The Detectability of Extrasolar Terrestrial and Giant Planets During Their Luminous Final Accretion

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Abstract

One of the outstanding scientific questions in astronomy is the frequency at which solar systems form. Answering this question is an observational challenge because extrasolar planets are intrinsically difficult to directly detect. Here I examine the direct detectability of planets during the short but unique epoch of giant impacts that is a hallmark of the standard theory of planetary formation. Sufficiently large impacts during this era are capable of creating a luminous, 1500-2500 K photosphere, which can persist for timescales exceeding 10^3 years in some cases. I examine the detectability of such events and the number of young stars one would need to examine to expect to find a luminous terrestial-class planet after a giant impact. With emerging IR interferometric technology, thermally-luminous Earth-sized objects can be detected in nearby star forming regions in 1-2 nights observing time. Unfortunately, predictions indicated that $\sim$250 young stars would have to be searched to expect to find one hot, terrestrial-sized planet. By comparison, the detection of Saturn and Uranus-Neptune-sized planets after a giant impact requires only 1-2 hours of observing time. A single Keck-class telescope should be able to determine whether such planets are common in the nearest star forming regions by examining about < 100 young stars over a few tens of nights. The results obtained herein suggest a new strategy for the detection of solar systems with the potential for the observational confirmation of the standard theory of late-stage planetary accretion.

Introduction

The direct detection of radiation from planets about another star has never been accomplished because planets like those in our solar system are not luminous enough to easily reveal themselves at interstellar distances. For example, the four terrestrial planets in our solar system have bolometric thermal luminosities between 6×10^{-11} (Mars) and $\approx 10^{-9}$ (Venus) $L_{\odot}$ (where the $L_{\odot}$ is the solar luminosity). Complicating matters, the terrestrial planets are so close to the Sun that similar planets orbiting nearby stars would lie within 0.1-1 arcsecond of their parent star. Although giant planets would likely lie farther from their parent star (e.g., 1-10 arcsec as seen from nearby stars), their bolometric luminosities are still very low, only $\sim 10^{-11}L_{\odot}$ for Neptune and $\sim 10^{-9}L_{\odot}$ for Jupiter. Here I evaluate the feasibility of another approach. This is the detection of planets during the late stages of accretion when giant impacts deposit sufficient energy to turn their surface molten and temporarily render them much more luminous at infrared wavelengths. This strategy shifts the focus of detection from mature solar systems with cool planets like our own, to solar systems during the late stages of planetary accretion, when planetary surface temperatures can be significantly elevated. Beyond its relevence for planetary detection, this concept offers the chance to directly confirm the standard scenario for late-stage planetary accretion (e.g., Wetherill 1990) by direct astrophysical observations.

It has been recognized for some time that the contrast between a planet and its star can be improved by making observations at IR wavelengths where the planet emits the bulk of its radiation, but the solar flux is significantly reduced (e.g., Bracewell 1978). The utility of the IR can be seen by comparing the *bolometric* brightness ratios given above, to the long wavelength contrast ratios of the Earth and Jupiter, which reach asymptotic limits of 5×10^{-6} and 2×10^{-4}, respectively.

Over the past three decades of intensive scientific inquiry, a standard model for planetary system formation has emerged (e.g., Wetherill 1990; Tonks & Melosh 1993). This model is supported by a body of modelling efforts, chemical and isotopic studies of lunar, meteoritic, and terrestrial samples (Palme & Boynton 1993), and astrophysical observations of star forming regions in the environments around young stars (Strom, et al. 1993). The salient phases in the standard planetary system formation scenario are: (i) nebular collapse to a disk; (ii) condensation and accretion of grains; (iii) growth from grains into planetesimals; (iv) the collisional accretion of planetesimals into planetary embryos; and (v) the merging of embryos with debris and other embryos to complete the formation of young planets.

The final stage of the standard scenario outlined above is now strongly associated with a significant number of giant impacts on each of the planets (cf., Wetherill 1990). Once a planetary embryo has reached a mass $\sim 0.1 M_{\oplus}$, the kinetic energy deposited in impacts with objects $\gtrsim 10\%$ of its own mass is sufficient to shock-heat and melt all or most of the embryo's surface (Tonks & Melsoh 1993).

Various evidence (e.g., Hartmann & Davis 1975; Dones & Tremaine 1993) suggests that the mass spectrum of accreting planetesimals during late-stage accretion of the terrestrial planets followed a power law of the form,

$$N(m > M) = CM^{1-b}, \tag{1}$$

over six orders or more of magnitude in mass. Here M is the impactor mass, and the coupling constant C provides the normalization. For $b = 2$ there is equal mass in each logarithmic interval, and the accreted mass is dominated by the largest impacts.

Power laws with $b \approx 1.8$ are obtained from studies of impact fragmentation cascades (Fujiwara et al. 1989), numerical simulations of planetary accretion (Dohnanyi 1972; Greenberg, et al. 1978), and numerical simulations of terrestrial planet formation (e.g., Wetherill 1990). As such, it appears that much of the mass and energy accreted on each terrestrial planet came from a few tens or hundreds of comparatively large impactors (Wetherill 1990). The Mars-sized terrestrial impactor believed responsible for the formation of the Moon was such an impact (Stevenson 1987). The stripping of Mercury's primordial mantle (e.g., Slattery et al. 1992) and the generation obliquities among many of the terrestrial planets (e.g., Lissauer & Safronov 1991; Dones & Tremaine 1993) may also have been caused by such giant impacts.

Even if a giant impactor approaches the Earth with negligible velocity (i.e., on an essentially-coplanar, zero-eccentricity orbit at 1 AU), its descent down the Earth's gravitational potential well will cause it to impact at velocities near 10 km s^{-1}. Studies of such impacts have been reported by various workers, including Sleep et al. (1989) and Zahnle & Sleep (1994). These workers find inelastic impacts of this scale will generate a rock-vapor atmosphere with a base pressure exceeding 100 bars. This atmosphere will radiate from a photosphere lying at a pressure level of 1-40 millibars and exhibiting a temperature of

1500-2500 K (Zahnle & Sleep 1994, and references therein), depending upon the size and composition of the vapor droplets.

In the case of a terrestrial planet with an Earth-class ocean, the dominant heat sink for impacts delivering $\lesssim 5 \times 10^{34}$ ergs will be ocean vaporization. The dominant heat sink for impacts delivering substantially more energy than this will be radiation to space. In what follows we adopt a minimum energy threshold of $E_{crit} = 10^{35}$ ergs for terrestial-planet impacts to create a luminous photosphere radiating at 1500-2500 K. Planets with less massive oceans than Earth would attain such a photosphere after smaller impacts.

A simple estimate of the radiative cooling timescale for such events can be obtained by dividing the fraction of the event's impact energy that is spent radiatively by the luminosity of the resuting planetary blackbody. This gives a radiative timescale t_R

$$t_R \sim \frac{M v_i^2}{8\pi R_p^2 \sigma T^4}, \tag{2}$$

where M is the impactor mass, v_i is the impact velocity, R_p is the planetary radius, σ is the Stefan-Boltzmann constant, and T is the photospheric temperature.

As an example, the radiative timescale for a lunar-mass impactor ($M = 7 \times 10^{25}$ g) striking a half-accreted Earth ($R_p = 5 \times 10^8$ cm) at $v_i = 1.4 \times 10^6$ cm s^{-1}, is $t_R = 290$ yr and $t_R = 960$ yr, for surface blackbody temperatures of 2500 K and 1500 K respectively. More sophisticated calculations that include latent heat and thermal conduction effects (Tonks & Melosh 1993; Melosh 1990; Zahnle & Sleep 1994) give cooling timescales of 800 yr at $T = 2500$ K and 2000-8000 yr at $T = 1500$ K. The fact that such high temperatures are able to persist for so long is a strong motivation for determining whether accreting terrestial planets might be detectable at interstellar distances.

Although the details are beyond the scope of our immediate interests, it is also worthwile to note that if an ocean was present to be vaporized, then after the atmosphere cools until the rock vapor has condensed, a high-pressure steam vapor atmosphere can remain. As described by Kasting (1988), this steam-atmosphere will persist for much longer than a 1500-2000 K rock-vapor photosphere because it radiates to space at a much lower (but for our purposes, less detectable) rate.

The Detectability of Luminous, Post-Impact Terrestrial Planets

Let us examine the detectability of planetary bodies enveloped by hot, rock-vapor atmospheres after suffering giant impacts. We begin by examining the flux from such objects. Later I will estimate the number of young star systems one nominally expects to examine in order to detect a terrestrial planet made luminous by a giant impact. The flux at Earth from a self-luminous, thermally-dominated, giant-impacted planet is

$$F = \left(\frac{R_p}{D}\right)^2 \int_{\nu_0}^{\nu_f} B_\nu(T)\, d\nu \tag{3}$$

where D is the distance to Earth, $B_\nu(T)$ is the Planck function, and the integration limits refer to the width of a given spectral bandpass.

Because the timescale between the time the terrestrial planets grow from 10% to 90% of their present mass was short (e.g., $\sim 4 \times 10^7$ years; cf., Wetherill 1990), the locations where such impacts would be expected to be occuring today would be in star forming regions. The nearest star forming regions are Taurus-Auriga and ρ Ophiuchus, which are $\approx$140 pc and 125 pc away, respectively (Lada, et al. 1993). There are about 100 identified young stellar objects in each of these birth clusters. The somewhat older clusters α Persei and the Pleiades have comparable numbers of stars and lie at 170 and 130 pc, respectively. In what follows I adopt 135 pc as a typical distance to nearby star clusters $< 10^8$ years in age.

To evaluate the detection feasibility for luminous planets, we first consider the detectability of such bodies in isolation (i.e., ignoring for the moment the more complicated problem of detectability next to their much brighter, parent star). Figure 1 depicts the blackbody flux curves for a solar-type (G2V) and a cooler (K5V) star, and two self-luminous accreting planets the size of the Earth: one at 1500 K and one at 2500 K (Melosh 1990), as seen from 135 pc. For comparison, Figure 1 also depicts blackbody curves for the present-day Earth and Jupiter as seen from the same distance, along with the IR sensitivity of the 10m-Keck telescope in the 2.2μm K, 4.8μm M, and 10.1μm N band telluric windows. Clearly, the 2.2μm K band is the optimal wavelength for detection. The comparison in flux between a luminous terrestrial-class planet that has suffered a giant impact and a mature Earth or Jupiter is dramatic. These calculations demonstrate that hot terrestrial-type planets are sufficiently bright to be detected from a flux sensitivity standpoint.

We now consider the complication that the planetary source must be detected in the presence of the parent stellar signal, which may functionally be considered a source of background noise. To make a detection in this realistic circumstance. two strategies suggest themselves: unresolved spectral measurements and interferometric imaging; I discuss each in turn.

First consider detection of the spatially-unresolved K band spectrum of the star plus planet. A 1 arcsec aperture centered on a star at 135 pc would encompass a circle 68 AU in radius about the parent star, so the planetary region would clearly be contained within this aperture. While direct in its implementation, the weakness in this strategy is twofold. First, extremely high S/N, on the order of several times the star/planet contrast ratio, would be required. Second, it would be difficult to definitively prove such an ***unresolved*** detection is due to an orbiting planet, as opposed to the stellar photosphere, dust in orbit around the star, or a faint background object in the unresolved field.

An alternative method for detecting and uniquely identifying the signature of a luminous planet in a nearby star forming region is to employ IR interferometry on baselines of 50 meters or greater. The infrared is a particularly good wavelength region for interferometry because IR atmospheric seeing cells are large, IR atmospheric dispersion is small, and IR atmospheric time constants are long; additionally, there are many reference stars in the infrared. Fringe control has been demonstrated by existing groundbased IR interferometers to levels of 1/50 fringe or 0.1 milliarcsecond (mas) at 2.2μm (cf., Burke et al. 1992).

The interferometric planetary detection technique (Burke, et al. 1992; Shao, personal communication) is based on the fact that the planet is not detectable at wavelengths significantly shortward of its Wien peak, but the parent star, being hotter and more luminous, is. Therefore a short wavelength, high S/N detection of the star is used as the phase reference, and the phase difference between this short wavelength and the longer wavelength at which the planetary thermal spectrum peaks is used as the interferometric measurement. This phase difference, which depends on the separation and the contrast ratio χ of the two objects, is measured in multiple spectral channels across the long wave band, which are then summed over the entire planet detection band (in our case, the K-band).

The angular resolution of an interferometer with elements separated by a distance L, operating at a wavelength λ, is $\theta = \lambda/(2L)$. The most promising IR interferometer presently planned is the pair of 10 meter Keck telescopes now under construction on Mauna

Kea. This device will offer an 85 meter baseline, which translates to an angular resolution of $\approx 1.5 \times 10^{-8}$ radians (i.e., 3 mas) at K band (2.2μm). At 135 pc, this corresponds to a spatial resolution of 0.35 AU, which is sufficient to marginally resolve a planet from its star: the resulting interferometric image will show two blended point spread functions, reminiscent, for example, of the blended discovery images of Charon orbiting Pluto.

Now consider the detection of such a source close to its much brighter stellar parent. This is more difficult than the simple detection of a perfectly isolated hot planet's flux, as shown in Figure 1. Figure 2 depicts the flux contrast ratios of the same two self-luminous, accreting planet cases shown in Figure 1, relative to standard K5V and G2V stars.

At 2μm the telescope and sky emission are negligible compared to the star, which is the dominant background source. The scattered light level from the star in an interferometer is controlled by the diffraction pattern of the individual telescopes, which for a 10m aperture like the Keck is about 45 mas. As such, the interferometer will detect the sum of the star and planet.

To achieve a given signal to noise ratio (SNR) for the detection of a planet in the presence of a strong stellar background, one must satisfy the criteria $P > SNR\sqrt{S}$ where SNR is the desired signal-to-noise ratio, S is the stellar signal collected during the observation, and P is the planetary signal collected. For a star:planet contrast ratio of 10^5:1, a S/N=4 detection would require roughly 4×10^{10} detected photons from the star, and 8×10^5 photons collected from the planet.

Table 1 gives detection S/N estimates for hot, terrestrial size planets the sizes of Earth and Mars in the presence of a G2V stellar primary. These estimates are for the two-Keck interferometer with adaptive-optics, and assume a 35% system QE, and a 50% Strehl ratio.

The data in Table 1 demonstrates that detections of 1500-2500 K bodies approximately Earth's size (or larger) should be achievable *in a single night* when such a system is in place. Smaller, Mars-sized (i.e., $\approx 0.5R_\oplus$) bodies will be detectable in a single night only if they are near 2500 K with with the same detection technology. Foreseeable advances could increase system QEs or Strehl ratios by $\sqrt{2}$, thereby reducing these detection times by a factor of two.

Objects detected in a single night should probably first be confirmed by a second observation. Then, over timescales of several months, candidate hot planets should reveal motion around their parent star. The combination of (i) discrete-object detection near the parent star, (ii) confirmation of the object's cyclic motion around the parent star, and

(iii) a size constraint from the object's luminosity and color temperature would provide powerful evidence that a *planet* has been detected.

Interestingly, the most common event likely to be detected in any power-law ensemble of impactors like we have discussed, would most likely be a comparatively low-energy impact (10^{35} erg) by a small (i.e., $\sim 10^{25}$ gm) impactor. Such events would have durations of months to a few years, depending largely on the effective radiating temperature. If color shifts revealed such a cooling, the cooling timescale could be measured, and the impactor mass could be constrained.

Search Requirements for Luminous, Post-Impact Terrestrial Planets

Given the detection limits just discussed for terrestrial planets made luminous by giant impacts, I now estimate the number of young stars that need to be searched to find a luminous young planet.

The probability of a given planetary system having a luminous planet at any given time is, in essence, an issue of the ratio of the total time all its accreting planets are brighter than some detection threshold ratioed to the total time during which giant impacts occur in the system, which I call t_{acc}. Since we are interested in determining the scope of a future search effort to detect such a system, I calculate the approximate number of stars in a given star forming region N_* that must be searched to find a single luminous planet. To a level commensurate with the spirit of these scaling calculations, this is given by:

$$N_* = \frac{1}{\overline{N}_p f_{ss}} \left(\frac{t_{acc}}{t_{\mathrm{HOT}}} \right) \qquad (4)$$

where $\overline{N}_p$ is the average number of accreting terrestrial planets per solar system, f_{ss} is the fraction of stars with planetary systems in the sample, and t_{HOT} is the total time a planet remains detectable due to impacts that turn its surface molten. The details of the rate and timing of collisions during t_{acc} do not matter for our purposes, and one can approximate t_{HOT} by dividing the total energy delivered in impacts large enough to melt the surface by the cooling rate after such collisions:

$$t_{HOT} = \frac{E_{tot}(\text{Impacts} > 10^{35}\text{ergs})}{4\pi R_p^2 \sigma T^4}. \qquad (5)$$

Here $E_{tot}(\text{Impacts} > 10^{35}\text{ ergs})$ is the total energy budget delivered in impacts greater than 10^{35} ergs. I adopt this minimum-energy threshold to ensure a terrestrial-class ocean would be a negligible heat sink, so that the post-impact thermal regime would be dominated by a radiatively cooling rock-vapor atmosphere (cf., Zahnle & Sleep 1994). A 10^{35} erg collision at an impact velocity of 14 km s^{-1} corresponds to an impactor mass of $\approx 10^{-3} M_{Moon}$ ($R \approx 200$ km). By comparison, the Mars-class impactor often associated with the trigger for lunar formation initially deposited $\sim 5 \times 10^{38}$ ergs on the Earth.

It is reasonable to assume $\sim 40\%$ of the Earth's mass (2.4×10^{27} g) was accreted in large impacts that occured in a period lasting $\approx 4 \times 10^{7}$ years (Wetherill 1990; Tonks & Melosh 1993). I denote this timescale $t_{\rm acc}$. To estimate N_*, I neglect surface-melting collisions on the many smaller (but less luminous) objects that dominate the embryo population by number. For a typical system during late-stage accretion, I assume 2.5 terrestrial-size planets (i.e., $\overline{N}_p = 2.5$), with typical radii $R_p = 0.9 R_\oplus$. Thus, the estimate for Earth-sized bodies is:

$$N_* \sim 250 f_{ss}^{-1} \left(\frac{4 \times 10^{7}\text{ yr}}{t_{acc}}\right) \left(\frac{E_{tot}}{2.4 \times 10^{39}\text{ ergs}}\right)^{-1} \left(\frac{T}{1500\text{ K}}\right)^{-4} \qquad (6)$$

These results lead us to conclude that if planetary formation commonly occurs in the mode believed to have created the Earth and other terrestrial planets, and the effective radiating temperature of these bodies is 1500 K when a rock vapor atmosphere is present, then the initial detection of an Earth-sized terrestrial planet after a giant impact requires searching the known population of young stars in the Taurus-Auriga and ρ Ophiuchus star forming clusters. Smaller (presumably more numerous) Mars-sized bodies can be detected in the same surveys when they are hotter than ≈ 2150 K.

A project to search 250 stars at the rate of one system per night would require 10-15% of the Keck interferometer for 5-7 years. As noted above, if either the system QE or Strehl ratio can be improved by $\sqrt{2}$, the nominal survey time would drop to 3-4 years. Although such an effort would be large, it is impressive to recognize that astronomical capabilities are now reaching the threshold of detecting accreting terrestrial planets in nearby star forming regions.

The Detectability of Luminous, Post-Impact Giant Planets

In closing, I briefly disuss one other aspect of the detection of self-luminous bodies in planetary systems: giant impacts on giant planets. The large obliquities of Saturn, Uranus, and Neptune have been attributed to giant impacts (e.g., Slattery, et al. 1992). Although the computation of an effective radiating temperature for such bodies is highly uncertain, temperatures of 1500-2500 K have been estimated. Owing to the much larger surface area of these bodies, such impacts would be 20-60 times more luminous than a terrestrial planet. (For the same reason, such impacts will cool faster as well).

The combination of higher event luminosities and the likelihood that giant planets would most probably be located an order of magnitude further from their parent star than a terrestrial planet, makes the detection of such events easier than the terrestrial planet events we have been examining. Figure 3 depicts the flux from such events 135 pc away. At 2.2μm, a *single* IR-optimized 10m-class telescope like the existing Keck could detect a 1500 K (2100 K) Uranus at S/N=20 (S/N=55) in 1 hour; such a telescope could also marginally resolve this source at 2.2μm, without invoking interferometry.

I crudely estimate that for an accretion timescale of 10^8 years and $\overline{N}_p = 3$ giant planets per system,

$$N_* \sim 60 f_{ss}^{-1} \left(\frac{10^8\text{yr}}{t_{acc}}\right) \left(\frac{E_{tot}}{2 \times 10^{40}\text{ergs}}\right)^{-1} \left(\frac{T}{1500\text{K}}\right)^{-4} \tag{7}$$

This indicates the bright sources created by a giant-impact on a Uranus- or Neptune-class planet may be much more likely to be found in a search of nearby star forming regions than are luminous terrestrial planets.

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Table 1

K-Band (2.2μm) S/N Predictions for Detection of Luminous Terrestrial Planets
(8 hour integration time on the Keck interferometer)

Temperature	Radius=Earth	Radius=Mars
1500 K	2.5	0.7
2100 K	7.7	2.2
2500 K	17	5.0

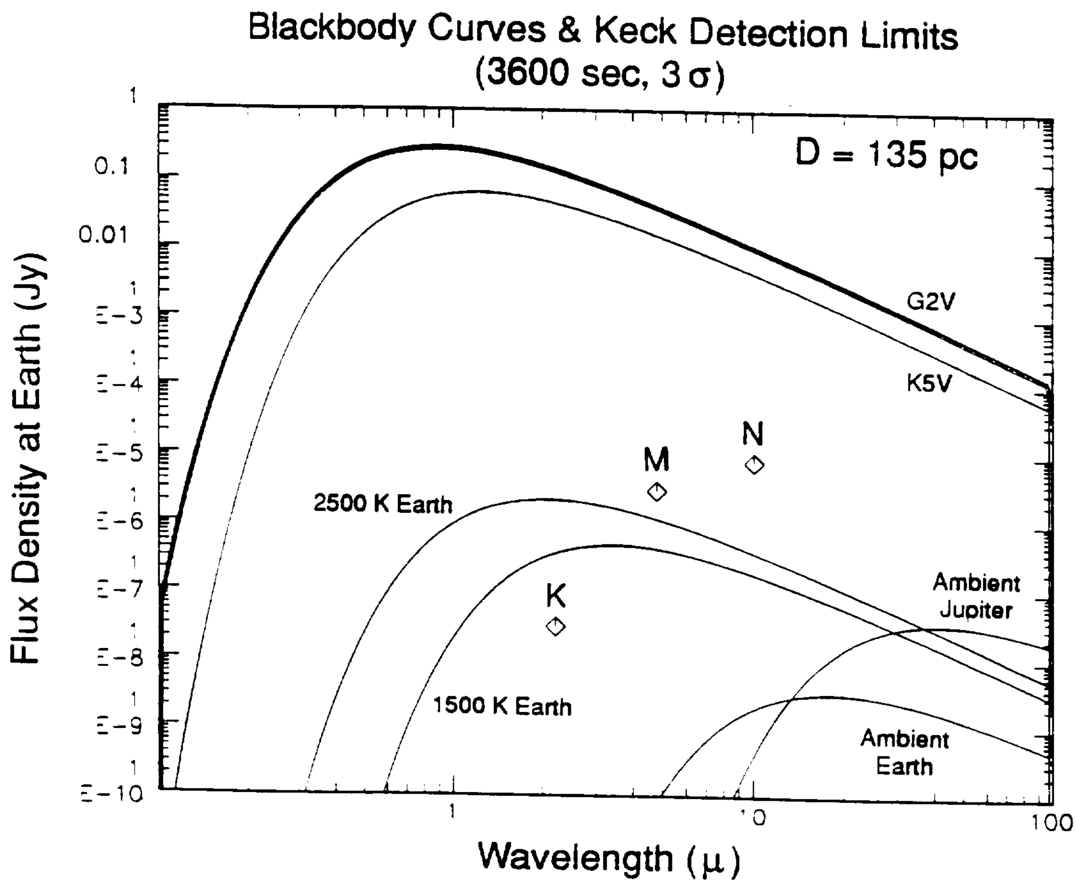
[1]Integration times of $\sim$ 8 hours or longer allow effective Earth-rotation synthesis of the interferometric baselines. These calculations assume the sources are not significantly extinguished by opacity effects between them and the telescope.

Figure Captions

Figure 1: Thermal flux curves for G2V and K5V stars. Earth-sized planets at 1500 and 2500 K, an ambient temperature (288 K) Earth, and an ambient temperature (126 K) Jupiter as seen from a distance of 135 pc, which is typical of nearby star forming regions. Also shown are the sensitivity limits for a 3σ detection by a single Keck 10m at the K, M, and N bands after a 1 hour integration. These data indicate (i) the increased luminosity of hot young planets over cool, mature planets, and (ii) the clear detectability of luminous planets in the ideal situation of a negligible stellar background. Table 1 presents S/N estimates for the more realistic case of hot planet detection near a far brighter stellar primary. Note that the scattered (i.e., reflected) light spectra of the Earth and Jupiter do not reach the lower limit of this graph.

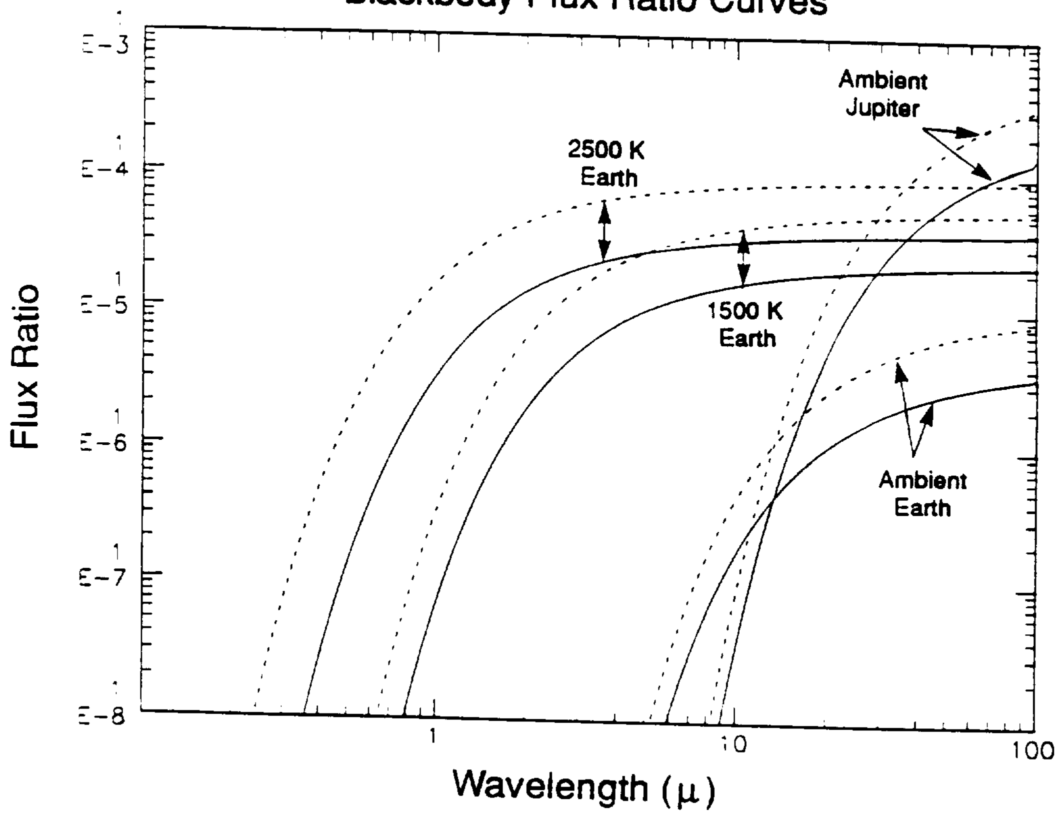
Figure 2: Here the four planetary blackbody luminosity sources shown in Figure 1 are ratioed to a G2V stellar spectrum (solid lines) and a K5V stellar spectrum (dashed lines).

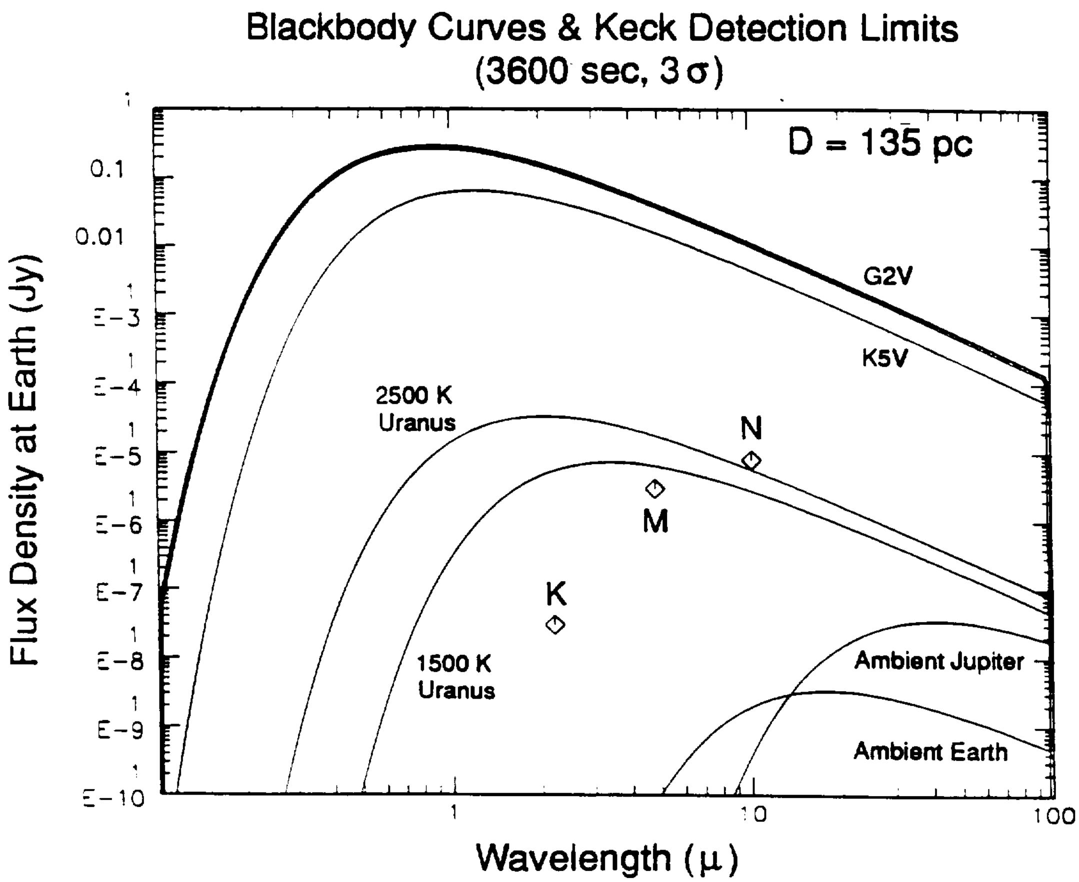
Figure 3: Like Figure 1, we present here thermal flux curves for G2V and K5V stars, Uranus-sized planets at 1500 and 2500 K, an ambient temperature (288 K) Earth, and an ambient temperature (126 K) Jupiter as seen from a distance of 135 pc, which is typical of nearby star forming regions. Also shown are the sensitivity limits for a 3σ detection by a single Keck 10m at the K, M, and N bands after a 1 hour integration.



Blackbody Curves & Keck Detection Limits
(3600 sec, 3σ)
D = 135 pc
G2V
K5V
N
M
K
2500 K Earth
1500 K Earth
Ambient Jupiter
Ambient Earth
Flux Density at Earth (Jy)
Wavelength (μ)
1
0.1
0.01
1
10
100

Blackbody Flux Ratio Curves




Blackbody Curves & Keck Detection Limits
(3600 sec, 3σ)
D = 135 pc
G2V
K5V
2500 K
Uranus
1500 K
Uranus
N
M
K
Ambient Jupiter
Ambient Earth
Flux Density at Earth (Jy)
Wavelength (μ)
0.1
0.01
1
10
100