The Transient High-Energy Sky and Early Universe Explorer (THESEUS)

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ABSTRACT

The Transient High Energy Sky and Early Universe Surveyor (THESEUS) is a mission concept under development by a large international collaboration aimed at exploiting gamma-ray bursts for investigating the early Universe. The main scientific objectives of THESEUS include: investigating the star formation rate and metallicity evolution of the ISM and IGM up to redshift ∼9–10, detecting the first generation (pop III) of stars, studying the sources and physics of re-ionization, detecting the faint end of galaxies luminosity function. These goals will be achieved through a unique combination of instruments allowing GRB detection and arcmin localization over a broad FOV (more than 1sr) and an energy band extending from several MeVs down to 0.3 keV with unprecedented sensitivity, as well as on-board prompt (few minutes) follow-up with a 0.6m class IR telescope with both imaging and spectroscopic capabilities. Such instrumentation will also allow THESEUS to unveil and study the population of soft and sub-energetic GRBs, and, more in general, to perform monitoring and survey of the X-ray sky with unprecedented sensitivity.

Keywords: X-ray astronomy: instrumentation; gamma-ray bursts; observational cosmology

1. INVESTIGATING THE EARLY UNIVERSE WITH GAMMA-RAY BURSTS

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution, extending at least to z ∼10 and their association with explosive death of massive stars, Gamma-Ray Bursts (GRBs) are unique and powerful tools for cosmology. In particular, GRBs represent a unique tool to study the early Universe up to the re-ionization era.[1] To date there is no consensus on the sources of re-ionization and GRB progenitors and their hosts are very good representative candidates. A statistical sample of highz GRBs (about 100 at $z >$ 6) can provide fundamental information such as: measuring independently the cosmic starformation rate, even beyond the limits of current and future galaxy surveys, the number density and properties of low-mass galaxies, the neutral hydrogen fraction, the escape fraction of UV photons from high-z galaxies. Even JWST and E-ELTs surveys, in the 2020s, will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8). The first, metalfree stars (the socalled Pop III stars) can result in powerful GRBs.[2] GRBs offer a powerful route to directly identify such elusive objects (even JWST will not be able to detect them directly) and study the galaxies in which they are hosted. Even indirectly, the role of Pop III stars in enriching the first galaxies with metals can be studied by looking to the absorption features of Pop II GRBs blowing out in a medium enriched by the first Pop III supernovae.[3] More generally, high-z GRBs will allow the cosmic chemical evolution to be investigated at early times.

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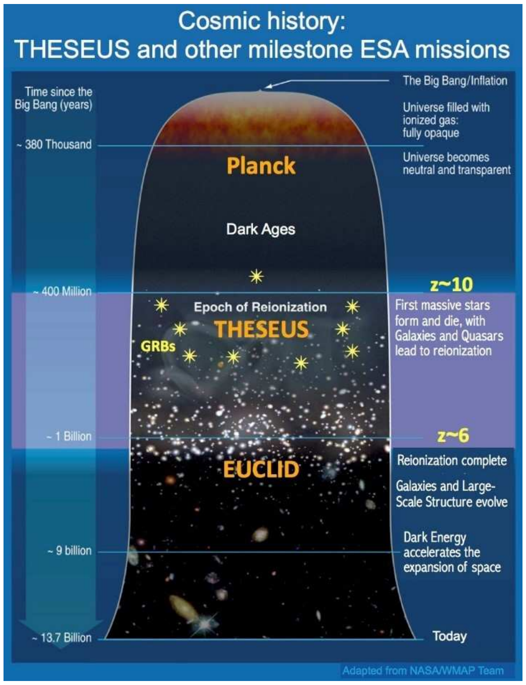

Figure 1. Example of the complementarity and uniqueness of the THESEUS mission w/r to other cosmological measurements.

2. THESEUS SCIENTIFIC GOALS

The main scientific goals of THESEUS can be summarized as follows.

(a) Exploring the Early Universe (cosmic dawn and re-ionization era) by unveiling the gamma-ray bursts (GRBs) population in the first billion years,[1] namely: to perform unprecedented studies of the star formation history up to $z \sim 8$–9 and more; to detect and study the primordial (pop III) star population (when did the first stars form and how did the earliest pop III and pop II stars influence their environments ?); to investigate the re-ionization epoch, the interstellar medium (ISM) and intergalactic medium (IGM) up to $z \sim 8$–9 and more (how did re-ionization proceed as a function of environment, and was radiation from massive stars its primary driver? How did cosmic chemical evolution proceed as a function of time and environment?); to investigate the properties of the early galaxies and what was the galaxies global star formation in the re-ionization era, and to investigate the dark energy properties and evolution. The complementarity of THESEUS under this respect with other "cosmology" mission investigating the CMB or the large scale structure of the Universe is illustrated in Figure 1.

(b) Performing an unprecedented deep survey of the soft X- ray transient Universe in order to: Fill the present gap in the discovery space of new classes of transients events, thus providing unexpected phenomena and discoveries; Provide a fundamental step forward in the comprehension of the physics of various classes of Galactic and extra-Galactic transients, like, e.g.: tidal disruption events TDE, magnetars /SGRs, SN shock break-out, Soft X-ray Transients SFXTS, thermonuclear bursts from accreting neutron stars, Novae, dwarf novae, stellar flares, AGNs / Blazars); Provide real time trigger and accurate (∼ 1 arcmin within a few s; ∼1 arcsec within a few minutes) location of (long/short) GRBs and high-energy transients for follow-up with next-generation optical (EELT), IR (JWST), radio (SKA), X-rays (ATHENA), TeV (CTA) or neutrino telescopes and identify electromagnetic counterpart of detections by next generation gravitational wave detectors.

Additional science. By satisfying the requirements coming from the above main science drivers, the THESEUS payload will also automatically be capable to perform excellent secondary and observatory science,

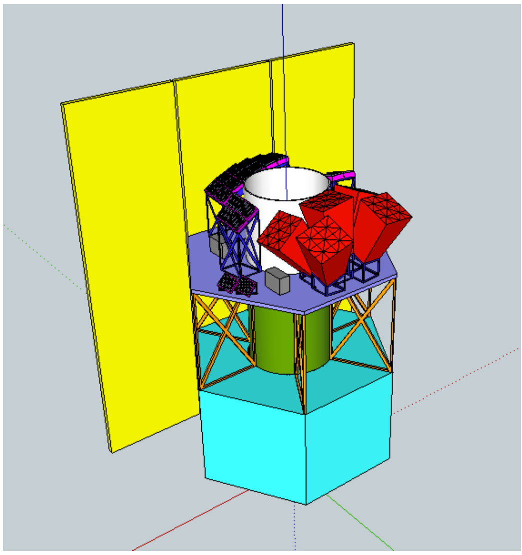

Figure 2. Schematic view of the payload and satellite in THESEUS; the central green and white tube contains the IRT detectors, optics and baffle; the red modules are the SXI; the black-pink modules are the XGS. Credits: the THESEUS Collaboration.

e.g.: unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse SNe; substantially increased detection rate and characterization of sub-energetic GRBs and X-ray flashes; IR survey and guest observer possibilities, thus allowing a strong community involvement; survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific synergy can be anticipated.

3. SCIENTIFIC REQUIREMENTS

The scientific goals which come from a full exploration of the early Universe requires the detection of a factor ten more GRBs (about 100) in the first billion years of the Universe ($z > 6$),[1] in the 3 years prime mission life time of THESEUS. Such a requirement is well beyond the capabilities of current and near future GRB detectors (Swift/BAT, the most sensitive one, has detected only very few GRBs above $z = 6$ in 10 years). As supported by intensive simulations performed by us and other works in the literature,[4] the needed substantial increase of high-z GRBs requires both an increase of ∼1 order of magnitude in sensitivity and an extension of the detector pass-band down to the soft X-rays (0.5–1 keV). Such capabilities must be provided over a broad field of view (∼1 sr) with a source location accuracy < 2, in order to allow efficient counterpart detection, on-board spectroscopy and redshift measurement and optical and IR follow-up observations. Such performances can best be obtained by including in the payload a monitor based on the lobster-eye telescope technique, capable of focusing soft X-rays in the 0.3–6 keV energy band over a large FOV. Such instrumentation has been under development for several years at the University of Leicester, has an high TRL level (e.g., BepiColombo) and can perform an all-sky survey in the soft X-rays with an unprecedented combination of FOV, source location accuracy (<1) and sensitivity thus addressing both main science goals of the mission. An on-board infrared telescope of the 0.5–1m class is also needed, together with spacecraft fast slewing capability (e.g., 30/min), in order to provide prompt identification of the GRB optical/IR counterpart, refinement of the position down to a few arcs (thus enabling follow-up with the largest ground and space observatories), on-board redshift determination and spectroscopy of the counterpart and of the host galaxy. The telescope may also be used for multiple observatory and survey science goals. Finally, the inclusion in the payload of a broad field of view hard X-ray detection system covering the same survey FOV as the lobster-eye telescopes and extending the energy band from few keV up to several MeV will increase significantly the capabilities of the mission. As the lobster-eye telescopes can be triggered by several classes of transient phenomena (e.g., flare stars, X-ray bursts, etc), the hard X-ray detection system provides an efficient means to identify true GRBs and detect other transient sources (e.g., short GRBs). The

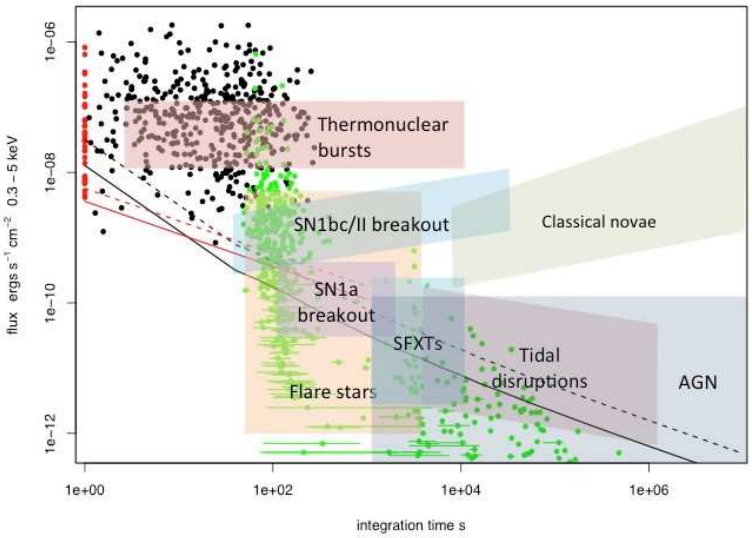

Figure 3. Sensitivity of the SXI (black curves) and XGS (red) vs. integration time. The solid curves assume a source column density of 5×10^{20} cm^{-2} (i.e. well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 10^{22} cm^{-2} (significant intrinsic absorption). The black dots are the peak fluxes for Swift BAT GRBs plotted against T90/2. The flux in the soft band 0.3-10 keV was estimated using the T90 BAT spectral fit including the absorption from the XRT spectral fit. The red dots are those GRBs for which T90/2 is less than 1 second. The green dots are the initial fluxes and times since trigger at the start of the Swift XRT GRB light-curves. The horizontal lines indicate the duration of the first time bin in the XRT light-curve. The various shaded regions illustrate variability and flux regions for different types of transients and variable sources. Credits: the THESEUS Collaboration.

joint data from the three instruments will characterize transients in terms of luminosity, spectra and timing properties over a broad energy band, thus getting fundamental insights into their physics.

4. PAYLOAD

Based on the above, the THESEUS payload consists of the instruments shortly described below.

Soft X-ray Imager (SXI): a set of Lobster Eye (0.3–6 keV) telescopes[5] covering a total FOV of 1 sr field with 0.5–1 arcmin source location accuracy. Each module is a focusing wide field lobster eye telescope based on the optical principles described in previous sections. The optics aperture is 290×290 mm^2 formed by an array of 7×7 square pore Micro Channel Plates (MCPs). The MCPs are 40×40 mm^2 and are mounted on a spherical frame with radius of curvature 600 mm (2 times the focal length of 300 mm). The open aperture provided by each plate is 38×38 mm^2; the outer dimension of the optics frame is 320×320 mm^2. The focal plane of each SXI module is a spherical surface of radius of curvature 600 mm situated at a distance of 300 mm (the focal length) from the optics aperture. The detectors for each module comprise a 2×2 array of large format CCDs baselined to be supplied by e2v technologies (UK) Ltd. Each CCD has an active area of 61×61 mm^2; the detectors are tilted to approximate to the spherical focal surface.

Infrared Telescope (IRT): a 70 cm class near-infrared (up to 2 microns) telescope (IRT) with imaging and moderate spectral capabilities. The telescope (optics and tube assembly) will be made of SiC, a material that has been used in other space missions (such as Gaia, Herschel, Sentinel 2 and SPICA). Simulations using a 0.7 m aperture Cassegrain space borne NIR telescope (with a 0.23 m secondary mirror), using a Teledyne Hawaii-2RG 2048x2048 pixels detector (18 m/pixels, resulting in 0.3 arcsec/pix plate scale) show that, for a 22.5 (H) point like source in a single 300 s exposure one could expect a SNR of 6. In order to achieve such performances the telescope needs to be cooled at 240 (+/- 3) K by passive means, conductive and radiative insulation. Regarding the instrument, the optics box needs to be cooled to 190 (+/- 5) K to by a two stage cooler for which the first

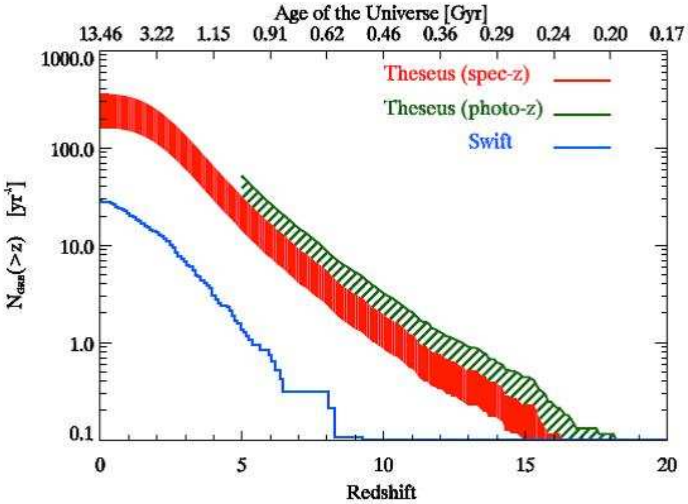

Figure 4. The annual rate of GRBs predicted for THESEUS SXI (red) compared to Swift (blue). The upper scale shows the age of the Universe. For Swift the actual number of known redshifts is approximately one third that plotted and none were determined on board (the blue curve has been linearly scaled upwards to match the total Swift trigger rate). For THESEUS the red region uses the simulations from Ref. 2 and adopts the instrument sensitivity for the SXI. Credits: the THESEUS Collaboration. .

stage will cool the optics and the second stage (the cold end) will cool the IR detector itself to 95 (+/-10) K: this allows the detector dark current to be kept at an acceptable level. The mechanical envelope of IRT is a cylinder with 80 cm diameter and 180 cm height. A sun-shield is placed on top of the telescope baffle for IRT stray-light protection. The thermal hardware is composed by a pulse tube cooling the Detector and FEE electronics and a set of thermal straps extracting the heat from the electronic boxes and camera optics coupled to a radiator located on the spacecraft structure. The overall telescope mass is 112.6 kg and the total power supply is 95W.

X-Gamma-rays Spectrometer (XGS): non-imaging spectrometer (XGS) based on Silicon Drift Detectors (SDD) and Cesium Iodine (CsI) crystal scintillators, covering the same FOV than the Lobster telescope extending its energy band up to 20 MeV. The XGS consists of 25 modules made of scintillator bars optically coupled to an array of (SDD) photo-diodes (PD) tightly packaged to each other.[6] Both SDD-PDs and scintillator detect X- and gamma-rays. The top SDD-PD, facing the X-/gamma-ray entrance window, is operated both as X-ray detector for low energy X-ray photons interacting in Silicon and as a read-out system of the scintillation light resulting from X-/gamma-ray interactions in the scintillator. The bottom SDD-PD at the other extreme of the crystal bar operates only as a read-out system for the scintillations. The discrimination between energy losses in Si and CsI is based on the different shape of charge pulses resulting from X-ray interactions in Si or from the collection of the scintillation light thanks to their different timing properties. Each bar is made of scintillating crystal 5×5×30 mm^3 in size. Each extreme of the bar is covered with a PD for the read-out of the scintillation light, while the other sides of the bar are wrapped with a light reflecting material convoying the scintillation light towards the PDs. The scintillator material is CsI(Tl) peaking its light emission at about 560 nm. The PD is realized with the technique of Silicon Drift Detectors with an active area of 5×5 mm^2 so matching the scintillator cross section.

A possible payload accomodation on a platform suitable for a launch with the Vega system is shown in Figure 2, sensitivity curves of the SXI and XGS are jointly shown in Figure 3, and the expected GRB detection rate as a function of redshift is shown in Figure 4.

5. MISSION PROFILE

The proposed mission profile includes an an on-board data handling (OBDH) system capable of detecting, identifying and localizing likely transients in the SXI and XGS FOV; the capability of promptly (within a few tens of seconds at most) transmitting to ground the trigger time and position of GRBs (and other transients of interest); and a spacecraft slewing capability of 30/min). The baseline launcher / orbit configuration is a launch with Vega to a low inclination low Earth orbit (LEO, $\sim$600 km, < 5), which has the unique advantages of granting a low and stable background level in the high-energy instruments, allowing the exploitation of the Earths magnetic field for spacecraft fast slewing and facilitating the prompt transmission of transients trigger and positions to ground. ASI antenna in Malindi and, as an option, the Brazilian antenna in Alcantara were proposed as ground stations. The basic observing strategy is based on alternating anti-sun and $\sim$ polar pointing, a compromise between maximum sky coverage, optimization of follow-up observations from the ground, instruments requirements (thermal, etc.). Considered prompt down-link options include: NASA/TDRSS, ESA/EDRS, WHF network, IRIDIUM network, ORBCOMM. MOC and SOC were proposed to be managed by ESA, while the SDC was proposed to be managed bu ASI (ASDC). The total payload mass of THESEUS, including all contingencies, was estimated to be $\sim$350 kg, and the total spacecraft dry mass about 1000 kg (power about 230 W and 800 W, respectively). The foreseen telemetry budget is fully compatible with the capabilities of the X-band, which will be the standard for next ESA M missions.

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