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A diagnostic for detecting atmospheres in potentially rocky planets

Prospective targets in the context of habitability

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Abstract. In this work, we present a diagnostic for detecting atmosphere in potentially rocky exoplanets hosted by F-G-K-M dwarfs under the habitability context. We compiled a sample of 114 exoplanets that may have liquid water on the surface, after applying stellar and planetary restrictions, making comparisons against planetary interior models and assuming isothermal atmosphere models. Atmospheric height scale and surface pressure were estimated for each exoplanet taking into account its surface equilibrium temperature and 3 kinds of atmosphere (H_2, N_2 and CO_2). We computed the minimum S/N ratio to record planetary transits in the optical region. Consequently, we are also able to define potential targets for observing transits and detecting atmosphere from ground and space-based instruments in other spectral regions.

Resumo. Neste trabalho, apresentamos um diagnóstico para detecção de atmosfera de exoplanetas potencialmente rochosos hospedados por anãs F-G-K-M, no contexto de habitabilidade. Aplicando-se filtros estelares e planetários bem como comparações com modelos de interiores de planetas e considerando-se atmosferas isotérmicas, identificamos 114 exoplanetas com condições de ter água líquida na superfície. Para cada exoplaneta, estimamos a escala de altura e a pressão atmosférica superficial, considerando sua temperatura superficial de equilíbrio e 3 tipos de atmosfera (H_2, N_2 e CO_2). Calculamos a razão S/N mínima para registrar trânsitos planetários na região óptica. Assim, tornando-se possível também indicar alvos em potencial para observação de trânsitos e detecção de atmosfera com instrumentos no solo e espaço em outras regiões do espectro.

Keywords. Astrobiology – Planets and satellites: atmospheres – Planets and satellites: composition – Planets and satellites: detection

1. Introduction

Atmospheric detection and characterization of exoplanets remain a challenge in the field, especially because these planets are small compared to their host stars and exhibit low or undetectable emission (Seager 2010; Madhusudhan 2019).

In particular, different phases of a star–planet light curve probe distinct physical processes. During transit (phase 0), the system flux decreases and the presence of an atmosphere introduces wavelength-dependent transit depths. At quadratures (phases 0.25 and 0.75), reflected and/or emitted planetary light produces a flux increase, reaching its maximum near the secondary eclipse (phase 0.5) (Esteves et al. 2015).

In this work, we present a preliminary diagnostic for detecting atmosphere in potentially habitable rocky exoplanets. We aim to identify atmospheric signatures through multi-band phase-curve analysis and, afterwards, to choose the best atmospheric composition is the most consistent with the observational data, taking into account a realist physical modeling as well.

2. Methodology

By applying stellar filters ($T_{\rm eff}$ and surface gravity) and planetary filters (radius, mass, mass density, insolation and $T_{\rm eq}$) in the *NASA Exoplanet Archive*, we selected an initial sample of 453 potentially habitable rocky exoplanets hosted by F, G, K and M-dwarf stars of any metallicity. We also adopted relative error constraints of up to 40% for planet mass and up to 20% for planet radius to ensure higher-quality measurements. To define the final planetary sample, consisting of 187 candidates, we used two homogeneous interior composition models proposed by Zeng et al. (2019), representing planets made of 100% iron and 100% rock.

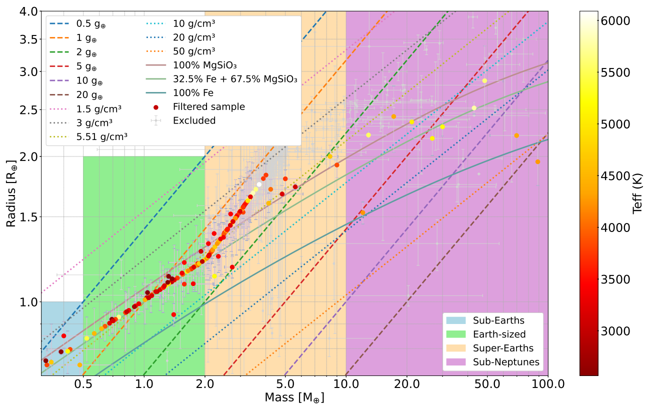

Figure 1. Mass-Radius diagram of the potentially habitable rocky exoplanets sample (host stars are classified by $T_{\rm eff}$).

We found that the potential planet targets range from sub-Earths to sub-Neptunes. Using the approximation of an isothermal atmosphere under hydrostatic equilibrium, we estimated the atmospheric scale height of a planet with mass M_P and radius R_P:

$$H = \frac{kT_{\rm eq}}{\mu m_{\rm H} g}, \quad (1)$$

where $m_{\rm H}$ is the mass of a hydrogen atom, k is the Boltzmann constant, μ is the average mass of an atmospheric particle and the acceleration of gravity $g = \frac{GM_P}{R_P^2}$; and the surface atmospheric pressure:

$$P = n_s k T_{\rm eq} = \frac{\rho_s}{\mu m_{\rm H}} k T_{\rm eq}, \quad (2)$$

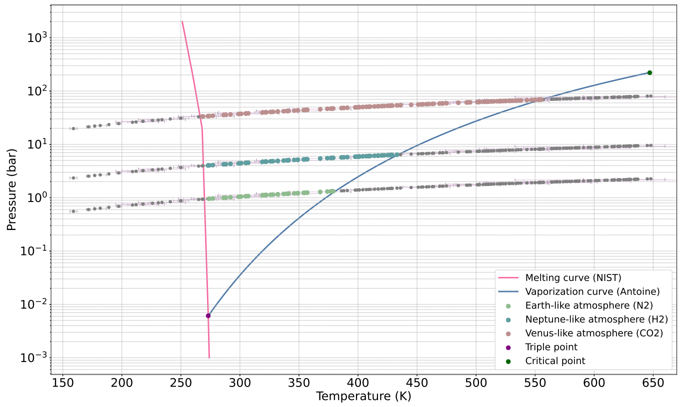

Figure 2. Water phase diagram: potentially habitable rocky exoplanets under different kinds of atmosphere for liquid state.

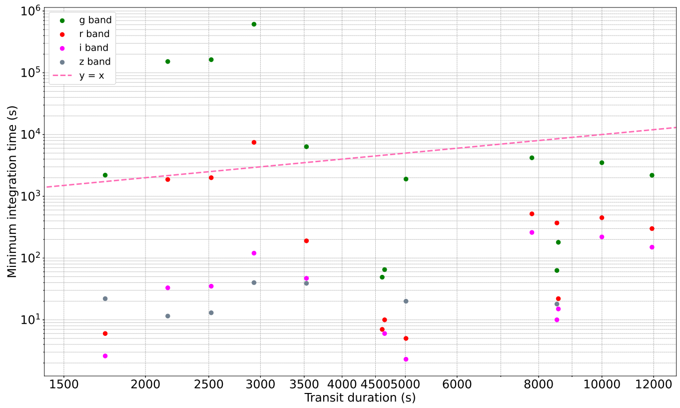

Figure 4. Minimum integration time for SPARC4 camera vs. transit duration considering CO_2-dominated atmosphere.

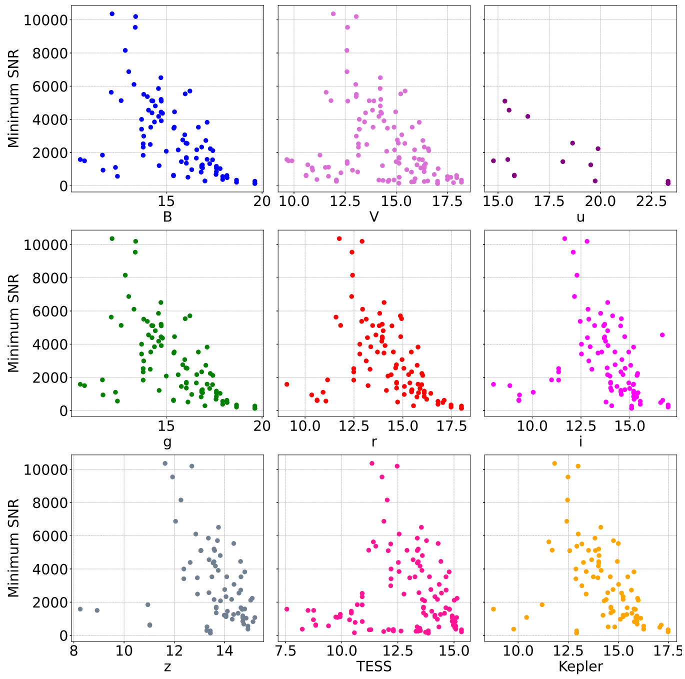

Figure 3. Minimum photometric SNR required for planetary transit detection vs. apparent stellar magnitude considering CO_2-dominated atmosphere.

considering three kinds of atmospheres, H_2, N_2 and CO_2 (Herbort et al. 2022), because they represent typical atmospheres for sub-Neptunes, Earth-like planets and Venus-like planets, respectively, we found a sample of 114 rocky exoplanets that could potentially harbor liquid water on their surfaces.

3. Results

We identified that the minimum and maximum possible surface pressures tend to decrease as the equilibrium surface temperature (T_{eq}) decreases (Fig. 2). We also found that: **i.** Planets with T_{eq} between 273 and 380 K may host liquid water on the surface, regardless of atmosphere type; **ii.** For T_{eq} above 558 K, water is expected to remain in the vapor state; **iii.** For intermediate temperatures (380 K $\leq T_{eq} \leq$558 K), the phase of water depends on the atmospheric composition.

These diagnostics allow us to prioritize observational targets both for transit photometry and for future transmission spectroscopy, providing a practical connection between our theoretical estimates and observational feasibility.

4. Conclusions

We identified, as the most promising potentially habitable rocky exoplanets, those with extensive atmospheres (Fig. 1), i.e., with scale heights ranging from 150–300 km for H_2-dominated atmospheres, 10–25 km for N_2-dominated atmospheres, 8–18 km for CO_2-dominated atmospheres. To detect and characterize these atmospheres, we estimated the minimum S/N ratio from the planetary transit depth across multiple photometric bands in the optical (Fig. 3) and computed the optimal integration time as a function of the host star apparent brightness and instrumental sensitivity, as in the case of the SPARC4 multi-band camera in the 1.6m OPD/LNA telescope (Fig. 4).

This diagnostic expands the number of exoplanets considered suitable for atmospheric characterization and provides direct observational criteria for prioritizing targets in upcoming surveys, contributing to strategies for detecting atmospheres in rocky exoplanets. As future prospects, we plan to investigate other ground and space-based instruments operating in other spectral regions for both photometric transit observations and spectroscopic acquisition of atmospheric transmission spectra, including JWST/NIRSpec–NIRISS, Gemini/GMOS–GNIRS, VLT/CRIRES+ and SOAR/Goodman.

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