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CURVED FOCAL PLANE TELESCOPE FOR OBSERVATION OF ULTRA-LOW SURFACE BRIGHTNESS OBJECTS

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Abstract. In spite of major advances in both ground- and space-based instrumentation, the ultra-low-surface universe (ULSB) still remains a largely unexplored volume in observational parameter space. These ultra-low levels (>28-29 mag/arcsec^2) are achieved by minimising internal scattering to produce a point spread function (PSF) as compact as possible while achieving a wide field of view within a fast optical design. We present here the results of full-system photon Monte Carlo simulations of a ground-based telescope with a curved focal plane design, that aims at testing the breakthrough technologies of curved sensors and carrying out ULSB observations. While the telescope has only one inevitable single refractive surface, it delivers a PSF with ultra-compact wings, which allows the detection of ULSB features.

Keywords: telescopes, detectors, ultra-low surface brightness, technology

1 Introduction

In spite of major advances in both ground- and space-based instrumentation, the ultra-low surface brightness universe (ULSB) still remains a largely unexplored part in observational parameter space. Yet, ULSB observations would critically improve our understanding of the evolution of the universe by detecting and characterizing ultra-faint galaxies and features, currently predicted to be abundant but missed by current surveys due to their lack of sensitivity to these extended objects (Bullock & Boylan-Kolchin 2017; Kazantzidis et al. 2008; Cooper et al. 2010, 2013; Barton & Thompson 1997; Fry et al. 1999; Atkinson et al. 2013). We present here the telescope demonstrator aimed at testing the breakthrough technologies of curved detectors and carrying out ULSB observations (Muslimov et al. 2017; Lombardo et al. 2019). This telescope has one inevitable refractive surface, the window for the cryostat, but it still delivers a Point Spread Function (PSF) with extremely compact wings, a key factor for the detection of ULSB features in the sky. As its focal surface is curved, the use of a curved CCD enhances the performances in terms of transmission and PSF shape. We also present here the design and the first results obtained through full-system photon Monte Carlo simulations. The great potential of our optical design is enhanced by the introduction of curved CCDs. This new technology hugely simplifies the overall system and also eliminates the need for field-flattening lenses, while preserving the wide field of view.

The impact of the curving process on the characteristics of the detectors has not been fully determined yet, while some manufacturer tested few prototypes and found increased values for the dark current (Gregory et al. 2015), others found no clear performance degradation with respect to the flat sensor case (Lombardo et al. 2019).

2 Telescope design & its End2End simulation software

The telescope is a fully reflective Schmidt design with an anamorphic primary, flat secondary and spherical tertiary mirror, and features a curved focal surface (Figure 1). In Table 1 its main characteristics are described. In spite of a small primary mirror (35.6 cm), it allows observations over a wide field of view of 1.6° × 2.6°.

It has one refractive element: the window of the dewar, which is necessary to cool down the CCD. In order to reduce as much as possible the number of refractive elements, we combined the window with the bandpass filter. It is also possible to design a solution in which we have two different filters, side by side, on the window

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Table 1. Parameters of telescope design.

Quantity & Value	
Field of view	$1.6° \times 2.6°$
F/#	2.5
Diameter	356 mm
Detector shape/radius of curvature	Convex/$\sim$800 mm

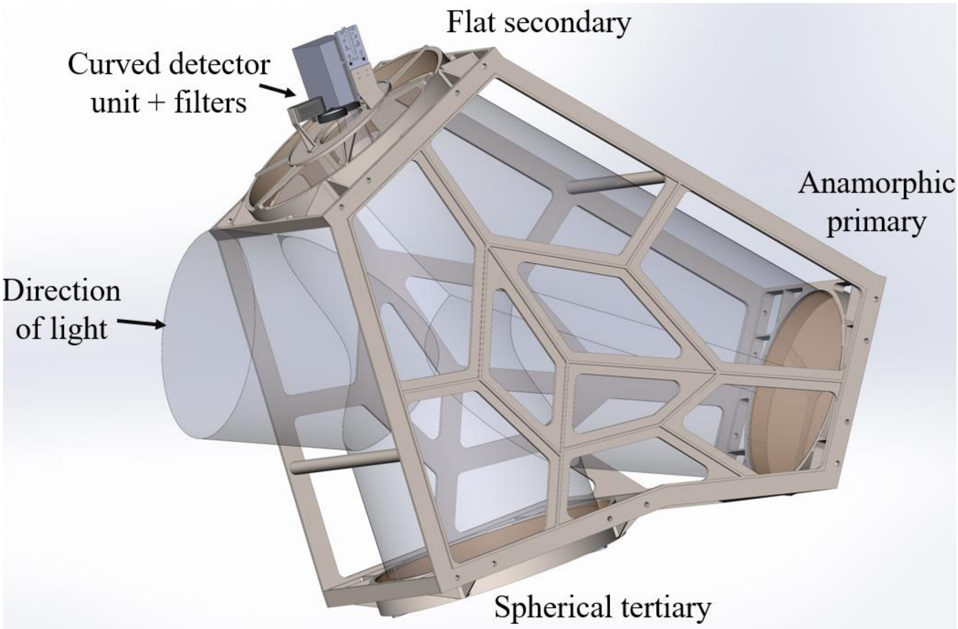

Fig. 1. Opto-mechanical design of the pathfinder: light reaches an anamorphic primary, is reflected by a flat secondary and a spherical tertiary yields a simple spherically-curved focal surface where a curved detector is placed.

so that we are able to observe in two wavelength bands. For simplicity, in the rest of the paper, we only consider one filter band that is a g LSST-like filter.

The location considered for the simulations is within the Observatorio del Roque de los Muchachos in La Palma. We use an end-to-end photon Monte Carlo simulation software `PhoSim` (Peterson et al. 2015) to verify the performances of the full telescope and characterise the PSF at very large distances from the center of the field of view.

The software simulates the full light path from the astrophysical source, passing through the Earth atmosphere, the telescope and can model also the CCD effects such as dark current, read out noise, CTE, etc. We also account for the altitude, typical seeing and wind speed/direction values for La Palma, to make the simulation as realistic as possible.

3 Results

The quality of the PSF of the telescope is a key aspect to consider in ultra-low surface brightness objects observations, as already discussed in previous publications (Abraham & van Dokkum 2014; Mihos et al. 2017). The telescope must provide PSF whose wings are as low as possible, such that the faint emission of these objects is not dominated by the PSF residuals of brighter stars or galaxies in the same observed field.

The PSF of the telescope is shown in Figure 2 as function of the radial distance in arcmin. This PSF is obtained from a simulation of a 9 mag star in the centre of the field of view and it includes all the effects of

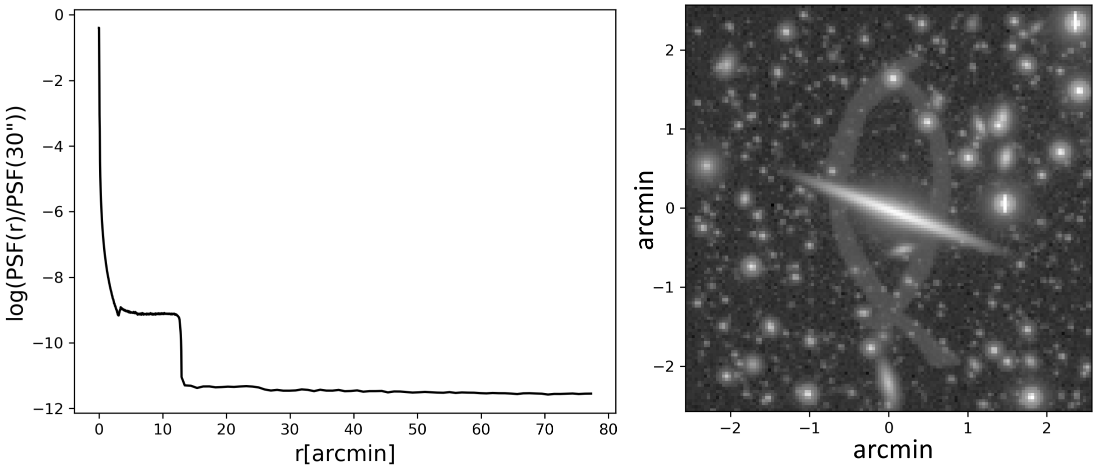

Fig. 2. Left: PSF of the telescope presented in this paper from photo Monte Carlo simulations. The PSF is normalized with its value within 30". Right: Simulation of a 5'×5' field observed by the ground-based pathfinder after an exposure time of 30 h.

optical design perturbations, atmosphere and seeing. The PSF is computed from an image composed of 140 different observations where the CCD was exposed for 40.5 s each time. The PSF of the pathfinder features very compact wings even at large distances from the center of the field of view, reaching averaged values of 10^{-9} around 3.0'. At this distance it plateaus until 13', due to the reflection off the CCD and by the scattering of the dewar window. Then it decreases again reaching averaged values of $10^{-11.5}$. This ghost, hence, does not degrade the PSF as it is suppressed by 8 orders of magnitudes with respect to the centre. These results show the importance of producing full-scale realistic simulations during the design stage, in order to test all the performances of the system and improve its possible weak points before the construction phase.

We can perform more tests and ascertain the capacity of the telescope to observe the ULSB realm, by simulating a field observed in the sky and injecting an ULSB feature of known surface brightness. The field is large 5'×5' and it is composed of stars and galaxies drawn from the Millennium Simulation and generated using `CatSim`*. In addition to this, a large elliptical galaxy (of 2.5' observed angular diameter) and an arch-like structure have been added to the simulation at the centre of the field. The galaxy has an integrated brightness of 13.5 mag and the arches have surface brightness of 29 mag/arcsec^2 which makes the full image similar to NGC5907 (Martínez-Delgado et al. 2010).

The results of the simulations of the 5'×5' field observed at the centre of the field of view of the pathfinder are shown in Figure 2. This image is integrated over 30 hours of exposures and it is composed by adding 288 images of 382 s each.

We can clearly observe the injected ULSB feature. Its presence in the image implies the capability of the pathfinder of observing such extremely faint and extended objects and of reaching a good S/N, even after just one week of nightly integration time.

4 Conclusions

The ultra-low surface brightness universe still remains a niche for observations, as a full-sky survey is missing. As observations of this kind demand a telescope with a highly optimized design, we propose here an alternative concept that uses a curved detector. The proposed telescope is a fully reflective, off-axis Schmidt design, with an anamorphic primary mirror of 35.6 cm diameter, a flat secondary mirror and a spherical tertiary mirror that focuses the light onto a convex spherically-curved CCD. In this paper we tested the full system through full scale photon Monte Carlo simulations, with the software `PhoSim`.

The results from the simulation of a star at the centre of the field of view have shown firstly that the wings

*`https://www.lsst.org/scientists/simulations/catsim`

of the PSF reach unprecedentedly low level. The normalised PSF decreases down to $10^{-11.5}$ at a radial distance from its centre of ∼13'. Before reaching these values, the PSF shows a plateau of $\sim 10^{-9}$ due to the ghost image of the star itself.

This unfocused image of the star creates a halo of photons that extends from ∼3' to ∼13' from the centre of the PSF. The PSF quality is not degraded by the presence of such ghost, as it is suppressed by 8 orders of magnitude with respect to the PSF central value.

Finally we simulated a field of galaxies and stars of 5'×5' observed at the centre of the field of view for a total exposure time of 30 hours. The final image clearly shows the presence of the extended structure injected in the simulation and that is faintly emitting at 29 mag/arcsec^2, typical brightness for the ultra-low surface brightness objects. These results illustrate the full potentiality of the pathfinder, that will not only be used to test the groundbreaking technology of the curved sensors, but also provide important science outcome.

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References

Abraham, R. G. & van Dokkum, P. G. 2014, PASP, 126, 55

Atkinson, A. M., Abraham, R. G., & Ferguson, A. M. N. 2013, ApJ, 765, 28

Barton, I. J. & Thompson, L. A. 1997, AJ, 114, 655

Bullock, J. S. & Boylan-Kolchin, M. 2017, ARA&A, 55, 343

Cooper, A. P., Cole, S., Frenk, C. S., et al. 2010, MNRAS, 406, 744

Cooper, A. P., D'Souza, R., Kauffmann, G., et al. 2013, MNRAS, 434, 3348

Fry, A. M., Morrison, H. L., Harding, P., & Boroson, T. A. 1999, AJ, 118, 1209

Gregory, J. A., Smith, A. M., Pearce, E. C., et al. 2015, Applied Optics, 54, 3072

Kazantzidis, S., Bullock, J. S., Zentner, A. R., Kravtsov, A. V., & Moustakas, L. A. 2008, ApJ, 688, 254

Lombardo, S., Behaghel, T., Chambion, B., et al. 2019, Appl. Opt., 58, 2174

Lombardo, S., Muslimov, E., Lemaître, G., & Hugot, E. 2019, MNRAS, 488, 5057

Martínez-Delgado, D., Gabany, R. J., Crawford, K., et al. 2010, AJ, 140, 962

Mihos, J. C., Harding, P., Feldmeier, J. J., et al. 2017, ApJ, 834, 16

Muslimov, E., Valls-Gabaud, D., Lemaître, G., et al. 2017, Appl. Opt., 56, 8639

Peterson, J. R., Jernigan, J. G., Kahn, S. M., et al. 2015, ApJS, 218, 14