

Theia - Observing the Universe in Motion

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The *Theia* mission will explore the Universe at unprecedented astrometric precision of $0.3\mu\text{as}$ over a field of about 1 degree. *Theia* is the divinity of sight and daughter of Gaia. Similarly, the instrument concept carries on the heritage of HIPPARCOS and Gaia missions combined to latest developments in precision metrology control. While giant telescopes and other observatories will do wonders in spectroscopy, imaging, photometry, etc. *Theia* will enable science cases unique to μas astrometry, a precision that will reveal the Universe in motion like Earth-like planets orbiting around our immediate stellar neighbors, the activity of the most extreme objects known (black holes and neutron stars) and unveil the local sub-structure of the dark matter halo in which the Milky Way resides. Conceived as an open observatory class mission, *Theia* will bring ultra-precise astrometry to the broader community, including target-of-opportunity science in the era of Extremely Large Telescopes.

1 Scientific goals

Sky survey telescopes and powerful targeted telescopes play complementary roles in astronomy. The *Theia* Astrometric Observatory, as a flexibly pointed instrument capable of high astrometric accuracy even on faint targets, is an ideal complement to current astrometric surveys and a unique tool for precision astrophysics. *Theia* will push the frontier of precision astrometry not only to detect and characterize planets down to the Earth mass around the nearest stars for evidence of habitable worlds, but also well out into distant Milky way objects up to the Local Group of galaxies. As we enter the era of the James Webb Space Telescope and the new ground-based, adaptive-optics- enabled giant telescopes, *Theia* will scrutinize for example the movement of clusters (young, open and globular) that can be used to study their evolution and physics and derive precise stellar masses, luminosities, and ages. By obtaining these high precision measurements on key objects that Gaia could not reach, *Theia* will consolidate our theoretical understanding of the local universe, enable extrapolation of physical processes to remote redshifts, and derive a much more consistent picture of cosmological evolution and the likely fate of our cosmos.

1.1 Nearby habitable terrestrial exoplanets

One of the objectives of *Theia* is a complete census of Earths ($M \leq 1.25 M_{\oplus}$) and Super-Earths ($M \leq 5 M_{\oplus}$) located in the Habitable Zone (HZ) of the 50 nearest FGK stars. Astrometry is unique in the sense that it can provide 3D orbits of planetary systems irrespective of their inclination and quasi-insensitive to stellar activity. Transits require lucky orbital alignments and the Doppler technique can only reach extreme sub-m/s precision on a small fraction of non-active G & K dwarfs ($\sim 5\%$). While both transits and Doppler spectroscopy techniques can identify thousands of planetary systems providing statistics and follow-up opportunities on moderately bright stars, they are not able to identify our closest Earth-analog neighbours. Sub-microarcsecond astrometry combined with long-term radial velocities measurements provides the only feasible way to obtain a complete sample of the closest planetary systems for future direct imaging missions (closer than 10-13 pc, e.g. Alpha Cen, Tau Ceti, 61 Cyg). These planetary systems are of great importance since they will be the only ones that direct-imaging/spectroscopic missions, either in the visible or in the thermal infrared, will be able to study with sufficient details and where biosignatures could be searched for. As astrometry can measure planetary masses and fully characterize their orbits (period, inclination, semi-major axis, eccentricity, angles and ephemeris) in multiple systems, these pieces of information allow comparative planetology for systems containing all sorts of planets and provide an unbiased picture of the three dimensional architectures of planetary systems. The main objective of such a census, is at least

double: (i) detection and determination of true masses of nearby telluric planets, a mandatory piece of information to estimate the nature of the planetary surface, prior to any astrobiology possible statement, (ii) if the mean number of terrestrial planet in the HZ of solar-type stars is small, as pointed by the recent estimates by Kepler ($\approx 10\%$), stars with potentially habitable worlds are rather rare, and the valuable time of a prospective direct imaging mission should not be spent on stars without them.

1.2 Extreme astrophysical objects

Black holes, neutron stars and white dwarfs are examples of the most extreme objects known to exist. However, little is known about their fundamental properties such as masses or internal structures. These are the end-products of stellar evolution thus their masses and spins put strong constraints on how stars evolve and how elements heavier than hydrogen are formed in the observed abundances. Moreover, they exist at the limit of known physics where our extrapolations might not be valid at all. A micro-arcsecond level astrometry will provide distances and proper motions to binary stars with exotic/invisible companions such as black holes and neutron stars. Precise masses will also be obtained from measuring their orbits at micro-arcsecond level astrometry, even if they are kiloparsecs away from the Sun (e.g. Cygnus X-1). Perspective acceleration measurements will provide direct mass-radius determinations thus testing proposed equations of state of degenerate matter in strong gravitational fields, and astrometric microlensing events of high proper motion will provide single-star mass determinations. In a cluster context, e.g. globular cluster, we will follow across the cluster the binary/multiple star statistics understanding the evolution pathways creating these extreme objects. The proposed mission concept should also be able to achieve 10^{-5} photometric precision at the same time, thus providing further astrophysical observables in the strong gravitational regime (asteroseismology of white dwarfs, self-lensing in binaries with compact objects).

1.3 Fundamental astronomy and Solar system observations

Micro-arcsecond astrometry for bright asteroids is very useful for mass determinations of these objects by close encounters and improvement of their ephemerides. Since these measurements require time-critical observations, an observatory class mission with flexible scheduling will be mostly needed. Dynamical drag due to thermal effects can be measured as well as constraints on the inner physics of asteroids deduced from these effects or from the bulk densities estimated with the close encounters.

Depending on the angular size and *Theia's* ability to centroid asteroid-type objects, high precision measurements of the orbits of the Galilean satellites combined with orbital observations by the JUNO spacecraft, can be used to measure or at least put strong constraints on the internal structure of Jupiter (and the other gas giants). Global astrometry is required to make sensible experiments related with the reference frame because large angles have to be measured. Nevertheless, at a final accuracy of $0.3 \mu\text{as}$, a number of subtle effects can be measured in the relativistic light deflection of Solar system bodies. Using selected optimally populated stellar fields with Jupiter in front of it and shortly afterwards without Jupiter, one can detect multipolar light deflection due to Jupiter's dynamical non-sphericity, gravito-magnetic light deflection due to both translational and rotational motions as well as leading enhanced post-post-Newtonian effects.

1.4 Galactic dynamics, stellar associations and dark matter

As determined by the Planck mission, 85% of the matter in our Universe is in the form of Dark Matter (DM), whose physical identity is presently unknown although its gravitational potential dominates at the scale of galaxies, and affect how galaxies form and the universe evolves. *Theia* will probe the shape, radial profile, and lumpiness of DM halos, especially for the Milky Way and M31.

From halo streams, to absolute and peculiar proper motions within globular clusters, microarcsecond level astrometry has the power to unveil not only the structure and distribution of dark matter in the Milky way, but also reveal the dynamics of these objects. While current HST and Gaia provide proper motions at $50 \mu\text{as}/\text{yr}$ (equivalent to $4 \text{ km/s} \times D_{\text{Kpc}}$), a 1 microarcsecond level astrometric mission with a wide field angle has the power to measure in 1 year baseline true tangential velocities and $100 \times D(\text{Kpc}) \text{ m/s}$ precision level on thousands of objects per pointing, thus unveiling detailed dynamical maps of such associations. In clusters like Omega Centauri, very strong constraints (or detection) of their possible intermediate mass

black holes (10^3 - 10^5 solar masses) will also be possible routinely. Similarly, obtaining proper motions of tens of thousands of stars with respect to background galaxies and quasars will provide absolute proper motions of these associations thus tracing the large scale structure of the dark matter halo of the Milky Way and unveil the dynamical fate of our Galaxy (possible collision with Andromeda and the Triangulum Galaxy within 4 Gyrs?). Precision astrometry of peculiar objects, such as runaway and extreme halo stars, will unveil the origin of such exotic objects (ejected by the central black hole of the milky way, leftover of supernova explosions in massive binaries from OB associations, etc.).

Theia can constrain the physical nature of dark matter. The heavier the dark matter particles, the lower their velocity dispersion when they have collapsed and thermalised. Measuring the shape of the central DM density profile will give access to their velocity dispersion (equilibrium Jeans equation). Dwarf spheroidal (dSph) galaxies, e.g. Draco, occupy the least massive dark matter halos. Measuring the tangential components of the velocity of their brightest stars will break the present degeneracy between cusp and core models, giving a precise indication on their particle mass. Hundreds of their stars are $V = (17 - 19)$, so the statistical information obtained from simultaneous measurement of 1 degree fields is essential to perform these measurements.

1.5 ...microarcsecond astrometry in 2025 and beyond

There is no ground based competition against space-based astrometry, even on fainter objects and large telescopes. While hundreds of echelle spectrometers and other precision techniques are available from the ground, achieving competitive precisions compared to HIPPARCOS is challenging even today, and can only be done on small samples of objects in very narrow field applications. As a result, astrometry has been relegated to large space-based projects (e.g. Gaia, L-class mission), with technology development cycles spanning decades and strongly protected/vetted science cases to newcomers, making astrometry very unattractive to young scientists and inter-disciplinary colleagues. The availability of an easy-to-use, observatory class instrument will allow systematic use of astrometry as one more tool to characterize astrophysical sources. *Theia* will build on the experience and legacy on Gaia to provide sustained access to micro-arcsecond precision astrometric measurements. Let us note that, contrarily to other techniques, astrometry will not benefit from Giant telescopes as measurements are mostly limited by calibration uncertainties that require space-based conditions. The *Theia* mission must be used as a true community observatory with a large fraction of open time including target-of-opportunity science (regular proposal cycles, and fast reaction target-of-opportunity proposals). *Theia* will be a 1 degree diffraction-limited imager, thus enabling numerous additional science cases requiring high resolution imaging and superb photometric stability.

In the era of giant telescopes as well as in the momentum of the Gaia mission, a new high precision astrometric observatory must be launched in order to observe the tiny motions that are associated to all objects in our Universe.

2 Possible mission configuration

The *Theia* mission is based on various technical studies involving ultra-high precision differential astrometry (NEAT, STEP,...). The actual baseline is not decided yet : we are considering two possible mission configurations, one based on a single Three-Mirror-Anastigmat (TMA) telescope or a version based on two satellites flying in formation.

In both version, a crucial ingredient is the metrology system in order to calibrate the optical path to allowing sub- μ as monitoring of all relevant distortions in the field-of-view. Several laboratory experiments are currently demonstrating the capability of these metrology systems and the necessary precision of the centroiding techniques. The focal plane would accomodate several detectors that would offer a total field of 1 degree with diffraction limited sampling. An active control of the primary and subsequent mirrors would help to maintain the stability of the overall optical structure. The mission would certainly fly at the Lagrange point L2.

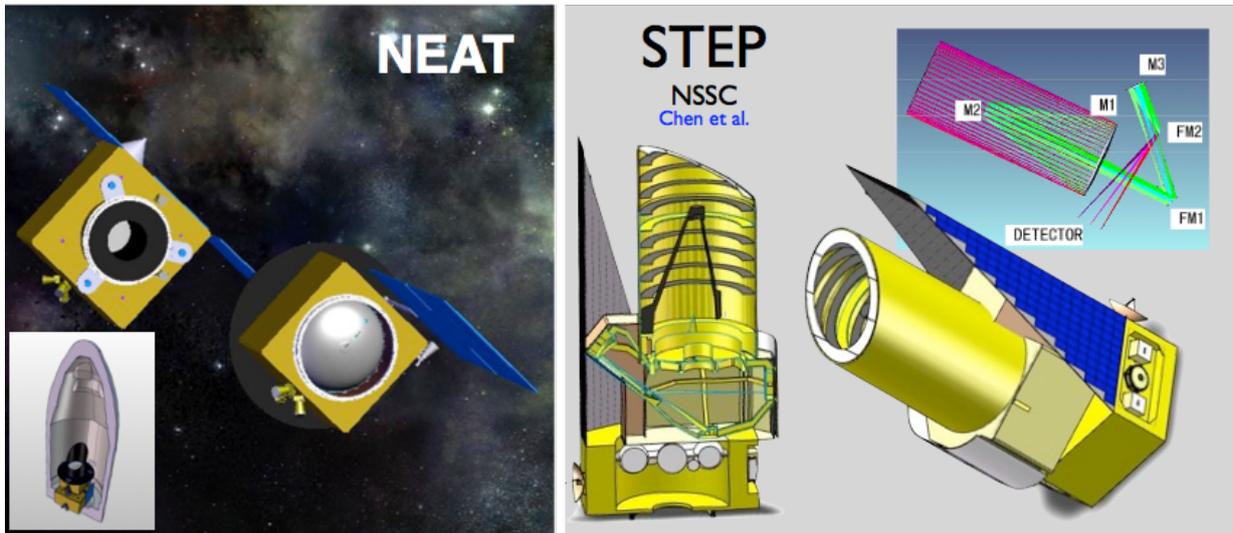


Figure 1: Left: the NEAT concept with two satellites flying in formation. Right: the STEP concept with a single TMA telescope.

3 Potential contribution and collaboration

Theia could benefit from several contributions. We are considering the possibility that the metrology and the focal plane could be part of the delivery of national contributions, as well as the telescope and the active control system. In the case of a formation flying system, some countries might be able to provide also some control elements. For the communication, we are looking for a collaboration with non-European countries that could provide the access to large antennas. Possible international contributors include USA and China.

4 List of supporters for *Theia*

The *Theia* mission proposal is currently supported by 50 scientists among 14 different countries including 10 ESA members.

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