Dark Energy from a Space-Based Platform

A White Paper Submitted to the Decadal Survey Committee

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1. Introduction

In 1998 two teams of astronomers observed high-redshift supernovae to measure the deceleration of the expansion of the universe, a keystone of the cosmological model. They were amazed to find instead that the expansion is accelerating (Riess et al. 1998, Perlmutter et al. 1999). Additional measurements using independent techniques and observables including the cosmic microwave background (most precisely by *WMAP*), large-scale structure and its variations, x-ray clusters, and the Integrated Sachs-Wolfe (ISW) effect have come to the same stunning conclusion. Even the most conservative interpretation of the acceleration is staggering; for our best theory of gravity, General Relativity, to remain valid we must invoke the presence of a mysterious "dark energy" comprising 70% of the universe whose gravity is repulsive. The phenomenon of dark energy offers a rare clue for questions at the nexus of many of the deepest and thorniest problems in physics, cosmology and astrophysics. *For Fundamental Physics*: Is dark energy the same as the theoretical vacuum energy whose preposterous size challenges our understanding of the quantum froth? Is dark energy a scalar field, similar in effect but different in energy scale from the field which give rise to Inflation? Is there dark energy, or is General Relativity incorrect? *For Cosmology*: If the density of dark matter and dark energy in the past and future universe are vastly different in scale, why are they so similar at the present moment? In light of dark energy, what is the fate and origin of the universe? Is the Cosmological Principle valid? *For Astrophysics:* How does dark energy influence the formation of large structures like clusters and voids? *For Relativists*: Is General Relativity an incomplete theory? *For String Theorists*: Does Dark Energy provide evidence for higher-dimensional branes or the multiverse? All of these questions may be boiled down to one pressing question; ***What* is Dark Energy?**

In this white paper we discuss the scientific advances possible in the coming decade for understanding dark energy with measurements from space as could be made with the Joint Dark Energy Mission (JDEM). Technological advances in large-format NIR and optical detectors enable an enormous step forward in the critical wide-field spectroscopic and imaging surveys needed for dark energy progress. All necessary technologies are flight ready at high TRL level.

2. Classes of explanations for Dark Energy

The present cosmological model provides a framework for considering possibilities for dark energy. Explanations for dark energy are classified by how they modify Einstein's equations which relate the geometry of space-time (left hand side) to the contents of the universe (right hand side). Explanations on the right hand side are considered to be "new energy components" and are characterized by the ratio of their pressure to energy density, w, the equation of state parameter. In some models, w, may vary with epoch, i.e., w=w(z). While our ignorance about dark energy provides no guidance for the form of w(z), the Figure of Merit Working Group (Kolb et al. 2009) has provided valuable metrics for quantifying the discovery space. Those that modify the left hand side are referred to as "modified gravity". Among the new models, a "cosmological constant" is the simplest with pedigree to Einstein, while scalar fields are motivated by particle physics. The most studied models for modified gravity are the "f(R)" models of photon propagation along the branes of string theory within the bulk (e.g., DGP).

Cosmological constant: A cosmological constant is an energy density term that is constant in space and time, i.e., $w(z)=-1$. It may arise from the sum of the numerous zero point energies of the quantum froth, but these estimates are a factor of ~10^{120} off of the cosmological measurements. A far smaller yet nonzero cosmological constant may arise from not-yet-understood quantum gravitational corrections or through deep symmetries.

Scalar field: A cosmic scalar field or quintessence (e.g., Peebles & Ratra 2003) can be weakly coupled to gravity, resulting in the same class of models that have been studied to obtain inflation. For quintessence models, $-1 \leq w \leq 1$. A slowly evolving field, $|dw/dz|<1$ whose potential energy dominates its kinetic energy can have w small enough to cause acceleration, $w<-1/3$ and yet $w>-1$. Another class of scalar field models is the "phantom" field models (Caldwell 2002). These can have $w<-1$ since they have a negative kinetic energy, motivated by string theory.

Modified gravity: The f(R) gravity models include a function of the Ricci curvature scalar R, into the action (see e.g. Woodard 2006 for a review). There is a lot of theoretical freedom in constructing f(R) models. One key constraint for them is to allow a matter dominated epoch to exist before the late-time cosmic acceleration. It is hoped that the development of a successful f(R) model would provide enough insight to a complete theory explaining its origin. The DGP gravity model explains cosmic acceleration by the effects of an unseen extra dimension at very large distances (Dvali et al. 2000); it corresponds to a 4-dimensional brane embedded in a 5-dimensional Minkowski bulk (see, e.g., Lue 2006). For distances greater than a characteristic length, gravity leaks into the bulk, making higher dimensional effects important. In practice, it has proven to be difficult to construct modified gravity models that meet all current observational and experimental constraints. The growth of cosmic large-scale structure in modified gravity models differs from that of General Relativity, providing a means to observationally separate a dark energy field from modified gravity.

3. Experimental Techniques

Dark energy can be measured with a variety of techniques, all optimally performed with JDEM. Some probe dark energy through its affect on the expansion rate. Others measure the growth rate of structure. Some are more powerful at one redshift range than another. Combinations of methods can break parameter degeneracies, test for consistency between cosmological observables, and cross-check results as a final bulwark against systematic errors.

BAO: The BAO scale takes advantage of a "standard ruler" to measure the expansion history of the universe. In the early universe, primordial density perturbations propagated as sound waves in the photon-baryon plasma. The distance that these sound waves propagate by the time of recombination defines a characteristic scale of the comoving sound horizon at recombination, $s \sim$ 150 Mpc. This BAO scale has been calibrated by WMAP and will be calibrated to 0.2% precision with Planck. This scale is imprinted in the 3-D clustering of galaxies, measurement it in angle, $\Delta\theta = s/D_A(z)$, and redshift, $\Delta z = s \cdot H(z)$. This provides a built-in consistency cross-check.

Supernovae: Type Ia SNe can be used as standardizable candles to measure the luminosity distance D_L-z relation. Since the absolute magnitude SNe is not known *a priori*, they can be used as a relative distance indicator to measure the *shape* of $D_L(z)$ and thus the history of the expansion rate. Calibration of the SN Ia distance scale through the observation of host Cepheids also remains the most precise way to measure H_0 whose determination extends the measure of dark energy to the present. SNe have greater precision per object than other techniques and are expected to provide the best constraint on dark energy in the local volume (i.e., at low redshifts).

Weak lensing: The shapes of distant galaxies are distorted by gravitational lensing by the matter distribution along the line of sight. The two-point correlation function of the galaxy ellipticities depends on both the cosmic distance scale (more distant galaxies are more distorted) and on the amplitude of the matter power spectrum (i.e. growth of structure). This measurement is nearly independent of the way in which galaxies trace the matter. It is also possible to construct higher-order correlation functions, and combinations of galaxy density-ellipticity correlation functions that cancel out the galaxy bias but retain dependence on the cosmological distance scale.

Other enabled tests: The galaxy survey that enables the BAO investigation can also be used for many additional dark energy tests. The *Alcock-Paczynski test* is based on the fact that any feature in the galaxy power spectrum should have the same length scale in the radial and transverse directions, at least statistically, thereby allowing a measure of $H(z)D(z)=\Delta z/\Delta\theta$. The peculiar velocities of galaxies change their observed redshifts and hence their inferred positions along the line-of-sight, leading to *redshift-space distortions*: A spectroscopic redshift survey can use the distortions to determine the rate of structure growth. Another way to measure the growth of structure is to count collapsed objects (clusters) above a certain mass threshold. A mass scale can be established using galaxy velocity dispersions and/or gravitational lensing measurements. Although not measured by JDEM, CMB data are crucial in breaking parameter degeneracies, e.g. setting the length of the acoustic scale in BAO or the initial matter power spectrum in WL.

4. Measurements and the Case for a Space Mission

What observational avenues offer the greatest potential for improved constraints on dark energy and large-scale gravity? Here we examine the prospects for substantial improvement in statistical precision and systematic accuracy over the coming decade.

Baryon Acoustic Oscillations: JDEM offers the opportunity to measure BAO over the full sky to about the cosmic-variance limit in the range $0.7 \leq z \leq 2.0$. The challenge for an aggressive BAO survey is to acquire an unprecedented precision spectroscopic survey of ~200 million galaxies over a large effective cosmic volume. The key to achieving the requisite survey speed is to take advantage of wide field slitless spectroscopy of the bright Hα line enabled by a space mission. For $0.7 \leq z \leq 2.0$ this line falls in the NIR; a space mission evades the bright infrared glow of the Earth's atmosphere and thus makes this approach possible. The Hα luminosity function is well enough known at these high redshifts that sufficiently accurate projections can be made to ensure line detectability. (This is to be distinguished from the 21-cm line observations where the HI luminosity function is not at all known.)

The JDEM BAO survey can approach the cosmic variance limit without being limited by systematic errors. This will then be the best possible cosmological measurement of BAO in this redshift range.

Type Ia Supernovae: Ground-based surveys in the coming decade will detect thousands of $z<1$ Type Ia supernovae. However, a space observatory is the only feasible route to obtaining ~1000 high-precision light curves in the NIR and rest-frame V band for $z>0.8$. At lower z the space-based calibration and NIR data will enable lower systematic errors than can be achieved from the ground. Improved dark-energy constraints from the SNIa Hubble diagram require substantial reduction in systematic errors of SNIa distance moduli, to 0.01 mag or less. They also benefit from an extension to $z>0.8$ where we currently have only a relative handful of events from HST.

Some systematic errors arise from calibrating flux over a wide range of redshift and wavelength. Calibration schemes proposed for future large ground-based surveys promise improved knowledge of their time-varying response functions, for wavelengths accessible from the ground (rest V-band for $z<1$). Space observatories can extend this to $z>1$, and have the fundamental advantage that the photometric system is stable, free of (varying) atmospheric absorption, and uninterrupted by weather or the lunar cycle. Other systematic errors arise from the potential for evolution in the supernova (or dust) population that masquerade as distance shifts.

Control of these astrophysical systematics will greatly benefit from space-unique capabilities like measurements toward the rest-NIR, where variability of both dust and SNe fluxes are reduced and precisely controlled sampling of light curves, colors, host properties and spectral features to detect and compensate for shifts in the SN population.

Weak Gravitational Lensing: The weak gravitational lensing measurement is made by obtaining shear and redshift estimates for each element of the source population. The CMB or reionization-era 21-cm emission can serve as source planes of well-determined redshift, but a source population spread throughout the $0<z<3$ range is needed to track dark energy evolution.

Current ground-based cosmic-shear surveys cover up to ~200 deg^2 of sky at varying depths, and surveys of 1500-5000 deg^2 will commence in the coming few years. The coming decade will feature the capability for multicolor weak lensing imaging of up to 20,000 deg^2 from both ground and space. The power of WL surveys to constrain dark energy and test gravitation theories will depend on the survey area, the sky density of sources with high-quality shape and photo-z data, and crucially the systematic error levels of both galaxy shapes and redshifts. Hemisphere-scale weak-lensing surveys will require an understanding of the imaging and photo-z data that are well beyond the demands of other astronomical analyses: parts-per-thousand errors in imaging PSF or photo-z redshift calibration will swamp the desired WL precision. The photo-z scale will need to be calibrated with spectroscopic redshifts, meaning that WL surveys will be limited to the depth to which high-completeness spectroscopic surveys can be completed.

Photo-z reliability and accuracy are greatly enhanced by NIR photometry. NIR data of the desired depth and coverage can be obtained only from space. The complete spectroscopic redshift surveys required to calibrate WL photo-z's will also be greatly enhanced by deep NIR spectroscopy, possible for the requisite ~10^5 targets only from space telescopes. JDEM surveys would acquire this data as a matter of course.

Weak lensing surveys to date have been significantly more limited and their results delayed by larger systematic errors than initially estimated. Clearly an increase in survey area or depth is not sufficient to make WL a cornerstone of dark-energy research. What will happen when surveys are 10^2 larger than today's? Understanding the time-, color-, and position-dependence of the imaging PSF is critical. A space observatory at L2 has a huge advantage: without wind or gravity loading, thermal fluctuations, or an atmosphere, the space PSF can be of desired stability. The angular resolution from space also greatly increases the number of galaxies that can be resolved to measure shapes (see Fig. 1). A better-resolved galaxy is less affected by errors in PSF estimation as well. Ground-based surveys, even if able to understand their PSFs, will suffer from crowding if attempting to measure a high density of galaxies.

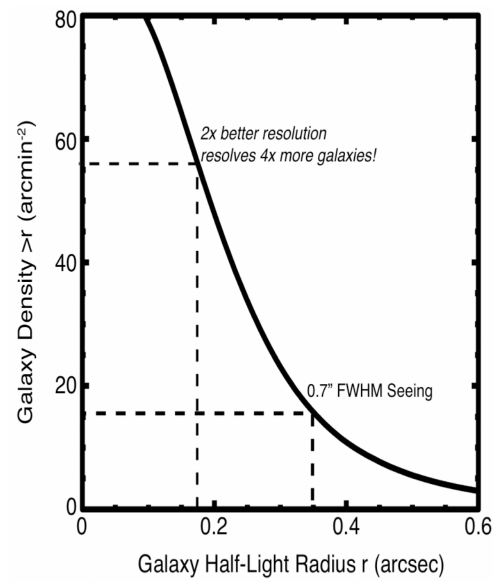

Fig 1. Galaxy density on the sky for galaxies with half-light radius larger than a given radius as a function of that radius. Many factors are important for galaxy shape measurements, including sensitivity and measurement stability, but angular resolution is critical. The >2x better resolution from space allows >4x more galaxies to be resolved.

Other Techniques: The best dark-energy constraints from galaxy cluster abundance data currently arise from x-ray surveys. Space NIR photometry will enable more precise photometric determination of these clusters' redshifts. Large-area WL surveys will also enable the detection of galaxy clusters via their lensing signatures. Lensing detection bypasses the difficulties of translating the baryonic x-ray signal into a mass. Thus a WL dark-energy survey will also greatly improve the utility of x-ray cluster catalogs. A well-designed BAO survey will yield excellent data for measuring the gravitationally induced velocity field. Tests of General Relativity that invoke comparisons among galaxy-density, velocity, and lensing fields are an area of active research. There appear to be strong gains from combining lensing and spectroscopic redshift data over the same survey area.

5. Possible outcomes and their significance

The significance of space-quality measurements of the expansion and growth history: On a broad level, the complementarity and accuracy of measurements from a dedicated, space-based platform will provide a huge step forward. Distance measurements spanning the 14 billion years between the decoupling era and the present will be a legacy data set Measuring the growth of structure in time slices from the matter dominated epoch into the accelerating epoch will likewise lay a foundation for our understanding of the universe and its structure. Supernovae, baryon acoustic oscillation, and weak lensing observations deliver all these. The cross-comparison of distances with the development of structure delivers a key test of the nature of gravity and whether microphysics or physics beyond Einstein's General Relativity is necessary.

Time dependence: Discovery of time dependence in the dark energy equation of state would have immediate fundamental implications: it would rule out Einstein's cosmological constant (raising issues of what new symmetry sets the vacuum energy to zero). This necessarily implies by Lorentz invariance that dark energy is also spatially varying. Accurate measurements of the time dependence allow determination of the class of new physics responsible for acceleration, i.e. a “thawing” or “freezing” field, or more unusual physics. In many unified field theories, the presence of a time-varying dark energy field leads to variation of quantities we thought were fundamental constants, such as G, the fine structure constant, particle masses, etc. Understanding the early time behavior of dark energy can shed light on the coincidence puzzle of why we live at the time of acceleration, and the late time behavior can reveal crucial clues to the fate of the universe – will it accelerate forever, limiting far-future astronomy to our local supercluster, or evolve into a negative vacuum state and suffer a doomsday collapse.

Modified gravity: Comparing measures of expansion rate vs. growth rate of structure can point to a new understanding of gravity. Practically speaking, a difference in the apparent measures of w from these two probes of dark energy would point to inadequacy of General Relativity. Modifications to gravity on the horizon scale raise issues of whether the graviton is truly massless, or whether hidden dimensions exist. In many theories these lead to modifications in gravity on microscopic scales and on properties of compact objects such as black holes. This can provide clues to an eventual theory of unified quantum gravity. Tests of gravity on many scales will be enabled by comparison of comprehensive gravitational lensing and dynamical data.

Better limits: Models exist for both dark energy and modified gravity where the tilt of the effective equation of state $1+w$ approaches arbitrarily close to zero. And yet, whether $1+w$ is a scintilla positive or negative has immense implications, defining whether dark energy density dilutes or grows with time and impacts the fate of the universe. For comparison, consider that the equivalent tilt $1-n$ in the inflationary power index will be determined by Planck to the few times 10^{-3} level. So determining $1+w$ to at least the 10^{-2} level is a commensurate start. Perhaps the most exciting result would be a tension between the three different probes of dark energy; seeing and understanding such a contrast requires space-based close control of all systematics. Such a discovery would either point to surprising astrophysics or to a deeper level of physics.

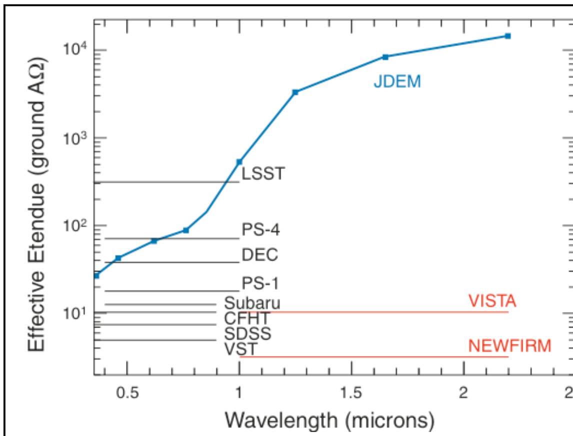

Fig 2. Effective etendue (product of field of view and telescope area, with corrections for sky brightness, duty cycle, and angular resolution) for JDEM and ground facilities. Horizontal lines show ground facilities. JDEM is a factor >300 faster than the ground at J, H, and K. Beyond the etendue statistic, space observations offer greater stability, guaranteed cadence, and the ability to resolve small galaxies. These advantages are critical for the weak lensing and supernovae programs.

6. Ancillary Science

A space telescope optimized to study dark energy would fill a crucial void in the arsenal of space observatories by providing wide-field, panchromatic imaging and spectroscopy at space-enabled resolution between 0.4 & 2.0 microns (see Fig. 1 and 2). It should be an excellent “finder scope” for all contemporary and future astrophysical observatories. Such capabilities will enable and support astrophysics investigations requiring the collection of high statistics and rare objects (as did SDSS) including, $z>9$ quasars, L and T dwarfs, local, low-surface brightness galaxies, tidal streams and satellites, strong lens systems, H-alpha based star formation histories from 10^8 galaxies, etc.

Conclusions:

Both the importance of the problem and the difficulty in making the requisite measurements begs for a dedicated space-based dark energy mission designed to complement a diverse set of current and planned ground-based measurements. Ground-based observatories can do much, but wide-field infrared measurements are required too, and for that a space mission is needed. Space observatories provide the large sky coverage in the NIR for spectroscopic surveys needed for BAO measurement. They obtain angular resolution over wide fields that cannot be obtained from the ground, greatly increasing the potential of WL observations and the speed of all high-redshift surveying. Precision measurements can be made of SNe into the NIR. The stability of an observatory and the background at L2 enables careful calibration and reduction of systematic errors well beyond what can be done from the ground, as well as uninterrupted observation. These were the key advantages of WMAP over terrestrial CMB observations, for example.

With the advent of wide format infrared sensors and their optimization and qualification for space by the JWST Project, the time is ripe to measure the dark energy to near the limits of reasonable experimental capability. A vast array of other astrophysical and cosmological data will flow from these observations as well.

It is ironic that dark energy is the majority constituent of the mass-energy of our universe, yet was not discovered until 1998. Even with an extensive community effort and the dedication of substantial telescope time on both ground and space telescopes, more than a decade later we still have not answered our most basic questions as to the nature of the dark energy. Does the equation of state of dark energy change with time like a rolling field? Is dark energy static like vacuum energy? Or, is dark energy an epicycle of a failing gravity theory, an indication of the need to modify General Relativity? To quote the NRC BEPAC report, "A JDEM mission will set the standard in the precision of its determination of the distribution of dark energy in the distant universe. By clarifying the properties of 70% of the mass-energy in the universe, JDEM's potential for fundamental advancement of both astronomy and physics is substantial. A JDEM mission will also bring important benefits to general astronomy."

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