AN IMPROBABLE SOLUTION TO THE UNDERLUMINOSITY OF 2M1207B: A HOT PROTOPLANET COLLISION AFTERGLOW

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ABSTRACT

We introduce an alternative hypothesis to explain the very low luminosity of the cool (L-type) companion to the ~25 $M_{\rm Jup}$, ~8 Myr old brown dwarf 2M1207A. Recently, Mohanty et al. found that effective temperature estimates for 2M1207B (1600 ± 100 K) are grossly inconsistent with its lying on the same isochrone as the primary, being a factor of ~10 underluminous at all bands between I (0.8 μm) and L' (3.6 μm). Mohanty et al. explain this discrepancy by suggesting that 2M1207B is an 8 $M_{\rm Jup}$ object surrounded by an edge-on disk comprised of large dust grains producing 2.5 mag of achromatic extinction. We offer an alternative explanation: the apparent flux reflects the actual source luminosity. Given the temperature, we infer a small radius (~49,000 km), and for a range of plausible densities, we estimate a mass $< M_{\rm Jup}$. We suggest that 2M1207B is a hot protoplanet collision afterglow and show that the radiative timescale for such an object is $\gtrsim 1\%$ the age of the system. If our hypothesis is correct, the surface gravity of 2M1207B should be an order of magnitude lower than that predicted by Mohanty et al.

Subject headings: circumstellar matter — planetary systems: formation —
planetary systems: protoplanetary disks —
stars: individual (2MASSW J1207334−393254) — stars: low-mass, brown dwarfs —
stars: pre–main-sequence

1. INTRODUCTION

While radial velocity surveys and other techniques have yielded over 200 extrasolar planets, there are to date no convincing images of an extrasolar planet around a star. A few candidate "planetary mass objects" have been identified comoving with pre–main-sequence stars and young brown dwarfs (e.g., GQ Lup, Oph 162225−240515, etc.; e.g., Neuhäuser et al. 2005; Jayawardhana & Ivanov 2006). However, further observations have shown these objects to be higher mass (e.g., Luhman et al. 2007a). A possible exception is the companion to 2M1207A (Chauvin et al. 2004; 2MASSW J1207334−393254 = TWA 26), for which mass estimates have ranged between ~3 and 8 $M_{\rm Jup}$. Although its mass inferred from evolutionary models is well below the deuterium-burning limit, it is unlikely that the object could have formed through classical core accretion in a circumstellar disk. Given its estimated mass ratio (~0.2–0.3) and separation (~50 AU), it is thought to have formed via gravitational fragmentation, similar to a binary star system (Lodato et al. 2005).

The properties of the 2M1207 system are discussed in detail in Mohanty et al. (2007). The most striking result from that study is that while both the colors and near-IR spectrum of 2M1207B are consistent with models of an unreddened ~1600 K object, the inferred luminosity for the object is ~2.5 mag (factor of ~10) below that expected for a ~5–10 Myr object at all wavelengths. Even more remarkable, the object is slightly fainter than the observed sequence of K and L' absolute magnitudes for older field objects with $T_{\rm eff} \simeq 1600$ K (Golimowski et al. 2004). Mohanty et al. (2007) rule out a handful of simple resolutions to explain the apparent underluminosity of 2M1207B, and ultimately settle for an unlikely but testable hypothesis: that the object is obscured by an edge-on disk of large circumstellar dust grains producing 2.5 mag of gray extinction. In this contribution, we propose an alternative explanation for the low luminosity of 2M1207B, namely, that it has

a small radius. In this scenario 2M1207B is the hot, long-lived afterglow of a recent collision between two protoplanets (cf. Stevenson 1987). The observational consequences of protoplanet collisions have been discussed elsewhere (Stern 1994; Zhang & Sigurdsson 2003; Anic et al. 2007). Here we review the problem of 2M1207B, introduce a new hypothesis, discuss its merits and deficiencies, and offer an observational test that can rule it out.

2. THE LUMINOSITY OF 2M1207B

We first review some observational properties of the 2M1207 system. 2M1207A is classified as M8 with emission-line activity characteristic of T Tauri stars (Gizis 2002). The system appears to harbor a circumstellar accretion disk as evidenced by broad Hα emission (Mohanty et al. 2003), mid-IR excess (Sterzik et al. 2004), and outflow activity (Whelan et al. 2007). The motion of 2M1207A is consistent with membership in the TW Hya Association (TWA), a loose group of ~20 stars with mean age ~8 Myr old situated at a mean distance of ~50 pc (Webb et al. 1999; Mamajek 2005). The optical/near-IR colors of 2M1207A are consistent with no reddening given its spectral type. Comparison of its position in the H-R diagram with theoretical models suggests a mass of ~25 $M_{\rm Jup}$ and age consistent with its membership in the TWA (Mohanty et al. 2007).

2M1207B shares common proper motion and parallax with 2M1207A within the astrometric uncertainties (milliarcsecond-level measurements over a few years; Chauvin et al. 2004, 2005; Song et al. 2006; Mohanty et al. 2007). The idea that B could be a foreground or background field L dwarf has been

ruled out. At a distance[1] of 66 ± 5 pc, the companion is at a projected separation of 51 ± 4 AU from the primary. Mohanty et al. (2007) concentrate their analysis of the temperature for 2M1207B on comparison of data to the Lyon group model atmospheres. From the available H- and K-band spectra, they determine the best-fit model atmosphere has $T_{\rm eff} = 1600 \pm 100$ K from the DUSTY grid of Allard et al. (2001). A range of surface gravity from $\log g = 3.5$–4.5 was explored, but the value is poorly constrained. They also compare the available photometry of 2M1207B from 0.9 to 4.0 μm with predictions from the DUSTY models and conclude that they are consistent with this temperature estimate. While Leggett et al. (2001) demonstrate that DUSTY models are a somewhat poor fit for old late L-type field dwarfs, Mohanty et al. (2007) have shown that they produce adequate spectral fits for the young objects 2M1207B and AB Pic B. 2M1207B is significantly redder and dustier than typical L dwarfs, as predicted for low surface gravity objects.

We explore a complementary approach, comparing the spectra published in Mohanty et al. (2007) as well as the available photometry with template objects drawn from wide field surveys (predominantly older objects). The low-resolution H- and K-band spectrum available at signal-to-noise ratio of 3–10 is morphologically similar to other L dwarfs suspected of having low gravity: 2MASS J01415823−4633574 (2M J0141; Kirkpatrick et al. 2006), 2MASS J22244381−0158521 (Cushing et al. 2005), and SDSS J22443167+2043433 (SDSS J2244; Knapp et al. 2004). All of these objects exhibit weak metal resonance lines (e.g., Allers et al. 2007; Gorlova et al. 2003), stronger than expected CO for their spectral type (Cushing et al. 2005; McLean et al. 2003), and unusual pseudocontinua in the H-band spectra attributed to collision-induced molecular hydrogen absorption (e.g., Borysow et al. 1997), all indications of low surface gravity. Given the morphological correspondence between the spectrophotometry of 2M1207B and these other low-gravity L dwarfs, it is reasonable to assume that 2M1207B has a similar nature. Further, the spectrum of 2M1207B shows no signs of CH_4 absorption, which would indicate $T_{\rm eff}$ below 1400 K.

The colors of 2M1207B are very red compared to observed sequences of field L dwarfs (e.g., Knapp et al. 2004; Golimowski et al. 2004). The anomalous L dwarfs listed above also exhibit this behavior, which can be attributed to low gravity (e.g., Burrows et al. 2006; Allard et al. 2001). Taking the observed ($J-H$) colors of 2M1207B and several plausible intrinsic colors matches, we searched for reddening solutions that would fit the SED of 2M1207B. Adopting the colors of 2MJ0141 (Kirkpatrick et al. 2006) as a low-gravity early L template, we derived $A_V \simeq 9$ mag, which matches the JHK photometry well. However, 2MJ0141 has $T_{\rm eff} = 2000$ K (Kirkpatrick et al. 2006), and $A_V \simeq 9$ mag implies $A_K \simeq 1$ mag, which would be insufficient to move 2M1207B above the old dwarf sequence for that $T_{\rm eff}$. Alternatively, adopting the colors of SDSS J2244 (Knapp et al. 2004) as a late-L low-gravity template, we arrive at $A_V \simeq 3.7$, again reproducing the colors of 2M1207B within the (rather large) errors from ~1 to 4 μm. However, the required reddening ($A_K \simeq 0.4$ mag) is insufficient to solve the underluminosity of 2M1207B. If we assume that

2M1207B has the ($J-H$) colors of a late-type M dwarf, we derive $A_V \simeq 11$ mag but cannot reconcile the observed colors without invoking excess emission in the K and L bands. In the limit of zero extinction, one can find models of extremely low gravity that fit the SED (e.g., Mohanty et al. 2007), so we take that as the simplest assumption consistent with the observed properties of known L dwarfs and informed by model atmospheres.

In order to estimate the bolometric luminosity of 2M1207B, we must also estimate an appropriate bolometric correction to apply to the observed absolute magnitude. Given the distance to the source, the lack of evidence for interstellar reddening, the available photometry, and the temperature estimate discussed above, we can apply a bolometric correction to any flux estimate from 0.9 to 4.0 μm. Golimowski et al. (2004) demonstrates that BC_K varies little as a function of spectral type for L dwarfs, so we apply the K-band BC to 2M1207B to minimize the uncertainties in the estimate of $M_{\rm bol}$ (=3.25 ± 0.14 mag; same as in Mamajek 2005). This results in a luminosity estimate of $\log(L/L_\odot) = -4.54 \pm 0.10$ dex. For $T_{\rm eff} = 1600 \pm 100$ K, the DUSTY models predict $BC_K = 3.56 \pm 0.07$ mag, and a luminosity of $\log(L/L_\odot) = -4.66 \pm 0.08$ dex. The difference between adopting the empirical or theoretical BC values is within the errors, so we conservatively adopt the empirically derived $\log(L/L_\odot)$ as an upper limit. Given its luminosity, 2M1207B lies 4–7 times below that expected for an age range of 5–10 Myr given its inferred temperature range of 1500–1700 K. Metchev & Hillenbrand (2006) derive an effective temperature for the young (~0.3 Gyr) L/T transition object HD 203030B that is considerably lower (by ~230 K) than that predicted for its spectral type (L7.5). If 2M1207B were in fact a late-L spectral type with a temperature of 1100 K, we could reconcile its position in the H-R diagram given its age. However, this is ~500 K cooler than the $T_{\rm eff}$ derived from spectral synthesis models according to Mohanty et al. (2007). Burrows et al. (2006) suggest that the temperature of L-T transition objects should only weakly depend on temperature. Exploring this solution to the 2M1207B problem requires higher SNR spectra and further study.

Can the theoretical evolutionary tracks be wrong in luminosity by such a large factor? As pointed out by Mohanty et al. (2007), another well-studied young, low-mass binary (AB Pic) exhibits HRD positions consistent with the age of the group (Tuc-Hor; ~30 Myr). Marley et al. (2007) have argued that the luminosities of young planets formed through core accretion are likely to be overpredicted in models that initially start objects in high entropy states. However, this argument does not apply if the object formed through gravitational fragmentation, as has been suggested (Lodato et al. 2005). The Marley et al. (2007) models predict that for ages >Myr after accretion has ceased, all planets that formed through core accretion with masses of <10 $M_{\rm Jup}$ will be colder than $T_{\rm eff} \simeq 800$ K and with $\log(L/L_\odot) < -5.2$ dex. Hence, while 2M1207B is vastly underluminous for its $T_{\rm eff}$ compared to the "hot-start" evolutionary models of Chabrier et al. (2000) and Baraffe et al. (2003), it is overluminous and too hot for the fiducial "cold-start" core accretion models for <10 $M_{\rm Jup}$ from Marley et al. (2007). Observationally, there seems to be no trend that would suggest an error in the evolutionary tracks that could account for the HRD position of 2M1207B.

As pointed out in Mohanty et al. (2007), one cannot reconcile the observed spectrum and SED of 2M1207B with its apparent low luminosity given the available models. Here we take a different approach, adopting the derived temperature of 1600 K,

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[1] Our adopted distance to 2M1207 via the cluster parallax method has increased by 2 σ compared to Mamajek (2005; 53 ± 6 pc) due to the effects of a improved proper motion for 2M1207 (Song et al. 2006), and a revised estimate of the TWA group velocity (22.4 ± 1 km s^{-1}, which follows Mamajek [2005] but omits the deviant parallax for TWA 9). The updated velocity increases the distances to the other TWA members in Mamajek (2005) by 7%.

and postulate that the observed source flux is a reflection of its actual luminosity.

3. A PLANET-COLLISION THEORY FOR 2M1207B

We hypothesize that 2M1207B is the result of a recent collision of two protoplanets (cf. Stern 1994). Adopting the temperature and luminosity in § 2, one derives a radius of $48,700 \pm 8800$ km ($= 0.68 \pm 0.12$ $R_{\rm Jup}$, 7.6 ± 1.4 $R_{\oplus}$). For a range of densities, the inferred mass and gravity are given in Table 1.

We hypothesize that the object is a hot protoplanet of density ~ 1 g cm^{-3}. With this radius and density,[2] the fiducial planet would have a mass of $M_{\rm B} = 81$ $M_{\oplus}$ ($0.85 M_{\rm Saturn} = 4.7 M_{\rm Neptune}$). Throughout this discussion we refer to hypothetical protoplanets B_1 and B_2, which merged to produce body B (2M1207B). In our solar system, the largest planetesimals to impact the planets during the late stages of accretion appear to have had mass ratios of order $\gamma = M_{B_2}/M_{B_1} \sim 0.1$, including the bodies responsible for producing the obliquities of Saturn, Uranus, and Neptune (Lissauer & Safronov 1991). Thus, we assume that our ~ 81 $M_{\oplus}$ object was the product of a collision between protoplanets with masses $M_{B_1} = (1 + \gamma)^{-1} M_{\rm B}$ and $M_{B_2} = \gamma(1 + \gamma)^{-1} M_{\rm B}$, or $M_{B_1} = 74$ $M_{\oplus}$ and $M_{B_2} = 7$ $M_{\oplus}$. Following Wetherill (1980) the *minimum* impact velocity for two planets will be their mutual escape velocity, defined as

$$v_{\rm mut}^2 = \frac{2G(M_{B_1} + M_{B_2})}{R_{B_1} + R_{B_2}} \qquad (1)$$

In the simplified case of identical densities ρ for bodies B_1, B_2, and B, one can simplify this equation in terms of mass and radius of the final planet B:

$$v_{\rm mut} = 11.2 \text{ km s}^{-1} \left(\frac{M_{\rm B}}{M_{\oplus}}\right)^{1/2} \left(\frac{R_{\rm B}}{R_{\oplus}}\right)^{-1/2} \frac{(1 + \gamma)^{1/6}}{(1 + \gamma^{1/3})^{1/2}} \qquad (2)$$

where the last factor is within <15% of unity for all $\gamma \leq 10^{-1}$. In our fiducial model, the radii of the fiducial impactors are 3.0 and 6.4 $R_{\oplus}$, respectively. This leads to a fiducial impact velocity >30.6 km s^{-1}. Following Stern (1994) one can calculate the radiative timescale of a long-lived afterglow from the collision of bodies B_1 and B_2:

$$\tau_{\rm rad} \sim 0.33 \text{ Myr} \left(\frac{M_{B_2}}{M_{\oplus}}\right) \left(\frac{R_{\rm B}}{R_{\oplus}}\right)^{-2} T_{1000}^{-4} v_{10}^2 \qquad (3)$$

where v_{10} is the impact velocity of the impactor in units of 10 km s^{-1}, $R_{\rm B}$ is the radius of the planet after collision, $R_{\oplus}$ is the radius of Earth, and T_{1000} is the temperature of the emitting photosphere in units of 1000 K. We can rewrite the radiative timescale in terms of the impactor mass ratio γ, the properties of the final body B, and assuming impact velocity equals $v_{\rm mut}$:

$$\tau_{\rm rad} \sim 0.41 \text{ Myr} \left(\frac{M_{\rm B}}{M_{\oplus}}\right)^2 \left(\frac{R_{\rm B}}{R_{\oplus}}\right)^{-3} T_{1000}^{-4} f \qquad (4)$$

where $f = \gamma(1 + \gamma)^{-2/3}(1 + \gamma^{1/3})^{-1}$. For $\gamma \ll 1$, $f \sim \gamma$ (to within

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[2] The giant planets in our solar system have bulk densities of ~ 0.7–1.4 g cm^{-3}, and the known transiting hot Jupiters have densities of ~ 0.3–1.3 g cm^{-3} (Bakos et al. 2007). The post-accretion evolutionary track of a 1 $M_{\rm Jup}$ object by Marley et al. (2007) has density ~ 0.5–0.6 g cm^{-3} in its first 10 Myr.

TABLE 1
Predicted Quantities for 2M1207B

ρ (g cm^{-3})	Mass ($M_{\oplus}$)	Mass ($M_{\rm Jup}$)	log g (cm s^{-2})
0.5	40.5	0.13	2.83
1.0	81.0	0.25	3.13
1.5	121.5	0.38	3.31
2.0	162.0	0.51	3.43

<40% accuracy for $\gamma < 10^{-1}$). For our fiducial model, $\tau_{\rm rad} > 59$ kyr or ~1% the age of the TW Hya association. These radiative timescales are not negligible and suggest that a hot afterglow could be visible for an appreciable fraction of the system lifetime. In modeling the collision of a Jupiter and an Earth-like protoplanet, Zhang & Sigurdsson (2003) estimate that less than 1% of the impact energy is radiated away in the initial prompt flash. They further argue that most of the collision-deposited energy is locked up deep in the post-collision planet and radiated over a long timescale as an afterglow that peaks in the IR. We propose that 2M1207B is such a long-lived afterglow.

Could a plausible circum(sub)stellar disk form a planetary system with the required properties? The formation and collision of two such large planetesimals at radii >10 AU in a protoplanetary disk surrounding a brown dwarf is very unlikely given the mass surface density and orbital timescales expected (Goldreich et al. 2004). Perhaps 2M1207B formed at smaller radii as the ice line in the disk of 2M1207A swept through a large range of inner radii from 10 to 0.1 AU (cf. Kennedy et al. 2006) as the young brown dwarf evolved (see Boss 2006 for an alternate scenario). If we consider a primordial disk surrounding 2M1207A that is marginally gravitationally stable $[(M_{\rm disk}/M_{\rm A}) \sim 0.1]$, it would have a total gas+dust mass of 2–3 $M_{\rm Jup}$. Adopting the protoplanetary core mass scenario of Ida & Lin (2004; see also Lodato et al. 2005), the time evolution of the mass of a planet accreting 10^{18} g planetesimals is

$$M_p(t) \approx 8 \; M_{\oplus} \left(\frac{t}{10^6 \text{ yr}}\right)^3 \left(\frac{\Sigma_d}{10 \text{ g cm}^{-2}}\right)^{21/5}$$
$$\times \left(\frac{a}{1 \text{ AU}}\right)^{-9/5} \left(\frac{M_{\rm A}}{M_{\odot}}\right)^{1/2}, \qquad (5)$$

where t is time, Σ_d is disk surface density of solids, a is the orbital distance, and $M_{\rm A}$ is the mass of 2M1207A. Assuming a disk with the above mass, mass surface density profile $\Sigma \propto a^{-1}$, and an outer radius of 15 AU, the total disk mass surface density at 3 AU is 250 g cm^{-2}. If we consider a gas to dust+plus ice ratio of 25 (100/4), we arrive at a mass surface density in solids of 10 g cm^{-2} at 3 AU. Using the above equation for a brown dwarf of mass 0.025 $M_{\odot}$, we estimate that a core of 5–10 $M_{\oplus}$ can form within ~3 Myr at this radius. In 10 Myr, a similar mass core could form at a distance of 5 AU from the brown dwarf. Assuming the above disk model parameters, roughly half of the total disk mass (solid and gas) resides inside of 7.5 AU and half outside. It is at least plausible that 2–4 cores of 5–10 $M_{\oplus}$ could form between 1 and 10 AU within 3–10 Myr in this system utilizing the bulk of available solids in the system. If two of those cores accreted enough gas to form Neptune-to-Saturn mass protoplanets, we can envision a scenario in which (1) failed cores of 5–10 $M_{\oplus}$ could collide with a successfully formed gas/ice giant protoplanet, creating the observed hot collisional afterglow and (2) another gas/ice

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giant, along with the presence of the remnant primordial disk, could eject 2M1207B to its observed orbital radius of 50 AU. Motivated by evidence for gas giants at large separations having created observed structure in debris disks, Veras & Armitage (2004) have investigated gas giant migration/ejection scenarios in disks. Thommes et al. (2003) have also proposed that Neptune and Uranus formed closer to the Sun (between Jupiter and Saturn) and were ejected to larger orbital radii through dynamical processes. We note that the remnant disk surrounding 2M1207A has a mass comparable to that we propose for the ejected 2M1207B (Riaz & Gizis 2007), although its outer radius is unconstrained from current observations. This is, of course, a highly improbable series of events.

4. PREDICTIONS

The hypotheses of whether or not 2M1207B is a hot protoplanet collision afterglow or is obscured by a dense disk of large dust grains can be tested. In the scenario proposed here, 2M1207B is actually a $\sim$80 $M_\oplus$ object with radius $\sim$49,000 km. The surface gravity of such an object in cgs units would be log $g \sim 3$ (Table 1). This is significantly lower than that for 5–10 Myr old, 3–8 $M_{\rm Jup}$ objects that have log $g \approx 4$ (Mohanty et al. 2007). If 2M1207B possesses an edge-on disk exhibiting gray extinction, then spatially resolved ground-based observations should reveal (1) an infrared excess at $\lambda > 4$ μm from the disk, (2) a 10 μm silicate absorption feature consistent with the disk being edge-on, (3) polarized emission from scattered light at shorter wavelengths, and/or (4) resolved scattered light emission consistent with an edge-on dust disk system (cf. Luhman et al. 2007b).

If 2M1207B is actually a physically smaller (and therefore lower mass) companion, it should exhibit near-infrared spectra (1) consistent with the 1600 K temperature advocated by Mo-

hanty et al. (2007) and (2) low surface gravity (log $g \sim 3$) in high S/N spectra. As mentioned above, surface gravity affects the spectra of very cool objects in ways that can be observed through analysis of atomic and molecular features. Gorlova et al. (2003; see also Kirkpatrick et al. 2006) suggest that log g can be estimated to within 0.3–0.5 dex from high S/N near-infrared spectra of M and L dwarfs. Allers et al. (2007) specifically investigate the gravity dependence of the Na I feature at 1.14 μm, while Gorlova et al. provide a preliminary calibration of the surface gravity effects of K I at 1.25 μm (see also McGovern et al. 2004). These effects should be clear in modest S/N spectra (20–30) easily distinguishing between the log $g \sim 4$ model of Mohanty et al. (2007) and the log $g \sim 3$ model proposed here. Further, we anticipate that our protoplanetary collision remnant would be metal-rich compared to the primary. Models from Burrows et al. (2006) as well as Fortney et al. (2006) demonstrate the significant differences in brown dwarf and gas giant planet atmospheric models by varying the metallicity. Such effects would be easily observable in S/N $\sim$ 20–30 spectra, obtainable in one to two nights of observing time on a 6–10 m telescope equipped with adaptive optics. Perhaps future surveys will uncover additional hot protoplanet collision afterglow candidates with even smaller inferred masses.

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