The Sub-orbital Transiting Exo-Planet Spectroimager (STEPS)
Astrophysics / Planetary

Overview:

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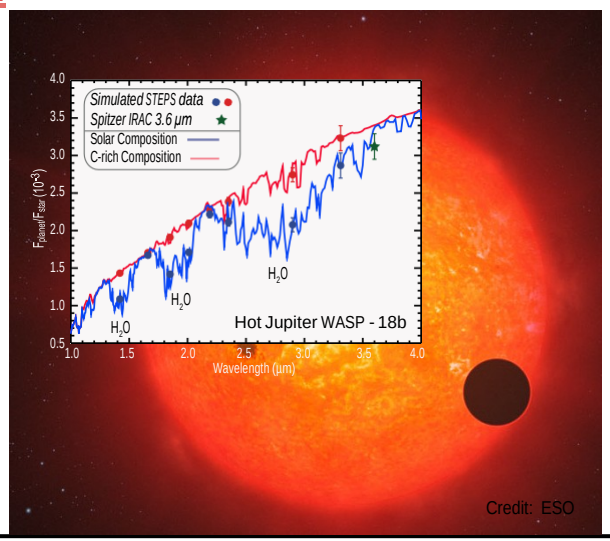
Mission Goals:

- STEPS would characterize the composition and atmospheric structure of a broad sample of known transiting exoplanets from Jupiter-mass down to Super-Earths around low-mass stars, at a cost many times lower than an orbiting space observatory
- STEPS will be able to confirm a possible new class of carbon-rich planets, differentiate between H2O-rich and H-rich atmospheres for Super Earths, and constrain the origin and evolutionary history of exoplanets through chemical taxonomy

Graphic:



Description:

- **Architecture:** The STEPS concept pairs a sub-orbital telescope with a NIR (1.0-3.5 µm) simultaneous multi-band wide field imager to provide simultaneous high-precision photometry of multiple wavelengths bands with real-time calibration of instrumental and telluric variability using bright reference stars in the wide FOV
- **Instrument**: STEPS's eight photometric bands would sample broad spectral features that probe a wide range of molecular species (e.g., H2O, CO2, CO, CH4, HCN, CN, polycyclic aromatic hydrocarbons, as well as broad ice and mineralogical features) that are not measureable from the ground due to telluric absorption and variability
- **Operations:** STEPS will conduct a large uniform survey of a broad sample of planets; based on stellar magnitudes and expected planetary emission and atmospheric scale height, STEPS should be sensitive to a planet- to-star flux ratio of < 10−4 for more than 100 of the currently known transiting planets.

Value to NASA:

2011 NASA Strategic Roadmap, Goal 2.2: *Discover how the universe works, explore how it began and evolved, and search for Earth-like planets.*

- As a stand-alone survey telescope, STEPS would drastically improve our constraints on composition and structure of exoplanets across a wide range of planetary characteristics. NASA is currently considering a $200B Earth-orbiting Explorer-class mission concept to accomplish the same goals.

2011 NASA Strategic Roadmap, Goal 3: *Create the innovative new space technologies for our exploration, science, and economic future*

- STEPS would advance technology for sub-orbital telescopes by spurring development of a serviceable and upgradable sub-orbital platform for long--duration observation of astrophysical and planetary targets. The cost to build, launch, and service a sub-orbital telescope would be drastically lower than a similarly-sized Earth-orbiting or L2-based telescope.

The Sub-orbital Transiting Exo-Planet Spectroimager (STEPS): A Mission Concept using the Large Space Optics

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Qualifications: A. M. Mandell is a civil servant research space scientist at NASA/GSFC studying the atmospheres of extrasolar planets using the transit method. A.M.M. uses the Keck telescope and HST, and has served as instrument scientist on an exoplanet instrument proposal for the SOFIA Telescope.

Primary Concept Goal Category: Astrophysics / Planetary Science

Concept Summary: We propose an innovative concept for utilizing the newly acquired Large Space Optics (LSO) to accomplish exciting new science at a low cost: a sub-orbital balloon-borne telescope equipped with a near-infrared wide-field multi-band imager. STEPS (Sub-Orbital Transiting Exo-Planet Spectroimager) would characterize the composition and atmospheric structure of a broad sample of known transiting exoplanets from Jupiter-mass down to Super-Earths around low-mass stars, at a cost many times lower than an orbiting space observatory. STEPS utilizes simultaneous wide-field imaging in eight different bands at once, with wavelength coverage optimized to target spectral regions that are heavily obscured from the ground but provide critical information on key constituents in exoplanet atmospheres. In addition to exoplanets, this new observatory would also be capable of exploring Trans-Neptunian Objects (TNO), brown dwarf atmospheres, and carbon chemistry in stellar populations. The STEPS instrument could also be integrated into a wider instrument suite for even greater versatility.

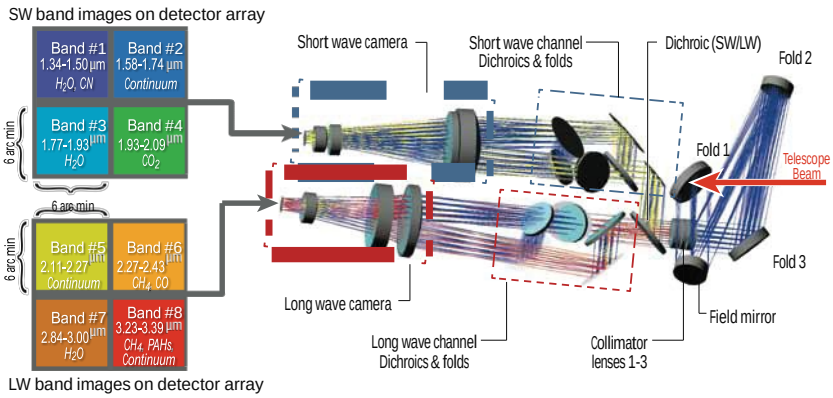

Figure-1: The STEPS optical layout has only one moving part, making it easy to implement and calibrate. The image rotator (not shown here) is used to maintain a fixed position angle on the detectors. The input beam is collimated and then dichroic beam splitters are used to separate eight simultaneous wavelength bands. There are two sets of camera optics (short-wave — SW, and long-wave — LW). Half of the 8 beams pass through the SW optics, and the other half through the LW optics. (see McElwain et al. 2012).

Mission Design: The STEPS concept pairs a sub-orbital telescope with a NIR (1.0-3.5 µm) multi-band wide-field imager providing simultaneous high-precision photometry of multiple wavelengths bands over a wide field of view. The STEPS optical design employs a tree of dichroics and fold mirrors to image multiple spectral band passes onto different regions of a single detector, and has already been developed as a mature instrument concept (Figure 1, further details in McElwain et al. 2012). STEPS's eight photometric bands would sample broad spectral features that probe a wide range of molecular species (e.g., H_2O, CO_2, CO, CH_4, HCN, CN, polycyclic aromatic hydrocarbons, as well as broad ice and mineralogical features) that are not measureable from the ground due to telluric absorption and variability. Each spectral band features a wide FOV to enable 1) decorrelation of time-variable effects using nearby reference stars and 2) the ability to image extended sources. The instrument produces a

three-dimensional data cube (images in eight different wavelength bands), providing many of the efficiency benefits of a low-resolution integral field spectrograph.

Moreover, STEPS's design is optimized to take advantage of a large aperture in the stratosphere for wide-field imaging within molecular bands in the NIR. A critical aspect of the optical design is that it maximizes precision by eliminating many of the problems that preclude high-precision measurements with traditional slit and integral field spectrographs on observing platforms that are not stable over multi-hour timescales, an essential requirement for measuring the change in stellar flux during a planetary transit. Precise, real-time calibration of instrumental and telluric variability using bright reference stars in the wide FOV enables high-precision spectrophotometric observations ($S/N > 10^4$) of moderately bright sources ($K_{mag} < 11$) in one hour.

Science Goals: The locations and bandwidth of the STEPS bands are optimized to measure key diagnostics for probing the structure and composition of exoplanet atmospheres. Water vapor is predicted to be a major component of nearly all transiting exoplanet atmospheres, and the STEPS bands are placed to measure warm and hot water vapor as well as other key molecular constituents (e.g., CH_4, CO_2, CO). By simultaneously observing multiple bands across a wide spectral range, STEPS will measure the composition and temperature structure of the atmospheres of exoplanets ranging from several times the mass of Jupiter down to a few times the mass of Earth around low-mass stars. Precise observations with STEPS can firmly identify which planets with temperature inversions (Knutson et al. 2008) and unusual carbon-to-oxygen ratios (Madhusudhan et al. 2011), and determine which Super Earth atmospheres dominated by hydrogen vs heavy elements (Figure 2), shedding light on the formation and evolution of planetary systems as a whole and enabling new insights in comparative planetology that would complement more detailed spectroscopy of individual objects with JWST.

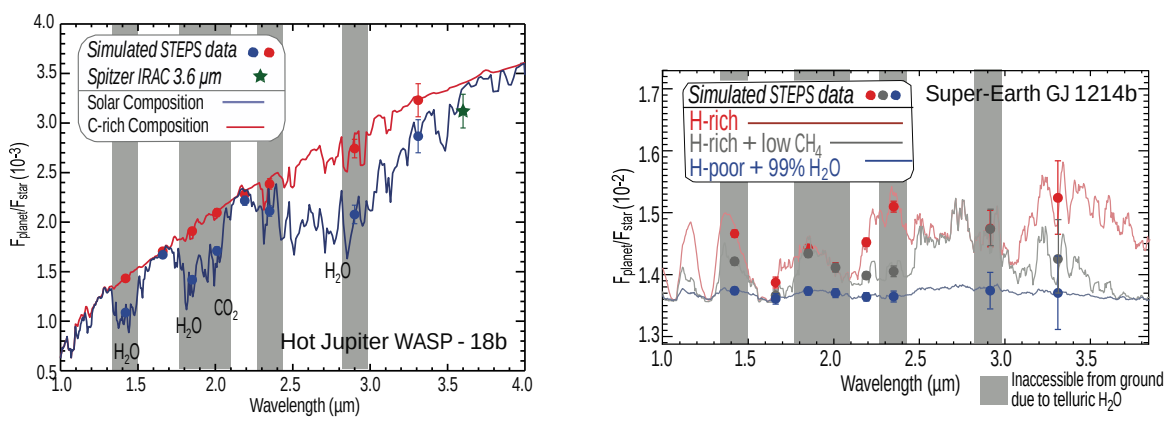

Figure-2: STEPS probes the regions of the NIR spectrum that are most sensitive to changes in the temperature and composition of exoplanet atmospheres. Left: Models of the ultra-hot Jupiter WASP-18b, with simulated STEPS data and uncertainties overlaid. STEPS will be able to confirm a possible new class of carbon-rich planets, a discovery impossible from the ground. Right: Models and simulated data for the super-Earth GJ 1214b with differing compositions. STEPS can differentiate between H_2O-rich and H-rich atmospheres, a key science goal for exoplanets over the next decade.

STEPS will conduct a large, uniform survey of a broad sample of planets; based on stellar magnitudes and expected planetary emission and atmospheric scale height, STEPS should be sensitive to a planet-to-star flux ratio of $< 10^{-4}$ for more than 100 of the currently known transiting planets. Furthermore, STEPS would provide high-precision observations for more than 20 systems that have complementary longer wavelength observations with *Spitzer*, providing a set of planets with high-precision photometry covering the STEPS bands as well as *Spitzer* bands between 3.6 and 24 μm. The number of exoplanets that can be analyzed with STEPS will continue to grow as more discoveries are made by ground-based wide-field surveys for nearby short-period exoplanets, including the highly successful Hungarian Automated Telescope Network (HATNet), Super Wide Angle Search for Planets (SuperWASP), and

recent MEarth and HAT-South surveys. This catalogue would be expanded further if a space-based all-sky survey for nearby transiting planets, such as the Transiting Exoplanet Survey Satellite (TESS; currently in Phase A development for the Explorer Program), is selected.

As a flexible, wide-field, multi-band imager STEPS can also make contributions in fields beyond exoplanets. Several examples include:

Solar System Science: Gas and Ice in Small Bodies: Comets and TNOs are rich in ices and have strong signatures in the 1-3.5 µm spectral region, and recent NIR observations of main-belt asteroids have revealed intriguing features from both simple and complex organic species. STEPS will be able to measure these molecular species in a wide range of bodies and identify hemispheric differences and variability of surface features.

Brown Dwarfs in the Solar Neighborhood: IR imaging surveys have uncovered a vast population of previously unrecognized very low-mass, very low-temperature brown dwarfs in the Solar Neighborhood. These objects have planetary-like atmospheres containing H_2O, CH_4, CO, CO_2, and NH_3 gases, as well as mineral and salt clouds. STEPS will monitor molecules such as H_2O and CH_4 in brown dwarfs, above the contaminating effects of the same molecules in our own atmosphere.

Benefits of the Concept: The most cost-effective strategy for utilizing the second optical telescope assembly from the LSO systems is as a modular and upgradable sub-orbital astrophysics and planetary science observatory; see the SOLOO concept (POC R. Lyons) for a detailed description of the technology required for a sub-orbital telescope concept. Sub-orbital balloon technologies have advanced to the point that the feasibility of months-long flights of heavy payloads at altitudes greater than 100,000 feet is no longer in doubt, and accurate telescope pointing and tracking on a sub-orbital gondola are currently being demonstrated. A serviceable sub-orbital telescope is attractive from both a technological and a cost perspective – the telescope and instrument hardware can continually be swapped out, upgraded, and repaired, and the cost to build and launch a sub-orbital mission would be drastically lower than a similarly-sized Earth-orbiting or L2-based telescope.

The multi-band imaging approach used for the STEPS instrument yields a simple and easily implemented design that will be able to meet the challenge of NIR spectrophotometric characterization in the sub-orbital operational environment over a variety of flight plans and operating altitudes. STEPS, therefore, has no strict altitude or water vapor depth requirements beyond the requirement of observations at stratospheric altitudes.

Conclusion: STEPS would provide high-precision wide-field photometry and imaging in eight near-infrared bands at once, enabling new breakthroughs in both astrophysics and planetary science. As a stand-alone survey telescope, STEPS would drastically improve our constraints on the composition and structure of exoplanets across a wide range of planetary characteristics. The STEPS instrument would also be an excellent addition to the suite of instrumentation on a facility-class balloon-borne observatory, for a small fraction of the cost of a similar space-based facility.

References:
Knutson, H.A., Charbonneau, D., Allen, L.E., et al. 2008, ApJ, 673, 526.
Madhusudhan, N., Harrington, J., Stevenson, K.B., et al. 2011, Nature, 469, 64.
McElwain, M. W., Mandell, A., Woodgate, B., et al. 2012, Proc. of the SPIE, 8446.

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