ASTEP 400: a telescope designed for exoplanet transit detection from Dome C, Antarctica

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ABSTRACT

The Concordia Base in Dome C, Antarctica, is an extremely promising site for photometric astronomy due to the 3-month long night during the Antarctic winter, favorable weather conditions, and low scintillation. The ASTEP project (**A**ntarctic **S**earch for **T**ransiting **E**xo**P**lanets) is a pilot project which seeks to identify transiting planets and understand the limits of visible photometry from this site. ASTEP 400 is an optical 40cm telescope with a field of view of 1° x 1°. The expected photometric sensitivity is 1E-3, per hour for at least 1,000 stars. The optical design guarantees high homogeneity of the PSF sizes in the field of view. The use of carbon fibers in the telescope structure guarantees high stability. The focal optics and the detectors are enclosed in a thermally regulated box which withstands extremely low temperatures. The telescope designed to run at -80°C (-110°F) was set up at Dome C during the southern summer 2009-2010. It began its nightly observations in March 2010.

Keywords: Telescope construction, Antarctica, low temperature, exoplanet, transit, photometry.

1. INTRODUCTION

The Concordia Base at Dome C, on the Antarctic Plateau, is a French-Italian scientific station built in the early 2000s. First dedicated to glaciology and climate sciences, the station rapidly interested astronomers. From 2000 to 2010, the FIZEAU Laboratory of the University of Nice-Sophia Antipolis has been operating several site testing instruments at Dome C including: Cn^2 sounding balloons, DIMM, Generalized Seeing Monitor and Scidar. The exploitation of these instruments gave the Laboratory a good understanding of the particularly harsh conditions on site and experience in coming up with technical solutions to cope with such conditions. In 2006, to begin astrophysical exploitation of the site by taking advantage of the 3 month long night, the Fizeau Laboratory and the Cassiopée Laboratory of the Observatoire de la Côte d'Azur jointly launched the ASTEP project. The major objective was to make photometric time-series observations to discover new transiting exoplanets. A pathfinder instrument called "ASTEP-south", a 4" refractor telescope, was installed in 2008 in order to evaluate the photometric capacities of the site. The main instrument, ASTEP 400, was then built in order to achieve the major objective of exoplanet detection. ASTEP 400 is the subject of this paper.

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2. TECHNICAL REQUIREMENTS

The technical requirements for ASTEP 400 were determined through simulations. The CCD sizes, the focal scale, the focal ratio and the aperture diameter were defined in order to observe a large number of stars at a time (~1000) without any resulting confusion of stars. The PSF characteristics (size, shape, uniformity, and stability) were determined in order to guarantee a photometric measurement accuracy of better than 1 millimagnitude. Table **1** summarizes the main technical requirements of ASTEP 400.

Table 1 : Main Top Level Requirements

N°	Requirement type		Value
1	Field of view		1° x 1°
2	Field scale		1 pixel < 1 arcmin < 1.2pixel
3	Science spectral band		600 – 800 nm
4	PSF size and shape	Size	2 pix < FWHM < 3 pix within the FoV
5		Aspect	~ Gaussian, no sharp edges, no central hole
6		Energy spread	• 97.7% of the energy inside a 3 on-axis FWHM diameter circle. • 35 to 90% of the energy inside a 1 on-axis FWHM diameter circle. • Energy in 1 pixel around the PSF peak must be between 4% and 50% of the total PSF energy.
7	PSF uniformity within the FoV	Variation of the PSF energy inside a 3 on-axis FWHM diameter circle	< 1.3%
8		Variation of the PSF energy inside a 1 on-axis FWHM diameter circle	< 70%
9	PSF energy stability	Flux variation in a 3 on-axis FWHM diameter circle	< 0.1% for one hour
10	Image position stability		Goal 0.2 pix, maximum 2 pix for 2 hours
11	Duty cycle		Goal 90% of clear sky time, minimum 75%
12	Temperature	Operating range	-50°C to -80°C (-60°F to -110°F)
13		Variation speed	up to 20°C / 24h (36°F / 24h)

3. OPTICAL DESIGN

The optical configuration of ASTEP 400 is a Newtonian design which includes a sophisticated field corrector. A focal box contains a science camera and a guiding camera. The field corrector consists of 5 spherical lenses whose first two also form a double-glazed window between the inside and the outside of the box.
The primary mirror diameter is 400mm (16”) with a focal ratio of 4.6. Because of the wide field and because of the layout of the optics and cameras in the focal box, the secondary mirror is quite big, giving a central obscuration of 42% of the primary diameter. Both primary and secondary mirrors are made in Zerodur®.

The science camera is an FLI Proline with a KAF 16801E, 4096 x 4096 pixels, and a 16 bits analog to digital converter. The pixels size is 9µm, and the CCD measures 36.8 by 36.8mm. The camera is cooled by a Peltier device.
The guiding camera is an SBIG ST402M.

A dichroïc mirror separates the science path from the guiding path, the red part of the spectrum leads to the science camera and the blue part to the guiding camera.

The science CCD is lightly defocused in order to spread the PSF FWHM to about 3 pixels. This reduces the jitter noise due to the inter-pixel and intra-pixel non-homogeneity. This defocus is 175µm extrafocal.

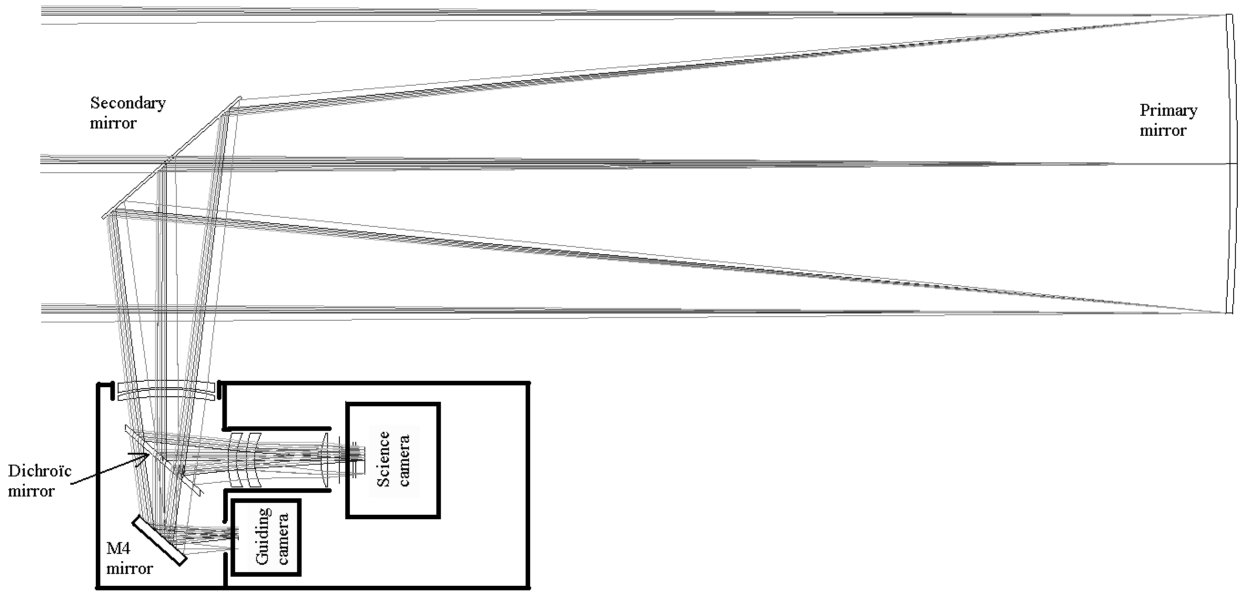

Figure 1: Optical layout

Figure 2 shows different defocused PSF, computed with ZEMAX, at the center and at different off-axis positions in the field. It shows that the theoretical PSF shape and size meet the requirements.

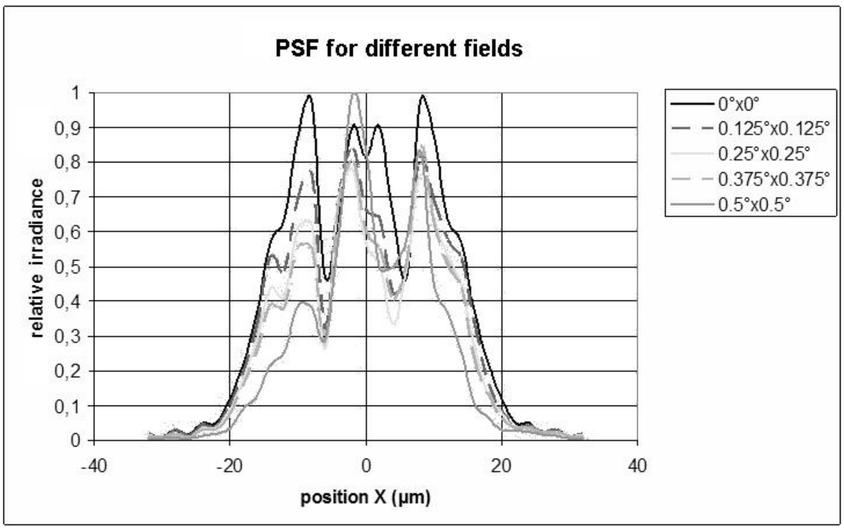

Figure 2 : PSF for different fields in the science path

Figure 3 shows spot diagrams in the center and in the 4 corners of the science CCD which confirms the excellent homogeneity of the entire field of view.

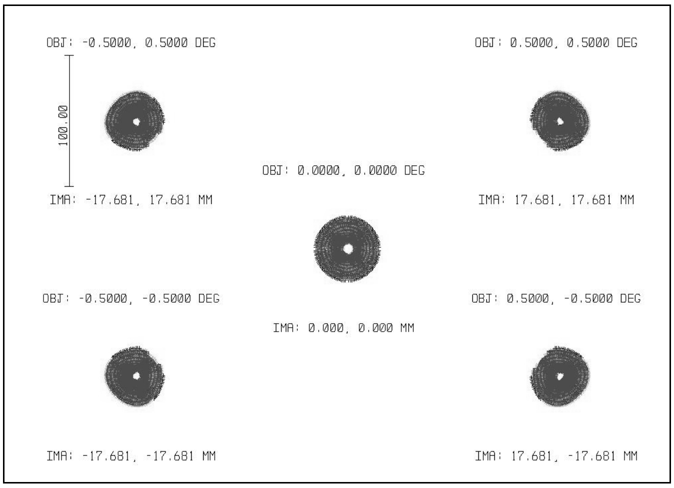

Figure 3 : Spot diagrams for different fields in the science path

Figure 4 is a photometric report for both the science and guiding paths which uses Silver or Aluminium reflective coatings on primary and secondary mirrors. A better transmission is obviously provided with Silver coatings. Nevertheless, Aluminium coatings have already shown very good resistance to the Antarctic environment, and we have as yet no experience with Silver coatings in such conditions. Thus, we chose Aluminium.

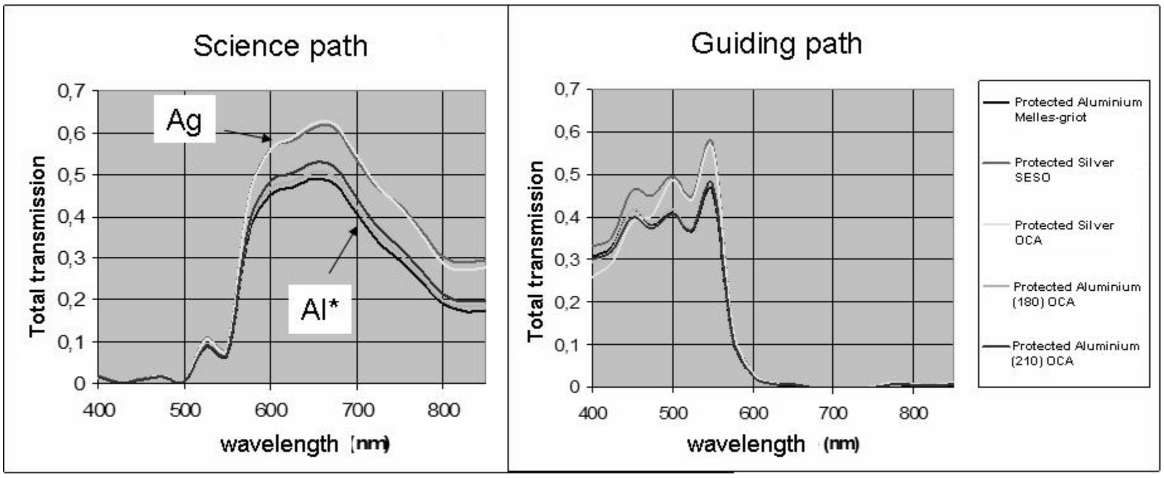

Figure 4 : Photometric report

We carried out a tolerancing study to define the opto-mechanical positioning requirements in order to meet the image homogeneity and stability requirements defined in Table **1** (line 4 to 9). Table **2** reports the main opto-mechanical requirements.

Table 2 : Main opto-mechanical requirements

Sub-assemblies	Position accuracy	Position stability	Optics in focal box	Position accuracy	Position stability
M1 lateral position (XY)	N/A (M1 is a reference)	+/- 0.05mm	Double window alignment (XY)	+/- 0.1mm	+/- 0.01mm
M2 position (XYZ)	+/- 0,25mm	+/- 0.05mm	Double window focus (Z)	+/- 0.1mm	+/- 0.01mm
Focal box alignment (at the entrance window) (XY)	+/- 0.5mm	+/- 0.05mm	M3 position (XYZ)	+/- 0.25mm	+/- 0.01mm
Focal box focus (at the entrance window) (Z)	+/- 0.25mm	+/- 0.1mm	Corrector position (XYZ)	+/- 0.25mm	+/- 0.01mm

4. MECHANICAL DESIGN OF THE TELESCOPE

The mechanical structure of the telescope is a fourth order Serrurier structure. The main frame in the middle of the structure is Aluminium, as are both the upper part of the structure (the secondary mirror spider assembly), and the lower part of the structure (the primary mirror barrel assembly). The hollow bars that link these three parts are made of Carbon fibers with Invar sleeves at each end. This combination of materials guarantees a very low coefficient of thermal expansion for the distance between the primary and the secondary mirror. Our calculations show that, with a temperature increase of 30K, this distance increases by less than 20µm. Consequently, in this temperature range, the optical distance between the primary mirror and the focal box varies only by 150µm. This guarantees the stability requirement of the focal box focus.

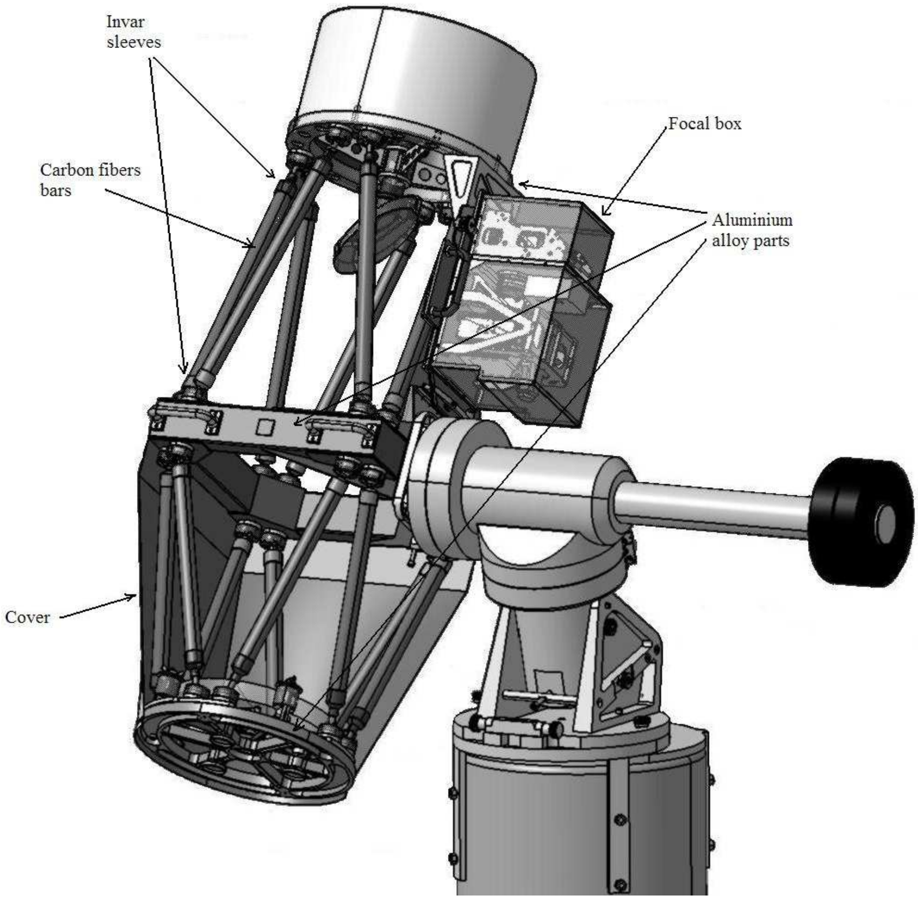

Figure 5 : Mechanical structure of the telescope

Finite element analysis was carried out in order to predict the deformations of the structure which are due to the varied positions the telescope takes, and to temperature variations. We then verified the impact of these deformations on PSF quality and stability. Table **3** reports the results of this analysis and compares the calculated values of several parameters with the required values.

Table 3 : Calculated performances with respect to some requirements

	Requirement type		Calculated value	Required value
6	Energy spread in the PSF	energy inside a 3 on-axis FWHM diameter circle	E > 98.6%	E > 97.7%
		energy inside a 1 on-axis FWHM diameter circle	55% < E < 66%	35% < E < 90%
		Energy in 1 pixel around the PSF peak	6.9% < E < 12%,	4% < E < 50%
7	PSF uniformity over the FoV	Variation of the PSF energy inside a 3 on-axis FWHM diameter circle	0.3%	< 1.3%
8		Variation of the PSF energy inside a 1 on-axis FWHM diameter circle	17%	< 70%
9	PSF energy stability	Flux variation in a 3 on-axis FWHM diameter circle	0.06% for 24 hours < 0.01% per hour	< 0.1% per hour

The bending and the thermo-elastic deformations of the structure are largely acceptable with respect to the image quality and stability requirements.

5. MECHANICAL AND THERMAL DESIGN OF THE FOCAL BOX

Figure 6 illustrates the design of the focal box. The focal box is divided into two compartments. The compartment containing the two cameras (in the lower part of the figure) is thermally regulated at about -5°C (23°F). This temperature guarantees the smooth functioning of the science camera shutter. The compartment containing the dichroïc mirror (upper part of the figure) is thermally regulated at about -30°C (-22°F). This intermediate temperature between the cameras' compartment and the air outside guarantees the long life of the dichroïc coating. It also minimizes the temperature gradient between the inside of the box and the air outside the optical window (the surrounding air temperature range is between -50°C and -80°C in winter). The double-glazed optical window minimizes heat loss and consequently prevents optical turbulence in the optical path. Its two meniscus lenses are in fused silica in order to minimize thermo-elastic deformations. These lenses, along with the three other lenses located between the dichroïc mirror and the science camera, contribute to field correction,

The focal box is mounted on a carbon fibers plate, which ensures rigidity and thermal stability. Most opto-mechanical mounts in the focal box are in Titanium alloy TA6V which is a good choice in terms of weight, strength and thermal expansion coefficient. The science camera is mounted on a remote controlled translation stage which adjusts its focal position with 5µm accuracy. It is removable in order to replace it with an He-Ne laser used for the alignment of the whole instrument.

The insulation of the focal box is made with both cellular polystyrene Depron plates which stem heat conduction, and reflective Kapton® layers to prevent heat radiation. The two compartments are heated with electric resistors, and PT100 thermometer probes are used to give feedback on regulators.

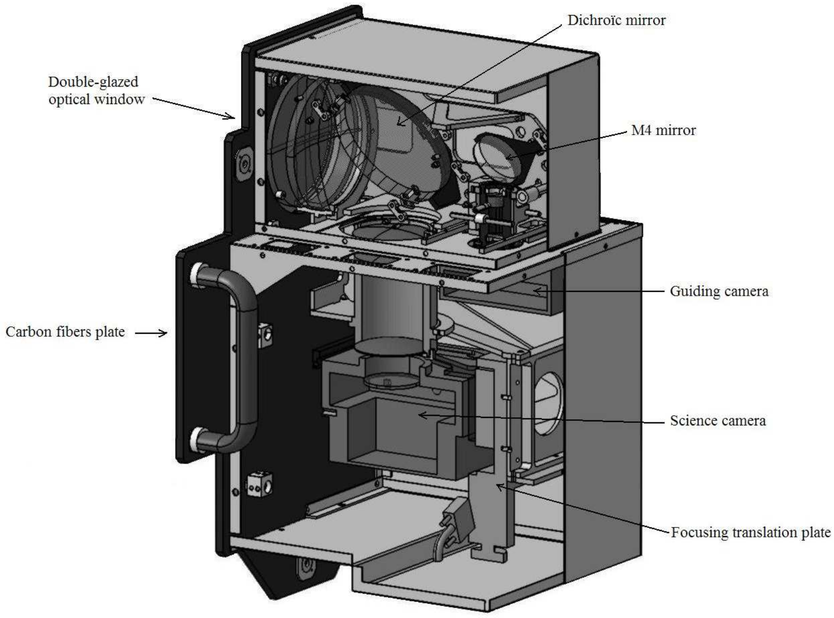

Figure 6 : Design of the focal box (cutaway view)

6. CONCLUSION

We have just described the optical, mechanical and thermal design of ASTEP 400; a telescope with two cameras enclosed in a focal box, built to observe exo-planet transits from the Concordia station in Antarctica. We outlined the requirements of the instrument, mainly in terms of image quality and stability, and explained the technical choices we made in order to meet these requirements. ASTEP 400 was installed in Antarctica in November and December 2009, and nightly observations began in March 2010. The instrument is now working well and has recently observed transits of several known exo-planets (qualification observations). Figure **7** shows the light curve of the WASP 19 transit observed by ASTEP 400 in May 2010. The star's magnitude is 12.6. This curve was obtained with a single observation. It is compared with the same planet's transit observed with the 2-meter Faulkes Telescope South by Hebb et al.

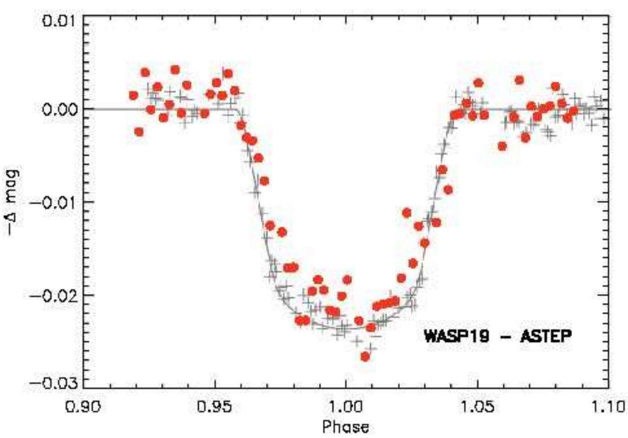

Figure 7 : WASP 19 transit observed by ASTEP 400 (dots), compared with the observation by Faulkes Telescope South (cross)

Figure 8 is a picture of the Tarentula nebula. Integration time is 50 s. The 1° x 1° field is homogeneous. The PSF FWHM is about 3 pixels, which conforms to the requirements for high precision photometry.

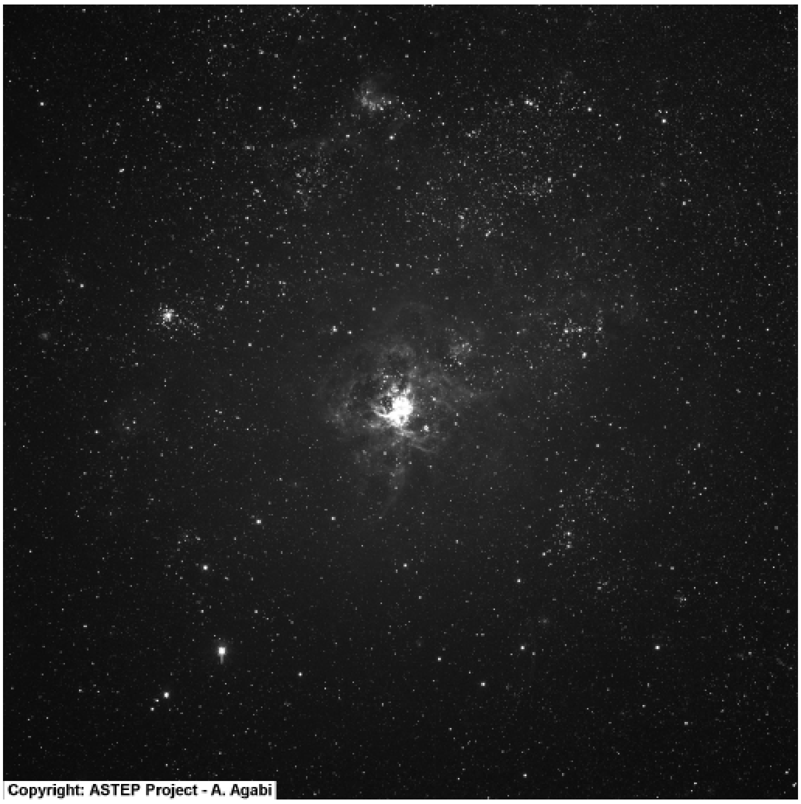

Figure 8 : Picture of the Tarentula nebula taken by ASTEP 400 at Dome C in April 2010

Figure 9 : ASTEP 400 at Concordia, Dome C, Antarctica

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