Astro2020 Science White Paper
The Sun-like Stars Opportunity

Thematic Areas: Planetary Systems

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Abstract:

Observations of exoplanets around Sun-like (i.e. FGK) stars will allow us to place our planet into a larger cosmic context and may offer the best chance of finding habitable, and inhabited, planets. New facilities beyond those currently planned would be required to accomplish these observations. Exoplanet community reports have emphasized the importance of observations of exoplanets in the habitable zones of Sun-like stars for over a decade. This trend continued in the recent Exoplanet Science Strategy report. We endorse the findings and recommendations published in the National Academy reports on Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe. This white paper extends and complements the material presented therein.

1. Introduction

The study of exoplanets is a young field, but it remains one of the most compelling and exciting areas of astronomy with popular appeal beyond the astronomical community. The path to characterizing habitable and inhabited worlds has already begun with ground- and space-based programs discovering planets in the habitable zones (HZs) of their stars. These potentially habitable planets, especially those orbiting M dwarfs, will be prime targets in coming years for spectral observations with the James Webb Space Telescope (JWST) and large ground-based facilities. However, while they are the simplest to observe, planets orbiting M dwarfs may face multiple barriers to habitability. Terrestrial planets in the HZs of Sun-like stars (i.e. FGK dwarfs) offer the best chance of discovering planets with conditions and evolutionary histories analogous to Earth's, as well as the best opportunity to detect unambiguous biosignatures.

A Consensus of Reports

The importance of observations of Earthlike planets around Sun-like stars has been reiterated by the exoplanet community for over a decade. The 2008 *Report of the ExoPlanet Task Force*[1] by the Astronomy and Astrophysics Advisory Committee (Lunine et al., 2008) called for "finding and characterization of a planet like our own, around a star like our own Sun." This report laid out two parallel tracks for the community: 1) study targets around M dwarfs using ground and space-based assets, and 2) invest in new technologies and space-based facilities to study planets around Sun-like stars (**Figure 1**). While major progress has and will continue to be made on the "M dwarf track" with existing and planned facilities, progress in discovering and characterizing habitable worlds around Sun-like stars still requires new space-based assets.

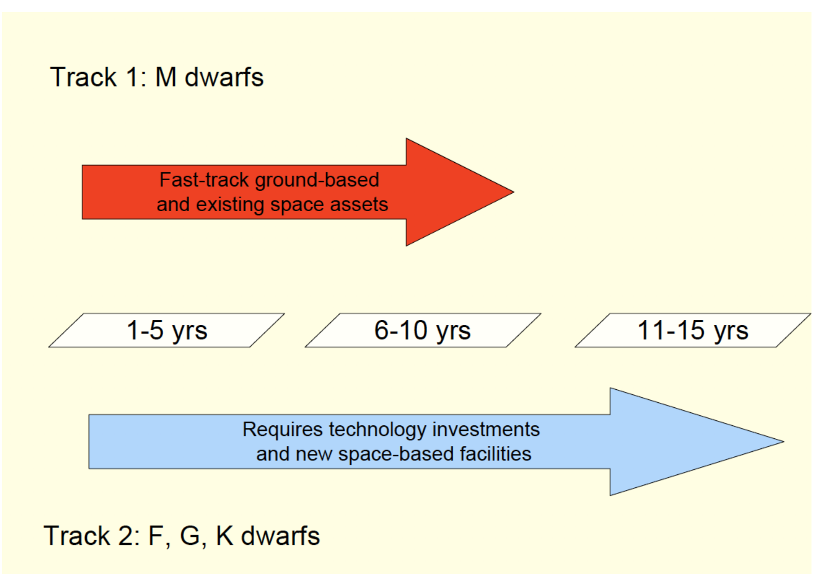

Figure 1: The recommended exoplanet science strategy from the 2008 *Report of the ExoPlanet Task Force*. Track 1 (M dwarfs) is now in progress. Track 2 (F, G, K dwarfs; i.e. "Sun-like" stars) will require major new technology and facilities for significant progress. Figure credit: Figure 1 from the *Report of the ExoPlanet Task Force* (Lunine et al., 2008).

[1] https://www.nsf.gov/mps/ast/aaac/exoplanet_task_force/reports/exoptf_final_report.pdf

Other community reports in the intervening years have reached similar conclusions. The 2010 *European Roadmap for Exoplanets*[2] (Hatzes et al., 2010) emphasized the importance of observations of exoplanets in the HZs of Sun-like stars. Similarly, the 2013 NASA Astrophysics Roadmap *Enduring Quests Daring Visions*[3] (Kouveliotou et al., 2013) stated that observations of exoplanets around Sun-like stars will give us "greater hopes of identifying and understanding life" compared to planets around lower mass stars. The 2014 Exo-C and Exo-S reports on probe-scale space missions reiterated the importance of observations of exoplanets in the HZs of Sun-like stars (Stapelfeldt et al., 2014; Seager et al., 2014). Most recently, the 2018 *Exoplanet Science Strategy* report (NAS 2018) repeated this emphasis in its first recommendation: "NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars."

2. Why Sun-like Stars?

Studies of planets around Sun-like stars will place our planet into a larger cosmic context and reveal how typical our world is. Furthermore, while the challenges of observing planets around Sun-like stars are not trivial, planets around these stars represent our best chance of finding life elsewhere, in the event that M dwarfs are inhospitable hosts for habitable planets. Here we will briefly outline why observations of rocky exoplanets in the HZs of FGK host stars should be sought as a high priority. Many of the reasons why Sun-like stars are important have been described in the recent *Exoplanet Science Strategy* report (NAS 2018); we concur with this report's findings, and this white paper extends and complements the material presented there.

The Sun-like Star Habitability Advantage

The extreme evolution and activity of M dwarf stars suggests Sun-like stars may be more hospitable hosts for habitable worlds. M dwarfs undergo an extended super-luminous (1-2 orders of magnitude brighter) pre-main sequence (PMS) phase that can last for to up to 10^9 years. This can cause extreme early water loss, such that planets even in the HZs of M dwarfs may be desiccated Venus-like worlds (Luger & Barnes 2015; Ramirez & Kaltenegger 2014; Tian & Ida 2015; Lincowski et al., 2018). Possibly, this fate can be avoided by late volatile delivery (Morbidelli et al., 2000; Wang & Becker 2013) or late migration of volatile-rich planets into the HZ (Luger et al., 2015). Furthermore, many M dwarfs maintain high stellar activity levels into old age (West et al., 2015; France et al., 2018). Their high EUV and X-ray luminosities (Shkolnik et al., 2014) and frequent energetic flaring (e.g. MacGregor et al., 2018; Loyd et al., 2018) may lead to severe – perhaps total – atmospheric loss on rocky HZ planets (e.g. Owen & Mohanty 2016; Airapetian et al., 2017; Dong et al., 2017; Garcia-Sage et al., 2017). However, the planets of ultra-cool dwarfs could perhaps retain sufficient water to remain habitable depending on initial water content (Bolmont et al., 2017).

[2] http://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=47854

[3] https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

By contrast, planets orbiting Sun-like stars will experience more moderate stellar evolution and activity. Early K dwarfs have been highlighted as especially promising hosts for habitable planets (Cuntz & Guinan 2016). Richey-Yowell et al., (2019) found that K dwarf FUV and X-ray radiation decreases after ~100 Myr, compared to M dwarfs whose high-energy fluxes may remain constant until ~650 Myr (Shkolnick & Barman 2014; Schneider & Shkolnick 2018). Additionally, Richey-Yowell et al., (2019) found that incident UV and X-ray fluxes are 5 - 50 times lower for planets orbiting K dwarfs in early stages of evolution compared to early-M dwarfs and 50 - 1000 times lower compared to late-M stars. This is due to less intrinsic activity from K dwarfs and the larger star-planet separations for planets in their HZs.

The Sun-like Star Biosignature Advantage

It may be easier to interpret biosignatures (remotely observable signs of life) on exoplanets orbiting Sun-like stars compared to M dwarfs. Studies over the last decade suggest that HZ planets around M dwarfs are especially prone to developing abiotic O_2 and its photochemical byproduct O_3, two of the most important biosignatures in Earth's atmosphere (e.g. Domagal-Goldman et al., 2014; Tian et al., 2014; Gao et al., 2015; Harman et al., 2015; Luger & Barnes, 2015). A summary of the four most obvious/important false positive mechanisms appears in **Figure 2**. As can be seen, only one applies to planets around any type of star (Wordsworth & Pierrehumbert, 2014); the others are expected to be applicable to M dwarf planets. The processes that lead to these abiotic "false positive" oxygen species involve water loss and photochemical effects.

False positive O_2 or O_3 can be effectively ruled out by the presence of reduced gases. The "classic" biosignature disequilibrium pairing for modern Earth is the simultaneous presence of O_2 and methane (CH_4), whose atmospheric abundances are orders of magnitude away from equilibrium values (Lovelock 1965, Hitchcock & Lovelock 1967; Krissansen-Totton et al., 2016). However, this classic pairing has not always been detectable throughout Earth's inhabited history, due to low oxygen abundances at early times with enhanced CH_4, and lower CH_4 abundances after the rise of oxygen (Olson et al., 2016; Reinhard et al., 2017, Schwieterman et al., 2018). Interestingly, M dwarfs and mid- and late-K dwarfs appear to offer longer CH_4 photochemical lifetimes in O_2-rich atmospheres, enhancing the simultaneous detectability of these gases (Segura et al., 2005; Arney 2019). However, since Sun-like stars appear to have less chance of presenting abiotic O_2 to begin with, simultaneous detection of O_2 and CH_4 to establish biogenicity of these gases is more critical for M dwarfs than it is for Sun-like stars.

Recent work also suggests that the productivity of oxygenic photosynthesis may be limited by light availability for planets orbiting M dwarf stars (Lehmer et al., 2018). In this case, atmospheric O_2 may not accumulate to detectable levels. For instance, an Earth-like planet in the HZ of a TRAPPIST-1-like star may be unable to support a biosphere as robust as modern Earth's due to a reduced incident flux of photons with sufficient energy (400-700nm) to drive the photosynthetic reaction, which is principally responsible for fueling our planet's biosphere. The biospheres on M dwarf planets may therefore be much smaller than Earth's. In this situation, the geologic processes of Earth-like planets, such as volcanic outgassing, could overwhelm any potential atmospheric biosignature (Lehmer et al., 2018). Furthermore, complex life may be more likely to evolve on planets orbiting G dwarfs than lower mass stars, since the

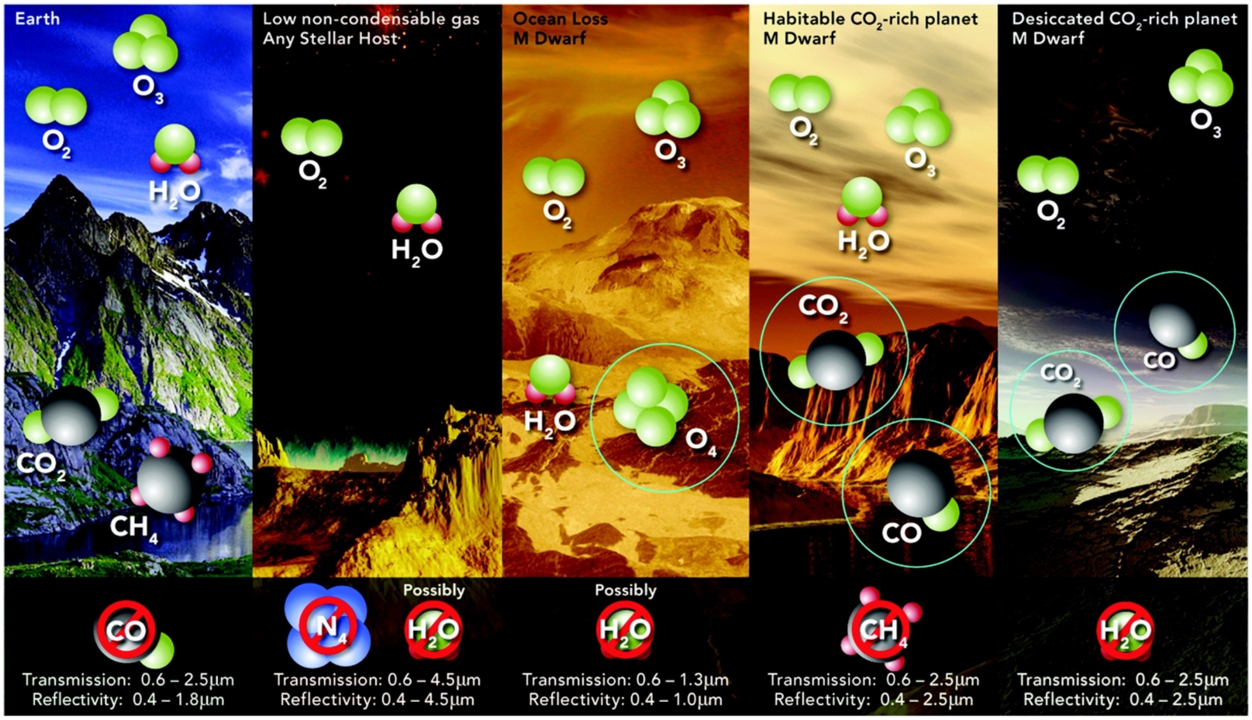

Figure 2: Possible O_2 and O_3 biosignature false positives. Top panels show atmospheric constituents. Circled gases show false positive indicators. Bottom panels indicate species that should be absent for a given false positive to apply. Only one scenario plausibly applies to Sun-like stars for planets with low non-condensable gas inventories (i.e. low-pressure atmospheres), but such a planet could be identified given constraints on total atmospheric pressure. This may be possible with sufficient signal-to-noise observations (Feng et al. 2018; discussion in T. Robinson whitepaper). Figure credit: Meadows (2017).

latter can have greater abundances of photochemical CO in their atmospheres (Schwieterman et al., 2019). CO is toxic to aerobic organisms, and high concentrations might limit the development of complex life throughout the entire HZs of late M dwarfs.

M Dwarfs as a Necessary Complement

The argument for observations of Sun-like stars is not an argument for ignoring M dwarfs. While there are significant questions about the habitability of rocky planets in the HZs of M dwarfs, they will provide fundamental tests of our theories of planetary evolution and biology that are derived from the Earth-Sun pairing, and they may inform us of different kinds of atmospheric processes (e.g. Yang et al., 2013; Fujii et al., 2017; Kopparapu et al., 2017; Ramirez and Kaltenegger 2018; Lincowski et al., 2018). If we find that some M dwarf HZ planets are truly habitable, this means habitable conditions are robust even in the face of significant challenges. This would have profound implications for the distribution and frequency of habitable worlds and the emergence of life in the galaxy, given that M dwarfs comprise 75% of all stars.

Characterization of small planets in the HZs of M dwarf stars will be dramatically advanced with the James Webb Space Telescope and future ground-based extremely large telescopes (ELTs). Space-based observatories are required for studies of Earth-like planets sufficiently small to be rocky (R < 1.6 Earth radii; Rogers 2015) in the HZs of Sun-like stars (e.g. see C. Stark's exo-Earth yield whitepaper); possibly, ELT facilities could provide complementary imaging at thermal wavelengths for a small number of targets, although the most detectable worlds around Sun-like stars from the ground may be too hot, or too large to be habitable (Quanz et al., 2015). An observatory that can directly image Earth-like planets around Sun-like stars would also enable high-fidelity transit spectroscopy of exoplanets around M dwarfs. **Table 1** summarizes challenges and opportunities of observations of exoplanets orbiting M dwarfs vs. FGK dwarfs.

3. Conclusions

The most complete understanding of the nature and distribution of habitable environments and life in the universe demands observations of multiple diverse planets orbiting stars with a range of masses. However, M dwarf worlds, although numerous and observable with upcoming facilities like JWST and ground-based ELTs, may not be habitable. To place our planet into a larger cosmic context and maximize our chances of detecting life elsewhere, observations of potentially habitable exoplanets orbiting Sun-like stars are needed. Such observations will require direct imaging using a next generation space-based telescope equipped with advanced starlight suppression technology.

Table 1: Challenges and opportunities for HZ planets around M dwarfs and FGK dwarfs.

	Challenges	**Opportunities**
Potentially habitable planets orbiting M dwarfs	Multiple barriers to habitability possible; e.g. desiccation during super-luminous pre-main sequence phase, stellar activity-driven atmospheric loss. Apparent high potential for false positive oxygen biosignatures. Challenging to observe via direct imaging due to the small planet-star angular separation. Even nearest planets require ELTs (Crossfield 2013).	Most common type of stars (~75%). Planets with significantly different histories to Earth valuable for comparative planetology. Transits of HZ planets more easily observed due to shorter orbital periods and deeper transit depths. May be possible with JWST and/or ELTs. Moderate planet-star contrast ratio (10^{-8} in reflected light). Nearest planets may be within reach of ELTs (Crossfield 2013).
Potentially habitable planets orbiting FGK dwarfs	Less common types of stars. Transit spectroscopy prohibitively difficult due to long orbital periods, small transit depths, lower transit probability. Challenging planet-star contrast ratio (10^{-10} for a Sun-Earth twin in reflected light) demands starlight suppression advances.	Less significant barriers to habitability due to moderate stellar evolution and activity. Understand Earth in the context of planets with similar histories. Is Earth typical? Observable with potential future space-based telescopes in direct imaging due to larger planet-star angular separation. Known that life can flourish on such planets. May be best opportunity for high-confidence detection of biosignatures.

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