Report on the Workshop

Multiwavelength Views of the ISM in High-redshift Galaxies

held at ESO Vitacura, Santiago, Chile, 27–30 June 2011

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Our knowledge of the formation and evolution of distant galaxies continues to advance dramatically with the advent of new facilities at most observable wavelengths. One of the outstanding questions related to this field is: How do galaxies get their gas? Over the next decade, radio and submillimetre facilities like the Expanded Very Large Array and the Atacama Large Millimeter/submillimeter Array will probe the chemistry, kinematics and obscured star formation properties of the interstellar medium in galaxies at high redshift, allowing this question to be addressed. We report on a timely workshop on the roles of theory and multi-wavelength observing facilities in furthering our understanding of interstellar medium physics in distant galaxies.

Introduction

Observational tracers of the gas and star formation activity in high-redshift galaxies can be probed across the entire electromagnetic spectrum. Large optical/infrared telescopes like the ESO Very Large Telescope (VLT) and the Keck telescope allow us to observe emission lines like Lyα, Hα and Mg II, which generally trace star formation and active galactic nuclei (AGN) activity. Far-infrared (FIR) lines like [C II] at 158 µm, the dominant cooling line in the interstellar medium (ISM) of galaxies, are now being surveyed in large samples of galaxies with Herschel, building on the pioneering work of the ISO satellite. These FIR lines are redshifted to the Atacama Large Millimeter/submillimeter Array (ALMA) bands for high-redshift galaxies, and with early ALMA science now about to begin, such observations will become routine. In the mm- and cm-wavelength regime, the redshifted emission lines of molecules like CO, HCN and HCO^+ trace the star-forming gas directly, and the lowest energy transitions of these molecules are observed with the Expanded Very Large Array (EVLA) and the 100-metre Green Bank Telescope (GBT) for galaxies above redshifts of $z > 1.4$. Current observations of the observable properties of these objects are being modelled by high quality numerical simulations, which include hydrodynamics.

The goal of the workshop was to bring together members of the Chilean and international astronomy communities to discuss the current state of models and observations of the gas in galaxies. The meeting was attended by more than 80 participants, including 25 students from the Chilean and international communities (see Figure 1). With early ALMA science due to commence later this year, and the deadline for cycle 0 falling in the week of the workshop, prospects for future observations with this facility were discussed, although this was not the main driver for the meeting. The conference programme was divided into six topics, and here we summarise the results of each of them.

Gas in nearby galaxies

The meeting began with excellent talks by A. Leroy and S. Martin, who described the molecular gas in nearby galaxies, which can be directly involved in fuelling star formation activity. Except for early-type galaxies, the CO molecule directly traces star formation, even though the ratio of star formation rate (SFR) to CO luminosity can vary in different galaxies. The conversion factor between cold molecular gas mass and CO line luminosity can also vary between galaxies of different types, depending on factors such as metallicity. From an overview of molecular line surveys in nearby galaxies, S. Martin described some of the diagnostic applications of a few of the 54 molecular line species that have been detected in nearby galaxies to date, and gave us a preview for what will be learned from similar surveys of high-redshift galaxies, now that broad bandwidth receivers are available on sensitive submillimetre/mm telescopes like ALMA.

Simulations and predictions for high-z ISM properties

In order to place the observed gas properties of high-redshift galaxies in the context of models of structure and galaxy formation, most of the Monday sessions focused on simulations and semi-analytic models of galaxy formation. Review talks were given by D. Narayanan and F. Bournaud, and we learned that many of the observed ISM properties of disc galaxies, as well as massive starburst galaxies, can be reproduced by hydrodynamic simulations. The submm continuum flux densities of starburst galaxies are reproduced by galaxies before and during major mergers. Major merger galaxies are detected in the large (10–20 arcseconds) single-dish beams as single submm sources. The observed CO line properties we observe in many classes of high-redshift galaxies, from the broad linewidths of quasar host galaxies during reionisation to the star-forming galaxies studied at $z \sim 2$ are reproduced by the models. Predictions of semi-analytic models of large-scale galaxy formation have also shown the evolution of properties such as the global star formation rate and the molecular gas mass function (talk by C. Lagos); predictions that will soon be tested by large ALMA surveys of molecular CO line emission (contribution by J. Gonzalez).

The Monday session finished with a great overview of the current status of ALMA commissioning by A. Peck. At the time ALMA had 15 antennas on the high site, and is preparing to begin early science operations toward the end of 2011. This talk prompted a discussion on ALMA proposal preparation, which was useful for both students and astronomers without previous experience of proposing for mm-array observations.

Outflows and star formation at high redshift

Tuesday morning began with an excellent invited talk by R. Somerville on star formation and feedback in cosmological simulations, where it was shown that observations of the gas content in high-redshift galaxies are needed to break

Figure 1. The conference participants braving the winter temperatures in front of the ALMA building in Vitacura, Santiago.

some of the degeneracies in the predictions of cosmological simulations. S. Ellison compared the importance of galaxy mergers *vs*. bars in triggering central star formation, and showed how bars experience enhanced star formation in galaxies with log($Mass/M_{\odot}$) > 10. Results of Hα imaging of star-forming galaxies was discussed by K. Menendez-Delmestre and E. Nelson, and it was shown that starburst galaxies selected at submm wavelengths have SFR surface densities similar to luminous infrared galaxies, even when they contain an AGN. M. Rodrigues discussed the evolution of the ISM in intermediate-mass galaxies.

Molecular gas properties of high-redshift galaxies

The Tuesday afternoon talks focused on the molecular gas content of high-redshift galaxies, with extensive invited overview talks provided by K. Coppin, D. Riechers and A. Weiss. Direct interferometric imaging of the cold molecular gas as traced by the lowest energy transitions of the CO line are now possible using the EVLA and the Australia Telescope Compact Array (ATCA), and we saw how this has lead to a wealth of new submm data on starburst galaxies, quasar host galaxies and BzK-selected star-forming galaxies at $z \sim 1.5$ (talks by D. Riechers, H. Dannerbauer, M. Aravena, B. Emonts and J. Hodge). It has been found that the submm starburst galaxies and radio galaxies display extended reservoirs of cold molecular gas, while quasar host galaxies do not. The excitation of this molecular gas was discussed by A. Weiss, who showed that multiple molecular gas components are needed to fit the CO line spectral energy distributions at high redshift, similar to what is seen in the inner disc of the Milky Way. Surveys of structure formation at high redshift are now becoming possible due to the wide bandwidth receivers available on facilities like the EVLA or the IRAM Plateau de Bure Interferometer; these surveys trace structure through molecular CO line emission (contributions by M. Aravena and J. Hodge).

The conference dinner on Tuesday night was held at the locally owned and operated restaurant, Dona Tina. The night was enjoyed by all who attended, and traditional Chilean cuisine was accompanied by live music.

Atomic gas properties of high-redshift galaxies

With ALMA about to begin early science observations, it is timely to discuss the FIR properties of nearby galaxies being studied by Herschel, as these lines will be redshifted to the ALMA bands at high-redshift. G. Stacey gave an invited talk on the diagnostic potential of ionised species of carbon, nitrogen and oxygen with transitions in the FIR, where extinction does not impact line intensities as it does at shorter wavelengths. All three species have now been detected at $z > 1$, mostly with the Redshift (z) and Early Universe Spectrometer (ZEUS). Large surveys of high-redshift [CII] line emission, which is the dominant cooling line in the ISM of galaxies, are now being conducted by submm-wavelength facilities, and the "[CII] line deficit" to the line luminosity observed in ultraluminous IR galaxies (ULIRGs) is also seen in the FIR luminous galaxies observed so far (talks by G. Stacey, E. Sturm, C. De Breuck, S. Gallerani). In E. Sturm's review we saw how many FIR lines are observable in gravitationally-lensed galaxies with Herschel, and how we are able to study the high-J CO emission lines in starburst galaxies and AGN.

The 2-cm transition of atomic hydrogen can be studied in absorption out to $z < 1.8$ (presentation by N. Gupta), and this has permitted studies of the cold molecular gas over cosmic time. Detecting this line in emission from high-redshift galaxies is challenging with current facilities due to its faintness, but large surveys are planned for low frequency arrays like the Australian Square Kilometer Array Pathfinder (ASKAP), Murchison Widefield Array (MWA) and the South African radio telescope array MeerKAT, which are considered to be pathfinders for the Square Kilometer Array (SKA). A. Baker showed how deep surveys with the MeerKAT will detect HI in galaxies beyond a redshift of one.

Figure 2. The participants on the ALMA tour visiting the assembly hall of the European ALMA antennas at the Operations Support Facility (OSF).

Metallicity, and the dusty ISM in high-redshift galaxies

The metallicity in galaxies tells us about their complete star formation history. An invited talk by G. Cresci showed how collisionally excited emission lines and faint recombination lines can probe the gas phase metallicity in high-redshift galaxies, where the measurement of stellar metallicities is more challenging. The VLT AMAZE and LSD surveys are providing the first metallicity maps at $z \sim 3$, showing evidence for massive infall of metal-poor gas feeding the star formation (talk by P. Troncoso).

Even in advance of the huge increase in submm/mm continuum sensitivity provided by ALMA, strong gravitational lensing of high-redshift galaxies has led to the discovery of significant samples of mm-bright galaxies in surveys by the South Pole Telescope and Herschel; their gas properties can be studied in detail with existing instruments, as described by T. Greve. The dust properties of submm-selected galaxies was discussed in an invited talk by A. Pope, who showed how polycyclic aromatic hydrocarbon (PAH) emission at mid-infrared wavelengths can distinguish between AGN and starburst dominance of the short submm-wavelength continuum emission, which is also evident in new observations of the FIR continuum emission properties of galaxies observed with Herschel. The highest redshift submm starburst galaxies have been studied in the COSMOS field, as described by V. Smolcic, and we now know of such objects out to $z = 5.3$. Deep ALMA surveys of the continuum emission in star-forming galaxies will soon allow us to study the obscured star formation in galaxies similar to the Milky Way out to very high redshifts (talk by E. da Cunha).

On the final morning of the workshop we heard from A. Updike on how gamma-ray bursts (GRBs) can be used to probe the dust in distant galaxies, where silicates may have been the dominant form of dust. G. Brammer presented the results of the NEWFIRM photometric survey of the AEGIS and COSMOS fields, and showed that the density of massive, quiescent galaxies has grown since $z = 2$. A. Smette presented a magnitude-dependent bias in the number density of damped Lyα emitters which may not be caused by dust along the line of sight.

Conference Summary

Rather than the standard meeting summary, we opened the floor to questions from the large number of students present at the meeting. A very lively discussion ensued on the long-term future of ALMA.

ALMA and APEX tour

As part of the meeting, 16 of the participants made use of the option to visit the ALMA and APEX facilities near San Pedro de Atacama. After an introduction by the ALMA director, Thijs de Graauw, the group went up to the 5000-metre-high Chajnantor plateau. In the ALMA Array Operations Site building, the participants received a guided visit of the ALMA correlator and the air-conditioning facilities. The harsh observing conditions at Chajnantor (temperatures of –15 °C) became obvious during the regular maintenance of the APEX bolometer arrays which was coordinated with the visit. After a lunch offered at the ALMA Operations Support Facility at 2900 metres, a tour was organised of the European ALMA antenna contractors’ camp, which allowed the visitors to get close to one of the dishes being assembled (see Figure 2). After a visit of the ALMA control room and laboratories, the meeting was formally closed with an amazing *asado* (barbecue) at the APEX base camp in Sequitor.

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