NNH16ZDA001N-HW: Habitable Worlds– Testing methods to detect 3D vegetation structure on exoplanets

PI- Chris Doughty - Northern Arizona University, USA
CoIs - David Trilling and Michael Mommert Northern Arizona University, USA
Collaborators -, Temuulen Sankey- Northern Arizona University, USA, Enric Palle - Instituto de Astrofisica de Canarias

Proposal summary - Over the next few decades, NASA and ESA are planning a series of space-based observatories (HabEx) to measure the spectral characteristics of Earth-sized extra-solar planets in regions where liquid water may be present. If they succeed in finding a planet with both biogenic gasses in the atmosphere and a red-edge characteristic of life, we would want to know whether the land-based life on this planet is similar to the green photosynthetic slime common for most of Earth's history, or whether this life has evolved to be diverse and multi-cellular. Multi-cellular photosynthetic organisms on Earth (trees) have a distinct bidirectional reflectance distribution function (BRDF) causing differing reflectance at different sun/view geometries. In previous work, we examined whether the BRDF could detect the existence of tree-like structures on an extra-solar planet, by using changes in planetary albedo as a planet orbits its star. We used a semi-empirical BRDF model to simulate vegetation reflectance at different planetary phase angles and found that even if the entire planetary albedo were rendered to a single pixel, the rate of increase of albedo as a planet approaches full illumination would be measurably greater on a vegetated planet than on a non-vegetated planet (Doughty and Wolf 2010 Astrobiology). We hypothesized that depending on how accurately planetary cloud cover can be resolved and coronagraph design, this technique could theoretically detect tree-like multi-cellular life on exoplanets in 50 stellar systems. However, such theoretical work needs empirical validation. We next carried out a proof of concept of this technique in a manner similar to Sagan et al. (1993) by using Galileo data to determine if multicellular life on Earth could be detected. However, we were unsuccessful, likely because there was no change in phase angle with these Galileo data and the technique requires a large change in phase angle (Doughty and Wolf 2016 PLOS One).

We propose here to further advance this technique with an improved proof of concept study by using existing data from the space probes EPOXI and OSIRIS-REx (with complementary variability in phase angle) to determine if 3D vegetation structure can be detected on Earth from a distance. Next, we plan to use Earthshine (light reflected from Earth off the moon and back to Earth) at different phase angles to determine if 3D structure can be detected. Finally, we will try the same technique on the nearby planets of Mars and Venus to measure the false positive effect. All such measurements are simple and can be completed with existing data or using our campus telescope with undergraduate astronomy students.

Next, we propose to further refine the technique with ground-based measurements. Near Northern Arizona University and Flagstaff USGS Astrogeology, NASA created cratered fields to mimic the moon for Apollo astronaut training. Also nearby are the landscapes of Sunset and Meteor craters, which mimic extraterrestrial landscapes. We propose to use drone-based spectrometers (operated by collaborator Sankey) to compare these non-Earth-like landscapes to the local vegetation landscapes. With these data, we will determine at which spectral

wavelengths the BRDF differences between vegetation and non-Earth-like landscapes are maximized.

Overall, we feel the proposal will fit within the Habitable Worlds call because the work will help identify the characteristics (multicellularity) of potentially habitable environments on exoplanets which could be used to inform future targeting and/or operational choices. Our work will include quantitative terrestrial field experiments that improve scientific understanding of this process. We are asking for funding to support a graduate student for three years to work on this project, which includes participation of NAU's Department of Physics and Astronomy and NAU's School of Informatics.

Table of Contents

NNH16ZDA001N-HW: Habitable Worlds– Testing methods to detect 3D vegetation structure on exoplanets

PI- Chris Doughty - Northern Arizona University, USA
CoIs - David Trilling and Michael Mommert Northern Arizona University, USA
Collaborators -, Temuulen Sankey- Northern Arizona University, USA, Enric Palle - Instituto de Astrofisica de Canarias

Project description –

Introduction –

Over the next few decades, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are planning a series of space-based observatories to measure the spectra from Earth-sized extra-solar planets in regions where liquid water may be present (Cockell et al. 2009; P. R. Lawson 2007). There has been much justifiable interest in developing methods of detecting life on these planets. Planetary biosignatures that have been considered include biogenic gases in the atmosphere (O_2 in the presence of H_2O, O_3, CH_4 with O_2, CH_3Cl, N_2O) (Des Marais et al. 2002) and surface reflectance spectra of vegetation (Ford et al. 2001; Kiang et al. 2007a; Kiang et al. 2007b; Seager et al. 2005; Tinetti et al. 2006a; Tinetti et al. 2006b).

A potential bio-signature is a planet's absorption spectrum (Kiang et al. 2007b). Earth's plants have a sharp, order of magnitude increase in leaf reflectance across 700-750 nm wavelengths due to the difference between photosynthetic absorption of photons (between 400-700nm) and reflectance and scattering at longer wavelengths not used for photosynthesis (>700nm). 700 nm is in the red, and the reflectance contrast is referred to as the "red edge." Such a sharp, order-of-magnitude change in reflectance is rare in nature and Earth's red edge has been confirmed as a planetary bio-marker both in the spectrum of Earthshine (spatially integrated light scattered off the moon and reflected to Earth) (Palle et al. 2009; Seager et al. 2005) and by remote sensing from the Galileo spacecraft (Sagan et al. 1993). Researchers have theorized that water-splitting photosynthesis is the only type of photosynthesis efficient enough to support plentiful life on an extra-solar planet (Wolstencroft and Raven 2002). The wavelength of an edge-like reflectance feature like the red edge could theoretically be determined if the planet's distance from the sun and the photons required to split water at this distance are known (Kiang et al. 2007b; Wolstencroft and Raven 2002).

If future space observatories such as HabEx succeed in finding a planet with both biogenic gasses in the atmosphere and a red-edge characteristic of life, we would want to know whether land-based life on this planet is similar to the green photosynthetic slime common for most of Earth's history (Beerling 2007), or whether this life has evolved to be diverse and multi-cellular. For instance, on Earth, the first fossil evidence of land plants, similar to modern bryophytes, was in the mid-Ordovician (490-430 mya) (Graham et al. 2000). Single celled photosynthetic organisms evolved as early as 3 billion years ago and were present on land as early as 1.2 billion years ago (Horodyski and Knauth 1994). High $\delta 13$ C values in pre-Cambrian rocks indicate that there was a significant cover of single cellular photosynthetic organisms on land during this period (Kenny and Knauth 2001). Therefore, viewed from space, from 1.2 billion years ago to 490 million years ago, the Earth could have had a red edge signal and biogenic gases in the atmosphere, but no visible multi-cellular life. Here we propose to develop a technique to determine whether multi-cellular life is detectable on exoplanets and whether vegetated planets can be distinguished from planets with less complex life.

Multi-cellular life on Earth is characterized by hierarchical branching networks, a topological structure ubiquitous in biology (Brown JH 2000). For multi-cellular photosynthetic organisms, this branching network is characterized by a “tree”, whose structural attributes and fractal topology are conserved over different phyletic groups and are independent of the environmental conditions accompanying ontogeny (West et al. 1999). Competition for light and the need to transport water and nutrients in multi-cellular photosynthetic organisms has led to the tree-like structure on Earth that emerges from a few general principles that are widespread in nature (West et al. 1999). As a consequence of these biomechanical and evolutionary constraints, the tree growth habit has evolved independently several times on Earth (Donoghue 2005). We make the assumption that such biomechanical constraints combined with Darwinian evolution will likewise produce tree-like structures for photosynthetic multi-cellular organisms, if they exist, on extra-solar planets. Thus, the “tree” would be the most abundant multicellular organism and the one our technique focuses on.

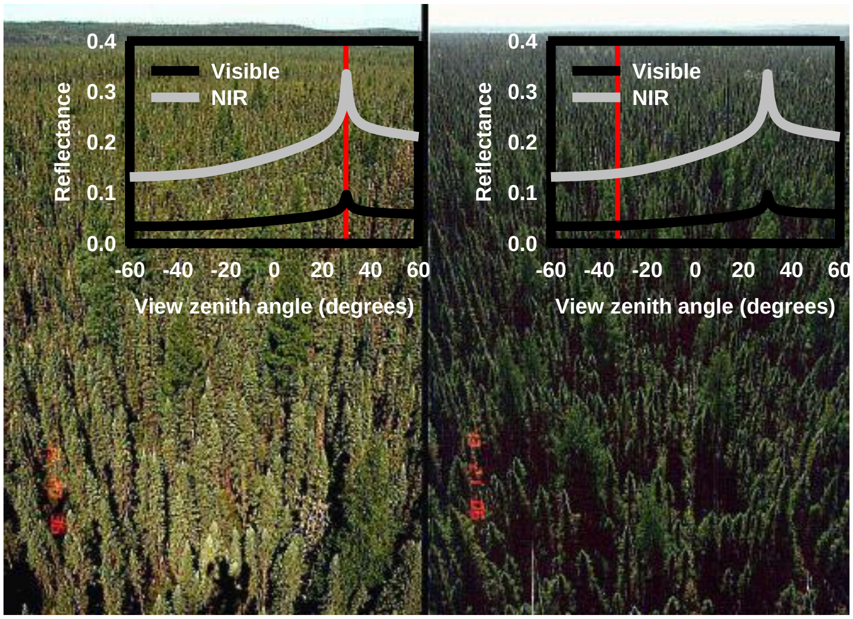

Figure 1 - Canadian black spruce showing backscattering (sun behind observer) on the left and forward scattering (sun opposite observer) on the right, Note the bright region (hotspot) where all shadows are hidden on the left. The graphs show the classic drop-off of BRDF from the hotspot to the dark spot along the principle plane for needle leaf forest. The red line shows the view zenith angle from each photo. Visible reflectance is different than NIR due to plants absorbing visible radiation for photosynthesis.

The same constraints that result in tree-like shapes of individual organisms result in predictable relationships between size, shape, and population density at the stand-level in forests (Enquist et al. 1998; West et al. 2009). These variations in the size and shapes of trees in forest stands result in strong differences in the reflectance of forest canopies as seen from different angles overhead (Breon et al. 2002; Breon et al. 1997; Li and Strahler 1992; Wolf et al. 2010). For example, forests as seen from two distinct view angles have very different reflectances (Figure 1).

The bidirectional reflectance distribution function (BRDF) is the change in observed reflectance with changing view angle or illumination direction (Schaepman-Strub et al. 2006). The BRDF is the ratio of the differential radiance (dL) (W m^{-2} sr^{-1}) to the differential irradiance (dE) (W m^{-2}), $f_r(\Omega_{I,}\Omega_v) = dL(\Omega_{I,}\Omega_v)/dE(\Omega_{I,})$, where Ω_i is illumination direction and Ω_v is the viewing direction. Surface albedo results if the BRDF is integrated over the entire viewing hemisphere.

Vegetation indices emerge from the differences in reflectance at the red edge. However, BRDF emerges from geometric optics, i.e. the shape and arrangement of objects within a pixel that transmit or block light (Torrance and Sparrow 1967). When viewed from space, forests appear brighter as the view angle approaches the sun angle and brightest when the observer is in line with the sun, called the hotspot (Figure 1). This occurs because at zero phase angle, all shadows cast by objects are obscured (Hapke et al. 1996) and at higher phase angles more shadows become visible to the observer, resulting in a darkening of the pixel's reflectance. The rate of change of the reflectance with phase angle, in both the zenith and azimuth directions, is closely linked to the size, shape, and number of trees in the scene, and there is a quantitative theory of the shape of the BRDF (Li and Strahler 1992). Observations of the BRDF from space demonstrate that less structured scenes, such as deserts and tundra, have a flatter BRDF as a function of view zenith angle, and more structured scenes such as savanna and forest have a more peaked BRDF (Bicheron and Leroy 2000; Breon et al. 1997). Here we propose to test whether this technique could be used to detect the existence of tree-like structures on the surface of an extra-solar planet.

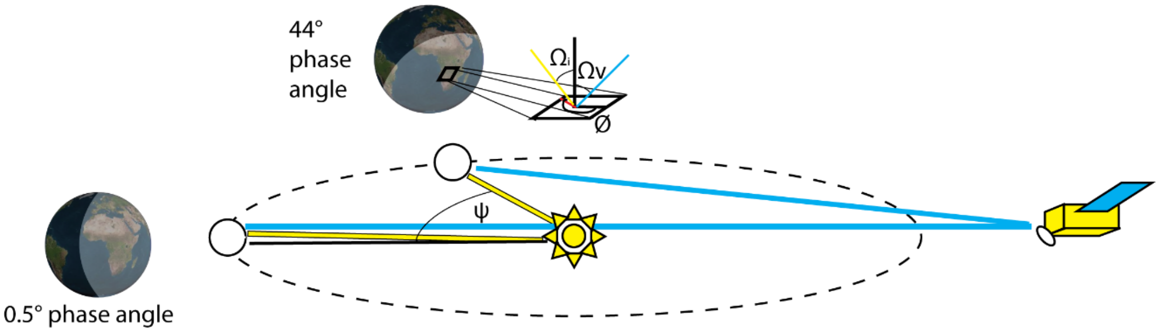

Figure 2 – A diagram of our proposed experimental design. The distant observer, a space telescope such as HabEx, would observe the rate of change of albedo near the phase angles of 0.5° and 44°. Ø is the azimuth angle, Ω_i is the solar zenith angle, Ωv is the view angle, and Ψ is the phase angle. Doughty and Wolf 2010 hypothesized that the rate of change of albedo on a vegetated planet would differ from that of a non-vegetated planet even if spectral information were averaged to a single pixel. However, these theories need to be tested empirically.

Mountains, asteroid craters, or other shadow-casting geological features can potentially confound the attribution of BRDF to multi-cellular life. However, most geological features such as asteroid craters or steep mountains (>45° slope) will be eroded by abundant liquid water, an oxygen atmosphere, and an active geology, which are likely to be present on any planet capble of sustaining multicellular life (Kasting and Catling 2003). A lifeless planet with similar climate to Earth will be topologically very similar to Earth, although most sediment will be less weathered (Dietrich and Perron 2006). Therefore, we can assume that in terms of slope, the Earth is typical of wet terrestrial planets with <1% of the surface with a slope greater than 45° (Hall et al. 2005). On other planets, as on Earth, there may be unique topological features like the hoodoo formations in Bryce canyon or limestone formations in Guilin, China that exhibit backscattering anisotropic effects. However, hoodoo structures will likely be uncommon (<1% for the surface) as they need a rare combination of basalt and tuff to form and will eventually succumb to erosion. However, the BRDF of structures such as craters have not been studied and further research is necessary to determine how they differ from that of forests.

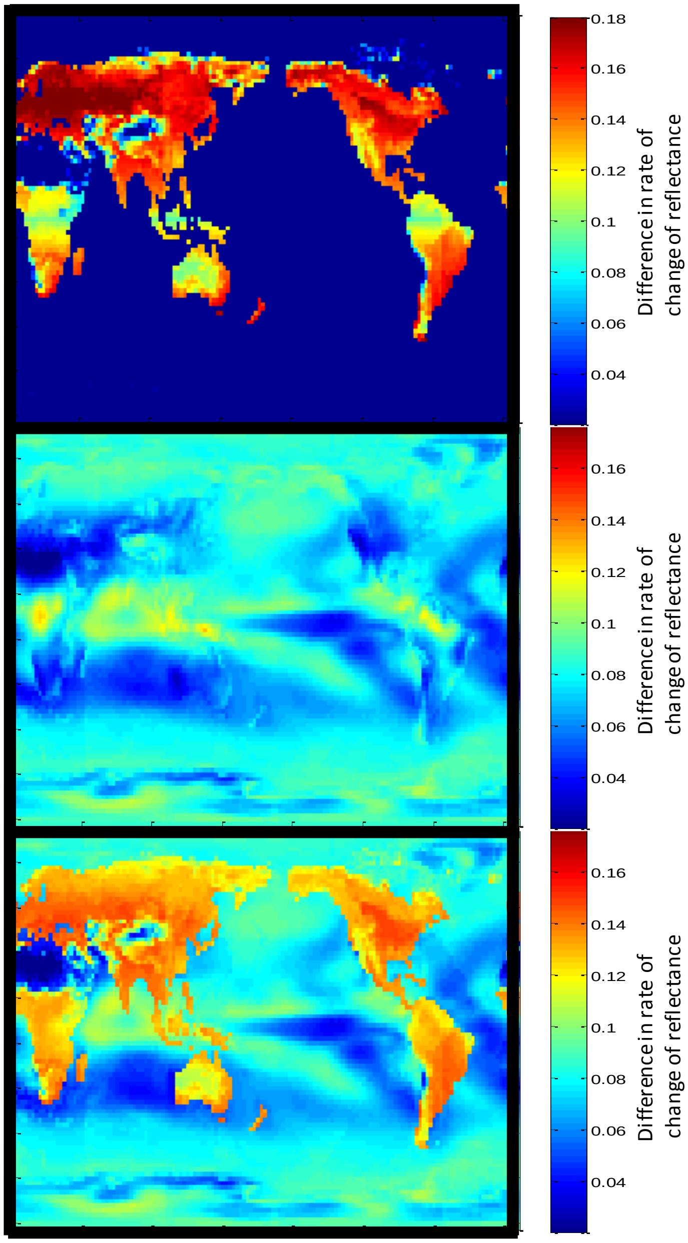

Figure 3 – The difference in the rate of change of albedo at 865 nm between phase angles 0.5° -3.5° and 44-47° for a vegetated planet with no clouds (top), a cloudy planet with no vegetation (middle), and a cloudy planet with vegetation (bottom).

Spectral information from a HabEx type mission will be averaged over the entire disk because the large distances to the planet prohibit greater spatial resolution. In previous work (Doughty and Wolf 2010), we developed a method to determine whether multi-cellular life, specifically 3D vegetation strucutre, could be detected on an Earth-like planet based on spectra that are averaged over the full disk for a full rotation period. We demonstrated that as Earth approaches full illumination, an observer in line with the star and planet will observe an anomalous increase in albedo as shadows cast by vegetation are blocked by the vegetation (Figure 2 and 3). Without 3D vegetation structure there would be no anomalous increase in albedo as a planet approaches full illumination. We tested the theory by combining a well-tested BRDF model with a global vegetation map and global cloud data and simulations to model Earth's albedo as viewed by a distant observer between phase angles of 0.5-44°. We found that even if the entire planetary albedo were rendered to a single pixel, the rate of increase of albedo as a planet approaches full illumination would be comparatively greater on a vegetated planet than on a non-vegetated planet (Figure 2 and 3). Depending on how accurately planetary cloud cover can be resolved and coronagraph design, this technique could theoretically detect tree-like multi-cellular life on exoplanets in 50 stellar systems. However, such theoretical work needs empirical validation.

We tried to empirically validate this work, as Sagan et al (1993) had, using first principles and Galileo data (Doughty and Wolf 2016). In previous work, Sagan et al. (1993) used first principles and the Galileo data to show various signs of life on Earth including biogenic gases in the atmosphere, a red edge in the Amazon, and radio waves as signs of intelligent life. In recent work (Doughty and Wolf 2016), we attempted to see if this same dataset could detect multicellular life, or 3D vegetation structure. We determined that it would be difficult to detect such structure on Earth with the Galileo dataset with confidence chiefly because the Galileo space probe lacked large phase angle changes (i.e. we hypothesized that our technique would require a phase angle change from 0-20 degrees while the Galileo data had a constant phase angle). Our theoretical model simulations demonstrate the potential validity of the technique but we need different empirical data to test our ideas. **We propose here a number of new ways in which to potentially validate this technique. If we are successful in proving this technique empirically, then this technique could be potentially used by future space telescopes to detect 3D vegetation structure on exoplanets and distinguish a planet with simple life from a planet with complex life.**

Overall – This proposal fits well within NASA’s Habitable Worlds program because the work will help identify the characteristics (multicellularity) of potentially habitable environments on exoplanets which could be used to inform future targeting and/or operational choices. Our work will include quantitative terrestrial field experiments that improve scientific understanding of this process. We request funding to support a graduate student for three years to work on this project which includes participation from both NAU's Department of Physics and Astronomy and NAU's School of informatics.

We propose to test the following specific questions

Part 1 – Can drone hyperspectral measurements clearly distinguish between vegetation and non-vegetated cratered landscapes using the change in BRDF?

Part 2 – Can OSIRIS REx and EPOXI data determine that Earth has 3D vegetation structure?

Part 3 – Can Earthshine reveal via BRDF that Earth has multicellular life and conversely can BRDF determine false positives on Mars and Venus?

Part 1 – Can drone hyperspectral measurements clearly distinguish between vegetation and non-vegetated cratered landscapes using the change in BRDF?

Can a change in BRDF clearly distinguish between vegetation structure and structured abiotic topography (such as craters) that is commonly seen on other planets? Vegetation structure on Earth has been analyzed extensively using BRDF (Breon et al. 2002; Breon et al. 1997; Li and Strahler 1992; Wolf et al. 2010) but never in comparison to more uncommon abiotic topography such as craters or non-vegetated volcanic substrate that might be more representative of an exoplanet without life. Can the change in BRDF distinguish between vegetation structure on exoplanets and potential false positives from the presence of abundant craters? We hypothesize that exoplanets with multicellular life will also have climate and weather, which will eliminate most such craters (as it has on Earth) through erosion. However, some exoplanets could conceivably have both abundant craters and multicellular life and it is therefore important to test the BRDF technique on both cratered fields and forests to see how the BRDF's differ. For instance, is there a specific spectral wavelength (visible or NIR) that works best to identify craters versus forests?

Figure 4. The Cinder Lakes Crater Fields northeast of Flagstaff, near the Sunset Crater Volcano, were used for Apollo-era training. Note the contrasting shadow structures between the ponderosa pines and the craters in the image on the left.

We propose to take advantage of the unique geography near our university (NAU) of Cinder Lakes Crater Fields. Moon-like craters were created by the USGS in 1967 by digging holes and filling them with various amounts of explosives, which were detonated to simulate different-sized lunar impact craters. The human-made craters range in size from 1.5-12 meters in diameter. This area was chosen for the craters because of the basaltic cinders from an eruption of the Sunset Crater volcano 950 years ago. After the explosions, the excavated lighter clay material spread out from the blast craters and across the fields, like ejecta from actual meteorite impacts. A total of 497 craters were made within two sites comprising 2,000 square feet. A smaller field, fenced off to vehicles, still contains many of the original craters used by Apollo astronauts, softened by time and weather but still visible. Because of our contacts at nearby USGS Astrogeology Center, we will have access to fly a drone over these sites and collect spectral data.

Specific plans

We propose to use a hyperspectral sensor (400 – 1000nm) on an octocopter drone to measure reflectance at different sun angles and at different heights over the "extraterrestrial" landscape near the Cinder Lakes Crater Field. These data will be compared to similar drone flights over nearby ponderosa pine forests and other nearby vegetation types. Here we propose to test our theory that forests will have a distinct and identifiable BRDF signal compared to the nearby cratered landscape. We also propose to determine empirically which wavelengths will maximize the differences so as to better inform detection of multicellular life at a larger scale.

A previous study (Wolf et al 2010) found that the sensitivity of dropoff in BRF (ΔBRF, here represented as the difference in reflectance at some angle minus the reflectance at the hotspot) varies substantially at large phase angles (20°) and comparatively little at small phase angles (5°). Low phase angles are superior for retrieving leaf area index due to the greater overall variance in reflectance, whereas high phase angles are superior for retrieving the set of parameters to which the slope of BRF is sensitive such as govern geometric optics, including the crown radius, tree number density and ground cover. We will specifically test whether trees can be distinguished from craters better with the slope at small phase angles (0-5 degrees) or by subtracting the hot spot reflectance from the dark spot (subtracting 0 from 50 degrees).

Collaborator Sankey (https://sites.google.com/a/nau.edu/remote-sensing-lab/uas) has the experience and equipment to fly and process the drone data and have agreed to be part of this project. She operates an octocopter that is equipped with a hyperspectral and LiDAR system. The hyperspectral sensor uses over 350 spectral bands (400-1000 nm) to image the earth's surface at up to 5 cm resolution. To use the drone and to employ a technician to collect and process the data will cost $5,760 per campaign and we envision two such campaigns. This is a special "at cost" price for NAU faculty. Specifically, we plan to fly repeated drone campaigns above the crater and basalt regions between phase angles of 0 to 50 degrees at progressively increasing heights. We then plan to compare these flights to similar type flights over several different nearby vegetation types. The specific goal is to determine whether the

Fig 5 - An example of NAU's octocopter drone that we plan on using for the analysis. This drone will fly over cratered and vegetated areas shown in Figure 4 collecting data with the hyperspectral sensor.

spectral regions near the hot spot (0-5 degrees) give more structural information than those near the dark spot (30-50 degrees). We will then compare our measurements to our predictions using BRDF theory.

Part 2 – Can OSIRIS REx and EPOXI data determine that Earth has 3D vegetation structure?

In recently published work (Doughty and Wolf 2016), we tried to use the Galileo space probe data and first principles to find evidence of whether life on Earth had three-dimensional vegetation structure. This paper was designed to empirically test our predictions from our 2010 astrobiology paper (Figure 2 and 3). We re-analyzed the data from Galileo to see if structured vegetation could have been detected in regions with abundant photosynthetic pigments through the anisotropy of reflected shortwave radiation. Specifically, we compared changing brightness of the Amazon forest (a region where Sagan et al. (1993) noted a red edge in the reflectance spectrum, indicative of photosynthesis) as the planet rotates to a common model of reflectance anisotropy. However, we concluded that we could not detect 3D vegetation structure with the Galileo data. The Galileo dataset had only a small change in phase angle (sun-satellite position) which reduced the observed anisotropy signal. Due to the small change in phase angle with the Galileo data, we determined that the Galileo space probe dataset was insufficient to empirically test our theory. This conclusion is the driving motivation behind this proposal since we are still convinced of the validity of the idea, but we need better datasets with larger changes in phase angles to empirically test the idea.

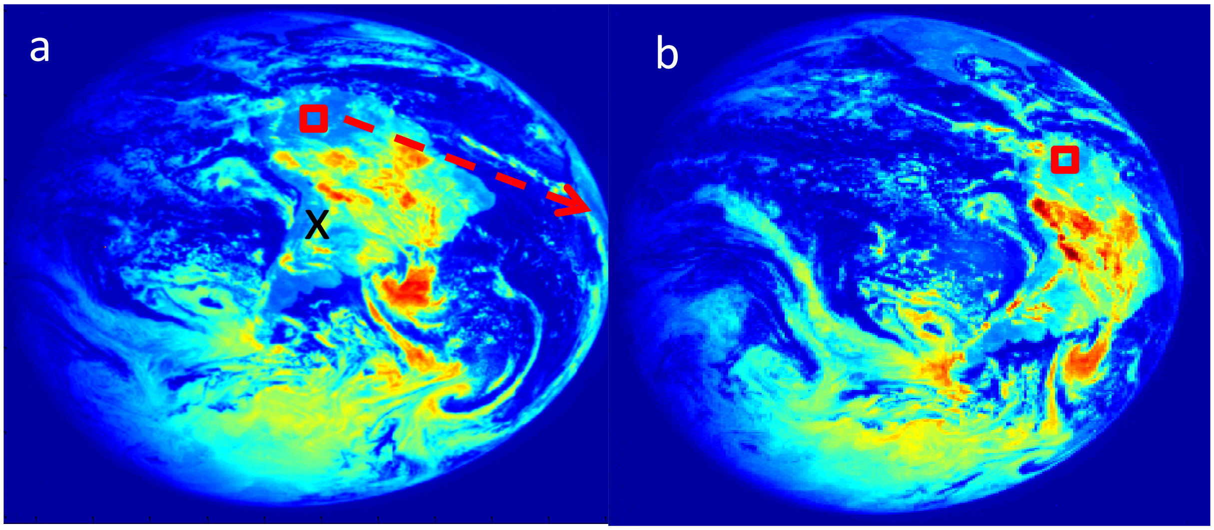

Figure 6 – Earth as viewed from the Galileo probe at (a) 3:12 GMT December 11, 1990 and again at (b) 4:25. The red arrow shows the direction of rotation. The red square is a 9x9 pixel (~10,000 km^2) patch of cloud free Amazon forest.

Data from Galileo do not provide sufficiently broad phase angle to test our theory, but there are other planetary probes with different sun Earth phase angles that could potentially better test the theory. For example, NASA's EPOXI mission observed the disc-integrated Earth and Moon at the end of Northern Hemisphere spring, 2008, from a range of 0.16 to 0.33 AU. These observations furnished high precision and high-cadence empirical photometry and spectroscopy of Earth. These data have previously been used to view Earth as an exoplanet to ‘‘ground truth’’ whether life could be detected with for example a red edge (Robinson et al. 2011 and Fujii et al 2011a and b).

P2 -1 – Use high phase angle data from the EPOXI mission

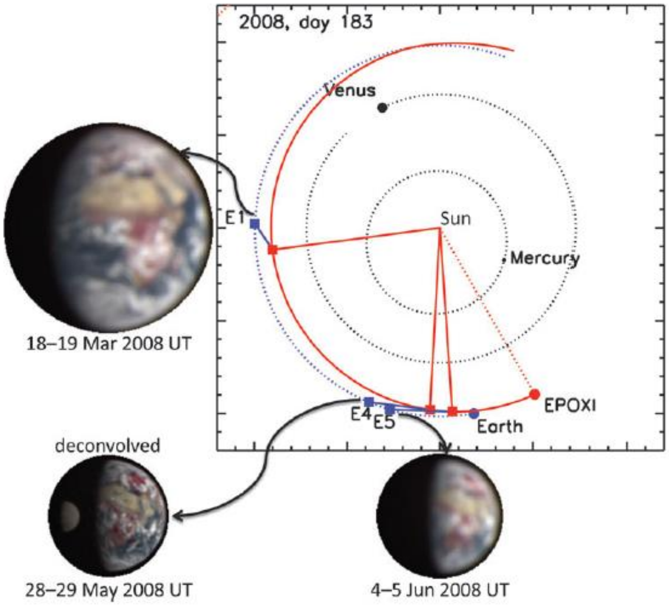

Fig 7. Orbital geometry for EPOXI observations of Earth with spacecraft and planet positions. The spacecraft position (red dot and orbital trajectory) led Earth (blue dot and dotted blue trajectory). Red squares show the spacecraft position, and blue squares show the Earth position at the time of observation.

Earth was observed during the EPOXI mission at near-equatorial sub-spacecraft latitude on 18–19 March, 28–29 May, and 4–5 June (UT), with 372–4540nm wavelengths (Robinson et al. 2011). These data are available online at http://pdssbn.astro.umd.edu/holdings/dif-e-hrii-3_4-epoxi-earth-v2.0/. Figure 7 shows the geometry that Earth was observed at three time periods. These three periods observed at sun Earth at phase angles of 57 and 76 degrees. This is not ideal for viewing Earth from the hot spot (0-20 degrees), but is ideal for viewing Earth from the dark spot which also contains significant structural information. With spectral data up to 4500nm, we can also test the change in BRDF at multiple wavelengths to determine which wavelength is best.

Because of the large phase angle (>50 degrees), we specifically propose to use the data from the EPOXI mission to test whether 3D vegetation structure can be detected in the dark spot. The data has been processed by previous studies which would make completion of the project much easier. Therefore, this large phase angle data with dark spot information will be combined with low phase angle data from the hotspot from the OSIRIS REx mission (see below).

P2 -2 – Use low phase angle data from the OSIRIS Rex mission

To complement the high phase angle data captured by the EPOXI mission, we will use low phase angle data collected by the OSIRIS REx mission. OSIRIS REx is a space probe designed to visit the near-Earth asteroid called Bennu, but it will pass by Earth in September of 2017. When it passes by Earth, just like the Galileo mission, Osiris Rex will point its instruments at Earth and we will use this spectral data collected to test for Earth's 3D vegetation structure. Data from the OSIRIS REx Earth flyby will be available (M. Nolan [deputy director of the OSIRIS REx mission], pers. comm.). We also have an estimate of the phase angles that OSIRIS REx will have as it flies by Earth (Figure 8).

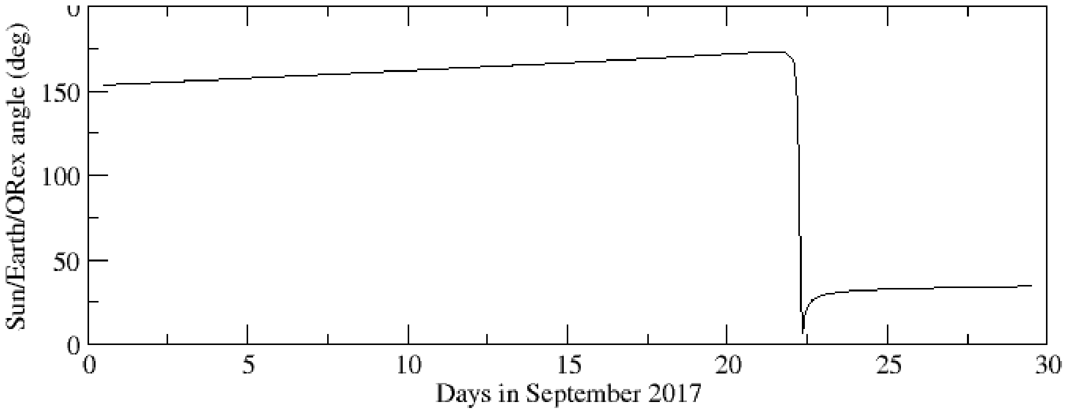

Fig 8 – A diagram showing the phase angle between OSIRIS REx the sun and the Earth during September of 2017.

Specifically, on around September 22, the phase angle of OSIRIS REx will vary between close to zero to about 25 degrees (Figure 8). We will then combine these data with the available phase angle data of 57 and 76 degrees captured by the EPOXI space probe. Therefore, combining the data from both of these missions, we will be able to view Earth both from the hot spot (near 0-20 degrees) and the dark spot (near 50 to 80 degrees) with a distant space probe. There is a debate on whether the hot spot or the dark spot provides more structural information about forests (Doughty and Wolf 2010 assume the hot spot is key, but Wolf et al 2010 finds more information in the dark spot). We both these datasets, we can then test both theories to see whether multicellular life and 3D vegetation structure can be detected and whether any specific structural information can be gained (trees versus grasses).

Other potential datasets also exist in which we can test our theories. For instance, recently the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter has taken pictures of Earth from Mars. http://solarsystem.nasa.gov/news/2017/01/06/your-home-planet-as-seen-from-mars (Figure 9). We will request several targeted additional HIRISE images of the Earth through the HiWISH program to improve our phase coverage of the Earth using that unique vantage point. Overall, the goal of this section of the proposal is to piece together from as many datasets as possible (three here are suggested) spectral data viewing Earth from space at various phase angles to determine if 3D vegetation structure can be detected.

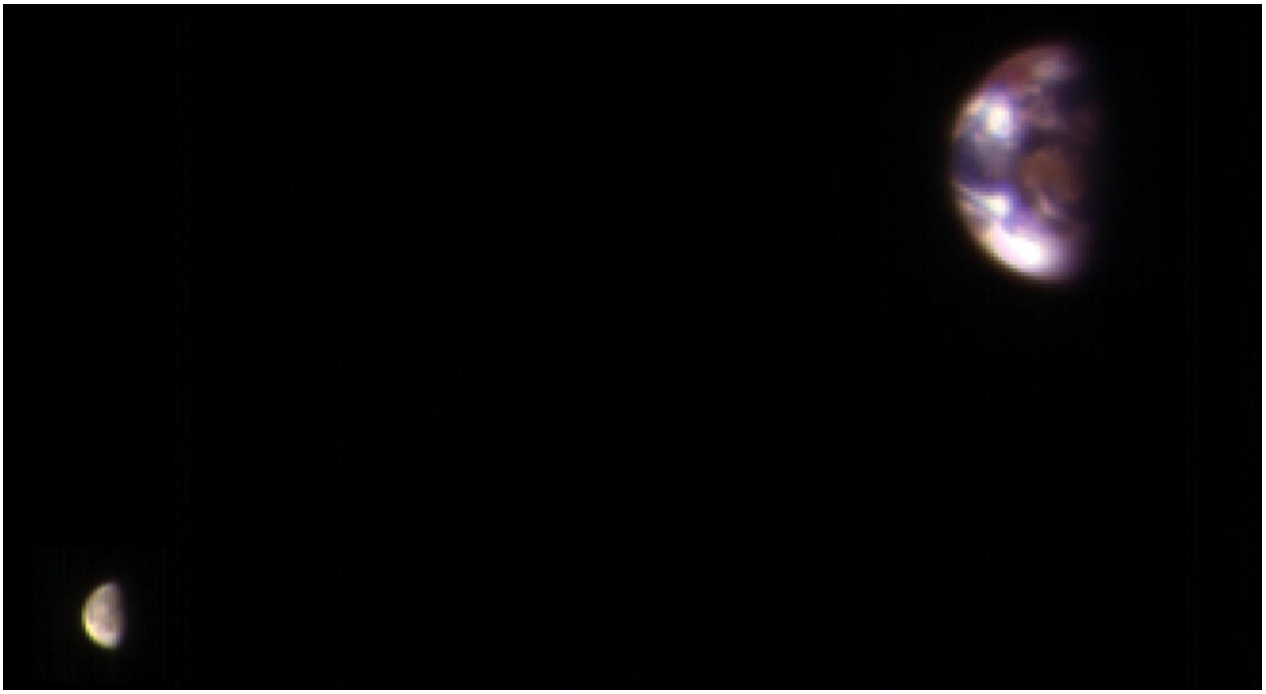

Figure 9 - A view of Earth and its moon, as seen from Mars. It combines two images acquired on Nov. 20, 2016, by the HiRISE camera on NASA's Mars Reconnaissance Orbiter.

Part 3 – Can Earthshine reveal via BRDF that Earth has multicellular life and conversely can BRDF determine false positives on Mars and Venus?

P3-1 – Use the change in BRDF from Earthshine to detect 3D vegetation structure on Earth

Over the past two decades researchers have measured Earth's albedo by measuring the amount of sunlight reflected from the Earth and, in turn, back to the Earth from the dark portion of the face of the Moon (the "earthshine" or "ashen light") (Figure 10) http://www.iac.es/proyecto/earthshine/pages.php. More recently, to get full coverage of the Earth, they have matched and carefully calibrated earthshine telescopes in both California and in the Cape Verde islands. This project is led in California by Prof. Phil Goode and in the Canary Islands by project collaborator Dr. Enric Palle.

This Earthshine group had previously used the Earthshine dataset for astrobiology purposes and has several astrobiology papers (Montañés-Rodríguez et al, 2005 and 2006, Palle et al 2009). This Earthshine data could be an ideal way to test our BRDF method because the Earthshine's spectrum are unresolved, just as terrestrial-like extrasolar planets. They have measured the earthshine spectra from a 60" telescope using its now decommissioned spectrograph with a coronagraph (see Qiu et al, 2003 for details of the instrumentation). With these data, they determined the temporal evolution of the vegetation signature of the Earth. In particular, they found a strong correlation between the evolution of the spectral intensity of the red edge and changes in the cloud-free vegetated area of the Amazon over the course of observations (Figure 11) (Montañés-Rodríguez et al., 2005, and 2006).

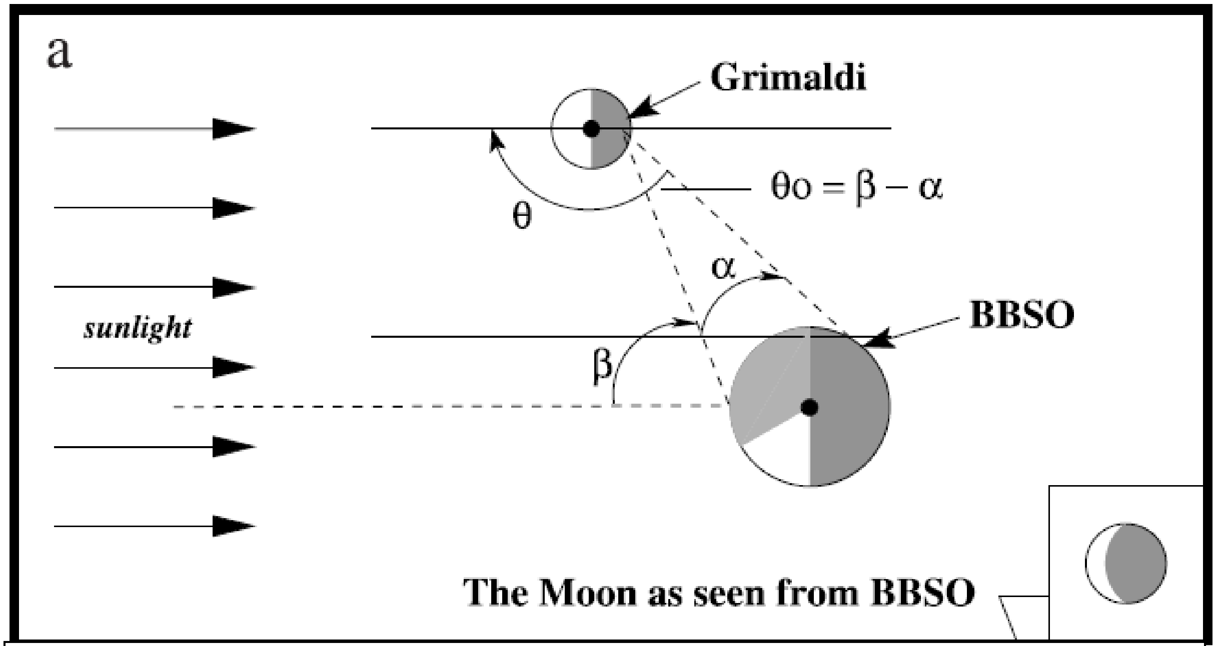

Fig 10 – A diagram showing how Earthshine data has been collected over the past 2 decades. The light reflected off the moon is unresolved, just as terrestrial-like extrasolar planets would be.

We have communicated with the PI's of the Earthshine project (Dr. Goode and Dr. Palle) and they are interested and enthusiastic about collaborating with us to use their two-decade time-series of Earthshine data to test our methodology. We will use their Earthshine data to test for 3D vegetation structure during periods when the Amazon basin is in view. We will specifically focus on the Amazon basin because their group has already published a paper using this same dataset to identify a red edge signal (Montañés-Rodríguez et al., 2005 and 2006). We therefore plan to reanalyse this same dataset under a range of different phase angles to determine 3D vegetation structure. We can compare this dataset to one over the Sahara Desert under similar phase angles to test for false positives. Because the Earth will be unresolved in reflectance seen in the earthshine, just as terrestrial-like extrasolar planets would be, this test will be the most accurate yet, of whether such a technique could be used on a HabEx type space telescope in the future.

P3-2 Can the change in BRDF detect false positives on Mars and Venus?

Mars and Venus present two contrasting planet types with which to test our technique for false positives. Mars is a rocky surface with few clouds while Venus is completely cloud covered. If we viewed both planets as they circle the sun (Fig 12), would we detect a false positive on either using our technique? Most exoplanets that we hope to use the technique on,

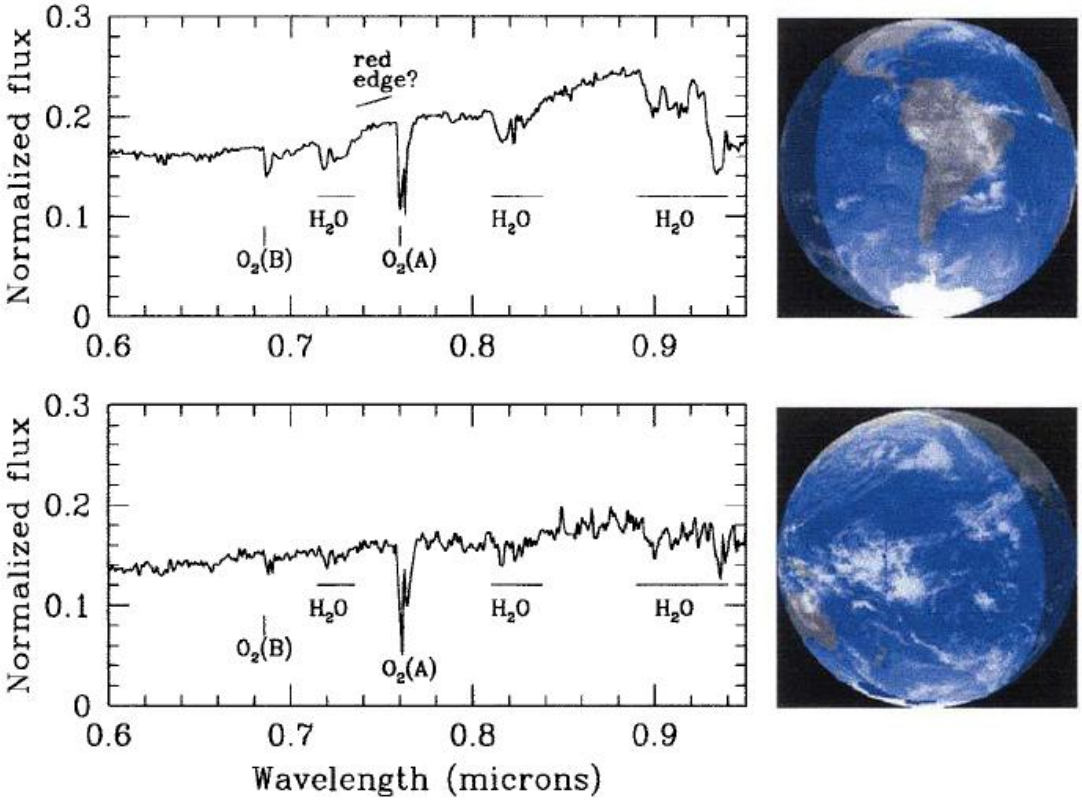

Fig 11 – A diagram showing how Earthshine data had been used to detect a vegetation red-edge in the Amazon basin.

will not have life and it is important to develop accurate techniques to screen out false positives. Mars and Venus are two ideal spectral endmembers representing two potential lifeless planets – one completely covered in clouds and one rocky. Such measurements will help us to control for false positives in the search for life on exoplanets.

We propose that NAU undergraduate astronomy students use our telescope to view Mars and Venus under a wide range of phase angles over a two-year period. We propose to view both planets to determine whether they have 3D vegetation structure with only first principles, much as we hope to view exoplanets. We hypothesize that the planets will display different BRDF signals from each other, but also different from those from the Earthshine measurements. Mars has phase angles 0--45 during any given year and it is always brighter than magnitude 2, which means that obtaining high quality photometric measurements with our campus telescope will be risk free. Venus undergoes a wide range of angles (from 0 to nearly 180 degrees) but can be difficult to observe due to its proximity to the Sun. Venus is always brighter than magnitude -4, making it one of the brightest astronomical sources in the sky. Obtaining high quality photometry will be difficult only when Venus is near the Sun. Such an exercise will also be useful to help develop techniques to learn more about the 3D structure of any future exoplanet viewed from HabEx.

Specifically, we will use the NAU campus telescope which is a 20 inch Ritchey-Chretien design equipped with a 1k APOGEE CCD camera with thermoelectric cooling standard astronomical broad-band filter set (Johnson-Cousins BVRI) operated by trained and certified students. Because we have institutional access, we can use the telescope at all times. We propose regular spectral data collections three nights a week for two hours a night over a two-year period. We have a standard undergraduate pay rate for the certified undergraduate astronomy students to make the observations.

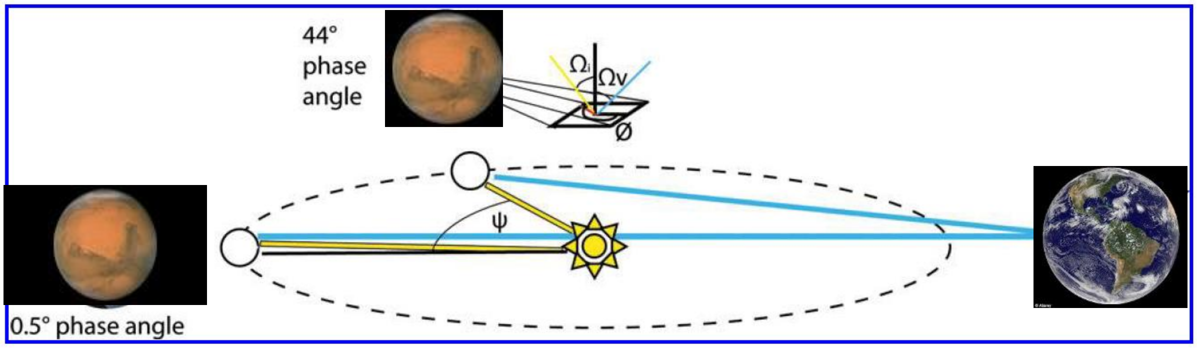

Fig 12 – Schematic of potential measurements of Mars at variable phase angles from Earth.

Project management plan – Dr. Doughty will devote a significant portion of his time to ensuring the success of this project and will lead the drone measurements with Dr. Sankey. Doughty will lead with Dr. Trilling, Dr. Mommert and Dr. Palle the interpretation of the already collected Earthshine data, and well as the probe data (OSIRIS Rex and EPOXI). Dr Trilling and Mommert will lead the data collection efforts of albedo of Mars and Venus using the campus telescope.

Task Management plan **-** Participants for each section.

	Doughty	Trilling	Mommert	Sankey	Palle	PhD student	Astro undergrads
P1 - 1 – Ground based measurements	X			X		X	
P2 – 1 – Osiris rex data analysis	X	X	X			X	
P2 – 2 – EPOXI data analysis	X	X	X			X	
P3 - 1 – Earthshine data analysis	X		X		X	X	
P3 –2 - Mars and Venus data collection		X	X			X	X

Risks and mitigation strategies **-** This project represents a highly novel and potentially seminal project for a very low cost. The risks associated with the project are very low because we will be using established and peer reviewed methodologies that have already been proven in several papers. Most key data has already been collected, substantially reducing the risk of this project. The drone data will be collected by a team with great expertise in this area from sites that are less than a few hours drive from our campus, meaning there is almost no potential that these data will not be collected. The observations of Venus and Mars are also very low risk because these will be simple measurements carried out with our campus telescope by trained students. Therefore, the risk of the project is very low because all the data needed either already has been collected or will easily been collected.

Management plan-The project will commence on July 2017 on the following schedule:

	July 2017	Dec 2017	July 2018	Dec 2018	July 2019	Dec 2019
P1-1. – Drone measurements	X	X				
P2 – 1 – OSIRIS REx and EPOXI data analysis		X	X	X		
P3 - 1 – Earthshine data analysis		X	X	X		
P3 –2 - Mars and Venus data collection	X	X	X	X		
Write up results				X	X	X

Project deliverables - We estimate a minimum of four, high quality publications as an outcome of this proposal (one addressing each of the above sections). More broadly, if our empirical results match our theoretical results this could be a major breakthrough for NASA’s goal of detecting life on other planets.

Data Management Plan

Types of data

1. Raw data: The primary (i.e., raw) forms of data are: 1) drone spectral data; 2) existing EPOXI and OSIRIS Rex probe data; 3) Earthshine data; and 4) collected brightness data of Venus and Mars. EPOXI and OSIRIS Rex probe data and Earthshine data have already been collected and are hosted by their original collectors. For instance, EPOXI data is currently within an online database (http://pdssbn.astro.umd.edu/holdings/dif-e-hrii-3_4-epoxi-earth-v2.0/). OSIRIS Rex data will also be collected and hosted by NASA. Earthshine data is available through the Earthshine collaborators (http://www.iac.es/proyecto/earthshine/pages.php) and hosted locally. However, the drone data and telescope observations will be saved on many individual computers, hard drives, as well as in the cloud. We currently have dropbox business accounts with large storage spaces as well as 4TB storage space on the NAU supercomputer MONSOON (https://nau.edu/hpc/).

3. Analysed data: All data will be analysed mainly using the commercially available program Matlab. All data will initially be compiled as individual files within the Monsoon supercomputing cluster. We will archive all analysed data used in our publications in one of the leading online data archives such as the Reaction Database Standard Search Interface. Also, academic journals will generally provide a public repository for any data associated with that paper and we will make use of this. In addition, NAU's library participates in an Arizona-wide data archive, whose point is to provide long-term public access to data for federally funded projects. The repository can be accessed at http://openknowledge.nau.edu/.

Metadata standards

Metadata is key for understanding of the raw data and we plan to carefully collect and post all relevant metadata. This involves careful use of standard terms and the addition of clear units for all posted numbers. As a guide, we will standardize our metadata following NASA's online archives of data such as EPOXI - (http://pdssbn.astro.umd.edu/holdings/dif-e-hrii-3_4-epoxi-earth-v2.0/).

Policies for access and sharing

All data, metadata, and analyses collected under the proposed experiments will be made publicly available as per NASA guidelines within 2 years of collection via published manuscripts, publicly available final reports to NASA, and via the online data archives. The PI will take guidance from NASA concerning the right to use the data prior to opening it up to wider use. There are no ethical or privacy issues involved in sharing of this type of data and it is unlikely that sharing will incur more than modest cost.

Data storage

All electronic data are saved in triplicate with two copies kept on-site (NAU computing cluster) and another kept off-site. As described, all data, whether in electronic or paper form, are copied, organized by sample number and recording day, and archived both on-site and off-site. There is no plan to destroy any collected data as the archive is not burdensome in cost or space. As such, data archives can be expected to be available for at least a period of ten years subsequent to publication of the relevant findings.

References and Citations

Bacour C, Bréon F-M (2005) Variability of biome reflectance directional signatures as seen by POLDER. Remote Sensing of Environment 98:80-95

Beerling D (2007) The Emerald Planet: How Plants Changed Earth's History. Oxford University Press.

Bicheron P, Leroy M (2000) Bidirectional reflectance distribution function signatures of major biomes observed from space. Journal of Geophysical Research-Atmospheres 105:26669-26681

Breon FM, Henriot N (2006) Spaceborne observations of ocean glint reflectance and modeling of wave slope distributions. Journal of Geophysical Research-Oceans 111:-

Breon FM, Maignan F, Leroy M, Grant I (2002) Analysis of hot spot directional signatures measured from space. Journal of Geophysical Research-Atmospheres 107:-

Breon FM, Vanderbilt V, Leroy M, Bicheron P, Walthall CL, Kalshoven JE (1997) Evidence of hot spot directional signature from airborne POLDER measurements. Ieee Transactions on Geoscience and Remote Sensing 35:479-484

Brown JH WG (2000) Scaling in biology. Oxford University Press, New York

Cockell CS et al. (2009) Darwin-A Mission to Detect and Search for Life on Extrasolar Planets. Astrobiology 9:1-22

Collins WD et al. (2006) The formulation and atmospheric simulation of the Community Atmosphere Model version 3 (CAM3). Journal of Climate 19:2144-2161

Des Marais DJ et al. (2002) Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. Astrobiology 2:153-181

Dietrich WE, Perron JT (2006) The search for a topographic signature of life. Nature 439:411-418

Donoghue MJ (2005) Key innovations, convergence, and success: macroevolutionary lessons from plant phylogeny. Paleobiology 31:77-93

Doughty, C.E., Wolf, A. (2016) Detecting 3D vegetation structure with the Galileo space probe: Can a distant probe detect vegetation structure on Earth? - PloS one

Doughty, C.E. and Wolf, A. (2010) Detecting Tree-like Multicellular Life on Extrasolar Planets. Astrobiology, 10(9): 869-879.

Enquist BJ, Brown JH, West GB (1998) Allometric scaling of plant energetics and population density. Nature 395:163-165

Fujii Y, Kawahara H, Suto Y, Taruya A, Fukuda S, Nakajima T, et al. Colors of a Second Earth: Estimating the Fractional Areas of Ocean, Land, and Vegetation of Earth-Like

Exoplanets. Astrophys J. 2010;715(2):866-80. doi: 10.1088/0004-637x/715/2/866. PubMed PMID: WOS:000277642100012.

Fujii Y, Kawahara H, Suto Y, Fukuda S, Nakajima T, Livengood TA, et al. Colors of a Second Earth. Ii. Effects of Clouds on Photometric Characterization of Earth-Like Exoplanets. Astrophys J. 2011;738(2). doi: Artn 184

Ford EB, Seager S, Turner EL (2001) Characterization of extrasolar terrestrial planets from diurnal photometric variability. Nature 412:885-887

Gatebe CK, King MD, Platnick S, Arnold GT, Vermote EF, Schmid B (2003) Airborne spectral measurements of surface-atmosphere anisotropy for several surfaces and ecosystems over southern Africa. Journal of Geophysical Research-Atmospheres 108:-

Gay J, Rabbia Y (1996) An interferometric method for coronography. Comptes Rendus De L Academie Des Sciences Serie Ii Fascicule B-Mecanique Physique Chimie Astronomie 322:265-271

Graham LE, Cook ME, Busse JS (2000) The origin of plants: Body plan changes contributing to a major evolutionary radiation. Proceedings of the National Academy of Sciences of the United States of America 97:4535-4540

Guyon O, Pluzhnik EA, Galicher R, Martinache F, Ridgway ST, Woodruff RA (2005) Exoplanet imaging with a phase-induced amplitude apodization coronagraph. I. Principle. Astrophysical Journal 622:744-758

Guyon O, Pluzhnik EA, Kuchner MJ, Collins B, Ridgway ST (2006) Theoretical limits on extrasolar terrestrial planet detection with coronagraphs. Astrophysical Journal Supplement Series 167:81-99

Hall O, Falorni G, Bras RL (2005) Characterization and quantification of data voids in the shuttle radar iopography mission data. Ieee Geoscience and Remote Sensing Letters 2:177-181

Hapke B, DiMucci D, Nelson R, Smythe W (1996) The cause of the hot spot in vegetation canopies and soils: Shadow-hiding versus coherent backscatter. Remote Sensing of Environment 58:63-68

Hapke BW, Nelson RM, Smythe WD (1993) The Opposition Effect of the Moon - the Contribution of Coherent Backscatter. Science 260:509-511

Horodyski RJ, Knauth LP (1994) Life on Land in the Precambrian. Science 263:494-498

Jin ZH, Charlock TP, Smith WL, Rutledge K (2004) A parameterization of ocean surface albedo. Geophysical Research Letters 31:-

Kasting JF, Catling D (2003) Evolution of a habitable planet. Annual Review of Astronomy and Astrophysics 41:429-463

Kenny R, Knauth LP (2001) Stable isotope variations in the Neoproterozoic Beck Spring Dolomite and Mesoproterozoic Mescal Limestone paleokarst: Implications for life on land in the Precambrian. Geological Society of America Bulletin 113:650-658

Kiang NY et al. (2007a) Spectral signatures of photosynthesis. II. Coevolution with other stars and the atmosphere on extrasolar worlds. Astrobiology 7:252-274

Kiang NY et al. (2007b) Spectral signatures of photosynthesis: Coevolution with other stars and the atmosphere on extrasolar worlds. Astrobiology 7:486-487

Li XW, Strahler AH (1992) Geometric-Optical Bidirectional Reflectance Modeling of the Discrete Crown Vegetation Canopy - Effect of Crown Shape and Mutual Shadowing. Ieee Transactions on Geoscience and Remote Sensing 30:276-292

Lucht W, Schaaf CB, Strahler AH (2000) An algorithm for the retrieval of albedo from space using semiempirical BRDF models. Ieee Transactions on Geoscience and Remote Sensing 38:977-998

Maignan F, Breon FM, Lacaze R (2004) Bidirectional reflectance of Earth targets: Evaluation of analytical models using a large set of spaceborne measurements with emphasis on the Hot Spot. Remote Sensing of Environment 90:210-220

Mishchenko MI, Rossow WB, Macke A, Lacis AA (1996) Sensitivity of cirrus cloud albedo, bidirectional reflectance and optical thickness retrieval accuracy to ice particle shape. Journal of Geophysical Research-Atmospheres 101:16973-16985

Montañés-Rodríguez, E. Palle, P.R. Goode, Measurements of the surface brightness of the Earthshine with applications to calibrate lunar flashes. The Astronomical Journal, 134, number 3, 1145, 2007

Montañés-Rodríguez, E. Palle, P.R. Goode,Vegetation signature in the observed globally-integrated spectrum of Earth: Modeling the red edge strength using simultaneous cloud data and applications for extrasolar planets. The Astrophysical Journal, 651, 544-552, 2006

Oleson KW, Bonan GB (2000) The effects of remotely sensed plant functional type and leaf area index on simulations of boreal forest surface fluxes by the NCAR land surface model. Journal of Hydrometeorology 1:431-446

P. R. Lawson OPL, K. J. Johnston, and C. A. Beichman (2007) Terrestrial Planet Finder Interferometer Science Working Group Report. In. Jet Propulsion Laboratory California Institute of Technology, Pasadena, California

Palle E, Ford EB, Seager S, Montanes-Rodriguez P, Vazquez M (2008) Identifying the rotation rate and the presence of dynamic weather on extrasolar earth-like planets from photometric observations. Astrophysical Journal 676:1319-1329

Palle E, Osorio MRZ, Barrena R, Montanes-Rodriguez P, Martin EL (2009) Earth's transmission spectrum from lunar eclipse observations. Nature 459:814-816

Qiu, P.R. Goode, E. Pallé, V. Yurchyshyn, J. Hickey, P. Montañés Rodriguez, M.-C. Chu, E. Kolbe, C.T. Brown, and S.E. Koonin, 2003, Earthshine and the Earth's Albedo: 1. Earthshine Observations and Measurements of the Lunar Phase Function for Accurate

Measurements of the Earth's Bond Albedo, J. Geophys. Res., Vol. 108, No. D22, 4709, ACL 12-1.

Robinson, TD., Victoria S. Meadows, David Crisp, Drake Deming, Michael F. A'Hearn, David Charbonneau, Timothy A. Livengood, Sara Seager, Richard K. Barry, Thomas Hearty, Tilak Hewagama, Carey M. Lisse, Lucy A. McFadden, and Dennis D. Wellnitz Earth as an Extrasolar Planet: Earth Model Validation Using EPOXI Earth Observations (2011) Astrobiology. 2011 Jun; 11(5): 393–408.doi: 10.1089/ast.2011.0642

Sagan C, Thompson WR, Carlson R, Gurnett D, Hord C (1993) A Search for Life on Earth from the Galileo Spacecraft. Nature 365:715-721

Schaepman-Strub G, Schaepman ME, Painter TH, Dangel S, Martonchik JV (2006) Reflectance quantities in optical remote sensing-definitions and case studies. Remote Sensing of Environment 103:27-42

Seager S, Turner EL, Schafer J, Ford EB (2005) Vegetation's red edge: A possible spectroscopic biosignature of extraterrestrial plants. Astrobiology 5:372-390

Serabyn E, Mawet D, Burruss R (2010) An image of an exoplanet separated by two diffraction beamwidths from a star. Nature 464

Tarbuck EJ, Lutgens, F.K. (2008) Earth, An introduction to physical geology. Prentice Hall, Upper Sadie River

Tinetti G et al. (2006a) Detectability of planetary characteristics in disk-averaged spectra. I: The Earth model. Astrobiology 6:34-47

Tinetti G, Meadows VS, Crisp D, Fong W, Velusamy T, Snively H (2005) Disk-averaged synthetic spectra of Mars. Astrobiology 5:461-482

Tinetti G et al. (2006b) Detectability of planetary characteristics in disk-averaged spectra II: Synthetic spectra and light-curves of earth. Astrobiology 6:881-900

Torrance KE, Sparrow EM (1967) Theory for Off-Specular Reflection from Roughened Surfaces. Journal of the Optical Society of America 57:1105-&

West GB, Brown JH, Enquist BJ (1999) A general model for the structure and allometry of plant vascular systems. Nature 400:664-667

West GB, Enquist BJ, Brown JH (2009) A general quantitative theory of forest structure and dynamics. Proceedings of the National Academy of Sciences of the United States of America 106:7040-7045

Wolf A, Berry JA, Asner GP (2010) Allometry constrains sources of variability in multi-angle reflectance measurements. Remote Sensing of Environment.

Wolstencroft RD, Raven JA (2002) Photosynthesis: Likelihood of occurrence and possibility of detection on earth-like planets. Icarus 157:535-548

Biographical Sketches
Christopher Doughty
(a) Professional Preparation:

University of California at Berkeley, Berkeley, Ca.	Environmental Science	B.A., 2001
University of California at Irvine, Irvine, Ca.	Earth System Science	Ph.D., 2008
Carnegie Institute, Stanford, Ca.	Carnegie Postdoctoral Fellowship	2008-2010
Oxford University, Oxford UK	Junior Research Fellowship	2010-2013

(b) Appointments

2016-	Assistant Professor, Department of Informatics and Computer Science, Northern Arizona University
2013 - 2016	Research Lecturer, Department of Geography and the Environment Oxford University, UK

Key publications

Doughty, C.E., Wolf, A. (2016) Detecting 3D vegetation structure with the Galileo space probe: Can a distant probe detect vegetation structure on Earth? - PloS one

Doughty, C.E. and Wolf, A. (2010) Detecting Tree-like Multicellular Life on Extrasolar Planets. Astrobiology, 10(9): 869-879.

Other recent publications

Doughty, C.E., Asner, G.P. and Martin, R.E. (2011) Predicting tropical plant physiology from leaf and canopy spectroscopy. Oecologia, 165(2): 289-299.

Doughty, C.E., Metcalfe, D.B., Girardin, C.A.J., Farfan Amezquita, F., Galiano Cabrera, D., Huaraca Huasco, W., Silva-Espejo, J.E., Araujo-Murakami, A., da Costa, M.C., Rocha, W., Feldpausch, T.R., Mendoza, A.L.M., da Costa, A.C.L., Meir, P., Phillips, O.L. and Malhi, Y. (2015) Drought impact on forest carbon dynamics and fluxes in Amazonia. Nature, 519: 78-82.

Doughty, C.E., Roman, J., Faurby, S., Wolf, A., Haque, A., Bakker, E.S., Malhi, Y., Dunning, J.B. and Svenning, J.C. (2016) Global nutrient transport in a world of giants. Proceeding of the National Academy of Sciences of the United States of America.

Chavana-Bryant, C., Malhi, Y., Wu, J., Asner, G.P., Anastasiou, A., Enquist, B.J., Caravasi, C., Doughty, C.E., Saleska, S.R., Martin, R.E., Gerard, F.F. (2016) Leaf aging of Amazonian canopy trees as revealed by spectral and physiochemical measurements. New Phytologist

Doughty, C.E., S. Faurby, A. Wolf, Y Malhi, J. Svenning. Changing NPP consumption patterns in the Holocene: from megafauna “liberated” NPP to “ecological bankruptcy” Anthropocene Review. 2016 PDF

Doughty, C.E., Faurby, S. and Svenning, J. (2016) The impact of the megafauna extinctions on savanna woody cover in South America. Ecography. PDF

Doughty, C.E., Roman, J., Faurby, S., Wolf, A., Haque, A., Bakker, E.S., Malhi, Y., Dunning, J.B. and Svenning, J.C. (2016) Global nutrient transport in a world of giants. Proceeding of the National Academy of Sciences of the United States of America.PDF

Doughty, C.E., Wolf, A., Baraloto, C. and Malhi, Y. (2016) Interdependency of plants and animals in controlling the sodium balance of ecosystems and the impacts of global defaunation. Ecography. PDF

Doughty, C.E., Wolf, A., Morueta-Holme, N., Jorgensen, P.M., Sandei, B., Violle, C., Boyle, B., Kraft, N.J.B., Peel, R.K., Enquist, B.J., Svenning, J., Blake, S. and Galetti, M. (2016) Megafauna extinction, tree species range reduction and carbon storage in Amazonian forests. Ecography. PDF

Doughty, C.E., Malhi, Y., Araujo-Murakami, A., Metcalfe, D.B., Silva-Espejo, J.E., Arroyo, L., Heredia, J.P., Pardo-Toledo, E., Mendizabal, L.M., Rojas-Landivar, V.D., Martinez, M., Valencia, M., Rivero, R. and Vare, L. (2014) Allocation trade-offs dominate the response of tropical forest growth to seasonal and interannual drought. Ecology, 95(8): 2192-2201. PDF

Doughty, C.E., Metcalfe, D.B., da Costa, M.C., de Oliveira, A.A.R., Netoc, G.F.C., Silva, J.A., Aragão, L.E.O.C., Almeida, S.S., Quesada, C.A., Girardin, C.A.J., Halladay, K., da Costa, A.C.L. and Malhi, Y. (2014) The production, allocation and cycling of carbon in a forest on fertile terra preta soil in eastern Amazonia compared with a forest on adjacent infertile soil. Plant Ecology and Diversity, 7(1-2): 41-53. Special Issue: Ecosystem Dynamics of Amazonian and Andean Forests..PDF

Doughty, C.E., Taylor, L.L., Girardin, C.A.J., Malhi, Y. and Beerling, D. (2014) Montane forest root growth and soil organic layer depth may have stabilized Cenozoic global change. Geophysical Research Letters, 41(3): 983-990. PDF

Doughty, C.E. (2013) Preindustrial human impacts on global and regional environment. Environment and Resources, 38: 503-527. PDF

Doughty, C.E., Wolf, A. and Malhi, Y. (2013) The impact of large animal extinctions on nutrient fluxes in early river valley civilizations. Ecosphere, 4(12). PDF

Doughty, C.E., Wolf, A. and Malhi, Y. (2013) The legacy of the Pleistocene megafauna extinctions on nutrient availability in Amazonia. Nature Geoscience, 6(2013): 761-764. PDF

Doughty, C.E. (2010) The development of agriculture in the Americas: an ecological perspective. Ecosphere, 1(6). PDF

Doughty, C.E. and Field, C.B. (2010) Agricultural net primary production in relation to that liberated by the extinction of Pleistocene mega-herbivores: an estimate of agricultural carrying capacity? Environmental Research Letters, 5. PDF

David Trilling

Professional positions:

Kavli Fellow
Associate Professor, Northern Arizona University (2013–)
Assistant Professor, Northern Arizona University (2008–2013)
Assistant Astronomer (Research Faculty), University of Arizona (2004–2008)
Lecturer, University of Pennsylvania (2003–2004)
Postdoctoral Researcher, University of Pennsylvania (2000–2004)
Postdoctoral Researcher, UCO/Lick Observatory (1999–2000)
Graduate student, Lunar and Planetary Laboratory, University of Arizona (1995–1999)
Max Planck Society Fellow, Max-Planck-Institut f¨ur Aeronomie, Germany (1994–1995)

Selected memberships and project leadership:

Co-chair, LSST Solar System Science Collaboration
External Scientist in the Pan STARRS 1 Inner Solar System Collaboration
PI of two Spitzer Exploration Science Proposals (1200+ hours total)
CoI on "TNOs are cool" Herschel Key Programme team
Spitzer Warm Mission Solar System Science Working Group
PI of the Spitzer Asteroid Catalog project

Students and postdocs supervised:

Four postdocs, ten Masters and PhD students, 25 undergraduate research students, and two scientific programmers supervised

Selected recent publications:

Chatelain et al. 2016, "Photometric colors of the brightest members of the Jupiter L5 Trojan cloud," Icarus, 271, 158
Mommert et al. 2016, "First Results from the Rapid-response Spectrophotometric Characterization of NearEarth Objects using UKIRT," AJ, 151, 98 Polishook et al. 2016, "A 2 km-size asteroid challenging the rubble-pile spin barrier - A case for cohesion," Icarus, 267, 243
Trilling 2016, "The Surface Age of Sputnik Planum, Pluto, Must Be Less than 10 Million Years," PLoS ONE, http://dx.doi.org/10.1371/journal.pone.0147386
Mommert et al. 2015, "ExploreNEOs. VIII. Dormant Short-period Comets in the Near-Earth Asteroid Population," AJ, 150, 106
Cartwright et al. 2015, "Distribution of CO2 ice on the large moons of Uranus and evidence for compositional stratification of their near-surfaces," Icarus, 257, 428
Mainzer et al. 2015, "Space-Based Thermal Infrared Studies of Asteroids," in Asteroids IV, U. Arizona press, 89
Mommert et al. 2014, "Physical Properties of Near-Earth Asteroid 2011 MD," ApJ, 789, L22
Mommert et al. 2014, "Constraining the Physical Properties of Near-Earth Object 2009 BD," ApJ, 786, 148
Bowell et al. 2014, "Asteroid spin-axis longitudes from the Lowell Observatory database," M&PS, 49, 95 Thomas et al. 2014, "Physical characterization of Warm Spitzer-observed near-Earth objects," Icarus, 228, 217

Michael Mommert

Northern Arizona University, Department of Physics and Astronomy PO Box 6010, Flagstaff, AZ 86011 Phone: 928-523-5595, Email: michael.mommert@nau.edu

Research Interests

Physical characterization of small bodies in the Solar System; the asteroid–comet continuum; automated data reduction and analysis

Education

Dr. rer. nat. (Ph.D. eq.) in Earth Sciences, Freie Universit¨at Berlin, Germany, 2013

Diploma (M.Sc. eq.) in Physics, Universit¨at Heidelberg, Germany, 2009

Employment

Research Associate, Northern Arizona University, starting 2016-present

Post-Doctoral Researcher, Northern Arizona University, 2013-2016

Invited Short-term Scholar, University of Arizona, 2011-2012

Ph.D. Student, Deutsches Zentrum f¨ur Luft- und Raumfahrt e.V., Germany, 2009-2013

Select Projects

PI of NASA NEOO program Systematic Characterization and Monitoring of Potentially Active Near-Earth Asteroids (2017-2020)

Co-I and thermal modeling lead of Spitzer Cycle 13 Legacy program NEOLegacy

Author of automated image data analysis pipeline: “PHOTOMETRYPIPELINE” (github.com/mommermi/photometrypipeline)

Select Publications

Mommert, M., Trilling, D. E., Borth, D. et al. 2016, First Results from the Rapid-response Spectrophotometric Characterization of Near-Earth Objects using UKIRT, AJ, 151, 98
Mommert, M., Harris, A. W., Mueller, M. et al. 2015, ExploreNEOs. VIII. Dormant Shortperiod Comets in the Near-Earth Asteroid Population, AJ, 150, 106
Mommert, M., Farnocchia, D., Hora, J. L. et al. 2014, Physical Properties of Near-Earth Asteroid 2011 MD, ApJL, 789, 22
Mommert, M., Hora, J. L., Farnocchia, D. et al. 2014, Constraining the Physical Properties of Near-Earth Object 2009 BD, ApJ, 786, 148
Mommert, M., Hora, J. L., Harris, A. W. et al. 2014, The Discovery of Cometary Activity in Near-Earth Asteroid (3552) Don Quixote, ApJ, 781, 25

Current and Pending Support

Current and Pending Support - Doughty

Project PI Doughty has no current or pending NASA grants.

He has three pending NSF grants but not in overlapping areas.

NSF - INFEWS N/P/H2O - Revitalizing the phosphorus pump: Creating a new paradigm of conservation and phosphorus restoration	Pending	$284,663.00
NSF - MSB-ECA - Fauna and forest biogeochemical cycling: modelled and measured impacts of fauna on phosphorus movement	Pending	$295,658.00
NSF - ABI Innovation: Modelling the ecosystem services of animals over space and time	Pending	$673,543.00

He currently has a 32,000 USD Google Earth Engine grant.

Current and Pending Support – David Trilling:

Note: Trilling's academic year salary is paid by NAU. Various projects below carry no explicit funding or funded work effort for Trilling because the relevant tasks are covered by his academic salary.

Current support: "NEOLegacy: The ultimate Spitzer survey of Near Earth Objects" (PI: Trilling) Sponsor: Spitzer Science Center Budget period: 10/1/16 – 9/30/19 (proposed) Trilling work effort: 1 summer month per year (with the remainder of the funds for a postdoc to be hired). Note: This is based on the expected amount, but the award amount has not yet been finalized.

"Constraining the history of the outer Solar System" (PI: Trilling) Sponsor: STScI Budget period: 2/1/15 – 1/31/17 Trilling work effort: 2 summer weeks total (the remainder of the salary is for postdoc Paulo Penteado) "Thermal infrared observations of near Earth objects" (PI: Trilling) Sponsor: NASA SSO Budget period: 1/1/15 – 12/31/17 Trilling work effort: 0.5 summer months per year (the remainder of the salary is for postdoc Michael Mommert)

"Rapid response near-infrared spectrophotometric characterization of Near Earth Objects" (PI: Trilling) Sponsor: NASA SSO Budget period: 1/1/15 – 12/31/17 Trilling work effort: 1.0 summer months per year (the remainder of the salary is for postdoc Michael Mommert)

"NEOSurvey" (Spitzer Exploration Science program) (PI: Trilling) Sponsor: Spitzer Science Center Budget period: 4/1/15 – 9/30/17 Trilling work effort: 1.0 summer months per year (the remainder of the salary is for postdoc Michael Mommert or a graduate student to be recruited)

"The Mission Accessible Near-Earth Objects Survey (MANOS)" (PI: Moskovitz) Sponsor: NASA NEOO Budget period: 7/1/14 – 6/30/16 Trilling work effort: 0 (all salary for postdoc Michael Mommert and grad student Mary Hinkle)

“The compositions of outer Solar System ices from ultra-low resolution spectroscopy” (PI: Trilling) Sponsor: NSF Budget period: 9/1/13 – 8/31/16 Trilling work effort: 0.5 summer months per year plus 3.6 months during 2014/15 academic year for sabbatical support

“Deep field TNO colors in archival Frontier Fields data” (PI: C. Fuentes) Sponsor: STScI Budget period: 12/1/13 – 11/30/16 Trilling work effort: 0 (all salary supports postdoc Paulo Penteado)

“TNOs in WFC3 archival fields” (PI: C. Fuentes) Sponsor: STScI Budget period: 10/1/11 – 9/30/16 Trilling work effort: 0 (all salary supports postdocs Cesar Fuentes and Paulo Penteado)

“MRI: Acquisition of an integrated telescope system for astrophysical surveys and transient discoveries” (PI: Trilling) Sponsor: NSF MRI (AST) Budget period: 10/1/12 – 9/30/16 Trilling work effort: 2 summer months per year plus ~2 academic months per year as part of NAU cost share

“Near Earth objects serendipitously detected in archival Spitzer data” (PI: Trilling) Sponsor: NASA NEOO Budget period: 10/1/12 – 9/30/16 Trilling work effort: 0 (all salary support is for postdoc Paulo Penteado)

“The most dangerous IEOs in the STEREO archive” (PI: Fuentes) Sponsor: NASA NEOO Budget period: 10/1/12 – 9/30/16 Trilling work effort: 0.08 FTE (additional support for postdocs Cesar Fuentes and Michael Mommert)

Pending support: “FRoST: An automated telescope for rapid response NEO follow-up” (PI: Trilling) Sponsor: NASA Solar System Observations Budget period: 1/1/2017 — 12/31/2019 Trilling work effort: 1 month / year

Current and Pending Support - Michael Mommert:

Current Support “Thermal infrared observations of near Earth objects” (PI: Trilling) Sponsor: NASA SSO Budget period: 1/1/15 – 12/31/17 Role: Co-I Work effort: 0.1 FTE

“Rapid response near-infrared spectrophotometric characterization of Near Earth Objects” (PI: Trilling) Sponsor: NASA SSO Budget period: 1/1/15 – 12/31/17 Role: Co-I Work effort: 0.15 FTE

“NEOSurvey” (PI: Trilling) Sponsor: Spitzer Science Center Budget period: 4/1/15 – 9/30/16 Role: Co-I Work effort: 0.25 FTE

“NEOLegacy” (PI: Trilling) Sponsor: Spitzer Science Center Budget period: 10/1/16 – 3/31/19 Role: Co-I Work effort: 0.25 FTE

“Systematic Characterization and Monitoring of Potentially Active Near-Earth Asteroids” (PI: Mommert) Sponsor: NASA NEOO Budget period: 7/1/17 – 6/30/20 Role: PI Proposed work effort: 0.25 FTE

“The Mission Accessible Near-Earth Object Survey (MANOS)” (PI: Moskovitz) Sponsor: NASA NEOO Budget period: 2/1/17 – 1/31/20 Role: Co-I Work effort: 0.25 FTE

Budget Justification

A. Senior Personnel

We are not requesting salary for the Senior Personnel for this project.

B. Other Personnel

We request funding for one PhD graduate student over a period of three years to complete the project and write-up the results. The PhD graduate student will be offered a three-year (9 months/year) research assistantship at $20,000 per year. This extended funding at standard NAU rates provides a mechanism to provide economic stability to the student and stability for the project. This comes to $60,000 in direct costs.

We request funding at 0.1 FTE for Dr. Mommert who will assist with supervising the undergraduates for a total request of $18,900.

A team of undergraduate astronomy students will make observations of Venus and Mars for the project. We imagine the students will work 6 hours/week for twelve months during the year over a two-year period, for a total of 312 person-hours per year to the project over each of the first two years. We plan to pay a rate of $10/hour. This comes to $6,240 in direct costs.

C. Fringe Benefits

Student employee-related expenses (ERE) are rounded estimates based on the projected cost of health, FICA and Medicare, and unemployment, relative to the employee's salary and/or wages, FTE, and election of benefits. Postdoc fringe benefits are calculated at 30.7% for a total of $5,802.The Graduate and Undergraduate fringe benefits package requested are equal to $38,784. The Graduate student fringe benefits includes $29,695 in tuition remission, $8,262 in health insurance coverage, and $300 in ERE.

D. Equipment - none

E. Travel

Domestic Travel

- The PI and the GRA will present our scientific results at one conference per year such as the American Geophysical Union ($2,100 travel, registration and subsistence × 3 conferences × 2 people = **$12,600**).

Foreign Travel:

- **No foreign travel**

F. Participant Support – none

G. Other Direct Costs

Materials and Supplies

To use the drone and to employ a technician to collect and process the data will cost $4,760 per mission. We propose two separate missions – forest BRDF and crater/basalt landscape. This will cover the costs of the field technician and the drone but not the field costs of the GRA and we also request an additional $500 to account for GRA field expenses. The total will be $12,020 USD.

Publication/Documentation/Dissemination: Total costs are **$4,000**.

We request $4,000 in page fees to publish 4 papers at 1,000 per paper (two case study papers and two modelling paper).

TOTAL DIRECT COSTS = $158,347

Indirect Costs (IDC): = $66,899

Indirect costs are requested at the 52.0% MTDC on-campus research rate in accordance with Northern Arizona University's approved Colleges and Universities Rate Agreement (February 7, 2013) (Cognizant Agency: U.S. Dept. of Health and Human Services). The MTDC base consists of all direct salaries and wages, applicable fringe benefits, materials and supplies, services, travel, subawards, and subcontracts up to the first $25,000 of each subaward or subcontract (regardless of the period of performance of the subawards and subcontracts under the award). MTDC excludes equipment, capital expenditures, charges for patient care, rental costs, tuition remission, scholarships and fellowships, participant support costs and the portion of each subaward and subcontract in excess of $25,000.

TOTAL DIRECT and INDIRECT COSTS =$225,246

Facilities and Equipment

We will use already collected data from the Earthshine project, EPOXI mission and OSIRIS Rex missions and these require no additional facilities or equipment.

Drone spectral measurements - Colleagues at NAU (Dr. Sankey) (https://sites.google.com/a/nau.edu/remote-sensing-lab/uas) have the experience and equipment to fly and process the drone data and have agreed to be part of this project. Specifically, they have an octocopter which is equipped with a hyperspectral and LiDAR system. The hyperspectral sensor uses over 350 spectral bands (400-1000 nm) to image the earth's surface at up to 5 cm resolution. To use the drone and to employ a technician to collect and process the data will cost $5,760 per campaign and we envision two such campaigns. This is a special "at cost" price for NAU faculty.

Campus telescope measurements - we will use the NAU campus telescope which is a 20 inch Ritchey-Chretien design equipped with a 1k APOGEE CCD camera with thermoelectric cooling standard astronomical broad-band filter set (Johnson-Cousins BVRI) operated by trained and certified students. Because we have institutional access we can use the telescope at all times. We propose regular spectral data collections three nights a week for hours a night over a two-year period.