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The Infra-Red Telescope on board the THESEUS mission

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Abstract. The Infra-Red Telescope (IRT) on board *THESEUS* will play a key role in identifying and characterizing moderate to high redshift Gamma-Ray Bursts afterglows. The IRT enables the on board GRB autonomous redshift determination, thus allowing the ground based telescopes to be triggered on a redshift pre-selected sample and finally fulfilling the cosmological goals of the mission. The IRT will be composed by a primary mirror of 0.7 m of diameter coupled to a single camera in a Cassegrain design. It will work in the 0.7–1.8 μm wavelength range, and will provide a 10×10 arc min imaging field of view with sub-arc second localization capabilities, and, at the same time, a 5×5 arc min field of view with moderate (R up to ~500) spectroscopic capabilities. Its sensitivity, mainly limited by the satellite jitter, is adapted to detect all the GRBs, localized by the THESEUS SXI/XGIS instruments, and to acquire spectra for the majority of them.

Key words. Gamma-ray burst: general, Astr. instrumentation, methods and techniques, Instrumentation: spectrographs, Cosmology: early Universe, Galaxies: high-redshift

1. Introduction

Despite the recent progresses in Gamma-Ray Burst (GRB) science, obtained in particular thanks to the *Swift* and *Fermi* satellites (Zhang 2014, e.g.), there are still many open questions

in the field. One concerns the mechanisms that power these extreme explosions (in a handful of seconds the isotropic equivalent energy emitted by GRBs spans from 10^{50} to 10^{54} erg, making them the most luminous events in the Universe), which are still unclear after about five decades since their discovery (Klebesadel et al. 1973). In particular, the content of the relativistic flow that produces the GRBs remains to be investigated – especially in terms of its bulk Lorentz factor, its magnetization, its baryon loading and their consequences on the possibility of GRBs being the sources of Ultra High Energy Cosmic Rays (UHECRs).

Another open issue concerns the nature of GRBs progenitors: while thanks to a couple of tens of spectroscopic associations with type I b/c Supernovae, long GRBs are currently considered the endpoint of very massive (>30–50 $M_{\odot}$) stars evolution (but their potential binary nature is an open issue), the situation is less clear for what concerns the short GRBs (Levan et al. 2016). The most popular models involve the possibility of a coalescence of two compact objects (black holes or neutron stars), and the first direct proof may be represented by GRB/GW 170817 for which a gravitational wave signal from two merging neutron stars has been associated with a short flash of gamma ray radiation, although the derived isotropic emitted energy is far below the one measured for previously known short GRBs (Fong et al. 2017).

In addition to particle acceleration, radiation physics, and stellar evolution, GRBs are also pertinent to other branches of astrophysics, like Cosmology. Indeed, thanks to their bright afterglows they allow the observers to pinpoint the most distant galaxies (Perley et al. 2016), and to study them thanks to the imprinting on the afterglow data of the GRB close environment and the intervening matter between the GRB and the Earth, gathering a wealth of information on the structure and physical state of the gas in the Universe through spectroscopy.

THESEUS (Transient High Energy Sky and Early Universe Surveyor) is a project submitted to the European Space Agency (ESA) in the framework of the call for the fifth medium size mission (M5) of the Cosmic Vision programme. One of its main scientific pillars is the study of the early Universe making use of GRB afterglows as beacons (Amati et al. 2018). The selected M5 mission will be flown as early as 2029. The *THESEUS* payload is composed by three instruments: a set of three coded mask telescopes, called XGIS for X and Gamma-ray Imaging Spectrometer, a set of four wide field X-ray telescopes (Soft X-ray Imager, SXI) making use of "Lobster Eye" optics, and an Infra-Red Telescope, the IRT (see Fig. 1). The IRT is the key enabling instrument for the Cosmological goals of the *THESEUS* mission: in fact the SXI (the most sensitive of the two triggering telescopes for distant GRBs) will provide up to 1000 triggers per year, and, thanks to the agility of the *THESEUS* platform (once a trigger is declared on board, a slew request will be issued in order to put the error box in the field of view of the IRT), the IRT will be able to observe them systematically within a few minutes providing a sub-arc second position and a spectroscopic redshift. The same combination of sensitivity, flexibility and availability would not be possible on Earth, unless one would provide a dedicated network of more than ten robotic infra-red telescopes of the 2 m-class, which is a very complex task.

In the following sections the IRT and its performances will be described, as well as the preliminary observation strategy.

2. The Infra-Red Telescope

The scientific goals of *THESEUS* (see Amati et al. 2018) require the following on-board capabilities for a near-infrared telescope to follow-up GRB triggers after a demanded spacecraft slew:

1. Identify and localize the GRBs found by the SXI and XGIS to arc second accuracy in the visible and near IR domain (0.7–2.0 μm);
2. Autonomously determine the photometric redshift of GRBs at redshift z>4 and provide redshift upper limits for those at lower redshift;
3. Provide spectra to precisely measure the redshift, quantify the intrinsic absorption

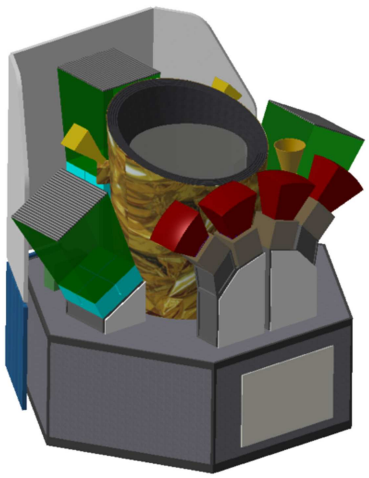

Fig. 1. The *THESEUS* satellite. The IRT is at the centre, and the four SXI telescopes are represented in red, while the three XGIS are represented in green.

(N_H), and possibly the metallicity for the majority of GRBs, and in particular those at redshift >4;

The IRT will be provided by a consortium led by France (CEA–Irfu, LAM, IRAP, GEPI, CNES) in collaboration with Switzerland (Université de Genève), Germany (IAAT) and Poland (SRC). The IRT will be composed by a primary mirror of 0.7 m of diameter (made of SiC) and a secondary mirror of 0.23 m in a Cassegrain configuration. It's total mass will be of about 110 kg for a power consumption of about 115 W. The telescope (provided by ESA) will be coupled to a camera (provided by the consortium) based on a 2048×2048 pixels HgCdTe detector (18 μm/pixels, resulting in a ~0.3 arcsec/pix plate scale). The detector will be optimised to be sensitive in the 0.7-1.8 (goal 2.0) μm wavelength range. This choice is based on the fact that, in order to measure the redshift, z, of GRB afterglows, the Lyman alpha break (at 0.126 μm at z=0) needs to be clearly identified. The selected wavelength range is hence adapted to measure redshifts between 4 and 10. Nowadays the bulk of GRBs are detected between redshift 2 and 3, hence this population is already well characterized, while the number of GRBs with measured redshift rapidly decreases above z=4–5.

In this configuration the expected sensitivity of the IRT will allow for a ~5 σ detection of a 20.6 magnitude (H, AB) point like source in a 300 s integration, see Table 1. The telescope sensitivity is partially limited by the platform jitter. Taking the latter into account (1 arc sec jitter over 10 s, at 3 σ level), we foresee to limit the image integration time to a maximum of 10 seconds per frame in order to correct for the jitter, and hence such short integration times will induce a high Read-out Noise (RoN) degrading in turn the IRT sensitivity. In addition, due to the absolute pointing error (APE) capability of the platform (2 arc minutes), the high resolution spectroscopy mode cannot make use of a fine slit, and a slit-less mode over a 5×5 arc min area of the detector will be implemented (similarly to what is done for the WFC3 on board the Hubble Space Telescope), with the idea of making use of the rest of the image to locate bright sources in order to correct the frames astrometry a posteriori for the telescope jitter. This is possible thanks to the selectable number of outputs (up to 32) of the Teledyne Hawaii 2RG detector[1], which is the current detector baseline. The same goal could also be obtained by making use of the information provided by the high precision star trackers mounted on the IRT. As a consequence the the maximum limiting resolution that can be achieved by such a system for spectroscopy is limited to R~500 for a sensitivity limit of about 17.5 (H, AB) considering a total integration time of 1800 s. The IRT expected performances are summarized in Table 1, and explained in more detail in Section 3, where we show that they are well adapted to the detection of the vast majority of GRB afterglows in the NIR band.

In order to keep the camera design as simple as possible (i.e. avoiding to implement

[1] Similar performances could be reached by a European 2k×2k detector, currently under development jointly by CEA-LETI and Sofradir and partly funded by ESA, which is expected to reach TRL 6 by 2021.

Table 1. IRT specifications and performances.

Telescope type	Cassegrain
Primary & Secondary Size	0.7 m & 0.23 m
Detector Type	HgCdTe 2048 x 2048 pixels (18 μm each)
Wavelength range	0.7-1.8 μm
Imaging plate scale	0.3 arc sec/pixel
Field of view	10′×10′ (imaging mode) — 10′×10′ (low resolution mode) — 5′×5′ (high resolution mode)
Spectral resolution ($\Delta\lambda/\lambda$)	2-3 (imaging mode) — 20 (low resolution mode) — 200-500 (high resolution mode)
Sensitivity (AB mag, 5σ)	H=20.6 (300 s) (imaging) — H=18.5 (300 s) (low resolution) — H=17.5 (1800 s) (high resolution)
Filters	ZYJH (imaging) — Prism (low resolution) — VPH grating (high resolution)

too many mechanisms, like tip-tilting mirrors, moving slits, etc.), we proposed to implement a design with an intermediate focal plane making the interface between the telescope provided by ESA/industry and the IRT instrument provided by the consortium, as shown in the block diagram in Fig. 2. The focal plane instrument is composed by a spectral wheel and a filter wheel in which the ZYJH filters, a prism and a volume phase holographic (VPH) grating will be mounted, in order to provide the expected scientific product (imaging, low and high-resolution spectra of GRB afterglows and other transients).

In order to achieve the performances described above (i.e. in conditions such that thermal background represents less than 20% of sky background) the telescope needs to be cooled at 240 (±3) K , and this could be achieved by passive means. Concerning the IRT camera, the optics box needs to be cooled to 190 (±5) K and the IR detector itself to 95 (±10) K: this allows the detector dark current to be kept at an acceptable level. Preliminary thermal studies making use of the Earth fluxes computed for the *SVOM* mission (Cordier et al. 2018), which will have a similar orbit in terms of altitude but with a higher inclination (30°), indicate that use of a Miniature Pulse Tube Cooler (MPTC) coupled to a 0.3 m^2 radiator, which periodically faces the Earth atmosphere, would allow to reach the desired temperatures for the camera detector.

2.1. Observing sequence

The currently proposed IRT observing sequence for an alert resulting in a platform slew can be summarized as follows:

1. The IRT will observe the GRB error box in imaging mode as soon as the satellite is stabilized within a few arc sec. Three initial frames in the ZJH-bands will be taken (10 s each, goal 19 AB 5σ sensitivity limit in H) to establish the astrometry and determine the detected sources colours.
2. The IRT will enter the spectroscopy mode (Low Resolution Spectra, LRS) for a total integration time of 5 minutes (expected 5 σ sensitivity limit in H 18.5 (AB)), see Fig. 3.
3. Sources with peculiar colours and/or variability (such as GRB afterglows) should have been pinpointed while the low-resolution spectra were obtained and IRT will take a deeper (20 mag sensitivity limit (AB)) H-band image for a total of 60 s. These images will be then added/subtracted on board in order to identify bright variable sources with one of them possibly matching one of the peculiar colour ones. NIR catalogues will also be used in order to exclude known sources from the GRB candidates.
   (a) In case a peculiar colour source or/and bright (< 17.5 H (AB)) variable source is found in the imaging step, the IRT computes its redshift (a numerical value if 4<z<10 or an upper limit z<4–5) from the low resolution spectra obtained at point 1) and determines its position. Both the position and redshift estimate will be sent to ground for follow-up observations. The derived position will then be used in order to ask the satellite to slew to it so that the source is placed in the high resolution part of the detector plane (see Fig. 2) where the slit-less high resolution mode spectra are acquired.

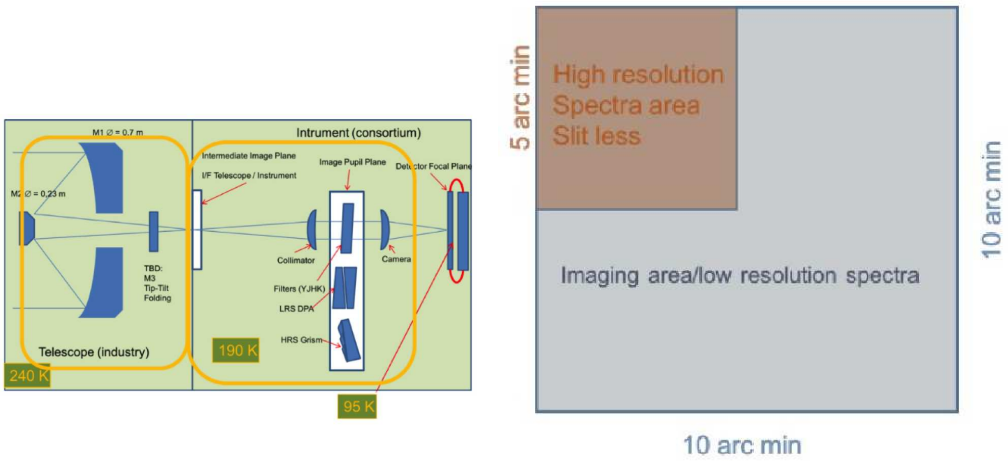

Fig. 2. Left: The IRT camera functional scheme. Right: The IRT focal plane: a 10×10 arc min field of view is available for imaging and low resolution spectroscopy, while only a 5×5 arc min field of view is used for slit-less high resolution spectroscopy to limit source confusion.

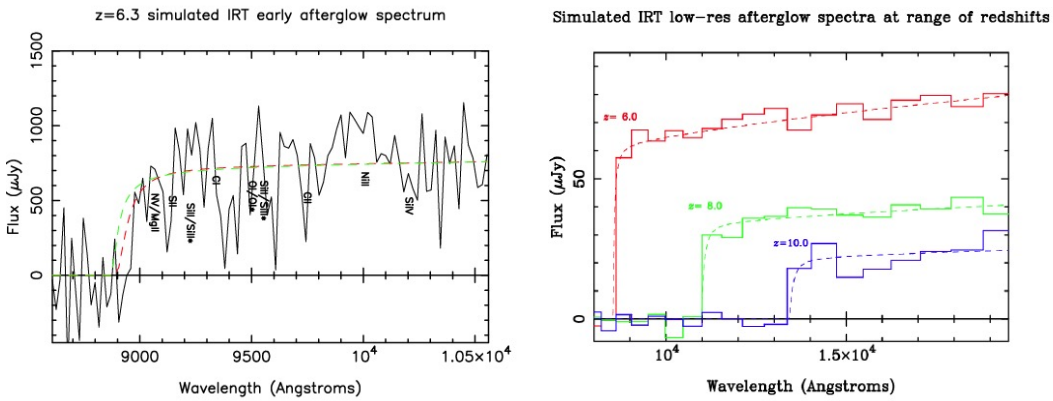

Fig. 3. Left: a simulated IRT high resolution (R=500) spectrum for a GRB at z=6.3 observed at 1 hour post trigger assuming a GRB similar to GRB 050904. Right: simulated IRT low resolution (R=20) spectra as a function of redshift for a GRB at the limiting magnitude AB mag 20.8 at z=10, and by assuming a 20 minute exposure. For more details about those simulations, see Amati et al. (2018).

Following the slew, the IRT enters the High Resolution Spectra (HRS) mode where it shall acquire at least three spectra of the source (for a total exposure time of 1800 s) covering the 0.7-1.8 μm range, see Fig. 3. Then it goes back to imaging mode (H-band) for at least another 1800 s (TBC). Note that while acquiring the spectra, continuous imaging is performed on the rest of the detector, see Fig 2. This will allow the on board software to correct the astrometry of the individual frames for satellite drift and jitter, leading to a final correct reconstruction of the spectra by limiting the blurring effects.

(b) In case that a faint (> 17.5 H (AB)) variable source is found, IRT com-

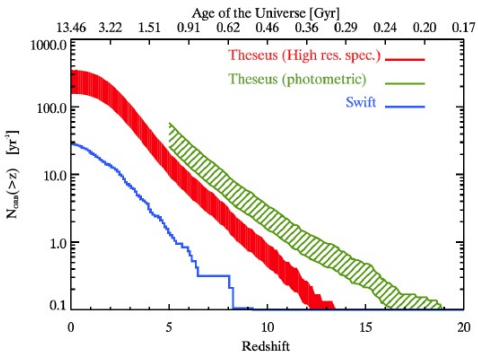

Fig. 4. The yearly cumulative distribution of GRBs with redshift determination as a function of the redshift for *Swift* and *THESEUS*. Details are provided in Amati et al. (2018)

putes its redshift from the low resolution spectra, determines its position and sends both information to the ground (as for 3a). In this case IRT does not ask for a slew to the platform and stays in imaging mode for a 3600 s time interval to establish the GRB photometric light curve (covering any possible flaring) and leading the light curve to be known with an accuracy of <5%.

3. Scientific performances

The number of expected GRBs triggers per year from the SXI and/or XGIS can reach up to 1000 (Amati et al. 2018). So one can expect up to three triggers per day. The IRT will follow-up systematically all the triggers providing the associated redshift estimate and possibly high resolution spectra. This will allow to fulfil the mission requirements, by detecting a large enough number of high-redshift GRBs, see Fig. 4.

IRT will be capable of detecting all afterglows known to date (see Rossi et al. 2018, for more details) and measure a photometric redshift for ~90% of the cases (H>19.5, AB system), starting observing in LRS mode even 20 min after the trigger. For more distant GRBs (assuming that z>6 afterglows have NIR properties similar to those observed up to date) more than 50% GRB will have H(AB)<19.5 5 min after the trigger, allowing for rapid photometric and LRS redshift determination.

There are chances that *THESEUS* could fly at the same time of the next generation X-ray observatory of ESA, *ATHENA*[2]. *ATHENA* will carry a high performance X-ray spectrometer (expected spectral resolution 2.5 eV), X-IFU, that will be used to study the chemical enrichment of the Universe. Observations of high-z GRB afterglows with the X-IFU will allow to simultaneously probe all the elements (C through Ni), in all their ionization stages and different binding states, and thus provides a model-independent survey of the metals during the early phases of the Universe. *THESEUS* will be able to provide redshift selected targets to *ATHENA* (*ATHENA* will implement a rapid response mode, <4 hours), and in addition simultaneous NIR spectra obtained with the IRT will provide complementary information about the elemental abundances of the GRB host galaxies.

We note that the only NIR sensitive telescope in space expected for the time of flying of *THESEUS* may be *JWST*[3]. While having a great sensitivity, *JWST* will have strong pointing constraints due to thermal reasons, and it is not designed to react quickly on alerts coming from other facilities. On the other hand, *JWST* will be a precious instrument in order to identify and spectroscopically characterize high redshift GRB host galaxies, once the afterglow has faded away.

We also note that all of the next generation ground based OIR facilities – TMT[4], GMT[5] and E-ELT[6] – have requirements for rapid response of 30 minutes or less, the most ambitious being the TMT with a 10 minute maximum response time including slewing, instrument and adaptive optics set up, before starting a science exposure. Observatory operational procedures are being planned that will allow rapid interruption of queue scheduled observations for high priority Target of Opportunity

[2] http://www.the-athena-x-ray-observatory.eu
[3] https://www.jwst.nasa.gov
[4] https://www.tmt.org
[5] https://www.gmto.org
[6] http://www.eso.org/sci/facilities/eelt/

(ToO) programs. Alerts sent to the observatory can be acted upon rapidly via automated processes or on time-scales as short as several minutes by the observing assistants. Some integrated fraction of time, possibly even as high as 10% to 20%, will be allotted for ToO programs but the interrupts could occur at any time during queue scheduled observations. However most probably none of these large observatories will be on target faster than the IRT and their schedule will be hardly overruled, unless a firm redshift determination is already available.

3.1. IRT and gravitational waves

We finally stress that the recent discovery of the electromagnetic counterpart of GW170817 has provided compelling evidence of the existence of kilonovae (e.g. Abbott et al. 2017; Pian et al. 2017). The temporal and spectral properties of these astrophysical phenomena encode crucial information that goes from the heavy element chemical enrichment of the Universe, the equation of state of neutron stars, the progenitor nature (e.g. NS-NS or NS-BH), etc. The high energy emission preceding a kilonova, e.g. a short GRB and/or an X-ray emission, can be detected with *THESEUS*/XGIS and SXI. However, only with an IRT observation in response to an SXI/XGIS trigger the source sky localization can be refined down arc second level thus enabling large ground-based telescopes as e.g. ELT, to observe and deeply characterize these cosmic events. The observations of GW170817 revealed that at 40 Mpc, the kilonova emission in the J and K bands reached its maximum 1.5 days after the merger with 17.2 mag and 17.5 mag respectively (Tanvir et al. 2017), thus consolidating the presence of a near infrared emission from such sources, which are well within the IRT capabilities at these distances.

By 2030 the horizon of ground based gravitational wave interferometers will grow, and a comparison between the expected IRT sensitivity and the expected emission from kilonova models between 50 and 200 Mpc is shown in Fig. 5. For more details on the *THESEUS* capabilities for multi-messenger astrophysics, see Stratta et al. (2018).

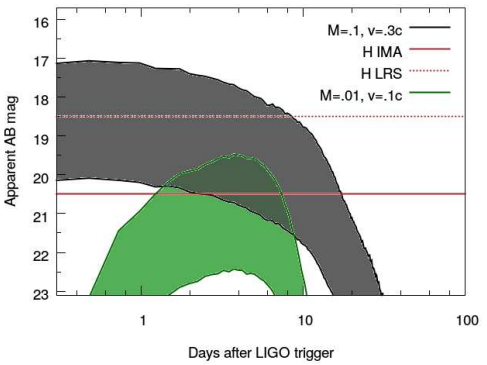

Fig. 5. Predictions of NIR kilonova light curve predictions as a function of distance (the lower curve for 200 Mpc the upper one for 50 Mpc), merger ejecta masses (M, in units of solar masses), and velocities (v, in units of speed of light) following Barnes et al. (2016). The IRT limiting sensitivities for imaging (continuous line) and spectroscopy (dashed line) are shown.

4. IRT observatory science

Based on our conservative estimate of GRB triggers, we expect that 30-40% of the IRT time will be available and open to the scientific community for additional guest observer (GO) science programs. On one hand, we expect that by the time of the launch of *THESEUS* a wide range of extragalactic science cases will be optimally addressed with the *Euclid*[7] survey (e.g. high-z obscured AGN and quasars, high-z clusters). *Euclid* (launch 2021) will cover 15,000 square degrees of the extragalactic sky, down to AB mag(YJH)=24, with R=380 slit-less NIR spectroscopy on the same area; this is ∼2 mag deeper than the IRT sensitivity in 1 hr exposure. However, *Euclid* will not have any ability to follow-up transients. In light of this, we will dedicate a fraction of the *THESEUS* observing time to fast Target of Opportunity (ToO) open to the community, in order to broaden our science cases. A spectro-photometric facility to follow-

[7] http://sci.esa.int/euclid/

up transient sources provides a unique service to the community at large and is known to yield high-impact science. A hard lesson that we are learning from current surveys is that the number of detected transients is very large and only a minimal fraction of them can be followed-up, resulting in a severe loss of efficiency (as a matter of fact, a large fraction of the newly-discovered transients remains unclassified). In the next decade, time-domain surveys (like CTA, LSST and SKA) and next generation multi-messenger facilities will revolutionise astronomy, providing insight in basically all areas but, at the same time, the need of follow-up facilities will dramatically increase. *THESEUS* will be a key facility to provide the multi-wavelength partner to any kind of transient survey (and will itself work as an X-ray transient factory thanks to the SXI and XGIS instruments). In recent years, at the dawn of time-domain astronomy, the experience of the *Neil Gehrels Swift Observatory* is enlightening. A large fraction of the *Swift* observing time is fully open to ToO observations from the community. Thanks to a flexible planning system, this open time has been optimally exploited, significantly contributing to the success of the *Swift* mission and the advancement in the science of transient and fast variable astrophysical phenomena. However, no other similar space missions with flexible scheduling are currently planned to be in operation around 2030. More importantly, while the astronomical community has (and likely will have in the future) a relatively easy access to optical imaging facilities (mainly ground based) dedicated to the follow-up of transients, the access to facilities operating in the NIR and/or with spectroscopic capabilities will remain difficult. To this end, a multi-frequency space mission equipped with a NIR telescope with spectro-photometric capabilities represents an asset, enabling a fast and efficient precise (sub-arc second) localisation and/or classification of newly-discovered transient sources through multi-frequency SED and spectroscopic characterization with very limited constraints with respect to ground-based observatories (day/night, weather, variable sky background). A flexible and efficient use of the non-GRB *THESEUS* time with GO and ToO programs will enable to tackle a wide range of studies of variable and transients sources. The near-infrared bands are critical for Solar-system object tracking and multi-epoch variability studies. Cool stars, whose photon fluxes peak in the near-IR, are ideal targets for the detection and characterization of exoplanets using the transit technique, either in surveys or for follow-up observations of individual sources (e.g. Clanton et al. 2012, and references therein). Simultaneous X-ray and NIR monitoring of samples of T-Tauri stars will shed light on the mechanisms responsible for the onset of the observed outbursts, and how the accretion rate of matter on these stars and the emission of jets can influence the formation of proto-planetary systems. Several open questions for low-mass X-ray binaries, hosting either neutron stars or stellar-mass black holes, require simultaneous IR and X-ray photometry (e.g. concerning the physics of jet emission from these sources; see, e.g., Migliari et al. 2010; Russell et al. 2013). Recent studies have found that the peak luminosity of SNe Ia are genuine standard candles in the NIR (e.g. Krisciunas et al. 2004; Burns et al. 2014). Considering also the reduced systematics in the NIR related to host-galaxy reddening, the IRT will represent an very efficient tool to construct a low-z sample of SNe Ia to be compared with the high-z samples that will be built by forthcoming IR facilities (e.g. *JWST*).

5. Conclusions

The IRT will play a key role in reaching the *THESEUS* scientific goals in the Cosmology field, as well as in the multi-messenger domain. Thanks to the implementation of a guest observer programme, it will also represent a powerful tool for the entire astrophysical community, which will benefit of a flexible, rapid, and sensitive near-infrared telescope in space with both imaging and moderate spectroscopic capabilities.

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