power currently available makes it impossible to treat all the physics relevant on the different scales self-consistently, making it necessary to treat the problem in pieces. This is the case of galaxy formation, in which a variety of physical processes taking place in different scales can have a large impact on the evolution of galaxies, such as stellar feedback on small scales to gas infall from filaments to the centre of dark matter (DM) halos, where galaxies reside, on large scales. Fig. 1 shows a visualisation of a DM only simulation and how galaxies populate DM halos as predicted by the semi-analytic model of galaxy formation GALFORM (Bower et al. 2006), emphasizing the role the cosmological paradigm plays in the theory of galaxy formation.

To study galaxy formation, it is necessary to simulate the evolution of baryons in the context of the cosmological growth of the DM structures, as this sets the gas inflow and merger histories of galaxies. There are two widely used approaches to study galaxy formation: hydrodynamical simulations or “parallel” approaches, which simultaneously follow the evolution of the DM and gas physics, and “serial” approaches or semi-analytic modelling of galaxy formation, which first solve the DM $N$-body problem and then deal with the gas physics. In the case of the hydrodynamical simulations, the main advantage is the sophistication of the simulations which help to avoid many (but not all) prior assumptions in the gas dynamics (e.g. Springel & Hernquist 2003). The main disadvantages are that the number of galaxies that can be simulated is still very limited and that, despite the sophistication of the technique, many of the physical processes
regulating galaxy formation occur on a scale well below the resolution of these simulations, and are viewed as sub-grid physics in this context, and are hence treated in a phenomenological way. In the case of semi-analytic models, a hybrid set of discrete and numerical physical models are implemented to treat galaxy formation and evolution. Semi-analytic models are able to simulate large cosmological volumes containing millions of galaxies over cosmic epochs making multiwavelength predictions (Baugh 2006). The main drawback of semi-analytic models lies in the large set of parameters used to model some of the most uncertain physics, which is also a problem affecting the sub-grid physics part of hydrodynamical simulations. The improvement of observational techniques and quality of the available data along with more accurate and sophisticated theoretical models of relevant physical processes, such as star formation (SF), help to remove some of the uncertainties in cosmological models and simulations of galaxy formation.

The modelling of the ISM in galaxies is of great importance in the theory of galaxy formation and even in cosmology; SF takes place in high density gas, which is primarily molecular. Star-forming regions are the places where the most massive stars reside and therefore where most of the energy and radiation feedback from stars are released. Large scale feedback in the ISM and outflows driven by supernovae (SNe) depend on the nature of the star-forming regions (i.e. density of the medium, star formation rate, etc.; Efstathiou 2000). Outflows induced by SNe feedback might have a large impact on the chemical enrichment of the intergalactic medium (e.g. Oppenheimer & Davé 2006, see Putman et al. 2012 for a recent review) and on driving turbulence in the ISM (Dobbs et al. 2011). The turbulence in the ISM can also have a direct impact on the infall of gas towards the centre of galaxies where supermassive black holes reside and consequently on the accretion and mechanical power of such black holes. A schematic view of the interplay of all the processes above is shown in Fig. 2 where the red square encloses all the processes directly depending on the modelling of the ISM. The schematic stresses the effect the modelling of the ISM can have on all the properties of galaxies and even on the gas outside galaxies.

In this review we summarise key observational results that have pushed the development of more realistic ISM and SF modelling in galaxy formation in §2, some important results from multi-phase hydrodynamical simulations in §3 and semi-analytic models of galaxy formation and the main lessons that can be taken from them in §4. We present conclusions in §5.
Figure 2: Schematic view of the physical processes involved in the formation of galaxy disks and the ISM. Galaxies are assumed to form embedded in DM halos and therefore the first step is to set the cosmological paradigm. This paradigm defines when and where structures form in the universe. Baryonic matter infalls into halos, which have a potential well largely dominated by DM. The gas cooling from shocked heated gas in the halo or direct infall of gas to the centre through filaments give rise to galaxies or feeds the existing galactic disk. The chart emphasizes the impact the modelling of the ISM and SF can have on the various components of a galaxy and even outside the galaxy, such as the intergalactic medium.

2. Characterisation of the star formation law and the ISM in galaxies

Large improvements in the resolution and quality of the imaging and spectroscopy of nearby galaxies have allowed a better understanding of one of the key physical processes in galaxies: star formation. This new set of observations has allowed us to identify in great detail the places where SF is taking place and the role played by the different phases of the interstellar medium in setting the star formation rate (SFR). As a result the field of SF has advanced to a new era in which new, sophisticated theoretical models and simulations have been developed to understand the triggering mechanisms of SF.

Improved observations include high quality, spatially resolved observations of atomic hydrogen (HI) (e.g. Walter et al. 2008) and carbon monoxide ($^{12}$CO; e.g. Helfer et al. 2003; Leroy et al. 2009), and of ultraviolet (UV) and infrared (IR) SFR tracers in samples of nearby galaxies. These data have allowed the accurate estimation of the molecular and atomic hydrogen contents of galaxies over a wide range of morphologies and gas fractions. In addition, more reliable estimates of the unobscured SF in the UV (e.g. Gil de Paz et al. 2007) and of dust-obscured SF in the IR (e.g. Calzetti et al. 2007) have allowed better determinations of the SFR, both globally and within individual SF regions. The combination of measurements of spatially resolved gas contents and SFR in galaxies led to a better characterisation of the SF law (i.e. the relation between the surface density of SFR and gas). There is now support for a SF law in which the SFR per unit area, $\Sigma_{SFR}$, and the molecular gas surface density, $\Sigma_{mol}$, correlate linearly, $\Sigma_{SFR} \propto \Sigma_{mol}$ (Wong & Blitz 2002; Bigiel et al. 2008). This relation is much stronger than that using either the surface densities of total cold gas or HI.
Towards the outskirts of galaxies, it has been observed that $\Sigma_{\text{SFR}}$ starts correlating with the atomic gas surface density, $\Sigma_{\text{atom}}$, but this correlation appears to be a result of the underlying correlation between $\Sigma_{\text{mol}}$ and $\Sigma_{\text{atom}}$ (Bigiel et al. 2010, Schruba et al. 2011). Most of the studies probing the $\Sigma_{\text{SFR}} - \Sigma_{\text{mol}}$ correlation rely on $^{12}\text{CO}$ observations (hereafter CO). The reliability of this proxy to trace the bulk of the molecular content of galaxies is compromised in low metallicity gas, typical of dwarf galaxies and the outskirts of spiral galaxies (e.g. Bell et al. 2006). However, recently, the linear correlation $\Sigma_{\text{SFR}} \propto \Sigma_{\text{mol}}$ has been confirmed in low metallicity environments through observations of dust column density and atomic hydrogen by (Bolatto et al. 2011), which are independent of the CO. At high redshifts, there are indications that the same form, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{mol}}$ could hold (Bouché et al. 2007, Genzel et al. 2010). The correlation of $\Sigma_{\text{SFR}}$ with $\Sigma_{\text{mol}}$ seems physically reasonable since stars are observed to form in dense molecular gas clouds (see Solomon & Vanden Bout 2005 for a review on the CO-IR luminosity relation and Kennicutt & Evans 2012 for a review on the SF law of local galaxies).

All of the observational support for the strong correlation between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{mol}}$ indicates that SF occurs only where the hydrogen in the ISM has been converted into molecular hydrogen ($\text{H}_2$). With this in mind, it is fair to say that any realistic galaxy formation simulation should incorporate molecular hydrogen and the subsequent SF taking place from it. The relevance of the different ISM phases in determining the SF, suggests that an understanding of star formation requires an understanding of the ISM and the formation of neutral warm (atomic) and neutral cold (molecular) gas phases.

3. **Hydrodynamical simulations including multi-phase ISM**

The characterisation of the SF law of local galaxies has pushed the field of SF to a new stage in which more and more accurate calculations have been carried out, in which processes such as $\text{H}_2$ formation and destruction, HI to $\text{H}_2$ transition in non-equilibrium chemistry, non-equilibrium thermal state, variations in the strength of the radiation field, and in some cases, radiative transfer, have been included (e.g. Pelupessy et al. 2006, 2009; Robertson & Kravtsov 2008; Gnedin et al. 2009; Dobbs et al. 2011; Shetty & Ostriker 2012; Glover & Clark 2012; see Klessen et al. 2009 for a status report on numerical simulations). In this section, we give a brief overview of the work developed to answer three broad questions.

*Is the relation between the surface density of $\text{H}_2$ and the SFR causal or is it the result of both quantities correlating to some third, more relevant quantity?* Theoretical models have explained the observed relation between the $\text{H}_2$ surface density and SFR surface density as resulting from an underlying correlation between temperature and the chemical state of the ISM (Schaye 2004). Although molecular hydrogen is not an important coolant in galaxies today (which have gas metallicities of $Z > 0.1Z_\odot$), it is an excellent tracer of cold, high-density gas. This happens since both $\text{H}_2$ and cold gas are sensitive to photo-dissociation from UV photons and are therefore found in places where the gas has self-shielded to prevent photo-dissociation. Given the fact that low temperatures are required for further gas fragmentation and SF, one would expect a correlation between SF and the chemical state of the gas to be present (i.e. the presence of $\text{H}_2$ molecules). This relation has been recently quantified by Gnedin & Kravtsov (2011), Feldmann et al. (2011) and Glover & Clark (2012) in which both the molecular hydrogen formation rate and the gas cooling rate correlate with column density of clouds. Glover & Clark show that molecular hydrogen is not a pre-requisite for SF as the low temperatures and high-densities needed to form stars are reached even in situations were the gas remains atomic. This might be the case for the ISM in low-metallicity galaxies, in which dust, the catalyst in the process of $\text{H}_2$ formation, is very scarce.

In low metallicity environments, thermal equilibrium is also expected to be reached much faster than chemical equilibrium, with the onset of SF taking place before chemical equilibrium is reached (Wolff et al. 2008). The predictions from simulations is that eventually, at very low metallicities, the observed $\Sigma_{\text{SFR}} - \Sigma_{\text{mol}}$ relation should break down. However, this is expected to happen only at metallicities smaller than $10^{-2}Z_\odot$ (e.g. Glover & Clark 2012). Even in such low metallicity galaxies, Krumholz (2012) argues that molecular gas is still a good tracer of where SF is taking place, given that a correlation between the time averaged $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{mol}}$ emerges after reaching chemical equilibrium. This result is very important for
cosmological galaxy formation simulations, in which the timescales involved are much longer than both the thermal and chemical equilibrium timescales in the ISM. Therefore, processes taking place on small scales in the ISM are part of the overall simplified physical treatment of sub-grid physics.

What sustains the turbulence in the ISM? Recent hydrodynamical simulations have included energy injection from SNe to study their effect on ISM turbulence and on galaxy structure with the aim of distinguishing it from turbulence driven by gravitational instabilities. Contradictory results have been obtained. Dobbs et al. (2011) show that feedback has an important effect on setting the scale height of the galaxy disk through its effect on the velocity dispersion, in a simulation of a large spiral galaxy, similar to the Milky-Way, and including the effect of spiral arms. Although Dobbs et al. show that the spiral arms contribute to increasing the rate of cloud collisions, driving the formation of larger and more massive molecular clouds in the disk, gravitational instabilities do not dominate the turbulence in the ISM. Shetty & Ostriker (2012) also find that SN feedback is the primarily source of turbulence in the dense environments of starburst galaxies. In addition, Acreman et al. (2012) compared simulated maps of HI with the observations of the Canadian Galactic Plane Survey and found that simulations match the observations only when SNe feedback is included. On the other hand, Bournaud et al. (2010) show in a simulation of a dwarf galaxy, with properties similar to the Large Magellanic Cloud, that feedback is not important in setting the scale height and that this is set by gravitational instabilities (which primarily determine the velocity dispersion in their simulation). Nonetheless, Bournaud et al. find that feedback is necessary to replenish the large scale turbulence which initiates the cascades to small scales and to suppress the formation of very dense, small gas clumps (see also Hopkins et al. 2012 and Shetty & Ostriker 2012). From the latter it is unclear whether the scale height in the simulation of Bournaud et al. is in equilibrium or not. There is still a lot of research to be done to get to the root of these discrepancies, such as to study the dependence on galactic environment, on the implementation of feedback, and study how the results vary with the details of the codes (grid vs. smooth particle hydrodynamics).

Cosmological applications of multi-phase ISM simulations. Recently, a number of papers have shown that galaxies with realistic properties can be obtained in cosmological simulations with a multi-phase treatment of the ISM and realistic gas density thresholds for the onset of SF (e.g. Murante et al. 2010; Guedes et al. 2011). The general agreement in hydrodynamical simulations is that it is necessary to resolve down to scales comfortably below the Jeans length in order to resolve star-forming regions (Schaye 2004).

We started this review pointing to the importance of cosmology in developing a complete galaxy formation theory. The problem can also be tackled in the opposite direction: cosmology should care about the way the ISM and SF are modelled. Two examples of this is (i) the number density of absorbers probed in lines-of-sight to backgrounds quasars and (ii) the metallicity-dependent SF law developed by Krumholz et al. (2009). Regarding (i), Altay et al. (2011) show that H$_2$ self-shielding is needed in cosmological, radiative transfer calculations to predict the sharp break observed in the number density of absorbers of large column densities, $N_H > 7 \times 10^{21}$ cm$^{-2}$, typical of condensed gas in the ISM of galaxies. Regarding (ii), for a long time feedback from massive stars has been suggested to be a primary way to quench SF in dwarf galaxies (Benson et al. 2003). However, recently the possibility of SF being reduced in dwarf galaxies simply by the fact that major coolants in the ISM are scarce have started to be explored. Kuhlen et al. (2012) show that the stellar mass in dwarf galaxies is greatly reduced if a metallicity-dependent SF law is included (Krumholz et al. 2009). This effect is manly seen in galaxies with $Z < 0.1 Z_\odot$. A lot of work still needs to be done to explore the effect the lower SF efficiency driven by lower metallicities can have on e.g. the well known problem of the overabundance of low-mass galaxies predicted by simulations and models (e.g. Crain et al. 2009; Bower et al. 2012).

4. Semi-analytic models including a two-phase ISM

Until recently, the ISM of galaxies in semi-analytic models was treated as a single star-forming phase (e.g. Cole et al. 2000; Springel et al. 2001). The first attempts to predict the separate HI and H$_2$ contents of galaxies in semi-analytic models postprocessed the output of single phase ISM treatments to add this information
It was only very recently that a proper fully self-consistent treatment of the ISM and SF in galaxies throughout the cosmological calculation was made (Cook et al. 2010; Fu et al. 2010; Lagos et al. 2011b; see Robertson & Kravtsov 2008 and Dutton et al. 2010 for examples of non-cosmological models). These work have shown that a consistent treatment in the ISM and SF in galaxies is necessary to make progress in understanding the gas contents of galaxies, for example in the relation between the H$_2$ and HI contents with other galaxy properties (e.g. Lagos et al. 2012; Kauffmann et al. 2012).

Semi-analytic models of galaxy formation have included formalisms to model the ISM and SF which assume hydrostatic and chemical equilibrium. The models of Lagos et al. and Fu et al. implemented two ways to estimate the partition between H$_2$ and HI in the ISM of galaxies: (i) the empirical relation of Blitz & Rosolowsky (2006), which relates the molecular-to-atomic surface density ratio to the hydrostatic pressure within the disk, estimating the SFR from the molecular gas surface density using the well measured molecular depletion timescale (Bigiel et al. 2008) (also used by Cook et al. 2010), and (ii) the theoretical law of Krumholz et al. (2009), which models SF as taking place in turbulent, marginally stable clouds, estimating the molecular abundance from the balance between the dissociating radiation flux and the formation of molecules on the surface of dust grains. Both models show that the empirical relation of Blitz & Rosolowsky allows a good fitting to the HI mass function at $z = 0$ (Zwaan et al. 2005 and Martin et al. 2010). Lagos et al. (2011a) used an improved resolution Monte Carlo simulation to show that the agreement between the model prediction and the observations extends down to HI masses of $10^6 M_{\odot} h^{-2}$. This same model predicts a clustering of HI selected galaxies in good agreement with observations (Kim et al. 2012). The inclusion of the Krumholz et al. theoretical law in the Fu et al. and Lagos et al. models leads to large overpredictions in the number density of intermediate HI mass galaxies. This is partially due to a cloud clumping factor (i.e. the ratio between the surface density of clouds and the diffuse medium) introduced by Krumholz et al., which is an unknown in galaxy formation models and most simulations.

Two key results obtained from semi-analytic models when a realistic ISM modelling is included are shown in Fig. 3. The steep decline of the SFR density with decreasing redshift observed in the Universe is closely connected to the steep decline of the molecular mass density, while the atomic hydrogen density is predicted to evolve very weakly with redshift (Lagos et al. 2011a). Lagos et al. explain this relation as arising from a combination of decreasing gas fractions and increasing galaxy sizes with decreasing redshift. Both act reducing the gas surface density and the hydrostatic pressure of the disk. Thus, the SFR density evolution can be linked with the evolution of the surface density of gas in the galaxies dominating the SFR in the Universe at each time.

The increasing hydrostatic pressure in galaxy disks and the increase in gas fractions with increasing redshift also lead to an increase in the molecular to dynamical mass ratios. This increase has been inferred in observations of normal galaxies in the Universe up to $z \sim 2.5$ (see Geach et al. 2011). Lagos et al. (2011a) show that the shape of the relation between the molecular gas fraction (i.e. the molecular to molecular plus stellar mass ratio) and redshift depends on the environment of galaxies, in a way that galaxies residing in low mass halos have larger molecular gas fractions than those residing in more massive halos, on average. The simulations of Narayanan et al. (2012a) and Davé et al. (2011) agree qualitatively with this prediction. A main problem arising when testing model predictions against observations of molecular gas is that observational samples are inhomogeneous. In order to constraint better the predictions of the simulations it is necessary to estimate properties of the environments of the observed galaxies at various redshifts, stressing the need for homogeneous, volume-limited samples of galaxies.

Saintonge et al. (2011) presented the first local Universe CO(1 – 0) volume-limited sample and in combination with the HI observations of Catinella et al. (2010), it was possible to study the relations between the atomic and molecular gas contents with other galaxy properties. This takes us to the second key result obtained in semi-analytic models, the molecular-to-atomic gas ratio correlates with stellar mass, and that there is an anti-correlation between the HI-to-stellar mass ratio and stellar mass. Fig. 3 shows the scaling relations of the gas content with stellar mass. The predicted relation between $M_{\text{H}_2}$ and the stellar mass, $M_*$, is close to linear for galaxies that lie on the active star-forming sequence in the $M_* – \text{SFR}$ plane (Brinchmann
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Figure 3: **Left panel:** Global density of the SFR in units of $M_\odot \text{yr}^{-1} \ h^3 \text{Mpc}^{-3}$ (black line), and of the atomic hydrogen (blue line) and molecular hydrogen (red line) in units of the critical density at $z = 0$, as a function of redshift for the Lagos et al. (2011a) model. The grey crosses correspond to the compilation of observational estimates of the SFR global density of Hopkins & Beacom (2006). The HI mass density from Zwaan et al. (2005) and Martin et al. (2010) from the HI MF, and Péroux et al. (2003), Prochaska et al. (2005), Rao et al. (2006), Guimaraes et al. (2009) and Noterdaeme et al. (2009) from DLAs are also plotted using blue symbols, as labelled. Also shown is the local Universe estimate of the $H_2$ mass density from Keres et al. (2003) using the CO(1 – 0) luminosity function as red symbol. **Right panel:** the ratios $H_2$-to-stellar mass (top panel) and HI-to-stellar mass (bottom panel) as a function of stellar mass for the Lagos et al. (2011a) model at $z = 0$. The dotted line show the approximate sensitivity limits below which CO(1–0) or HI are not detected in the different surveys. Contours show the regions within which different volume-weighted percentages of the galaxies lie for a given stellar mass and above the sensitivity limit, with the scale shown by the key. For reference, the dashed line shows the median of the model distributions. Observational data from the HERACLES survey (Leroy et al. 2009), the GASS catalogue (Catinella et al. 2010), the COLD GASS survey (Saintonge et al. 2011) and the literature compilation of Bothwell et al. (2009) are shown as symbols.

What drives the close to constant SFR/$M_\star$ and $M_{H_2}/M_\star$ ratios for galaxies on the active star-forming sequence is the balance between accretion and outflows, mainly regulated by the timescale for gas to be reincorporated into the host halo after ejection by SNe (Lagos et al. 2011b). It is precisely the evolution of this balance that causes the decline in the global molecular gas density with decreasing redshift shown in the left panel of Fig. 3 (Kaufmann et al. 2012) show that an important constraint on models is imposed by the non-detections obtained in the volume-limited surveys since they represent quenched galaxies, i.e. galaxies with small gas reservoirs. Kaufmann et al. show that models do not easily reproduce the observed trends between the fraction of galaxies detected in CO(1–0) emission and galaxy concentration, stellar mass and surface density. A possible explanation for this is that semi-analytic models do not take into account
gas flows in the ISM and dynamical drivers, such as bars, which would require better modellings of the morphological transformation of galaxies.

Observations of the molecular gas at high-redshift are very scarce and limited to individual examples. The situation with observations is changing very rapidly with the development of more powerful millimeter and radio telescopes. An example of this is the recent observational campaign with the JVLA instrument presented by Aravena et al. (2012), which follow up the COSMOS field in CO(1 − 0) emission, which in addition to the previous estimate of Daddi et al. (2010), add important constraints to the CO(1−0) luminosity function at high-redshift (see symbols in Fig. 4). These campaign suggest a strong evolution in the number density of bright CO(1 − 0) galaxies from \( z \sim 0 \) to \( z \sim 2 \). The few constraints on the high-redshifts CO(1−0) luminosity function already help to ruled out some of the available models. Physical models for the CO emission in galaxies have started to be explored in cosmological simulations with encouraging results, such as the one shown in Fig. 4 and the CO-IR luminosity relation (Lagos et al. 2012; Narayanan et al. 2012b).

\[ \text{Figure 4: Left panel: The CO(1 − 0) luminosity function inferred in observations by Keres et al. (2003) at } z = 0 \text{ (open triangles) and Aravena et al. (2012) (filled circle and open diamond) and Daddi et al. (2010) (open square) at } z = 2. \text{ The predictions from the two semi-analytic models, Obreschkow et al. (2000; black line) and Lagos et al. (2012; red line), which include a physical calculation of the CO emission in the ISM of galaxies are also shown (Fig. credit for Manuel Aravena). Right panel: simulated observations of the CO(3 − 2) and CO(6 − 5) flux maps in declination vs. right ascension of a typical star-forming galaxy at } z = 2 \text{ predicted by the Lagos et al. (2012) model. Flux is in units of mJy/beam and the flux scale is shown at the top of each panel. Maps correspond to hypothetical observations of the full ALMA configuration (50 antennae) band 3 after 20 mins (top panel) and band 6 after 5 hours of integration (bottom panel). Ellipses at the bottom-left corner indicate the beam size and shape and the cross shows 1×1 arcsec}^2. \]

5. Conclusions

We have discussed two broad theoretical approaches to study galaxy formation and evolution: hydrodynamical simulations, or “parallel approach” and semi-analytic models, or “serial approach”. The main advantage of the former is the study of complex phenomena in detail and the development of physical models describ-
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ning for example SF and the phases of the ISM. The main advantage of the latter is the extensive testing of
the parameter space and the broad comparison with observations through large statistics.

Regarding hydrodynamical simulations, we discuss recent findings that explain the observed relation
between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{mol}}$ as arising from an underlying relation of both quantities with the surface density of
gas and the effect of SNe feedback on sustaining the turbulence in the ISM of galaxies. We also give two
examples of the importance of the ISM modelling in key cosmological questions. Regarding semi-analytic
models, we show that the inclusion of hydrostatic, chemical equilibrium descriptions for the ISM and SF
help the models explain the observed HI and H$_2$ mass function and the observed scaling relation of the
atomic and molecular gas with other galaxy properties, and the observed trend of increasing molecular gas
fraction with redshift. We have also discussed open problems and lines of investigation both techniques are
now starting to explore.

So far, semi-analytic models and simulations of galaxy formation have a plethora of predictions of the
relation between the H$_2$ and HI gas contents with galaxy properties, and even the CO excitation levels of
galaxies at different cosmic epochs. The dramatic improvement in the quality and quantity of data expected
over the next decade with the next generation of radio and sub-millimeter telescopes such as the Australian
SKA Pathfinder, the Karoo Array Telescope and the Square Kilometre Array which aim to detect 21 cm
emission from HI, and the Atacama Large Millimeter Array, the Large Millimeter Telescope and the Cornell
Caltech Atacama Telescope, which are designed to detect emission from molecules and dust, will help
constrain and improve the models discussed in this review.

Acknowledgements

CL thanks Inti Pelupessy, Giuseppe Murante, Claire Dobbs and Peter Creasey for the discussions and help in
understanding better hydrodynamical simulations. CL is grateful to the organizers of the symposium for the
invitation and the exciting discussions on the ISM of galaxies and the challenges the field currently faces.

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