Destiny

Dark Energy Space Telescope

DESTINY is a ~1.8m class near-IR telescope/camera orbiting at Earth-Sun L2. It is a candidate architecture for the NASA-DOE Joint Dark Energy Mission (JDEM).

Science Objectives: **"To constrain the nature of dark energy"**

1. In combination with rich ground-based SN samples at $z < 0.8$, constrain w_o to ~0.02 and w' to < 0.2 over the complete redshift interval $0 < z < 1.7$.
    - Obtain precision photometry, light-curves, and redshifts of >2000 SN Ia over the redshift range $0.5 < z < 1.7$.
    - Observe spectral evolution of all SN Ia over their lifetimes; track effects of metallicity and other systematics.
    - Characterize SN II and other SN types present in the observations for independent analysis.
2. Investigate dark matter distributions and large-scale structure to constrain dark energy.

Mission Profile and Measurements:

1. Observe a < 7.5 sq. degree "blank-sky" field near the north ecliptic pole.
2. Obtain NIR grism images of individual camera fields with 4 – 8 hr exposures to build up light-curves over the total contiguous survey area. Repeat observations of the field with a 5-10 day cadence.
3. Observe for a 3-month interval while holding spacecraft roll constant. Roll ~90° at the conclusion of the interval and continue monitoring the survey area.
4. At the conclusion of the initial year, use image-differencing to isolate SN spectra from the complementary year.
5. Automate spacecraft operations; no time critical decisions or scheduling for survey observations.
6. Grism spectra provide SN classification, redshifts, and photometry; eliminates k-corrections.
7. Imaging mode available for lensing and galaxy assembly studies.
8. Data immediately public, similar to HST Treasury or Spitzer Legacy programs, for rapid community follow-up and coordination.

Performance Requirements and Implementation Summary:

Telescope:	~1.8m class primary mirror; three-mirror anastigmat
Image Scale:	~ 0.13 arcsec/pixel
Wavelength Coverage:	< 0.85 – 1.7μm
Field of View:	< 15′× 60′
Wavelength Multiplexing:	Grism provides continuous R ~ 75 spectral coverage over 0.85 – 1.7μm
Detectors:	< 36 hybridized 2k×2k HgCdTe focal plane arrays
Data Volume:	< 30 GB per day raw; < 1 GB per day with on-board image stacking
Mission Duration:	2-yr minimum mission; up to 6-yr extended mission

Proposal History: Approved as a NASA Type-1 Dark Energy Probe mission concept study.

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Science & Technology Related Missions: HST-ACS/WFC3, Spitzer, Kepler, WISE, JWST

1. The Nation's Multi-Agency Science Enterprise

We support the appointment of a Dark Energy Task Force (DETF) to examine the best approaches to studying the "dark energy" that drives the acceleration of universal expansion, perhaps the greatest mystery in modern physics and cosmology. With the potential of dark energy research to uncover new, fundamental physics governing the origin, evolution, and destiny of the universe, we concur with organizing a body of knowledgeable scientists to help "systems engineer" the government's research enterprise. The DETF along with the CMB Task Force serve as models for coordinating other cross-cutting scientific areas, such as galaxy and star formation, extrasolar planets, fundamental physics of the Big Bang, etc. Such task forces should also be aligned with future NRC Decadal Surveys on the physics of the universe, astronomy and astrophysics, and planetary science.

2. Dark Energy Research with *Destiny*: A Coordinated Investigation

The science community has voiced strong support for future dark energy research that would rely on resources and facilities provided by NSF, NASA, and DOE. We emphasize the need for interagency cooperation and coordination to foster a range of dark energy investigation strategies; our understanding of dark energy, and the physics underlying it, is in its infancy. The NASA-DOE Joint Dark Energy Mission (JDEM) should be viewed as one component of a multi-agency sequence of investments.

Resources for dark energy research (whether for theoretical studies, mission and instrumentation construction, or data analysis – all of which are crucial) should be competed openly to the community. National labs and centers should play important managerial roles in this coordination, but the total effort should derive from a partnership of academic institutions, industry, and national labs/centers.

The philosophy behind our approach to the space-based *Destiny* dark energy mission concept for JDEM is to minimize cost and complexity. By collecting as much complementary data as possible via cheaper ground-based facilities, we can ensure that JDEM's requirements are confined solely to the information that can only be obtained from space observations. (Indeed if JDEM's requirements are too broad, it may be more cost-effective to construct separate smaller missions instead of one large facility.) Our strategy emphasizes openness and efficiency in sharing ground-based and space-based data and results among researchers.

2.1 *Destiny* Mission Concept

While the properties of dark energy may be explored through many observational paths, its existence was first revealed through SN Ia observations. More critically, its plausible equations of state and their possible variations with cosmic time make clear and discriminatory predictions for what a richly observed SN Ia Hubble diagram will look like (e.g., see the review by Kirshner 2003). We have therefore focused *Destiny*'s capabilities towards providing SN Ia photometry and spectra over redshifts $0.5 < z < 1.7$. These observations will be coordinated with a vigorous ground-based effort to obtain equivalent data at the lower redshift range of $0 < z < 0.8$. We seek to optimize the path to a complete description of the expansion history of the universe for $z < 1.7$ by blending the complementary strengths of ground-based programs at low redshifts with those of a near-infrared (NIR) space-based camera for higher redshifts. The complete program will provide full coverage over $0 < z < 1.7$, while allowing for cross-calibration of the ground and space photometric data in the overlapping range of $0.5 < z < 0.8$.

Using a space-based camera to focus on $z > 0.5$ is also the most sensible path for building on ground-based work (e.g., CfA Supernova Program, ESSENCE, CFHT Legacy, Katzman Automatic Imaging Telescope, Carnegie Supernova Program, Nearby Supernova Factory) and space-based observations with *HST* (e.g., PANS) that are already underway. In the coming years we should see excellent statistics in the SN Ia Hubble diagram at $z < 0.8$ and additional constraints from *HST* for $z < 1.7$ (especially if the WFC3 instrument is installed).

A complete exploration of the suite of dark energy candidates requires suitable SN Ia statistics over the full range $0 < z < 1.7$ (Linder & Huterer 2003). We can parametrize the properties of the dark energy in terms of its equation of state, $p/\rho c^2 = w$, that connects the energy density to the pressure. The simplest case of a cosmological constant, $w = -1$ at all redshifts, yields a specific prediction of how the present epoch of acceleration transitions to deceleration at redshifts best explored by a NIR space-based camera. More generally, however, many dark energy models, such as quintessence, predict variable w with z. Parameterizing this possibility as $w = w_0 + w' z$, these models may be distinguished by their locations in the w_0 vs. w' plane. Disentangling w_0 from w' is only possible with a large redshift interval well beyond what can be sampled precisely from the ground. These considerations are not trivial: while the cosmological constant (or vacuum energy) is the most venerable candidate for the dark energy, its small but non-zero value is difficult to understand (Weinberg 1989) and has disturbing consequences for any theory of quantum gravity (Dyson, Kleban & Susskind 2002). Adequate statistics built on precise SN Ia observations of the expansion history at $z > 0.8$ are required no matter how $w(z)$ is parameterized; the interval $z < 0.8$ is much too limited to discriminate among the various dark energy candidates.

The *Destiny* mission concept is a ~1.8-meter class NIR grism-mode space telescope optimized to return a richly sampled Hubble diagram of Type Ia supernovae over the redshift range $0.5 < z < 1.7$. These data will be important for determining cosmological distances, inferring the expansion rate of the universe as a function of time, and characterizing the nature of dark energy.

The primary instrument on *Destiny* is an all-grism NIR survey camera. SNe will be discovered by repeated imaging of an area located at the north ecliptic pole (NEP). Grism spectra with resolving power $\lambda/\Delta\lambda = R \approx 75$ will provide broad-band spectrophotometry, redshifts, SN classification, as well as valuable time-resolved diagnostic data for understanding the SN explosion physics. This approach features a single instrument, with a single mode of operation, and a single detector technology. The multiplex advantage of being able to observe a large field-of-view over a full octave in wavelength simultaneously makes this approach highly competitive with broad-band imaging techniques.

Destiny is designed as a cost-effective investigation of the nature of dark energy in the universe; it will return *essential* information that *must be gathered from space*. Data gathered from *Destiny* will be combined with those of other facilities (e.g., LST, JWST, etc.) studying large-scale structure and the Cosmic Microwave Background (CMB) to provide a complete picture of how dark energy manifests itself in the past evolution and fate of the universe. By limiting the scope of *Destiny* to the essential capabilities only, we will be able to retain the lifetime mission costs within a “medium-size” funding envelope. In our mission concept, NASA funding would be used to construct the observatory and launch it; DOE funding would be used for mission operations, flight software development, and data storage and analysis. We also would propose for NSF support of a ground-based coordinated observing program. *Destiny* relies on synergistic interagency cooperation toward a common scientific goal that leverages expertise and experience of each agency and organization.

The basic goals in this mission concept are to detect and characterize SNe at redshifts $z > 0.5$ with high efficiency, while minimizing instrumentation requirements, operating modes, telemetry, costs, and complexity. Our concept (1) requires only one detector technology and minimizes the total pixel count; (2) eliminates the need for a separate spectrograph; (3) restricts the number and complexity of operational modes; (4) minimizes the required simultaneous FOV; (5) eliminates k-corrections; (6) heavily leverages observing techniques and technologies developed for other missions such as *HST* and *JWST*.

The SN Ia Hubble diagram requires photometry, but the *Destiny* grism spectra will also yield redshifts and discriminate between SN Ia and SN II events; we will obtain time-resolved grism spectra of *all* supernovae in our survey. Thus we will gather large datasets on both SN Ia and SN II events (plus other rarer SN types). We may therefore make use of the SN II data to provide independent luminosity-based distance measurements (e.g., Hamuy & Pinto 2002). Even if the derived SN II Hubble diagram is less precise, severe deviations from the SN Ia results could reveal important systematic effects in one or both methods.

The design of the grism survey is dictated by the basic exposure sequence, plus the need to resample the survey area at regular intervals to track the luminosity evolution of SN events. The fiducial exposure time is 4 hours for each *Destiny* field. During the exposures, the spacecraft pointing remains fixed, minimizing the overhead associated with acquiring guide stars, repointing, etc. We adopt an orbit (L2 or earth drift away) that allows continuous observation of the survey area at the NEP.

Because we focus on SN Ia at $z > 0.5$, the corresponding time dilation eases the cadence of repeat visits over that required for an investigation that also observes SN Ia at low redshifts. Our initial expectation, based on Monte Carlo simulations by one of us (PP) of $z > 0.5$ SN light curves for LSST, is that a 5-day sampling interval is sufficient. Conservatively adopting the local SN Ia rate of 5.2×10^{-5} Mpc^{-3} yr^{-1} (Tonry et al. 2003), for $\Omega_0 = 1$, $\Omega_\Lambda = 0.7$, and $H_0 = 72$, then ~2500 SN Ia within $0.5 < z < 1.7$ should be observed in a nominal two-year mission. At $z = 0.5$, ~150 SN Ia are expected in a $\Delta z = 0.1$ bin in two years. The yield reaches ~230 events at $z = 1.0$, declining only slightly to ~190 events at $z = 1.7$. Recent measurements of the SN Ia rate at $z \sim 1$ (Dahlen et al. 2004) imply higher numbers than we presented here.

A two-year mission will yield a Hubble diagram accurate to 1% on the $\Delta z = 0.1$ scale, given the 0.1 mag dispersion in SN Ia peak luminosity, after correcting for the light-curve decay rate. For w constant with z, Linder & Huterer (2003) show that $\sigma_w < 0.05$ should be readily achieved. Allowing for the possibility that w varies with z, covariance between w_0 and w' makes the errors on each a strong function of the limiting redshift of the survey. Combining these observations with similar data from ground-based facilities over $0 < z < 1.7$, the 1-σ error in w_0 is ~0.05, with a corresponding error in w' of ~ 0.2. However, combining SN measurements with results from weak lensing and other surveys will improve the uncertainties in w_0 and w' considerably.

Focusing on a SN-based investigation requires that we address potential systematic uncertainties in (1) the absolute and relative photometric calibration across the mission band-pass; (2) the cross-calibration of our measurements with complementary observations from other facilities; and (3) the fidelity of using SNe Ia (and other SN types) as standard candles across a large redshift range. We discuss the first issue in the next section. We can achieve precise cross-calibration with ground-based observations through coordinated observing of the hundreds of $z < 0.8$ SNe in the survey field. Co-observing with LST and/or other ground facilities will tie together light-curve data and provide independent measurements of host galaxy metallicities to track "second parameter" effects.

Advancing our understanding of the physics of SN explosions is an area of emphasis for the *Destiny* team. We advocate for a strong theory component in our program and believe that our data product (time-resolved grism spectra) is well-suited for extracting clues to the underlying explosion mechanisms and progenitors. While SN Ia (thermonuclear deflagration of degenerate stars) are being used to measure the history of cosmic expansion, the exact mechanism leading to these explosions remains unclear. Environmental effects, such as chemical composition and evolution of the parent population and the white dwarfs they produce, that may influence the SN luminosity, and hence the suitability of its use as a standard candle, continue to be evaluated (e.g., Timmes et al. 2003); such effects may be more significant at higher redshifts. (See the discussion in a related DETF white paper by Kirshner.) A robust measurement of the SN Ia rate by itself will constrain the evolutionary time-scale for these events, a crucial clue for models of their origin.[1]

At this time most aspects of SN theory are not sufficiently developed to be predictive. Thus using SNe as distance indicators will remain largely empirical for the foreseeable future. Theory can guide the interpretation of observations, however, and progress has been made toward a qualitative understanding of many aspects of SN explosions. We advocate strong investments over the next decade in theoretical research for identifying and correcting small systematic effects in the SN Ia distance scale.

The dataset collected by *Destiny* will also be profoundly valuable, at no additional mission cost, for a wide range of other problems. After 2 years, we will have deep NIR $R \approx 75$ time-sampled spectra for all objects over a several sq-degree region of sky. Total exposure time will be 500+ hours, with implied 5σ depths in R=5 broad band-passes of 10 nJy that should readily detect forming galaxies at $z > 5$ as well as nearby brown dwarfs. This dataset will allow many parallel investigations into the nature of dark energy. The galaxy power spectrum will be measured on large co-moving spatial scales over $1 < z < 2$, a redshift interval that is difficult to probe from the ground. Rich clusters of galaxies at $z > 1$ will be visible, again providing information on the galaxy power spectrum on large scales. Comparing the power spectrum at high redshifts to that at the present epoch probes the growth rate of structure, which in turn depends on the dark energy equation of state. The *Destiny* dataset will also offer valuable support for LST investigations of w via large-scale measurements of cosmic shear. The NIR grism spectra will provide superb calibration of the LST multi-filter color-redshifts. Over 5 million galaxies will be used in this calibration.

2.2 Precursor Observations and Fundamental Calibrations

JDEM concepts to measure the SN Ia Hubble diagram with sufficient precision to distinguish various possible dark energy equations of state require that the expansion history of the universe be specified at approximately the 1% level out to $z \sim 1.7$ (Linder & Huterer 2003; Aldering et al. 2004). Such concepts, including *Destiny*, will seek to observe thousands of SNe in order to populate the Hubble diagram with points having sufficiently small error bars. This need to observe and accurately measure precise photometry of thousands of SN events drives most critical aspects of the mission concepts. Large numbers of observed events (together with Poisson statistics) will ultimately yield errors bars of the required size.

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[1] The high redshift cut-off of our survey at $z \sim 1.7$ is predicated on observing Si II 6150Å and the maximum flux from SN Ia within our band-pass. In practice, the U-band is available out to $z \sim 3$.

However, this effort will be effectively undermined if an adequate level of absolute and relative photometric precision is not maintained over the NIR band-pass out to ~1.7 μm (i.e., redshift range out to $z \sim 1.7$), which provides the most leverage for distinguishing among the various dark energy models.

At peak luminosity, the SNe Ia targeted by JDEM (and other investigations, including ground-based) have approximate magnitudes AB ~ 24 – 28 in the $0.5 < z < 1.7$ range with most of the light from the SNe falling at NIR wavelengths (*J* band mags of ~22.5 – 26.5). Achieving the required systematic uncertainties in the SN Ia measurements necessitates both improving the absolute calibration of stellar fluxes, particularly at longer wavelengths extending into the NIR, and extending this calibration to standard stars of fainter magnitude. The required level of accuracy can be accessed from detailed studies of simulated Hubble diagrams produced by the various mission concepts, but a nearly uniform requirement is 3% knowledge of the photometric calibration at the 3σ level. This is a stringent requirement and presently is only approached in the optical near 0.5 μm. Careful space-based and ground-based work will be needed to achieve this objective at longer wavelengths and to extend it to fainter standards.

The reason for this high level of photometric calibration can be understood by considering the Hubble diagram. The standard candle assumption implies that, to first order, the absolute luminosities of SN events in a given band are constant. When observed as a function of redshift the band effectively shifts to the red, so that comparing the luminosities at one wavelength and *z* requires knowledge of the relative photometry with respect to bands at longer wavelengths and higher z. Any systematic photometric errors between different bands will distort the resulting Hubble diagram and bias the results. This differs from standard stellar photometry where band-dependent photometric errors typically lead only to systematic biases in effective temperatures, gravities, or metallicities. In precisely determining the Hubble diagram the basic effect being sought is itself jeopardized or made ambiguous by photometric errors.

In order to meet the photometric requirements of JDEM concepts, as well as LST and other experiments, we advocate that one or more suborbital observing programs are needed to absolutely calibrate carefully selected DA (pure H) white dwarfs as fundamental standard stars in the red and NIR. These programs should be supplemented by a vigorous ground-based program that links the results to the existing Vega and white dwarf based stellar flux scales. The suborbital observations must be directly referenced to an on-board absolute black body calibration source and tied through stellar models and dedicated ground-based work to a wide range of DA white dwarfs of different temperatures and apparent magnitudes that can be observed by future missions.

The chief reason that DA white dwarf stars are so useful is that their atmospheres and emergent fluxes can be modeled with considerable confidence and precision. This is particularly true of the DA stars with temperatures between about 12,000 K and 50,000 K. These stars have thin, stable, radiative photospheres of essentially pure H. As such, it is possible to define the dominant sources of opacity (neutral and ionized H and electrons) in terms of fundamental physics. At optical and UV wavelengths such models presently represent the closest practical approximation to a 'standard' emission source that can be realized in stellar astrophysics. In this respect they can serve as 'calibrators' that approach the usefulness of black bodies in terms of fundamental physics used to describe the emitted radiation field. The models themselves are complex numerical calculations but recent comparisons involving independent LTE and NLTE codes by P. Bergeron, D. Koester, and I. Hubeny have arrived at a consensus that the current generation of models are mutually consistent at the 1% level, with the chief differences occurring in the details of the Balmer line cores. In summary, the models of DA white dwarfs can uniquely specify the energy distribution and the detailed line shapes of actual stars by specifying just three well defined parameters: the effective temperature, the surface gravity, and a monochromatic flux normalization.

The traditional standard for absolute stellar fluxes is the star Vega. But since Vega is too bright to observe with present as well as future missions such as JDEM and *JWST* that are optimized to detect faint targets (a factor of $\sim 10^{10}$ brighter than distant SN Ia), a host of fainter secondary standard stars are necessary. One of the best documented and widely used systems of flux standards is that employed by *HST*, which is defined by the model atmosphere fluxes of four DA white dwarf standard stars: GD 71, GD153, G191B2B, and HZ 43. Recently, Bohlin & Gilliland (2004) used observations of Vega with *HST*-STIS to directly link Vega with the white dwarf standards. Extrapolating to NIR wavelengths the Bohlin & Gilliland fluxes are about 2% lower than the widely used Vega calibration of Cohen et al. (2003), since the latter authors employ a slightly different model of the atmosphere for Vega. Recognizing the need for better absolute calibration measurements in the NIR, that are traceable to pedigreed laboratory sources, Bohlin & Gilliland call for additional fundamental measurements in this band. The proposed suborbital program(s) could accomplish this task. The results will be important for both ground and space experiments over the next decade and beyond.

Summary of Recommendations

We have presented a brief discussion of issues concerning the study of dark energy and the *Destiny* concept for the planned NASA-DOE Joint Dark Energy Mission (JDEM). We summarize as follows:

(1) Due to budget constraints at all three federal funding agencies (NSF, NASA, DOE), maximum usage should be made of extant facilities in the near-term to study dark energy. New generation instrumentation for wide-field imaging and multi-object spectroscopy on 4-10 meter class ground-based telescopes and the installation of the Wide Field Camera 3 (WFC3) instrument aboard *HST* would significantly advance our characterization of dark energy.

(2) JDEM and the Large Survey Telescope (LST) should be viewed as vital but complementary components of a suite of facilities used to investigate dark energy. JDEM in particular should focus on obtaining data that cannot otherwise be obtained, due to the high cost of building and operating space missions. Our *Destiny* concept for JDEM focuses on making such measurements. *Destiny*'s efficient design and simple operations allow it to fit within a medium-size mission cost envelope.

(3) It is paramount to control systematics and biases in conducting precision cosmology experiments. We emphasize the need for theoretical studies, not only of the nature of dark energy, but of the cosmological tracers (e.g., supernovae, large-scale structure) used to detect its effects. The community should also establish a set of precise absolute and relative visible/near-IR spectrophotometric calibrators for ground and space during the next several years.

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