# CENTER OF EXCELLENCE FOR ASTROPHYSICS AND ASSOCIATED TECHNOLOGIES (CATA).

## FIRST FIVE YEARS REPORT

## INTRODUCTION.

The ultimate goal of the Center for Astrophysics and Associated Technologies (CATA) is *to* ***add local intelligence to a valuable Chilean natural resource, which is its unique geographical location with the best conditions for astronomical observations*** that have attracted countries with the highest technological development to install and operate their observatories from northern Chile.

The astronomical facilities currently available in the north of Chile include some of the world's best optical and infrared telescopes like the Very Large Telescopes (VLT, European Southern Observatory) and VISTA at Paranal, Gemini-South telescope (National Science Foundation) at Cerro Pachón, the Magellan telescopes (Carnegie +) at Las Campanas.

In the Chajnantor area, east of San Pedro de Atacama, there is a unique radio synthesis telescope: the Atacama Large Millimeter Array (ALMA, US+ESO+Japan+Taiwan), which opens a new window for astronomical research. It is an interferometer formed by sixty six antennas, all working in concert to provide sub-arcsecond angular resolution.

In addition, new mega-telescopes will be coming on-line, in Chilean territory, before the end of this decade, such as the Large Synoptic Survey Telescope (LSST) at Cerro Pachón, the Cornell-Caltech Atacama Telescope (CCAT) at Chajnantor, the Giant Magellan Telescope (GMT, a 24m telescope), and an even more ambitious project, currently under development by ESO, the E-ELT, a 39m telescope to be installed at Cerro Armazones near Paranal.

The privileged access of Chilean astronomers to this unparalleled suite of instruments places them in a unique position to be able to address some of the most fundamental problems in modern astrophysics, ranging from questions like how planets, stars and galaxies assemble and evolve, investigate the existence of life in other worlds, to how does the large scale structure of our universe looks like and what will be its ultimate fate.

During these first five years of existence CATA has constituted a unique instrument to generate the conditions for boosting local astrophysics in order to place Chile among the world leaders in this area. It has transformed the nature of Chilean astrophysics from individual research efforts into a coherent, coordinated and collaborative endeavour in science technology and education.

The main thrusts of CATA are:

**I Promote research in astrophysics related to the origin and evolution of celestial objects.**

**II Educate and train the new generation of Chilean astronomers, expected to make optimal use of all world-class astronomical facilities located in the country.**

**III Create and drive a strong program of technological creation and innovation related to astronomical instrumentation.**

**IV Astronomical outreach**

CATA has made significant progress in all areas mentioned above. This is particularly true in the case of astronomical research, which takes advantage of the access to the best observatories in the world operating in the North of Chile. Results are clearly appreciated from the list of publications and citations. Today, Chilean astrophysics is in a competitive position, internationally, in several major areas of current interest. The Center has provided Chilean astronomers with the proper environment and tools to achieve this goal.

Thanks to the contribution of CATA the graduate programs in astronomy in the three associated Universities have become very strong and internationally recognized, today a large fraction of our PhD students come from abroad, manly Latin America, and Europe but also India and Nepal. The number of graduate students has steadily increased from 65 to 83 in these first five years.

For technological developments, CATA has worked in partnerships with initiatives from the institutions that host the Center (Universities). As an example at PUC a center for Astro-engineering (CAE) was created and CATA has contributed to it with the objective of building new optical and infrared instrumentation. The CAE is now building sophisticated optical instruments in addition to taking the first steps to become a preferred place for the international observatories to maintain and upgrade their instruments.

Another outstanding project is that of the Radio-Frequency Laboratory, started with CATA funds at University of Chile, which motivated U. Chile to start a PhD program on Astronomical instrumentation at the Electrical Engineering Department. Today PhD and undergraduate Engineering students work at the Lab, CATA and U. Chile share appointments of engineers working at the Lab and teaching at the Engineering School. Thanks to this synergy today the CATA Radio Lab has produced the first prototype for ALMA Band 1 receiver (as promised in the original project) but also works in designing and integrating parts of other receivers for Band 3 and 5-6), becoming a trustworthy place where ALMA partners feel confident to service an upgrade their instruments.

Some of the abovementioned technological developments have been published in International Journals and the process of patenting some of these developments is starting to happen.

CATA has also contributed to the creation of a laboratory at U. de Concepción where Center astronomers and engineers are developing and building radiometers that are important for observatories like ALMA. The construction of an automated telescope design to search and follow supernova has also been partially funded by CATA, the telescope (installed at Cerro Tololo Observatory) is starting to achieve its objective.

Almost all of the Key projects supported by the Center are surveys that are generating huge amounts of data. To deal with the vast flood of data from telescopes like VST, VISTA, and ALMA, the Center supported the creation of a National Data Center located at one of the Associated Institutions (PUC) which has committed additional resources and infrastructure. This National Data Center is serving not only astronomers at the Center for Astrophysics but also the rest of the Chilean astronomical community, providing quick and easy access to the data and thus promoting better research.

Regarding outreach, the Center has had a considerable impact at a national level, with multiple participations in the written press, television and radio (more than one thousand) in addition to conferences for a diversity of audiences from school children to general public, political authorities and professional business people.

The publication of several astronomy books by members of CATA (some for children) has proven to be very successful and very well taken by the educational authorities of the country who have included some of these titles in school libraries. One of the CATA members (MT Ruiz) has won this year a "Fondo Nacional del Libro" to publish an Astronomical Anthology (Ed. Catalonia), for general public and high school students.

CATA has substantially contributed in the increase of the human resources devoted to astronomical research or astronomical instrumentation in each of its Associated Institutions. During these five years of operation a total of sixteen (16) new researchers were incorporated to the Center on a full-time basis: eleven (11) astrophysicists and five (5) engineers. The new members were selected to fill expertise gaps in research areas, substantially broadening the research base in each astronomy site within CATA, and have strengthened the teaching of astrophysics in all astronomy Ph.D. programs. Particular efforts were made to incorporate engineers, theoreticians and sub-mm wavelength specialists in all the Associated Institutions. This proved to be crucial for achieving several of the scientific goals and to exploit the new generation of instruments located in Chile, in particular ALMA. Also during this period, CATA incorporated into its research and academic activities, scientists from institutions other than the Associated to the Center, on a partial time-basis.

CATA is strongly promoting and fostering collaborations among astronomers working in related topics across the country, as well as internationally. In particular, CATA is encouraging scientists from the three Chilean institutions to work together in large collaborative projects that are beyond the scope of small research groups. Key programs have been already implemented and granted considerable amounts of observing time in several telescopes at the International Observatories in Chile. These programs enable Chilean astronomers to pursue more ambitious research goals than ever before, supporting the creation of large research groups and fostered close collaborations between members of different areas. Also CATA has enabled theorists and observers to join in common research projects. The large, as well as small more individual, projects are fulfilling one of the goals of CATA, which is to broaden the research base in each astronomy site within the country.

Collaborative work among Center members is rapidly and steadily increasing with time, ensuring the fulfilment of one of the scientific goals of CATA which is to boost strong scientific collaborations between members of the different participant institutions. Thirty-one percent of the refereed papers published during the last five years have two or more CATA members as co-authors. A quantitative measurement of this is provided by the *collaboration index* between Center members, measured from ISI publications, which grew from sixty five (65) in 2008 to two hundred and eleven (211) in 2011, an increase in collaborations by more than a factor of three. About 20% of the papers involved postdoctoral fellows and 12% graduate students. A look at the list of authors of the papers by CATA members clearly shows that there is a well-established international collaboration in each of the on-going science projects. In particular, the Key Projects involve a

considerable number of international collaborators from all over the world, mainly from USA and Europe. There have been more than two hundred (200) visits between Center members and international collaborators (in both directions). The strong international partnerships have been one of the key to the scientific success of the Center.

In accordance with the strong commitment to increase human resources and networks for National Astronomy, CATA decided to foster collaborations and provide support for scientific activities to selected researchers at other Universities. These researchers are V. Motta and J. Borissova at the University of Valparaíso, R. Barba at University of La Serena and G. Pignata at University Andrés Bello (UAB).

The main partners to operate CATA are the three associated universities: Universidad de Chile, Pontificia Universidad Católica and Universidad de Concepción. They provide most of the infrastructure where the CATA activities take place and share operational costs and salaries of researchers, support personnel and students. There is a strong symbiosis between the Universities and CATA. Without CATA, astronomical development at the Universities would have been minimal. Without the Universities, CATA would have had much less impact in its scientific output and in the technological development.

In addition to the contributions from the host institutions, CATA members have accreted important resources from competitive national funds (Fondecyt projects and Milenium Nucleus) as well as from international astronomy funds (ALMA, GEMINI and ESO). The national funds are mainly devoted to travel support, to the renewal of computer equipment and to pay page charges. The extent that these resources cover the actual need in these items is variable and depends on each project, but often CATA has to contribute towards the same objectives because their funds are not enough. With respect to the competitive international funds an important fraction of the granted resources have been devoted to buy new equipment very much needed at the CATA laboratories in order to achieve the goals in the technology areas.

The activities undertaken by CATA have established the fertile ground for its scientific personnel to successfully apply to other sources of funds that enhances the objectives of the Center but their contribution to the running of the Center is limited. All of the above mentioned funds, including the contribution from the host universities, are tied to a particular purpose and cannot be use in other ways. Basal funds are thus not only crucial in providing a large fraction of the needed resources but also are important to run the Center with the flexibility necessary to move in the best direction to achieve our final goals.

## I RESEARCH

CATA is providing Chilean astronomers with the proper environment and tools to undertake the proposed research, giving them the opportunity to undertake ambitious Key projects which have put them at the forefront of astrophysics. These projects favour strong interaction among researchers and make the best use of all the available research facilities. During the first four years the Center had six main areas of astrophysics cultivated by its members, during the last year a seventh area was created :

### 1) Birth and evolution of structures in the Universe

**2) Stellar populations in the local Universe**
**3) The extragalactic distance scale**
**4) Star formation**
**5) Extrasolar planets and Brown dwarfs**
**6) Supernova and dark energy**
**7) Theoretical Astrophysics** (only since year 5)

Each of the areas is led by a Principal Investigator (P.I.) who is responsible for the guiding progress in order to achieve the science goals expected in his or her area of research.

At the beginning of the fifth year Mario Hamuy (PI of area 6) had to reduce his time commitment to CATA and could no longer be a PI, as a consequence Alejandro Clocchiatti became the PI of Area 6, on the other hand Nelson Padilla became the PI of the new Area 7, which includes computer simulations and theory.

The scientific work performed in all seven research areas of the CATA during the five years of operation has been considerable and fully in accord with the science goals as formulated in the original proposal. During this period, CATA members published eight hundred and twenty three (823) papers in refereed journals. CATA members have investigated various problems of fundamental scientific importance, covering the origins and nature of a broad range of objects, from the largest scales ---by studying galaxy formation and evolution---to the smallest scales---by studying the collapse of an individual star and the formation of planets. Given the ample scope of the research and the amount of work done by CATA members during these five years, a fair summary is impracticable. The list of refereed (ISI) publications is presented in Appendix 1. More than four hundred (400) contributions were published in non-refereed journals, most of them corresponding to proceedings of congresses. In summary, research activities in all areas proceeded in-line with the initial science objectives.

Thanks to CATA a considerable increase in Human resources, dedicated to accomplish the goals of the Center, has taken place.

CATA has allowed a substantial increase in the number of researchers and engineers working at all three Associated Universities. Sixteen (16) new researchers -- eleven astronomers and five engineers -- have been hired with the Center support and received continuous support for their scientific activities. In the following we give the names of the new researchers, the year of incorporation to the Center, their areas of research and the University in which they were hired (Universidad de Chile (UCH), Pontificia Universidad Catolica (PUC), Universidad de Concepcion (UdC)) : (The new faculty positions were filled through international competitions)

| | | |
|---|---|---|
| Escala, Andrés | 2008 | Astronomer UCH |
| Jordán, Andrés | 2008 | Astronomer PUC |
| Mena, Patricio | 2008 | Engineer UCH |
| Vanzi, Leonardo | 2008 | Engineer PUC |
| Altamirano, Pablo | 2009 | Engineer UCH (left during year 3) |
| Bauer, Franz | 2009 | Astronomer PUC |
| Cuadra, Jorge | 2009 | Astronomer PUC |
| Demarco, Ricardo | 2009 | Astronomer UdC |

| | | |
|---|---|---|
| Fellhauer, Michael | 2009 | Astronomer UdC |
| Dünner, Rolando | 2010 | Astronomer PUC |
| Bustos, Ricardo | 2010 | Enginner UdC |
| Puzia, Thomas | 2010 | Astronomer PUC |
| Muñoz, Ricardo | 2011 | Astronomer UCH |
| Treister, Ezequiel | 2011 | Astronomer UdC |
| Julio Chaname | 2012 | Astronomer PUC |
| Ricardo Finger | 2012 | Engineer UCH |

CATA supported some researchers, from other Universities in Chile, in order to increase the scientific collaboration with their newly established astronomy groups. The Center provided them with funds for travel and expansion of human resources, in particular for the hiring of postdoctoral fellows with research interests close to those of the Key projects. S. Sharma and R. Muñoz were hired at Universidad de Valparaiso and G. Gunthardt and M. Soto were hired at Universidad de La Serena. The researchers from other Universities that became associated to the Center are:

Rodolfo Barba, Universidad de La Serena
Jura Borissova, Universidad de Valparaiso
Veronica Motta, Universidad de Valparaíso
Giuliano Pignata, Universidad Andres Bello
Matthias Schrieber Universidad de Valparaiso

Accomplished scientific research by CATA members in the different Areas :

**AREA 1: Birth and Evolution of Structures in the Universe.**

**P.I.: Leopoldo Infante**

The long-term goal of Area 1 is to contribute in the understanding of the nature and evolution of structures in the universe. Center members doing research in this Area include Barrientos, Bauer, Bronfman, Cuadra, Galaz, Dunner, Jordán, Lira, López, Minniti, Padilla, Quintana, Reisenegger and Richtler.

This Area emphasizes the study of primeval galaxies, clusters of galaxies and dwarf galaxies, and is carrying out with prominence large surveys of high redshift galaxies, superclusters and clusters of galaxies. It developed from no theory at all to a significant amount of cosmological simulations, galaxy evolution simulations and primordial star formation theory at redshifts greater than 11.

One important objective envisioned in the original project was to prepare the extragalactic community for the ALMA era. At that time there were no extragalactic radio astronomers in our community. Today, after these five years, we are pleased to say that this objective is being accomplished. Proof of this is the increase in the number of faculty, postdoctoral fellows and students working in projects related to ALMA and the number of extragalactic proposal submitted in cycle 0 to ALMA; 11 out of 34 proposals. These

proposals range in topics from studies of the local universe to quasars, AGN, star forming galaxies at z~1-3 to sub-mm emission in the most distant galaxies ever discovered at z>7.

In what follows we highlight three lines of research that are been carried out successfully in Area 1: the MUSYC survey, the QbC project and Cosmo-galaxy simulations. We also mention the latest result, the discovery of the largest and most powerful distant cluster of galaxies ever discovered (El Gordo), which recently received worldwide media attention.

**Quasars behind Clusters (QbC) survey:** This survey is aimed at studying the effect of galaxy group and cluster-sized environments on the gaseous content of galaxies at redshifts $0.2<z<0.9$. To this end, the QbC probes MgII absorbing galaxies along sight lines to background QSOs that were selected to be in close projection to foreground cluster galaxies.

**MUSYC** (MUltiwavelength Survey by Yale-Chile)**:** The main design of this survey is to study formation and evolution of galaxies and their black holes at redshifts z~3. It includes deep infrared, optical and narrow band imaging and covers four 30x30 square arc-minute fields. Also, Chandra X-ray observations, Spitzer IR imaging and extensive spectroscopy were carried out. The survey has been most successful for studies of Lyman Alpha Emitting galaxies (LAE) at redshift z~3.

**EL GORDO:** Since 2008 CATA members have been reporting results from their Atacama Cosmology Telescope (ACT) survey collaboration which includes USA and Chile astronomers and physicists. The ACT is a sub-mm radio telescope built to measure the Cosmic Microwave Background radiation (CMB) at high resolution. It is located in Cerro El Toco near the ALMA site in Chile. The Center group has been in charge of detecting clusters of galaxies through the Sunyae-Zeldovic (SZ) imprint in the CMB.

## AREA 2. Stellar Populations in the Local Universe

### PI: Doug Geisler

Center members working in this Area are Catelan, Costa, Geisler, Gieren, Infante, Jordan, Mendez, Mennickent, Minniti, Pietrzynski, Richtler, Rubio, Zoccali and Borissova (only an associated member), several postdoctoral fellows and graduate students. The overarching scientific goals of Area 2 are closely aligned with those of Area 1, viz. to study the formation and evolution of structures, in particular galaxies, but using the resolved stars within a galaxy instead of its global, integrated properties as tracers.

**Globular Cluster Systems.** *The Dark Matter Halo of NGC 1399*. Central galaxies in galaxy clusters can be key discriminators between competing theories of galaxy formation and dynamics; in particular between the cold dark matter (CDM) paradigm and modified Newtonian dynamics (MOND). Using several instruments they obtained velocities of 656 globular clusters out to a galactocentric distance of 80 kpc.

**Stellar Populations in Nearby Galaxies.** *Chemical Evolution of the Galactic Bulge*. Does the Milky Way possess a ”classic” bulge, formed very rapidly and very early in the

history of our Galaxy, or is it instead a "pseudo-bulge" formed via secular evolution of the disk driven by a bar over an extended time? The answer has important implications for Galaxy formation theories and can be constrained from detailed chemical studies - elemental ratios are sensitive to the previous history of star formation. In particular, the relative abundances of iron and alpha-elements play a key role: the [alpha/Fe] ratio depends on the relative contribution of SNII and SNIa progenitors, and therefore it depends on the timescale of star-formation, as these two processes have very different timescales. Center members obtained high resolution spectra for a large sample of bulge giants and measured alpha and Fe abundances. [alpha/Fe] is found to be higher in bulge stars than in thick disk stars, which were known to be more alpha enhanced than thin disk stars. These results support a scenario in which the bulge formed before and more rapidly than either thin or thick disks, and therefore our bulge is a prototypical old spheroid, with a formation history similar to that of early-type (elliptical) galaxies.

**The VVV Survey.** The Vista Variables in the Via Lactea Survey (D. Minniti PI) is the public ESO near-IR variability survey scanning the Milky Way bulge and an adjacent section of the disk. The survey will take 1929 hours of observations with the ESO 4-m VISTA telescope during 5 years (2010 - 2014), covering $10^9$ point sources across an area of $520 deg^2$. The final product will be a deep near-IR atlas in five passbands (0.9-2.5 μm) and a catalogue of more than $10^6$ variable point sources. The VVV is the Key Project of Area 2 and is proving to be every bit as much of a goldmine as anticipated. Center members reported (see ESO Press Release 1128) the discovery of ~100 new open star clusters. These are so-called embedded clusters - very young and still surrounded by their cocoons of dust and gas, and thus invisible to optical surveys.

**Multiple Populations in Globular Clusters.** Globular clusters, long considered as the prototype of simple stellar populations, have recently been found instead to be more complex, and thus more interesting, than regarded by this traditional wisdom. In particular it has been discovered that the most massive globular clusters have chemical inhomogeneities. Center members studied stars in NGC1851 belonging to the two RGBs visible in the Stromgren CMD, finding that the double RGB appears to be related to a bimodal distribution of the light and heavy s-element abundances. The cluster also hosts a bimodal SGB, which was theoretically explained with two populations having the same age but different C+N+O content. They proved instead that stars in NGC 1851 share the same C+N+O content. In this case pollution by SNeII appears to have ocurred. On the other hand, for M4 Center members established that the cluster is formed by two stellar populations with distinct patterns of light and light-s elements. These patterns suggest that the second generation was formed by material polluted by ejecta of massive stars ($M > 15 M_\odot$). This implies an age difference between the two populations of 10-40 Myrs.

## AREA 3. The Extragalactic Distance Scale

### PI: Wolfgang Gieren

The work in Area 3 has been mainly conducted by four Center scientists (Gieren, Pietrzynski, Mennickent and Minniti), several postdoctoral fellows and students, and a

considerable number of international collaborators from the USA and Europe. The main science and Key Project of this Area is the *Araucaria Project* whose goal was to improve stellar standard candles, and in particular Cepheid variables, to yield distances to nearby galaxies (out to a few Mpc) accurate at the few percent level and this way lay the ground for a truly accurate (<3%) determination of the Hubble constant independent from CMB anisotropy studies.

In the Cepheid work, CATA members performed as a first step wide-field optical searches for Cepheids in the Araucaria target galaxies, which included all Local Group irregulars and 4 spiral galaxies in the Sculptor Group (NGC 55, 247, 300 and 7793). The ground-breaking initial work was conducted in NGC 300 where they found 117 classical Cepheid variables with periods between 5-115 days. In a follow-up study they obtained near-IR photometry at the ESO VLT for a subsample of these Cepheids and developed a multi-wavelength VIJK technique to determine the distance to NGC 300 with a total error of 3%, unprecedentedly small. This technique was later applied to all other Araucaria target galaxies and yielded in all cases Cepheid distances accurate to better than 5%. Since the project involved a huge observational effort, members applied for and were granted numerous semestral programs at the ESO Paranal and La Silla observatories, and at Las Campanas Observatory (Magellan, Warsaw 1.3-m imaging telescope used for the OGLE Project). Most of the wide-field imaging surveys for Cepheids and the other stellar candles were conducted with the Warsaw telescope in which members were allocated observing time in many nights, to allow proper phase coverage of the variables and making the Cepheid work possible.

The work on the Cepheid PL relation from both the Araucaria Project approach, and the IRSB technique has yielded, as a very firm result, that the *Cepheid PL relations in the near-infrared J and K bands are truly universal*, unaffected by the metallities of the observed Cepheid samples. The IRSB distances to 36 LMC Cepheids have further yieldes an accurate LMC barycenter distance of 18.45 mag, with a 5% systematic error and in line with our first analyzed late-type eclipsing binary system (see next section).

Center members discovered from OGLE 2 data the first 8 eclipsing binaries in the LMC composed of two red giants, bright enough for measuring accurate orbital radial velocity curves with 4-8-m class telescopes. These systems have an enormous potential for accurate distance determinations, and for precision measurements of the masses and radii of their component stars.

As part of the LMC eclipsing binary programme, members were lucky enough to detect the first ever two classical Cepheids in eclipsing systems with a stable red giant star as a companion in both cases. This allowed them to solve the famous “Cepheid mass discrepancy problem” in favour of the pulsation mass, given that the Cepheid dynamical masses could be measured to 1%. The result was published in Nature (also see ESO Press Release 1046, 2010). Due to this result and the disappearance of the annoying mass problem, Cepheids are now an even more reliable tool for calibrating the first rungs of the distance ladder.

Through the collaboration in the Araucaria Project with the University of Hawaii group, Center members achieved to set up a completely new, and first spectroscopic stellar method to measure precision distances out to at least 10 Mpc with blue supergiant stars. The accuracy is very competitive (5% with 10 blue supergiants in a given galaxy), has the advantage of yielding individual metallicities and reddenings as a by product, and uses the brightest normal stars in the Universe.

## AREA 4. Star Formation

### PI: Guido Garay

The main scientific goal of this area is to understand and characterize the formation process of low and high mass stars that takes place within dense molecular cores. Faculty members doing research in this Area include Bronfman, Casassus, Escala, Garay, Mardones, May (deceased during the third year of the Center) and Rubio, several postdoctoral fellows and more than 15 thesis students.

The Key Project in this Area, entitled *Studies of massive star forming regions in the southern hemisphere*, has been designed to specifically undertake a thorough study of the formation process of high-mass stars within massive dense cores, in particular to determine the gas kinematics prior to and during the onset of the gravitational contraction. This survey, using SEST/SIMBA, allowed Center members to determine the physical characteristics of the molecular cores harboring high-mass YSOs. They showed that the formation of massive stars takes place in molecular structures with distinct physical parameters, namely sizes of ~0.4 pc, dust temperatures of ~30 K, masses of ~2000 Msun, column densities of ~$3 \times 10^{23}$ $cm^{-2}$, and densities of ~$4 \times 10^{5}$ $cm^{-3}$.

As a byproduct of the 1.2 mm dust continuum emission survey, Center members discovered the first few luminous objects without counterparts at mid-infrared (Midcourse Space Experiment [MSX]) and far-infrared (IRAS) wavelengths. They concluded that these objects correspond to massive, dense, cold cores in very early stages of evolution, prior to the formation of a central massive object and that will eventually collapse to form high-mass stars.

Soon after the ASTE and APEX telescopes became operationally, CATA members started the second part of the Key project. This consisted in a galactic survey of the dust continuum emission at 850 microns. Center members joined forces with the European ATLASGAL team to carry out a survey of the whole Galactic plane using LABOCA, allowing them locate in an unbiased way the cold and dense massive molecular cores in which massive stars will eventually form.

Follow up work is being done using a variety of instruments available in order to: (a) investigate the dynamic interaction between embedded massive protostars and their parent cores; (b) Study the spatial distribution of massive protostars within GMCs and across the inner galaxy; and (c) Investigate the origin of jets and molecular outflows. One of the major astronomical results of the last two decades has been the discovery that star formation is accompanied by energetic, collimated mass outflow.

Center members are also carrying out studies of Infrared Dark Clouds, namely cold, dense molecular clouds seen as extinction features against the bright Galactic infrared background. They have mapped the emission in several molecular lines, using MOPRA, toward a large number of filamentary IRDCs in order to better characterize the various stages of high-mass star formation as well as the timescales and physical conditions during the collapse into proto-stellar cores. In addition, Center members are part of a large international project (MALT90) to make maps in 16 molecular lines near 90 GHz, using MOPRA, of 3,000 dense cores in the galactic plane.

Finally, Center members are building up data on the topic of the gas content in proto-planetary disks, and also on signs for on-going planet accretion. Molecular lines were observed with APEX towards a dozen of high mass star forming cores showing kinematical

signatures for the presence of a rotating disk. The aim is to search for enhanced abundance of certain molecular species based on the prediction from chemical models of disks. This will provide reliable candidates to spatially resolve a disk surrounding a high mass star with the ALMA telescope.

In summary, CATA members have been able to study and characterize the long-sought onset of massive star formation within cores. The Key project of this Area turned out to be a strong pathfinder for ALMA studies. Center members are now using ALMA to study the density structure and kinematics of massive protostellar envelopes, inner disks and winds at sub-arcsecond resolution, yielding detailed information on massive star forming cores at scales of 10 – 100 AU.

## AREA 5. Extrasolar Planets and Brown Dwarfs

### PI.: Dante Minniti

More than ten Center members were involved in the successful development of this new area of research. Faculty members include: Geisler, Gieren, Jordan, Kurtev, Mendez, Minniti, Pietrzynski, Rojo, Ruiz, Zoccali and Borissova (an associate member from U. Valparaíso).

Undoubtedly the biggest success in research of Area 5 has been the creation of large key programmes, which reach far beyond the normal scientific activities. These large key programmes developed slowly at the beginning, but already started to bring fruits after only a few years of operation, and the future looks most promising. The large programmes in line with the scientific goals of Area 5 are:

**(1) ESO Large Programme 666 on Extrasolar Planets at the ESO VLT**. This, the Key Project of the Area, has produced a considerable number of newly discovered objects for which the main physical parameters were determined. These data are allowing to test the different planetary models of atmospheres, of internal structure, and of evolution, of objects at the bottom of the main sequence and beyond.

**(2) The HAT-South Planet Search Programme at Las Campanas Observatory**. This is a global network of small, custom made telescopes that were installed during 2009 in Australia (Siding Springs), Namibia (HESS site) and Chile (Las Campanas), and that is providing 24-hr monitoring of selected fields to discover transiting exoplanets more efficiently than ever before. Euler/CORALIE and duPont/Echelle runs to confirm transiting exoplanet candidates from HATnet.

**(3) The Magellan Planet Search Programme at Las Campanas Observatory**. This radial velocity search for planets made a dozen new discoveries. Center members are now finishing up a study of the HK chromospheric activity of a large sample of stars and improving the precision of M-dwarf radial velocity observations, which resulted in the discovery of the super-Earth in the habitable zone of GJ667c

**(4) The Calan-Hertfordshire Extrasolar Planet Search (CHEPS) survey with HARPS and CORALIE.** Even though the project is still very much in its infancy, discoveries and orbits have been published for three exoplanets and a brown dwarf, or extreme Jupiter-like

planet. The target selection was done using FEROS, with two publications of chromospheric activities, kinematics, rotational velocities, and metallicities for a sample of over 950 nearby, Sun-like stars.

Another initiative involves perfecting new techniques to measure exoplanetary atmospheres and proto-planetary disks. A first attempt involves using high-resolution IR spectrographs, available to the Chilean community, to attempt detecting the Doppler wobble of the exo-atmospheric molecular lines. These studies will be complemented with ALMA, to ultimately gain new knowledge of planetary "weather", the structure of atmospheric wind and the variations in chemical constituents. Studies of proto-planetary disks will also be carried out using the recently available IR facilities. ALMA observations will provide definite answers regarding their formation and evolution.

Among other on-going research projects in this Area are:

**1)** Planet search around bright giant stars in the southern hemisphere using the FEROS and FECH spectrographs;
**2)** Search for proto-BDs in Barnard 30. A few candidates have been already detected with APEX and are now being observed with ALMA
**3)** Search for cool Brown Dwarfs (UCDs) using VVV. Center members developed a set of automatic procedures for identification, reduced proper motion and photometric classification of the UCD population using VVV catalogs. As a result a candidate list from late-M to T-Y spectral types was built. A massive campaign for spectral follow up on VLT, Magellan, SOAR and du Pont telescopes is in course;
**4)** Spectral synthesis analysis of main sequence and subgiant stars using FEROS optical spectroscopy. Center members are applying a new method for abundance analysis of Sun-like stars to a large sample of stars to analyse them for future planet search and also for analysis of abundance trends in the galaxy;
**5)** Search for benchmark brown dwarf with white dwarfs or subgiant binary companions. As part of this effort, Center members discovered the first white dwarf - T-dwarf binary system.

## AREA 6. Supernovae and Dark Energy.

**PI: Mario Hamuy** (first 4 years, now is A. Clocchiatti)

The long-term goals of Area 6 are twofold: (1) The determination of extragalactic distances using supernovae, and (2) the understanding of the physics of supernovae and of dark energy. Faculty members doing research in this Area include: Clocchiatti, Hamuy, Gieren, Maza, and Pignata (postdoc). The activities performed during the reported period along these two lines are summarized below.

Since the beginning of our activities on 2008, CATA members have carried out a complete study of nearby supernovae (SN) in order to understand the origin of the dark energy of the Universe and its properties. With this in mind, the SN group carried out (1) a nearby supernovae search ($z<0.03$) in the southern hemisphere with four of the six robotic PROMPT telescopes in Cerro Tololo. (2) a follow-up program, in close collaboration with

the *Carnegie Supernova Project*, to establish a database with hundreds of nearby supernovae ($z<0.07$) of both thermonuclear and gravitational core collapse nature in optical and infrared (IR) wavelengths.

The first step along this research line consists in discovering supernovae. With this purpose Center members are carrying out a systematic search of several hundred galaxies using four of the six PROMPT robotic telescopes at Cerro Tololo. This project, which involves the participation of several undergraduate students, has secured more than 1120 hours of observation each year. Every night, several hundred galaxies are observed, the images are downloaded to our computers in Santiago, and an automatic search pipeline is triggered. During 2008-2012 the search project, dubbed CHASE, discovered 150 nearby supernovae. The supernovae discovered by CHASE are all nearby and generally young supernovae ($cz < 25000$ km $s^{-1}$).

The second step in this research line is obtaining photometric and spectrometric follow-up data for the discovered supernovae by CHASE (and additional equatorial or southern supernovae found at other observatories). This project was done in collaboration with the Carnegie Supernova Program that used 280 nights every year, between 2004-2009, in the 1 and 2.5m telescopes in the Las Campanas Observatory, in the north of Chile, to study supernovae with redshifts less than 0.07. The collaboration with CSP observed a total of 129 Type Ia supernovae, in the ugriYJHK filters and with optical spectrographs. So far, Center members have analyzed the first batch of 35 supernovae.

CATA members also performed a study on distance determinations using the Standardized Candle Method for Type II plateau supernovae, using a sample of 37 objects with BVRI photometry and optical spectroscopy obtained by them between 1986 and 2003. Using these data they implemented a procedure to fit analytic functions to the light curves, color and expansion velocity curves. Then they demonstrated that the V-I color toward the end of the plateau phase can be used as a good indicator of host-galaxy dust reddening and we recovered the luminosity-velocity relation previously published in the literature.

## AREA 7. Theoretical Astrophysics

### PI: Nelson Padilla

Center members working in this new Area are Cuadra, Escala, Fellhauer and Padilla. Simulations of structure and galaxy formation allow Center members to become competitive in the field. Highlights of this specific area include: a first, physically based, definition of a galaxy supercluster; simulations which show that dark matter merges and that gas accretion into dark matter haloes generate turbulent and supersonic environments, where cooling molecules trigger primordial star formation; simulations of the universe at several different scales, from the large-scale structure, to the physics of galaxy formation, to the dynamics of star forming regions, to the inner pc scales of central supermassive black-holes, both via semi-analytic models and full hydrodynamic simulations.

## II EDUCATION AND TRAINING

CATA has played a fundamental role in educating and training the new generations of young astronomers. These are the ones that will take full advantage of the unique opportunities available in Chile to carry out world-class research. The number of graduate students at the three Associated Institutions has steadily increased during the last years, reaching a value of 83 students in 2013. One of the key ingredients in this accomplishment is support provided by CATA to graduate students, awarding full fellowships and stipends to participate in observing runs and attend congresses and workshops. In particular, the Key projects have broadened the range of thesis topics available to students today, allowing them to engage in first-class frontier research, with a positive impact on the graduate programs. During the five years of operation thirty one (31) students obtained Ph.D. degrees and forty two (42) students obtained Master degrees.

CATA has invited world experts on different astrophysical topics. The contribution of the visiting scientists has been positive, supplying the expertise needed for an expansion and broadening of the areas of research cultivated at the Center, and providing the theoretical support needed in the young Ph.D. programs. Several of them have given concentrated courses, during periods of 6 to 8 weeks.

CATA also contributed to a substantial increase in the number of **postdoctoral fellows** at their associated Institutions, providing either full fellowships or resources for their travels and operations. Post-doctoral associates turn out to be key elements in establishing strong scientific collaborations among Center members.

The Center provided the funds and visibility necessary to attract young scientists from all over the world. Most of the postdoctoral positions were selected through international competitions, and we hired postdoctoral fellows from Argentina, Australia, Brazil, Bulgaria, Germany, Italy, Mexico, Poland, United Kingdom and USA. With the presence of these postdocs the CATA has gathered a real international team working at Chilean institutions. Postdoctoral fellows have been central to the success of the Key projects of the Center, which required lots of manpower in the experimental and analytical work.

## III TECHNOLOGY

CATA is playing a key role in the development of high technology in Chile, supporting a number of initiatives of its members at the different Associated Institutions concerning technological innovation. The initiatives in astronomical instrumentation, high performance astronomical computing and robotics are developing at the expected pace and made significant progress towards reaching the main original objectives. All these projects are involving professors of electrical engineering and engineering students from the associated institutions. After five years of operations we see CATA as an important seed for the development of astronomical engineering in the country.

After CATA was funded by CONICYT, all three Universities associated to the Center decided to invest considerable amounts of resources in infrastructure in order to allow the development of instrumentation in astronomy in Chile, one of the goals of CATA.

**ALMA band 1 prototype receiver construction.**

**P.I.: Leonardo Bronfman**

**Millimeter Wavelength Laboratory.**

In 2008, with CATA support, Universidad de Chile built a millimeter wavelength (mm-wave) laboratory at Cerro Calán Observatory, led by Professor Leonardo Bronfman, where Center members carry out the development of receiver technology. The need for a mm-wave laboratory arises from the installation of the world's largest sub-mm-wave telescope in Chile, the ALMA telescope, which presents a tremendous opportunity for the education and training of qualified personnel to support the development of engineering and of astronomical instrumentation in the country. The mm-wave laboratory is serving as a hands-on training for Chilean engineers and graduate students specializing in astronomical instrumentation. This laboratory is carrying out state-of-the-art projects in astronomical instrumentation, focusing on receiver development, in collaboration with recognized institutes (e.g. California Institute of Technology, ESO, University of Cologne, Harvard-Smithsonian Center for Astrophysics, Chalmers University of Technology). The goal is to boost the local development of the technological ability to design and construct receivers.

**Receiver design and construction.**

The foundational project of CATA in Astronomical Instrumentation is to develop an ALMA Band 1 receiver prototype and study the feasibility of producing 66 operational receivers for the ALMA project, the largest array telescope in the world, consisting of 66 antennas, each housing 10 low-noise receivers in different bands between 31 and 950 GHz. A prototype Band 1 receiver, covering the 31.3 - 45 GHz range, was developed, during these five years of CATA, at the Millimeter-Wave Laboratory of the Astronomy Department, in collaboration with the Electrical Engineering Department, both at the Universidad de Chile.

In 2008 Dr. Patricio Mena, formerly at SRON, was hired by the Electrical Engineering Department as Assistant Professor, and became involved in the project. Two major pieces of equipment were purchased to set up the Millimeter-wave Laboratory at the National Astronomical Observatory in Cerro Calán; a high sensitivity Vector Network Analyzer and a high-precision Computer Numerically Controlled (CNC) Drilling and Milling Machine. A preliminary design of the receiver was produced, and electromagnetic modeling of several parts was carried out. A mechanical technician, José Pizarro, was hired and trained. A preliminary physical layout of the receiver was completed in 2009 and the key components specified. Construction of key optic components was carried out in the laboratory machine-shop, including the receiver feed horn and the Ortho Mode Transducer (OMT). A beam scanner for measuring the horn pattern was built and implemented. A first Low Noise Amplifier (LNA), based on commercial GaAs chips was designed, built, and tested at the laboratory.

Cryogenic capabilities were set up in 2010. A NAOJ Cryostat (for ALMA cartridges testing) was set to work, and a CBI Cryostat was modified for component testing. The horn was successfully characterized using our beam scanner; the OMT design was improved; a series of LNAs based on MMIC was produced improving our knowledge of the fabrication process. The optical design was completed and an analysis of the different alternatives was

done in collaboration with HIA. For the design of the complete receiver, the internal dimensions of the main components were defined, allowing a detailed design of the receiver.

At present we are taking the necessary steps to be ready when ALMA requests the construction of about 70 Band 1 receivers, this will be accomplished in collaboration with laboratories and companies from Canada, USA and Taiwan and Chile.

**Spin offs:**

**1.- ALMA Band 5 pre-production and full production study.**
The mm-wave laboratory is involved in the assembly, integration, and verification of 6 receivers for the Band 5 of ALMA (186-211 GHz), through a collaboration with an UE-FP6 program that includes ESO, GARD (Sweden) and RAL (UK). While our original participation focused on the training of Chilean engineers, the development of laboratory facilities allowed us to design and build the Beam Scanner Test source (BeaSTS) to measure the receiver beam pattern. A high precision waveguide probe was machined at home, the highest frequency emitter ever built in a Chilean laboratory. Presently we participate of a full production study, having constructed in 2011 the Mixer Block and OMT prototypes.

**2.- Side-band separating mixer for ALMA Band 9**
Center members are collaborating with the Netherlands Institute for Space Research (SRON) in the implementation of a new sideband-separating receiver for ALMA Band 9 (600-720 GHz). We participated in the design and successfully fabricated, until 2011, three units of the split block that contains the RF waveguide circuitry of the receiver. The resulting receiver has been tested at SRON, giving sideband rejection ratio and noise temperature compatible with ALMA specifications.

## High performance computing

**P.I.: Alejandro Clocchiatti** (since last year PI is Padilla)

The Computing Lab (CL) of the Center for Astro-Engineering (AIUC) at Pontificia Universidad Catolica de Chile (PUC) started was motivated in part by the projects of wide angle survey telescopes that are going to be installed in Chile, with the promise of delivering very massive amounts of data, and also by the need of theoretical astrophysicists who require massive computational power to model a given survey, or the evolution of astrophysical objects. The concept started to become a reality with the approval CATA in December 2007, which invested 30% of its initial funds for large capital investment in the computer for the CL (computer name Geryon).

Putting Geryon to work involved several steps which involved identifying the appropriate machine, to buy it, to construct a computer room, install the machine, test operating and qeue systems, install the software suites, and to try and test-bench the computer. The first applications envisioned were both observational and theoretical, and the new computer immediately allowed us to enter scientific grade development and number

crunching locally, experiment with queues and, finally, open the system to the whole community.

Putting the CL to work required, in addition to the computer, a focus on hiring Computer Scientists with interest in Astronomical applications and establishing the necessary collaborations.

As a result, the CL has already acted as a consultant for the computing industry in Chile. The experience developed by the engineers and technicians that set up Geryon has been required by other public and private institutions that were following our steps. Therefore, in addition to providing a unique computing service to the astronomical community, the CL has contributed to capacity building within the Chilean academia and industry.

The computer equipment consisted of 96 CPUs, each 4 cores, each core with 1GB of RAM, for a total of 384 GB of RAM, 13 TB of iSCSI disk, three 10 KVA UPSs, Gigabit Ethernet equipment and a 19" rack, which was received in March 2009, and was installed by April 2009. At the time, it was the most powerful machine for exclusive astrophysical use in Latin-America.

Geryon was fully installed in its definite place by April 2010. The event was celebrated with a workshop "Supercomputer Techniques in Astrophysics," which brought many specialists from around the world to our campus. During the following months several small grants from different researchers were joined to achieve the expansion of the memory to the necessary 1TB of RAM for a total of 2Gb per core. The computer power of the system was 2 TFLOPS.

The second semester of 2010 the system was available to the whole Chilean astronomical community. A protocol was established to access the resource. The system has been continuously upgraded with the contribution of individual and collective grants.

This High performance computer center (CL) is part of the Astroengineering Center at PUC (Director is P. Infante) where a very successful project (also supported by CATA) aimed at designing and building optical and infrared instrumentation as well as providing service to instruments at several of the international observatories operating in the country. Several new instruments have been delivered and agreements for servicing and upgrading optical/IR instrumentation are in place.

## IV OUTREACH

### PI: José Maza

CATA is convinced that a strong link with society is invaluable, and thus is carrying out a vigorous policy of outreach and general education, supporting and funding important activities directed to the general public, high-school students and their teachers. To enhance the interest and culture in astronomy in the community several actions have taken at the three associated Institutions. A Visitor Center was built at the Universidad de Concepción, while at Universidad de Chile the Center funded the purchase of three portable telescopes for *Project Carina,* a project designed to educate high school students of public schools in the neighborhoods of Santiago. Most Center members were involved in outreach activities at different levels. Press Releases and media dissemination of scientific results from Center members were frequently made.

Among the highlights in Outreach we can mention the publication of a series of astronomy book directed at the general public but with emphasis on high-school students, written and edited in full by CATA members. The first four volumes are: "Hijos de las estrellas" by María Teresa Ruiz (in third edition); "Mundos lejanos" (two editions), by Dante Minniti; "Con ojos de gigantes" (two editions) by Felipe Barrientos and Sebastián López; and "Supernovas" by Mario Hamuy and José Maza (two editions). Other books of outreach supported by CATA are "Estrellas Variables" by Ronald Mennickent and "El Universo: Ciencia y Ficción" (second edition) written by Maria Teresa Ruiz. The publication of several astronomy books by members of CATA (some for children) has proven to be very successful and very well taken by the educational authorities of the country who have selected "El Universo: Ciencia …." in school libraries. One of the CATA members (MT Ruiz) has won this year a "Fondo Nacional del Libro" to publish an Astronomical Anthology (Ed. Catalonia), for general public and high school students.

Regarding outreach, the Center has had a considerable impact at a national level, with multiple participations in the written press, television and radio (more than one thousand) in addition to conferences for a diversity of audiences from school children to general public, political authorities and professional busyness people. The web page of CATA (www.CATA.cl) has sustained a steady increase of visits, which today amount to about 1800 per month.

Finally, CATA is supporting the training of high school science teachers. So far, more than one hundred science teachers coming from all over the country have been trained in astronomy for a week at Cerro Calán Observatory where they received lectures, practical sessions, observing sessions and a large quantity of material including a special booklet prepared and printed for them.