ExO: The Exoplanet Observatory
Astrophysics

Overview

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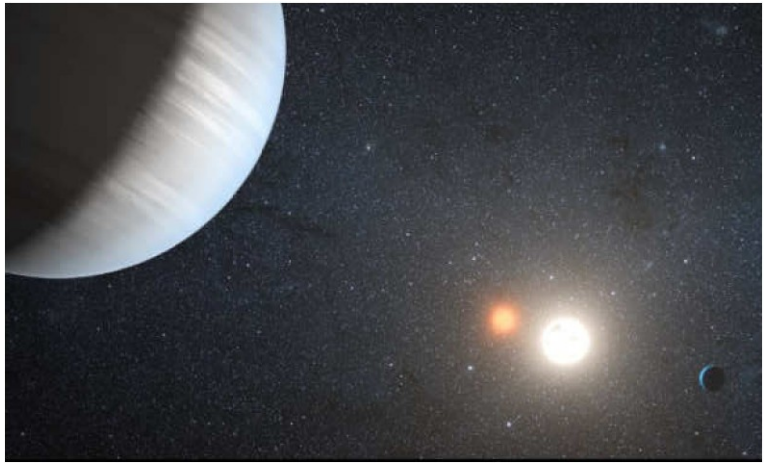
Key collaborators: Exoplanet Exploration Program Office and names listed on concept cover page.

Goals: The prime objective of the Exoplanet Observatory will be to provide a detailed portrait of exoplanets around our nearest F, G,K,and M stars. ExO will operate at visible and near-infrared wavelengths to directly image gas/ice giants down to the largest of terrestrial planets. ExO will measure their spectra and determine their orbits. It will image debris disks and characterize exozodiacal dust. ExO complements this data through astrometry to measure exoplanet masses and orbits, and through spectroscopy to study large transiting planets close to their stars.

ExO's General Observer Program will provide new opportunities for NASA Cosmic Origins science and Planetary Science.



Description

Instruments:

- 2.4m on-axis telescope. High-contrast coronagraph with IntegralField Spectrograph,imaging over 0.4-1.0 µm, at 10% bandwidths, with working angles of3-60 JJD, 10·9 contrast (baseline) and 10·10 (goal) post-processed, with 8x8 arcsec FOV,spatial resolution 0.05 arcsec, and R = 70
- Astrometric Imaging camera with 3 x 3 arcmin FOV
- Time-resolved Spectrometer observing 0.8-2.4 µm, R=1000

Operations: From a Sun-Earth L-2 orbit, the observatory will sequentially observe accessible nearest-neighbor F, G, K, and selected M stars once per quarter, with direct imaging and astrometry. Transit spectroscopy will be used for appropriate targets.

Opportunities:

- Instrumented to be fully compatible with a starshade, co-launched or launched separately
  Leverages and complements ground-based radial-velocity observations
- Excellent potential for 50% GO science and international collaboration

Human exploration: The observatory will be designed for robotic servicing

Value to NASA

Advances the Priorities of NASA's Astrophysics Division

- *ExO* addresses New Worlds, New Horizons 2010 #1 medium-scale recommendation for a New Worlds Technology Development Program to address *"preparation for a planet-imaging mission beyond 2020, including precursor science activities"* (p. ES-6).
- *ExO* addresses NWNH 2010 small-scale recommendation *"understanding the birth of galaxies,* stars,*end planets"* (p. ES-4).

Advances Technology highlighted by NASA's Space Technology Mission Directorate

- Advances high-contrast imaging and spectroscopy technology
  Prepares NASA for a later mission to image Earths and search for signs of life.

Provides Education and Public Outreach opportunities tied to the exploration for life in our galactic neighborhood.

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ExO: THE EXOPLANET OBSERVATORY

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Concept Category: Astrophysics

Summary

The Exoplanet Observatory (*ExO*) is an observatory dedicated to exoplanet science, focusing on exoplanets orbiting our nearest-neighbor stars. *ExO* will observe as a single spacecraft observatory from a Sun-Earth L-2 orbit with a 5-year baseline mission and is designed for robotic servicing. *ExO* will have beacons and telemetry to enable observation with a possible starshade launched separately. *ExO* will search for gas giant, ice giant, and super-Earth exoplanets and debris disks around about 100 of the nearest F, G, K, and selected M stars with high-contrast imaging and spectroscopy. Astrometric observations will discover exoplanets and measure their masses. Near-infrared time-resolved spectroscopy will enable observations of known nearby transiting objects, potential M-star transits, and more distant exoplanets. *ExO* leverages and complements ground-based radial-velocity surveys and tests planet formation theories. *ExO* employs three complementary instruments to develop "family portraits of our nearest neighbors": a high-contrast coronagraph imager to discover and characterize the spectra of imaged exoplanets; a time-resolved spectroscopy instrument for studying atmospheres of exoplanets that transit; and an astrometric instrument to measure the masses and orbits of planets. This suite of instruments will also enable a comprehensive ~50% General Observer (GO) program in astrophysics and planetary science.

Science Goal of *ExO*

ExO will advance exoplanet science toward the long-term objective of finding life elsewhere in the universe. *ExO* will detect and characterize super Earths in the outer habitable zone around the very nearest stars. It will detect and characterize debris disks and large planets in orbits beyond the habitable zone. Analogs to our own Kuiper belt (with brightnesses inferred from Herschel) will be detectable around the nearest stars. *ExO* will produce an inventory of larger planets around stars in the solar neighborhood. These systems will become high-priority targets in our future search for Earth-like planets and life.

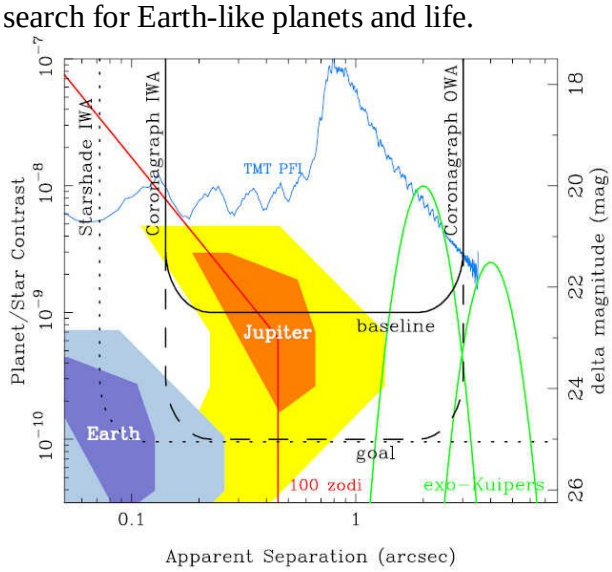

Figure 1. *ExO* will directly image and characterize gas giants, ice giants, super-Earths and debris disks around nearby F, G, K, and selected M stars. The operating limits of a coronagraph and starshade are shown. For a Jupiter at 5.2 a.u. around the nearest 300 stars the contours enclose 40% and 80% of observations. Likewise for Earths at 1 a.u. Exozodi contours are for 1x and 100x solar system level. Kuiper belts are shown schematically.

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Benefits of *ExO*

ExO directly supports the goals and long-term objectives of the Exoplanet Exploration Program and NASA's Astrophysics Division. It supports the *2011 NASA Strategic Plan*, goal 2.4, to "Discover how the universe works, explore how it began and evolved, and search for Earth-like planets." It supports NASA strategic objective 2.4.2, "Improve understanding of the many phenomena and processes associated with galaxy, stellar, and planetary system formation, and evolution from the earliest epochs to today". It also supports NASA strategic objective 2.4.3, "Generate a census of extra-solar planets and measure their properties".

The science goals support the NRC 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH), which recommends advancing the technology and science of exoplanets this decade. *ExO* will enable a new era of exoplanet exploration, and further test planet formation theories which have yet to explain distributions of exoplanets discovered to date.

Instrumentation for *ExO*

ExO will operate at Sun-Earth L-2 for thermal stability, sky coverage, and for possible formation-flying observations with a starshade. Instruments and spacecraft will be modular, enabling future robotic servicing, e.g., to extend the mission.

Its design leverages work done for the Astrophysics Focused Telescope Assets (AFTA) study. *ExO* has three instruments, described in science priority order.

I. Coronagraph and Spectrometer

ExO will have a high-contrast coronagraph achieving 10^{-9} contrast (one sigma after post-processing). A coronagraph with selectable components allows tuning the choice of instrument (e.g., Lyot, shaped pupil, vector vortex, PIAA) to match the target, since these designs differ in their contrast and inner working angle values (IWA in Figure 1). Two deformable mirrors provide wavefront control. A low-order wavefront sensor enables fine-guidance and low-order aberration suppression. The coronagraph feeds an Integral Field Unit (IFU), an imaging spectrograph with approximately 0.4–1.0 μm wavelength range, 8×8 arcsec field of view, 0.05 arcsec spatial resolution, and spectral resolution of about 70 This concept is explored in greater detail in a SALSO submission by John Trauger et al.

ExO will be starshade-compatible with beacons and telemetry to guide formation flying, to enable operation with a later-launched starshade. A starshade allows *ExO* to operate at a smaller inner working angle (~0.07 arcsec), and it has a large outer working angle. A starshade extends the inner working angle for detection of Earths (Figure 1). Starshade observing would use the coronagraph in a "straight-through" mode, with masks and stops removed, so the planet light reaches the IFU directly. The starshade option is explored further in a companion SALSO white paper by Jeremy Kasdin et al.

II. Astrometric Camera

The outer field of the image focused by the telescope will be sent to the astrometric camera, which measures exoplanet orbits and masses. These instruments work simultaneously, allowing outer planet spectra to be recorded while the astrometric instrument makes repeated visits to trace out the inner planet orbit. The proposed implementation requires imprinting a 2-D grid of tiny dark spots on the primary mirror, to generate faint stellar diffraction spikes that map the star's location in the field at the sub-microarcsec level. With 2.7 μas precision per observation it would be capable of determining masses and orbits of giant planets in the habitable zone, and possibly super-Earths. This concept requires no moving parts, but it does require a

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wide field, hence a third powered optic, to give a 3×3-arcmin field of view, and a very large detector in the focal plane. This concept is explored further in a SALSO submission by Olivier Guyon et al.

III. Time-Resolved Spectrometer

A visible/near-infrared transit spectrometer completes the suite of instruments envisaged for *ExO*. The transit method delivers unique information about a planet's diameter, and its atmospheric absorption spectrum, giving physical conditions and chemical composition. Eclipses and phase curves provide additional information. The transit technique complements the astrometry instrument, as transits are more sensitive to short-period planets. It will also complement the transit studies done by JWST. Since M stars are more abundant than FGK stars, and close-in transits of M stars will give a higher signal-to-noise ratio than transits of later-type stars, this instrument will be ready for characterizing these events. The observatory will likely operate at 250 K or above, allowing wavelengths up to the thermal cutoff, so a spectral range 0.8–2.4 μm, and a resolution of R = 1000, will allow molecular bands of CH_4, H_2O, NH_3, collision-induced H_2, and other species to be observed. This concept is explored further in a SALSO submission by Mark Swain et al.

Mission Design

ExO will be launched into an Earth-Sun L-2 orbit using a Falcon 9 launch vehicle which provides a total payload mass of about 3700 kg. The payload comprises: the telescope system, spacecraft bus, including propulsion for orbit insertion and station-keeping at L-2, telecom (up to 100 Mbps using the Deep Space Network), power system (solar panels providing about 3kW plus batteries), attitude control system (assuming HST-class pointing requirements), and thermal control for room temperature operation. About 550 kg is available to accommodate the three instruments described above.

Astrophysical Example Programs

ExO includes a robust 50% GO program for astrophysics and planetary science. *Cosmic Origins Science:* *ExO* could make narrow-field images of Active Galactic Nuclei with the coronagraph IFU (in straight-through mode). The astrometric camera could make wide-field, broad-band images of targets of opportunity (e.g., using HST-like filters), and could provide follow-up to weak-lensing observations to constrain models.

Planetary Science: As examples, *ExO* could monitor seasonal atmospheric changes of planets and moons in the outer solar system using the coronagraph IFU (in straight-through mode), and molecular abundances using the infrared spectrograph. The astrometric camera could be used to obtain asteroid orbits.

Anticipated Science Results

ExO will be a discovery instrument, conducting a detailed inventory of planets and dust disks orbiting roughly 100 of our nearest-neighbor stars. *ExO* will discover large outer planets, large terrestrial planets, bright exozodiacal disks, and outer debris disks around the nearest-neighbor F, G, K and selected M stars. Its coronagraph spectrometer will record the optical spectra of these planets, providing detailed information on the physical and chemical compositions of their atmospheres. The transit spectrometer instrument will characterize the atmospheres of nearby transiting exoplanets, including M-star transits yet to be discovered.

ExO sets the stage for a future imager of Earth twins – terrestrial size planets in the habitable zone – and the quest for signs of life. *ExO* is a crucial step, both scientifically and technologically, on the path toward that ambitious future mission.

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