Space-Based “Probe Class” Missions for Exoplanet Research

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Abstract

A new class of “Probe-scale” space missions for exoplanet science, ranging in scope through and above the current Discovery mission cost cap but smaller than flagship missions, is needed to enable significant steps in planet detection and related technology. We present here several examples of significant advancements using several techniques of planet-finding that could be enabled by a Probe-class mission; these achievements would be significantly more difficult or otherwise impossible within currently available mission programs.

Introduction

Recent searches for extrasolar planets have produced astounding results from both ground and space. Ground-based telescopes have uncovered over 200 new planets, mostly gas giants, including some “hot Jupiters” orbiting very near their parent star. Space-based flagship facilities such as HST have obtained deep, high-spatial resolution images of circumstellar debris disks not possible from the ground, and HST and Spitzer have obtained visible and infrared spectra from the atmospheres of these “Exosolar Giant Planets” (EGPs). We anticipate further discoveries on exoplanetary systems with planned flagship missions such as JWST (see whitepaper by Clampin et al.), and eventually with TPF.

However, we are very early in the “discovery era” of exoplanetary research, and significant new results can be obtained with smaller, focused missions. In recent years, several concepts have been developed to allow advances in specific approaches to planet-finding and characterization at costs much lower than that required for flagship missions. The Kepler mission, for example, will search a crowded star field for planets using sensitive detections of transits. Due to launch in 2008, Kepler is a Discovery-class mission.

P.I.-class competed missions like this are strongly supported by the scientific community. They allow scientists to propose and carry out missions with significant scientific return using only a fraction of the time and expense required to develop a multi-billion-dollar flagship mission such as HST or JWST. The 2007 AAAC report (Illingworth et al 2007) recommends that NASA rebalance their mission portfolio to include a range of mission sizes:

> “…The Astrophysics program should be rebalanced as a part of any increase for science, or at the least when funds become available as the major

> astrophysics missions pass their spending peaks. **The balance between small, medium and large programs in the NASA Astrophysics Division has been undermined. The AAAC recommends that the funding "wedge" in FY09/10 be used to add some funding for R&A and small missions, to rebalance the program.**" [bold text in the original report]

NASA's Mid-Explorer and Discovery missions typically have cost caps of ~ $280 M and ~ $425 M, respectively. We are now reaching the situation where further advances in exoplanet detection and characterization require mission capabilities that, in many cases, exceed these cost caps. Significant capabilities would be enabled, however, if a mission class of ~$700M "Exoplanetary Probes" were to be supported by NASA to allow competed exoplanet science missions, mirroring the scale and cost-cap of the New Frontiers program for Solar System planetary probes.

We think that it is vitally important to establish a Probe mission line devoted to the study of exoplanets. For concepts exceeding the cost of Explorers, the only avenue for proposing such a mission is through the Discovery program. This program is executed by the Solar System Exploration Division in NASA's Science Mission Directorate, and, even with the selection of Kepler as a Discovery mission, the priority for the program is on solar system missions – not exoplanets.

Exoplanet science advanced by several different techniques (coronagraphy, interferometry, transits, astrometry, and lensing) would be possible in this new mission class. Without endorsing or evaluating these possible techniques, we provide below a short description of some existing concepts that may fit within the Probe mission class in order to show the diversity of research that could be enabled:

Visible/Near IR Coronagraphy

Coronagraphy allows study of circumstellar material and planets by blocking the intensity of the central starlight to allow the detection of surrounding emission many orders of magnitude fainter. Several modest aperture (~ 1.5 meter) mission concepts have been developed to characterize extrasolar giant planets (EGPs) in orbits with semi-major axes between 2 and 10 AU (The Extrasolar Planetary Imaging Coronagraph (EPIC; Clampin, PI); Eclipse (Trauger, PI); TOPS (Angel and Guyon)). These missions have proposed different techniques for suppressing the light of the central star (EPIC - Nulling coronagraph, Eclipse - Lyot coronagraph, and TOPS - the pupil mapping technique (PIAA)). Nevertheless, all of these missions are designed to find and characterize EGPs and the exosolar debris disks around the central star (see whitepaper by Stapelfeldt et al).

While these missions have been proposed as Discovery-class missions, substantial augmentations to science and technical capabilities could be achieved if a higher cost-cap were available. Some of these missions are designed to work in orbits far from Earth (Sun-Earth L2 or an Earth-trailing orbit) for thermal/optical stability necessary for precise coronagraphy. This drives up the cost relative to low-Earth orbit missions. Probe-class budgets could potentially allow a larger primary mirror e.g. up to 2.0 meters in size. This would provide a larger discovery space, by virtue of the improved inner working angle, and thus the ability to detect and characterize a larger number of gas giant planets. In addition, Probe-class budgets would allow increased capability of the science instrumentation, such as in spectroscopy or polarimetry.

External Occulter

While the construction of a telescope facility with a completely separate occulting spacecraft would exceed a Probe budget, the addition of an external occulter to an existing telescope may be an ideal Probe concept. One intriguing idea is to pair an occulting spacecraft with the SOFIA airborne observatory, to observe exoplanets within about 30 pc of the Earth. This technique is similar to occultation observations (where solar system objects were used as occulters) previously taken by the Kuiper Airborne Observatory. SOFIA will fly at speeds of approximately one half of the Earth's equatorial rotation velocity, so flying away from equatorial regions greatly reduces the effect of the Earth's rotational motion. An occulter spacecraft can be located near geostationary orbit and cast its shadow over the SOFIA telescope for relatively long periods of time with only modest velocity changes. This configuration would require considerably less spacecraft propellant and would significantly reduce the dead time between observations compared to using the occulter with JWST ("The New Worlds Discoverer" Discovery mission proposed by W. Cash, 2006), two major weaknesses of that concept. Detection sensitivity would be limited only by the occulter inner working angle (IWA) and the sensitivity of the 2.5-m SOFIA telescope. At least 5-10 of the currently known exoplanets should be easily observable with a 30-m diameter occulter and SOFIA. These planets should be detectable with existing visible and near-IR SOFIA cameras in about an hour of integration time per filter. The contrast required is relatively modest (~18 mag; a suppression of ~2x10^7). New SOFIA instruments could also be built and installed quickly to make specialized exoplanet observations.

Interferometry

The secondary eclipse technique using the Spitzer Space Telescope has been used to directly measure the temperature and emission spectrum of transiting extrasolar planets in the infrared by detecting photons emitted from the planets themselves. However, only a small fraction (<5%) of known extrasolar planets are in transiting orbits. Thus, a simplified nulling interferometer, which produces an artificial eclipse or occultation, and operates in the near- to mid-infrared (e.g. ~ 3 – 8 or 10 μm), can characterize the atmospheres of this much larger sample of the known but non-transiting exoplanets. Many other scientific problems can be addressed with a system like this, including imaging debris disks, active galactic nuclei, and low mass companions around nearby stars.

Nulling interferometry is the analogue of optical corongraphy and can provide starlight suppression on the order of 10^{-6}, sufficient to detect and characterize Earth-like planets in the habitable zone in the mid-infrared from the emission from their atmospheres. Interferometry is employed at mid-infrared wavelengths because the resolution necessary to detect planets in the habitable zone cannot be obtained with a large cooled filled aperture telescope such as JWST, despite its 6 m aperture. Fundamentally, coronagraphs are limited by the inner working angle needed to obtain sufficient starlight suppression, and this angle is ~ 4 λ/D = 1.4 arcsec for JWST at 10 μm. The habitable zones of the nearest sun-like stars have an angular scale of ~ 0.1 arcsec at 10 pc, so coronagraphy at infrared wavelengths has had little appeal for astronomers. However, interferometry allows for much higher resolution, producing an inner working angle of ~ λ/(2B), where B is the baseline. One type of space interferometer is the structurally connected interferometer, meaning the telescopes in the array are on a boom, which can be as large as about 36 m and still fit into the shroud of an Atlas V or Delta IV rocket. Such a structurally connected nulling interferometer would have an inner working angle of ~ 0.028 arcsec, well-inside the habitable zone of nearby stars.

The Fourier-Kelvin Stellar Interferometer (FKSI; Danchi, PI), for example, is a well-developed concept for a mid-sized structurally connected interferometer. It is a passively cooled interferometer operated at 60 K, with two 0.5 m telescopes on a 12.5 m boom, operating from 3 – 8 or perhaps as long as 10 μm. The inner working angle for this system is ~0.04 arcsec at 10 μm. A basic goal for this mission concept is the characterization of the atmospheres of all the known non-transiting exoplanets using moderate resolution spectroscopy (R~25). To reach this goal, the technique allows the observer to resolve the sin (i) ambiguity from radial-velocity measurements and allows the direct determination of the temperature, molecular composition, density, planet radius, temperature variability for planets in eccentric orbits, albedo, surface gravity and composition.

A thorough cost estimate of this mission has shown that it is of Probe-class (~$600 M, FY06 based on grass-roots, Price-H and parametric models). A similar, but formation-flying, interferometer called Pegase has been proposed to the French Space Agency CNES. Interest in combining these two missions has been expressed, which could substantially reduce the cost to NASA. Nevertheless, there is a consensus within the exoplanet interferometry community that a Probe-class mission would greatly advance the field in preparation for a large TPF-I mission and would complement observations that can be done using major facilities like JWST.

Transits

Detection of transits allows the detection and characterization of terrestrial planets. Both the planet's size and orbital parameters are of interest as these provide information as to whether such planets are potentially habitable. With the development of the HARPS-North radial velocity instrument by Michel Mayor (Geneva) and Dimitar Sasselov (Harvard), even masses of short period terrestrial planets can be determined. Combining this information with the planet size from the transit observation, the composition (water world, rocky world, or iron planet) can be estimated by comparison with density models of planet structure. The Kepler and COROT Missions should provide early results for these parameters if terrestrial planets are frequent. Investigators have calculated that the infrared spectra of planets discovered by these two missions can be obtained from JWST observations of eclipses, but because most of these planets will be at distances of a few hundred parsecs at visual magnitudes from 12 to 14, observations will be difficult.

Because of its limited field of view, the Kepler Mission will observe only 1/400th of the total sky. The COROT field of view is even smaller although it observes several fields during its lifetime. However a transit-search Probe mission designed specifically to cover a large fraction of the sky could observe 20,000 stars brighter than tenth magnitude. The brightness and nearness of these stars would make them excellent targets for obtaining spectra from JWST and for follow-on missions. A future transit-search mission would be designed around "all sky" optics such as used in ground-based automated observations of the aurora or would use "fly's eye" optics where many small lenses focused different portions of the sky on CCDs. In either case it should be feasible to develop a mission that continuously monitored well over 25% of the total sky. By scaling from Kepler for the complexity of the optical system and focal plane, such a mission is estimated to fall into the Probe class. The mission results would provide an inventory of nearby stars with terrestrial planets, their size and orbital distributions and associations with star type. Large numbers of both gas giants and icy giants would also be found.

Astrometry

Planets orbiting a star will make it 'wobble" around the center of mass, which can be detected by precise astrometric techniques. The Space Interferometry Mission (SIM) is designed to have the sensitivity to detect Earth-mass exoplanets around nearby stars. However, smaller Probe-scale missions, such as the Full Sky Astrometric Mapping Explorer (FAME) (Johnston et al. 2000) and the Origins Billion Star Survey (OBSS) (Johnston et al. 2006) could measure the positions of stars accurately to 10 to 50 micro-arcseconds, respectively (a factor of 10 larger than SIM in its narrow-angle and wide-angle modes, respectively). Such missions would have the capability to detect hundreds to many thousands of EGPs. Orbit solutions would be possible for most of these exoplanets, yielding masses.

The OBSS was an Origins Probe mission concept study of a 1.5m, 3 mirror anastigmat telescope with ~ 1 degree field of view operated at Sun-Earth L2. The OBSS mission concept may not fit within the Probe budget, but a similar mission with capabilities between OBSS and FAME with an aperture of ~ 1m would be feasible and would detect hundreds to ~1000s of EGPs in a survey mode. In the sky survey mode, the OBSS concept is in a step-stare mode. The telescope is pointed to a star field, the CCDs are read out after the integration. The telescope is then pointed to a new field (or stepped) to give overlapping sky coverage. In this way the entire sky is covered with overlapping images and a global solution is made using block adjustment (Zacharias and Dorland, 2006). This method gives two-dimensional positions where as GAIA in the scan mode produces one-dimensional positions along the scan direction. The OBSS concept references its positions to extragalactic sources, which are in the ~1 degree field of view.

Given that the OBSS telescope points and integrates, the mission can also stare at a field of view of interest. In order to overcome the limitations imposed by CCDs (dynamic range in the images and susceptibility to cosmic radiation) USNO is investigating the use of hybrid CMOS detectors in the instrument's focal plane. This should allow the reading out of individual pixels with different integration times and make possible the study of a bright star against a fainter background. USNO is actively working to bring the hybrid CMOS detector and pointing technology to TRL8. In this mode, if GAIA is successful, the OBSS modified mission would allow follow-up of interesting candidates with single epoch measurements of order 10-20 microarcseconds. If this mission were contemporary during the later part of the GAIA mission, it could follow up immediately on interesting discoveries, refining the orbits of exoplanets using its superior astrometric measurements due to its longer integration time.

This type of mission would also make precise photometric measurements allowing planetary transits to be observed in several spectral bands. Observations of a large number of EGP transits are needed to estimate their range in density allowing an understanding of their bulk composition, leading to constraints to planet evolution.

Lensing

Gravitational microlensing is a proven exoplanet detection method that has already demonstrated its capability to detect low-mass planets at orbital separations of a few AU (see whitepaper by Gould et al.). A space-based microlensing survey can extend this capability down to planetary masses of $0.1M_{earth}$ at orbital separations from 0.5 AU to infinity, including free-floating planets that have been ejected from exoplanet systems of their birth (see whitepaper by Bennett et al.). A space-based survey would also identify the planetary host stars for the majority of the exoplanets detected, which will allow the precise determination of the host star and planetary masses.

The planets detected by a space-based microlensing survey, when supplemented with the results from Kepler for planets in orbits of ≤ 1 AU, will provide a nearly complete (statistical) census of all type of exoplanets. Such a census, taken of distant stars toward the Galactic bulge, will provide critical insights into the process of planet formation that cannot be obtained by other methods. The sensitivity of space-based microlensing extends down to the regime of planetary embryos at $\sim 0.1M_{earth}$, and it covers the range of separations where most planets are likely to form.

A space-based microlensing survey requires no new technology and can be accomplished for a mission cost of <~$500M, such as the proposed Microlensing Planet Finder (MPF). The requirements of a space-based microlensing survey are also compatible with other concepts, such as a stare-mode astrometry mission (see whitepaper by Johnston et al.). So, it might be possible to combine a space-based microlensing survey with an astrometric planet search mission under the Probe line.

References

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