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A European vision for a "Polar Large Telescope" project

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Abstract. The Polar Large Telescope (PLT) project is primarily aimed at undertaking large, wide band synoptic astronomical surveys in the infrared in order to provide critical data to the forthcoming generation of observational facilities such as ALMA, JWST, LSST and the E–ELT, and to complement the observations obtained with them. Sensitive thermal IR surveys beyond 2.3 µm cannot be carried out from any existing ground based observatory and the Antarctic Plateau is the only place on the ground where it can be envisaged, thanks to its unique atmospheric and environmental properties, such as the turbulence profile (image quality), the low opacity and the reduced thermal background emission of the sky. These unique conditions enable high angular resolution wide field surveys in the near thermal infrared (2.3–5 µm). This spectral range is particularly well suited to tackling key astrophysical questions such as: i) investigating the nature of the distant universe, the first generation of stars and the latest stages of stellar evolution, ii) understanding transient phenomena such as gamma ray-bursts and Type Ia supernovae, iii) increasing our knowledge of extra-solar planets. Further instruments may broaden the expected science outcomes of such a 2 – 4 m class telescope especially for the characterization of galaxies at very large distance to provide new clues in the mysteries of dark matter and energy. Efforts will be made to merge this project with other comparable projects within an international consortium.

Keywords. telescopes, surveys

1. Introduction

Advances in understanding the Universe arise from improvements in our capacity to scrutinize the sky to greater depth, in previously unexplored wavebands, with better photometric and astrometric accuracy, or with improved spatial, spectral and time resolution. Thanks to the dramatic progress in computing science and technology and the rapidly increasing capacity of data archiving, future sky surveys will completely change our future perception of the Universe. The next-generation instruments, and the surveys carried out with them, will maintain this progress.

The pivotal astrophysical problems of the next decade, recently soundly discussed and synthesized in the prospect surveys carried out in Europe and the USA (Cosmic Vision, ASTRONET, US Decadal Survey, etc...) consist of the determination of the nature of dark energy and dark matter, the study of the evolution of galaxies and the structure of our Galaxy, the opening of the time domain to single out faint variable objects and transient events, the deep exploration of small bodies in the Solar System, and the identification of habitable extra-solar planets. All require wide-field frequently repeated deep imaging of the sky in a wide range of spectral bands. In the optical domain, the Large Synoptic Survey Telescope (LSST), a 6.5 m wide-field telescope equipped with a ~10 square degrees camera, will repeatedly survey the sky with deep short exposures.

Thanks to the recent industrial production of larger infrared arrays (up to 16 Mpixels) and to the assessment of exceptional sites in Antarctica, one can now seriously contemplate to carry out similar surveys in the infrared and particularly in a spectral range that has been little scrutinized systematically from the ground, so far. It spans between 2.3 and 5μm.

The Antarctic Plateau offers considerable advantages for astronomy (*see* recent review by Burton 2010), in particular to undertake infrared surveys beyond 2.3 μm. The atmosphere is very cold, thus, the thermal emission of the sky background is about 20 times less than in the best temperate sites in the K band, and because most of the atmospheric turbulence lies in the first few tens of metres above the ground, one can easily overcome its deleterious effect on the image quality (spread of the PSF) by installing the telescope on top of a tower above this turbulent layer and possibly by using ground layer adaptive optics techniques. An optimised combination of both would provide quasi permanently exquisitely resolved images, down to 0.3 arcsec, *i.e.* twice as a good as with the LSST itself! These outstanding prospects were debated during the last 5 years and particularly within the earlier ARENA EC network (Epchtein *et al.*, 2010) lead us to consider that time is ripe to propose within the European Union (EU) a conceptual design study for a so-called Polar Large Telescope aimed at achieving, for the first time, a deep synoptic sky survey in the thermal infrared.

2. Project context and concept

The framework of the EU is indeed ideal to carry out this design study because Europe is playing a leading role in astronomy in large scale astronomical sky surveys particularly in the infrared (e.g. IRAS, 2MASS, DENIS, VISTA, CFHT, *see* Price 2009) and because

Europe is also at the forefront of polar research. Two member states, France and Italy, have implemented and are successfully operating all year round a multi-disciplinary scientific station, Concordia, sited in the heart of Antarctica at Dome C. Other sites are currently operating or are under development on the Antarctic Plateau, namely, the Amundsen-Scott station at the South Pole, Dome A (Kunlun) and Dome F (Dome Fuji) exploited by scientists from the USA, China and Japan, respectively. All of them have or plan to develop an astronomical observatory benefiting from the Antarctic environment. These sites offer exceptional astronomical conditions demonstrated by the thorough monitoring studies of the critical atmospheric parameters carried out during the last 10 years mostly by the US, Australian, Italian and French teams (e.g. Philips *et al.*, 1999, Walden *et al.*, 2005, Travouillon *et al.*, 2009, Aristidi *et al.*, 2009, Gredel 2010). Although they share common obvious properties (cold, dry, low sky emissivity), they are not equivalent and before installing any sort of costly instrument, a thorough comparison of their properties, based on modelling and long period monitoring of the critical parameters in each site, is mandatory. It is also timely and urgent that the Europeans carefully evaluate the feasibility and their ability to study and build such a facility in the coming decade and possibly give to it a label of *Large European Research Infrastructure*.

The consortium that was set up in 2010 gathers the various and often distant skills and expertise required to successfully carry out a Design Study from astrophysics to atmospheric physics and polar engineering and logistics. The important work already done by the UNSW group during the PILOT phase A study would serve us as a basis for the PLT. But instead of proposing a multi-purpose telescope ranging from visible to FIR, the PLT would primarily focus on near–IR windows unaccessible from other mid-latitude sites. The PLT must be elaborated and advertised as a complementary tool to future large ground-based telescopes and space-borne observatories.

The key features and objectives of the PLT are: 1) to cover very large sky areas, repeatedly and thus explore systematically the time domain. PLT will do that for the first time in the infrared. 2) To improve the ultimate detection sensitivity at all wavelengths. This is the case of PLT at 2μm. 3) To explore in depth new spectral domains. PLT will explore systematically the 2.3–4μm range. 4) To improve the angular resolution using exquisitely good site and/or using adaptive optics techniques. PLT will provide the best images ($0.3''$) ever at 2 μm thanks to the unique turbulence properties of Antarctic sites and the use of an optimized adaptive optics system. 5) To increase the size of statistical samples of all sorts of astrophysical objects and phenomena. PLT will achieve this goal as a consequence of the previous items.

3. Scientific objectives

The overall objective of the PLT Project is to prepare the conceptual foundations for the first, world wide leading, near infrared research infrastructure in the Antarctic. With the PLT, European astronomical would be able to explore for the first time the time domain in the 2–5 μm spectral range at unprecedented sensitivity, angular and time resolutions, and will cover large selected areas of the sky totalising several thousands of square degrees. With its unique surveying capability, the PLT would be an enthralling tool for the entire European astronomical community to remain at the forefront of the new generation sky surveys in the E–ELT era.

The science cases have been already discussed at length (see e.g. in Zinnecker *et al.*, 2008) and precisely established to support a phase–A study of the former Australian project PILOT (Lawrence *et al.*, 2009abc), but a list of highest priorities matching the characteristics of the PLT is currently being scrutinized for the soon to come *PLT Science*

Book. The PLT Design Study will also investigate the most efficient and most promising strategy in terms of scientific impacts and observing time efficiency for the PLT. This will identify the optimal integration time of each visit of the selected targets field, the most suitable number of visits per elapse of time, the best bandpass of the filters, the number of colours in which each target area should be observed, etc.

At the present time four major astrophysical fields are identified that will take considerable benefit from the PLT, i) the investigation of the distant universe, ii) the stellar populations, formation and evolution in our Galaxy and in the Local Group, iii) the characterization of exo-planets, and iv) the identification and characterization of small bodies in the Solar System. These fields are in common with other instruments that will operate at the same period, and in particular the LSST, but the PLT will explore a different spectral range at an even smaller angular resolution. The PLT and the LSST data could be managed using similar procedures and both instrument teams could be able to alert each other during the overlapping period of operation for an optimal follow–up of transient events.

(*a*) **Distant Universe.** PLT will be the most powerful and sensitive wide field imaging collector in the near thermal infrared. It is thus particularly well suited to the exploration of the distant universe, notably wherever the dust extinction strongly hampers the optical observations, such as the disks and bulges of galaxies where the largest space density of stars – and thus of SN candidates – are found. Moreover, it will explore the time dimension during a period of 10 years at different time resolutions from minutes to years. A coordination with the LSST, space surveyors at all wavelengths (such as GAIA, EUCLID, etc.), and the E–ELT for even more resolved images and spectroscopy, all planned to operate during the decade 2020–30 will be extremely efficient. The most promising domains, already mentioned in the PILOT proposal encompass:

- A near-infrared search for pair-instability supernovae (via a dedicated periodically repeated wide field survey) and gamma-ray burst afterglows (via alerts from high energy satellite, LSST detections), events which represent the final evolutionary stages of the first stars to form in the Universe.
- A deep survey in the near-infrared to study galaxy structure, formation and evolution via the detection of a large sample of high redshift galaxies.
- A near-infrared search for Type Ia supernovae to obtain light curves that are largely unaffected by dust extinction and reddening, allowing tighter constraints to be placed on the expansion of the Universe; and a study of a sample of moderate-redshift galaxy clusters aimed at understanding galaxy cluster growth, structure and evolution.

(*b*) **Stellar formation and evolution, galactic ecology.**

- Thermal infrared imaging is ideally suited to probe the stellar content of our Galaxy and galaxies of the local groups, especially young stellar objects, stars in the late stage of evolution and very low mass stars. Repeated observations will provide hundred of thousands of light curves that will improve our knowledge of the mass loss process, enrichment of the interstellar medium in heavy element and the internal physical processes occurring in the AGB phase.
- An optical/near infrared survey of disk galaxies in the local group to study the processes of galaxy formation and evolution.
- An infrared survey of nearby satellite galaxies to trace their outer morphology, structure, age and metallicity.
- A deep repeated infrared survey of the Magellanic Clouds in order to understand the star formation, its history and the evolution processes in galaxies of different metallicities. The Magellanic Clouds will indeed receive special attention because

Table 1. *Main Site Characteristics*

	Location of the 3 main sites
Concordia	Dome C (alt.: 3,233m; lat.: 75S)
Kunlun	Dome A (alt.: 4,093m, lat : 80S)
Dome Fuji	Dome F (alt.: 3,810m, lat.: 77S)
	Operators
Concordia	IPEV (France); PNRA/ENEA (Italy)
Kunlun	Polar Research Institute of China
Dome Fuji	National Institute of Polar Research (Japan)
Median fraction of photometric time (Concordia)	$\sim$70%
Median value of free seeing (above turbulent layer, typically $\sim$30 m) (Concordia)	0.3″
Median precipitable water vapour content (Concordia)	$\sim$300 μm (tbc)
External extreme temperature range (°C)	Summer: -20 to -40; Winter -40 to -90
Operation temperature range (°C)	$\geqslant -85°$
Fraction of sky observable from Dome C	40% (at 60° from zenith) (16 000 deg^2)
Declination range permanently observable from Dome C	$-90° < \delta < -30°$ (10 000 deg^2)

Table 2. *Main Telescope Characteristics*

FOV (unvignetted field)	$\geqslant 1°$
Effective clear aperture	2.5 m
Configuration	Ritchey-Chrétien, 2 Nasmyth foci, Alt-az field rotator
Etendue	5 m^{2}deg^2
Primary mirror material	Zerodur or SiC (tbd)
Surface quality (rms)	$\lambda/8$ at 2 μm
Coating of M1 and M2	Al or Au (lowest emissivity at 3 μm)
Spectral range of operation	2–5 μm (possibly extended to 10–30 μm)
Sky coverage	Goal: 5 000 deg^2 (at least 20 times a year)
Final f ratio	f/5 (primary f/1.2)
Diameter of 80% encircled energy spot at 2.4μm (optics)	0.2″ (goal)
Absolute pointing accuracy	5″ (goal: 1″)
Slew time (any direction in sky)	< 3 minutes
Tracking accuracy	< 0.2″ per period of 10 seconds
Total emissivity of the telescope at 2.4 μm	<5%
Height of tower (above ground level)	<30 m
Expected life time	$\geqslant$ 10 yrs

they offer the opportunity to study in a relatively limited area a considerable number of stars of various metallicity. Moreover, they are continuously observable in optimal condition from Antarctica.

(*c*) **Exoplanet science, very low mass stars and brown dwarfs.**
- The search for free-floating planetary mass objects.
- the follow-up of gravitational microlensing candidate detections based on alerts from dedicated survey telescopes.
- the collection of high precision photometric infrared light curves for secondary transits of previously discovered exoplanets.

(*d*) **Small bodies of the Solar System.** The PLT, with its unique sensitivity and angular resolution in the thermal infrared, will be particularly efficient in the detection of nearby small bodies and will provide critical additional data to the LSST.

4. The largest optical/IR telescope in polar environment

The following elements reproduce part of the proposal for a PLT Design Study (PLT DS) that was submitted to the European Commission in late 2010 (Epchtein & the PLT consortium). Although unsuccessful (ranked 6$^{\rm th}$ in the final stage), it provides the basis and key elements that should be studied for the telescope, and upon completion,

Table 3. *Near Infrared Camera and system performances*

Array Type	HgCdTe HAWAII 4RG 4k×4k (Teledyne)
Pixel size	10 μm or 15 μm (tbd)
Scale	0.16/0.22″/pxl (tbd)
Field of View	$\geqslant 40' \times 40'$
Final PSF FWHM (with tip-tilt and/or GLAO)	0.3″ across full FOV
Array operating temperature	40 K (cryocooler)
Cold stop	Yes T<100 K
Filter slots number	3 (minimum) to 8 (goal)
Filter set	K_d, L_s , L' (+ possibly: K_s, M', narrow bands, Grisms)
Read out time	5 sec
Integration time per frame (typical)	20 to 100 sec
Focal plane configuration	16 buttable Hawaii RG4
Single visit depth (5 /100 s) mAB	goal: Kdark ∼22 / L short ∼18 [AB mag]
Coadded depth mAB after one year	goal: Kdark ∼25.5/ L short ∼21 [AB mag]

Table 4. *Observing strategy and Data Management*

Coverage per period of 24 h	500 deg^2
Number of visits/yr of selected targets	$\geqslant$20
Cumulative coverage/yr	100 000 deg^2 (i.e. $20° \times 5,000°$) (goal)
Raw pixel data per 24 h periods	0.5 TB to 1 TB
Yearly (200 days) archive amount	100 TB to 200 TB
Computational requirements	Necessary to process up to 1Tb per day locally (tbd) Necessary to archive, give access and process up to 1 Pb (remote centre) (tbd)
Bandwidth of communications Telescope to base	∼0.5 Gib/sec
Base to remote archive	Through high capacity physical media (hard disk, mag. tape)

would constitute the ground for future developments of large IR telescopes in Antarctica. The final PLT DS document can be retrieved from https://sites.google.com/site/pltantarctica/. The main characteristics of the PLT are summarized in Tables 1 through 4, and the sections below detail some of the listed features.

The PLT with its 2.5 m aperture, would be the largest optical/IR telescope ever studied operating in the extreme polar environment. Studies of the best technical solution to face the peculiar polar constraints (icing, wind, low ambient temperature and large short range temperature variations) will focus on:

- The telescope mechanical structure.
- The optical material (primary, secondary and tertiary).
- The enclosure and its effect on turbulence ("dome seeing" study).
- The high stiffness, low vibration and oscillation tower.
- The electronics devices, cables, optical fiber connection.
- The thermalization of the telescope in order to smooth the possible large fluctuation of external temperatures (especially if it is set up at several tens of metres).

The PLT Design Study will produce a cost efficient estimation of the requested level of automatization, robotization, intelligent remote control of the telescope, i.e., able to manage permanently the observing strategy. The risk and cost of using light mirrors made for instance of SiC for the primary mirror will be also technically assessed and estimated. A reduced weight of the primary mirror would have a considerable impact on the rest of the structure and consequently reduce drastically the logistics means (and induced costs and time delay) to deploy.

All these studies will have an important impact on industrial progress in the use of material and structures operating under extreme climatic conditions and will improve the know-how for other polar instruments.

4.1. *Wide field of view infrared camera*

The PLT IR camera is the largest ever proposed for the 2–5 μm range in terms of pixel number (250 Mpixels). Its FPA basically consists of an assembly of 16 buttable 4k×4k arrays covering a field of view of ∼40 square arcminutes, with a pixel size of 0.15 arcsec. Teledyne Technology Inc. in the USA produces suitable state-of-the art infared arrays for astronomy (Hawaii–4RG). Although arrays of this size are not yet commercially available, they are likely to be on the market by 2013, thus timely in the PLT schedule. This camera is particularly efficient and challenging, and the Design Study will have to identify possible show stoppers in its definition and its capacity to support the Antarctic environment conditions and consequently its high level of reliability and automatization.

4.2. *Adaptive optics techniques in polar atmospheric conditions*

One considerable advantage of the Antarctic sites is the unique behaviour of the atmospheric turbulent ground layer of the atmosphere. It is much thinner than above any other ground sites with a median measured value of its thickness of ∼30 m (Aristidi *et al.*, 2009), to be compared to the hundreds of metres usually found at the best astronomical sites (Mauna Kea, Paranal). If one can permanently benefit from seeing conditions close to 0.3 arcsec – basically twice as good as anywhere else on the Earth – this would provide an enormous advantage for larger instruments to be later implemented at Dome C or other comparable Antarctic sites. It is thus among the major impacts of the PLTDS to determine, essentially through modelling, whether one can fully benefit from the so called Ground Layer Adaptive Optics (GLAO) techniques across a large field of view of ∼40 square minutes to alleviate the effect of turbulence, and thus leading to reduce the height of the tower.

A major outcome of the PLTDS is to produce a full assessment model of GLAO able to reach this goal: **an image quality pattern of the order of 0.3 arcsec quasi permanently. This would be in itself a major advance in astronomical observations from the ground**.

These (mostly) theoretical studies, based on the results of the site assessment studies currently on going on site (turbulence profiles and seeing measurements) will also determine the optimal height of the tower supporting the telescope and the parameters of the GLAO system to be implemented (deformable mirror, number of actuators, frequencies). This study should ultimately lead to R&D studies and the implementation of a prototype of the GLAO subsystem that could be, for instance, assessed on an already existing telescope at Concordia such as IRAIT.

4.3. *A massive data pipeline and processing centre in an extremely remote environment*

The IR camera will yield one to several Tbytes of data per period of 24 hours and the estimated final data product amount after 10 years of operations is in the Pbyte range. Although there is no major technological challenge to achieve this task in the near future (the LSST will produce 10 times more data), the challenge is that the processing must be done essentially on-site because, due of the very small existing and foreseeable bandpass of the telecommunications (Inmarsat, Iridium), one cannot transfer electronically such a huge amount of data from Antarctica to the rest of the world. There will be a massive data centre in Europe (for instance at CC–IN2P3 in Lyon), but most of the raw data processing will have to be carried out on site.

The present design study will investigate the most efficient way to transfer the raw data from the telescope/camera to the dedicated control room (very likely to be set up in one of the existing Concordia buildings), to run, manage and maintain the data centre with only one person available during the winterover periods, to single out rapidly transient events

(SNe, GRBs, transits...) and to alert the community of these events with the shortest elapse of time. On the other hand, the PLT controler should be able to receive alerts from other survey telescopes and make appropriate observation decision, accordingly. Finally, the most appropriate and safe physical media on which the ∼100 Tbytes data could be transferred bi-annually from Antarctica to the data centre in Europe will have to be investigated.

5. Provisional conclusion

Although time is not particularly favourable to make prospects of costly instruments in Antarctica, we, as well as several other groups around the world, are convinced that there is a bright future to the exploitation of a polar astronomical station equipped with performing instruments, dedicated to just a few well identified science cases and objectives. We believe that surveying the sky at an extreme depth, in new spectral bands, at high angular resolution, is one of the top priorities for a middle-size polar instrument. The PLT could provide invaluable data for several high priority science cases and could be in many cases be a cheaper and more flexible alternative to space missions. To optimize and secure its development, the instrument should be studied, built and operated by an international team, after a careful selection of the most appropriate Antarctic site. Therefore, in the meantime, we strongly recommend to proceed with coordinated campaigns of site qualification at the currently running stations, and possibly elsewhere, to foster the links between the groups involved in these studies all over the world, to specify the most exciting science cases and to carry out appropriate design studies and *in-situ* demonstrators (e.g. to test GLAO devices). Installing a facility in a harsh environment is not a question of competition, but clearly of world-wide cooperation.

We hope that this Symposium will be an opportunity to give a new impetus to this prospect in the future.

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