Tracing the Formation and Evolution of Clusters and their Central Massive Galaxies to $z > 4$: a Progress Report

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1. Introduction: The Host Galaxies of Distant Radio Galaxies

Luminous distant radio galaxies are unique probes of the early Universe. About 15 years ago at Leiden some of us started a programme to find distant radio galaxies, study their properties and use them as probes of the early Universe. The project began as a result of the technique we developed during the late eighties to pinpoint distant radio galaxies, based on their ultra-steep radio spectra (spectral index $\alpha < -1$). Finding these objects was the subject of an ESO Key Programme in the early nineties, that discovered a substantial fraction of presently known distant radio galaxies (e.g. see *Messenger* articles Miley et al. 1992; Röttgering, Miley, & van Ojik 1996). There are now around 150 $z > 2$ radio galaxies known, the majority of which were found using this technique, the most distant of which, TN J0924–2201, has a redshift of 5.19.

During the last decade multi-wavelength studies of these high-redshift radio galaxies (HzRGs, $z > 2$) have produced strong evidence that they are massive galaxies in the process of formation, most probably the ancestors of central cluster galaxies.

Relevant results include:

• HzRGs trace the bright envelope in the infrared Hubble diagram, implying that they are amongst the *most massive* galaxies in the early Universe (e.g. De Breuck et al. 2002).

• HzRGs are usually surrounded by *giant Lyα emitting gas halos*, whose sizes (~100 kpc; van Ojik et al. 1997) are comparable to those of cD galaxy envelopes (for an example, see Fig. 1).

• HzRGs appear extremely clumpy on *HST* images, strikingly similar to simulations from hierarchical models of *forming* massive galaxies, e.g. brightest cluster galaxies (e.g. Fig. 2, Pentericci et al. 1998). The sizes, profiles and luminosities of the clumps are similar to those of Lyman Break Galaxies (e.g. Steidel et al. 1996).

• Long-exposure optical spectra and observations of their luminous dust emission show that HzRGs are undergoing *vigorous star formation* (e.g. Dey et al. 1997).

Further evidence that HzRGs are in cluster environments is the large measured depolarization, indicative of a dense hot gas (Carilli et al. 1997).

These properties, taken together, provided strong indirect evidence that luminous distant radio sources pinpoint forming massive galaxies at the centres of protoclusters.

2. Finding Distant Protoclusters: a Pilot Project

One of the most intriguing questions in modern astrophysics concerns the formation of structure in the early Universe (e.g. Bahcall et al. 1997). Although there are various scenarios for the development of large-scale structure, the epoch and mechanism of the formation of galaxy clusters are still open questions. Using conventional optical and X-ray techniques, the detection of clusters with $z > 1$ is difficult. In the optical, the density contrast is low due to the contaminating foreground, while in the X-ray the detection of extended hot cluster gas is challenging because of cosmological surface brightness dimming. Because distant radio galaxies have properties expected from forming massive galaxies in protoclusters, we instigated a VLT programme to search for *direct* evidence of galaxy overdensities around them.

First, we conducted a pilot project to search for an excess of Lyα emitters around the radio galaxy PKS 1138–262 at $z = 2.2$. This radio galaxy was chosen because it is extremely clumpy, it has the largest radio rotation measure in a sample of 70 HzRGs (Pentericci et al. 2000a) and has a large (120 kpc) Lyα halo (see Fig. 1). Furthermore, the redshifted Lyα of this radio galaxy falls in one of the narrowband filters of FORS. As the first visiting observers project, narrowband and broadband images were taken in March 1999 with FORS1 on ANTU. These data resulted in a list of ~ 50 candidate Lyα emitters (Kurk et al. 2000). Subsequent multiobject spectroscopy in March and April 2000 on FORS1 revealed 15 Lyα emitters at the same distance as the radio galaxy and an additional 5 objects having continua also consistent with galaxies at redshift 2.2. All the Lyα emitters were found to have redshifts in the range 2.16 ± 0.02, centred around the redshift of the radio galaxy, and are within a projected physical distance of 1.5 Mpc from it (Pentericci et al. 2000b). We had now confirmed that in one case there is a substantial galaxy overdensity associated with a distant luminous radio galaxy.

3. VLT Large Programme: Searching for Protoclusters to $z > 4$

The next step was to investigate whether the overdensity around 1138–

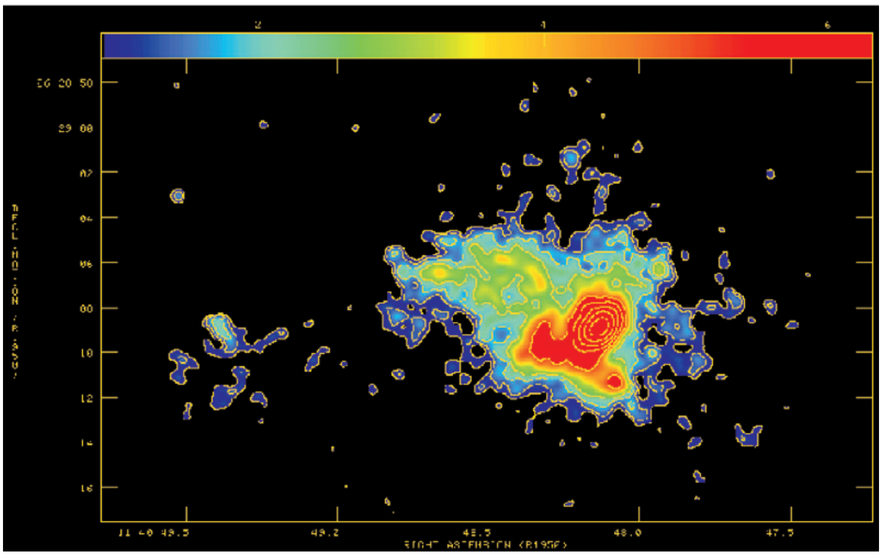


Figure 1: Lyα image of radio galaxy PKS 1138–262 at z = 2.16. The image is a 14,400 s exposure in a narrowband, taken with the FORS1 camera on ANTU. The size of the halo is roughly 120 kpc.

262 is typical for distant luminous radio galaxies as a class. We therefore initiated a Large Programme on the VLT to search for Lyα emitting galaxies around luminous radio galaxies at $2 < z < 4.1$. Our Large Programme was awarded 18 nights, spread over three periods, on the VLT/FORS2.

The targets for the Large Programme were selected from a list of ~150 radio galaxies with $z > 2$. Suitable targets satisfied the following criteria: (i) large radio luminosities ($P_{178} > 10^{26}$ W Hz^{-1}), (ii) luminous optical and infrared continua and (iii) redshifts suitable for Lyα imaging with the available VLT narrowband filters. This resulted in a list of objects with redshifts between $2.1 < z < 3.2$. We added one object with an even higher redshift (a radio galaxy at $z = 4.1$), for which we purchased a custom narrowband filter. This allowed us to cover a redshift range from $2 < z < 4.1$.

The strategy for finding Lyα emitters near the radio galaxy was the same as in our pilot project: each target was observed with a narrowband filter, which contained the redshifted Lyα line of the radio galaxy. The fields were also observed in broadbands, selected for having peak just redward of the Lyα line in order to measure the UV continuum. Comparison of the narrowband image with the broadband image allowed us to find objects with an excess flux in the narrowband. These excess objects were our candidate Lyα emitters. In Figure 3 an example is shown. On the left a section of a 33,300 s narrowband image is plotted of the field around the radio galaxy TN J1338–1942 at $z = 4.1$. On the right the same field is shown but this time observed in the broadband R. The encircled objects can be easily seen in the narrowband image, but they almost disappear in the broadband image. This means that more flux falls in the narrowband than expected from the broadband "continuum" image. These objects were our primary candidates for spectroscopy.

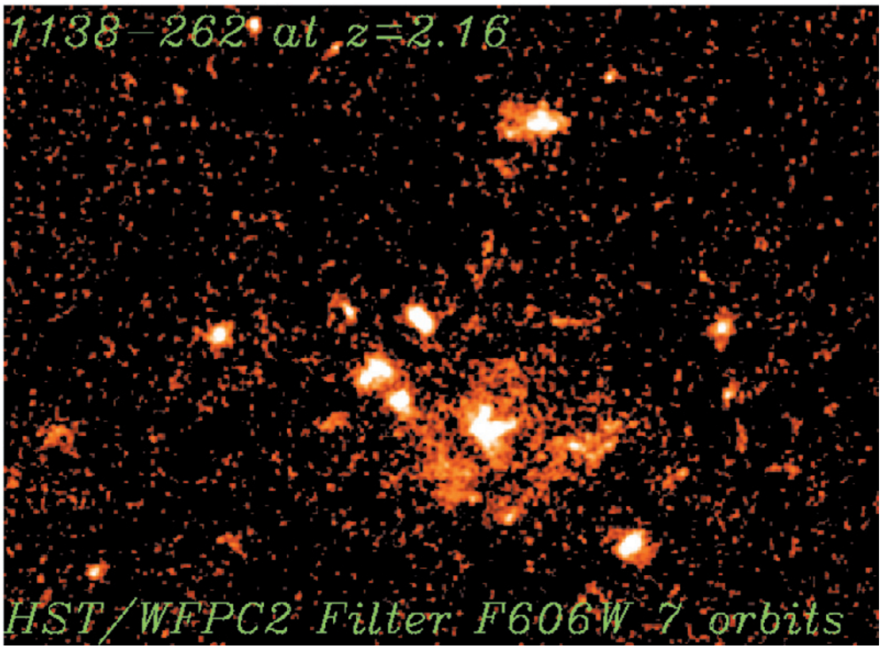


Figure 2: Seven orbit HST image of PKS 1138–262 (Pentericci et al. 1998). The image is taken through the F606W filter and shows the UV continuum.

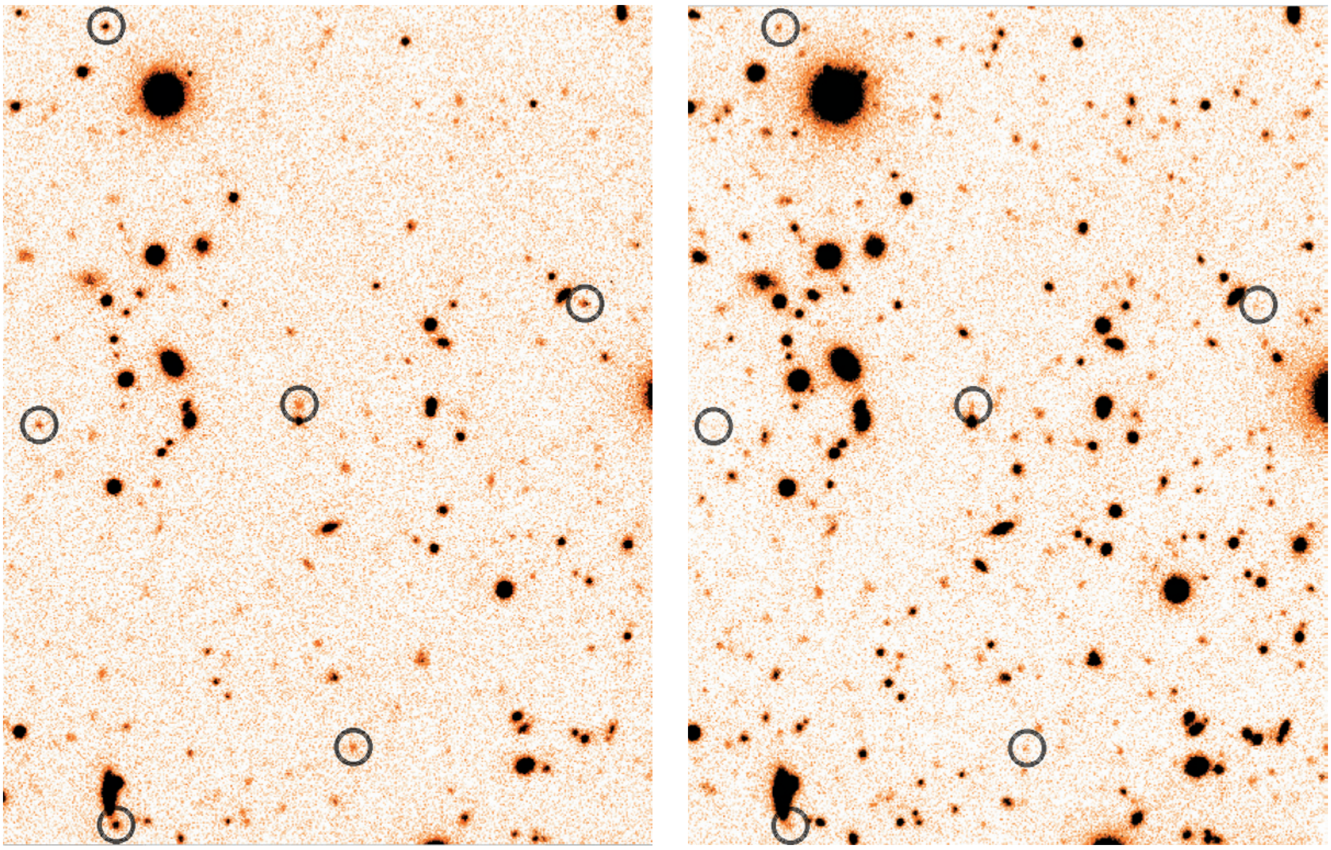


Figure 3: Narrowband and broadband image of a field near the radio galaxy TN J1338–1942 at $z = 4.1$. The narrowband filter used for the image on the left is centred at $\lambda = 6210$ Å, which corresponds to Lyα emission at $z = 4.1$. The filter used on the right is the R filter, which measures the UV continuum at $z = 4.1$. The encircled objects all have an excess flux in the narrowband, and were our candidates for follow-up spectroscopy.

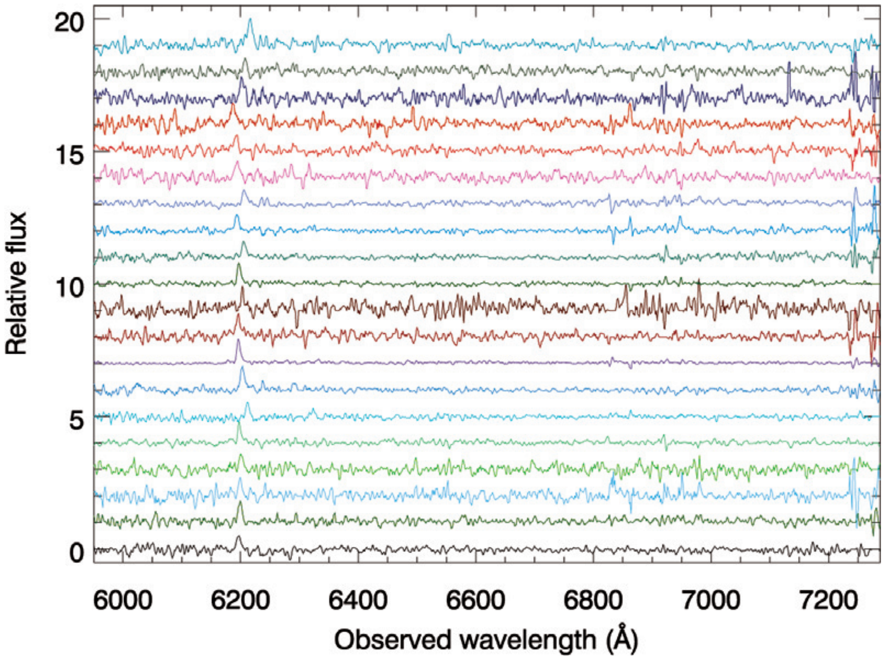


Figure 4: Spectra of 20 Lyα emitting galaxies detected around TN J1338–1942 at z = 4.1. All the emission line galaxies show a line near 6200 Å. Analysis of the spectra confirmed that all the lines are from Lyα at z = 4.100 ± 0.012 (Venemans et al. 2002).

Follow-up spectroscopy of the brightest candidate emitters was carried out with the multiobject spectroscopy mode of the FORS2 spectrograph. The aim was to confirm whether the candidates were cluster members and to measure cluster velocity distributions. Our selection technique proved to be very successful: 70%–85% of all candidates that were observed spectroscopically showed an emission line. Our success rate for the brightest candidate emitters (with a predicted line flux greater than 1.5×10^{-17} erg s^{-1} cm^{-2}) exceeded 90%. In Figure 4 an example is plotted for 20 confirmed emitters at $z = 4.1$.

4. Preliminary Results

We have now carried out imaging and spectroscopy to a sufficient depth of five radio galaxy fields. A sixth target, TN J2009–3040 at $z = 3.2$, although observed for a comparable time, could not be studied to the same intrinsic depth due to the relatively high extinction.

The programme has been extremely successful. All five well-observed radio galaxies have > 20 spectroscopically confirmed Lyα and/or Hα companions. In addition, despite its high extinction, TN J2009–3040 has 12 spectroscopically confirmed companions. The density of Lyα emitters found around all 6 radio galaxies can be compared with the density of emitters found in blank fields (see e.g. Cowie & Hu 1998, Rhoads et al. 2000). Taking into account the difference in volume and in depth, the overdensity of Lyα emitters in radio galaxy fields is 5–15. Furthermore, the velocity dispersions are found to be ~ 300–1000 km s^{-1}, concentrated around the redshift of the radio galaxy. This is significantly smaller than the width of the narrowband filters used in the initial imaging, providing further evidence that the groupings of galaxies are indeed associated with the radio galaxies.

The spatial distribution of the Lyα emitters is in most cases homogeneous over the field, indicating that the structure sizes generally exceed the 7 × 7 arcmin^2 FORS field, which corresponds to sizes greater than ~ 3 × 3 Mpc^2. An exception is the distribution of Lyα emitters around TN J1338–1942 at $z = 4.1$, shown in Figure 5. The protocluster appears to be bound in the northwest, but the field of view is not large enough to show a boundary in the south. Note that in this field the radio galaxy is not in the centre of the protocluster.

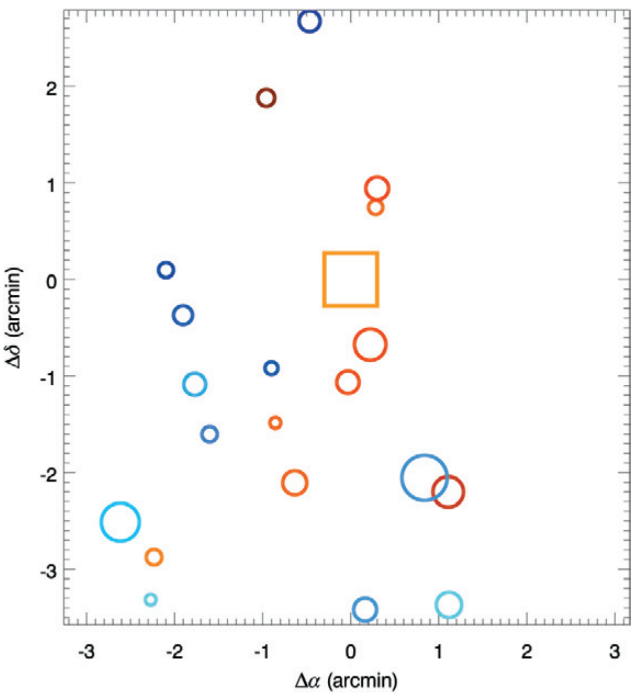
The mass can be estimated using the volume occupied by the overdensity, the mean density of the Universe at the redshift of the protocluster, the measured galaxy overdensity and the bias parameter (Steidel et al. 1998). The computed masses are in the range 10^{14}–10^{16} $M_\odot$, comparable with the mass of present-day rich clusters of galaxies. Taken together, the properties of the radio galaxy hosts and those of the newly-discovered structures demonstrate that luminous distant radio sources can be used to pinpoint protoclusters, the ancestors of rich clusters.

5. Conclusions

We have discovered substantial galaxy overdensities around radio galaxies at z = 2.16, 2.86, 2.92, 3.13, 3.15 and 4.10.

Although preliminary, we can draw the following conclusions: (i) HzRGs are generally associated with the most massive forming galaxies at the centre of protoclusters and can be used to pinpoint such structures. (ii) Because the radio lifetimes (few $\times 10^7$ yr) are small by the standard of cosmic evolution, there must be orders of magnitude more "dead" radio sources than living ones. When the protoclusters have evolved, the luminous radio sources are likely to be extinguished, explaining why $z < 1$ clusters do not generally harbour active luminous radio sources. (iii) The luminosity functions and lifetimes of luminous distant radio sources are consistent with such objects being associated with every pronounced veloci-

Figure 5: Distribution of the confirmed Lyα emitters (circles) at z ~ 4.1 on the sky. The square shows the position of radio galaxy TN J1338–1942. The size of the circles is scaled according to the Lyα flux of the object, ranging between 0.3 and 4.1 × 10^{-17} erg s^{-1} cm^{-2}. The colour of the symbols is an indication of the redshift of the object. Blue objects have a lower redshift than the median redshift of the emitters, red objects have a higher redshift. The redshifts range between 4.088 and 4.112. Note that the radio galaxy is not centred in the galaxy distribution.



ty spike in the space density of Lyman break galaxies.

Our distant protoclusters are unique laboratories for studying the most extreme overdense regions in the early Universe and crucial locations for tracing the formation and evolution of clusters and galaxies. We are in the process of analyzing more than 100 confirmed Lyα emitting galaxies that lie within our protoclusters and in addition we are obtaining observations with other facilities, including the Advanced Camera for Surveys on the *HST* to find and study the various other populations of galaxies expected within the protoclusters. A detailed study of the morphologies and SEDs of protocluster members between $z \sim 4$ and $z \sim 1$ will be used to trace the history of *galaxy assembly* and *star formation*.

Acknowledgements

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TELESCOPES AND INSTRUMENTATION

ESO and NSF Sign Agreement on ALMA

Green Light for World's Most Powerful Radio Observatory

(From ESO Press Release 04/03, 25 February 2003)

On February 25, 2003, the European Southern Observatory (ESO) and the US National Science Foundation (NSF) signed a historic agreement to construct and operate the world's largest and most powerful radio telescope, operating at millimetre and sub-millimetre wavelengths. The Director General of ESO, Dr. Catherine Cesarsky, and the Director of the NSF, Dr. Rita Colwell, acted for their respective organizations.

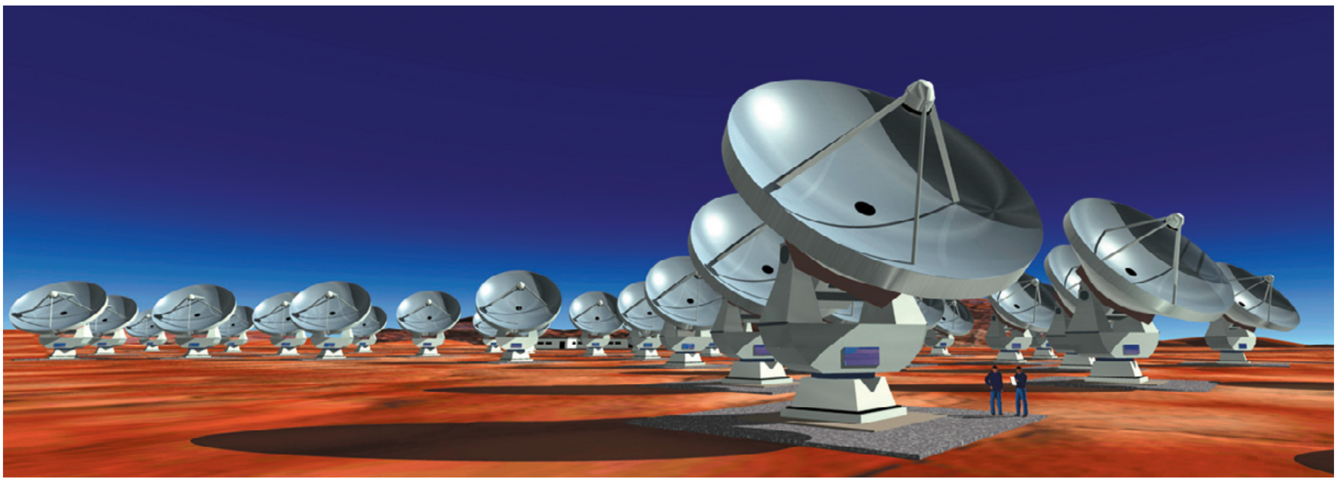
Known as the Atacama Large Millimeter Array (ALMA), the future facility will encompass sixty-four interconnected 12-metre antennae at a unique, high-altitude site at Chajnantor in the Atacama region of northern Chile.

ALMA is a joint project between Europe and North America. In Europe, ESO is leading on behalf of its ten member countries and Spain. In North America, the NSF also acts for the National Research Council of Canada and executes the project through the National Radio Astronomy Observatory (NRAO) operated by Associated Universities, Inc. (AUI).

The conclusion of the ESO-NSF Agreement now gives the final green light for the ALMA project. The total cost of approximately 650 million Euro is shared equally between the two partners.

Dr. Cesarsky is excited: "This agreement signifies the start of a great project of contemporary astronomy and astrophysics. Representing Europe, and in collaboration with many laboratories and institutes on this continent, we together look forward towards wonderful research projects. With ALMA we may learn how the earliest galaxies in the Universe really looked like, to mention but one of the many eagerly awaited opportunities with this marvellous facility."

"With this agreement, we usher in a new age of research in astronomy", says Dr. Colwell. "By working together in this truly global partnership, the international astronomy community will be able to ensure the research capabilities needed to meet the long-term demands of our scientific enterprise, and that we will be able to study and understand our universe in ways that have previously been beyond our vision".



Artist's view of the Atacama Large Millimeter Array (ALMA), with 64 12-m antennae.