Research Methods in Astrophysics
An Abridged Tail: Mapping the Palomar 5 Tidal Stream with DECam

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Abstract of Scientific Justification (will be made publicly available for accepted proposals):
Palomar 5 (Pal 5) is a gravitationally disrupting Milky Way globular cluster exhibiting prominent tidal tails. These tails show tantalizing evidence for stellar density variations. Such features can form when a dark matter subhalo passes through the stream, heating stars and creating density irregularities. However, variations are also a natural consequence of the cluster’s dissolution process, with eddies and wakes predicted along the debris tail. At the depth of SDSS, the observed Pal 5 density variations are at the level of stochastic background variations, and cannot yet verify or rule out either scenario. We propose to image the entire Pal 5 system with DECam to gzi=24, two magnitudes fainter than the SDSS limit. Our goal is to create a high significance density map along the entire stream to test the origin of density variations. We will map beyond the SDSS footprint, providing improved constraints on the interaction history of Pal 5 with the Milky Way. The FOV and sensitivity of DECam are well matched to this experiment. The proposed data will yield unique insights into the clumpiness of the Milky Way’s dark matter halo, as well the physics of cluster dissolution.

Summary of observing runs requested for this project

<table>
<thead>
<tr>
<th>Run</th>
<th>Telescope</th>
<th>Instrument</th>
<th>No. Nights</th>
<th>Moon</th>
<th>Optimal months</th>
<th>Accept. months</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CT-4m</td>
<td>DECam</td>
<td>3</td>
<td>dark</td>
<td>May - Jun</td>
<td>Apr - Jul</td>
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Scheduling constraints and non-usable dates (up to four lines).
Scientific Justification

Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.

Stellar streams in the Milky Way halo provide irrefutable evidence that our Galaxy was formed, at least in part, hierarchically via the tidal disruption of dwarf galaxies and globular clusters. Finding and characterizing tidal streams is a crucial test for structure formation models. On global scales, streams can constrain the radial profile, shape and orientation of the Milky Way’s dark-matter halo (e.g., Koposov et al. 2010, Law & Majewski 2010). Streams are also useful probes of small-scale dark matter structures. While debris from larger satellites such as the Sagittarius dwarf galaxy are largely unaffected by small subhalos in the Milky Way (Johnston et al. 2002), long cold streams from systems such as globular clusters are expected to suffer direct impacts from these ‘missing satellites’. Impacts with dark matter subhalos can both dynamically heat a stream and create gaps in surface density along the debris (Yoon et al. 2011, Carlberg 2012).

Pal 5 – A Unique Probe of the Milky Way Potential: The Pal 5 tidal stream is thin and long, spanning an impressive $\sim 30^\circ$ in the SDSS (Odenkirchen et al. 2003, Carlberg et al. 2012). No other globular cluster shows such prominent tidal tails at a comparable distance ($\sim 23$ kpc). The tails hint at a pattern of stellar over- and under-densities which cannot be explained by reddening variations alone. While some studies attribute density variations to subhalo encounters (e.g., Siegal-Gaskins & Valluri 2008, Carlberg 2013), the physics of tidal disruption also impart such inhomogeneities in the form of epicyclic overdensities (e.g., Küpper et al. 2008). Thus any interpretation requires disentangling the effects of nature (internal dynamics) versus nurture (influence of the parent halo) on a tidal stream.

Internal Dynamics versus Dark Matter Clumps? Internal and external processes are predicted to have different effects on a stream. Gaps induced by perturbations from passing dark subhalos will be irregularly spaced and have larger amplitude as compared to internal cluster dynamics (Yoon et al. 2011). Internal effects are episodic over the phase and eccentricity of an orbit, thus variations should appear regularly spaced along the debris (Küpper et al. 2012). There is tantalizing evidence that the more ‘regular’ overdensities close to the Pal 5 cluster ($227^\circ < \alpha < 234^\circ$; Fig. 1) can be attributed to intrinsic stream dynamics (Küpper et al. 2012, Carlberg et al. 2012), while a large gap at $\alpha > 234^\circ$ may be dark matter induced (Carlberg 2009). However, at the SDSS depth, the analysis requires significant smoothing which influences the number and position of the recovered overdensities. Further, the signal is dominated by foreground Milky Way stars such that the size and distribution of the gaps cannot be unambiguously identified. To robustly differentiate between these processes, the density of the Pal 5 stream must be mapped to deeper magnitudes (and therefore higher significance) than the current SDSS data allow.

At a magnitude limit of $r \sim 22$, within the color-magnitude region occupied by Pal 5, we observe 70% Milky Way foreground stars with a stochastic variation of 10-20%, and 30% Pal 5 stars (based on the SDSS data itself). The variation in the Milky Way foreground are comparable to that of the predicted epicyclic variations. Deeper imaging increases the contrast between Milky Way and Pal 5 stars, although it also increases the signal from unresolved background galaxies (Figure 3). At $r = 24$, we predict 70% Pal 5 stars and 30% foreground, therefore ensuring that variations of $\sim 30\%$ are significantly above the background fluctuations (Figure 2).

DECam as a Major Advance: We propose DECam imaging of the entire Pal 5 stream to $gzi = 24$. Unlike any previous imager, the DECam FOV includes both the Pal 5 stream and background regions in a single pointing. We will map the stream beyond the SDSS footprint in both directions. These data will place definitive constraints on the physics of tidal streams and on dark matter substructure in the Milky Way halo.
References


Figure 1: (Left) A stellar density map obtained via matched filtering in SDSS DR8 (see Bonaca et al. 2012 for details). The Pal 5 cluster and stream are visible as darker areas corresponding to higher stellar density regions. (Right) Stellar density map of an N-body model of the Pal 5 system that fits the current SDSS data. Overplotted on both panels is the DECam footprint showing our observing strategy: 30 pointings along the stream that have 3% overlaps and extend the SDSS coverage by 4° for the trailing arm and 15° for the leading arm. Pointings outside the SDSS footprint are shown in blue. The pointing of the cluster center is bolded.
Figure 2: (Top) Stellar density profile based on a N-body model of Pal 5 in the stream coordinate system, where $x = 0$ is the cluster center, and $x$ increases along the trailing tail. Shown are two magnitude cuts: $g < 22$ in gray, comparable to the SDSS coverage, and $g < 24$ in black, comparable to the proposed DECam data. (Bottom) Corresponding stellar density maps at these two photometric depths. Deeper photometric coverage will double the confidence in recovery of Pal 5 overdensities, while the expected increase in the Milky Way foreground variations is marginal.

Figure 3: We will observe Pal 5 in the $gzi$ filters to minimize unresolved background galaxy contamination. Data from the DECam Magellanic Clouds survey (SMASH) suggests that the $gzi$ filters are optimal for star-galaxy separation. (Left) Color-color diagram of all stellar-like objects in LMC fields, the stellar locus is marked with a red-white dashed line. (Center) CMD for all the photometric sources, including the “cloud” of unresolved galaxies at $g > 23$. (Right) CMD after applying the stellar locus cut, which removes most of the unresolved galaxies. The Pal 5 isochrone is overplotted in white for comparison.
Experimental Design

Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you’ve requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)

Overview: Our goal is to map stellar density along the Pal 5 stream accurately and homogeneously. Such observations can differentiate the effect of subhalo encounters on a stream from non-uniformities due to internal stream dynamics. To achieve this we will use DECam to image the entire Pal 5 stream \( \sim 2 \) magnitudes deeper than SDSS to a depth of 24 in three bands: \( gzi \). The depth is chosen based on our calculations of the expected density of Pal 5 stars as a function of magnitude.

Observing Strategy: The need for homogeneous photometry is as important as the depth. The reddening, \( E(B-V) \), varies from 0.04 – 0.14 along the stream, resulting in a maximum of 0.3 difference in extinction across the requested fields (Schlafly & Finkbeiner 2011, Schlegel et al. 1998). We will integrate slightly longer in regions of higher reddening to ensure that we reach uniform depth at all pointings. We will also integrate a half magnitude deeper at the center of Pal 5 (\( gzi = 24.5 \)) in order to construct a high S/N template CMD in the same filter system when searching for weak signals in the tail. Finally, we will build in 3% overlaps between all of our pointings to ensure consistent photometry.

The SDSS footprint covers the trailing tail of Pal 5 (to the left in Fig. 1) significantly further than the leading tail. As seen in the right panel of Fig. 1, models suggest the extent of the tails should be nearly symmetric (Küpper et al. 2012). The surface density of the trailing tail broadens and drops off quickly at \( \alpha > 240^\circ \) (Küpper et al. in prep), implying that the SDSS coverage may be approaching the end of the stream. We therefore propose to extend coverage of the trailing stream by \( 4^\circ \) to test whether the stream does indeed end there. We will extend coverage of the leading tail to match the trailing one, mapping \( 15^\circ \) further than the SDSS coverage. Since both tails are expected to broaden, we will fan out the pointings on either side. Our observing strategy is shown in Fig. 1.

Background Contamination: In addition to Milky Way foreground stars, an important contamination source at \( g \sim 24 \) is unresolved galaxies. Co-I Nider has performed detailed analysis of star/galaxy separation using \textit{ugriz} data from the DECam Magellanic Clouds survey (SMASH). Selecting only sources in the \( gzi \) stellar locus defined in the right panel of Figure 3 removes most of unresolved galaxies from the sample. We will further rely on shape parameters (DAOPHOT chi/sharp and SExtractor stellaricity) in order to minimize galaxy contamination. We will use our best seeing conditions for \( i^-\)imaging to improve our shape measurements.

Our Team: Our team is well poised to attain these science goals. The proposed data will be part of Co-I Bonaca’s PhD thesis, supervised by PI Geha. Bonaca led the discovery of the most recent Milky Way stream (Bonaca, MG, NK 2012) and is currently working on numerical modeling of streams in the Via Lactea simulation. PI Geha will have overall responsibility for the project. Bonaca will lead the data reduction and analysis supervised closely by Geha. Co-I Küpper has extensively modeled the global orbit and the small-scale structure of the Pal 5 system. Together with Bonaca and Johnston, Küpper will lead the theoretical modeling of the data (e.g., Küpper et al. 2012). Kallivayalil has expertise in Local Group dynamics and orbit modeling (e.g., Kallivayalil et al. 2013). Nidever is experienced with the DECam instrument, and will advise on the data reduction and analysis and star-galaxy separation (Figure 3).

Proprietary Period: 18 months
No additional observing resources are required to achieve our science goals stated above. However, we have several ongoing projects focused on Pal 5 which supplement the proposed data.

**Velocities in the Stream:** PI Geha has amassed a dataset of radial velocities for ~ 150 Pal 5 stream members - a factor of 10 increase over published measurements - with KECK/DEIMOS and WIYN/HYDRA. These will provide additional phase space constraints in modeling the stream. We note, however, that the effects of substructure on a stream's velocity signature are more complex as compared to photometry, and generally thought to broaden the dispersion along a stream. The experiment proposed here is by contrast relatively straightforward with deep imaging.

**HST Proper Motion of Pal 5:** Co-I Küpper is PI on a successful Cycle 20 HST proposal to measure the proper motion of the Pal 5 core, and of two pencil-beams through the stream. This will greatly aid in constraining the Pal 5 orbit, and reduce the phase-space involved in modeling the global properties of the system. The density measurements proposed here will complement the radial velocity and proper motion data to fully characterize the Pal 5 system.

**Numerical Modeling of the Pal 5 Stream:** Co-I Küpper is leading a theoretical study aimed at modeling the Pal 5 stream using a Bayesian approach. The investigation uses the 17 radial velocities of the Pal 5 stream from the literature and the SDSS data to constrain the gravitational potential of the Milky Way, specifically its mass profile and shape to better than 20% accuracy. The modeling yields accurate estimates of Pal 5’s mass and distance, independent of other methods. The requested imaging data in combination with the above available radial velocity data will boost the accuracy of constraints coming from such investigations.

**Grants:** The proposed data will be part of Co-I Bonaca’s PhD thesis. PI Geha has sufficient funding to support Bonaca throughout her thesis, as well as funds for observing travel.

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**Previous Use of NOAO Facilities**

List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.

The PI has not obtained data through NOAO in the past two years.
Observing Run Details for Run 1: CT-4m/DECam

## Technical Description

Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).

**Target Depth and Accuracy:** We will map the Pal 5 stream using DECam in the gzi bands down to 24th magnitude. The requested photometric depth is two magnitudes below the SDSS limit. Our goal is to create a high significance density map along the entire stream to test the origin of density variations. For the Pal 5 cluster itself, we will observe to gzi=24.5 (one pointing) in order to build a higher S/N template for this analysis. We chose three photometric bands to improve star/galaxy separation (Figure 3) and will use the best-seeing conditions to image in the i-band to improve shape measurements. We aim for a S/N=20 (magnitude errors of 0.05) in gi and S/N=10 in z in order to get high-precision photometry at the requested depth.

**Exposure Time Request:** As shown in Fig. 1, we request 30 pointings along the stream with 3% overlaps. We will integrate a half magnitude deeper in the pointing centered on the core of the cluster. The DECam ETC estimates that to reach a S/N = 20 in the giz-bands requires 800s, 800s and 1000s, respectively. This is confirmed via pilot observations from Co-I Nidiver shown in Figure 3. We will use a 5-point dither pattern at each of these pointings in order to minimize pixel-based errors. Taking into account a readout time of 40s per dither-pointing and an additional 3 minutes overhead for field acquisition and small-angle changes associated with the dithering, we calculate 2800 seconds per field. We request a total of 30 pointings, or a total time request of 24 hours. Assuming 8 hours of dark time per night, we request 3 nights with the CTIO DECam.

**Data Reduction Plan:** We will use the products from the DECam Community Pipeline which produces flat, calibrated images. We will perform point source photometry using DAOPHOT’s ALLFRAME on individual images and estimate photometric uncertainties and completeness levels via artificial star tests. The availability of SDSS data for a majority of the proposed DECam region will be used for accurate photometric calibrations. We will select Pal 5 members from our final catalogs using a matched filter technique and produce final stellar density maps similar to the methods described in Bonaca, Geha & Kallivayalil (2012). We will make our final photometric catalogs and Pal 5 density maps publicly available after publication.

## Instrument Configuration

<table>
<thead>
<tr>
<th>Filters: g, z, i</th>
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<tbody>
<tr>
<td>Grating/grism:</td>
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<tr>
<td>Order:</td>
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<td>Cross disperser:</td>
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<table>
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<tr>
<th>Slit:</th>
<th>Multislit:</th>
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<td>λ_{start}:</td>
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<td>λ_{end}:</td>
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<td>Fiber cable:</td>
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<td></td>
<td>Corrector:</td>
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<td></td>
<td>Collimator:</td>
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<tr>
<td></td>
<td>Atmos. disp. corr.:</td>
</tr>
</tbody>
</table>

**R.A. range of principal targets (hours):** 14 to 16

**Dec. range of principal targets (degrees):** -15 to 8

## Special Instrument Requirements

Describe briefly any special or non-standard usage of instrumentation.
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Why learn SQL?

SQL is the query language used most commonly in Astronomy (SDSS, Millenium simulation), but also in other industries.

Learning SQL has the added benefit of forcing you to confront and understand the data structures used to store information. Becoming comfortable with the tables in your database may be key to sprouting new scientific ideas.

Good Book on SQL accessible for free from the UVa library:

http://search.lib.virginia.edu/catalog/u5401648
Intro to Databases

- What is a Database? A *database* is nothing more than a set of related information.

- Massive: much larger than PC memory; TB; PB

- Data is the constant: as opposed to programs; multiple programs operate on the same data

- “Concurrency control”: multi-user

- Physical data independence: operations on data are independent from the way the data is laid out.

- Related concept: high level, ‘declarative’, query languages (SQL)
The Relational Model

In 1970, Dr. E. F. Codd of IBM’s research laboratory published a paper titled “A Relational Model of Data for Large Shared Data Banks” that proposed that data be represented as sets of tables. Rather than using pointers to navigate between related entities, redundant data is used to link records in different tables.

show video on “intro to relational model”
Useful to underscore that:

- relations = tables
- attributes = columns
- tuple = row has a value for each attribute
- each attribute has a type or domain
Useful to note that queries return relations (or tables) “closure of a language”
What Is SQL?

Along with Codd’s definition of the relational model, he proposed a language called DSL/Alpha for manipulating the data in relational tables. Shortly after Codd’s paper was released, IBM commissioned a group to build a prototype based on Codd’s ideas. This group created a simplified version of DSL/Alpha that they called SQUARE. Refinements to SQUARE led to a language called SEQUEL, which was, finally, renamed SQL.
**SQL: A Nonprocedural Language**

Most programing languages = defining variables, using conditional logic (i.e., if-then-else) and looping (i.e., do while ... end), and breaking your code into small, reusable pieces (i.e., objects, functions, procedures).

Compiler ----> executable = exact results (complete control).

Java, C#, C, Visual Basic, etc. ----> *procedural* language.

SQL ----> give up some control. SQL statements define inputs and outputs.

Statement execution ----> *optimizer*.

The optimizer ----> table configuration, available indexes ---› decides the most efficient execution path.

*Optimizer hints* (e.g., suggesting indexes to be used).

Most SQL users leave such tweaking to their database administrator or performance expert.
• SQL or “sequel” (apparently the “in thing” in industry).

• Supported by all major commercial database systems.

• Been around for decades; standardized.

• Interactive via GUI or prompt.

• Based on relational algebra (formal language).
Two components

- Data Definition Language (DDL):
  - create table, etc.

- Data Manipulation Language (DML):
  - select, insert, delete, update, etc.
The basic “SELECT” statement:

Select $A_1, A_2, \ldots, A_N$
From $R_1, R_2, \ldots, R_N$
Where condition
The basic "SELECT" statement:

3. Select \( A_1, A_2, \ldots, A_N \)
2. From \( R_1, R_2, \ldots, R_N \)
1. Where condition
The basic “SELECT” statement:

3 Select $A_1, A_2, \ldots, A_N$
1 From $R_1, R_2, \ldots, R_N$
2 Where condition

what to return
relations
combine/filter

show “Basic SELECT statement” video
Next Generation: LSST
• Next generation: LSST (2020 or so).

• Wide, fast, deep: 8.4m, f/1.9 primary, $9.6^2$ degrees FOV, 3.2 Gpixel camera.

• 10,000 sq. degrees of sky to be covered twice per night every 3 nights.

• Over half the sky will be visited 1000 times over 10 years. Top ranked in Decadal Survey.
Every ten years the National Research Council releases a survey of astronomy and astrophysics outlining priorities for the coming decade. The most recent survey, titled “New Worlds, New Horizons in Astronomy and Astrophysics”, provides overall priorities and recommendations for the field as a whole based on a broad and comprehensive examination of scientific opportunities, infrastructure, and organization in a national and international context.

Key areas: Cosmology and Fundamental Physics; Galaxies Across Cosmic Time; The Galactic Neighborhood; Stars and Stellar Evolution; Planetary Systems and Star Formation; Electromagnetic Observations from Space; Optical and Infrared Astronomy from the Ground; Particle Astrophysics and Gravitation; and Radio, Millimeter, and Submillimeter Astronomy from the Ground.
Decadal Survey (2010)

Panel on Stars and Stellar Evolution (SSE) Membership
Roger Chevalier, Chair, University of Virginia
Robert Kirshner, Vice Chair, Harvard-Smithsonian Center for Astrophysics
Deepto Chakrabarty, MIT
Suzanne Hawley, University of Washington
Jeffrey Kuhn, University of Hawaii
Stanley Owocki, University of Delaware
Marc Pinsonneault, The Ohio State University
Eliot Quataert, University of California at Berkeley
Scott Ransom, National Radio Astronomy Observatory
Hendrik Schatz, Michigan State University
Lee Anne Willson, Iowa State University
Stanford Woosley, UCSC

Panel on Optical and Infrared Astronomy from the Ground (OIR) Membership
Patrick S. Osmer, Chair, The Ohio State University
Michael Skrutskie, Vice Chair, University of Virginia
Charles Bailyn, Yale University
Betsy Barton, University of California Irvine
Todd Boroson, National Optical Astronomy Observatory
Daniel Eisenstein, University of Arizona
Andrea Ghez, University of California Los Angeles
J. Todd Hoeksema, Stanford University
Robert Kirshner, Harvard-Smithsonian Center for Astrophysics
Bruce Macintosh, Lawrence Livermore National Laboratory
Piero Madau, University of California Santa Cruz
John Monnier, University of Michigan
Iain Neill Reid, Space Telescope Science Institute
Charles E. Woodward, University Of Minnesota
The survey took place over eighteen months and had two overlapping phases.

Phase I: concerned with establishing a science program, fact-finding, and establishing a procedure for the second phase. The second phase will be mostly

Phase II: concerned with creating a prioritized, balanced, and executable series of research activities—that is, ground- and space-based research programs, projects, telescopes, and missions—that will define the forefront of astronomy and astrophysics for the decade 2010-2020.
New Worlds, New Horizons in Astronomy and Astrophysics

Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010
Community Input

An unprecedented response

- 324 Science White Papers (a unique snapshot of the field)
- 69 State Of The Profession Position Papers
- 70 White Paper on Technology Development, Theory, Computation, and Laboratory Astrophysics
- 108 Community Responses to a Request for Information on Research Activity Proposals
- Email Inputs to the Committee
- Community-organized Town Halls
Science Objectives

• Building on the science priorities identified by the survey, the recommended program is organized by three science objectives that represent its scope:
  − Cosmic Dawn
  − New Worlds
  − Physics of the Universe

• Success in attaining these science goals will enable progress on a much broader front

• Also foster unanticipated discoveries
Cosmic Dawn
Searching for the first stars, galaxies, and black holes

- We have learned much about the history of the universe, from the Big Bang to today
- A great mystery now confronts us: when and how the first galaxies formed and the earliest stars started to shine - our cosmic dawn
- JWST, ALMA and radio telescopes already under construction will help point the way
- Approaches:
  - Locating “reionization” – finding the epoch ~0.5 billion years, when light from the first stars split interstellar hydrogen atoms into protons and electrons
  - “Cosmic paleontology” – finding the rare stars with the lowest concentrations of heavy elements
New Worlds
Seeking nearby, habitable planets

- Nearly 500 extrasolar planets now detected - extraordinarily rapid progress
  - Huge range of properties exhibited, surprisingly different from those in our own solar system
  - Many ongoing approaches seek new “Earths” – potentially habitable rocky planets with liquid water and oxygen
  - New techniques being developed
- Kepler data adds over 300 "candidates" to the list, including many less than twice the size of Earth
- Next great step forward: understand frequency of different types of planets and lay scientific and technical groundwork to inform future strategies for detailed study of nearby Earth-like planets
Physics of the Universe
Understanding Scientific Principles

- Determine properties of dark energy, responsible for perplexing acceleration of present-day universe
- Reveal nature of mysterious dark matter, likely composed of new types of elementary particles
- Explore epoch of inflation, earliest instants when seeds of structure in the universe were sown
- Test Einstein’s general theory of relativity in new important ways by observing black hole systems and detecting mergers
Balancing the Program

- Large *and* small/medium activities
- Existing *and* new facilities
- Known science objectives *and* discovery space
- Promise *vs.* risk
- Ground *and* Space
- 2020 *and* 2030
Large Scale Space Program - Prioritized

1. Wide Field InfraRed Survey Telescope (WFIRST)

2. Explorer Program Augmentation

3. Laser Interferometer Space Antenna (LISA)

4. International X-ray Observatory (IXO)
WFIRST - Science

Near infrared wide-field telescope with a set of key science objectives:

- **Dark energy** (part of a coherent ground-space strategy):
  - Baryon acoustic oscillations
  - Distant supernovae
  - Weak lensing

- **Exoplanet statistics**
  - Gravitational microlensing

- Guest investigator mode enabling survey investigations
Explorer Program - Science

- Rapid, targeted, competed investigations
- Versatile program delivers high scientific return
- WMAP, Swift, GALEX, WISE… are extraordinarily successful past examples
- NuSTAR, GEMS, Astro-H very promising
• In past, program reduced to pay for costs of major NASA activities

• **RECOMMEND Restoration of Explorer line** to enable astrophysics launch rates originally envisaged

• Proposed increase from $40M to $100M per year for astrophysics missions -- Low risk

• Support two new MidScale (MIDEX), two new Small (SMEX) Explorers, and at least four Missions of Opportunity (MoO) over decade

• Essential to maintaining breadth and vitality of space astrophysics program
Medium-Scale Space Program - Prioritized

1. **New Worlds** Technology Development Program

2. **Inflation** Technology Development Program
New Worlds Technology Development Program

• To achieve New Worlds objective – studying nearby, habitable exoplanets - need preliminary observations before choosing a flagship mission:
  – Planetary demography over wide range of conditions:
    ▪ Kepler, WFIRST, integrated ground-based program
  – Measurement of zodiacal light:
    ▪ Ground-based telescopes.
    ▪ Sub-orbital and explorer mission opportunities.

• In parallel, need technology development for competing approaches to make informed choice in second half of decade

• RECOMMEND $100-200M over decade

• Planned integrated ground-space exoplanet program
Inflation Technology Development Program

- Ground-based microwave background telescopes seek “B-mode polarization,” sensitive signature of processes from epoch of inflation, thought to have occurred during earliest moments of the universe.

- If signal is seen from ground then space-based mission with at least ten times greater sensitivity is warranted and associated technology development is needed.

- RECOMMEND $60-200M over decade, conditional on signal detection.
Large-scale Ground-based Program - Prioritized

1. Large Synoptic Survey Telescope (LSST)
2. Mid-Scale Innovations Program
3. Giant Segmented Mirror Telescope (GSMT)
4. Atmospheric Cerenkov Telescope Array (ACTA)
LSST- Science

- Efficient, deep optical survey telescope
- Will transform observation of the variable universe and address broad questions:
  - Dark energy using gravitational lensing and supernovae
  - Dark matter
  - Near-Earth, Kuiper-belt objects
  - Solar neighborhood
  - Transient phenomena
    - Gamma-ray bursts, Variable stars, Supernovae…
- Publicly accessible archive – >100 Pbyte