Report on the Workshop

Science with ALMA Band 11 (1.0–1.6 THz)

held at The Queen’s College, University of Oxford, United Kingdom, 19–20 March 2013

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The workshop formed an important part of an ALMA Development Plan Study, funded by ESO, and covered the science cases for terahertz observations with ALMA. About fifty participants, mostly from Europe, but also from North America and East Asia attended. The meeting was very successful in identifying both extragalactic and Galactic science cases for all three accessible atmospheric transmission windows (centred at 1.04, 1.33 and 1.51 THz) and also discussed the potential of the ALMA site for terahertz observing.

Introduction

Beyond 1 THz there are three atmospheric windows accessible to ALMA on the Chajnantor Plateau. These are collectively known as Band 11, following on from the current ALMA naming scheme, in which Band 10 covers 787–950 GHz. The recent deluge of exciting results from the Herschel mission and, in particular, spectroscopic observations with the Heterodyne Instrument for the Far-Infrared (HIFI) and the Spectral and Photometric Imaging Receiver Fourier Transform Spectrometer (SPIRE-FTS) instruments, have revealed the tremendous scientific potential of observing in the THz bands. ALMA Band 11 has the potential to follow up these observations with high angular resolution. The angular resolution at 1.6 THz is ≈ 0.04 arcseconds for a fairly compact array configuration with a maximum baseline of 1 kilometre. In ALMA’s most extended configuration, the resolution would be ≈ 3 milliarcseconds (although maintaining phase stability over such long baselines would then be a major challenge).

In 2010, a consortium of UK institutes proposed an ESO ALMA Development Study to re-examine the science case for Band 11. This was funded and work began in 2012 (in parallel, the Science & Technology Facilities Council [STFC] is funding technical development of mixers for Band 11). The consortium members are: Astrophysics, University of Oxford; STFC Rutherford Appleton Laboratory; and the Cavendish Laboratory, University of Cambridge. One of the key elements of the ESO study was a community workshop to develop the science case. This was held at The Queen’s College, Oxford and further details are available at the meeting website[1].

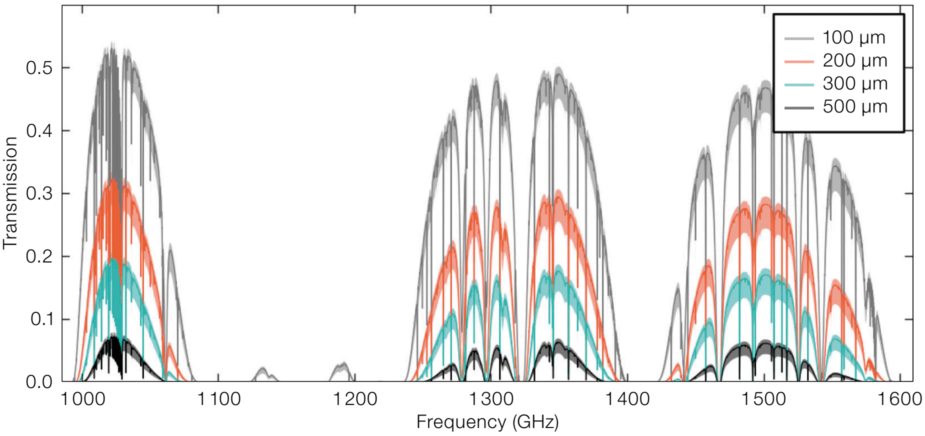
The meeting began with status reports on ALMA and its development programme from Pat Roche and Robert Laing. Although the aim of the meeting was primarily to review the science case, this cannot be done without understanding the atmospheric limitations (which are considerable even at the ALMA site). Sarah Graves presented an overview of the site conditions, concentrating on transparency, atmospheric noise and sensitivity estimates (see Figure 1), and Scott Paine discussed atmospheric modelling using his Atmospheric Model (AM) code.

The science sessions of the workshop explored in detail the advances that the extension of ALMA’s capabilities to THz frequencies would bring to the Observatory. Particular emphasis was placed on science applications that would uniquely benefit from the capabilities of Band 11. The workshop focussed on two main scientific areas: galaxies and the high-redshift Universe; star formation, stars and protoplanetary systems. Invited speakers reviewed the science in each area, followed by contributed talks, and there were extended discussion sessions.

Galaxies and the high-redshift Universe

In the extragalactic session, the case for [C II] observations from intermediate redshift ($0.3 < z < 1$) galaxies was given a clear priority (talks by Roberto Maiolino and Georgios Magdis). Cooling lines are very important as they allow the collapse of molecular clouds and the formation of stars; they also regulate the radiative equilibrium of the interstellar medium (ISM). The [C II] line at 158 μm is the main cooling line of the Milky Way. Recent observations of [C II] emission from nearby ($z < 0.4$) galaxies with Herschel (e.g., Figure 2) and distant galaxies with both Herschel and ALMA have established the importance of the [C II] intensity as a proxy for the star formation rate of a galaxy. Already in Cycle 0, [C II] has been detected from many galaxies at $3 \leq z \leq 6.5$ using ALMA Bands 6 and 7. Band 5 (currently

Figure 1. A plot of the transmission at the ALMA site in the three atmospheric windows that collectively make up Band 11. The transmission curves are shown for four different precipitable water vapour (PWV) columns of 100, 200, 300 and 500 μm. For average conditions on Chajnantor, the PWV column is < 270 μm for 5 % of the time.



Sarah Graves

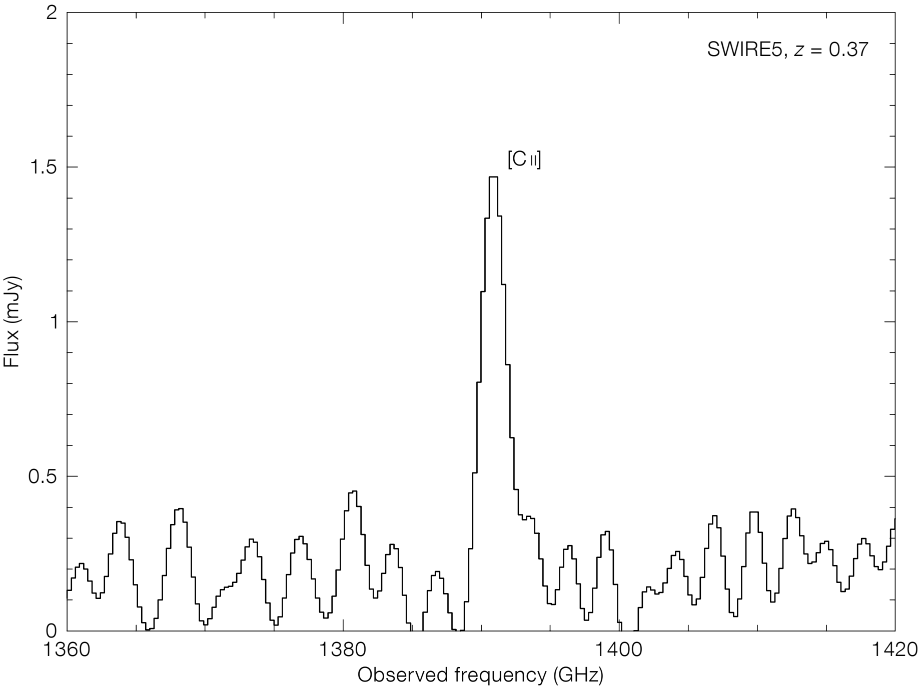


Figure 2. A spectrum of the [C II] line, rest wavelength 158 μm, from a galaxy at a redshift of 0.366, obtained with the SPIRE-FTS instrument on Herschel (from Rigopoulou et al., 2013).

under development) will extend [C II] detections into the early Universe (e.g., Laing et al., 2010). Band 11 has a complementary and critical role in studies of extragalactic [C II]. The redshift range $0.3 \leq z \leq 1$, covered for [C II] with ALMA Band 11, is a crucial phase in galaxy evolution: it is exactly in this range that the star formation density of the Universe increases steeply, becoming essentially flat at $z \geq 1.5$. [C II] observations of galaxies in this very energetic phase of the Universe will establish the long-sought link between the local and high-z Universe and allow us to form a “benchmark” for future studies of [C II] at very high redshifts.

ALMA Band 11 has another unique application: detection of molecular hydrogen (H_2) from primordial galaxies before the reionisation era (talk presented by Dimitra Rigopoulou). H_2 is the most abundant molecule in the Universe and plays a fundamental role in many astrophysical contexts (e.g., Dalgarno, 2000). It is found in all regions where the shielding of the ultraviolet (UV) photons, responsible for its photo-dissociation, is sufficiently large. H_2 makes up the bulk of the mass of the dense gas in galaxies and could represent a significant fraction of the total baryonic mass of the Universe. It is key to our understanding of the ISM, as its formation on grains initiates the chemistry of the interstellar gas. The role of H_2 emission as a contributor to the cooling of astrophysical media is even more significant in the early Universe.

The first generation of stars formed through gravitational collapse of primordial clouds induced by H_2 line cooling (e.g., Saslaw & Zipoy, 1967). How the first (Population III) stars formed out of primordial gas is indeed one of the most exciting questions in modern astrophysics. It has long been realised that the formation of molecular hydrogen plays a key role in this process, serving as an effective coolant at temperatures below 10^4 K, and the primary coolant of UV and X-ray irradiated gas in regions of low metallicity. Kamaya & Silk (2002) and Mizusawa et al. (2004) considered the H_2 rotational emission from primordial molecular cloud kernels to be associated with the formation of the first stars at the earliest epochs of $z \sim 20$. With Band 11, it will possible to detect the S(1) transition of H_2 (locally the strongest of the mid-infrared pure rotational transitions; e.g., Rigopoulou et al., 2002) in $z \geq 10$ galaxies. Based on the expected strength of these lines as predicted by various theoretical models, the detection of emission from primordial H_2 in early galaxies could be feasible with ALMA Band 11 with a few hours of observation.

Continuum observations with Band 11 will probe the dust emission on the long-wavelength side of the far-infrared peak for galaxies at $1 \leq z \leq 4$, putting constraints on the shape of the spectral energy distribution (SED) of the galaxies close to the peak of the star formation and active galactic nucleus (AGN) activity in the Universe. It should also be possible to trace the spatial distribution of the warm dust emission ($T_{\mathrm{dust}} \sim 40$–70 K), providing clues about the heating mechanism. For higher-redshift galaxies, the shape of the SED in the poorly known rest-wavelength range of 40–80 μm will become measurable.

Star formation, stars and protoplanetary systems

Paola Caselli and Jose Cernicharo reviewed applications of ALMA Band 11 to the ISM and to star formation, respectively. In the area of star formation (particularly the study of the physical and chemical structures of molecular clouds), Band 11 provides access to a number of unique tracers of the densest regions. Deuterated nitrogen-bearing molecules (e.g., N_2D^+, NH_2D) are the best tracers of dense and cold gas. As we rely on such species to study the physical structure of clouds where star formation is going to take place (the pre-stellar cores), or where star formation has just started (protostellar envelopes in Class 0 sources), it is crucial to understand their formation and destruction paths. The main chemical processes affecting the deuterium fraction in dense clouds are the exothermic proton–deuteron exchange reaction $H^+ + HD \rightarrow H_2D^+ + H_2$ and the ortho-to-para ratio of H_2 molecules (as ortho-H_2 can drive the exchange reaction back, reducing the deuteration).

The only way to advance this field is to constrain the H_2 ortho-to-para ratio observationally, which relies on observations of species sensitive to this ratio (as ortho and para H_2 cannot be observed in cold gas). The most important species are: ortho-and para-H_2D^+, and

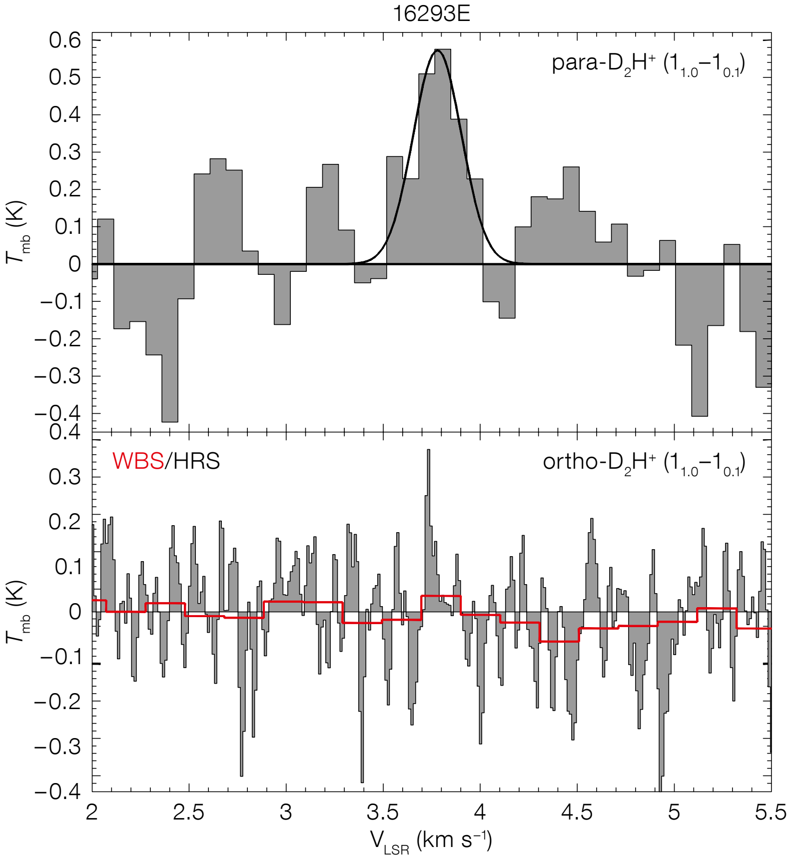


Figure 3. Upper: Spectrum of the para-D_2H^+ line at 692 GHz from the binary protostar IRAS 16293-2422 observed by the Caltech Submillimeter Observatory. Lower: The corresponding ortho-D_2H^+ at 1476 GHz, observed with Herschel HIFI (from Vastel et al., 2012).

ortho-and para-D_2H^+. The ortho-H_2D^+ line can be observed at 372 GHz (in ALMA Band 7), and para-D_2H^+ at 692 GHz (Band 9). The other two lines, para-H_2D^+ at 1370 GHz and ortho-D_2H^+ at 1476 GHz are both observable in Band 11 with relatively good (40–50 %) atmospheric transmission. Figure 3 shows a detection of the 692 GHz line from the ground and the 1476 GHz line with HIFI from the same source. Additionally, the deuterated N-bearing molecule ND has its (2-1) transitions between 1018 and 1077 GHz and these are only accessible in Band 11. Together with detection of NH^+ (whose 1-1 transition is at 1012 and 2-2 at 1019 GHz), such observations will allow the astrochemistry community to set tight constraints on the chemical networks in star-forming clouds.

Continuum observations in Band 11 will allow measurement of the peak of the SED of cold protostars and prestellar cores at 1.5 THz, thereby greatly improving estimates of their temperatures and masses (talk by Derek Ward-Thompson). This is important because the cores have typical temperatures ~ 10 K, so all current ALMA bands sample the Rayleigh–Jeans tail of the SED. High-J CO lines and light hydrides trace the cavity walls and shocked gas in protostellar out-flows, enabling the study of UV and shock heating.

Michiel Hogerheijde reviewed the potential of Band 11 for studies of protoplanetary discs. The band will provide higher angular resolution than Band 10: this may be needed to resolve gas streams around (proto-)planets, which early ALMA results show to be complex and non-axisymmetric. Band 11 also traces higher excitation gas that can help to constrain the temperature structure of the disc and identify localised regions of heating such as shocks around (proto) planets. Finally, it may be possible to measure the ortho/para ratio of H_2D^+ in the disc mid-plane, as noted earlier for star-forming regions.

In the area of evolved stars, mapping of a number of THz water lines (e.g., at 1278 and 1296 GHz) and SiO lines that fall in Band 11 will allow a better understanding of the dynamics of individual clouds (presentation by Anita Richards). As the star is optically thick at large radii or lower frequencies, the THz regime allows the optical photosphere to be probed (currently only detectable at optical and shorter wavelengths), enabling measurement of the continuum brightness temperature and hence separating the photospheric and chromospheric contributions.

Synergies

In addition to the detailed discussions of Herschel results, which provided motivation for the entire meeting, observations taken in two THz windows at the Atacama Pathfinder Experiment (APEX) were also described (by Friedrich Wyrowski and Martina Wiedner), as were the synergies between ALMA Band 11, the Stratospheric Observatory for Infrared Astronomy (SOFIA), the Cerro Chajnantor Atacama Telescope (CCAT) and future far-infrared space observatories (presentations by Peter Schilke and Matt Griffin). The meeting concluded with presentations on the science case for Band 11 from an East Asian perspective by Norikazu Mizuno and Satoki Mathushita.

Acknowledgements

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Links

[1] Workshop web pages: http://www.physics.ox.ac.uk/almaband11