MAPLE: Reflected Light from Exoplanets with a 50-cm Diameter Stratospheric Balloon Telescope

Christian Marois[a], Colin Bradley[b], John Pazder[a], Reston Nash[b], Stanimir Metchev[c], Frédéric Grandmont[d], Anne-Lise Maire[e], Ruslan Belikov,[f], Bruce Macintosh[g], Thayne Currie[h], Raphaël Galicher[i], Franck Marchis[j,k], Dimitri Mawet[l], Eugene Serabyn[m], Eric Steinbring[a] and the MAPLE science team

[a] National Research Council of Canada, 5071 West Saanich Rd, Victoria, V9E 2E7, Canada;
[b] University of Victoria, 3800 Finnerty Rd, Victoria, V8P 5C2, Canada;
[c] University of Western Ontario, 1151 Richmond St, London, Ontario, N6A 3K7, Canada;
[d] ABB, 585 boul. Charest E., suite 300, Quebec, Qc, Canada;
[e] INAF - Osservatorio Astronomico di Padova Vicolo dell'Osservatorio 5, 35122, Padova, Italy;
[f] NASA Ames Research Center, Moffett Field, CA, 94035-1000, United States;
[g] Stanford University, 450 Serra Mall, Stanford, CA, United States;
[h] University of Toronto, 50 St. George Street Room 101, Toronto, Ontario, Canada M5S 3H4;
[i] LESIA, Observatoire de Paris, CNRS, UPMC Paris 6 and Denis Diderot Paris 7, 92195 Meudon, France;
[j] SETI Institute, Carl Sagan Center, 189 Bernardo Av., 94043 Mountain View CA, USA;
[k] Iris AO Inc., 2680 Bancroft Way, Berkeley CA 94704, USA;
[l] European Southern Observatory, Alonso de Córdova 3107, Vitacura, Santiago, Chile;
[m] Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109, United States

ABSTRACT

Detecting light reflected from exoplanets by direct imaging is the next major milestone in the search for, and characterization of, an Earth twin. Due to the high-risk and cost associated with satellites and limitations imposed by the atmosphere for ground-based instruments, we propose a bottom-up approach to reach that ultimate goal with an endeavor named MAPLE. MAPLE first project is a stratospheric balloon experiment called MAPLE-50. MAPLE-50 consists of a 50 cm diameter off-axis telescope working in the near-UV. The advantages of the near-UV are a small inner working angle and an improved contrast for blue planets. Along with the sophisticated tracking system to mitigate balloon pointing errors, MAPLE-50 will have a deformable mirror, a vortex coronograph, and a self-coherent camera as a focal plane wavefront-sensor which employs an Electron Multiplying CCD (EMCCD) as the science detector. The EMCCD will allow photon counting at kHz rates, thereby closely tracking telescope and instrument-bench-induced aberrations as they evolve with time. In addition, the EMCCD will acquire the science data with almost no read noise penalty. To mitigate risk and lower costs, MAPLE-50 will at first have a single optical channel with a minimum of moving parts. The goal is to reach a few times 10^9 contrast in 25 h worth of flying time, allowing direct detection of Jovians around the nearest stars. Once the 50 cm infrastructure has been validated, the telescope diameter will then be increased to a 1.5 m diameter (MAPLE-150) to reach 10^{10} contrast and have the capability to image another Earth.

Keywords: Planetary Systems, Exoplanets, High-Contrast Imaging, Reflected Light, Space Observatory, Wavefront Control, Coronagraph

Further author information: (Send correspondence to C. Marois)
C. Marois: E-mail: christian.marois@nrc-cnrc.gc.ca, Telephone: 1 250 363 0023

Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann, Jr., Mark Clampin, Giovanni G. Fazio, Howard A. MacEwen, Proc. of SPIE Vol. 9143, 91432R · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2056747

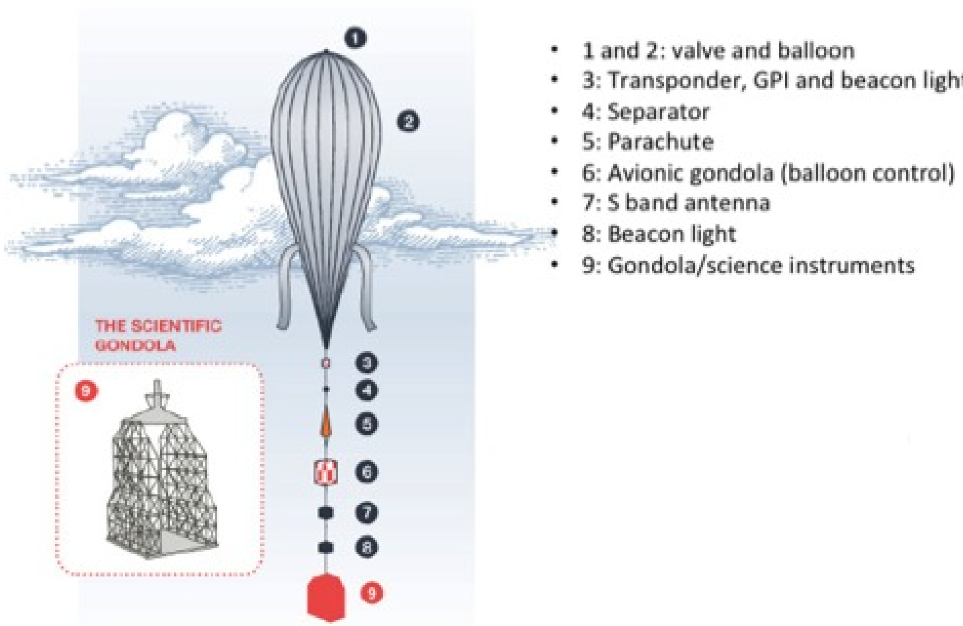

Figure 1. Typical stratospheric balloon components (from CSA website).

1. INTRODUCTION

Over many centuries, science has made enormous leaps in understanding our place in the Universe; we live on a small rocky planet, orbiting the Sun in a large galaxy hosting hundred of billions of stars, just one among billions of known galaxies. The quest to find a second Earth in orbit around another nearby star, where life (as we know it) may exist, is one of the biggest challenges in modern astronomy.

During the last 20 years, the exoplanet research field has made steady progress toward taking the first image of another Earth. The first discovery of a gas-giant planet, similar to Jupiter, orbiting another sun-like star was made in 1995.[1] The first images of gas giant planets orbiting other stars were acquired in 2008.[2–5] Recently, the *Kepler* spacecraft and Doppler-based spectroscopic radial-velocity surveys have finally discovered Earth-sized/mass exoplanets.[6] We now know that they are numerous in our galaxy, from maybe one Earth-mass/size planet per system and with possibly 6% of Sun-like stars having an Earth twin.[7] However, an important distinction needs to be made. While the *Kepler* and radial velocity discoveries are impressive, the technique offers limited data on the planets' mass, radius and orbital configuration, but no information at all about the planet's atmosphere and how Earth-like it is. Hence, the existence of a true Earth twin has not yet been confirmed.

Earth-like planets are defined as planets with a similar size, mass, and atmosphere as the Earth, and also located in the habitable zone of their star. The habitable zone being a temperate region around the star allowing liquid water, which could allow life familiar to us to develop. To confirm the planet's habitability, a spectrum of the candidate planet's atmosphere must be obtained to verify the presence of biomarkers (e.g. ozone, water, oxygen) and even signs of vegetation, land, oceans and seasons. Consequently, developing and applying a more direct exoplanet characterization method is the next step in answering this big question. Planets discovered with *Kepler* are generally too far away to allow direct characterization; Earth-like planet candidates must be found in the solar neighbourhood to allow this. Those few close-by terrestrial planet will be prime targets for in-depth characterization by a next generation of observatories.

The direct imaging of exoplanets is an extremely challenging undertaking. Using current ground-based adaptive optics (AO) systems, a few warm and young giant planets have been imaged in the thermal infrared

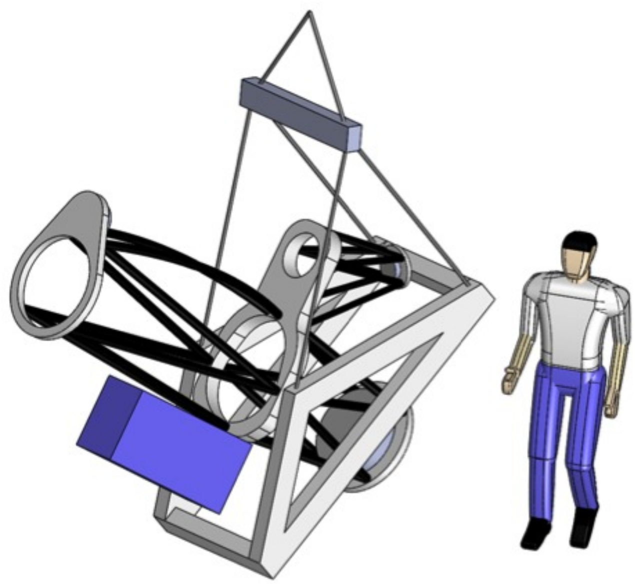

Figure 2. A preliminary CAD drawing of MAPLE-50's optical bench.

spectrum.[2–5] These observations are of planets (gas giants similar to a young Jupiter) whose brightness is 1/100,000 of the parent star. However, all of these planetary systems are believed to be too young, being less than one hundred million years old, to host any kind of life. In mature planetary systems, i.e. greater than one billion years old, such as our Sun and most of the stars in the solar neighbourhood, the systems' planets barely emit enough thermal light for detection. It is thus impossible to search and characterize these old planets using ground-based near-infrared instrumentation on current 10m class telescopes. The mature Earth-sized planets need to be detected by reflected light, i.e. light being emitted by the system's star and being reflected back to us from the planetary atmosphere or surface. The reflected light can require up to a 10 billion-to-one contrast, or be 100,000 harder than detecting a young gas giant planet in the near-infrared with ground-based telescopes.

We propose to embark on the exciting journey of acquiring that historic first pale blue dot picture of a nearby Earth-like planet through the development of the Exoplanet Imaging Laboratory (ExoLAB) at the University of Victoria and the subsequent development and implementation, within the ExoLAB, of the MAPLE endeavor (Mission to find A Planet Like Earth). MAPLE first project will be a stratospheric balloon-borne 50 cm diameter optical instrument (MAPLE-50) dedicated to directly imaging candidate exoplanet targets during several planned flights from the Canadian Space Agency's (CSA) launch facility in Timmins, Ontario. The overall MAPLE goal is to develop and implement the astrophysical instrumentation technology that can acquire an actual planetary image or the reflected light spectrum in order to confirm its Earth-like properties and undertake detailed studies of such planets.

2. THE MAPLE-50 BALLOON-BORN OBSERVATORY

Several space satellite programs promising high-contrast imaging of nearby Earth-like planets are planned, although none are currently funded to launch. Despite great potential, these missions are inherently complex, costly, and risky; none could be ready before ~ 2024. The MAPLE approach is entirely the opposite: simple, relatively cheap, and using (reusable) heritage stratospheric-balloon infrastructure. This allows a quicker iterative design and validation process in parallel with observation - providing near-term opportunities for breakthrough science. Over the years, the telescope diameter will be increased in steps to finally reach the capability of directly imaging and characterizing another Earth.

MAPLE's first iteration will be a 50 cm diameter off-axis telescope (MAPLE-50) mounted on an existing stratospheric balloon gondola. The balloon will fly at 40 km altitude, i.e. above most of the Earth's atmosphere.

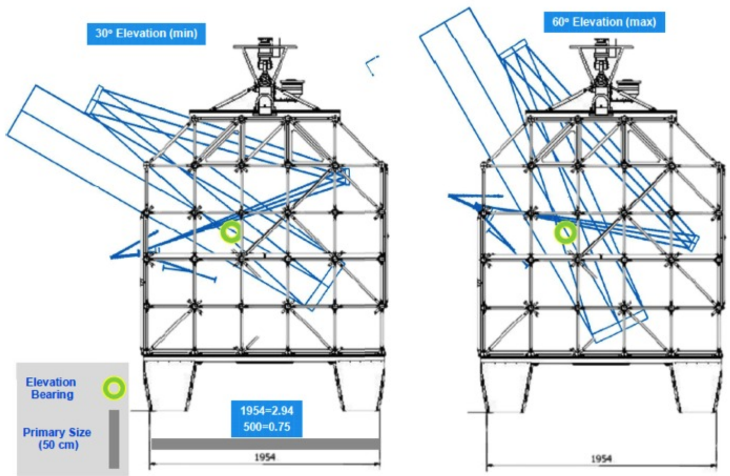

Figure 3. MAPLE-50's spherical optical design overlaid on the CNES CARMES gondola.

The initial smaller primary makes it easier and cheaper to polish the M1 glass substrate, the telescope and instrument are more compact, it fits on general use gondolas, and it is also less sensitive to tip/tilt, one of the biggest challenges that needs to be overcome. Otherwise, this concept is similar to previously proposed balloon telescopes.[8–10]

To further lower the cost of building and testing MAPLE-50, already available equipment and pre-arranged balloon flights will be utilized. This opportunity is made possible through the CSA which will hold a yearly competition to fly payloads up to about 1000 kg. The entire balloon and gondola system (Fig. 1) will be supplied by Centre National D'Étude Spatiales (CNES) and will include all infrastructure to support MAPLE-50 on its missions. For example: balloon, gas, parachute, gondola, azimuthal sky tracking, gondola stabilization, power supply, communication, support frame, transponder, GPS, connection to the balloon and instrument retrieval. No new development costs are required for this aspect of the flights, and would come free to the project; a contribution of an existing CSA/CNES 10-year agreement. The MAPLE team can then concentrate solely on the telescope and instrument, focusing on those precision pointing, stabilization, thermal-gradient, and flexure issues.

MAPLE-50 will have a minimal telescope and camera optics enclosure to protect the mirrors during ascent/descent, a protected electronics crate, a thermal Sun shield, and an electrical temperature control system to minimize thermal gradients and keep the bench at a constant operating temperature. A preliminary CAD model of MAPLE-50 is shown in Fig. 2. MAPLE-50, even with its 50 cm diameter, is a tight fit in the CNES Carmes gondola (see Fig. 3). A wider-field 7 cm diameter acquisition telescope will also be mounted on the main telescope. A NÜVÜ 1024×1024 EMCCD operating at 16.5 Hz will acquire a $11' \times 11'$ field-of-view and perform a centroid analysis on the bright science target.[11] This guiding signal will control the altitude/azimuth platform with a goal of reaching < 1 arcsec guiding accuracy. The team plans to launch this prototype MAPLE-50 acquisition telescope on an earlier CSA/CNES small payload piggyback flight to test hardware and overall system performances as well as to characterize optical atmospheric aberrations from the gondola.

The instrument path will have a single deformable mirror. We are looking into designs using a 32×32 Boston Micromachines Corporation or an IRIS AO segmented deformable mirror,[12,13] a beamsplitter, a pyramid wavefront sensor for increased sensitivity to low-order aberrations,[14] a charge 4 vortex coronagraph,[15] a Lyot-based wavefront sensor,[16] a reflecting Lyot stop with the self coherent camera pinhole located outside the pupil,[17,18] an interference filter and a 512×512 NÜVÜ EMCCD. To minimize risks and cost, MAPLE-50 will have a minimum of moving parts in its first implementation. MAPLE-50's instrument block diagram is shown in Fig. 4.

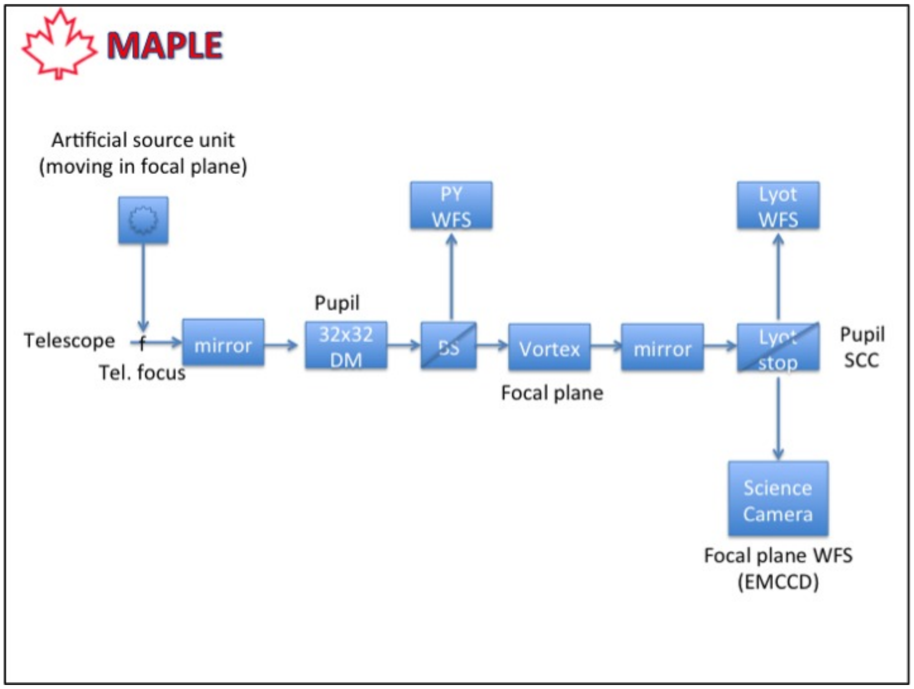

Figure 4. MAPLE-50's instrument block diagram. MAPLE-50 will have an artificial internal light source for testing the instrument, a deformable mirror, a vortex coronagraph and perform focal plane wavefront sensing with an EMCCD.

3. MAPLE-50'S OPTICAL DESIGN

The MAPLE-50 preliminary optical design is presented in Fig. 5 and Fig. 6. The optical design has driven basic component specifications, e.g. telescope mirrors, mirror mounting dimensions, overall spatial constraints, and the size/quality of all subsequent optics in the train. The optical design is based on a 50 cm aperture tri-Schiefspiegler telescope. The design uses 3 spherical mirrors (M1, M2, M3), greatly simplifying manufacture; the spherical mirrors can be fabricated with very small micro-roughness and mid-spatial frequency surface errors, both parameters extremely critical to achieving the light suppression for exoplanet detection. The cost of manufacture is much lower than by using complex off-axis optics usually employed in telescopes. We are also looking into an off-axis parabola design with two flats and potentially making it more compact for a better fit in the CNES CARMES gondola.

A coronagraph and AO bench that is also designed with spherical optics follow the three mirrors. The AO system is located before the coronagraph and uses a deformable mirror commanded by a pyramid wavefront sensor to clean up any optical aberrations from the telescope and the atmosphere. The wavefront sensor is fed by a partial transmitting coating on the AO f/50 imager. This eliminates the need for an additional optic in the path, minimizing non-common path errors and scatter. The light reflecting from the f/50 imager mirror is sent to the vortex coronagraph. Telescope pointing control is critical for the vortex coronagraph performance, where an accuracy of 5 mas RMS is needed to reach 10^8 contrast and a $1.7\lambda/D$ inner working angle (IWA).[19] The system is designed with a second wavefront sensor by imaging the light being reflected off the Lyot stop, i.e. a Lyot wavefront sensor. The Lyot wavefront sensor is fed by the light reflected off the Lyot stop and provides a highly accurate tip-tilt and other low orders error sensor. This low order Lyot wavefront sensor will serve as a backup to other techniques to derive these aberrations directly from the focal plane images.[20] These errors are fed back to the deformable mirror. Coarse tip-tilt errors, such as created by gondola sway, are corrected with the tertiary mirror and potentially by also continuously offloading re-orientation commands to the telescope altitude/azimuth platform.

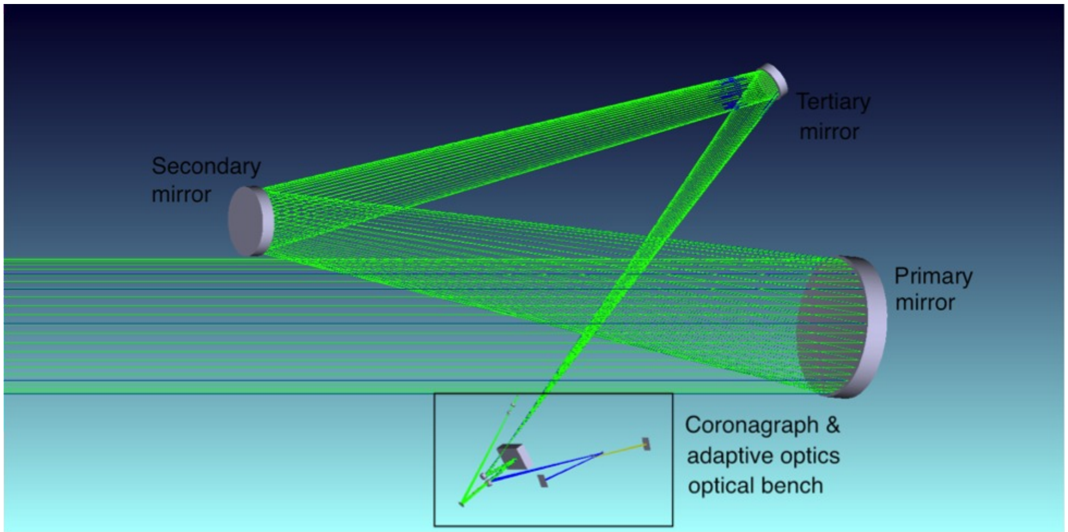

Figure 5. The overall MAPLE-50 spherical optical design.

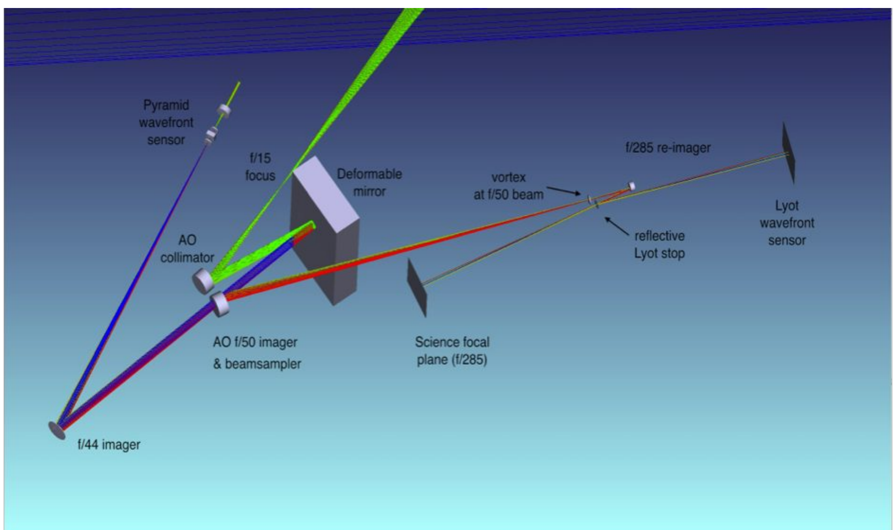

Figure 6. Maple-50's instrument optical design.

4. MAPLE-50 PREDICTED PERFORMANCE

MAPLE-50, with its modest 50 cm diameter primary, will be limited in its science reach during the short < 25h duration flights, but it still allows some exciting science to be performed. Each target can be acquired when they rise 25 degrees above the Earth's limb and be tracked until the star sets or if the target is occulted behind the balloon (35 degrees from Zenith). A large amount of exoplanetary system dust (analogous to the Zodiacal Light in the Solar system) may prevent the detection of small planets with MAPLE-50, but knowledge of dust levels is itself important for further steps. Moreover, given our technical and cost limitations, and the fact that only a bigger aperture can solve this problem, we need to start with a smaller aperture first to scale-up the design in the future.[21]

Observations will be acquired at 450 nm with a 10% bandpass, being a compromise between the number of available G-type star photons, the improved spatial resolution of shorter wavelengths, and better contrast to blue planets (planets like Neptune or Earth). The analysis performed so far indicates that 25-hour flight durations is sufficient to enable direct imaging of Jupiter-like planets in reflected light at 5 or more sigma. The

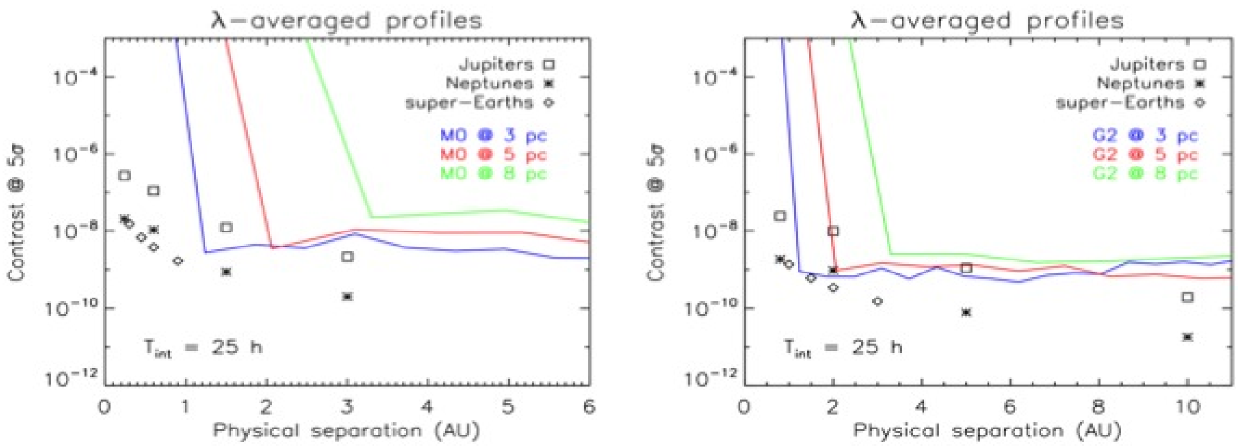

Figure 7. Predicted MAPLE-50 contrast for a 25h sequence on typical nearby M0 and G2 stars.[22] MAPLE-50 will be sensitive to Giant planets around nearby stars. The simulations are for photon noise only (no readnoise), 16% total transmission, no zodiacal/exozodiacal clouds and 10% bandpass.

results of this analysis are presented in Fig. 7. Imaging Neptune-like and super-Earth planets could require up to 100-hours of observing time, which means conducting the flights from other international sites, under the CNES/CSA agreement (e.g. Alice Springs, Australia). Fig. 7 illustrates clearly the infrastructure optimization (minimizing the telescope size in order to lower the cost and reduce the risk) while still allowing frontier science discoveries. On longer flights, MAPLE-50 could reach super-Earth planets around the nearest GKM-type stars.

Our analysis shows it would take 15 and 30-hours respectively to detect planets Epsilon Eridani b and Upsilon Andromedae e with MAPLE-50 (5-sigma and a 10% bandpass, see Fig. 8). Thus, each planet is a feasible target in a single balloon flight. These planets have never been directly detected nor characterized. Epsilon Eridani is low in the sky from Timmins Ontario (Dec = −9 degrees), but it is not occulted by the balloon thus allowing a long uninterrupted integration sequence to be acquired, while Upsilon Andromedae is higher, it will be occulted by the balloon as it transits the local meridian near Zenith (Dec = +41 degrees). Both are visible in late summer/fall during night time.

For the most nearby star system, Alpha Centauri A (southern hemisphere flights) MAPLE-50 could detect an Earth-like planet located in the habitable zone. Due to the system proximity (1.3 parsec) the star's habitable zone is located at ∼0.9 arcsec, or 5 lambda/D at 450 nm for MAPLE-50. Assuming a starting contrast of a few 10^8 at that separation, 100 hours' integration time would reach 10^{11} contrast.

For young planetary systems detected by ground-based near-infrared surveys, such as HR 8799bcde or Beta Pictoris b, MAPLE-50 could characterize the planets at 800 nm and 1 micron, increasing the spectral coverage for better temperature fitting and model comparison. Typical contrast for the HR 8799cde planets at those wavelengths are a few 10^9.

5. BEYOND MAPLE-50

It is a goal to increase MAPLE-50's diameter to a 1.5 m observatory (MAPLE-150) in the next decade to perform a nearby star survey using week-long balloon flights, dramatically increasing the observatory's science potential. The overal gondola, optical design and pointing control will all need to be improved to reach the 10^{10} contrast goal on a large enough star sample. The improved contrast will be achieved with a combination of better pointing accuracy, longer balloon flight time and post processing. The idea is also to start performing detailed characterization of these planets using an imaging spectrograph to study the atmosphere and search for biomarkers. Fig. 9 shows a simulated nearby planet sample with an overlay of the expected performances

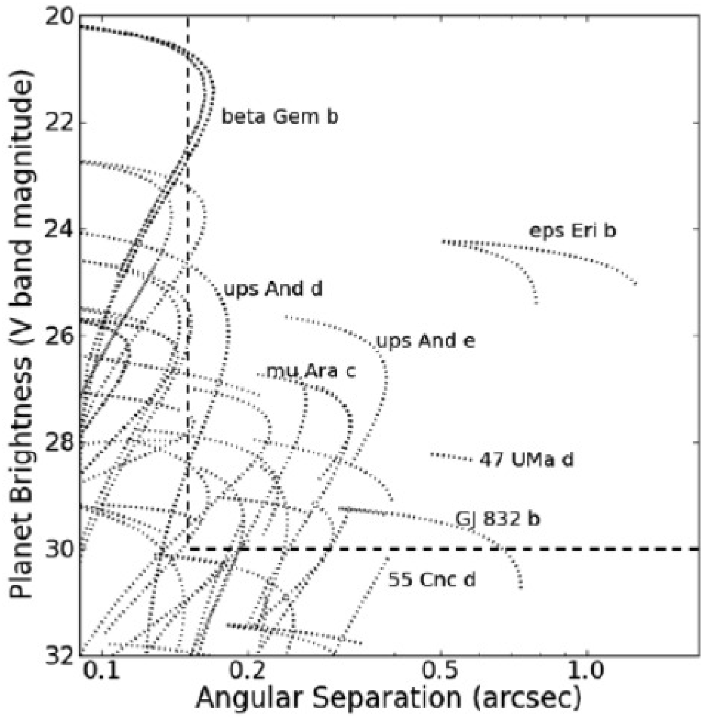

Figure 8. Nearby planetary systems detected by radial velocity. Epsilon Eridani b and Upsilon Andromedae e are the two most promising known systems accessible with MAPLE-50. The arc-like curve for each planet is the change of brightness due to the planet phase (fraction of surface being illuminated as seen from Earth). MAPLE IWA is $\sim 0.3''$ at 0.45 micron. Image from the Exo-C STDT Interim Report.

of MAPLE-50 and MAPLE-150. While MAPLE-50 is limited to gas-giant planets and super-Earths, a 1.5 m diameter version would be sensitive to Earth-like planets around several stars in the solar neighbourhood.

In addition, it is anticipated that other science may be enabled by the exquisite image quality afforded by Maple-50 and Maple-150, and opening up some time for the broader community may be considered.

6. CONCLUSIONS

The MAPLE-50 infrastructure is a small scale, low risk and low cost project to fly a balloon-borne high-contrast 50 cm diameter observatory at 40 km altitude, allowing rapid validation of concepts, quickly solving practical technology implementation problems, and thereby do forefront science. A heritage and scalable infrastructure allow the observatory infrastructure to be improved in a natural progression in time, with the goal of increasing the primary diameter to 1.5 m in the next decade. This could allow the first true Earth-like planet to be detected and characterized. The technological know-how that will be gained by developing the MAPLE infrastructure can be applied to future large-scale ground-based telescopes, such as the Thirty Meter Telescope[24] or future space observatories.

REFERENCES

[1] Mayor, M. and Queloz, D., "A jupiter-mass companion to a solar-type star," *Nature* **378**(6555) (1995).
[2] Marois, C., Macintosh, B., Barman, T., Zuckerman, B., Song, I., Patience, J., Lafrenière, D., and Doyon, R., "Direct imaging of multiple planets orbiting the star HR 8799," *Science* **322**(5906), 1348 (2008).
[3] Kalas, P., Graham, J. R., Chiang, E., Fitzgerald, M. P., Clampin, M., Kite, E. S., Stapelfeldt, K., Marois, C., and Krist, J., "Optical images of an exosolar planet 25 light-years from earth," *Science* **322**(5906), 1345 (2008).

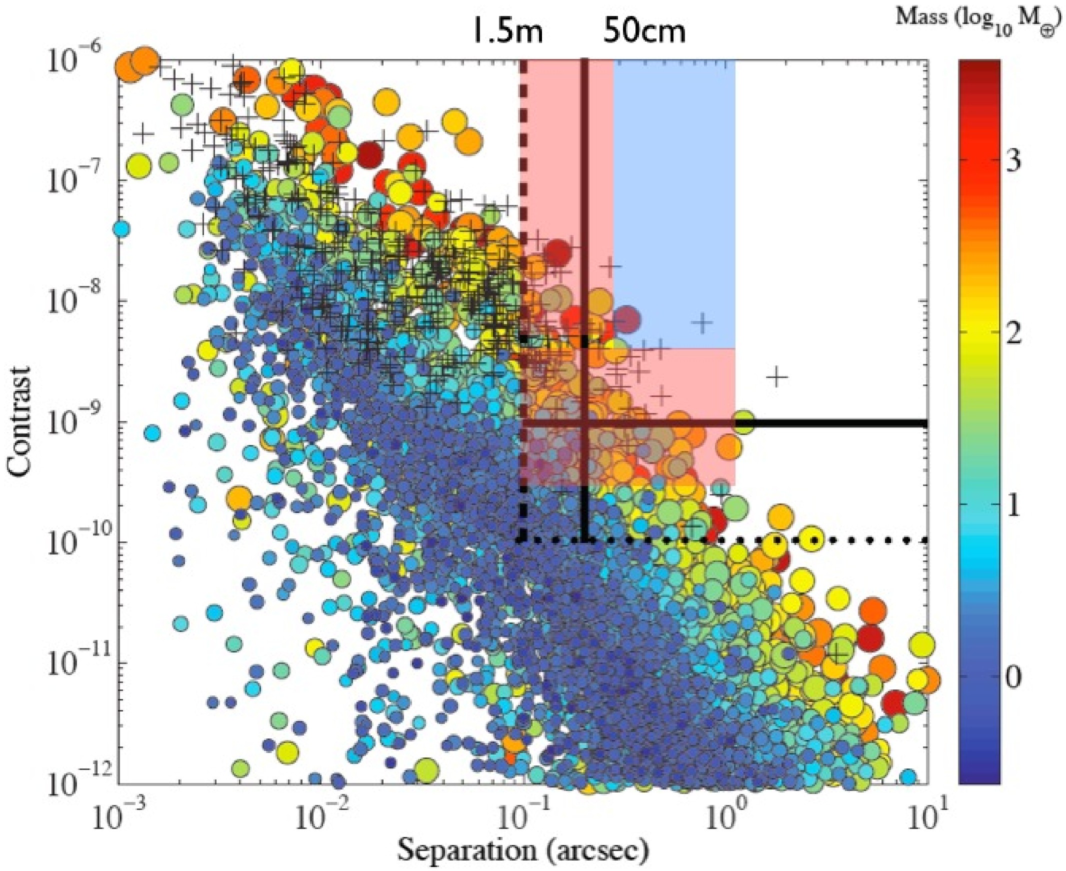

Figure 9. Simulated planet sample[23] around nearby stars: large circles are gas-giant planets similar to Jupiter/Saturn; light blue circles are Neptune-like planets; and, dark blue circles are Earth-like planets. Blue-shaded area is the search space for MAPLE-50 while the red shaded area is for MAPLE-150 (see online version for proper colour rendering).

[4] Lagrange, A.-M., Gratadour, D., Chauvin, G., Fusco, T., Ehrenreich, D., Mouillet, D., Rousset, G., Rouan, D., Allard, F., Gendron, E., Charton, J., Mugnier, L., Rabou, P., Montri, J., and Lacombe, F., "A probable giant planet imaged in the β pictoris disk. vlt/naco deep l'-band imaging," *Astronomy and Astrophysics* **493**(2) (2009).

[5] Lafrenière, D., Jayawardhana, R., and van Kerkwijk, M. H., "Direct imaging and spectroscopy of a planetary-mass candidate companion to a young solar analog," *The Astrophysical Journal* **689**(2) (2008).

[6] Quintana, E. V. and et al., "An earth-sized planet in the habitable zone of a cool star," *Science* **6181** (2014).

[7] Petigura, E. A., Howard, A. W., and Marcy, G. W., "Prevalence of earth-size planets orbiting sun-like stars," *Proceedings of the National Academy of Sciences* **110** (2013).

[8] Traub, W. A., Wesley, A., Chen, P., Kern, B., and Matsuo, T., "Planetscope: an exoplanet coronagraph on a balloon platform," *Proceedings of the SPIE* **7010** (2008).

[9] Bryden, G. and et al., "Zodiac ii: debris disk science from a balloon," *Proceedings of the SPIE* **8151** (2011).

[10] Roberts, L. C., Bryden, G., Traub, W., Unwin, S., Trauger, J., Krist, J., Aldrich, J., Brugarolas, P., Stapelfeldt, K., Wyatt, M., Stuchlik, D., and Lanzi, J., "The debris disk explorer: a balloon-borne coronagraph for observing debris disks," *Proceedings of the SPIE* **8864** (2013).

[11] Daigle, O., Djazovski, O., Laurin, D., Doyon, R., and Artigau, E., "Characterization results of emccds for extreme low-light imaging," *Proceedings of the SPIE* (2012).

[12] Bifano, T. G., Perreault, J. A., and Bierden, P. A., "Micromachined deformable mirror for optical wavefront compensation," *Proceedings of the SPIE* **4124** (2000).

[13] Helmbrecht, M. A., He, M., and Kempf, C. J., "High-actuator-count mems deformable mirrors," *Proceedings of the SPIE* **8725** (2013).

[14] Esposito, S., Feeney, O., and Riccardi, A., "Laboratory test of a pyramid wavefront sensor," *Proceedings of the SPIE* **4007** (2000).

[15] Palacios, D. M., "An optical vortex coronagraph," *Proceedings of the SPIE* **5905** (2005).

[16] Singh, G., Martinache, F., Baudoz, P., Guyon, O., Matsuo, T., Jovanovic, N., and Clergeon, C., "Lyot-based low order wavefront sensor for phase-mask coronagraphs: Principle, simulations and laboratory experiments," *eprint arXiv* **1404**(7201) (2014).

[17] Baudoz, P., Boccaletti, A., Baudrand, J., and Rouan, D., "The self-coherent camera: a new tool for planet detection," *Proceedings of the IAU Colloquium #200* (2006).

[18] Mazoyer, J., Baudoz, P., Galicher, R., and Rousset, G., "High-contrast imaging in polychromatic light with the self-coherent camera," *Astronomy and Astrophysics* **564** (2014).

[19] Mawet, D., Pueyo, L., Moody, D., Krist, J., and Serabyn, E., "The vector vortex coronagraph: sensitivity to central obscuration, low-order aberrations, chromaticism, and polarization," *Proceedings of the SPIE* **773914** (2010).

[20] Mas, M., Baudoz, P., Rousset, G., and Galicher, R., "Tip-tilt estimation and correction using fqpm coronagraphic images," *Astronomy and Astrophysics* **539** (2012).

[21] Noecker, C. and Kuchner, M., "Detecting exoplanets in the presence of exozodiacal dust profiles," *eprint arXiv* **1012**(0977) (2010).

[22] Maire, A.-L., Galicher, R., Boccaletti, A., Baudoz, P., Schneider, J., Cahoy, K., Stam, D., and Traub, W., "Atmospheric characterization of cold exoplanets using a 1.5-m coronagraphic space telescope," *Astronomy & Astrophysics* **541** (2012).

[23] Spergel, D. and et al., "Wfirst-2.4: What every astronomer should know," *eprint arXiv* **1305**(5425) (2013).

[24] Sanders, G. H., "The thirty meter telescope (tmt): An international observatory," *Journal of Astrophysics and Astronomy* **34**(2) (2013).