Summary of the DUNE Mission Concept

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ABSTRACT

The Dark UNiverse Explorer (DUNE) is a wide-field imaging mission concept whose primary goal is the study of dark energy and dark matter with unprecedented precision. To this end, DUNE is optimised for weak gravitational lensing, and also uses complementary cosmological probes, such as baryonic oscillations, the integrated Sachs-Wolf effect, and cluster counts. Immediate additional goals concern the evolution of galaxies, to be studied with groundbreaking statistics, the detailed structure of the Milky Way and nearby galaxies, and the demographics of Earth-mass planets. DUNE is a medium class mission consisting of a 1.2m telescope designed to carry out an all-sky survey in one visible and three NIR bands (1deg^2 field-of-view) which will form a unique legacy for astronomy. DUNE has been selected jointly with SPACE for an ESA Assessment phase which has led to the Euclid merged mission concept.

Keywords: Cosmology, Dark energy, Large scale structure, surveys, Galaxy evolution, extrasolar planets, DUNE, Euclid

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1. INTRODUCTION

Dark energy and dark matter comprise the bulk of the mass-energy budget of the Universe and pose some of the most fundamental questions in physics. The Dark UNiverse Explorer* (DUNE) is a wide field mission concept designed to study these dark cosmic components with unprecedented precision. To do so, DUNE will use weak gravitational lensing along with other cosmological probes. In these proceedings, we give a brief summary of the DUNE mission concept which was recently proposed to ESA's Cosmic Vision programme. A description of the focal plane instrumentation can be found in an adjoining paper[1] and a more detailed description of the ESA proposal is provided in a previous publication.[2] An earlier and simpler version of DUNE was described in previous SPIE Proceedings.[3,4]

Gravitational deflection of light by intervening dark matter concentrations causes the images of background galaxies to acquire an additional ellipticity of order of a percent, which is correlated over scales of tens of arcminutes. Utilisation of this cosmological probe relies on the measurement of image shapes and redshifts for several billion galaxies, both requiring space observations for PSF stablity and photometric measurements over a wide wavelength range in the visible and near-IR (NIR).

Furthermore, in order to break as many degeneracies as possible, and to provide independent constraints, complementary approaches should be used. DUNE has thus been designed to provide three additional cosmological probes : Baryon Acoustic Oscillations (BAO), the Integrated Sachs-Wolfe effect (ISW), and galaxy Cluster Counts (CC). It is therefore a unique mission to probe the dark Universe in different independent ways. DUNE will tackle the following questions: What are the dynamics of dark energy? What are the physical characteristics of the dark matter? What are the seeds of structure formation and how did structure grow? Is Einstein's theory of General Relativity the correct theory of gravity?

DUNE will combine its unique space-borne observations with existing and planned ground-based surveys, and hence greatly increases the science return of the mission while limiting costs and risks. The panoramic visible and NIR surveys required by DUNE's primary science goals will afford unequalled sensitivity and survey area for further studies. Additional surveys at low galactic latitudes and in deep patches of the sky will open new scientific windows. DUNE will explore the nature of Dark Matter by measuring precisely the sum of the neutrino masses and by testing the Cold Dark Matter paradigm. It will test the validity of Einstein's theory of gravity. In addition, DUNE will investigate how galaxies form, survey all Milky-Way-like galaxies in the 2π extra-galactic sky out to $z \sim 1$ and detect thousands of galaxies and AGN at $6 < z < 12$. It will provide a detailed visible/NIR map of the Milky Way and nearby galaxies and provide a statistical census of exoplanets with masses above 0.1 Earth mass and orbits greater than 0.5 AU.

Furthermore, DUNE surveys will provide a unique all-sky map in the visible and NIR at unprecedented spatial resolution for such large scale of 0.25 and 0.3 arcesec respectively. It will thus complement other space missions.

The DUNE mission will allow the investigation of a broad range of astrophysics and fundamental physics. These and the corresponding surveys are described in present and following section. The last sections describe the mission profile, payload instrument and the current status of the mission concept.

1.1 The Dark Universe

1.1.1 The nature of Dark Energy

A variety of independent observations overwhelmingly indicate that the cosmological expansion began to accelerate when the Universe was around half of its present age. Presuming the correctness of General Relativity this requires a new energy component known as Dark Energy. The simplest case would be Einstein Cosmological Constant (Λ), in which the dark energy density would be exactly homogeneous and independent of time. However, such an interpretation conflicts with predictions of vacuum energy from Particle Physics by 120 orders of magnitude. For this reason, cosmologists are motivated to consider models of a dynamical dark energy, or even to contemplate modifications to General Relativity.

DUNE will deduce the expansion history using the distance-redshift relation ($D(z)$) and growth of structure. It can thus probe the nature and properties evolution of dark energy in two independent ways. A single accurate technique can rule out many of the suggested members of the family of dark energy models, but it cannot test the fundamental assumptions about gravity theory. If General Relativity is correct, then either $D(z)$ or the

*http://www.dune-mission.net

growth of structure can determine the expansion history. In more radical models that violate General Relativity, however, this equivalence between $D(z)$ and growth of structure does not apply. For this purpose, DUNE will use a combination of the following cosmological probes.

Weak Lensing - A Dark Universe Probe: As light from galaxies travels towards us, its path is deflected by the intervening mass density distribution, causing the shapes of these galaxies to appear distorted by a few percent. The weak lensing method measures this distortion by correlating the shapes of background galaxies to probe the density field of the Universe. By dividing galaxies into redshift (or distance) bins, we can examine the growth of structure (as a function of redshift) and make three-dimensional maps of the dark matter. As the evolution of the growth of structure is different in different scenarios of Dark Energy and dark matter, we have access to the nature of these dark components. An accurate lensing survey, therefore, requires precise measurements of the shapes of galaxies as well as information about their redshifts. High-resolution images of large portions of the sky are required, with low levels of systematic errors that can be achieved only via observations from a thermally stable satellite in space. Analyses of the dark energy require precise measurements of both the cosmic expansion history and the growth of structure. Weak lensing stands apart from all other available methods because it is able to make accurate measurements of both effects.[5,6] Given this, the optimal dark energy mission (and dark sector mission) is one that is centred on weak gravitational lensing and is complemented by other dark energy probes.

Baryon Acoustic Oscillations (BAO) – An Expansion History Probe: The scale of the acoustic oscillations caused by the coupling between radiation and baryons in the early Universe can be used as a 'standard ruler' to determine the distance-redshift relation. Using DUNE, we can perform BAO measurements using photometric redshifts yielding the three-dimensional positions of a large sample of galaxies. All-sky coverage in the NIR enabled by DUNE, but impossible from the ground, is essential to reach the necessary photometric redshift accuracy for this BAO survey.

Cluster Counts (CC) – A Growth of Structure Probe: Counts of the abundance of galaxy clusters (the most massive bound objects in the Universe) as a function of redshift are a powerful probe of the growth of structure. There are several ways to exploit the DUNE large-area survey for cluster detection: weak lensing, strong lensing, optical richness, and cross-correlation with X-ray or Sunyaev-Zeldovich surveys (eg. Planck, E-Rosita, etc).

Integrated Sachs-Wolfe (ISW) Effect – A Higher Redshift Probe: The ISW effect is the change in CMB photon energy as it passes through a changing potential well. Its presence indicates either space curvature, a dark energy component or a modification to gravity. The ISW effect is measured by cross-correlating the CMB with a foreground density field covering the entire extra-galactic sky, as measured by DUNE. The presence and shape of the spectrum of this cross-correlation will thus inform us about the nature of dark energy. Because it is a local probe of structure growth, ISW will place complementary constraints on dark energy, at higher redshifts, relative to the other probes.[7]

The combination of all these probes will provide strong constraints on the properties and evolution of dark energy (see Fig. 1).

1.1.2 Properties of Dark Matter

Besides dark energy, one major component of the concordance model of cosmology is dark matter ($\sim 90\%$ of the matter in the Universe, and $\sim 25\%$ of the total energy). The standard assumption is that the dark matter particle(s) is cold and non-collisional (CDM). Its nature *may* well be revealed by experiments such as the Large Hadron Collider (LHC) at CERN, but its physical properties may prove to be harder to pin down without astronomical input. One way of testing this is to study the amount of substructure in dark matter halos on scales 1-100", which can be done using high order galaxy shape measurements and strong lensing with DUNE. Weak lensing measures with DUNE can constrain the total neutrino mass and number of neutrino species through observations of damping of the matter power spectrum on small scales. Combining DUNE measurements with Planck data would reduce the uncertainty on the sum of neutrino masses to 0.04eV, and should therefore measure the neutrino mass.[8]

1.1.3 The Seeds of Structure Formation

It is widely believed that cosmic structures originated during inflation from vacuum fluctuations in primordial quantum fields stretched to cosmic scales. In the most basic inflation models, the power spectrum of these fluctuations is predicted to be close to scale-invariant.

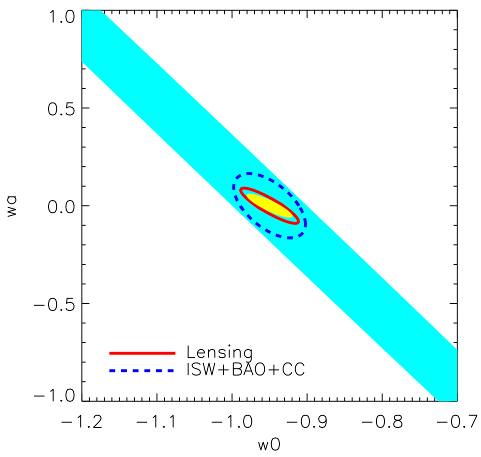

Figure 1. Expected errors on the dark energy equation of state parameters (in a scenario where $w(a) = w_0 + (1-a)w_a$) for the four probes used by DUNE. The light blue band indicates the expected errors from Planck. By combining BAO, CC and ISW we begin to reach similar accuracies to that of the lensing survey. This combination thus gives DUNE two independent and comparable measures of dark energy.

As the Universe evolved, these initial fluctuations grew. CMB measurements probe their imprint on the radiation density at $z \sim 1100$. Density fluctuations continued to grow into the structures we see today. Combined with Planck, the DUNE weak lensing observations and auto-correlation function of galaxies will provide a measurement of the shape of the primordial spectrum with unprecedent accuracy (1% on σ_8 and n_s).

1.1.4 Probing Einstein's Gravity

Various modifications to gravity on large scales (e.g. by extra dimensions, superstrings, non-minimal couplings or additional fields) have been suggested to avoid the need to invoke dark matter and dark energy. The weak lensing measurements of DUNE will be used to test the underlying theory of gravity, using the fact that modified gravity theories typically alter the relation between geometrical measure and the growth of structure. DUNE will be able to measure the growth factor exponent γ (signature of the deviation from Einstein gravity[9]) with a precision of 2%.

1.2 Tracking the Formation of Galaxies and AGNs

In order to disentangle the complex processes involved in galaxy formation, we need high-resolution near-IR space-based images to study galaxy morphology and large area for crucial, rare events, such as the merger rate of very massive galaxies; DUNE will provide this to $z \sim 1.5$.

Using DUNE's weak lensing maps, we will study the relationship between galaxy mass and light, the bias, by mapping the total mass density and stellar mass, luminosity, morphological type of glaxies. While at present only a few massive clusters at $z > 1$ are known, DUNE will find hundreds of Virgo-cluster-mass objects at $z > 2$, and several thousand clusters of M=$1 - 2 \times 10^{13}$Mo; the latter are the likely environments in which the peak of QSO activity at $z \sim 2$ takes place, and will hold the empirical key to understanding the peak period of QSO activity.

Using the Lyman-dropout technique in the near-IR, a deep survey (DUNE-MD) will be able to detect the most luminous objects in the early Universe ($z > 6$): $\sim 10^4$ star-forming galaxies at $z \sim 8$ and up to 10^3 at $z \sim 10$, for SFRs $> 30 - 100$Mo/yr. It will also be able to detect significant numbers of high-z quasars: up to 10^4 at $z \sim 7$, and 10^3 at $z \sim 9$. By applying the Gunn-Peterson test to this large statistically relevant sample of objects we will put stringent constraints on the end of the period of reionisation of the Universe.

DUNE will also detect a very large number of strong lensing systems: about 10^5 galaxy-galaxy lenses, 10^3 galaxy-quasar lenses and 5000 strong lensing arcs in clusters.[10] It is also estimated that several tens of galaxy-galaxy lenses will be double Einstein rings,[11] which are powerful probes of the cosmological model as they simultaneously probe several redshifts.

In addition, during the course of the DUNE-MD survey (over 6 months), we expect to detect ~ 3000 Type Ia Supernovae with redshifts up to $z \sim 0.6$. This will yield a measurement of the SN rate with unprecedented accuracy, thus providing information on their progenitors. This survey will also discover a comparable number of Core Collapse SNe (Types II and Ib/c), out to $z \sim 0.3$, whose rate provides an independent measurement of the star formation history.

1.3 Studying the Milky Way

DUNE will also leas to breakthroughs in Galactic astronomy. The extragalactic survey, DASS-EX, complemented by the shallower survey of the Galactic plane (DASS-G with $|b| < 30$) will provide all-sky high resolution (0.23" in the wide red band, and 0.4" in YJH) deep imaging of the stellar content of the Galaxy, allowing the deepest detailed structural studies of the thin and thick disk components, the bulge/bar, and the Galactic halo (including halo stars in nearby galaxies such as M31 and M33) in bands which are relatively insensitive to dust in the Milky Way.

DUNE will be little affected by extinction and will supersede all of the ongoing surveys in terms of angular resolution and sensitivity (photometric depth and low background). DUNE will thus enable the most comprehensive stellar census of late-type dwarfs and giants, brown dwarfs, He-rich white dwarfs, along with detailed structural studies, tidal streams and merger fragments. DUNE's sensitivity will also open up a new discovery space for rare stellar and low-temperature objects via its H-band imaging. Studying the Galactic disk components requires the combination of spatial resolution (crowding) and dust-penetration (H-band) that only DUNE can deliver. It will also yield the most detailed and sensitive survey of structure and substructure in nearby galaxies especially of their outer boundaries, thus constraining merger and accretion histories.

1.4 Search for Extra-Solar Planets

Using the microlensing effect, DUNE can provide a statistical census of exoplanets in the Galaxy with masses over $0.1 M_{\oplus}$ from orbits of 0.5 AU from their parent star to free-floating objects. This includes analogues to all the solar system's planets except for Mercury, as well as most planets predicted by planet formation theory. Microlensing is the temporary magnification of a galactic bulge source star by the gravitational potential of an intervening lens star passing near the line of sight. A planet orbiting the lens star, will have an altered magnification, showing a brief flash or a dip in the observed light curve. Because of atmospheric seeing, and poor duty cycle even using networks, ground-based microlensing surveys are only able to detect a few to 15 $M_{\oplus}$ planets in the vicinity of the Einstein ring radius (2-3 AU). A dedicated survey (DUNE-ML), using the high angular resolution of DUNE, and the uninterrupted visibility and NIR sensitivity afforded by space observations will provide detections of microlensing events using as sources G and K bulge dwarfs stars and therefore can detect planets down to $0.1 - 1 M_{\odot}$ from orbits of 0.5 AU. Moreover, there will be a very large number of transiting hot Jupiters detected towards the galactic bulge as a free ancillary science.

2. SURVEYS

To achieve the scientific goals described above, DUNE will perform four surveys detailed in the following.

2.1 Wide Extragalactic Survey: DASS-EX

To measure dark energy to the required precision we propose a high precision weak lensing survey with a large area to provide large statistics and the control of systematic errors. DUNE will make measurements over the entire extra-galactic sky (20000 deg^2) to a depth which yields 40 gal/arcmin^2 useful for lensing with a median redshift $z_m \simeq 0.9$. This will be achieved with a survey (DASS-EX) that has AB-magnitude limit of 24.5 (10σ extended source) in a broad red visible filter (R+I+Z). Based on the fact that DUNE will focus on observations that cannot be obtained from the ground, the wide survey relies on two unique factors that are enabled by space: image quality in the visible and NIR photometry. Central to shape measurements for weak lensing the PSF of DUNE needs to be sampled better than 2.3 pixels per FWHM, to be constant over 50 stars around each galaxy (within a tolerance of $\sim 0.1\%$ in shape parameters), and to have a calibratable wavelength dependence.[12] Accurate measurement of the redshift of distant galaxies ($z \sim 1$) requires photometry in the NIR where galaxies have a distinctive feature (the $4000A$ break). Deep NIR photometry requires space observations. The wide survey will provide NIR photometry in Y, J and H down to AB-magnitude of 24 (5σ Point Source) providing an ideal synergy for ground based survey complement([13]), as recommended by the ESO/ESA Working Group on Fundamental Cosmology.[14]

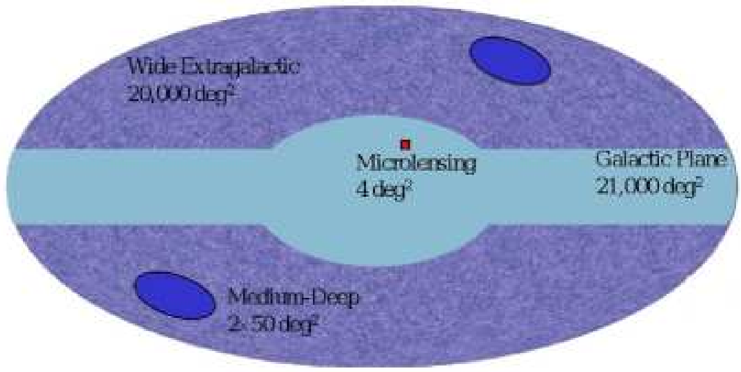

Figure 2. Schematic view of the surveys performed by DUNE

2.2 DUNE-MD

We propose to allot six months to a medium deep survey (DUNE-MD) with an area of 100 deg^2 to magnitudes of 26 in Y, J and H, located at the North and South ecliptic poles. This survey can be used to calibrate DUNE during the mission, by constructing it from a stack of > 30 sub-images to achieve the required depths. The PSF properties would be the same as the DASS-EX survey.

2.3 DASS-G

DUNE will also perform a wide galactic survey (DASS-G) with shorter exposures on the remaining 20000 deg^2. The limit AB-magnitude would be 23.8 in visible and 22 in NIR.

2.4 DUNE-ML

DUNE will also perform a microlensing survey (DUNE-ML) with short exposures over 4 deg^2 in the galactic bulge. Besides the DASS-EX and DUNE-MD, this survey needs low levels of stray light.

3. MISSION PROFILE AND PAYLOAD INSTRUMENT

The mission design of DUNE is driven by the need for the stability of the PSF and large sky coverage. PSF stability puts stringent requirements on pointing and thermal stability during the observation time. The 20,000 deg^2 survey (DASS-EX) demands high operational efficiency, which can be achieved using a drift scanning mode (or Time Delay Integration, TDI, mode) for the CCDs in the visible focal plane. TDI mode necessitates the use of a counter-scanning mirror to stabilize the image in the NIR focal plane channel. The baseline orbit for DUNE is a Geosynchronous Earth orbit (GEO) with an Highly Elliptical Orbit (HEO) as a possible alternative.

The telescope is a passively cooled 1.2m diameter Korsch-like $f/20$ three-mirror telescope. with two focal planes, visible and NIR covering together 1 deg^2 (see Figure 3). After the first two mirrors, the optical bundle is folded just after passing the primary mirror (M1) to reach the off-axis tertiary mirror. A dichroic element located near the exit pupil of the system provides the spectral separation of the visible and NIR channels.

The visible Focal Plane Array (VFP) consists of 36 large format red-sensitive CCDs, arranged in a 9×4 array. Four additional CCDs dedicated to the attitude control (AOCS) measurements are located at the edge of the array. All CCDs are 4096 pixel red-enhanced e2v CCD203-82 devices with square 12 μm pixels. The physical size of the array is 466x233 mm corresponding to 1.09 deg $\times$0.52 deg. Each pixel is 0.102 arcsec, so that the PSF is well sampled in each direction over approximately 2.2 pixels, including all contributions. The VFP operates in the red band from 550-920nm.

The VFP will be used by the spacecraft in a closed-loop system to ensure that the scan rate and TDI clocking are synchronised. The two pairs of AOCS CCDs provide two speed measurements on relatively bright stars (V $\sim 22 - 23$). The DUNE VFP is largely a self-calibrating instrument. For the shape measurements, stars of

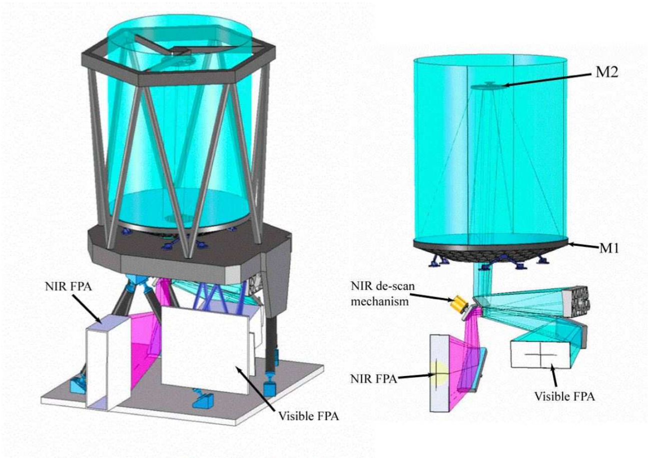

Figure 3. Telescope and focal planes designs

the appropriate magnitude will allow the PSF to be monitored for each CCD including the effects of optical distortion and detector alignment. Radiation-induced charge transfer inefficiency will modify the PSF and will also be calibrated through in-orbit self-calibration.

The NIR FPA consists of a 5×12 mosaic of 60 Hawaii 2RG detector arrays from Teledyne, NIR bandpass filters for the wavelength bands Y, J, and H, the mechanical support structure, and the detector readout and signal processing electronics. The NIR FPA is operated at a maximum temperature of 140 K for low dark current of $0.02e^{-}$/s. Each array has 2048 x 2048 square pixels of 18 μm size resulting in a 0.15×0.15 arcsec^2 field of view (FOV) per pixel. The mosaic has a physical size of 482×212 mm, and covers a FOV of $1.04° \times 0.44°$ or 0.46 square degrees. The HgCdTe Hawaii 2RG arrays are standard devices sensitive in the 0.8 to 1.7 μm wavelength range.

As the spacecraft is scanning the sky, the image motion on the NIR FPA is stabilised by a de-scanning mirror during the integration time of 300s or less per NIR detector. The total integration time of 1500 s for the 0.4° high field is split among five rows and 3 wavelengths bands along the scan direction. The effective integration times are 600 s in J and H, and 300 s in Y. For each array, the readout control, A/D conversion of the video output, and transfer of the digital data via a serial link is handled by the SIDECAR ASIC developed for JWST. To achieve the limiting magnitudes defined by the science requirements within these integration times, a minimum of 13 reads are required. Data are processed in the dedicated unit located in the service module.

The spacecraft platform architecture is fully based on well-proven and existing technologies. The mechanical, propulsion, and Solar array systems are reused from Venus Express (ESA) and Mars-Express. All the AOCS, μ-propulsion, Power control and DMS systems are reused from GAIA. Finally, the science telemetry system is a direct reuse from the PLEIADES (CNES) spacecraft.

4. CONCLUSIONS

The DUNE mission concept can be seen as the next step in precision cosmology. ESA's Planck mission will bring unprecedented precision to the measurement of the high redshift Universe. This will leave the dark energy dominated low redshift Universe as the next frontier in high precision cosmology. Constraints from the radiation perturbation in the high redshift CMB, probed by Planck, combined with density perturbations at low redshifts, probed by DUNE, will form a complete set for testing all sectors of the cosmological model. In this respect, a DUNE+Planck programme can be seen as the next significant step in testing, and thus challenging, the standard model of cosmology. DUNE will offer high potential for ground-breaking discoveries of new physics, from dark energy to dark matter, initial conditions and the law of gravity. DUNE will (i) measure both effects of dark energy by using weak lensing as the central probe; (ii) place this high precision measurement of dark energy within a broader framework of high precision cosmology by constraining all sectors of the standard cosmology model (dark matter, initial conditions and Einstein gravity); (iii) through a collection of unique legacy surveys be able to push the frontiers of galaxy evolution and the physics of the local group; and finally (iv) be able to obtain information on extrasolar planets, including Earth analogues.

Table 1. DUNE Baseline summary

Science objectives	Cosmology and Dark Energy Galaxy formation, Extra-solar planets
Surveys	20,000 deg^2 extragalactic 20,000 deg^2 galactic 100 deg^2 medium-deep, 4 deg^2 planet hunting
Requirements	1 visible band (R+I+J) for high-precision shape measurements 3 NIR bands (Y, J, H) for photometry
Payload	1.2m telescope, Visible & NIR cameras with 0.5 deg^2 FOV each
Service module	Mars/Venus express, Gaia heritage
Spacecraft	2013kg launch mass
Orbit	Geosynchronous
Launch	Soyuz S-T Fregat
Operations	4 year mission

The DUNE concept has been recently proposed to ESA's Cosmic Vision programme and has been selected jointly with SPACE[15] for an ongoing ESA Assesment Phase which has led to the merged *Euclid* mission concept.

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