Lunar or space-based hypertelescope for direct high-resolution imaging

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Introduction

Hypertelescopes are innovative extended versions of optical stellar interferometers, incorporating many mirror segments for operating as a dilute giant telescope. Their dilute mosaïc mirror, and focal beam combiner with pupil densification produces direct high-resolution images with full luminosity and the high resolution defined by the size of the meta-aperture . They also reach much fainter magnitude limits than conventional interferometers. The recent observation of an exoplanet's light with the Very Large Telescope Interferometer (Lacour et al. , 2018) confirms that a larger hypertelescope in space can likely produce multipixel images of exoplanets, usable for searching photosynthetic life on their surface.

Since described (Labeyrie, 1996), the concept and theory of hypertelescopic imaging, have been developed by different authors, confirming that many small subapertures, within a giant dilute meta-aperture, can produce much more science than few ones of larger size, at given total collecting area and meta-aperture size (Lardière et al., 2007, Labeyrie et al., 2010) . And the cost is lower since large mirrors have to be thicker, thus using more glass.

A terrestrial hypertelescope prototype is being tested in a southern Alpine valley since 2012. Its opto-mechanical system, with fixed mirror segments at near-ground level and a cable-suspended movable focal camera tracked with millimetric accuracy , is now considered mature for replication in a lunar crater . For a space-based hypertelescope, a flotilla of mirrors is considered, with different propulsion options.

1. Science questions for hypertelescopes in space

The direct-imaging capability of hypertelescopes, including for coronagraphic observations of faint exoplanets near their bright parent star, are of interest for varied types of sources, from stars to galaxies and the faintest cosmological sources yet detected .

1.1 Stellar physics

The partial information on stellar surfaces yet provided by conventional interferometers has contributed to their physical modelling, but the prospect of high performance spectro-imaging with hypertelescopes, showing granulation etc… is obviously of interest for improved models .

1.2 Exoplanet multipixel imaging

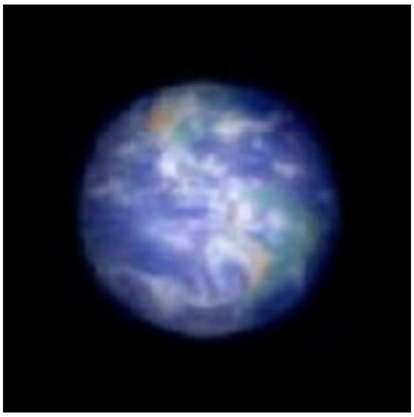

Figure 1: Numerical simulation of direct imaging with a 150km hypertelescope in space, showing an exo-Earth at 3 parsecs. Its contrast is enhanced by subtracting a uniform level, but the parent star's contamination is ignored in this simulation, and will in practice require efficient coronagraphy.

The seasonal color changes of the green vegetated areas seen in fig. 1 are likely detectable and may provide a robust biosignature (Labeyrie 2018).

1.3 Neutron stars, pulsars

The Crab pulsar, believed to be a 20km-sized rotating neutron star, is expected to become resolved with a 100,000km meta-aperture. This is likely feasible in the form of a mirror flotilla, preferably using a hierachical beam combiner for keeping the primary mirrors affordably small.

Resolved images of such pulsars, and those in binary systems which may incorporate black holes, are of obvious interest for exploring their physics .

1.4 Optical counterparts of gravitational wave events

Optical counterparts of gravitational wave events, as recently observed by many telescopes, will likely become observable in more detail with hypertelescopes.

2. Space missions: gains from the absence of atmospheric « seeing », and the much larger meta-aperture diameter possible with Moon or flotilla-based hypertelescopes L,M, S

The testing of the terrestrial hypertelescope prototype has shown that major improvements are possible in space, both on the Moon or as a free-flying flotilla . Atmospheric turbulence, with its tigtht isoplanatic angle, even if partially corrected with adaptive optics, is a strong limitation on Earth, especially for exoplanet coronagraphy.

Another strong limitation is the existence of concave terrestrial sites for nesting large arrays. Their size is limited to one or a few kilometers. And the focal camera, if carried by a drone, cannot be much higher than a few tens of kilometers, and is difficutl to stabilize in the presence of winds .

Several options are considered for Large, Medium, or even Small missions using cube-sats . Flotillas can be up-graded by adding mirror elements

2.1 Moon based missions

The opto-mechanical concept can be similar to that tested with the terrestrial Ubaye Hypertelescope prototype (Mourard et al. 2018).

2.2 Space missions with a mirror flotilla

The PRISMA space testing of controlled formation flying for stellar interferometry, with a pair of nanosatellites, has verified the feasibility of the larger flotillas considered for hypertelescopes.

3. Worldwide context

NASA conducted a NIAC study (http://www.niac.usra.edu/files/library/meetings/annual/oct05/1202McCormack.pdf) of the laser-trapped mirror concept (Mc Cormack et al), before it became realized that it could be more readily applied to arrays of small mirrors than to giant ones. A concept for a steerable terrestrial hypertelescope was also published by NASA scientists (Gezari et al. ,2003) . A detailed analysis of hypertelescope optics is also given by Tcherniavski (2014).

A collaboration has been initiated with chinese astronomers toward ground and space-based hypertelescopes .

4. Technology challenges

The various concepts and options for Moon or space based hypertelescopes raise differet technology challenges .

4.1 On the Moon:

The arraying of many mirrors, typically smaller than 0.5m and supported by fixed tripods in a lunar basin, is perhaps feasible by a robotic rover. Instead of a cable for suspending a focal camera, stretched between high points on edges of the basin, the proposed « Lunar Space Elevator »( ) is potentially applicable for a much higher altitude, reaching 65,000km and thus favoring a much larger meta-aperture . The sky coverage yearly obtainable has to be calculated as part of the evaluation .

4.2 In space :

The accurate control of a flotilla containing many small mirrors and at least one focal camera is achievable with conventional micro-thrusters, or small solar sails, or else pairs of counter-propagating laser beams (Labeyrie et al. 2010, Labeyrie 2018). The latter option is particularly attractive since thousands of passive nano-spaceships, in the form of membrane mirrors, appear controllable, with only three « laser herding » spaceships. Following some preliminary testing made in high vacuum (Labeyrie et al. 2010), much of the system can be further tested in the laboratory, and test-flown in the ISS .

References

A.Labeyrie, Resolved imaging of extra-solar planets with future 10-100 km optical interferometric arrays , Astron. Astrophys. Suppl. Ser. 118, 517-524 (1996)

A. Labeyrie, Multi-Pixel Imaging of Exoplanets with a Hypertelescope in Space, in Handbook of Exoplanets, (2018) H.J. Deeg, J.A. Belmonte (eds.)Springer 2018https://https://doi.org/10.1007/978- 3- 319- 30648- 3_168- 1
https://link.springer.com/content/pdf/10.1007%2F978-3-319-30648-3_168-1.pdf

O. Lardière, F.Martinache,F. and F.Patru, Direct imaging with highly diluted apertures I. Field of-view limitations, Mon. Not. R. Astron. Soc. 375, 977–988 (2007) doi:10.1111/j.1365-2966.2006.11362.x –

A. Labeyrie, Hypertelescopes: potential science gains, current testing and prospects in space, in "Mathematical Tools for Instrumentation & Signal Processing in Astronomy", D.Mary, R.Flamary, C Theys & C.Aime(eds), EAS Publication Series, , 78-79 (2016), 45-70, doi: 10.1051.eas/1678004

A. Labeyrie, P. Riaud, S. Residori, U. Bortolozzo, F. Vakili, Hypertelescope Optical Observatory (HOO): 1 to 100km flotilla for direct images at micro-arcsecond resolution on stars, exo-planets and deep fields . Proposal submitted to the European Space Agency (2013) https://lise.oca.eu/IMG/file/WhitepaperProposalHypertelescope.pdf

Labeyrie,A., H. Le Coroller, S. Residori, U. Bortolozzo,J.-P. Huignard and P. Riaud, Resolved Imaging of Extra-Solar Photosynthesis Patches with a "Laser Driven Hypertelescope Flotilla" in Pathways Towards Habitable Planets, ASP Conference Series, Vol. 430, (2010). Vincent Coudé du Foresto, Dawn M. Gelino, and Ignasi Ribas, eds. articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?2010ASPC..430..239L&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf

A.Labeyrie, Comparison of ELTs, interferometers and hypertelescopes for deep field imaging and coronagraphy, Comptes Rendus de l'Académie des Sciences-Physique , **8**, 3-4, p.426-437 , (2007). https://lise.oca.eu/IMG/file/CRAS-2007/ComparisonHyper15.pdf

A. Labeyrie, Lipson,S.G. & Nisenson, P.,, "An introduction to optical stellar interferometry" / Cambridge University Press,, p.212, (2006).

D. Mourard, A. Labeyrie, T. Lepine, T. et al. , Progress of the Ubaye hypertelescope project, Exp Astron 46: 561 (2018). https://doi.org/10.1007/s10686-018-9596-z

McCormack et al. Laser Trapped Mirrors: NASA/NIAC study http://www.niac.usra.edu/files/library/meetings/annual/oct05/1202McCormack.pdf

Lacour,S., Nowak. & Wang. First direct detection of an exoplanet by optical interferometry Astrometry and *K*-band spectroscopy of HR 8799 e , A&A 623, L11 (2019) https://doi.org/10.1051/0004-6361/201935253

D. Y. Gezari; Richard G. Lyon; Robert A. Woodruff; Antoine Labeyrie Large sparse aperture densified pupil hyper-telescope concept for ground-based detection of extrasolar planets Proceedings Volume 4860, High-Contrast Imaging for Exo-Planet Detection; (2003) https://doi.org/10.1117/12.457673

I. Tcherniavski (2014) Possibility of detection of earth-like exo-planets and recognition of their surface areas with a hypertelescope. Opt Eng 53(2):023106. https://doi.org/10.1117/1.OE.53.2. 023106