DECaLS and DECaPS: DECam Surveys of the Northern Galactic Cap and Southern Galactic Plane

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LBL
DECam NFC 2018
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The DESI Legacy Imaging Surveys

- Extragalactic sky with $\delta > -10^\circ$, 14,000 deg$^2$
- $grz$ filters
- Three telescopes and instruments
  - Blanco 4m + DECam ($grz$, $\delta < 33^\circ$)
  - Bok 2.3m + 90Prime ($gr$, $\delta > 33^\circ$)
  - Mayall 4m + Mosaic3 ($z$, $\delta > 33^\circ$)
- WISE forced photometry
- 3 epochs per filter
- Coadded depths $>24.0$, 23.4, 22.5 mag $grz$ for small galaxies
DESI Legacy Imaging Survey Objectives

- DESI targeting
- Gas in IGM
- Finding and characterizing galaxy clusters
- High redshift quasars
- Milky Way dwarfs & streams
DESI Legacy Imaging Survey Objectives

- DESI targeting ← most effort is here!
- Gas in IGM
- Finding and characterizing galaxy clusters
- High redshift quasars
- Milky Way dwarfs & streams
DESI Legacy Imaging Survey Coverage

DESI Imaging Footprint

Kitt Peak

DECam

DECam

$\delta$ (°)

$\alpha$ (°)

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DESI Legacy Imaging Survey Coverage

![Diagram of survey coverage with DECam and Kitt Peak labels]
DESI Legacy Imaging Survey Coverage
DESI Legacy Imaging Survey Coverage

![Graph showing survey coverage with DECam and Kitt Peak labeled.]
Dynamic Exposure Times

- Ideally want each exposure to robustly detect emission line galaxies of a particular mass and redshift
- Using past exposures, guess exposure time necessary to achieve this
- In DESI, plan is to do this in real time from guider PSF
The Tractor

SDSS

DECam Coadd
The Tractor

SDSS sources

DECam Coadd
The Tractor

New sources

DECam Coadd
The Tractor

Blobs

DECam Coadd
The Tractor

DECam Coadd

DECam Coadd
The Tractor

Model + Noise

DECam Coadd
The Tractor

Model

DECam Coadd
The Tractor

Residuals

DECam Coadd
The Tractor
The Tractor
The Tractor
Catalog Comparison

![Plot showing SDSS data with 'stars' and 'galaxies' plotted on a g - r vs. r - z magnitude diagram.]
Catalog Comparison
WISE Satellite

- **Wide-field Infrared Survey Explorer**
- **Mid-infrared:** W1 ($3.4 \mu m$), W2 ($4.6 \mu m$), W3 ($12 \mu m$), W4 ($22 \mu m$)
- **Primary survey:** 2010-2011; reactivated in 2014–present
- **W1 & W2:** $\sim 100$ exposures of each part of the sky
- **6–7 arcsec FWHM**
WISE photometry

(Targeted in BOSS W3 ancillary; quasar at $z = 2.71$)
The DECam Plane Survey

- DECam survey of southern Galactic plane
- *grizY* filters
- $\delta < -30^\circ, |b| < 4^\circ (5^\circ > l > -120^\circ)$
- roughly main-sequence turn-off at 8.5 kpc through $E(B - V) = 1.5$
- 23.7, 22.8, 22.3, 21.9, 21.0 mag in *grizY* in single exposures
- 3 epochs per filter, observed on adjacent nights
- 3D structure of the Milky Way’s stars, gas, and dust
Source Density

![Source Density Plot]

- Source density distribution over the sky, with latitude ($b$) and longitude ($l$) axes.
- The graph shows variations in source density across different regions of the sky.
- Extending to $|b| < 10^\circ$ now!
20 billion detections of 2 billion objects
Extending to $|b| < 10^\circ$ now!
Pipeline

- Concept: find and fit sources to steadily improve model of image
  - repeat source finding on residual images to find fainter, blended sources
  - Same idea as DAOPHOT, DOPHOT, DOLPHOT.

- Steps:
  1. Sky subtraction
  2. Source detection
  3. Position, flux, and sky determination
  4. PSF determination
  5. Repeat
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Open Cluster NGC 2660
Open Cluster NGC 2660

Very narrow sequence! Secondary binary sequence visible?
CMDs

(236°, −14°)
CMDs

\( (240^\circ, 0^\circ) \)
CMDs

\[(0^\circ, 0^\circ)\]
PS1 Comparison

![PS1 Comparison Diagram]

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PS1 Comparison

![PS1 Comparison Diagram]

DECaPS

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The Legacy Survey Viewer

Browse the sky plane in Dustin Lang’s viewer

Things to do:

- Kitt Peak DESI footprint
- DECam DESI Footprint
- WISE
- Dust and protostars
- White dwarfs
- Clusters
- Nebulosity
- Crowding

http://legacysurvey.org/viewer
The Legacy Survey Viewer

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http://legacysurvey.org/viewer
Conclusions

- DESI Imaging Surveys wrapping this year and early next year
- DECam Plane Survey complete in $|b| < 4^\circ$, ongoing extension to $|b| < 10^\circ$
- Large surveys largely untapped for near-field cosmology work
- Data publicly available at:
  - http://legacysurvey.org
  - http://decaps.skymaps.info
    - images
    - catalogs
    - viewer
    - SQL database via the NOAO Data Lab
Photometric Calibration

- We wish to place all of the DECam observations onto a common magnitude scale, removing the effect of sensitivity variations between
  - the system throughput from night to night
  - the opacity of the atmosphere (from night to night)
  - different regions of the DECam focal plane
- We achieve this by adopting a simple model for the system throughput over the course of the survey
- We constrain the model using repeat observations of the same stars
Photometric Calibration Flat Field

- Flat fields show $\sim 5$ mmag corrections
- True effect is presumably largely chromatic
- Pupil ghost
- Tree rings
- PSF-fitting-related artifacts
- Unstable S7 amplifier
- mounting board in $Y$

$\mu: -1.7 \quad \sigma: 8.2$
Photometric Calibration Flat Field

- Flat fields show $\sim 5$ mmag corrections
- True effect is presumably largely chromatic
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- Unstable S7 amplifier
- mounting board in $Y$

$r
\mu: -1.3
\sigma: 4.4$

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Photometric Calibration Flat Field

- Flat fields show $\sim 5$ mmag corrections
- True effect is presumably largely chromatic
- Pupil ghost
- Tree rings
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- Unstable S7 amplifier
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\[ \mu : -0.2 \quad \sigma : 6.6 \]
Photometric Calibration Flat Field

- Flat fields show $\sim 5$ mmag corrections
- True effect is presumably largely chromatic
- Pupil ghost
- Tree rings
- PSF-fitting-related artifacts
- Unstable S7 amplifier
- mounting board in $Y$

$\mu: 0.0 \quad \sigma: 3.6$
- Flat fields show $\sim 5$ mmag corrections
- True effect is presumably largely chromatic
- Pupil ghost
- Tree rings
- PSF-fitting-related artifacts
- Unstable S7 amplifier
- mounting board in $Y$

\[
\begin{array}{c}
\mu : 0.6 \\
\sigma : 7.4
\end{array}
\]
Median colors of stars
Sky Subtraction

- Improve sky relative to best model so far
- Sky determination should give zero if the model is perfect
- Needs to be fast
- We just take the median in $20 \times 20$ pixel regions
- This should change depending on seeing!
Source Detection

- Convolve image with PSF
- $> 5\sigma$ peaks are candidate sources
- Candidate sources passing blending criteria added to source list
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- $> 5\sigma$ peaks are candidate sources
- Candidate sources passing blending criteria added to source list
- $S_I/S_M > 2B$ or $(S_I/S_M > B) \& (I/M > B)$
  
  $I$ residual image
  $M$ model image
  $S_I$ signal-to-noise of residual image
  $S_M$ signal-to-noise of model
  $B$ blending threshold
Position, flux, and sky determination

- Everything is a point source—life is easy!
- Sky and fluxes are completely linear
- Positions can be linearized via first derivative
- Plug into large sparse linear algebra code
- LSQR, conjugate-gradient type solver, Stanford Systems Optimization Laboratory
- We fit up to 30k stars per $1024 \times 1024$ pixel region, for $\sim 100k$ simultaneous parameters
PSF determination

- Start with best model so far
- Get model for image from linear least squares fit
- Subtract neighbors around each star from model
- Use newly isolated stars to model PSF
- (though we probably should be thinking about an EM solution...)

![PSF Determination Diagram](image-url)
DECaPS PSF model

- start with “ideal-seeing” PSF models
- find parameters of spatially-varying Moffat that convolve with ideal-seeing PSF to match neighbor-subtracted PSFs
- pixel-by-pixel spatially varying model of PSF core (9 × 9 pixel)
- Need to do better!
  - “analytic” model tends to be dominated by core and fail in the wings (∼ 2″ from center)
  - “aperture correction” is the dominant source of photometric calibration error
  - diffraction spikes don’t quite match
  - lots of structure in PSF wings!
  - variations in PSF with color and brightness
Ideal-seeing PSFs

- average PSFs over large numbers of bright stars on very good seeing nights
- Extend 255 pixels from PSF center
- Deconvolved with good-seeing Moffat
- Modeled as sum of Moffats and diffraction spikes
- → noise-free, ideal-seeing PSF
- needs improvement? ideal-seeing PSFs often dominate in the wings
Nebulosity

- How should one deal with ...
Nebulosity

- How should one deal with ...
Nebulosity

- How should one deal with nebulosity?
- No good techniques I know of!
- Only 0.1% of footprint affected
- mask and apply stronger blending & sharpness cuts in these regions
Nebulosity

- How should one mask nebulosity?
- Simple approaches (variance in sky estimates on different scales) break down around bright stars and in crowded regions
- Neural network trained on $\sim5,000$ hand-classified $512 \times 512$ pixel images
- Ultimately did an excellent job flagging nebulous regions
- This image: 100% nebulous ✓
Photometric Calibration

- We calibrate each detection with a zero point $Z$ so that
  \[ m = m_{\text{inst}} + Z \]
- We take \( Z = a - kx + f \), with
  - $a$: system zeropoint (one parameter per night)
  - $k$: atmospheric opacity (one parameter [whole survey!])
  - $x$: airmass of observation
  - $f$: flat field (10,000 parameters)
- We then solve for the parameters of this model for $Z$, to minimize
  \[
  \chi^2 = \sum_o \sum_i \frac{(m_{o,i} - \overline{m}_o)^2}{\sigma_{o,i}^2}
  \]
- Note: 10,000 parameters, constrained using hundreds of millions of observations
- Same technique as Padmanabhan et al. (2008) for the SDSS
Photometric Calibration Nightly QA

- 5 mmag precision in any given exposure
- 1% rms residuals, correlated with wings of PSF
- poor “aperture correction”; c.f. \( \sim 3 \) mmag in PS1
- we should have enough information to get this right!
Mosaicing scheme

- Don’t want to fit $4096 \times 2048$ pixel images simultaneously
- Cut into $1024 \times 1024$ pixel blocks (primary plus 50 pix overlap)
- Add stars from primary regions of other blocks to model for this block, fixing their fluxes.
- Really should have done sky subtraction, source detection, and PSF fitting steps on full image, and just introduced a mosaicing scheme for the least-squares fit.