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SIMULATIONS OF INFRARED VERY LONG BASELINE INTERFEROMETRY OF THE EXOPLANETS GLIESE 581C AND GLIESE 581D

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ABSTRACT

There are several potential advantages to the use of interferometry for direct detection of extrasolar planetary emission. Destructive interference can be used to strongly suppress emission from the much brighter primary star. High angular resolution, which can be significantly better that the diffraction limit of the individual telescopes, will help to separate the emission from an extrasolar planet and its primary star as well as from sources of background emission. This paper presents research and calculations pertaining to the development of a preliminary model of an interferometer designed to detect mid-IR emissions from Gl 581c and GL 581d (Bloh et al. 2007). The instrument model is used to analyze emissions from Gl 581d based on a simple model atmosphere and radiative transfer calculation. The atmosphere is assumed to be a pure CO_2 blackbody with a single temperature, the effective temperature, and the surface a blackbody 100 K warmer. The surface is broken up into 32 subsections of equal latitude and longitude intervals and a disk averaged spectrum is calculated.

Subject headings: solar system: general — stars: individual (GL 581) — techniques: interferometric

1. INTRODUCTION

Following the discovery of the first extrasolar planet over a decade ago, the detection and characterization of extrasolar planets has proceeded at a rapid pace. Over 270 extrasolar planets have been detected with at least 25 stars hosting multiple planets. Most extrasolar planets have been detected using indirect ground-based techniques: radial velocimetry, planetary transits, or gravitational lensing, with velocimetry providing by far the largest number of detections. Velocimetry and transit observations are biased toward finding large, Jovian-mass, planets orbiting relatively close to their primary star. Velocimeteric sensitivity has been steadily improving to the point where it is now capable of detecting Earth-mass planets around M dwarf stars. Recently, two Earth-mass planets, GL 581c and GL 581d, were discovered orbiting close to the nearby M dwarf star Gl 581; both planets may orbit within, or near the star's habitable zone (Bloh et al. 2007). Direct detection of planetary emissions to search for possible atmosphere is not possible with current technology.

Nulling interferometry may be capable of achieving the high dynamic range and angular resolution required for direct detection of extra-solar planets (Angel and Woolf, 1997). Atmospheric distortion, however, limits the performance of ground-based interferometry and the necessary dynamic range may not be achievable. Two large space-based observatories, the Terrestrial Planet Finder (TPF) (Beichman, 1999) and Darwin (Fridlund, 2000), slated for launch as early as 2015, are developing multi satellite mid-infrared nulling interferometry systems designed to study extra-solar planets. With either of these observatories spectra of extrasolar planets should be possible and will dramatically increase our knowledge of extrasolar planets.

Very Long Baseline Interferometry (VLBI) relies on recording the amplitude and phase of radiation from an astronomical source at widely separated telescopes and then correlating the data later in a computer. It is not currently possible to measure amplitude and phase at optical wavelengths but it is possible at mid-infrared wavelengths, and this is where the contrast between extrasolar planets and their primary star is most favorable. Current timing accuracy using atomic clocks should be able to provide mid-IR phase measurements with a precision of about $\lambda/100$. In this paper we begin a study of the use of VLBI to observe mid-IR spectra of the extrasolar planets Gl 581c and Gl 581d. First, a simple model of the planetary system is developed to compute the disk-averaged spectra of the planets, including reflected starlight and thermal emission. Then a model of the nulling interferometer is developed, using Fourier optics, and tests are begun without the inclusion of any noise sources to verify the performance of the model.

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2. PLANETARY SYSTEM CHARACTERISTICS

The central star, Gliese 581, has spectral class M3, a luminosity of $L = 0.013 \pm 0.002 L_{\odot}$, an effective temperature of T_e = 3480 K, and an age of about 2 Gyr (Bean et al. 2006). It has been found to have a sub-solar metallicity measured at $[Fe/H]$ = –0.25 (Bonfils et al. 2005) and $[Fe/H]$ = –0.33 (Bean et al. 2006). In addition to the Earth-like planets Gl 581c and Gl 581d, the system also host a Neptune-mass planet, Gl 581b. Theoretical models studying planetary formation show that systems such as this, where the primary star is of low-mass and low metallicity, provides an adverse environment for the formation of giant planets. However, this environment places no restriction on the formation of low-mass planets, as is verified by their presence in this system (Bean et al. 2006).

TABLE 1
ORBITAL PARAMETERS

Name	Discovery Date	Mass ($M_\oplus$)	Semi-Major Axis (AU)	Orbital Period (Days)	Eccentricity
Gl 581c[a]	2007	5.03	0.073	12.932±0.007	0.16±0.07
Gl 581d[a]	2007	7.7	0.25	86.3±0.7	0.2±0.1

[a]Bloh et al. 2007; Udry et al. 2007

TABLE 2
PLANETARY PARAMETERS

Name	$T_{eq}(K)$[a]	Radius ($R_\oplus$)	Tidally Locked	V (mag)	Contrast (v)	N (mag)	Contrast (N)	Elongation (mas)
Gl 581c	327	1.53	Likely	25.7	3.8×10^{-7}	15.0	1.3×10^{-4}	12
Gl 581d	177	1.71	Likely	28.1	4.0×10^{-8}	17.0	2.6×10^{-5}	40

[a]Equilibrium temperature does not account for atmospheric warming effect

2.1. *Orbital Parameters*

Both Gl 581c and Gl 581d are similar to Earth in size and overall characteristics. They are somewhat larger than Earth, with masses of 5.03 $M_\oplus$ for Gl 581c and 7.7 $M_\oplus$ for Gl 581d. They orbit close to their parent star, with semi-major axes of 0.073 AU for Gl 581c and 0.25 for Gl 581d AU, both smaller than that of Mercury. Table 1 offers a general overview of the orbital characteristics of the two planets (Udry et al. 2007).

2.2. *Planetary Parameters*

A stellar habitable zone (HZ) is the region around a star wherein the physical conditions of a planet, especially its surface temperature and atmospheric pressure, would allow the presence of liquid water on a planet's surface. The equilibrium temperature of a planet describes an energy balance between incident stellar radiation and emitted planetary radiation and is given by:

$$T_{eq} = [F_p(1-A_b)/4\epsilon\sigma]^{1/4} \quad (1)$$

where the incident stellar flux (F_p) depends on the star's luminosity and the planet's distance, the Bond albedo (A_b) gives the amount of starlight reflected, and the amount of thermal radiation emitted depends on the planet's emissivity (ϵ). Planetary emissivity is assumed to be $\epsilon = 0.9$. The Bond albedo however depends strongly on a planet's atmospheric properties, particularly the total pressure. We used an Earth-like value of $A_b = 0.3$ for the calculations given in Table 2.

With an atmosphere present, a planet's surface temperature can be anywhere from 10s to 100s of degrees higher than T_{eq} due to greenhouse warming. A star's luminosity and its age play important roles in determining the atmospheric pressure of its planets, and in turn, its habitable zone.

Tidal locking must also be taken into account. Peale states that the tidal locking radius r_T can be estimated (given a circular orbit) from

$$r_T = 0.027(P_0 t/Q)^{1/6} M_\star^{1/3} \quad (2)$$

where P_0 is the original rotation period of the planet, t is the time, Q^{-1} is the dissipation function and $M_\star$ is the stellar mass. Taking into account the assumptions and calculations made by von Bloh et al.(2007) it is highly probable that both Gl 581c and Gl 581d are tidally locked. Weaker intrinsic magnetic fields are expected for tidally locked planets but von Blon et al.(2007) estimate that the field strengths for both Gl 581c and GL 581d might be strong enough to protected their surfaces from hot coronal winds.

Finally, we estimated the planetary radii using the mass-radius relationship established by Valencia et al.(2007) which theorizes that for Earth-like planets in the mass range of 1-10 $M_\oplus$ the mass-radius relationship is

$$R \propto M^{0.267} \quad (3)$$

This relationship assumes that these super-Earth planets are similar in composition to Earth, and it takes into account their large compressional effects and high internal temperatures. This gives a radius of 1.53 $R_\oplus$ for Gl 581c and 1.71 $R_\oplus$ for Gl 581d.

The numerical model established by von Bloh et al.(2007) couples the stellar luminosity, the silicate-rock weathering rate, and the global energy balance to obtain partial pressure estimates of carbon dioxide, the mean global surface temperature, and the biological productivity as a function of time for a habitable extrasolar planet. They maintain that the most important issue is a balance between the CO_2 sink of the atmosphere-ocean system and the metamorphic (plate-tectonic) sources. Simulations completed by von Bloh et al.(2007) showed that Gl 581c remains well outside the HZ, with too high a surface temperature, for all trial luminosities and eccentricities and that GL 581d remains within the HZ, with a surface temperature above freezing, for most of the trial luminosities and eccentricities considered. For the model observations described here we use a simple model with the surface temperature 100 K above T_{eq}. With the calculated equilibrium temperatures given in Table 2, this provides good agreement with the von Bloh et al.(2007) model simulations. Although the suspected planetary conditions do not appear promising for complex life, it is possible that a simpler form of life could potentially exist upon or below the surface of Gl 581d.

3. OBSERVATIONAL CHARACTERISTICS

The plausibility of directly observing emission from GL 581c and GL 581d depends on several factors, including the planets' apparent magnitude, its contrast with the central star, and its angular separation from that star. The contrast ratio, given by

$$F_{p,\Delta\nu}/F_{\star,\Delta\nu} = 10^{-0.4(m_{p,\Delta\nu}-m_{\star,\Delta\nu})} \quad (4)$$

compares the flux from the planet (p) to the flux from the star ($\star$), over the bandpass $\Delta\nu$. To determine the apparent magnitudes and the contrast ratios at various wavelengths we must calculate the amount of starlight reflected by the planet toward the Earth and the amount of planetary thermal emission received at the Earth. The amount of reflected starlight visible from Earth depends on the planet's phase angle at the time of the observation; the amount of thermal emission depends on the planet's temperature structure. For the purpose of simulating observations of the GL 581 system we developed a simple model of the planetary spectra.

3.1. *Model Spectra of Gl 581c and GL 581d*

To model the planetary spectra, the following assumptions are made: both the star and the planetary surfaces emit as blackbodies, The stellar temperature is 3480 K, the planet's have surface temperatures of T_{eq} + 100 K, and they have uniform density, CO_2 atmospheres with temperatures of T_{eq}.

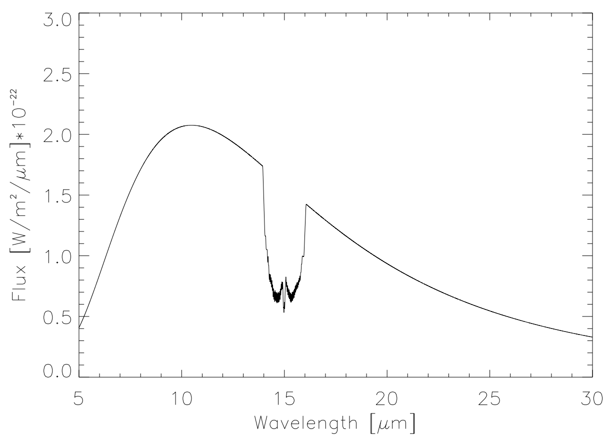

FIG. 1.—Model spectrum of GL 581d, including reflected and thermal emission. The spectrum is dominated by thermal emission from the planet's surface with a strong absorption feature near 15μm, characteristic of the assumed CO_2 atmosphere.

Planetary surfaces were broken up into thirty-two regions, or pixels, of equal latitude and longitudinal intervals. The program calculates the area of a given pixel, along with the incident (from the star) and reflection (toward the earth) angles (relative to the local surface normal) for each pixel. This depends on the planetary phase. From this, a simple model atmosphere and radiative transfer calculation gives the intensity of each element. Then using the solid angle of each pixel, as seen from Earth, the intensity is converted to the flux density at the Earth, and all regions visible from the Earth are summed to give a disk-averaged spectrum. The calculated model spectrum of GL 581d from 5-30μm is shown in Figure 1. This spectrum shows a strong absorption feature centered around 15μm characteristic of the assumed CO_2 atmosphere.

Model calculations of the apparent magnitudes and contrast ratios for visible (v) and mid-infrared (n) bands are given in Table 2. It is clear from this, that contrast ratios in the mid-infrared are significantly better that those in the visible.

3.2. *Angular Separation*

Angular separations at greatest elongation, θ_d, between Gl 581 and its planets Gl 581c and Gl 581d are given in Table 2. The angular resolution of any telescope system is ultimately limited by diffraction. Light passing through a circular aperture generates an Airy pattern where the angle of the first dark ring is given by.

$$\theta = 1.22\lambda/D \tag{5}$$

where λ is the observed wavelength and D is the telescope aperture's diameter. This angle is also the minimum angular separation for resolving two equal intensity point sources. The apparent separations for both Gl 581c and Gl 581d are well below the angular resolution of any current or planned telescopes.

4. MODEL INTERFEROMETER OBSERVATIONS

Interferometry can significantly improve angular resolution. The angular resolution of an interferometer for two equal intensity point sources is given by:

$$\Delta\Theta = \lambda/2B \tag{6}$$

where $\Delta\Theta$ is the angular resolution, λ is the observed wavelength (in our case, mid-infrared values between 5-30μm), and B is the interferometer's baseline.

Nulling interferometry is, in principle, capable of extinguishing an on-axis point source perfectly (Bracewell, 1978) and may help to achieve the high dynamic range required for the detection and analysis of exra-solar planets. Phase errors introduced by atmospheric seeing, even with the use of an adaptive optical system, will reduce the quality of the null. Angel & Wolf (1997), along with Mennesson & Marriotti (1997), suggested that in order to reach a better null for resolved stars, one would desire a nulling interferometer with more than two telescopes.

4.1. *The Interferometer Model*

Our interferometer model currently consists of two apertures, each 10 m in diameter, with an aperture separation of 175 m, chosen to place the fringe maxima of GL 581d over the fringe minima of GL 581. The central star, Gl 581, remains centered in the focal plane of each telescope as it is tracked across the sky. The direction of the star's motion is assumed to be in the direction of the interferometer baseline. The planet remains at a constant angular separation from from the star, also in the direction of the baseline. The two signals are combined with a variable delay nulling combiner that provides a constant phase shift of π for the on-axis star.

The model uses a Fourier optics description of diffraction and interference within the system. The model's performance is illustrated in Figure 2 for equal intensity point sources separated by 1.22λ/D, without nulling; and then in Figure 3 for two observations of GL 581 plus GL 581d, first without (upper curve) and then with nulling (lower curve). Since no noise is included in the model yet, nulling of the bright central star, GL 581, is complete.

4.2. *Noise and Background Emissions*

Now that the interferometer model and atmospheric model are set up, future research will begin to investigate the possibility of the direct detection of emission from Gl 581c and Gl 581d. We will include the effects of imperfectly corrected seeing-induced random phase errors and timing errors for VLBI. We will also investigate whether or not there is an optimum baseline, and the use of three telescopes.

With the main starlight blocked out, the remaining background sources are the zodiacal dust emission (from both the

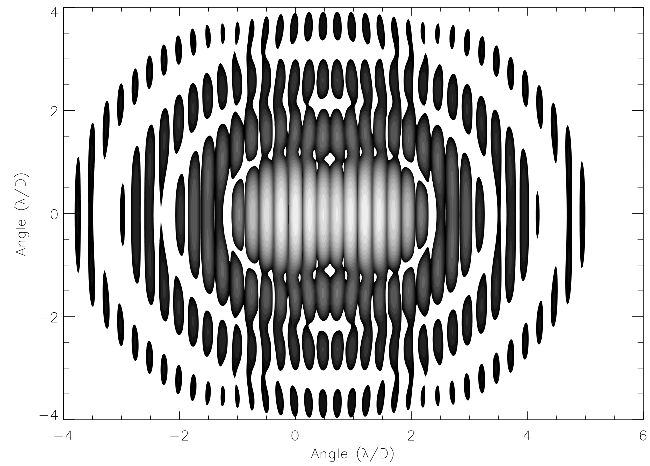

FIG. 2.—Grey scale image from the interferometer model that has two 10 m diameter telescopes separated by a baseline of 40 m. Shown here are two equal intensity point sources with an angular separation of $1.22\lambda/D$.

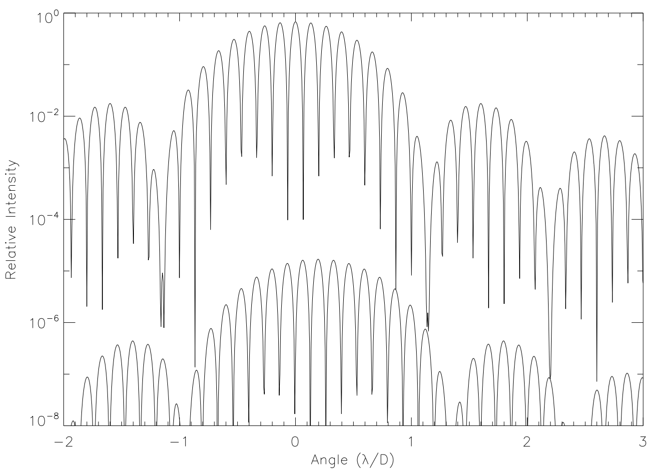

FIG. 3.—Two model observations of GL 581 + GL 581d using the interferometer model with a baseline of 75 m. The upper curve shows an observation using a constant delay, the lower curve is for an observation using a variable (nulling) delay giving a constant phase shift of π for the on axis star.

Solar system and the GL 581 system), emission from the Earth's atmosphere and emission from the telescope optics. There are however ways of accounting for this. The fringes of Gl 581d should appear quite distinct and separate from the somewhat stronger but smoother emission expected from zodiacal dust, the atmosphere and the telescope. Another solution involves observing the system over a much longer time frame, for as the dust remains motionless, the planetary spectrum will shift through the cloud.

5. CONCLUSIONS

Throughout this paper we have addressed several of the key points relating to the plausibility of using mid-IR interferometry or VLBI for the collection and analysis of extrasolar planetary spectra. We have discussed issues involving both the orbital and planetary parameters as well as those regarding the angular separation and sources of background emission. Significant progress has been made toward investigating the possibility of using mid-IR interferometry for the direct detection of planetary emission from GL 581c and GL 581d. A model of a two telescope nulling interferometer has been developed and tested and a simple model of the emission from the GL 581c and GL 581d has been completed.

Before any serious claims regarding the plausibility of this model can be made, several important facets of the model need investigation: Will the contrast ratio be high enough for the case of a finite bandpass and in the presence of random, seeing induced, phase errors? Is there any advantage to be gained by the use of VLBI and if so, is the absolute timing reference accurate enough?

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