

## A PALETTE OF CLIMATES FOR GLIESE 581g

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### ABSTRACT

We consider a range of possible climates for the habitable-zone planet candidate, Gliese 581g, contingent on a plausible set of hypothetical atmospheres and assuming the planet to be tide locked. The two most habitable states we find are (1) a nearly airless Super-Europa with thin ice at the substellar point and (2) an “Eyeball Earth” which is mostly frozen but supports a substantial stable pool of open water centered on the substellar point. We discuss the prospects for observational determination of what kind of climate 581g actually supports.

*Key words:* astrobiology – planetary systems – stars: individual (GJ 581 HIP 74995)

*Online-only material:* color figures

### 1. INTRODUCTION

Gliese 581g (Vogt et al. 2010) sits squarely in the habitable zone of its star based on Selsis et al. (2007), in the sense that it would support a liquid water ocean with Earth-like temperatures at its surface, given suitable composition and an atmosphere with a sufficiently strong greenhouse effect. In this Letter, we discuss a range of possible climates for Gliese 581g, based on a range of hypotheses about the composition of the planet and the kind of atmospheres most likely associated with each composition. The preliminary parameters of 581g are likely to be shared by a great number of M dwarf super-Earths awaiting discovery in the outer regions of the habitable zone. Our discussion applies to this entire class of planets.

We will assume that 581g is in a circular orbit and tide locked. Other spin states are conceivable, but will not be considered here. The incident stellar flux at orbit is taken as  $F_{\odot} = 866 \text{ W m}^{-2}$ . For size and gravity, we adopt the representative values  $1.6r_{\oplus}$  and  $16 \text{ m s}^{-2}$ . The hypothetical atmospheres will be based on a composition space of silicate, carbonate, water and  $\text{N}_2$ .  $\text{N}_2$  is a likely requirement for life as we know it, since N is an essential building block for amino acids and DNA. The  $\text{N}_2$  is idealized as being transparent to infrared. The  $\text{N}_2$  collision-induced continuum has a weak tail that extends beyond  $250 \text{ cm}^{-1}$ , and at high surface pressure this can affect thermal infrared opacity for Earth-like temperatures. Laboratory measurements in this regime are lacking, but a crude estimate based on data in Courtin (1988) suggests that the  $\text{N}_2$  greenhouse effect could become important for surface pressures exceeding 5 bar, given super-Earth surface gravity.

The weak Coriolis force on tide-locked habitable-zone planets leads to quite horizontally uniform atmospheric temperatures (Joshi et al. 1997; Merlis & Schneider 2010). This property has long been utilized in weak-temperature-gradient (WTG) idealized models of Earth’s tropics (Williams et al. 2009), and plays a central role in our discussion of 581g climates.

After a discussion of a range of possible climates that are not habitable in the traditional sense, we show a detailed simulation of a habitable state. Prospects for observational discrimination of the climate are discussed.

### 2. SURVEY OF PLANETARY COMPOSITION AND CLIMATES

#### 2.1. Airless with Rocky Surface

Gliese 581g may be a rocky body without any significant atmosphere. If 581g is tide locked in a circular orbit, the substellar point is geographically fixed and the night side never receives any radiation from the primary, unlike Mercury or the Moon.

The temperature at the substellar point is given by  $\sigma T^4 = (1 - \alpha)F_{\odot}$ , where  $\alpha$  is the Bond albedo. With  $\alpha = 0.2$  this yields  $T = 332 \text{ K}$ . The temperature decays toward the terminator. The night side is heated only by heat conducted to the surface from the interior. On Earth, this flux is about  $0.1 \text{ W m}^{-2}$ , which would maintain a temperature of 36 K; if it were a factor of 10 larger on 581g, the temperature would rise to 64 K. The night side would thus be nearly isothermal, with a temperature well under 100 K.

#### 2.2. $\text{N}_2$ Atmosphere with Dry Rocky Surface

Next suppose that the planet is cloaked in a pure  $\text{N}_2$  atmosphere. We will neglect atmospheric absorption of incoming stellar radiation. Rayleigh scattering increases the planetary albedo, though this effect is slight for the relatively long-wavelength M dwarf spectrum.

Employing the WTG approximation, we will assume the atmosphere to have a horizontally uniform temperature maintained by efficient dynamic heat transport, and let  $T_a$  be the near-surface temperature of this atmosphere. The planetary surface exchanges heat with the atmosphere only by fluxes due to boundary layer shear turbulence; dry turbulent fluxes can be approximated as being proportional to the temperature difference between the surface and the overlying air. Though the atmospheric temperature is uniform, the surface temperature varies in response to the geographical variation in stellar radiation absorbed at the surface. We will adopt a latitude coordinate  $\theta$  with  $\theta = 0$  at the terminator and  $\theta = \frac{\pi}{2}$  at the substellar point.

The surface energy balance is

$$(1 - \alpha)F_{\odot} \sin \theta = \sigma T_g(\theta)^4 + a \cdot (T_g(\theta) - T_a) \quad (1)$$

on the day side, where  $\sin \theta > 0$ ; on the night side the left-hand side is replaced by zero, and the equation yields uniform

nightside temperature. The turbulent coupling coefficient  $a$  is  $\rho_s c_p C_d U$ , where  $\rho_s$  is the surface density of the atmosphere (determined by  $T_a$  and surface pressure  $p_s$  via the ideal gas law),  $c_p$  is its specific heat,  $U$  is a typical surface wind speed and  $C_d$  is a dimensionless drag coefficient, having a typical value of 0.0015 over moderately rough surfaces (Garrett 1994). This equation determines  $T_g$  in terms of  $T_a$ . Making use of the transparency of the atmosphere, the top-of-atmosphere budget requires

$$\frac{1}{2} \int_0^{\frac{\pi}{2}} (1 - \alpha) F_{\odot} \sin \theta \cos \theta d\theta = \frac{1}{2} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sigma T_g^4 \cos \theta d\theta. \quad (2)$$

For constant  $\alpha$ , the left-hand side integrates out to  $\frac{1}{4}(1 - \alpha)F_{\odot}$ , which is the absorbed stellar radiation per surface area of the planet. Equations (1) and (2) form a closed system determining the constant  $T_a$ , which can be solved by a Newton iteration. We will call this the WTG Energy Balance Model (EBM).

In the limit of low  $p_s$ ,  $a$  is vanishingly small and the solution reduces to the airless case treated previously. For very high  $p_s$ , Equation (1) forces the surface temperature to be uniform, leading to the familiar result  $\sigma T_g^4 = \frac{1}{4}(1 - \alpha)F_{\odot}$ . For 581g with an assumed  $\alpha = .2$ , we obtain  $T_g = T_a = 235$  K. With  $U = 5$  m s<sup>-1</sup>, which is typical of Earth's surface winds and somewhat below the typical winds in Joshi et al. (1997), the substellar point temperature, nightside temperature, and surface atmospheric temperature are 316 K, 173 K, 217 K for  $p_s = 10^4$  Pa; 269 K, 221 K, 233 K for  $p_s = 10^5$  Pa; and 240 K, 233 K, 235 K for  $p_s = 10^6$  Pa. Thus, as little as 1 bar of N<sub>2</sub> is enough to substantially reduce the dayside/nightside temperature contrast. Stronger surface winds would keep the temperature uniform at lower pressure. Weaker winds allow a stronger temperature gradient. For example, with  $U = 1$  m s<sup>-1</sup> the temperatures are 307 K, 191 K, 224 K for 1 bar surface pressure.

### 2.3. Super-Europa: a Pure Iceball with N<sub>2</sub> Background Atmosphere

Suppose that 581g is a pure water world whose composition is dominated by H<sub>2</sub>O; it may have a rocky core, but we will assume in this case that the core does not participate in the determination of atmospheric composition. We will also allow for N<sub>2</sub> in the atmosphere. The atmosphere will be a mix of N<sub>2</sub> and water vapor, the latter in equilibrium with the planet's water reservoir as determined by the Clausius–Clapeyron relation. Water vapor provides the only greenhouse effect. The ocean surface may freeze, leading to a partial or total cover of high-albedo crust.

Is the water vapor greenhouse alone sufficient to keep this planet from freezing over? Let us consider this first in the limit where the N<sub>2</sub> surface pressure is high enough to keep the surface nearly isothermal, so that the problem can be addressed with a one-dimensional radiative–convective model (implemented using the NCAR CCM radiation model (Kiehl & Briegleb 1992) with hard convective adjustment to the moist adiabat). Water vapor is fixed at saturation in the troposphere and assumed well mixed horizontally. Carrying out this calculation, we find that the absorbed stellar radiation per unit surface area needed to maintain surface temperatures at 273 K is 267 W m<sup>-2</sup> for a surface pressure of 10<sup>5</sup> Pa. Even with a planetary albedo of 0.1, 581g would absorb only 195 W m<sup>-2</sup>, averaged over the surface. Thus, if the atmosphere is thick enough to equalize surface temperature, a water world would freeze over.

If the atmosphere is thick enough to maintain horizontally isothermal conditions, the surface temperature of the frozen state

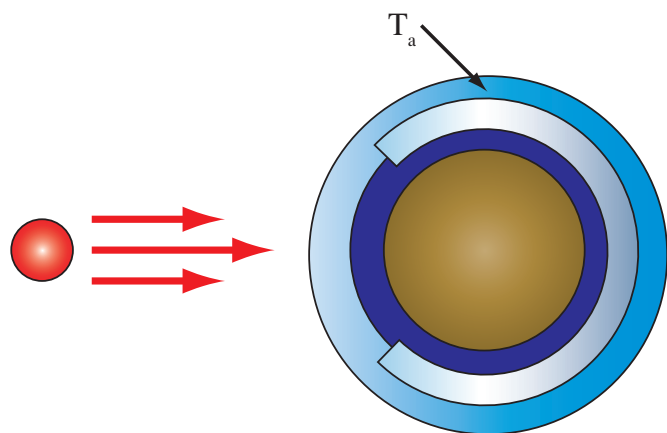
drops to 192 K for a planetary albedo of 0.65, corresponding to frozen conditions. However, if the atmosphere is so thin that the substellar point does not lose heat through dynamical heat transport, the substellar point temperature at this albedo becomes 270 K, and a slight reduction in albedo from dust or other contaminants might even be able to cause melting. Even if the ice crust fails to melt through, surface temperatures approaching freezing lead to very thin ice, supposing a sufficient supply of heat flux from the interior of the planet (Warren et al. 2002; Pollard & Kasting 2005). This should be considered a habitable state, insofar as similar solutions have been proposed for the survival of eukaryotic life during a Snowball event on Earth. However, it does not take much atmosphere to eliminate the thin-ice solution. Using the WTG EBM with high albedo, a 10<sup>4</sup> Pa N<sub>2</sub> atmosphere brings the substellar point surface temperature down to 247 K, and a 10<sup>5</sup> Pa atmosphere brings it down to 206 K.

### 2.4. Dry Rocky World with Massive CO<sub>2</sub> Atmosphere

The stellar flux received by 581g is well below the threshold (Selsis et al. 2007) needed to sustain a true runaway greenhouse, but one should entertain the possibility that it formed initially with little water but a high inventory of CO<sub>2</sub> (or carbonates which can lead to outgassing from the interior).

If a planet absorbs too little stellar radiation, CO<sub>2</sub> eventually condenses at the surface rather than accumulating indefinitely in the atmosphere. Early Mars is on the boundary of this regime, as is 581d (Wordsworth et al. 2010). It has been argued that this criterion likely determines the outer edge of the habitable zone, and it has been shown that the threshold-absorbed stellar radiation can be derived from a generalization of the familiar water vapor runaway greenhouse criterion to CO<sub>2</sub> (Pierrehumbert 2009). For a super-Earth, the threshold-absorbed radiation (per unit surface area) is about 80 W m<sup>-2</sup>. For albedos typical of a rocky surface, 581g exceeds this threshold by a wide margin, so CO<sub>2</sub> would accumulate indefinitely in the atmosphere, if not checked by silicate weathering.

For a dense atmosphere the surface temperature should be uniform, as on Venus, and so estimates based on radiative–convective modeling suffice. For this case, we employ the simplified real-gas exponential sums radiation code used in Pierrehumbert (2009) and described fully in Pierrehumbert (2010). For a planetary albedo of 0.2, a pure CO<sub>2</sub> atmosphere with 20 × 10<sup>5</sup> Pa surface pressure yields a 440 K surface temperature rising to 623 K at 100 × 10<sup>5</sup> Pa, comparable to the surface pressure of Venus. With the assumed albedo, 581g would actually absorb somewhat more stellar radiation than Venus, with its reflective clouds, absorbs, so it is no surprise that 581g could support Venus-like temperatures given sufficient CO<sub>2</sub>. This calculation overestimates the temperature, however, since Rayleigh scattering would increase the albedo. A more consequential issue regarding albedo is the possibility that trace amounts of water vapor and SO<sub>2</sub> on 581g could lead to the formation of highly reflective Venus-like sulfuric acid clouds. On Venus, these clouds are even more reflective than surface ice, and with an albedo of 0.75, 581g would only absorb 56 W m<sup>-2</sup> averaged over the surface. This would put it in the regime where CO<sub>2</sub> condenses at the surface rather than accumulating in the atmosphere, and likely alter the cloud-forming processes. Determining the consistent equilibrium climate states of such a system is a challenging problem, left for future work.



**Figure 1.** Sketch of the Eyeball Earth state, with open water under the substellar point and the rest of the planet frozen over.

(A color version of this figure is available in the online journal.)

### 2.5. Hot Water/ $\text{CO}_2$ World

From the standpoint of planetary formation, a more plausible variation on the hot-climate theme is a planet with a water ocean and large  $\text{CO}_2$  inventory, in which the silicate weathering which normally limits  $\text{CO}_2$  is somehow inhibited, allowing  $\text{CO}_2$  to build up to very high values. The end state of this process cannot be a true runaway greenhouse for the orbit of 581g, but instead would consist of a hot ocean and an atmosphere containing large amounts of both  $\text{CO}_2$  and water vapor. For any given  $\text{CO}_2$  surface pressure, the climate would be hotter than the values given in the preceding case, by virtue of water vapor feedback.

We will not pursue this case here, but several interesting questions can be posed. How much water vapor would such an atmosphere contain, and what would be the vertical structure of water vapor and temperature? Could such a state lose water through photolysis and hydrogen escape as in the wet runaway proposed for Venus (Kasting 1988)? What is the lifetime of the hot ocean state, and how much  $\text{O}_2$  and  $\text{O}_3$  would be present in such an atmosphere?

### 2.6. A Habitable Eyeball Earth

The most Earth-like hypothetical state for 581g consists of silicate-rich world endowed with both  $\text{H}_2\text{O}$  and  $\text{CO}_2$  as volatiles, with the concentration of the latter controlled by a silicate/carbonate weathering cycle similar to that discussed in Berner (2004). The essence of this state is most easily introduced for an ocean world with little continental area. The situation, depicted in Figure 1, is similar to the WTG energy balance states, with temperature declining monotonically from the substellar point. The novelty is that if one places open water near the substellar point, the low albedo may lead to high enough temperatures to keep the pool open; as one approaches the terminator, temperature eventually drops below freezing, allowing ice to form and increasing the albedo. The ice margin is determined by the requirement that, including effects of the ice/water transition on albedo, the temperature at the ice margin be equal to the freezing point of the ocean. The central question to be answered in modeling this state is: what is the size of the open-water pool as function of the  $\text{CO}_2$  concentration? Can open water be maintained with amounts of  $\text{CO}_2$  that could plausibly be maintained in the atmosphere?

A problem with the Eyeball state is that the completely frozen state is generally available as an alternate stable solution, since the high albedo at the substellar point easily keeps the surface temperature below freezing there. If the planet ever were to fall into this Snowball state, it could be impossible to get out; it is hard enough to get out of a Snowball on Earth (Abbot & Pierrehumbert 2010), and with the lower incident radiation on 581g it would be far harder. Among other things, a frozen state with an albedo of 65% would absorb only  $76 \text{ W m}^{-2}$  averaged over the surface, which puts it in a similar radiative regime to 581d, which is just at the boundary where  $\text{CO}_2$  condenses out into a surface reservoir instead of accumulating in the atmosphere (Pierrehumbert 2009; Wordsworth et al. 2010).

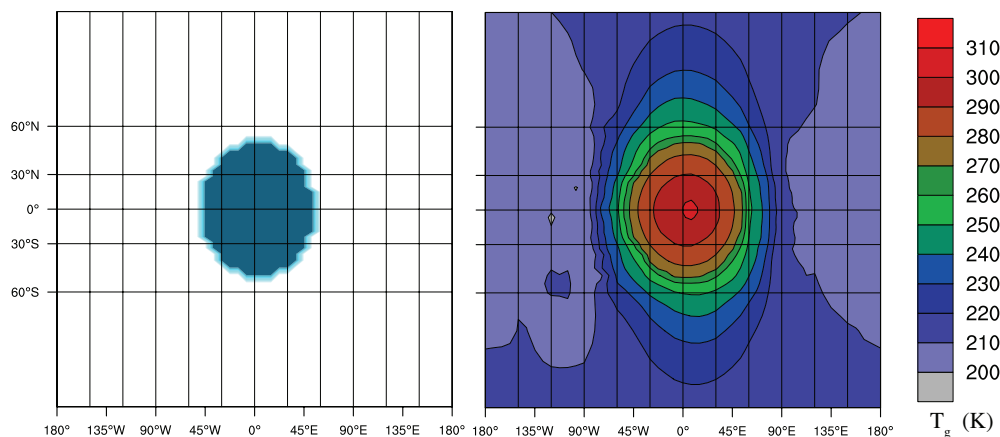
Spiegel et al. (2009) used a diffusive energy balance model to consider the occurrence of open water on planets with a variety of orbital characteristics. The climate of Eyeball Earth can be studied using a straightforward extension of the yet simpler WTG energy balance model incorporating ice-albedo feedback and the atmospheric greenhouse effect, but instead, we leap directly to a general circulation model (GCM) simulation which includes full representations of atmospheric dynamics, the hydrological cycle (including determination of atmospheric humidity), radiative processes, and cloud formation.

## 3. SIMULATIONS OF EYEBALL EARTH

The simulations were carried out using the FOAM general circulation model, which has been extensively used for studies of Snowball Earth and other deep-time paleoclimate problems (Pierrehumbert 2004, 2005; Abbot & Pierrehumbert 2010). The model was run coupled to a mixed layer water ocean with no horizontal oceanic heat transport, though given the steady insolation the thermal inertia of the ocean (and hence the mixed layer depth) is of little importance. The ocean surface can freeze and form sea ice, which is treated by a thermodynamic sea ice model incorporating the effects of snow cover. In the simulations reported here, we assumed a water world without continents, since this case adequately demonstrates the existence of stable states with open water. Basic planetary characteristics are as stated in the Introduction. The incoming stellar radiation was assumed to have a blackbody distribution with temperature 3500 K. The model was initiated with open-ocean conditions and run until the ice margin reached equilibrium.

Figure 2 shows the ice margin and surface temperature for a simulation with a surface pressure of  $10^5 \text{ Pa}$  and  $\text{CO}_2$  concentration of 20%. Under these conditions, the open-water pool has a width of  $90^\circ$  in latitude and longitude, with a maximum temperature of 310 K at the substellar point. The nightside surface temperature is nearly uniform, at approximately 210 K. On a Mercator projection the pool looks small, but its area for a super-Earth is half the area of Earth's oceans. With higher  $\text{CO}_2$  or greater total surface pressure, the greenhouse effect is stronger and the pool would get larger.

This simulation confirms the utility of WTG theory in thinking about such climates. The mid-tropospheric temperature (not shown) varies between 248 K and 258 K over most of the planet, with the exception of a pair of small high-latitude vortices where the temperature drops to 236 K. As in the simulations of Joshi et al. (1997), the circulation consists of inflow into the subsolar point at low levels, outflow at high levels, and subsidence on the night side. The divergent circulation is superposed with a super-rotating jet which is weaker in our simulation than in Joshi et al. (1997).



**Figure 2.** GCM simulations of 581g Eyeball state, with an atmosphere containing 20% CO<sub>2</sub> mixed with N<sub>2</sub> and 10<sup>5</sup> Pa net surface pressure. Left panel: open water (blue) and ice (white). Right panel: surface temperature. Results are presented on a latitude–longitude grid with the equator in the plane of the orbit and the prime meridian at the substellar point.

(A color version of this figure is available in the online journal.)

Given composition and tectonics that support CO<sub>2</sub> outgassing, CO<sub>2</sub> will build up until silicate weathering balances the outgassing rate. Continental weathering requires liquid water raining down on silicate rock, and therefore tends to stabilize CO<sub>2</sub> at above-freezing conditions (Berner 2004). However, Le Hir et al. (2008) have shown that sea-floor weathering, which does not require above-freezing surface conditions, could limit CO<sub>2</sub> to a value that is uncomfortably near to 20%. Sea-floor weathering is poorly understood, and thus emerges as a key habitability issue that needs to be resolved for the climate of extrasolar water worlds in an orbit like 581g.

Introduction of continents away from the substellar point would not be any threat to habitability, and if they remain snow free could even heat up and provide open-water coastal habitat. A large continent at the substellar point would be more problematic, since it would occupy the prime location for forming open water and (depending on size) might not heat up enough to maintain a strip of coastal open water. Moreover, such a continent receives a great deal of hot precipitation if adjacent to open water, and thus may enhance silicate weathering so much that CO<sub>2</sub> was drawn down sufficiently to lock the planet into a Snowball state, much as has been proposed for Snowball initiation on Earth.

#### 4. DETECTION AND DISCRIMINATION OF CLIMATE STATES

The easiest state to detect is the airless rocky case. In superior conjunction, the thermal infrared ( $>5 \mu\text{m}$ ) flux from the hot day side is  $3.4 \times 10^{-19} \text{ W m}^{-2}$  measured at Earth, while at inferior conjunction the cold night side radiates essentially nothing. The resulting thermal infrared phase curve fluctuations are 1.7 parts per million of the thermal infrared output of the primary. At longer wavelengths, on the Jeans tail of the planetary emission, the ratio approaches a part per thousand. Finding that 581g is airless would be a disappointment, but ruling out this state would be the first step on the way to verifying that the planet has an atmosphere.

The Super-Europa state would have a similar thermal infrared variation to the airless case, but its amplitude would be much smaller owing to the colder substellar point. Detection of a high visible albedo through visible band photometry would provide a key clue to this state, though high albedo in itself could also

indicate a hot, dry Venus-like state with reflective sulfuric acid clouds. With or without clouds, the hot states with very high CO<sub>2</sub> are problematic for infrared photometry as the emission all comes from the upper atmosphere and provides no information about the surface.

Detection of an Eyeball state would proceed through broadband visible photometry, detecting the albedo reduction as the open-water patch comes into view, and infrared photometry with coarse spectral resolution to detect the contrast between thermal emission from the warm water versus cold night side. Some spectral resolution is needed because the thermal emission in a broad region around the  $15 \mu\text{m}$  CO<sub>2</sub> absorption band comes from the relatively warm atmosphere, and so the dayside/nightside thermal emission contrast is strongest on the long-wave and short-wave side of this feature. The CO<sub>2</sub> absorption band is spectrally compact for surface partial pressures of  $2 \times 10^4$  Pa or lower, as in our simulation, but when pressure approaches several times this level, the window closes and detection of surface variations becomes impossible. For moderate CO<sub>2</sub> concentrations, water vapor interferes with detection of surface emissions from the warm water pool at wavelengths above  $17 \mu\text{m}$ , because our simulation predicts a quite moist atmosphere there. Examination of the cloud albedo fields from the simulation indicates that clouds do not significantly interfere with the visible photometry signature.

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