Report on the ESO workshop

ALMA and ELTs: A Deeper, Finer View of the Universe

held at ESO Garching, Germany 24–27 March 2009

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The workshop explored the scientific synergies between ALMA and the extremely large telescopes that are being planned. The main goal of the workshop was to bring the ALMA and ELT communities together, to identify the common science cases and to outline instrumentation/upgrade priorities for the ALMA and ELT facilities. We provide a brief account of the scientific sessions and the wide-ranging discussions held during this very lively four-day meeting.

The workshop on synergies between ALMA (Atacama Large Millimeter/submillimeter Array) and ELTs (Extremely Large Telescopes) was held at the ESO Headquarters in Garching from 24–27 March 2009. It was motivated by a growing interest the ALMA and ELT communities to understand the capabilities of these large infrastructures better, as they will dominate ground-based astronomy for the next two to three decades. The workshop was particularly timely as both ALMA and the ELTs are actively shaping their future in the coming months: investigating possible upgrade paths for the future in the case of ALMA; and consolidating the priorities for their sites, their instrument suites and adaptive optics capabilities in the case of the ELTs.

Close to a hundred participants from all over Europe, North America and East Asia shared their views and ideas on submm and optical/near-infrared astronomy over the four days. The audience was delighted by outstanding reviews and many interesting scientific highlights. The discussion sessions were very lively and productive. All talks can be found online through the programme pages of the workshop[1].

The programme presented an overview of all the facilities under consideration — ALMA, the Giant Magellan Telescope (GMT), the Thirty Metre Telescope (TMT) and the European Extremely Large Telescope (E-ELT) — on the first day. This was followed by two topical science days, with the first dedicated to distant (extragalactic), the second to nearby (the local Universe) research, before wrapping up with some technical talks as well as a summary and final discussion on the last day.

The ESO Director General opened the meeting by reminding all those present of the privileged position of ESO in co-ordinating both the European efforts on ALMA, as well as leading the largest of the ELT projects. The impressive progress over the last year on ALMA construction was reviewed by Richard Hills, Lars-Åke Nyman presented the concepts of Science Operations and Andrew Blain summarised the scientific cases for the ALMA upgrades for the 2020brizon. The ELT projects were introduced by Pat McCarthy and Steve Shectman (GMT), Paul Hickson (TMT) and Roberto Gilmozzi (E-ELT), who each summarised the exceptional capabilities of their projects and showing all the projects to be at very similar stages, with completion expected for 2018.

Science days

The two science days were organised with four reviews in the morning and science highlights and discussion in the afternoon. The extragalactic day split the reviews into “Fundamental physics, cosmology, relics of the early Universe”, presented by Frank Bertoldi and Xiaohui Fan, and “Galaxy and ISM Evolution” presented by Linda Tacconi and Alvio Renzini. The following day, focusing on the local Universe, split into “Star formation from re-ionisation to the present” reviewed by Ewine van Dishoek and Rob Kennicutt, and “Solar Systems near and far” scrutinised by Bryan Butler and Didier Queloz.

The original idea was to hold discussions on the different strategies of approaching a given topic with ALMA or the ELTs and then highlight the synergies in the various science goals between the different facilities. Perhaps surprisingly, one of the clear outcomes of the meeting was that the submillimetre and optical/infrared communities have already approached each other much more than was originally anticipated, leading to a situation where all reviews already included the full wavelength range — not only in the context of future research, but also in the current state-of-the-art! To many, this general overview strengthened further the impression that ALMA and the ELTs cannot be seen as stand-alone facilities, but each must be viewed as an extremely strong complement to the other, allowing us to tackle the most exciting scientific questions in astrophysics and cosmology in the coming decades. Towards the end of the meeting some talks highlighted the synergies with other major facilities of the future, the James Webb Space Telescope (JWST) and the Square Kilometre Array (SKA), demonstrating how modern astrophysics has gone beyond the old compartmentalisation of wavebands and ground- *v.* space-borne facilities.

Some of the highlights of the cosmology reviews that would be tackled by a combination of ALMA and ELTs included: the prospects for studying both molecular and ionised gas in objects at the epoch of reionisation; various tests of the variability of fundamental constants, such as the fine structure constant (see Figure 1), the electron/proton mass ratio, the proton gyromagnetic ratio, as well as of general relativity; several tests on the nature of dark matter; the evolution of the intergalactic medium (IGM) and stellar populations with cosmic time and various ways of measuring the cosmic deceleration. In tackling many aspects of these topics, ALMA and the ELTs will complement each other almost perfectly.

The extragalactic reviews emphasised how the combination of ALMA and the ELTs is ideally suited to the study of early galaxy evolution from high redshifts to today (see Figure 2). Using examples of the synergies that have developed between the VLT and the Institut de Radioastronomie Millimétrique (IRAM), it was shown that the interplay of the giant facilities will answer many questions, such as: what fraction of star formation is due major *v.* minor mergers *v.* steady accretion; how do galaxies get their gas; how do discs evolve and how do bulges form; what drives the internal evolution of high-*z* star-forming galaxies; how important is feedback; how does chemical enrichment

proceed; how does the co-evolution of black holes, Active Galactic Nuclei (AGN) and their host galaxies vary with redshift?

The second science day started with reviews on star formation in which the immense power of ALMA in studying the various phases of star and planet formation was emphasised, but also the key role of the ELTs in complementing these studies was stressed, in particular for the understanding of the inner disc regions in protostellar systems (Figure 3). These facilities will straddle the boundaries of Galactic and extragalactic star formation. Targets for ALMA–ELT studies have and will come from unbiased submillimetre and infrared wide-field surveys. We were also reminded that there are many areas where we currently know little or nothing at present, and how important their understanding will become for the full exploitation of ALMA/ELT data. High impact will come from investigations of fundamentals such as the initial mass function (IMF), the CO to H II ratio, the structure of the interstellar medium, the formation of complex molecules and stellar physics.

Finally, the last science session considered our Solar System and exoplanets. Bryan Butler reminded us that the planets in our Solar System are "not just calibrators" — understanding their structure and properties is a very lively research field and a "Rosetta Stone" for our understanding of other planetary systems. Even in an era of *in situ* exploration by space vehicles, ground-based facilities will still play a key role in the study of the Solar System. ALMA and the ELTs will complement each other strongly in the study of planetary atmospheres, as well as in characterising Trans-Neptunian Objects (TNOs) and minor rocky bodies beyond their simple dynamical parameters. This study would open the doors to a full understanding of the formation of planetary systems. Beyond our Solar System, the strength of ALMA is to be able to detect protoplanets forming within protoplanetary discs, while the ELTs will observe young to old planets. Earth-like exoplanets will probably have been found by the advent of the ELTs, but their characterisation and systematic imaging will be the tasks of the new facilities.

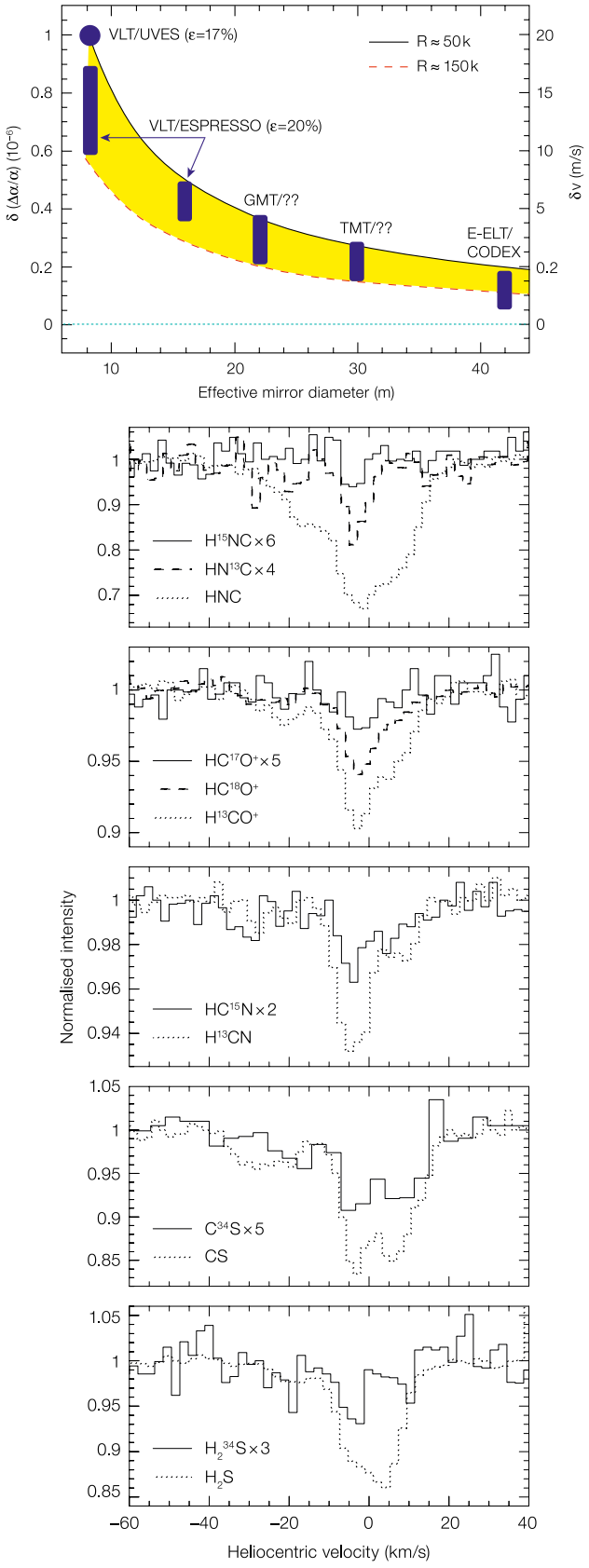

Figure 1. Prospects for measuring the possible cosmic variation of the fine structure constant with current and future high resolution optical spectrographs. The expected precision reachable with high resolution ultra-stable optical spectrographs is shown as a function of the telescope effective diameter (adapted from Murphy). ALMA will be able to provide complementary constraints by measuring the cold narrow molecular lines at extremely high spectral resolution; as an example, the mm absorption line system at $z = 0.89$ along the line of sight to PKS 1830-211 is shown (Muller et al., 2006).

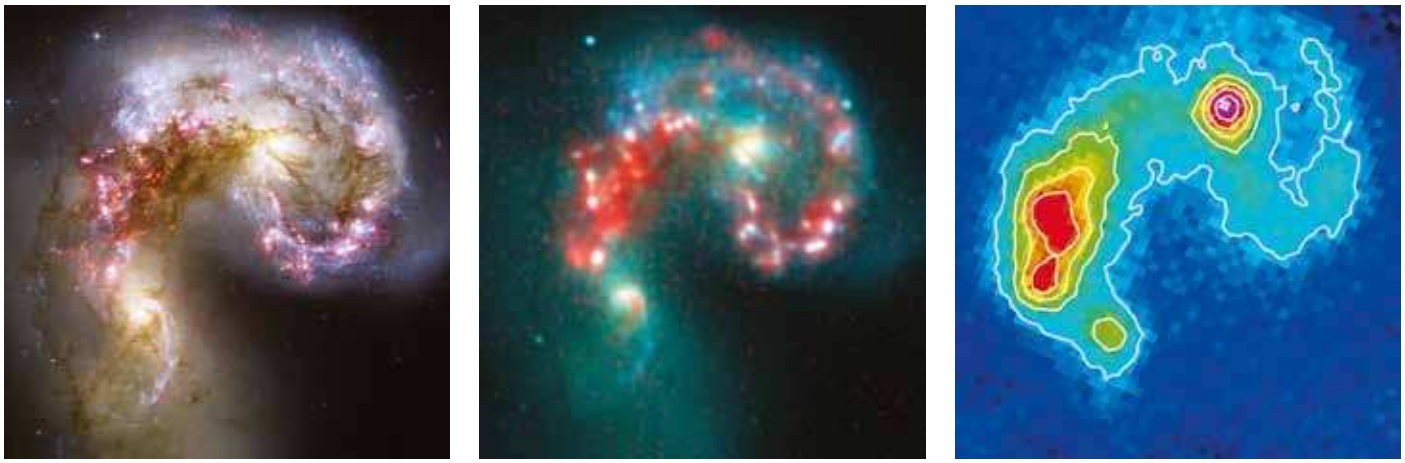

Figure 2. The Antennae galaxy merger, a relatively nearby merger that triggered intense star formation and the production of super star clusters. From left to right images in the optical (Hubble Space Telescope), infrared (Spitzer Space Telescope) and millimetre continuum (Caltech Submillimeter Observatory). ALMA and the ELTs will allow images to be obtained at a comparable level of detail for mergers at high redshift.

Discussions

The discussion session focused on questions such as what are the main synergies between the facilities? Which ELT instruments and/or ALMA upgrades would maximise the synergies? Do the communities of the facilities need to be brought still closer together? Do formal links between the communities/facilities have to be established? Should systematic programmes be established with ALMA to prepare for ELT observations?

All these questions were discussed in the various sessions and picked up in the conference summary presented by James Di Francesco. The overall impression was that very strong synergies existed in all fields of astrophysics and that the community had already identified the vast majority of them and was actively preparing to meet the challenges. Young astronomers are being trained across the wavelength domains and are not waiting for the giant facilities to operate in order to prepare themselves for the optimal use of the data. Yet, further cross-fertilisation activities should be organised to keep up the momentum and institutes should aim at hiring the right mix of researchers from both communities. Top-rated instruments for ELTs that would clearly enhance the synergy with ALMA are high resolution optical and infrared spectrographs and near-/mid-infrared imagers and integral field spectrographs, while ALMA would profit from long baselines and Bands 1 and 5. Formal connections between the projects seem premature at this point, but will certainly be thought of in due time. More importantly, the data from all facilities should be made accessible to the entire community and the reduction/analysis tools should be designed to encourage non-experts to use them.

In summary, the meeting was very well attended and enabled very lively discussions between the communities. It demonstrated, maybe even more strongly than had already been assumed, the huge impact that the combination of ALMA and the ELTs will have on the full breadth of observational astrophysics and cosmology, extending to planetary science and fundamental physics. We are truly looking forward to two most exciting decades in astronomy. A summary of the workshop in the form of a 30-page booklet will appear in the course of 2009.

Acknowledgements

The organisers are most grateful to the SOC and the LOC (in particular to Christina Stoffer for handling the full logistics, and Annalisa Calamida for her help with the workshop pages). The review speakers are also thanked for their excellent job in summarising their fields, and all the speakers for very interesting and enjoyable talks, all of a high standard.

Links

[1] http://www.eso.org/almaelt2009

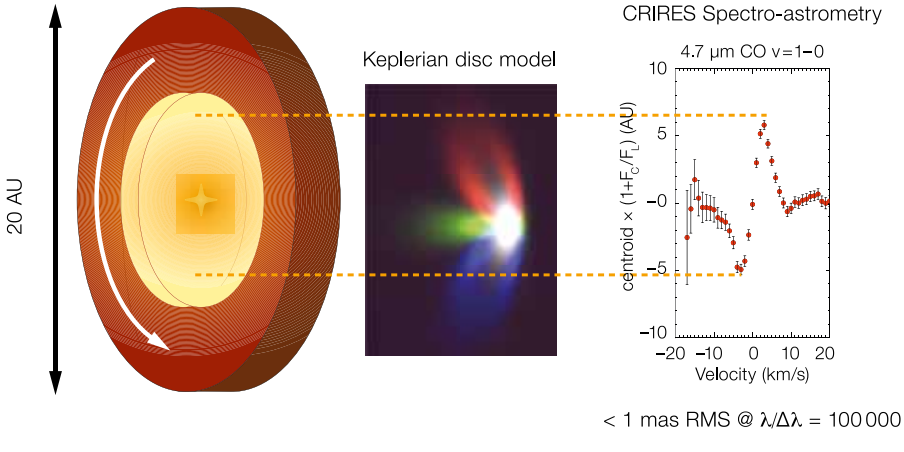

Figure 3. The inner regions of a protoplanetary disc explored with spectroastrometry with CRIRES. The ELTs equipped with high spectral resolution infrared spectrographs will allow a detailed study of the gaseous component of the inner regions of protoplanetary discs, while ALMA will provide a unique view of the processes in the cold outer regions of the systems (adapted from Pontoppidan et al., 2008).