Understanding the connection between star formation and the gas content of galaxies

Claudia Del P. Lagos - ESO fellowship

Recent high-resolution studies of the inter-stellar medium (ISM) and star formation in galaxies have revolutionized our view of how stars form (e.g. Leroy et al. 2008). These discoveries have called into question one of the most fundamental assumptions made in galaxy formation models: that stars form from the whole gas content of the ISM (e.g. White & Frenk 1991, Lagos et al. 2008). It is now clear that the real picture is not this simple: stars form only from the coldest component of the ISM, i.e. the molecular gas (e.g. Bigiel et al. 2010). This implies that fuelling star formation is not only about providing newly cooled gas, but taking this gas to a still colder, molecular phase. As part of my thesis work, I revisited the treatment of star formation in galaxy formation models based using a more realistic scenario in which the transformation of gas into stars, and the associated flow of mass and metals between the hot and cold gas phases are treated in a more general way, with stars forming from molecular gas (Lagos et al. 2011a, 2011b). This work constitutes the first major improvement to the treatment of star formation since the original calculations in Cole et al. (1994). My new modelling allowed, for the first time, a statistical assessment of the relation between the different ISM components, star formation, and other galaxy properties, such as stellar mass and luminosity, allowing a physical explanation of observed local and high-redshift relations between the atomic, molecular hydrogen abundances with other galaxy properties (Lagos et al. 2011b; Geach et al. 2011; see Fig. 1). However, there are open questions that I aim to address with this fellowship that I discuss below.

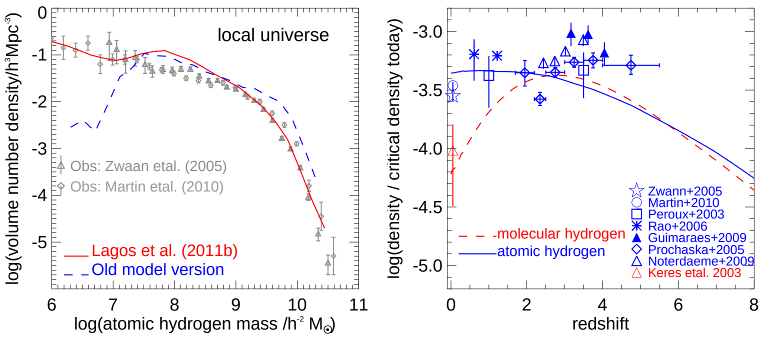

Figure1: Two key predictions of the model presented in Lagos et al. (2011a, 2001b): the local atomic hydrogen mass function (left panel) and the redshift evolution of the atomic and molecular hydrogen global density (right panel). Observations are shown by symbols in each panel. As can be seen from the left-hand panel, the original model, with the old treatment of star formation, underpredicts the number of low atomic hydrogen mass galaxies by two orders of magnitude, whereas the new model agrees very well with the observations.

Where is the atomic hydrogen in the Universe?

How much of the atomic hydrogen in the universe is in the ISM of galaxies? How much of it is in the form of cold flows coming into the galaxy halo? These are crucial questions in galaxy formation, since they determine which channels fuel star formation. High-quality measurements of the 21 cm emission in large surveys of local galaxies (Zwaan et al. 2005) and absorption-line measurements in the spectra of quasi-stellar objects (Noterdaeme et al. 2009), have allowed an accurate measurement of the evolution of the global density of atomic hydrogen. These observations suggest very little evolution of the atomic hydrogen global density with redshift.

In my semi-analytic model, by including the atomic hydrogen content in the ISM of galaxies, I am able to explain the observed atomic hydrogen global density at $z < 2.5$ (see the right-panel of Fig. 1). At higher redshifts, the model underpredicts the atomic hydrogen global density by a factor of $\gtrsim 2$, suggesting that the atomic hydrogen at higher redshifts might be primarily outside galaxies. On the other hand, hydro-dynamical simulations show that $\approx 50\%$ of the atomic hydrogen in the universe at $z \approx 3$ is expected to be outside galaxies, in the form of cold flows (Van der Voort et al. 2011). However, a key part in answering the questions above comes from the challenge of modelling how much atomic hydrogen is accounted for in cold flows, in a self-consistent way. I aim to estimate the contribution from cold flows to the atomic hydrogen abundance in the semi-analytic model to test the suggestions above.

Another key component needed to answer these questions is in the confrontation of theory and observations, which will be possible by collaborating with the ESO group targeting atomic hydrogen in galaxies and halos (e.g. Martin Zwaan, Carlos De Breuck). This will allow me to test the physical treatment of the gas included in galaxy formation models, further improving the physics involved. This will also help to make direct predictions for the new generation of radio telescopes, such as the Australian Square Kilometre Array Pathfinder, the WALLABY, ASKAP HI All-Sky Survey and the Square Kilometer Array. I am also part of the WALLABY project, closely collaborating with the group at Western University, Australia. I have been invited to speak at the WALLABY workshop in Nov., 2011.

What is the nature of luminous Infrared galaxies?

How common are luminous Infrared galaxies at high-redshift? Are they representative of the entire high-redshift galaxy population? Are they Milky-Way progenitors? Galaxy formation models have shown to be very successful in explaining statistically, the properties of galaxies, suggesting that the physics included on them is roughly correct (e.g. Baugh et al. 2006). However, the properties of specific populations of galaxies, such as massive galaxies, are more challenging in hierarchical cosmologies.

Why are luminous infrared galaxies interesting and 'special'? Much effort has been made to increase the redshift limit to observe 'normal', star-forming galaxies. Successful campaigns have brought new, exciting results about how much molecular gas resides in a relatively small number of luminous infrared galaxies (Tacconi et al. 2010, Geach et al. 2011), showing that they seem to have much higher gas-to-total mass ratios than local universe counterparts. These samples are the best we have to date at high-redshifts to study the ISM of galaxies. Geach et al. (2011), compiled available observational data to show that the gas-to-total mass ratio seems to evolve with time, revealing how the observed trends can be explained by my model, Lagos et al. (2011a), and concluded that this evolution is expected to be very sensitive to the dynamical mass of galaxy host halos.

This work suggests that it is not trivial to make the connection between these high-redshift galaxies and the low-redshift galaxy population. In order to identify the descendants of these high-redshift, molecule-rich galaxies, it is necessary to tackle their evolution. A theoretical framework of galaxy formation is necessary to place these luminous infrared galaxies in the big picture of galaxy formation, given that their evolution is predicted to depend on their star formation history, accretion history, the environment they reside in and their dynamical properties. The semi-analytic model of galaxy formation gives us the opportunity to select galaxies in the same way as in observations. Furthermore, it makes it possible to track the evolution of all galaxy properties. Based on simple approximations to estimate the Carbon-Monoxide emission, which is what is measured in observations, I show in Lagos et al. (2011b) that the predicted properties of these galaxies agree with observations as a consequence of my new modelling of star-formation.

A major step, however, is to connect the molecular content of galaxies with the Carbon-Monoxide emission in a more physical way. For this I have started a collaboration with Estelle Bayet (Oxford), Serena Viti and Tom Bell (UCL) whose expertise is in modelling the ISM of galaxies. I led the development of a novel hybrid approach which aims to estimate theoretically the Carbon-Monoxide emission of galaxies by combining the galaxy formation model with the ISM simulations performed by the Oxford-UCL group (Lagos et al. 2011c, in prep.). This will allow us to study theoretically, for the first time, the relation between Carbon-Monoxide, molecular hydrogen, stellar content, and other galaxy properties, in a realistic universe. The expertise in star formation in high-redshift galaxies at ESO led by Wolfram Freudling, Paola Andreani, Eelco van Kampen and Andy Biggs will reinforce these studies, given these experts comprehensive view of what observations tell us about the ISM of these galaxies and how their star formation proceeds.

ARE SUPERNOVAE RESPONSIBLE FOR QUENCHING STAR FORMATION?

How is the star formation history of galaxies affected by supernovae feedback? Is this feedback powerful enough as to drive the global star formation rate decline of the universe? Supernova feedback represents a long standing problem in galaxy formation model. Currently, toy models are used to treat supernova feedback, which are parametrized to reproduce the faint-end of the luminosity function (Cole et al. 2000; Guo et al. 2010). These toy models do not take into account key physical conditions, such as the density of the ISM of galaxies or how much energy is being released by supernovae. This is a fundamental issue in galaxy formation models, given the importance of supernova feedback in determining the star formation history of galaxies.

What have we learned from observations? Spectroscopic campaigns of distant galaxies suggest that powerful, extended outflows might be common place at high-redshift (e.g. Shapiro et al. 2009). If these outflows are big enough to compensate for gas accretion onto the galaxy, they could be sufficient to quench star formation. This would imply that supernova driven outflows play an important role in the transition from active star-forming galaxies to passive, dead galaxies. However, the importance of these outflows it not clear yet given the lack of information on gas accretion.

From the point of view of galaxy formation theory, supernova driven outflows can be modelled in a more physical way by following their evolution from the point of energy injection to the supernova remnant, until it breaks-out from the galaxy and becomes an outflow (Ostriker & McKee 1988). However, this is only possible after making assumptions about the properties of the ISM, such as the filling factors of the warm and cold gas in the ISM (Lagos et al. 2012, in prep.). By doing so, I want to tackle in a more realistic model the effect of supernovae feedback on star formation and whether parametric forms used are good descriptions of these events. A key component to address how well the new modelling does, is to compare the predicted outflow velocities with observations. I also want to test how realistic are the assumptions made about the ISM and whether or not these need to be systematically different at low and high-redshifts.

In extreme systems, such as starburst galaxies, it has been proposed that radiation pressure acting on the dust can become sufficiently to blow out all the gas in the ISM, quenching star formation (Thompson, Quataert & Murray 2005). Such extreme systems would certainly present very powerful outflows that can be probed in observations. I aim to include a formal description of these starbursts in the galaxy formation model to study how outflows generated in these environments could be observed. Another powerful source of feedback, extensively used in semi-analytic models, comes from Active Galactic Nuclei (AGN; Lagos et al. 2008, 2009a). Galaxy formation models do not consider AGN feedback during its brightest stages (quasi-stellar objects) as an effective source of mechanical feedback, even under the evidence of massive outflows in radio-quite objects (Alexander et al. 2010). This assumption can be tested within the scheme of evolving outflows I am currently developing (Lagos et al. 2012, in prep.) by studying the mass loading during QSO activity. The expertise of Harald Kuntschner, Carlos De Breuck and Mark Westmoquette at ESO on outflows of local and high-redshift galaxies and the best techniques to observed them, would give this project a great impetus with the necessary feedback from observations.

ASSESSING THE CAPABILITY OF NEW INSTRUMENTS TO CARRY OUT GALAXY SURVEYS

Galaxy formation models have shown to be the best tools to perform capability studies for instruments with different specifications (Cai et al. 2009). They allow the introduction of typical instrumental errors and the manipulation of the selection criteria of galaxies. I am currently involved in the use of lightcones generated from my Lagos et al. (2011b) model to assess the capability of millimeter telescopes to carry on galaxy surveys (PI: James Geach). This represents an important step to statistically assess the relation between the stellar and gas content of galaxies in observations.