The Atacama Pathfinder EXperiment

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APEX, the Atacama Pathfinder Experiment, is operational on Llano de Chajnantor, on what is considered one of the world's best sites for submillimetre astronomy. With its large primary reflector of 12 m diameter, carefully adjusted to a surface smoothness of only 17–18 µm r.m.s, APEX will allow observations up to 200 µm, through all atmospheric submm windows accessible from the ground. Scientific opportunities to explore the 'cold universe' are discussed, and first scientific results are presented.

Go Atacama!

Because submillimetre radiation from space is heavily absorbed by water vapour in the Earth's atmosphere, APEX is located at an altitude of 5100 metres in the high Atacama desert on the Chajnantor plains, 50 km east of San Pedro de Atacama in northern Chile. The ALMA site characterisation, covering the years 1995 to 2004, has shown that the location is one of the driest places on Earth: the 50 (25) % quartile of the precipitable water column is 1.0 (0.6) mm, respectively. During the Chilean winter months (June through September), for an appreciable fraction of the time conditions are better than 0.3 mm pwv – exceptional conditions for which the supra-THz atmospheric windows become transparent for dedicated experiments (see Figure 2).

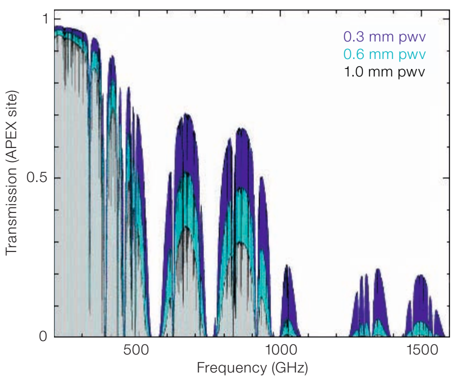


Figure 2: Zenith transmission of the atmosphere above Llano de Chajnantor at submillimeter wavelengths. Using data from the ALMA site characterisation, we calculate the 50 and 25 % quartile columns of precipitable water to 1.0 and 0.6 mm, respectively – excluding data taken during the Bolivian winter months (day numbers 15–90). The dark blue figure corresponds to 0.3 mm pwv, a rare, but not uncommon event that opens up the supra-THz windows.

A brief project history

By the mid 1990s, the astronomical richness of the submillimetre wavelength range had been demonstrated by the early successes of the 15-m James Clerk Maxwell telescope and the Caltech Submillimeter Observatory 10.4-m telescope, both operating on the 4000-m high Mauna Kea on Hawaii. At that time, in North America, Europe, and Japan plans for a large millimetre interferometer array were made and extensive site testing campaigns were undertaken. In the course of these, the 5100-m high Llano de Chajnantor was identified as possibly the best accessible site on Earth for submillimetre astronomy, outside of Antarctica. In fact, the weather statistics for that site looked so good that the initial interferometer concept was extended and, despite its name, the Atacama Large Millimeter Array (ALMA) was planned to cover all the millimetre *and* submillimetre windows with good transmission to the ground.

Photo: A. Lundgren, ESO

Convinced of the quality of the Chajnantor site, Karl Menten persuaded the Max-Planck-Society to provide funding to acquire a copy of one of the ALMA prototype antennas (at that time three prototypes were planned) with as early as possible deployment to Chajnantor – as a pathfinder for ALMA. ESO and the Onsala Space Observatory (OSO) appeared as natural partners, since they had been operating the highly successful 15-m Swedish-ESO Submillimetre Telescope (SEST, Booth et al. 1987) since 1987 on the lower altitude La Silla. The new ESO Director General, Catherine Cesarsky, and Onsala Space Observatory Director Roy Booth welcomed the idea enthusiastically – the Atacama Pathfinder EXperiment was born.

Immediately after the Memorandum-of-Understanding between the partners was signed on 02 July 2001, MPIfR contracted the design and construction of the telescope to VERTEX Antennentechnik GmbH, Germany. Construction at the high site started in spring 2003; commissioning began in spring 2004. After successful verification of the performance of the telescope to specifications, the facility was inaugurated on 25 September 2005. With operational readiness the responsibility for operation of the facility was entrusted to ESO, and responsibility was transferred from Rolf Güsten (Project Manager since spring 2004, during the commissioning phase) to the Station Manager Lars-Åke Nyman.

Operation of the Facility

The unique observing opportunities come with the costs of demanding logistics required to operate a frontier science observatory at a place as remote as Llano de Chajnantor. The telescope is operated from the APEX base in Sequitor in San Pedro de Atacama at an altitude of 2 440 m. However, it was essential that infrastructure to support operations and maintenance of the telescope was built on Chajnantor as well as in Sequitor. Duty staff sleep in the Sequitor base. The telescope can be controlled remotely from Sequitor through a 36 Mbit/s microwave link and the Sequitor base has a 2 Mbit/s connection to the outside world. Chajnantor is accessed either by the international highway to Argentina, the Paso Jama road (paved), for the first 60 km, followed by a 15-km dirt road, or through the ALMA road, which is now being constructed.

Figure 1: Panoramic view of the ALMA site, Llano de Chajnantor, taken from Cerro Chico. The APEX telescope is seen to the left, and our next neighbour, the CBI experiment, to the right. The ALMA AOS technical building (now under construction) and the compact array configuration will be located in the centre of the picture.

The telescope is situated on Chajnantor about 2 km north of the newly constructed ALMA AOS building and array centre. The area includes the telescope and a set of containers consisting of a control room, emergency dormitory, laboratory, kitchen, storage and sanitary facilities. The control room and dormitory are oxygenated to a level of 29 %, which makes it reasonably comfortable to work inside. For outside work the staff use portable oxygen systems. Electrical power is provided through two generators, each producing 450 kVA at sea level (downgraded to about half of that at 5100 m). Telephone connections and network are provided through the microwave link, and there is radio communications equipment for contact between the pick-up trucks, Chajnantor and Sequitor. Work at the high altitude is governed by strict safety rules; access to the site requires authorisation by the Station Manager.

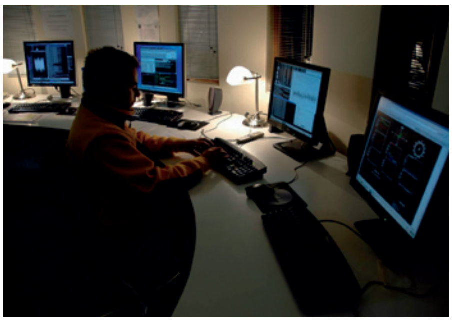
The Sequitor base is situated about 6 km south of the centre of San Pedro de Atacama on 2.2 ha of land. It is located in the oasis of San Pedro with trees and vegetation, and access to irrigation water every three weeks. The buildings are made of adobe and follow the local style of construction. There is a building containing offices, laboratories and a control room, as well as 17 dormitories, a cafeteria, a meeting/recreation building and storage. Power is provided through two generators, water is provided from San Pedro, hot water is produced through a combined solar/electrical heating system and there is a sewage treatment plant as well as a gasoline station.

The staff of 25, including astronomers, operators, engineers, technicians and maintenance personnel, is contracted to ESO. The APEX staff must deal with the many kinds of logistics activities of a remote site, including trips and transfers for staff and visitors, transport of materials to and from Santiago and abroad, deliveries of diesel fuel for the generators, catering and cleaning services, infrastructure maintenance and truck maintenance (APEX operates five pick-up trucks).

APEX is part of the local community of Sequitor and San Pedro de Atacama, and participates in local activities and contributes funds for educational, cultural and community projects.

Figure 3: The APEX control room in the Sequitor base, from which Claudio Agurto operates the telescope (lower left). The radio link transmitters are visible on top of the building. To the left, the laboratory wing is seen, with our open air meeting room.

Photos: A. Lundgren, ESO



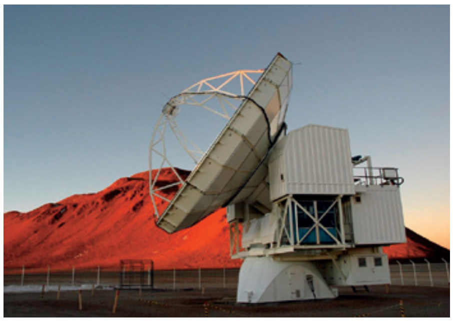


Figure 4: APEX at sunset with Cerro Chajnantor in the background.

The Telescope

The APEX telescope is a modified copy of the VERTEX ALMA prototype, customised for stand-alone (single-dish) operation. Two additional Nasmyth cabins for heterodyne receivers and two large instrument containers for supplementary equipment (such as spectrometers, synthesizers, compressors and chillers) add to a total mass of the modified antenna of ~ 125 t.

The telescope is a Cassegrain system with a parabolic main reflector, on an alt-az mount. The 12-m-diameter reflector, consisting of 264 aluminium panels in 8 rings, is mounted on a carbon fibre reinforced plastic (CFRP) back-up structure of 24 sandwich shell segments. The back-up structure is supported by an INVAR cone, which is attached to the top of the Cassegrain cabin. The adjustable panels, manufactured to a surface accuracy of 8 μm rms, have been chemically etched to scatter solar radiation, allowing daytime observations.

The aluminium secondary reflector, supported by CFRP quadripod legs, provides a field-of-view suitable for wide-field bolometer arrays in the Cassegrain cabin. For operation (of basically the heterodyne receivers) in the Nasmyth cabins, the telescope waist from the secondary is transformed (through the elevation tube) by refocusing optics into the Nasmyth waists. The tertiary mirror package is on a rotary support to select between the two Nasmyth foci and to clear the optical path for the bolometer pick-up mirror (on the floor of the Cassegrain cabin).

Figure 5: Adjustment of the surface. 1320 positioners on in total 264 aluminium panels were adjusted with a few μm accuracy. The small images show APEX engineer Juan Fluxa riding the cherry picker, and Leo Vanzi with Jorge Corante in the cage.

Photos: R.Güsten, MPIfR

Striving toward the perfect telescope

The coupling efficiency of a radio telescope to an astronomical source is basically controlled by the surface smoothness ε of its parabolic reflector: the classical *Ruze* formula describes the loss of efficiency with wavelength λ as an exponential decrease $\propto \exp(-(4\pi\ \varepsilon/\lambda)^2)$, i.e. for $\varepsilon = \lambda/15$ the antenna coupling efficiency has decreased to half its maximum already. In order to operate with high efficiency in the last of the classical atmospheric windows (around 300 μm wavelength, see Figure 2), the specifications for the APEX require for a surface smoothness of better than 20 μm rms. This requires that, over the 12-m diameter of the main dish, the deviation from the perfect parabola has to be less than one fifth of the average thickness of a human hair – a rather challenging requirement on the manufacturing, assembly and adjustment of the antenna.

After assembly, the main reflector was pre-aligned by VERTEX by means of optical photogrammetry to 35–40 μm rms surface accuracy. From there on the APEX holography team performed near-field holography with a 92.4 GHz transmitter located near the summit of Cerro Chajnantor, at an elevation angle of 13 deg. During three holography sessions (May and June 2004, April 2005), in an iterative process, phase residuals were measured and converted to surface error maps which were then used to correct for panel-to-panel misalignments and panel flexures. The manual adjustment of the (maximally) 1320 vertical adjuster elements typically took a full workday, depending on the environmental conditions, with teams working in shifts (Figure 5). In April 2005, the surface was finally set and verified to an excellent 15 μm rms smoothness towards the transmitter (Figure 6). Because of gravitational deformations the performance of the antenna would rapidly degrade towards higher elevations. Therefore the finite-element model of the APEX dish was used to pre-load and thus optimise the surface settings for elevations that will actually be used for astronomical observations. The effective surface smoothness for the elevation range 30–80 deg, calculated to 17–18 μm, is confirmed by carefully calibrated measurements of the telescope's coupling efficiencies to astronomical sources (planets). This makes APEX a superb telescope with performance well within specifications that allows observations into the supra-THz windows.

Science with APEX

As its name implies, APEX is a pathfinder for other (sub)millimetre wavelength missions, most directly for ALMA. This giant array of 50 12-m antennas separated by baselines up to 14 km, will also be located on Llano de Chajnantor (Figure 1) and is expected to start operation in 2012 (*www.eso.org/projects/alma*). There are great complementarities to the Herschel Satellite and the Stratospheric Observatory for Infrared Astronomy (SOFIA), whose instruments will reach to higher frequencies into the far-infrared wavelength range not accessible from the ground. Towards longer wavelengths, APEX picks up where the wavelength coverage of, e.g., the IRAM 30-m telescope on Pico Veleta (Spain) ends. Together, the latter two instruments cover all atmospheric windows observable from the ground between 0.2 and 4 mm with comparable angular resolution (the half-power beamwidth of the 30-m antenna at the frequency of the CO(2–1) transition, ~ 11″, compares nicely with the 9″ resolving power of APEX observations of warm CO(6–5) at 690 GHz).

What does APEX observe? Mostly the cold and cool universe, through radiation from molecules and dust. Molecular lines in the submillimetre range sample warmer and denser gas than millimetre lines, so the formation of stars and galaxies and the astrochemistry associated with these events are central work areas for APEX. Molecular cores show very line-rich spectra in the submillimetre range, the analysis of which gives insight into the ignition phase of, particularly massive, stars. Studying the submillimetre region is also crucial for understanding the feedback of newly born stars, through outflows and the creation of photon dominated regions. APEX will make particularly valuable contributions to the study of galaxies, where we are faced with the somewhat paradoxical situation that the high-J (submillimetre) CO lines are well observed in highly redshifted objects, since the frequencies are shifted to the millimetre range, but we know very little about the very same transitions in nearby starburst and merger galaxies. Particularly the CHAMP$^+$ heterodyne array will remedy this imbalance.

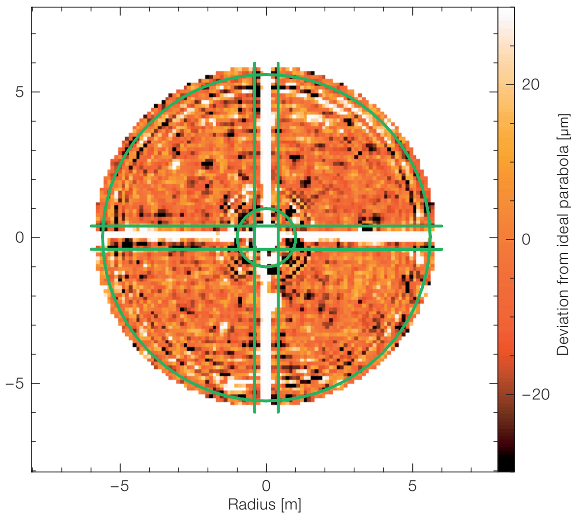


Figure 6: The surface error pattern of the APEX main reflector after the final (April 2005) holography session. The surface smoothness is 14.7 μm rms (Güsten et al. 2006).

Early results from the first months of science observations since operation readiness will be published soon in a special issue of Astronomy & Astrophysics Letters. Here we highlight a few examples to demonstrate APEX's immediate impact on different fields of astronomy.

APEX detects a new molecular ion

More than 120 different molecules are known in the interstellar medium, about 10 % of them positively charged ions. Most of these molecules contain hydrogen, oxygen, carbon, and nitrogen, the four most abundant elements. A few molecules containing silicon, sulfur, phosphorus and one even containing iron have been found as well. However, only two halogen-bearing molecules had been known to exist in the interstellar medium: HCl and HF. HF, the main reservoir of interstellar fluorine, unfortunately is impossible to observe from the ground but was detected with the Infrared Space Observatory by a team led by David Neufeld (Johns Hopkins University) that included APEX project scientist Peter Schilke. Neufeld and colleagues recently put fluorine chemistry to closer scrutiny and predicted CF^+ to be the second most abundant F-containing species.

In a concerted effort with the IRAM 30-m telescope, APEX has identified for the first time CF^+ (fluoromethylidynium) in space. While its two lowest energy (and lowest frequency) spectral lines were discovered with the former, APEX clinched the identification with a third line. This interesting molecule exists in an UV exposed molecular interface region where the hot stars that excite the famous Orion Nebula also provide the ionising radiation. Our observations indicate that models of the chemistry of fluorine-bearing molecules are realistic and that these molecules can be used to probe interstellar clouds. They thus open a new chapter in interstellar chemistry.

APEX reveals the nature of the BHR71 outflow

It is commonly believed that highly-collimated outflows are the first stage in outflow evolution, and their study is thus central to understand the interaction of the jet with the surrounding cloud. BHR71, a small Bok globule at 200 pc distance, harbours a beautiful example of such a highly collimated outflow. This outflow is powered by a young low-mass protostar, IRS1, belonging to a binary system. Submm observations with APEX of the CO(3–2) emission have confirmed the existence of a second fainter and more compact bipolar outflow, associated with the other protostar of the binary system (Parise et al. 2006). Temperature enhancements in the lobes of the extended outflow are constrained by

Figure 7: HST image of the Orion nebula. Towards the so-called Orion 'bar' interface region APEX, together with the IRAM 30-m telescope, have detected a new ion molecule: CF^+ (Neufeld et al. 2006). Credit: NASA, C. R. O'Dell and S. K. Wong (Rice University).

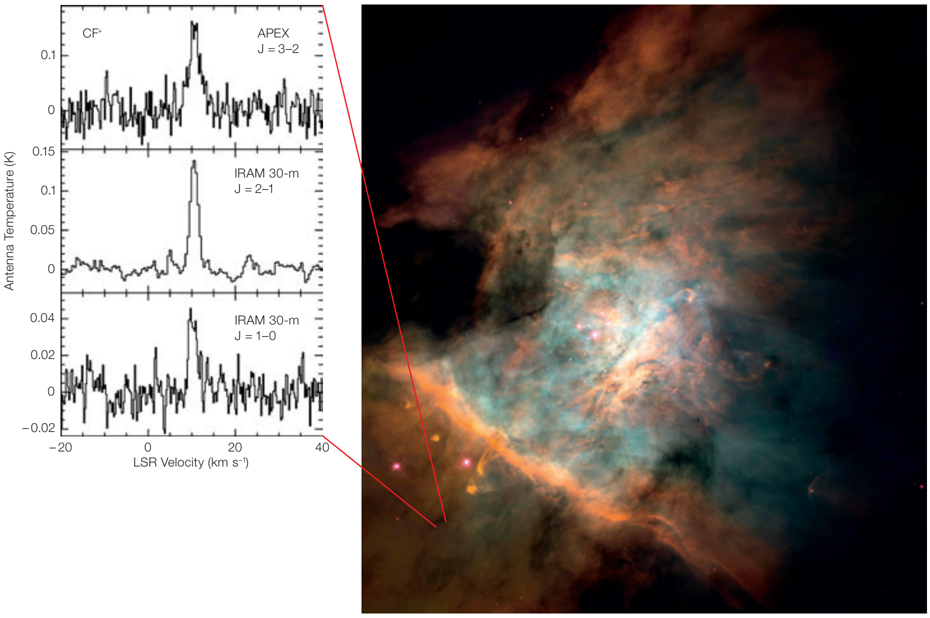
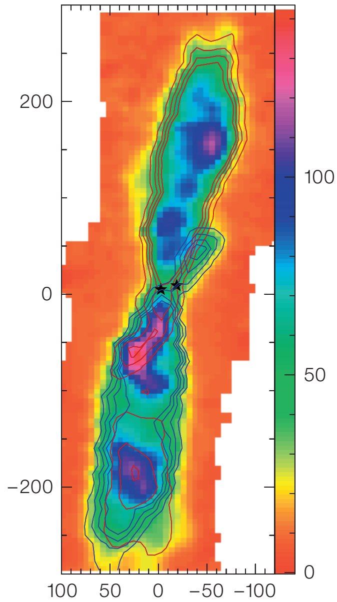


Figure 8: CO(3-2) map of the BHR71 outflow. The colour scale represents the integrated intensity over the whole velocity range of the IRS1 outflow. Red and blue contours mark the integrated intensities of the two lobes of the outflow powered by IRS2 (Parise et al. 2006).



observations of high-energy lines of methanol. The authors derive temperatures between 30 and 50 K, with densities ~ 10^5 cm^{-3}. The small outflows appear to be even warmer (up to 300 K).

APEX goes extragalactic from the beginning

The first extragalactic object at which APEX was pointed during its commissioning was NGC 253, which is considered – with M82 – the archetypical nuclear starburst galaxy. Because of its proximity, less than 10 million light years away in the southern constellation of Sculptor, APEX can spatially resolve its central circumnuclear gas layer. In Figure 9 we display the emission of the CO J = 4–3 rotational transition (at a wavelength of 650 μm), superimposed on an optical image of the galaxy. Mapping different CO and atomic carbon lines allows studies of the density and temperature of the gas in this interesting environment. By modelling the excitation of CO(4–3) and CO(7–6), we derive a kinetic temperature of 60 K and H_2 density of ~ 10^4 cm^{-3} for the central gas layer. The submm rotational transitions of CO are shown to be the main cooling lines of the warm dense interstellar gas, peaking at J = 6–5 for the central 250 pc of NGC 253.

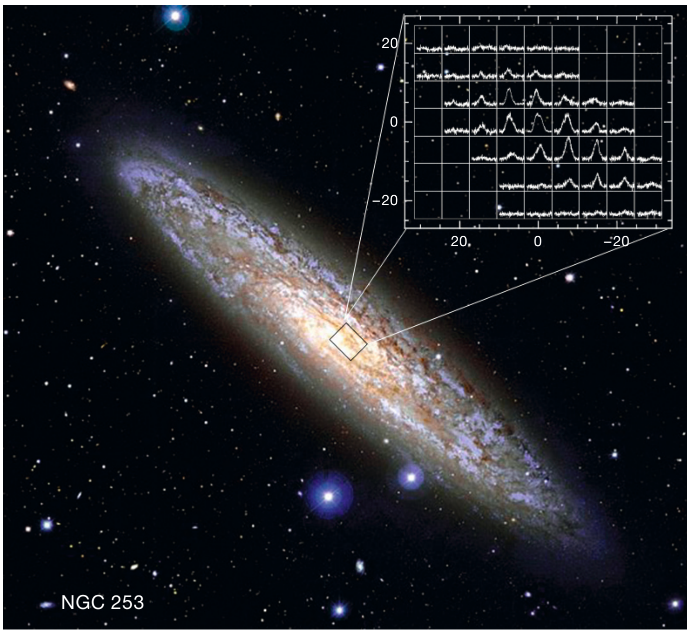


Figure 9: Distribution of warm carbon monoxide, as measured with APEX in its J = 4–3 rotational transition at 461 GHz (Güsten et al. 2006), superimposed on an optical image of NGC 253. Spectra have been sampled at half beam spacing (the beam of APEX at this frequency is 13.3″).

These very first observations of a nearby starburst nucleus reveal the potential of APEX in constraining the gas excitation in these nuclei. With broader band spectrometers and the chopping secondary coming soon, and given the exceptional observing conditions at the site, the impact of this facility on extragalactic astronomy will be significant.

Instruments for APEX

In parallel to the construction and commissioning of the APEX, a demanding cutting-edge technology programme has been launched to provide the best possible detectors for this outstanding facility. For its first observations, APEX was equipped with state-of-the-art submm receivers developed by MPIfR's Division for Submm Technology (FLASH I and II, Heyminck et al. 2006, with new technology Fast-Fourier-Transform spectrometers, Klein et al. 2006) and with a first facility receiver (working in the 345 GHz atmospheric window) build at Chalmers University (Risacher et al. 2006).

Soon the first array receivers will be commissioned: LABOCA, the 870 μm 295 pixel facility bolometer camera, is scheduled for June this year, and later in August the Champ$^+$ 2 × 7 pixel heterodyne array of the MPIfR will be commissioned. In December OSO will deliver a suite of single pixel facility receivers covering the 210–500 GHz frequency range.

Observing with APEX

The observing time will be shared in proportion to the partner's investments (45 % MPIfR, 24 % ESO, and 21 % OSO), with 10 % allocated to Chile as host nation. On the ESO side, APEX proposals are reviewed by the ESO OPC and deadlines follow the normal ESO deadlines for proposal submission. The APEX web pages (*www.apex-telescope.org*) include technical descriptions of the system and observing time calculators. The observations are done in service mode, mainly during night-time. The Principal Investigators are asked to fill in a project submission form found in the web pages, which includes all information necessary for the APEX staff to perform the observations. The APEX raw data are stored in MBFits, the calibrated data in CLASS format. ESO and Swedish data are transferred to the ESO archive, and the release of data follow the ESO archive rules.

Acknowledgements

We thank the APEX staff and our teams at the home institutes, whose outstanding support during the build-up and commissioning phase has made this project become reality on a compressed schedule. We acknowledge with pleasure the support from Dave Morris and Albert Greve (both retired from IRAM), and Nimesh Patel and T. K. Sridharan (CfA) for the holography of the telescope.

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ALMA News

Tom Wilson (ESO)

ESO has selected Dr. Paola Andreani as the ARC Manager for ESO. Dr. Andreani will begin work at ESO Garching on 1 June 2006. Dr. Andreani is presently an Associate Astronomer at the Astronomical Observatory of Trieste, a part of INAF. Dr. Andreani is also a Co-I of Herschel/PACS and the local Project Manager of Herschel/SPIRE. She has been a working group manager of the Italian Herschel community, participating in the Herschel GTO process. Dr. Andreani is a well-known researcher in the field of extragalactic astronomy, and has carried out significant work on the Sunyaev-Zeldovich effect using the SEST.

Dr. Paola Andreani