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The Dark Energy Survey Camera (DECam)

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FOR THE DARK ENERGY SURVEY COLLABORATION

Abstract

The Dark Energy Survey (DES) is a next generation optical survey aimed at understanding the expansion rate of the Universe using four complementary methods: weak gravitational lensing, galaxy cluster counts, baryon acoustic oscillations, and Type Ia supernovae. To perform the survey, the DES Collaboration is building the Dark Energy Camera (DECam), a 3 square degree, 570 Megapixel CCD camera that will be mounted at the prime focus of the Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory. CCD production has finished, yielding roughly twice the required 62 2kx4k detectors. The construction of DECam is nearly finished. Integration and commissioning on a "telescope simulator" of the major hardware and software components, except for the optics, recently concluded at Fermilab. Final assembly of the optical corrector has started at University College, London. Some components have already been received at CTIO. "First-light" will be sometime in 2012. This oral presentation concentrates on the technical challenges involved in building DECam (and how we overcame them), and the present status of the instrument.

Keywords: Dark Energy; Dark Energy Camera; Blanco Telescope; Cerro Tolo Inter-American Observatory

1. Introduction

The Dark Energy Survey (DES) is an international collaboration, with over 120 senior scientists from over 20 institutions in the US, the UK, Spain, Brazil, and Germany. The DES [1-2] will measure dark energy parameters using four complementary techniques: galaxy cluster counting, baryon acoustic

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oscillations, weak gravitational lensing, and type Ia supernovae. The wide-field survey will produce images of 5000 square degrees of the southern galactic cap collected during 525 nights of observing from 2012 to 2017. A 30 square degree field will be imaged repeatedly to produce a supernovae survey. In order to carry out these surveys, the DES Collaboration requires a new instrument, the Dark Energy Camera (DECam), to be installed in the prime focus of the 4-meter Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile. See Figure 1.

This paper outlines the science and survey and then provides details about the technical description of DECam, concentrating on the challenges involved in building the camera. Finally we provide the present status and an update on anticipated "first light".

2. The Science and Survey

2.1. DES Science

In 1998 two teams studying Type 1A supernovae concluded [3-4] that the expansion of the Universe is accelerating. A new cosmological "standard model" was developed whereby the energy in the Universe was carried by relativistic particles (photons and neutrinos), the normal matter particles (baryons and other leptons) the unseen dark matter, and the physical source of the acceleration, which was named "dark energy". The fraction of the energy in the Universe carried by the relativistic particles and normal matter is approximately 4%, by the dark matter 23%, and by the dark energy 73%.

Figure 1. The Victor M. Blanco Telescope. The mirror cover (4 white sections) is closed. DECam will replace the entire Prime Focus Cage (black) and instrument at the upper end.

The physical cause of "dark energy" is not understood. However, we can characterize the relationship between a materials density, ρ, and pressure, p, in a ratio, $w = p/\rho$, known as the "equation of state". Matter has $w = 0$. Radiation (photons and neutrinos) has $w = +1/3$ (light pushes against the walls of a container). Dark energy has $w < -1/3$, a negative pressure; it is self-repelling. The story presented by the cosmological model is that after the Big Bang, 13.7 billion years ago, the density of the matter in the expanding Universe was sufficient for its gravity to cause initial deceleration of the expansion rate. About 4 billion years ago the matter density had decreased sufficiently for the repelling effect of dark energy to dominate and cause the expansion to accelerate. It has been doing so since.

The Dark Energy Survey will measure the equation of state of dark energy using four separate techniques. These are galaxy cluster counting, baryon acoustic oscillations (BAO), weak gravitational lensing (WL), and type Ia supernovae (Sn Ia). In galaxy cluster counting we measure the number of galaxy clusters and their mass as a function of redshift, *z*. The more dark energy there is, the more time the Universe must have taken to reach its present size, so there will be more massive clusters than otherwise. BAO studies measure the characteristic angular spacing between galaxies and between galaxy clusters that arose from the initial matter density fluctuations from the early Universe and which has expanded since that time. This characteristic angular diameter is measured as a function of *z*. It provides a direct measurement of the expansion rate through geometry as well as the growth of structure. In WL we make a direct measurement of the mass of the dark matter halos that have resulted in galaxies and galaxy clusters by the deflection, due to their gravity, of the light from even more distant galaxies behind them along their line-of-sight. This tests the growth of structure and the angular diameter distance versus *z*. Finally measurements of the apparent luminosity of Sne Ia, which are a kind of standard candle, versus their respective redshifts provides a test of the expansion rate history. With more dark energy, the SN appear more dim because they are further away than would otherwise be expected for an object of that redshift That is, the expansion would have been slower until "recently". Dark Energy Survey will be the first experiment that takes advantage of the strengths of all four of these techniques to make a combined dark energy measurement, bringing to bear not only proper treatment of the systematic uncertainties but also taking into account the information each technique brings to the others to optimize the science reach.

2.2. The Survey

The DES will perform an imaging survey covering 5000 sq-deg of the Southern Galactic Cap (direction away from our own Milky Way). The 10σ detection sensitivity in SDSS *g,r,i,z,* and *Y*-band filters is magnitude 24.6, 24.2, 24.4, 23.8, 21.5, respectively. We expect to make images with better than 2% photometric precision and *i*-band seeing of 0.9" (FWHM). This unprecedented volume will yield approximately 300M galaxies with photometric redshifts and 30,000 galaxy clusters. In addition, there will be 30 sq-deg of SN field which is visited at intervals of less than 4 days to capture the rising light curve of 4000 Sn Ia. DES will be performed over 525 nights during 5 Southern Summers, roughly October to February. The survey region has 4000 sq-deg of overlap with the survey region of the South Pole Telescope [5] (microwave), which will provide the masses of some galaxy clusters using the Sunyaev-Zel'dovich Effect, and Vista Hemisphere Survey [6], which will supply imaging in the near-IR bands (J,H,K) to improve the redshift measurements.

3. The Dark Energy Camera

Carrying out the wide-field survey described above requires a new wide-field instrument to be built and installed on a telescope that can support it. The 4m Victor M. Blanco Telescope at Cerro Tololo Inter-American Observatory is located in the Andes Mountains near La Serena, Chile. The latitude and longitude are -30.2 deg and 70.8. The elevation is 2240 meters above sea level. The Blanco is an equatorial mount Ritchey-Chrétien telescope with a 34,000 lb F/2.7 primary mirror and prime focus cage supported on a steel Serrurier Truss [7] structure. It was commissioned in 1974 at a time when observers operated the shutter and changed photographic plates while riding around in the prime focus cage [8]. This is relevant because the sturdy telescope structure can support the mass of a new large wide-field mosaic camera, DECam [9], at the prime focus. Figure 2 shows a cartoon of all of the camera elements at Prime Focus.

DECam will have a 3 square-degree field of view accomplished using a new optical corrector with five lenses made from fused-silica, an 8-filter housing [10], and a two-blade shutter with a 600 mm diameter circular aperture. The imager [11] is a 520 Mpixel digital camera comprised of sixty-two 2048 x 4096 CCDs [12]. An additiona1 twelve 2048 x 2048 CCDs will be used for guide and focus applications [13]. The CCDs were manufactured at Dalsa and LBNL. They are 250 microns thick and are the fully-depleted, back-illuminated, red-sensitive, p-channel devices with two output amplifiers each. The CCDs were packaged and tested [14-16] at Fermilab. That work yielded 124 science grade CCDs. The quantum efficiency (QE) versus wavelength is shown in Fig. 3, along with a plot of the number of cosmetic defects on the science grade packages. The CCDs are cooled to -100C using a two-phase flow LN2 cryogenic system [17] in a closed-loop mode. The CCD readout is performed using a system [18-20] based on the National Optical Astronomy Observatory (NOAO) Monsoon electronics. The camera is readout in 17 seconds with < 10 e^- per pixel readout noise. Crosstalk is < 10^{-3} and is limited to the opposite amplifier on each CCD. Figure 4 shows photographs of the interior camera from the front and back. All of this is controlled by online software called "SISPI", a user interface which stands for Survey Image System /Process Integration (SISPI) [21-22]. The instrument is attached to a new prime focus cage by a large hexapod, which centers the instrument with respect to the primary mirror, removes tilt, and performs the focus adjustment.

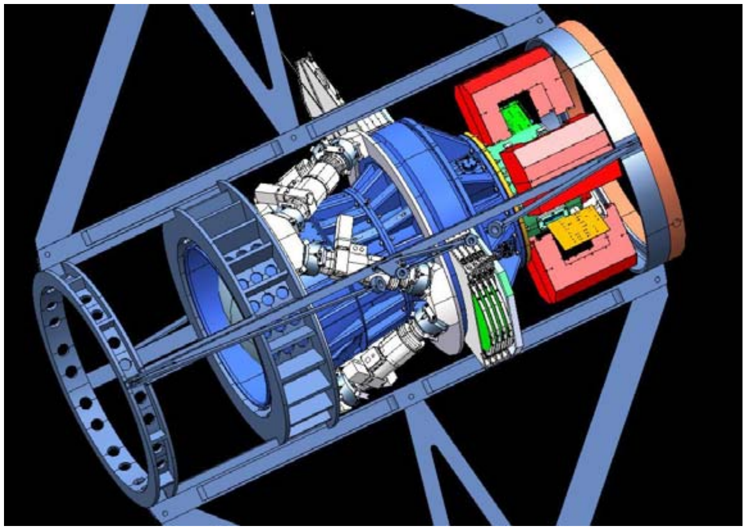

Figure 2. The major systems in DECam. The structure (blue-grey) is the prime focus cage and support "spider", the hexapod (white) is connected to the cage and to the barrel structure (dark blue) that houses the corrector optics, which is oriented as if the primary mirror was to the left of the camera. The filter changer and shutter are housed in the barrel. Some filters (green) protrude out of the barrel. Of course there is a cover, not shown. The imager Dewar (also green) is mostly obscured by the readout electronics crates (pink). Also not shown are the light baffle at the entrance of the corrector, the f/8 dummy weight, and the cage covers.

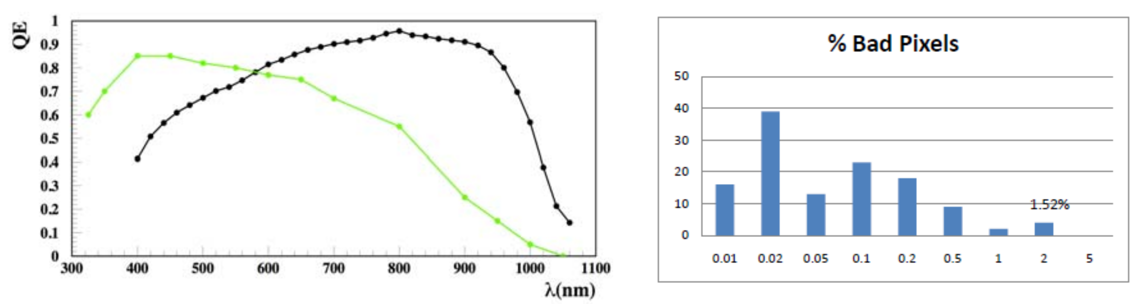

Figure 3. The QE versus wavelength (left) for DECam CCDs (black) is compared to a conventional astronomical CCD (green). The average % bad pixels for the best 62 of the 124 science grade CCDs available for the DECam have ~ 0.014% bad pixels, corresponding to less than 1 bad column per CCD.

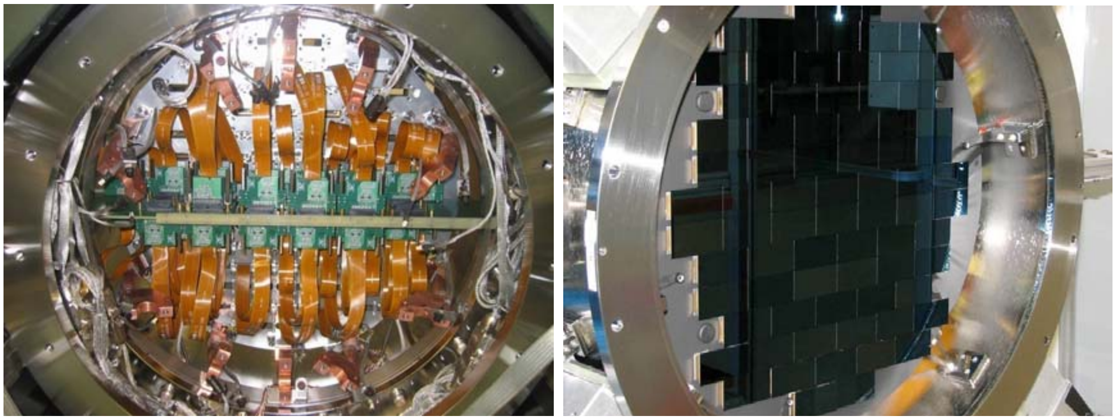

Figure 4. The DECam Dewar interior shown with the back cover, LN2 cooling loop, and front vacuum window (C5) removed. We see (let) the kapton flex cables attached on one end to the vacuum interface boards (VIBs), which span the middle of the Dewar. There is a preamp card (green) visible on the VIB end of this cable. There is a source follower circuit on the CCD end. These flex cables penetrate the focal plane support plate and mate with connectors on the back of CCDs. The CCDs are in 4-side buttable packages and are shown (right) mounted on the front side of the focal plane support plate (FPSP). There are silicon photodiodes in the corners and 4 RTDs that look like buttons mounted on the front of the FPSP as well.

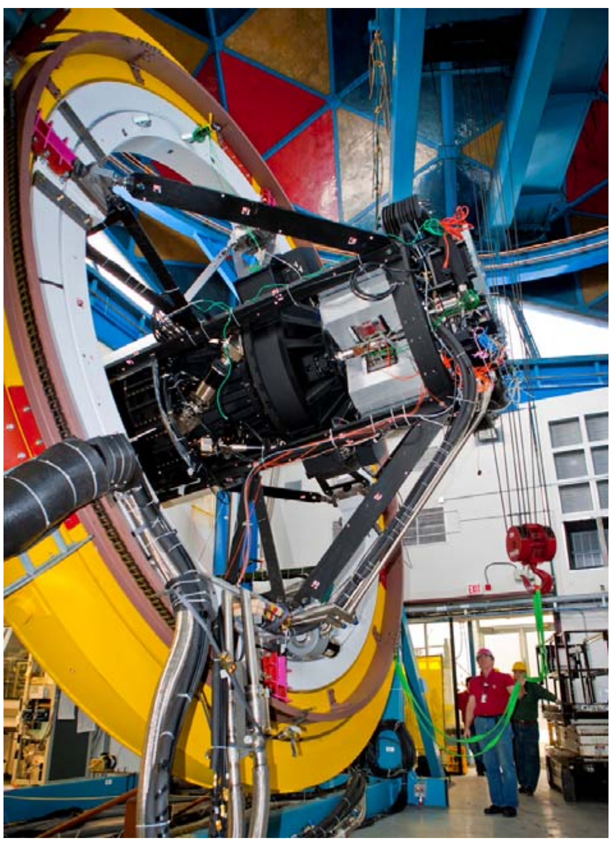

Figure 5 (left) shows DECam mounted in the Telescope Simulator at Fermilab. The two white rings and the fin support structure are a copy of the components on the Blanco. The camera is suspended in the center. The cage, barrel, hexapod, and imager crates are easily identified. The cage covers were not attached during these tests.

In addition to the camera itself, the DECam Project is supplying infrastructure and equipment required for operations in the Blanco Dome. This includes a new secondary mirror (f/8) installation/removal platform that preserves the ability to use instruments at the Cassegrain Focus, a DECam Imager mount/dismount fixture to be operated on the telescope's northwest platform, a filter-changer installation/removal platform, a spectrophotometric calibration system [23] and an all-sky infrared camera [24].

4. DECam Testing and Pre-Installation Commissioning at Fermilab

Most of the camera assembly, testing, and initial integration was performed at Fermilab. For this purpose the Project constructed a "Telescope Simulator" [25], shown in Fig. 5, which was a copy of the two upper rings that attach the Prime Focus Cage onto the telescope. These rings were supported on a stand that allowed them to be rotated about their axis and tilted from horizon to zenith. The DECam hexapod and barrel was inserted into the new Prime Focus Cage and the assembly installed onto this ring system, using a circular ceiling crane that is similar to that attached to the telescope dome. In doing so it allowed us to develop and practice the procedures that will be used to install the instrument on the telescope. Then the DECam imager was installed onto the camera barrel using the imager installation/removal hardware that is being provided to CTIO. See Fig. 6. We operated with the camera oriented in 6 positions: with the imager pointed down, as if the telescope was at zenith, and with the imager aimed near the horizon in 5 roll orientations covering 131 degrees. We verified [26] that all systems at hand were operating according to their technical specifications and requirements [27].

We performed “simulated observing as if DECam was being used on the telescope. We didn’t have the corrector optics, which was being aligned and assembled at Univ. College, London, UK. Instead we had a copy of the barrel with dummy weights in place of the optics and their cells. The Dewar had a flat optical window instead of C5. We took biases, darks, flats, focus images of “star fields” projected from the “primary mirror end” of the Cage, and traditional focus sequence exposures. We performed “region-of-interest” readout using the guide CCDs even though we didn’t have a telescope to guide. The full observing sequences were carried out using SISPI: readout previous image, change filter, adjust hexapod, open and close shutter, and readout again. This was done in “manual” mode as well as using an automatic sequence from an exposure table. SISPI components performed diagnostics of image health, made image displays, and kept records of the images and their characteristics in appropriate databases.

Figure 6. The DECam imager installation fixture (mostly pale yellow) at the Telescope Simulator. On the left we see the imager, which is attached to the installation fixture on 6 stout rods, being drawn up to the barrel. The electronics crates and cables (blue) from vacuum interface boards to the readout electronics are particularly visible. On the right we see the imager has been attached to barrel and a side view of the Telescope Simulator with the copy of the “NW Platform” at CTIO stacked on top of concrete blocks.

Performing this work at Fermilab, we reduced the risk of extended telescope down-time when we install the instrument on the telescope, and we minimize the amount time required for integration and commissioning at CTIO.

5. DES Data Management, Science Simulations, and Preparations for Survey Data

The DES Data Management System [28] will archive and process the DES data and produce science-ready data products.

The DES Collaboration performs simulations to test the data analysis pipelines and to validate the scientific techniques described in Section 2.1. This process is analogous to the use of Monte Carlo Simulation in high energy physics. An n-body simulation of dark matter halos in a large volume of the Universe is created [29] and evolved until the present time using the chosen cosmology. Galaxies are "painted" [30] onto the matter haloes according to a statistical distribution consistent with the SDSS data. The shapes of background galaxies are distorted by the gravitational lensing from more nearby haloes along the line-of-sight. Stars in our "own galaxy" are added. Mock images are formed [31] using the footprints of the DECam imager, including the addition of cosmic ray hits and bad pixels typical of the science grade CCDs. These mock images are then processed using the actual image data software pipeline [28]. Galaxy and star catalogs are produced and compared with the original simulation. The science codes are tested to determine whether we correctly measured the original cosmology. In addition to validation, this process allows us to estimate the size and correlation of systematic uncertainties within and between measurements.

This process has been carried out in a series of "data challenges", now occurring at decreasing time intervals as first light becomes closer. These data challenges test the preparations of the software algorithms and pipelines so that we are ready-to-operate well before we install the camera at CTIO.

6. Preparations at CTIO Prior to Delivery of DECam

CTIO is making preparations for the arrival of the new camera. Several improvements will improve the image quality and stability. The telescope radial mirror supports, some of which had broken off allowing the mirror to slide around as much as 2 mm depending on declination angle and with "considerable hysteresis", were redesigned and replaced [32] in 2009. A systematic study of the Blanco Dome environment was conducted [33] resulting in a new design for the mirror plenum. The telescope control system is being modernized [34]. The primary mirror aluminizing chamber has been improved. A new control room was built on the ground floor. This larger, more comfortable room includes a new computer room, with support services to include the DECam computers, adjacent to it. A new cleanroom was added to the main floor, in a room adjacent to where the telescope resides. The data transport system is being improved. Changes to the infrastructure required to support the camera services are underway.

7. Discussion

A big part of the success of the DECam Project was due to the early and continuous focus on integration and testing. A full-size prototype imager Dewar, which we called "the Multi-CCD Test Vessel", was among the 1st expensive items that we purchased during R&D in 2004. It allowed us to perform integration work during the design phase and to continue it throughout the project. A consequence was to improve technical planning through its use as a test-bed for every system, as well as several important discoveries and innovations. Using a Telescope Simulator as an integration platform was a novel idea that we expect will be copied in future projects of this scale.

In advance of the DECam Project, we knew that the optical corrector and the CCDs were going to be the long lead-time items. We got started on those two items as early as was possible. Even so, the optical corrector is the last component of DECam to be delivered to CTIO. Our choice of the LBNL CCDs, instead of commercially-available CCDs, was considered an early risk but we felt the improved QE in the near-IR was important-enough to take the chance. Fully-depleted red-sensitive CCDs of this kind are still generally commercially unavailable. Because we did our own CCD packaging and testing, we gained a lot of experience in using the devices, which has lead to “spin-offs” in astrophysics and dark matter searches [35-38].

The emphasis on data challenges ensures that the data management system will be ready in time for the start of the Dark Energy Survey.

8. Summary

The Dark Energy Survey Collaboration will perform a 5000 sq-deg survey of the southern sky and use the data to constrain the dark energy equation of state. In order to perform the survey, it is building the Dark Energy Camera, which will be an NOAO community instrument [39] for the 4m Blanco Telescope at Cerro Tololo. DECam construction is nearly complete. Integration and commissioning on a "telescope simulator" of the major hardware and software components, except for the optics, recently concluded at Fermilab. Most components have been received at CTIO. The SISPI computers, F/8 handling system and LN2 cooling system have been installed. The filter-changer, shutter, and hexapod arrived safely and have been retested there. The imager itself is being held at Fermilab until CTIO is ready for it (expected during October 2011). The optical corrector will be the last part to be shipped to CTIO, arriving during November of this year (2011). First light will be in 2012. The Dark Energy Survey is expected to start in September 2012.

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