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Report on the ESO Workshop

Getting Ready for ALMA Band 5 — Synergy with APEX/SEPIA

held at ESO Headquarters, Garching, Germany, 1–3 February 2017

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The workshop provided an overview of the wide range of results from the first two years of science operations with the ALMA Band 5 (163–211 GHz) receiver in the Swedish ESO PI Instrument for APEX (SEPIA) ahead of the ALMA Cycle 5 call for proposals, when the Band 5 receivers will be offered for the first time. The frequency range of the Band 5 receiver has never been fully covered by existing receivers; the talks presented at the workshop illustrate the importance of several lines in this frequency range that provide crucial diagnostics of the interstellar medium.

SEPIA, the Swedish ESO PI Instrument for the Atacama Pathfinder EXplorer (APEX) was developed around a pre-production Band 5 receiver (157–212 GHz) built for the Atacama Large Millimeter/submillimeter Array (ALMA). It was installed on APEX in early 2015 (Immer et al., 2016), and is already being used by European astronomers to reveal the new science that can be done in this relatively unexplored frequency band. The Band 5 receivers are in the process of being installed in ALMA and the previous article (Humphreys et al., p. 7) describes the Science Verification (SV). The timing was therefore right for a workshop on the Band 5 science already achieved with SEPIA.

The goal of the meeting was to discuss and highlight the role of APEX as an ALMA complement and to encourage European ALMA users to focus on the science that will be enabled by the new Band 5 receivers ahead of the ALMA Cycle 5 call for proposals. The workshop was attended by more than 50 astronomers and submillimetre instrument builders (see Figure 1) and also featured some SEPIA science with the Band 9 receiver.

Development of the Band 5 receivers

As explained by Victor Belitsky, who gave the opening invited talk, the idea of building a receiver to cover the frequency gap between ALMA Bands 4 and 6, and across the 183.3 GHz atmospheric H_2O absorption line, started in 2005. Thanks to a specific grant as part of the European Union's Sixth Framework Program (FP6), a first set of six "pre-production" receivers was built by the Group for Advanced Receiver Development (GARD) at the Chalmers University of Technology in Gothenburg in collaboration with the Rutherford Appleton Laboratory (Billade et al., 2012). After successful testing at ALMA, a full set of optimised receivers was built by GARD and the Nederlandse Onderzoekschool Voor Astronomie (NOVA) in Groningen, with the local oscillators (LO) and warm electronics built by the National Radio Astronomy Observatory (NRAO) in the USA.

Giorgio Siringo from the Joint ALMA Observatory (JAO) gave a detailed progress report of the installation and verification of the Band 5 receivers at ALMA. Production and delivery of the receiver cartridges is expected to be completed (including all spares) by the end of 2017, while completing the installation and verification for use within the ALMA antennas depends on the scheduling of Front End maintenance at the Observatory. The current estimate is that Cycle 5 science operations for Band 5 receivers will commence in March 2018 (see Humphreys et al., p. 7).

Evolved star science with Band 5

One of the areas where the Band 5 receiver has already made a significant impact in its two years of science operations at APEX is the field of evolved stars (overview talk by Elvire De Beck). The outer layers of these stars are laboratories where a wide range of molecules are formed and fed into the interstellar medium (ISM) through stellar winds. Although no CO lines are present in

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Figure 1. The participants at the APEX/ALMA Band 5 workshop outside the ESO Headquarters building.

Band 5, there are many other important molecules such as HCN, HNC, HCO^+ (talk by Karl Menten), H_2S (Taïssa Danilovich), and many others, including key isotopomers to study fractionation, which are found in spectral line surveys (Elvire De Beck). By combining the constraints from these lines with spectral surveys at other frequencies, one is now obtaining a full inventory of the circumstellar gas. This in turn allows the chemical state to be constrained in the various classes of evolved stars (for example, split by chemical types or density regimes), and their different evolutionary paths.

One important advantage of Band 5 is that the bright H_2O and SiO maser transitions at 183.3 and ~173 GHz can be observed simultaneously (Liz Humphreys). This allows the physical conditions, dynamics and even the magnetic field strengths and morphologies throughout the outflow to be traced. One of the interesting new applications of the dual polarisation Band 5 receiver in SEPIA was to look for polarised emission in SiO and H_2O masers. As SEPIA is located in the Nasmyth A cabin without a de-rotator, recovering the polarisation angle is very complicated. However, one can still look at the difference between the two polarisations, and can thus identify which of the maser lines are significantly polarised. Humphreys et al. (submitted to A&A) have indeed found that only some components of the SiO masers are polarised, while the H_2O emission is not.

The ability to perform accurate line and polarisation observations is a key strength of the ALMA Band 5 receiver, as shown by the SV data for VY CMa (Humphreys et al., p. 7). In this source, ALMA data showed that both SiO and H_2O (as well as the continuum) show polarised emission. The combination of APEX surveys with ALMA high-resolution follow-up in this area is thus expected to produce transformational results in the coming years.

The 183.3 GHz water line

The most challenging Band 5 observation is across the $3_{1,3}$–$2_{2,0}$ atmospheric absorption line of H_2O centred at 183.3 GHz. However, with precipitable water vapour (PWV) < 0.5 mm, this line does become observable from Chajnantor, and is a powerful probe of the ISM, as water controls the chemistry of many other species (Floris van der Tak). The detection of H_2O in protoplanetary disks will allow us to determine and study the snowline, a key missing piece of the puzzle to understand the distribution of life-supporting volatiles in planetary atmospheres.

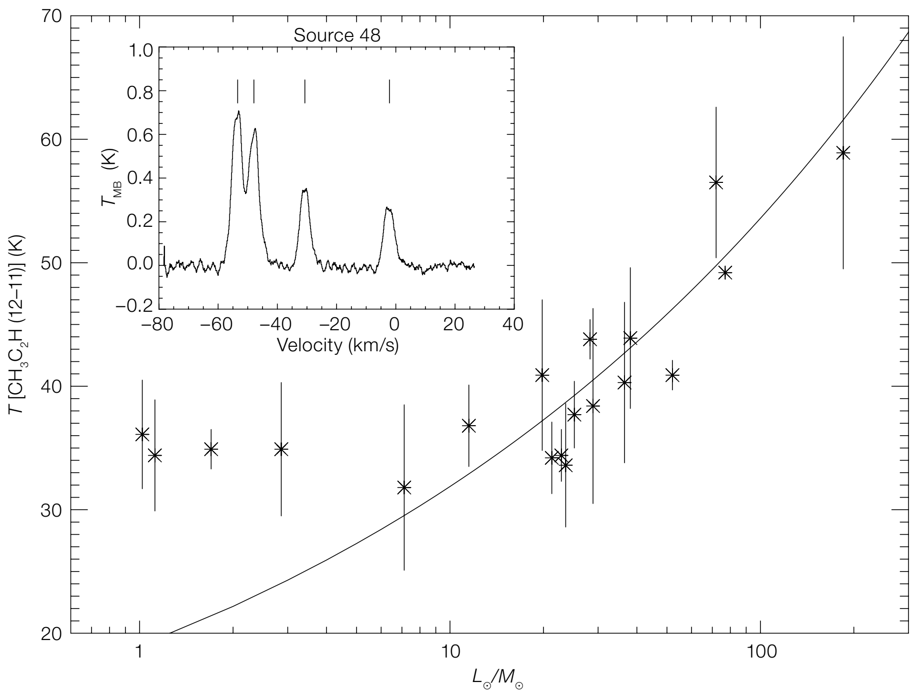

Figure 2. CH_3C_2H(12–11) gas temperature as a function of the luminosity to mass ratio (L/M) for high-mass protocluster candidates from the Hi-GAL survey. The inset shows one of the SEPIA CH_3C_2H spectra (adapted from Molinari et al., 2016).

Nevertheless, such observations may be challenging even with the sensitivity and spatial resolution of ALMA (Michiel Hoogerheijde and Ruud Visser), requiring significant time investment for this key science goal of ALMA Band 5. As explained by John Carpenter, Band 5 observations of discs will also offer many other lines that will provide powerful diagnostics of turbulence, the snowlines of various volatiles, nitrogen fractionation, deuteration and ionisation. As a byproduct of any line observations of discs with ALMA, it will be possible to observe the dust emission at high spatial resolution to probe grain properties using continuum and polarisation measurements.

Friedrich Wyrowski reported strong H_2O detections in hot molecular cores using SEPIA. When combined with other water lines at higher frequencies, in particular the optically thin $H_2^{18}O$ line at 203 GHz, still within the Band 5 receiver frequency range, one can determine the relative roles of maser versus thermal excitation of water.

When looking for water in external galaxies, even a small redshift helps to improve the atmospheric transmission. However, special care will have to be taken to properly calibrate broad emission lines across the varying atmospheric absorption in the shoulders of the atmospheric water line. As discussed by Immer et al. (2016), the application of APEX offline calibration is required across the water absorption line to avoid large amplitude discrepancies across the SEPIA passband. Upgrades of the APEX OnlineCalibrator are planned to provide this higher-resolution calibration by default.

SEPIA observations of extragalactic water have led to the confirmation of the previously reported H_2O line in the ultra-luminous infrared galaxy Arp 220 at z = 0.018 (Galametz et al., 2016), and a weaker tentative detection in IRASF17207-0014 at z = 0.043 presented by Zhi-Yu Zhang (Yang et al., in prep.). The Arp 220 system was also observed as part of the ALMA Band 5 SV (Humphreys et al., p. 7). The comparison of the APEX, ALMA and previous observations of the water line shows a remarkable stability (in terms of intensity and line profile) of this masing line in Arp 220 (König et al., 2017); see Figure 5 of Humphreys et al., p. 7.

Other gas tracers in Band 5

The first spectral line surveys in Band 5 have already shown a remarkable richness of molecular lines, as illustrated, for example, by the Sgr B2(N) spectrum observed with both ALMA and SEPIA (Fig. 5 of Humphreys et al. p. 10), or the D-Dor survey shown in De Beck's talk. Apart from the aforementioned H_2O and $H_2{}^{18}O$ lines, which probe the location of the snowline and the thermal structure in disks, the SO_2 line can be used to determine the shock chemistry and system geometry, while the CH_3OCH_3 and C_2H_5CN lines provide information on the grain surface chemistry (van der Tak). The CH_3C_2H line has also been used as a powerful temperature probe for dense gas (Molinari et al., 2016). By selecting dense clumps from the Hi-GAL survey of our Galaxy, Sergio Molinari and Manuel Merello reported a remarkably strong correlation between the CH_3C_2H line strength and the luminosity–mass ratio (Figure 2).

The presence of important H, C, N, O, and S isotopomers for several key molecules in this band will also allow to extend important work on element fractionation in various phases of the interstellar medium. Examples discussed at the workshop included (besides $H_2{}^{18}O/H_2O$ studies) the studies of H fractionation using some of the (3–2) lines of singly and doubly deuterated formaldehyde (Sarolta Zahorecz) and potentially the study of the $^{14}N/^{15}N$ ratio using the (2–1) lines of HNC, HCN and N_2H+ isotopomers (Figure 3).

In star-forming regions, the brightest lines in Band 5 are the 2–1 transitions of HCN, HNC and HCO^+. In a pilot survey of pointed observations within the LMC and SMC, Maud Galametz found large spatial variations between the HCO^+(2–1) and the other lines such as HCN, HNC and CO. A first mapping campaign has been started to better probe the origin of these variations (see Figure 4).

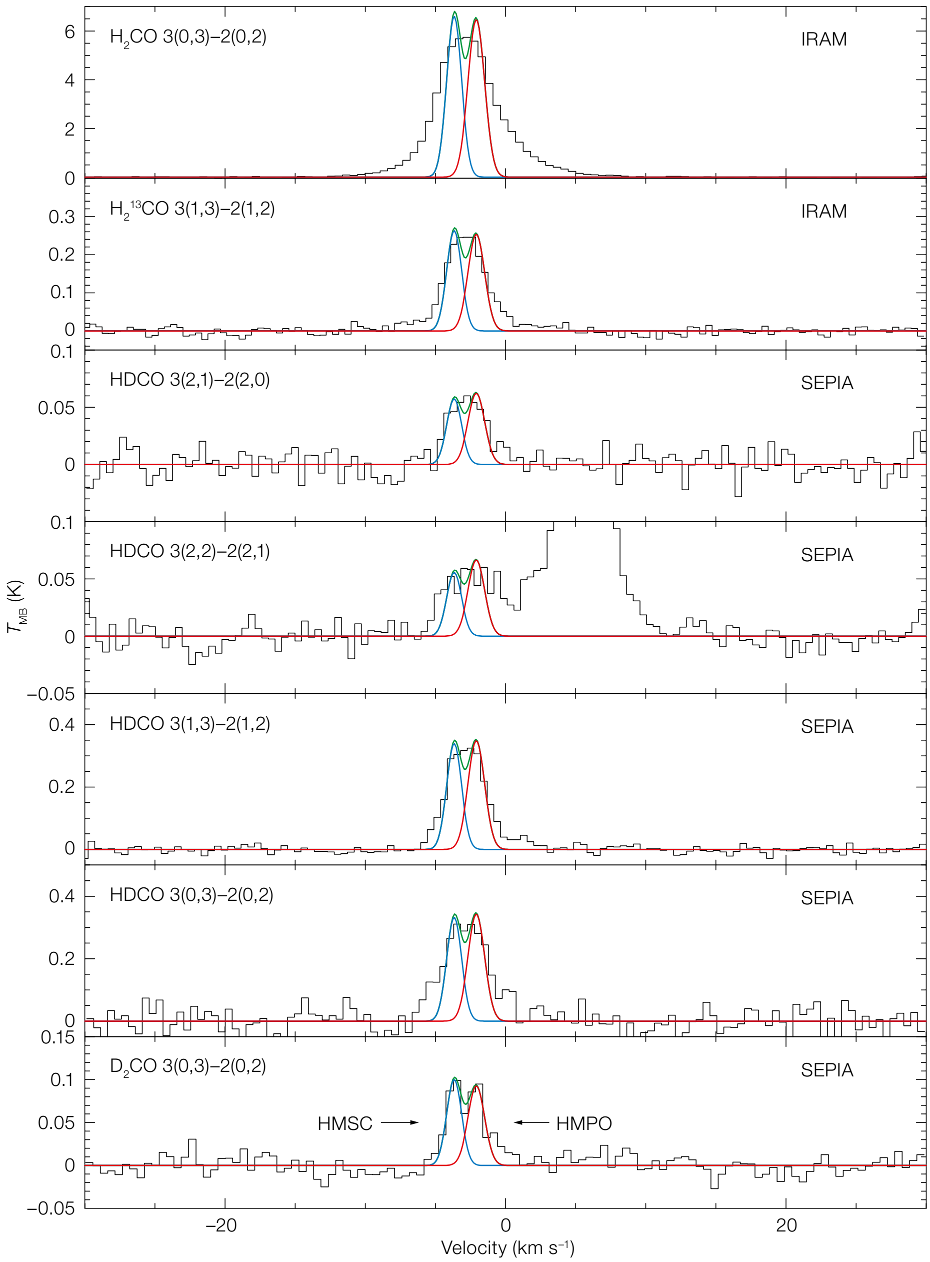

Figure 3. SEPIA HDCO and D_2CO spectra for the high-mass star-forming region AFGL 5142, compared with H_2CO and $H_2{}^{13}CO$ measurements from the Institut de Radioastronomie Millimétrique (IRAM) 30-metre telescope (adapted from Zahorecz et al., 2017). The blue profile is associated with the high-mass starless cores (HMSC) and the red profile with the high-mass protostellar objects (HMPO).

The high redshift Universe

Kirsten Knudsen and Maria Strandet summarised the role of Band 5 for high-redshift science, highlighting respectively the CO and fine structure lines that move into the frequency range of Band 5 for different redshift ranges. Band 5 extends the redshift coverage of the CO(2–1) line out to z = 0.46, and SEPIA has already started to fill the existing redshift gap (from Edo Ibar). To cover the CO spectral line energy distribution, continuous frequency coverage is essential (from Bitten

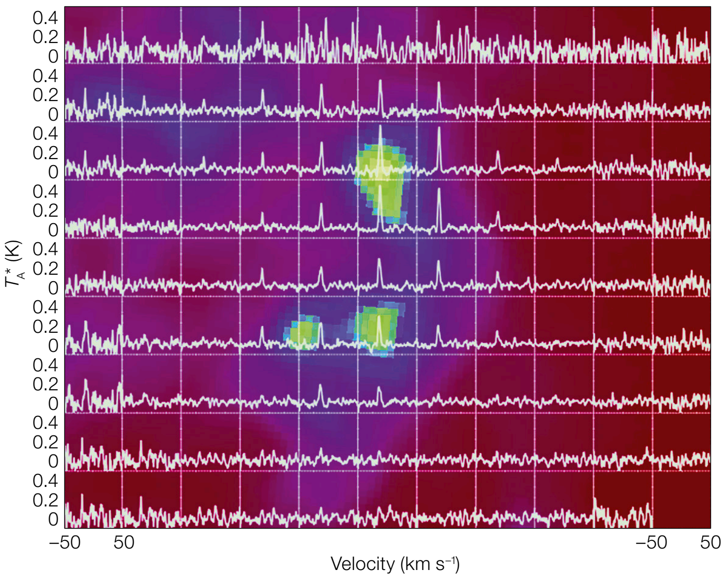

Figure 4. An HCO+(2–1) map of the Large Magellanic Cloud region N159W obtained with APEX/SEPIA Band 5 (Galametz et al., in prep.).

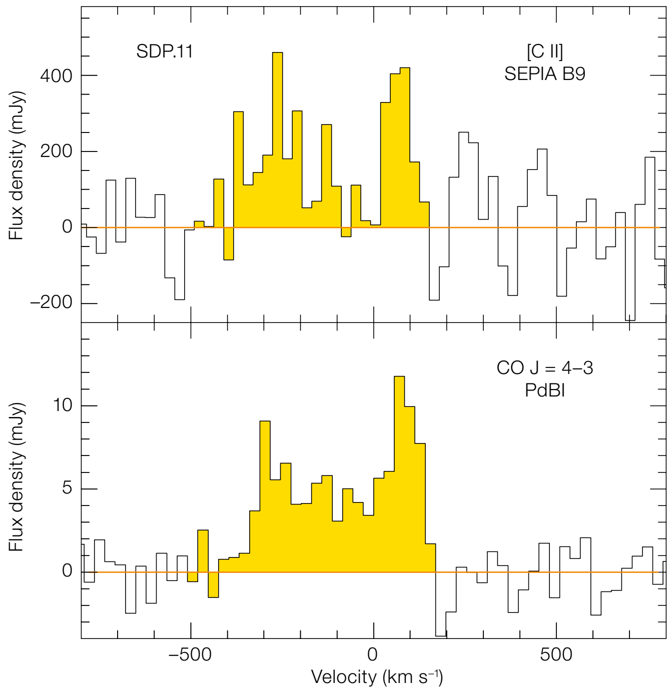

Figure 5. The [C II] 158 μm line detected with the Band 9 receiver of SEPIA in the z = 1.8 dusty star-forming galaxy SDP.11 (Zhang et al., in prep.). The velocity profile in this short SEPIA observation is fully consistent with the IRAM Plateau de Bure CO(4–3) data of Oteo et al. (2017).

Gullberg). For fine-structure lines, the most important lines shifting into Band 5 at 1.33 < z < 2.11 and 2.84 < z < 4.13 are the [C I] 609 μm and 370 μm lines, respectively. Paola Andreani and Matt Bothwell highlighted the importance of the [C I] line as an alternative tracer for the H_2 mass, and reported several SEPIA detections. By filling the frequency gap in the ALMA coverage, the SEPIA Band 5 receiver has also manifested itself as an ideal follow-up instrument for ALMA, confirming ambiguous redshifts obtained with ALMA Band 3 spectral scans (Strandet et al., 2016).

Synergy with Band 9

While the main topic of the meeting was the Band 5 receiver, the other receiver currently installed inside SEPIA, a Band 9 (600 to 722 GHz) ALMA receiver, has a very similar synergy with ALMA.

A number of talks presented first results, such as the intriguing ArH+ line results in the Crab Nebula (Ilse De Looze) and the 658 GHz vibrationally excited water lines presented by Alain Baudry. Even for extragalactic science, the Band 9 receiver now has sufficient bandwidth to allow the detection of broad emission lines, such as the z ~ 1.9 [C II] lines observed during SV by Zhi-Yu Zhang (Figure 5), and the tentative [O III] 88 μm detections by Carlos De Breuck. The Sgr B2(N) spectral scan highlighted the difficulty of using the current double sideband (DSB) receiver for line-rich sources, due to overlapping signal coming from the two sidebands (Katharina Immer). With future upgrades to a sideband-separating receiver and a doubling of the spectral bandwidth, we can hope for an APEX pathfinding role for ALMA in this band too.

Practical sessions

As Band 5 has some special features due to the presence of the deep atmospheric absorption feature, the ALMA Regional Centre and APEX staff explained to the participants how to optimally prepare for their Service Mode observations. Users should in particular pay attention to the placement of the image band, as this may have little transparency if placed near the 183 GHz band. The new features in both the ALMA Observing Tool and the APEX Phase 2 web submission tool were also presented. As the ALMA and APEX archives are also growing steadily, demonstrations were given of how to optimally use the query forms. Future developments (for example, better visualisation tools) were also mentioned on how to better mine the ALMA and APEX data archives.

Acknowledgements

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