EMU (Multi-User Equipment) Project:

PAU - BRASIL
acquisition of CCD detectors for the wide field camera of the PAU (Physics of the Accelerating Universe) survey

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Abstract
Dark energy, or the source of the recent acceleration of the expansion of the Universe, is presently Cosmology's deepest mystery. A key observation to help determining the nature of dark energy is the detection of baryon acoustic oscillations (BAOs), which are ripples in the distribution of baryonic matter (atoms) that were imprinted on them at the time of recombination, when the cosmic microwave background (CMB) was formed and the Universe was only about 400 thousand years old. We will map positions and redshifts for tens of millions of galaxies over an unprecedented volume of the observable Universe to detect BAO imprints and to provide the deepest glimpse into the nature of dark energy by the time our survey (Physics of the Accelerating Universe – PAU) is finished (2016).

To achieve this goal we will build a wide field camera for the 2.5m JAO (Javalambre Astrophysical Observatory) telescope, which is being built in Teruel, Spain, and will be fully dedicated to the PAU survey until its completion.

The PAU camera, with its field-of-view (FoV) of 6 sq. deg., is a crucial element in this strategy. The camera, which will be the sole instrument at the JAO 2.5 m telescope for at least seven years, will image the sky with many (up to 50) narrow filters in the visible part of the spectrum (between 3500 Å and 9700 Å). The core of the camera consists of 14 CCDs of 10.5k × 10.5k pixels each, which we plan to purchase through this EMU project. The camera will be designed and built by a team of scientists and engineers from many Brazilian institutions, coordinated by Observatório Nacional (ON), at Rio de Janeiro.

The JAO facility, which is fully funded by our Spanish collaborators (cost: 17 million euros), will be 100% dedicated to the PAU project during the period of the survey (4-5 years). The PAU survey will map an area of 8000 sq. deg. up to $i_{AB} \simeq 25$, which means that, besides the positions and spectrophotometric redshifts for tens of millions of galaxies ($z \lesssim 0.9$ for red luminous galaxies) to an accuracy better than $\Delta z/(1+z) \leq 0.0035$, it will have an immense impact on several other areas of astronomy. The survey's rich legacy archive will allow investigations of extra-galactic astronomy (e.g., stellar populations), of the Galaxy (e.g., halo populations, satellite debris), and even of solar system objects (e.g., asteroids).

After the initial 4-5 year period, the instrument will be open to new surveys, to be decided jointly by the Brazilian and Spanish communities. The instrument will be operated, during the seven years after commissioning (estimated to begin early 2012), in collaborative mode by the Brazilian consortium and the *Centro de Estudios de Física del Cosmos de Aragón*, which is fully responsible for building the JAO facility and for funding its operation.

The funds we are seeking from FAPESP totalize 1.68 million euros (or 4.3 million reais) and will be used to purchase the 14 CCD detectors required for the camera.

1 Description of the EMU and its impact

With this proposal we plan to partially fund the wide field camera which will be mounted on the 2.5 m telescope of the Javalambre Astrophysical Observatory (JAO), in Teruel, Spain. This observatory will be responsible for the *Physics of the Accelerating Universe* (PAU) survey, whose main objective is to measure baryon acoustic oscillations (BAOs) to unprecedent accuracy by the time of its completion (2016-2017). We expect to measure positions and redshifts for over 14 million red, luminous ($L > L^*$) galaxies with $i_{AB} \lesssim 22.5$ (and in the redshift interval $0. < z < 0.9$) in 8000 sq. deg. in the sky during four years. The survey will deliver an accuracy of the order of 5% in the dark energy equation of state parameter w, if assumed constant, and can determine its time derivative when combined with CMB measurements (see Benitez et al., arXiv:0807.0535, for a more complete description of the survey).

The camera will be built in Brazil by a team of scientists and engineers from several institutions from São Paulo and other states, coordinated by Observatório Nacional, in Rio de Janeiro: the PAU-Brasil consortium. JAO (commissioning estimated by December 2011) is managed by the *Centro de Estudios de Física del Cosmos de Aragón*, which is also responsible for operating the facility. It will contain two robotic telescopes: one with a diameter of 2.5 m (T250) and an auxiliary, with diameter of 0.8 m (T80). Both telescopes are designed to have flat focal planes, homogeneous throughput and good optical quality, as well as a very wide FoV: diameters of 3 deg. for T250 and 1.7 deg. for T80. The cost of the telescopes, domes and other necessary infrastructure is approximately 17 million euros, which are already fully funded by the Spanish side of the collaboration. The Brazilian side is responsible for the main detector: the PAU camera, to be installed in T250. T80 will be equipped with a small camera and will be used for calibration and testing of data reduction and analysis pipelines.

The heart of the PAU camera will be a mosaic of 14 10.5 k $\times$ 10.5k pixels CCDs (enough to cover the 6 sq. deg. FoV with a scale of 22.67 arcsec/mm and 9 μm/pixel). The camera, which integrates the array of CCDs, electronics for data acquisition and control, cryogenic cooling, interface, filter trays and mechanical parts (no fore-optics is necessary because of the flat focal plane), will be designed and assembled by a team of scientists and engineers from several Brazilian institutions.

We anticipate at least three major impacts from this proposal. The first is scientific. The PAU survey should allow us, to great accuracy, discover whether the dark energy is consistent or not with a cosmological constant. It is worth mentioning that this survey will be competitive to address the problem of dark energy not only through BAOs but also through cluster counts (see, e.g., the U.S. Dark Energy Task Force white paper, Albrecht et al. 2006, astro-ph/0609591). The legacy of this survey, low resolution spectra ($R \gtrsim 50$) for million of stars and galaxies, will also be useful for many other astrophysical studies like integrated stellar populations in galaxies, stellar populations in our galaxy halo, tidal debris of Milky Way satellites, asteroids, etc, to mention a few. The second impact we foresee is academic: the preparation of the survey and the analysis of its deliverables should be useful for the work of several MSc and PhD students. Finally, the opportunity to build this camera will strength the emerging vocation of IAG, LNA and other Brazilian institutions in the competitive field of high performance astronomical instrumentation.

Finally, we are confident that our participation in the PAU survey will greatly enhance the impact and the visibility of the science produced in São Paulo.

2 Description of the Associated Projects

1. **Galaxy Populations in the Universe**
   (2006/00490-4)

   Principal Investigators:

   (a) Prof. Laerte Sodré Jr. (**coordinator**) – Departamento de Astronomia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo.

   Description of the Project:
   We have been applying techniques of empirical population synthesis to the analysis of galaxy spectra produced by the Sloan Digital Sky Survey (e.g., Cid Fernandes et al., MNRAS, 358, 363, 2005). Such an approach allows to constrain the integral properties of the stellar populations in the galaxies and has proved to be a powerful tool to investigate how galaxies evolve and how the environment affects their evolution. As part of this project, a virtual observatoty is being developed at São Paulo (www.urania.iag.usp.br) aiming to publish the data products of our studies (as well as from other researchers at IAG). We have also been investigating properties of large scale structures, like galaxy clusters. These projects led to the publication of more than 20 papers in first rank astronomical publications since 2005, as well as to 2 and 4 PhD and MSc thesis, respectively, at IAG.

2. **New Physics from Space: formation and evolution of structures in the Universe**
   (2006/562139)

   Principal Investigators:

   (a) Prof. Reuven Opher (**coordinator**) – Departamento de Astronomia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo.
   (b) Dr. Thyrso Villela Neto – Department of Astrophysics, National Institute for Space Research (INPE), and Brazilian Space Agency (AEB)
   (c) Prof. Claudia M. de Oliveira – Departamento de Astronomia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo.
   (d) Prof. Jacques R. D. Lepine – Departamento de Astronomia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo.

   Description of the Project:
   The Big-Bang model is our fundamental framework to understand how the universe evolved from a high level of uniformity to the structures- like galaxies and clusters of galaxies- that we observe today. The main objective of this project is to investigate, through an observational and theoretical approach, several problems related to the structure formation in the universe, clarifying the mechanisms and physical process responsible for the formation of the observed structures. This is being addressed by theoretical studies, numerical simulations, analysis of CMB observations, and observations of galaxies and clusters in the optical and X-ray wavelengths.

3. **Cosmology in the Precision Era – CMB, dark energy and dark matter**
   (2004/13668-0)

   Principal Investigators:

(a) Prof. J. Ademir S. de Lima (**coordinator**) – Departamento de Astronomia, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidadede São Paulo.
(b) Prof. L. Raul Abramo – Departmento de Física Matemática, Instituto de Física, Universidade de São Paulo.
(c) Prof. Rogerio Rosenfeld – Instituto de Física Teórica, Universidade Estadual Paulista.

Description of the Project:
This project (1996-2010) aggregates many aspects of theoretical astrophysics and cosmology, their interface with fundamental physics, as well as phenomenological studies such as constraints on cosmological models and parameters. Some of the subjects that have been studied include the physics of CMB temperature and polarization, galaxy clusters (X-ray observations, cluster counts in future Sunyaev-Zel'dovich and weak lensing surveys), structure formation in dark energy scenarios, type-Ia supernovas, old galaxies at high redshift, and the very early universe (inflation and preheating.) In 2009 alone the PIs of this project have produced more than 10 papers in journals such as the Astrophysical Journal, Physical Review and JCAP. The PIs have also advised more than 15 graduate students since the beginning of the Project, and some of them have been already hired for permanent positions at research universities.

4. **Title: Gravitation and Cosmology: Perturbations, Phenomenology and Exact Results (2006/07148-0)**

Principal Investigators:

(a) Prof. Elcio Abdalla (**coordinator**) – Departmento de Física Matemática, Instituto de Física, Universidade de São Paulo
(b) Prof. Antonio Lima Santos – Departmento de Física, Universidade Federal de São Carlos

Description of the Project:
This project focus on some theoretical challenges to observational cosmology. The biggest one is the comprehension of Dark Matter and Dark Energy in terms of field theory. This project tries to regard dark matter and dark energy in terms of field-theoretical arguments, and consider elements of particle physics such as the interaction of Dark Matter and Dark Energy – which could also explain some problems (such as the age of the Universe), which have not completely satisfactory explanations in the standard cosmological model. Researchers associated with this project published more than 28 papers since 2006, as well as six PhD and three MSc thesis. In fact, this project is the continuation of a long-term scientific effort that already produced 73 scientific papers, and 6 PhD and 16 MSc thesis.

3 Description of the Impact expected on Associated Projects

The themes that permeates the research projects which support this EMU proposal are extragalactic astrophysics and cosmology. The PAU project constitutes a unique opportunity for the Brazilian community to be at the core of an international effort to build, operate and fully explore a state-of-the-art instrument with potential for high scientific impact. By the time the first survey (PAU) is finished, it will be the best dataset to study BAOs. It will not only provide the strongest constraints in what is one of the four main strategies to study the nature of dark energy (Albrecht *et al.* 2006, arXiv:astro-ph/0609591), but it will also be competitive in at least another one of these strategies: cluster counts.

As we will show below, there are multiple applications of the resulting dataset, including not only cosmology, but also areas as diverse as stellar populations in our galaxy, asteroids and meteorites, variable objects and supernovas, among others. This variety of possible applications can be explained by the three dimensions of a spectrophotometric survey: the imaging dimension, the wavelength dimension, and the timescale dimension. Each region of the sky will be imaged approximately 40 different times, in each of the ~ 40 different filters spanning the range 3500-9700 Å. These overlaying maps will generate an immense "datacube" from which astronomers can take different slices, depending on their interests. This is what characterizes the PAU survey as a "multi-layer, multi-user" dataset. Furthermore, after the initial survey is finished, the camera can be employed for at least 2 years for other purposes, such as a detailed map of the structure of our galaxy and its stellar populations.

3.1 Cosmology with PAU

The main application of the PAU survey will be to measure with exquisite accuracy the baryon acoustic oscillatons (BAOs) that were imprinted on baryonic matter during the era of recombination ($z \sim 1100$, when the Universe was less than 400.000 years old.) During that epoch, coupled acoustic oscillations between baryons and photons imprinted ripples on the distribution of baryonic matter, which have survived up to the present time. These ripples, or waves, have a characteristic length scale, proportional to the sound horizon at the time of recombination (146.8 ± 1.8 Mpc – see, for instance, D. Eisenstein and W. Hu 1998, Astroph. J. 496: 605.) The potential to constrain theories of dark energy and dark matter lies in this "standard ruler", which is essentially model-independent and, therefore, provides extremely robust constraints on dark energy (C. Blake and K. Glazebrook 2003, Astroph. J. 594: 665; J. Seo and D. Eisenstein 2003, Astroph. J. 598: 720.)

Recently, the immense potential of BAOs started to be tapped with both spectroscopic (D. Eisenstein *et al.* 2005, Astroph. J. ; W. Percival *et al.* 2007) as well as photometric (N. Padmanabhan *et al.* 2007; C. Blake *et al.* 2007) surveys. However, the incompleteness and shallowness of the existing spectroscopic surveys, and the poor redshift binning allowed by photometric surveys (which effectively reduce the detection of BAOs to the transverse direction to the lines-of-sight), are difficult challenges for these observing strategies, with the result that the full potential of BAOs to constrain cosmology has not yet been fully realized.

The spectrophotometric survey PAU is ideal to fill this gap (N. Benítez *et al.*, arXiv: 0807.0535.) The imaging of the same regions of the sky in ~ 40 filters equally distributed between 3500 Å and 9700 Å will result in an excellent spatial resolution along the line-of-sight [$\Delta z \lesssim 0.0035(1+z)$ for luminous red galaxies - LRGs]. The dedicated 2.5m telescope, on the other hand, will allow us to reach up to $z \sim 1$ over an area of 8.000 $\deg^2$. These very large volumes are needed to reach the accuracy desired in the parameters that characterize dark energy, since only a large number of galaxies can reduce the shot noise below the irreducible component due to volume sampling variance. Spectrophotometric surveys are therefore a compromise between redshift accuracy (better with spectroscopic surveys) and large volumes (easier with photometric surveys) that optimizes the sensitivity of BAOs to the parameters of dark energy, with the added bonus that the generated dataset can have multiple other applications. We forecast a maximal redshift error for LRGs of $\sim 0.003(1+z)$ and a total volume of approximately 10 $(\mathrm{Gpc/h})^3$ in order to obtain significant improvements upon the present constraints. This can be achieved with the 2.5m telescope and a 6 $\deg^2$ FoV camera, observing 8.000 $\deg^2$ of the sky over 4-5 years.

However, not only BAOs will emerge as a cosmological application of this survey: the mass power spectrum and the two-point galaxy correlation function; galaxy cluster counts; Integrated Sachs-Wolfe effect of the CMB and large-scale structure cross-correlation; and the discovery of type Ia supernovas, are possible applications of the PAU survey's datacube. It is our aim to explore these data products to their full extent, maximising the impact of this investment.

3.2 Astrophysics with PAU

As a wide FoV survey in many wavelengths and at many different times, the resulting dataset can be explored in several different ways, depending on the objects under study. The cadence of the survey has not been decided yet (for the purposes of BAOs this is largely irrelevant), which means that the observation strategy in the time domain can be optimized for the discovery of variable objects. Since we expect around 180 observation nights per year, and each FoV (6 $\deg^2$) will be visited ~ 40 times, the average cadence would be around 60 days for each field. However, the sky can be sampled more frequently in smaller areas in order to diminish this interval. Depending on the application (supernovas, variable stars, meteorites and asteroids etc.) and the location (near or far from the galactic disk, inside or outside the ecliptic plane), this cadence can be tuned to suit the discovery of the desired objects.

This opens the possibility of employing the PAU survey for many other purposes, such as: a detailed spectrophotometric map of the galaxy and its environment, such as satellite galaxies; a survey of stellar populations in the galaxy; the discovery of meteorites and asteroids; and the discovery of type Ia supernovas, possibly without the need of spectroscopic follow-up.

3.3 Impact of the instrument

The results of this survey will touch upon science issues which are central to all Associated Projects listed above. The large impact of these observations will benefit not only these projects, but the Brazilian community at large.

Notice that Brazilian scientists have never before participated in the planning, construction and operation of a wide FoV survey instrument. In the past participation has been on a limited basis (e.g., some software), which has damped initiatives in extragalactic astrophysics and cosmology. We believe that this new instrument will mean a leap forward not only in these areas, but in many others for which wide FoV instruments and/or resolution in the time domain are useful tools.

As regards the advancements in astronomical instrumentation, this is indeed a golden opportunity for the Brazilian community to participate actively and directly in a "big science" international project, managing the construction of the main instrument, helping design the observational strategy, the internal organization of the collaboration, receiving the data directly and on-the-fly. This experience will be extremely helpful in searching for future similar opportunities of the brazillian astronomical community (e.g. for the LSST).

4 Management of the EMU

The JAO facility (including the camera) will be operated for at least seven years under a structure which shares the administrative and scientific decisions between the Spanish side and the Brazilian side of the collaboration. The CEFCA will take full responsibility for funding the non-scientific staff and technical support to ensure JAO operations with minimal down time.

The PAU survey will be managed by a council composed by the PIs of the Science Working Groups (SWGs) and of the Instrument Working Group (IWG) plus two general coordinator (GCs) and an operation coordinator (OC). The GCs will be Narciso Benítez (Granada) for the Spanish side, and Renato Dupke (ON), for the Brazilian side. The OC will be Mariano Moles, as the JAO director. The GCs will supervise the overall structure and suggest procedures for solving problems, keeping a close link with the OC.

The decisions will be taken in flat power structures except when deadlines are imminent and executive decisions are acceptable, or when there is no consensus for an unacceptably long time. Internal small meetings (even through teleconferences), which should take place frequently, will be useful to clarify most points and build consensus in a direct and fast way. We also plan periodic, presential meetings with panel discussions and review of the developments as a venue for decisions as well.

The number of SWGs will be defined over the next few months, as well as the compositions of the SWGs and IWG. We propose a flat power structure inside the SWGs, with each one having a PI in charge of reporting periodically the development of the group to the GCs and OC for the purpose of evaluation of the time frame and the resources needed to carry out the project.

Regarding the data policy we propose that the release of the data would be done in steps (the actual periods can still change): one year for the SWG + IWG and close collaborators; 6 to 9 months extra for the astronomical communities that took part in the project (Brazil and Spain/Europe). From then on the access to the data will be free.

The general idea for the publication policy is that all the SWGs (assuming that people actually collaborated enough during the pre-observation phase) would go in all the first survey papers. People (collaborators) that did significant work would be authors too, and the authorship would be by merit. The second round of papers would be only by merit and not necessarily involve all the SWGs. Again authorship order would go by merit. Students and post-docs can participate of the WGs as well as in the papers produced by the collaboration, if their contribution is judged satisfactory by the WG PI's and/or by their thesis advisors.

The PAU survey should take 4-5 yrs. At the 3rd or 4th year we will open an “Announcement of Opportunity” for both communities (it should be a broad call for ALL community) for new surveys to be implemented. A panel review will be formed to evaluate and select the new survey(s) to be conducted at JAO.

5 Infrastructure support

The operational infrastruture for the operation of the telescopes at JAO will be provided by the *Centro de Estudios de Física del Cosmos de Aragón* (CEFCA). The handling, data reduction process, archiving and accessing by the community will also be the responsibility of the Center.

The Brazilian institutions, in particular IAG and INPE in São Paulo and Observatório Nacional in Rio de Janeiro, will also ofer their infrastructures for the development and assembling of the PAU Camera.

6 Equipments already available

The PAU survey will benefit from the computational park already assembled by the institutions participating of the project. In the case of São Paulo we have also instalations appropriate for the integration and testing of the camera at IAG and INPE that have been used for the development of the BTFI instrument, which will be put in operation in the SOAR telescope.

7 Costs

The camera will consist of 14 large format (10.5k $\times$ 10.5k pixels) that will cover the focal plane of the T250 telescope. The Brazilian collaboration, involving several institutions around the country, will be responsible for the design and construction of the camera.

The design and general management of the camera construction will be responsability of Observatório Nacional, RJ. We plan to hire the services of Keth Taylor as instrument manager, following the sucessfull model adopted for the BTFI development. The funding counterpart of state of São Paulo will be the acquisition of the CCDs. We need 14 of them, at an individual cost of 120 thousand euros each, or 4.3 million reais for all detectors.

It is worth mentioning that, at this date, only one company, STA, is able to provide large-size back-thinned scientific detectors optimized for 350-970 nm as required by this project. That is why only one quote for detectors accompanies this proposal.