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

Christian Marois[a], Colin Bradley[b], John Pazder[a], Reston Nash[b], Stan Metchev[c], Frédéric Grandmont[d], Bruce Macintosh[e], Anne-Lise Maire[f] and the MAPLE 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, 500 Rue du Binôme, Québec, Canada;
[e] Stanford University, 450 Serra Mall, Stanford, CA, United States;
[f] INAF - Osservatorio Astronomico di Padova Vicolo dell'Osservatorio 5, 35122, Padova, Italy

ABSTRACT

The imaging discovery of the reflected light of exoplanets is the next major milestone in the search and characterization of another Earth by direct imaging. Many innovations by the community have been achieved in the laboratory over the last 10 years to solve the high-contrast and small angular separation challenges. The technology has sufficiently mature to allow initial on-sky testing. Due to the high-risk and cost associated to flying satellites and limitations imposed by the atmosphere for ground-based instruments, a stratospheric balloon experiment called MAPLE is proposed. MAPLE consists of a 50 cm diameter off-axis aperture working in the near-UV. The advantages of going in the near-UV are a small inner working angle and an improved contrast to blue planets. Beside the proper tracking system to mitigate balloon pointing errors, MAPLE will have a low-order deformable mirror, a vortex coronagraph and will use the self-coherent camera focal plane wavefront sensing concept to correct for residual speckles and an EMCCD as a science detector. The EMCCD will allow photon counting at the KHz speed to rapidly detect and correct atmospheric and optical speckles as the telescope and instrument bench are slowly evolving due to pointing, vibration, thermal drift or gravity changes. In addition, the EMCCD will be acquiring the science data with no read noise penalty, allowing on the fly high-speed speckle correction and science data acquisition. To mitigate risk and lower the cost, MAPLE will at first have a single optical channel with a minimum of moving parts (single wavelength bandpass). The goal is to reach a few times 1E9 contrast in 25 h worth of flying time, allowing the imaging discovery of Jovians and ice-giant planets around the nearest stars.

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

1. INTRODUCTION

Over the millennia, science has made enormous progress in understanding our place in the universe; we live on a small rocky planet, orbiting the Sun in a large galaxy hosting hundred of millions of stars lost in a Universe of billions of galaxies. The quest to find another planet, similar to Earth, in orbit around a star where life-as-we-know-it exists is one of the biggest challenges in modern astronomy. The progress made towards answering this fundamental question has captivated the interest and imagination of the public and professional astronomers alike.

During the last 20 years, the exoplanet research field has made steady progress toward answering this question. The first discovery of a gas giant planet, similar to Jupiter, orbiting another star was made relatively recently in 1995.[1] The first images of gas giant planets orbiting other stars were acquired in 2008.[2–5] Recently, the Kepler

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

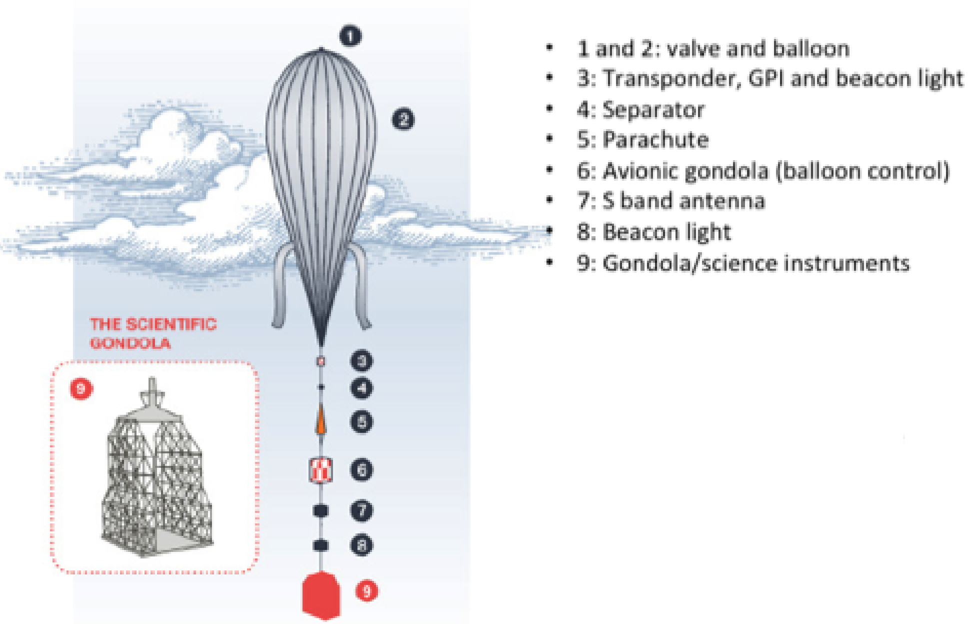

Figure 1. Typical stratospheric balloon components (from CSA website).

spacecraft and Doppler-based spectroscopic radial velocity surveys have finally discovered Earth-sized/mass planets.[6] We now know that they are numerous in our galaxy, with possibly up to 6% of Sun-like stars showing an Earth-sized planet that could be similar to Earth.[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. Hability claims have been based on untested/unproven models. Hence, the existence of other Earth-like planets has not yet been confirmed.

Earth-like planets must have a size and mass similar to Earth and be located inside the stars habitable zone; a mild temperature region around the star where liquid water and life-as-we-know-it could develop. To confirm the planet's hability potential, a spectrum of the candidate planets atmosphere must be obtained to verify the presence of biomarkers (ozone, water, oxygen) and even signs of vegetation, land, oceans and seasons. Therefore, developing and applying a more direct exoplanet characterization method is the next step in answering this grand challenge. The Kepler spacecraft discoveries are usually too far away to allow direct characterization. Earth-like planet candidates must be found in the solar neighborhood to allow proper characterization. These close-by terretrial planets will be prime targets for in-depth analysis using advance space observatories.

The path for close-by Earth-like planet characterization is not unique. The TESS satellite, due to launch in 2017, will use the same technique as the Kepler spacecraft (the transit method where the planet moves in front of the star as viewed from Earth) to survey for possible exoplanets.[8] The satellite will not have any planet characterization capability and it is unlikely that TESS will find the closest Earth-like planet, as the planet needs to transit its star to be detected (requiring a very specific alignment). Future near-infrared radial velocity instruments will hunt for Earth-mass planets around the nearest low-mass M stars using the radial velocity technique. It will likely find a large number of candidate Earth-like planets, potentially the closest one to Earth, however, planet characterization will also not be possible with these instruments. For both TESS and near-infrared radial velocity instruments, the idea is to find the most promising *transiting* Earth-size/mass planet candidates located in the stars' habitable zone. Subsequently, the James Webb Space Telescope will be used for hundred of hours to acquire a low signal-to-noise ratio planet spectrum (via the transit spectroscopy method) for characterization.[9] While being a valid approach, the number of potential planets that will be characterized is small, and it is unlikely that the closest Earth-like planet is transiting. By contrast, a high-contrast imaging

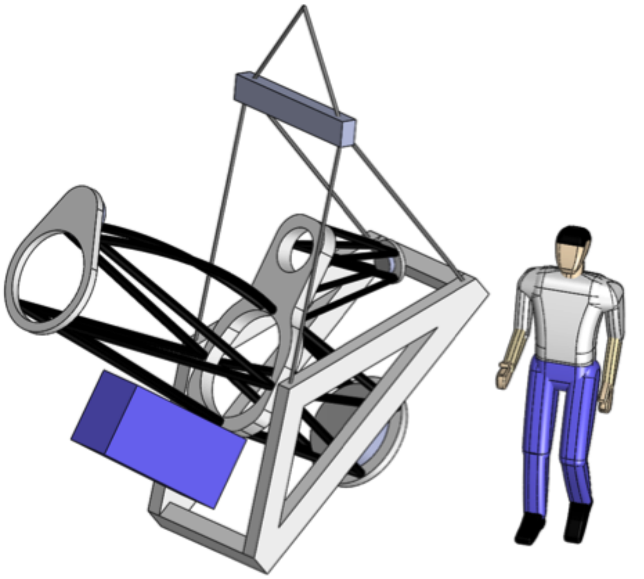

Figure 2. A preliminary CAD drawing of MAPLE's optical bench.

observatory will have the capability to both identify and characterize planets regardless of whether or not the planet transits the star, with the capability to find and characterize the closest Earth-like planet to the Sun, the logical first "safe-heven" destination outside our solar system.

The direct imaging of exoplanets is an extremely challenging undertaking. Using current ground-based adaptive optics systems (e.g. the Keck and Gemini telescopes, or the newly commissioned state-of-the-art Gemini Planet Imager (GPI)), a few warm and young giant planets have been imaged in the thermal infrared spectrum.[2,10] These observations are of planets with a brightness that is 1/100,000th of the neighbouring stellar brightness (gas Giants similar to a young Jupiter). However, all of these planetary systems are thought to be too young, being less than one hundred million years old, to host life. In mature planetary systems, i.e. greater than one billion years old, such as the Sun's and most of the stars in the solar neighbourhood, the systems planets barely emit enough thermal light. It is thus impossible to search and characterize these old planets using ground-based near-infrared instrumentation on the current 10m class telescopes. The mature Earth-size planets need to be detected by their reflected light, i.e. light being emitted by the system's star and being reflected back to us on the planet's surface/atmosphere. The reflected light can be up to a 10 billion-to-one contrast, or 100,000 harder than detecting a young gas giant planet in the near-infrared with ground-based telescopes.

We are proposing to embark on this 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 observatory. MAPLE will be a stratospheric balloon-borne 50 cm diameter optical instrument dedicated to directly imaging candidate exoplanet targets during several planned flights from the Canadian Space Agencys (CSA) space-port in Timmins, Ontario. The overall goal of the proposed project is to develop and implement the astrophysical instrumentation technology that can acquire a planets actual image or 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

While there are very promising multi-billions high-contrast imaging projects that are currently being studied to detect and characterize nearby-Earth like planets, none are currently funded for launch. Despite their great potentials, these missions are complex, costy and risky. MAPLE goes at the opposite side of the spectrum with a simple, cheap and less risky infrastructure to valide concepts, to iterate the design, and to still allow

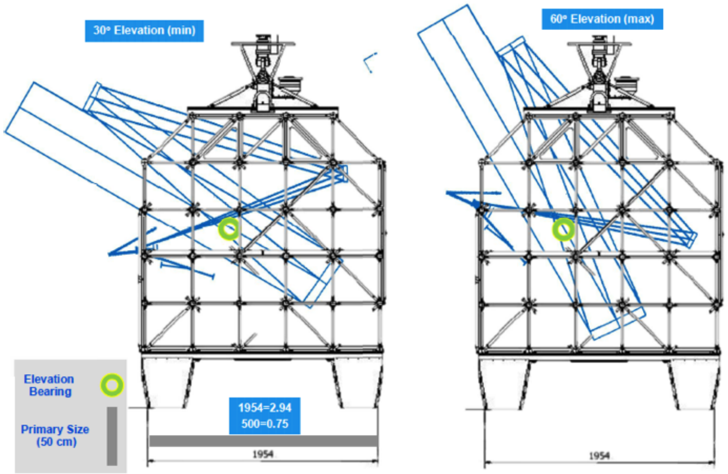

Figure 3. MAPLE's spherical optical design overlayed on the CNES CARMES gondola.

breakthrough science to be performed. Over the years, the telescope diameter will be increased in steps to finally reach the capability to directly image and characterize another Earth.

MAPLE's first iteration will be a 50 cm diameter off-axis telescope mounted on a stratospheric balloon gondola. The balloon will fly at 40 km altitude, i.e. above most of the Earth's atmosphere. The initial smaller primary makes it easier and cheaper to polish the M1 glass subtraste, 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 challenge that needs to be overcome. The concept is similar to previously proposed balloon telescopes.[11–13]

To further lower the cost of building and testing MAPLE, no money was requested for flights nor its gondola. The plan is to used the yearly CSA balloon competition to secure one of the 1,000 kg ”free flights”.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 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, instrument retrieval, etcetera. These contributios are free if MAPLE is allocated a flight through CSA; these balloon flights are part of a CSA/CNES 10 year agreement. The MAPLE team can then concentrate solely on the telescope, instrument and pointing stabilization/thermal gradient/gravity flexure problems. We are currently discussing with US colleagues and the SETI Institute into designing/building our own gondola, having private sponsors and taking advantage of the NASA flight program and/or getting access to commercial flights, ensuring a long legivity and optimal operation of the MAPLE observatory.

MAPLE will have a clean telescope enclosure to protect the mirrors during ascent/descent, an electronic enclosure, thermal Sun shield and a temperature control system to minimize thermal gradient and keep the bench at a constant operating temperature. While the rough < 1 arcmin gondola azimuth guiding will be performed using the gondola azimuth gear, MAPLE will be mounted on its own azimuth/altitude plateform. A preliminary CAD model of MAPLE is shown in Fig. 2

MAPLE, 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.[14] This guiding signal will control the az/alt plateform with a goal of reaching < 1 arcsec guiding accuracy. The team plans to launch MAPLEs side scope on an early CSA/CNES small payload piggyback flight to test hardware and overall system performances as well as to characterize the 40 km atmospheric turbulence.

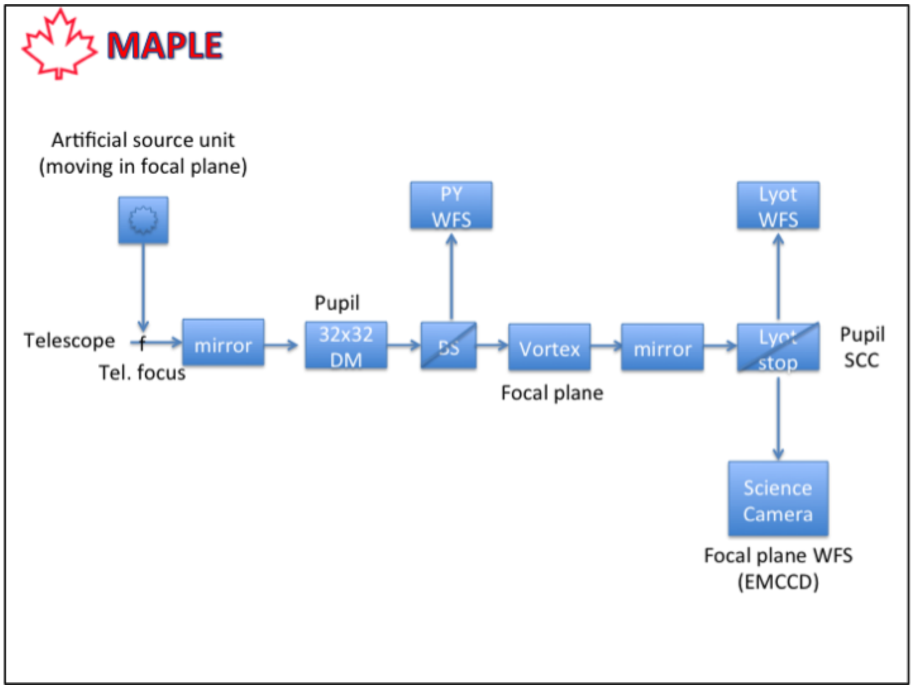

Figure 4. MAPLE's instrument block diagram. MAPLE will have an artificial internal light source to produce for testing the instrument, a deformable mirror, a vortex coronagraph and perform focal plane wavefront sensing with an EMCCD.

MAPLE's instrument path will have a single deformable mirror (a 32 × 32 BMC or an IRIS AO segmented deformable mirror),[15,16] a beamsplitter, a pyramid wavefront sensor for increase sensitivity to low order aberrations,[17] a vortex coronagraph,[18] a Lyot-based wavefront sensor,[19] a reflecting Lyot stop with the self coherent camera pin hole located outside the pupil,[20] an interference filter and a 512 × 512 NÜVÜ EMCCD. To minize the risk and cost, MAPLE will not have any moving mechanism in its first implementation. MAPLE's intrument block diagram is shown in Fig. 4.

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. Note that we are also looking into an OAP-design with two flats and potentially making it more compact for a better fit in the CNES CARMES gondola.

A coronagraph and adaptive optics bench that is also designed with spherical optics follow the three mirrors. The adaptive optics system is located before the coronagraph and uses a deformable mirror commanded by a pyramid wave front sensor to clean up any optical aberrations from the telescope and the high atmosphere. The wave front 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 X RMS is needed to reach 1E8 contrast. The system is designed with a second wavefront sensor by imaging the light being reflected off the Lyot stop, i.e. a Lyot wave front sensor. The Lyot wave front sensor is fed by the light reflected off the Lyot stop and provides a highly accurate tip-tilt

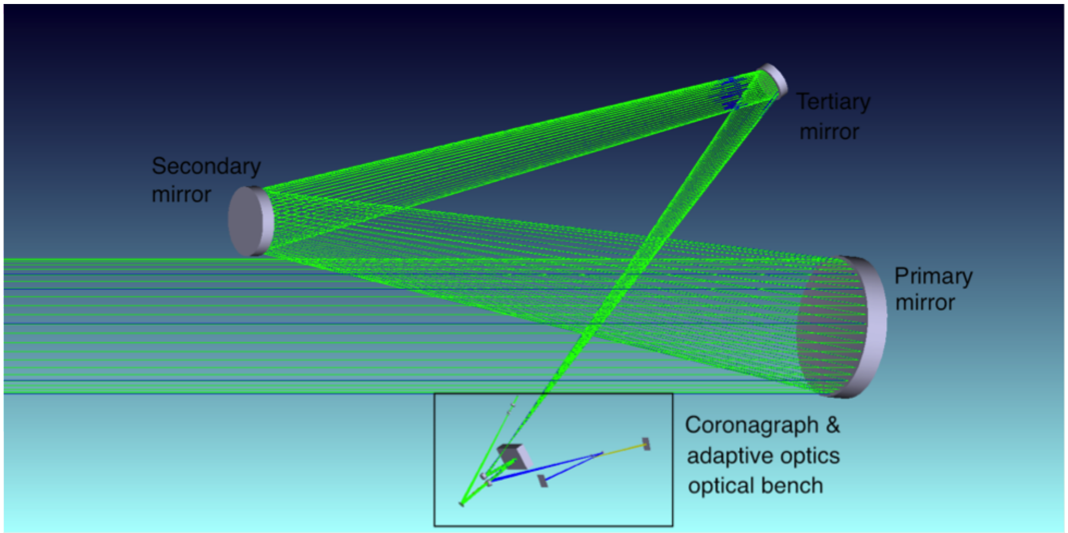

Figure 5. The overall MAPLE spherical optical design.

and other low orders error sensor. These errors are fed back to the deformable mirror. Coarse tip-tilt errors, such as created by gondola sway, are corrected by tilt on the telescope tertiary mirror and/or re-orientating the telescope altitude/azimuth plateform.

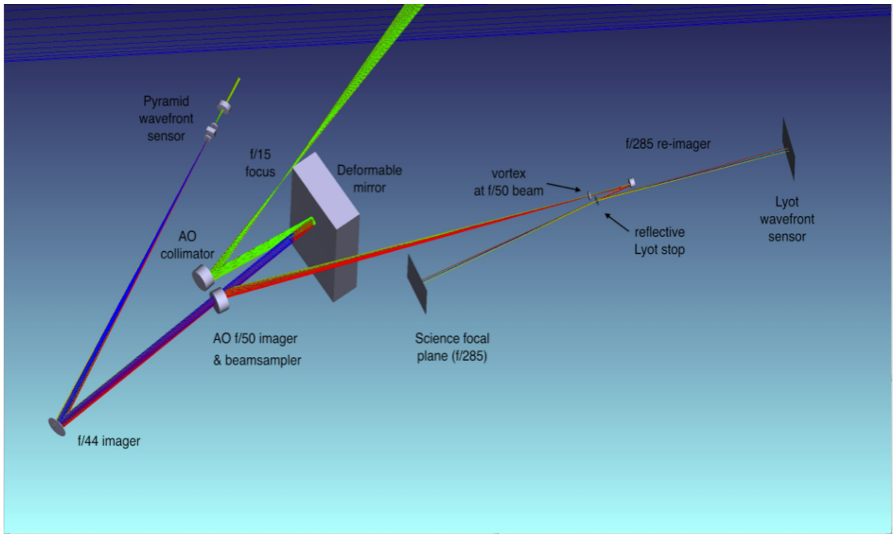

Figure 6. Maple's instrument optical design.

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 or less 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). High amount of exoplanetary dust may prevent the detection of small planets with MAPLE, but 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]

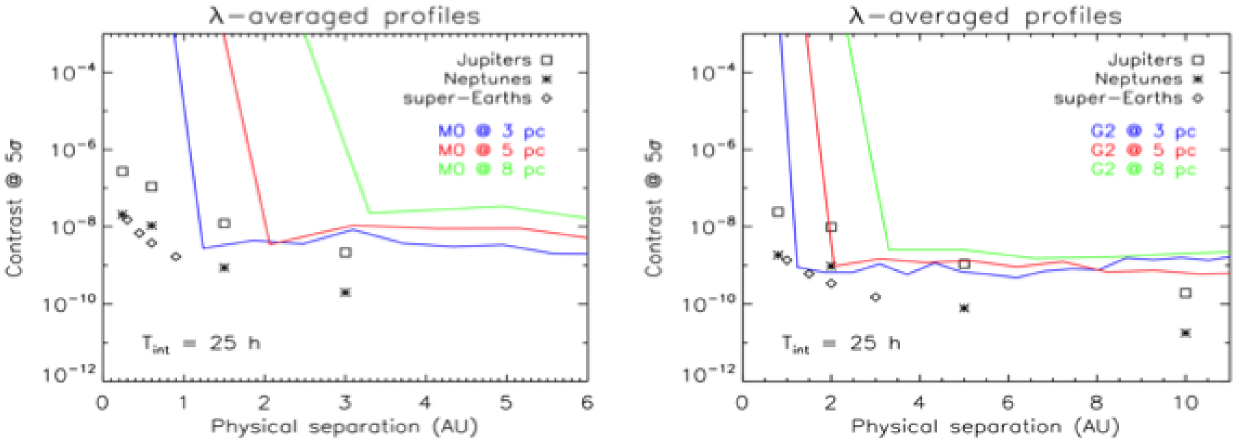

Figure 7. Predicted MAPLE contrast for a 25h sequence on typical nearby M0 and G2 stars. MAPLE will be sensitive to Giant planets around nearby stars.

Observations will be acquired at 450 nm with a 15% bandpass, being a compromise between the number of available G-type star photons, the improve spatial resolution of shorter wavelenths, and better contrast to blue planets (planets like Neptune of 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 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.

The analysis shows it would take 15 and 30-hours respectively to detect planets Eps Eri b and Ups And e with MAPLE (5-sigma and a 15% 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. Espilon Eridani is low in the sky from Timmins Ontario (Dec = −9 degrees), but it isn't occulted by the balloon thus allowing for a long uninterrupted integration sequence to be acquired, while Ups And is higher up but it is 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.

On one specific star, Alpha Centauri A (southern hemisphere flights), MAPLE-50 could detect an Earth-like planet located in the stars habitable zone. Due to the system proximity (1.3 parsec), the stars 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 1E8 at that separation, 100 hours worth of integration time would reach 2E11 contrast.

For young planetary systems detected by ground-based near-infrared surveys, such as HR 8799bcde or Beta Pic 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 wavelength are a few 1E9.

5. BEYOND MAPLE-50

It is a goal to increase MAPLE's diameter to a 1.5 m observatory (MAPLE-150) by 2022-2025 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 2E11 contrast goal on a large enough star sample. 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

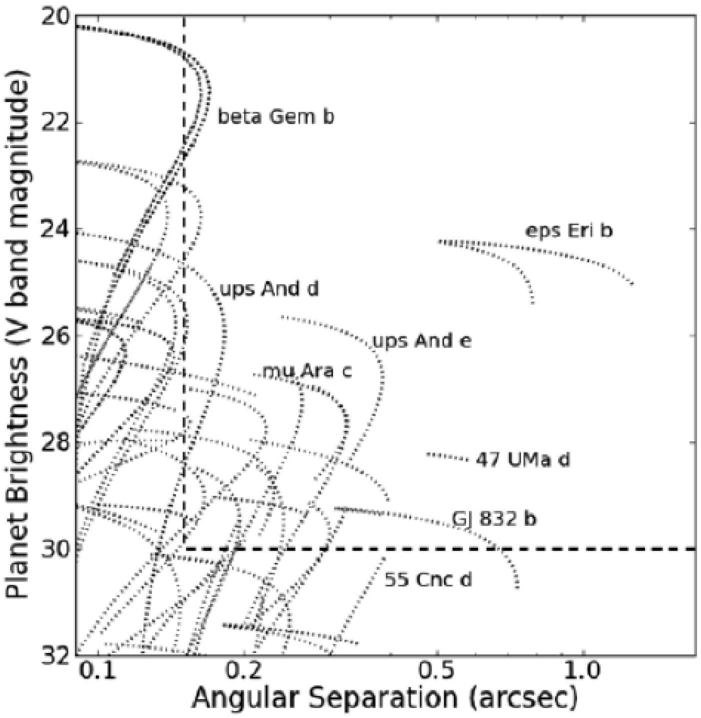

Figure 8. Nearby planetary systems detected by radial velocity. Eps Eri b and Ups And e are the two most promising known systems to observe with MAPLE. The arc-like curve for each planet is the change of brightness due to the planet phase (fraction of surface being illuminated as seen from Earth). Image from the Exo-C STDT Interim Report.

nearby planet sample with an overlay of the expected performances of MAPLE-50 and MAPLE-150. While MAPLE-50 is limited to gas giant planets and super-Earth, a 1.5 m diameter version of MAPLE would be sensitive to Earth-like planets on several nearby stars.

There is also interest at opening a fraction of the MAPLE-50 observing time to the community for other science applications.

6. CONCLUSIONS

The MAPLE infrastructure is a small scale, low risk and low cost project to fly a balloon high-contrast observatory at 40 km altitude to validate concepts, to work at solving pratical technology implementation problems, and to start doing frontier science. With its a scalable infrastructure, the various observatory components will be improved with time with a goal of increasing the primary diameter to 1.5 m in the next decade, allowing for nearby Earth-like planets to be detected and characterize. The technology and known-how that will be gained through developing MAPLE will be apply to future large scale ground-based telescopes, such as the Thirty Meter Telescope[23] or future space observatories.

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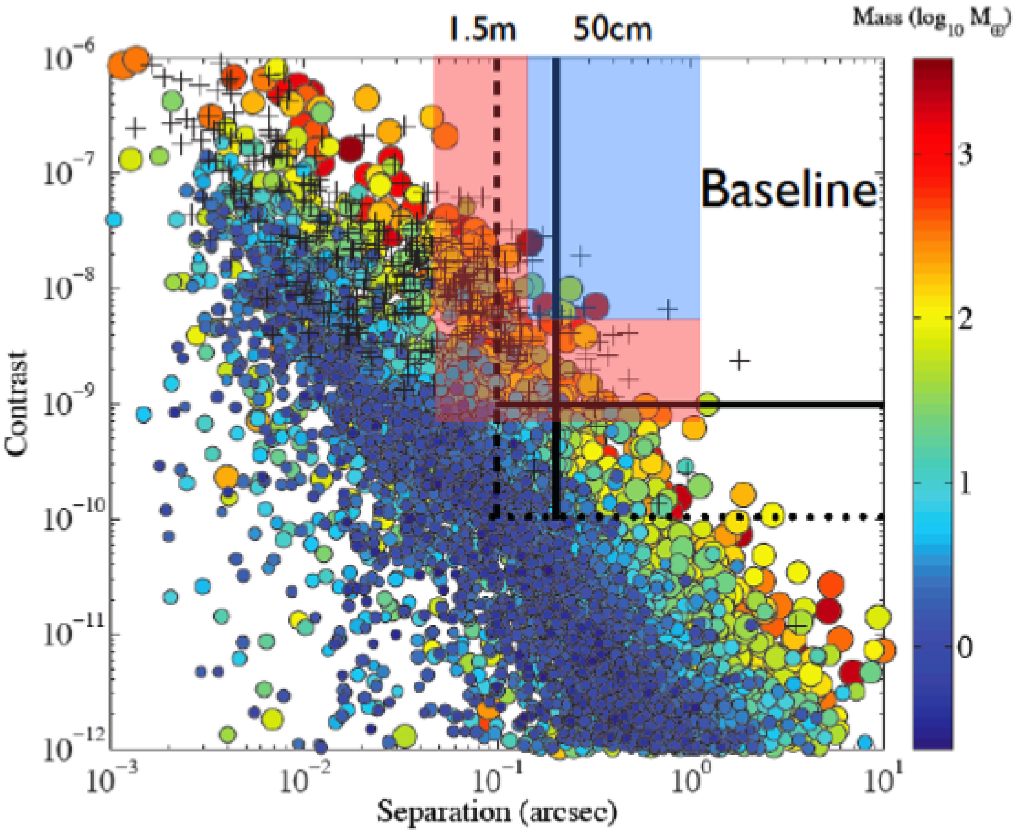

Figure 9. Simulated planet sample[22] around nearby stars: large circles are gas giant planets similar to Jupiter/Saturn; light blue circles are Neptune-like planets; and, dark blue circles are Earth-like planets. Blue shade area is the search space for MAPLE-50 while the red shaded area is for MAPLE-150 (see online version for proper color rendering).

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