The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution
Proceedings IAU Symposium No. 276, 2010
A. Sozzetti, M. G. Lattanzi & A. P. Boss, eds.

doi:10.1017/S1743921311020461

Super-Earths and life - a fascinating puzzle: Example GJ 581d

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Abstract. Spurred by the recent large number of radial velocity detections and the discovery of several transiting system and among those two planets, that are consistent with rocky composition, the study of planets orbiting nearby stars has now entered an era of characterizing massive terrestrial planets (aka super-Earths). One prominent question is, if such planets could be habitats. Here we focuss on one particular planet Gl581d. For Earth-like assumptions, we investigate the minimal atmospheric conditions for Gl581d to be potentially habitable at its current position, and if habitability could be remotely detected in its spectra. The model we present here only represents one possible nature an Earth-like composition - of a planet like Gl581d in a wide parameter space. Future observations of atmospheric features of such super-Earths can be used to examine if our concept of habitability and its dependence on the carbonate-silicate cycle is correct, and also assess whether Gl581d is indeed the first detected habitable super-Earth. We will need spectroscopic measurements to probe the atmosphere of such planets to break the degeneracy of mass and radius measurements and characterize a planetary environment.

Keywords. astrobiology, stars: individual (Gl581), planetary systems, Earth, techniques: spectroscopic

1. Introduction

The recent large number of radial velocity detections of planets with minimum masses below 15 Earth masses (Mayor *et al.* 2009) and the discovery of the transiting systems CoRoT-7b (Leger *et al.* 2009) and Kepler 10b (Bourucki *et al.* 2011), that have a mean density that is consistent with rocky material, have advanced our study of potential habitats significantly. Here we pick the Gl581 system, that is a particularly striking example among these new discoveries, consisting of an M3V star orbited by a minimum of 4 planets, 3 of which are in the Earth to super-Earth range (Udry *et al.* 2007, Mayor *et al.* 2009). Two super-Earths in this system are located on either edge of the Habitable Zone (HZ). Could these objects be potential habitats? Detailed calculations (Selsis *et al.* 2007, von Bloh *et al.* 2007) show that the inner super-Earth, Gl581c, is too close to its star to maintain water on its surface, if no specific extreme cloud coverage can be invoked. It would thus loose all its water to space, leaving the planet hot and dry. Gl581d, on the other hand, with an updated orbital period of 66.8 days (Mayor *et al.* 2009) was placed within the Habitable Zone of the system with a semi-major axis of 0.22 AU. Its high eccentricity of 0.38 ± 0.09 brings it even closer to its host star and increases the mean flux received by the planet (Williams & Pollard 2002, Spiegel *et al.* 2009, Dressing *et al.* 2010): the mean flux at Gl581d is equivalent to that for a circular orbit around Gl581 with $a = 0.20$AU. Even so this planet lies within the HZ of its parent star, the specific atmospheric composition needed to maintain liquid water on its surface are not analog to current Earth because of its location on the outer edge of the HZ. The goals of our paper are to explore the atmospheric conditions under which this planet may be habitable (see also Wordsworth *et al.* 2010, von Paris *et al.* 2010, von Bloh *et al.* 2007, Selsis *et al.* 2007) and the remote detectability of such spectral features and biosignatures (see e.g. Kaltenegger *et al.* 2010a, DesMarais *et al.* 2002). For spectroscopic features that could be remotely detected for this planet in transmission and emergent spectra, see also (Kaltenegger *et al.* 2011).

Low mass Main Sequence M dwarfs are the most abundant stars in the galaxy, and representi about 75% of the stellar population. Using this argument, many planets like Gl581d are likely to be found in the near future. Such planets also provid excellent targets for future space missions as shown in this paper, due to their lower contrast ratio to their host star (Scalo *et al.* 2007, Tarter *et al.* 2007, Kaltenegger & Traub 2009, Kaltenegger *et al.* 2010b). This decreased contrast ration should allow us to search for signposts of biological activity in such planetary atmospheres.

2. The star Gl581

Gl581 is an M3 dwarf at a distance of 6.3 pc from the Sun. From the V -band bolometric correction (Delfosse *et al.* 1998), on can infer a bolometric luminosity L_{Star}= 0.013 L_{Sun} ((Bonfils *et al.* 2005b) and a mass $M_{Star} = 0.31\ M_{Sun}$. We adopt these values unchanged. For this mass, the solar-metallicity evolutionary tracks (Baraffe *et al.* 1998; specifically, the tracks denoted BCAH98 models.) imply a radius $R_{Star} = 0.30 \pm 0.01\ R_{Sun}$ for ages ranging all the way from 150 Myr to 10 Gyr. Similarly, assuming a reasonable age of 5 Gyr suggested by its kinematic properties, intermediate between young disk and old disk, i.e., between 3 and 10 Gyr (Delfosse *et al.* 1998), the radius predicted by these tracks is 0.30 R_{Sun} (consistent with the 0.29 R_{Sun} cited by Bonfils *et al.* 2005b) and recent measurements by van Braun *et al.* (in press). Combined with the empirical luminosity, the latter radius yields an effective temperature T_{eff} = 3561K; we thus adopt the rounded-off value T_{eff} = 3600K. The magnitude of the stellar chromospheric UV radiation incident on the planet is also very important for calculating the planetary atmospheric properties (Segura *et al.* 2005). With very scant UV observations available for the vast majority of M dwarfs, chromospheric and coronal Hα and X-ray emission have usually been used as proxies for the expected UV emission from these stars. Walkowicz *et al.* (2008) have shown that some M dwarfs with very low Hα and X-ray emission may still have non-negligible near-UV emission, so the use of the former two as a proxy for the latter may not always be accurate. There is very likely no such thing as an M dwarf with no chromosphere, however, with absolutely no indication of activity in Hα or X-rays in Gl581, our conservative approach is to assume a negligible UV as well, instead of speculating. Future direct observations of UV are required to settle the issue.

3. Atmosphere Model Description

In this article we use the term Super-Earths for planets that differ from giant planets (Jupiter- and Neptune-like ones) in that they have a surface: a solid-to-gas or liquid-to-gas phase transition at their upper boundary similar to Earth (see also Valencia *et al.* 2007a, Sasselov et. al. 2008, Sotin *et al.* 2007, Zahnle *et al.* 2007). That surface separates a vast interior reservoir (e.g., Earth's mantle) from an atmosphere with insignificant mass compared to that of the planet. Like on Earth, the atmosphere is fed from the interior reservoir, and its chemical balance is achieved via interactions with the interior (outgassing and burial) and with the parent star (photochemistry and loss to space). These interactions are usually described in terms of geochemical cycles; e.g. on Earth the carbonate-silicate cycle maintains a temperate environment through a feedback cycle of outgassing, rain-out and burial of CO_2.

For Gl581d we adopt a mass and radius of 7 M_{Star} and 1.69 R_{Star} respectively and scale the surface gravity according to the increase in mass and radius (see Valencia *et al.* 2007, Seager *et al.* 2007, Sotin *et al.* 2007). Assuming outgassing and loss rates similar to Earth's, the increase in gravity should proportionally increase the surface pressure. We thus initially set the surface pressure to 2.45 bar in our models, and investigate a range of CO_2 levels (implying e.g. an active carbonate-silicate cycle and resulting CO_2 buildup to stable condition between outgassing and rainout) to explore habitable conditions on the outer edge of the HZ. In our calculations presented in this paper, we concentrate on the case of efficient heat transfer, following recent studies demonstrating that heat transfer should not be limited on a planet with a high density atmosphere even in a synchronous rotation (see Joshi *et al.* 2003; Edson *et al.* 2011. Wordsworth *et al.* 2011, Heng *et al.* 2011). We model atmospheric composition from high oxygen and low CO_2 content to high CO_2 and low oxygen content. These two atmospheric compositions should roughly bracket conditions due to an active carbonate-silicate cycle on a rocky planet in the outer part of the HZ.

To model the atmospheric composition, temperature and spectral features (see Kaltenegger *et al.* 2010 for details on the models), we use Exo-P, a coupled one-dimensional code developed for rocky exoplanets based on the 1D climate (Kasting *et al.* 1984a, 1984b, Haqq-Misra *et al.* 2008), 1D photochemistry (Kasting & Ackerman 1986, Pavlov *et al.* 2000, Kharecha *et al.* 2005, Segura *et al.* 2007) and radiative transfer model based on SAO98 (Traub & Stier 1978, Kaltenegger & Traub 2009) to self consistently calculate the atmosphere and hypothetical spectra of Gl581d, assuming a rocky Earth-analog composition. These codes have been used to calculate HZs around different types of host stars (Kasting *et al.* 1993) as well as model spectra for Earth-analogs around different host stars (Segura *et al.* 2003, 2005, 2007; Kaltenegger & Traub 2009, Kaltenegger & Sasselov 2010) and throughout geological evolution of Earth (Kaltenegger *et al.* 2007).

Atmosphere simulations. In our models we focus on two scenarios for rocky super-Earth atmospheres, $[ModelsA]$ assume a nominal surface pressure of 2.45bar consistent with the increased gravity while $[ModelsB]$ are set to a surface pressure that allows for habitable conditions in our models. $[ModelA1]$ assumes present Earth-like atmospheric composition with 0.21 O_2 and 335 ppmv or 1PAL of CO_2 (PAL = Present Atmospheric Level)).We then increase the amount of CO_2 from 1 PAL $[A1]$ to a mixing ratio of 0.9 $[A2]$ to explore if the surface temperature of the planet would rise above freezing without a surface pressure increase.

Models B explore the minimum amount of CO_2 needed to maintain an average surface temperature above freezing on the planet's surface in an atmosphere with a 0.9 CO_2 mixing ratio with either abiotic $[B1]$ or two different biotic levels of oxygen $[B2andB3]$ (see also Kaltenegger *et al.* 2011).

4. Results

Model Atmospheres. For models A, where the total surface pressure of the planet is scaled to 2.45 bar, we examine two cases within this scenario: the first is an Earth-analog oxygen-rich model $[modelA1]$, which has biotically produced O_2 with a terrestrial mixing ratio of 0.21 and a CO_2 mixing ratio equal to 1 PAL. We assume a CH_4 ougassing of 4.13 x 10^9 molecules s^{-1} cm^{-2}, that scaled to Gl581d surface is 4.93 x 10^9 g yr^{-1}. (Fig. 1)

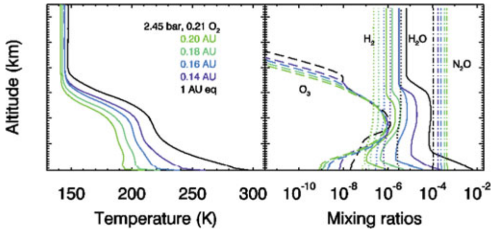

Figure 1. Fig.1: (left) Temperature profile (right) chemical composition for an Earth-like atm. composition for Gl581d-like vs. distance to its host star

shows the atmospheric temperature and mixing ratio profiles as a function of distance from the star for 1 PAL.

Next, we raise the atmospheric CO_2 level in our models to explore what level is actually required in the planet to maintain its mean surface temperature above freezing, and thus provide a habitable environment at its orbit. This in turn sets the surface pressure on the planet. Fig. 3 shows that even a 90% CO_2 (and low, abiotic oxygen) planetary atmosphere yields a temperature of only 237 K well below freezing at Gl581d's 0.2AU nominal orbital radius, if the total surface pressure remains fixed at 2.45 bar (model A2). Increasing the surface pressure to 7.6 bar while maintaining this high level of CO_2 (model B1) increases the surface temperature to an above-freezing value of 275 K (Fig. 2), implying potential habitable conditions. Such a level of atmospheric pressure increase due to CO_2 is reasonable with even a moderate carbonate-silicate cycle or increased outgassing of CO_2.

Note that methane production in these models is kept to abiotic levels, which results in CH_4 concentrations of 1.21 x$10^{-4}$and 1.13x10^{-4} in models $[A2]$ and $[B1]$ respectively. While increasing methane levels can also amplify the greenhouse effect on a planet, we concentrate here on CO_2 levels supplied by the carbonate-silicate cycle to define the outer edge of the HZ, which encapsulates our assumption that it is the carbonate-silicate cycle that regulates habitability.

We use model $[B1]$ as a representative atmosphere for minimal conditions for potential habitability on Gl581d. Having found $[modelB1]$ to yield habitable conditions, we now explore how much biotic oxygen such an atmosphere can support. We examine two such models, both for a 7.6 bar atmosphere: $[modelB2]$, with an O_2 mixing ratio of 10-3 and 90% CO_2; and $[kmodelB3]$, with an O_2 mixing ratio of 10-2 and 90% CO_2. We adopt model $[B2]$ (7.6 bar atmospheric pressure, 90% CO_2 and $10^{-3}O_2$), which provides above-freezing surface conditions for a minimum atmospheric pressure and CO_2 mixing ratio, as our habitable biotic scenario for Gl581d to assess remotely detectable spectral features.

Detectable Spectral Features. In this section we focus on the detectable atmospheric spectral features of a potentially habitable Gl581d. Spectra of terrestrial exoplanets could be obtained in the near future with the same techniques that have successfully provided spectra of Earth (see e.g. Christensen *et al.* 1997, Irioni 2002, Paille *et al.* 2009, Kaltenegger & Traub 2009, Cowan *et al.* 2010) and extrasolar giant planets (EGP) (see e.g. Grillmair *et al.* 2008, Swain *et al.* 2008). The emergent spectra of rocky planets in the HZ are dominated by reflected starlight in the visible to near-IR and thermal emission from the planet in the mid-infrared, while transmission spectra result from starlight that is filtered through the planet's atmosphere. Such spectroscopy provides molecular band strengths of multiple transitions (in absorption or emission) of a few abundant molecules in the planetary atmosphere. We generate synthetic spectra of Gl581d from 0.4 μm to 40μm to explore which indicators of biological activities in the planet's atmosphere may

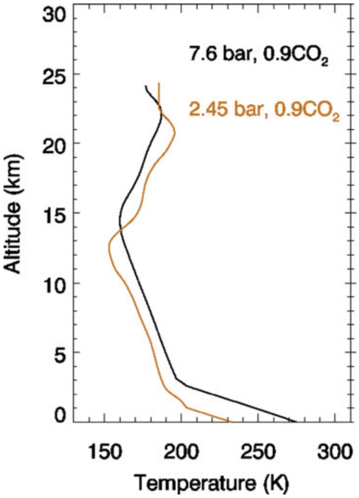

Figure 2. Fig.2: Temperature for a 2.45bar (A2) vs. a 7.6bar(B1) abiotic high CO_2 atmosphere

be observed by future ground- and space-based telescopes such as the Extremely Large Telescope (E-ELT) and the James Webb Space Telescope (JWST).

We use as our template the atmospheric $[model B2]$ (7.6 bar atmosphere, with 90% CO_2 and biotic O_2 with a mixing ratio of 10-3), which is habitable both in the absence of tidal-locking as well as under conditions of relatively efficient heat-transfer in the presence of tidal-locking (see Kaltenegger *et al.* 2011). For simplicity, we restrict ourselves here to spectral features arising from this model in the absence of tidal-locking. The planet is unlikely to be synchronous rotating (see e.g. Leconte *et al.* 2010), or even if it were, the heat transfer should be efficient, given that at least 77% of its surface is likely directly illuminated (see discussion in Selsis *et al.* 2007).

The spectral distribution of M-stars, such as Gl581, generates a different photochemistry on planets orbiting within the HZ of M stars, compared to planets within the HZ of Sun-like stars (Segura *et al.* 2005). In particular, the biogenic gases CH_4, N_2O, and CH_3Cl have substantially longer lifetimes and higher mixing ratios than on Earth, making them potentially observable by space-based telescopes. In addition, the low effective temperatures of M dwarfs yield spectra dominated by molecular absorption bands that redistribute the radiated energy in a distinctly non-black-body fashion. Both effects are crucial to determining the observable spectral features and biosignatures of habitable planets (see e.g. Kalteneger *et al.* 2010a, Kaltenegger *et al.* 2011) around these cool low-mass stars.

The observable quantity to remotely derive what atmospheric features exist in a planet's atmosphere is the contrast ratio versus wavelength, as shown in Fig. 3 for emergent model spectra (for transmission spectra of Gl 581d see Kaltenegger *et al.* 2011). The Sun emits a large fraction of its energy in the visible, a wavelength domain where the atmosphere of a habitable planet is highly reflective, because of the Rayleigh backscattering varying like λ^{-4} and because of the lack of strong H_2O absorption bands. The emission of Gl581, a star with a low effective temperature, peaks in the near-infrared where the contribution of Rayleigh scattering to the albedo becomes negligible and the strong absorption bands of H_2O, CO_2 and CH_4 cause additional absorption of stellar radiation and overall lower the planet's albedo as long as no additional reflective cloud layer forms.

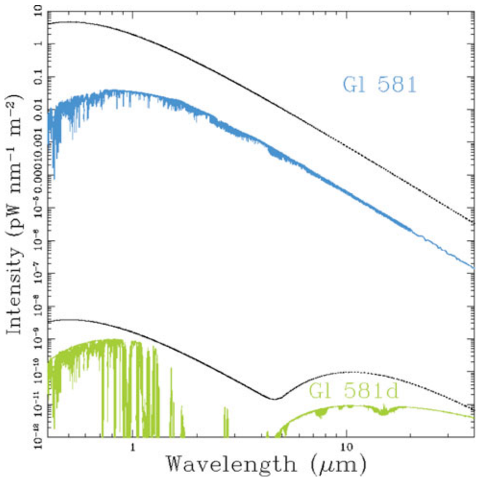

Figure 3. Fig.3: Planet-star contrast ratio for emergent sectra for a clear atmosphere (Model B2). The upper line indicates the levels of the Sun and the Earth for comparison (modified from Kaltenegger *et al.* 2011

For the emergent spectra, the larger surface area of a Super-Earth makes the direct detection and secondary-eclipse detection of its atmospheric features and biosignatures easier than for Earth size planets. Even though Gl581d orbits its host star at a distance less than 1AU, the integrated flux received on top of the planet's atmosphere is half the flux received by Earth. Since Gl581d orbits an M star, it has a lower Bond albedo and thus a smaller part of the stellar light is reflected, making Gl581d appear dimmer in reflected light than an equivalent planet orbiting at 1AU around a sun-like star. Even though the bond albedo decreases from Earth's 0.29 to Gl581d's 0.12, the increased surface area increases the overall reflected flux of the planet by about 15% over Earth's reflected Sunlight (see (Fig. 3). In the MIR the flux increases proportional to the surface area of the planet if the effective temperature is equal. In our model the decrease in effective temperature for Gl581d due to the high CO_2 concentration, reduces its flux in the MIR compared to the Earth significantly.

5. Discussion

One prominent question about planets with masses below 15 Earth masses are, if such planets could be potentially be habitats. Many question regarding this are still open, like if such planets would maintain tectonics in their interior and magnetospheres that can shelter their primary atmosphere. Note that the model we present here only represents one possible nature of a planet like Gl581d in a wide parameter space that includes Mini-Neptunes.

In addition composition of the planet will influence the atmosphere substantially, e.g. the abundance of oxygen found in the abiotic case strongly depends on the oxydation state of the superficial layers and possible oceans of the planet. If e.g. the surface of the planet were highly oxidized, a higher buildup of oxygen would be expected for the same production levels (see e.g. Zahnle *et al.* 2007, Kasting *et al.* 1984b). If e.g. a sulfur cycle were present on a planet, the outer edge of the HZ would shift outwards due to increased greenhouse effect of SO_2 in addition to CO_2 (see Kaltenegger & Sasselov 2009, Domagal-Goldman *et al.* in press,), which would reduce the amount of CO_2 needed to maintain Gl581d's surface temperature above freezing. Note that a planet found in the

HZ is not necessary habitable, since many factors may prevent surface habitability like the lack of water or ingredients necessary for the emergence of life.

This parameter space is very wide and we concentrate on Earth analog models here, to explore the case if an Earth-like planet could produce signatures of habitability that we could remotely detect.

6. Conclusions

We show that Gl581d is potentially habitable, assuming the carbonate-silicate cycle controls the atmosphere of the planet. We calculate the surface temperature and atmosphere including potential biomarkers assuming different atmospheres compositions, high oxygen atmosphere analogous to Earth's as well as high CO_2 atmospheres with and without biotic oxygen concentrations (Fig. 1 to Fig. 2). We find that a minimum CO_2 partial pressure of about 7 bar, in an atmosphere with a total surface pressure of 7.6 bar, are needed to maintain a mean surface temperature above freezing on Gl581d. The model we present here only represents one possible nature - an Earth-like composition - of a planet like Gl581d in a wide parameter space. The surface temperature of a simulated 90% CO_2 and low oxygen planetary atmospheres at 0.2 AU changes from 237 K to 278 K when increasing the surface pressure from 2.45 bar to 7.6 bar surface pressure (see Fig. 2). Such a level of atmospheric pressure increase due to CO_2 is reasonable even with a moderate carbonate-silicate cycle or increased outgassing of CO_2. Additional greenhouse gases like CH_4 and SO_2 as well as clouds assuming a net warming could decrease this amount due to their added warming effect.

Our concept of the habitable zone is based on the carbonate-silicate cycle that should increase the level of CO_2 on the outer part of the HZ. Even so the measurements are hard this concept can be probed by observing detectable atmospheric features by future ground and space- based telescopes like E-ELT and JWST on planets like Gl581d.

Observation of the emergent spectrum could also determine if Gl581d is the first habitable world we have discovered.

Acknowledgements

L.K. acknowledges support from NAI and DFG funding ENP Ka 3142/1-1.

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