Homogeneous comparison of directly detected planet candidates: GQ Lup, 2M1207, AB Pic

Ralph Neuhäuser

Astrophysikalisches Institut, Schillergässchen 2-3, D-07745 Jena, Germany, rne@astro.uni-jena.de

Summary. We compile the observational evidence for the three recently presented planet candidates imaged directly and derive in a homogeneous way their temperatures and masses. For both AB Pic b and 2M1207 b, we derive a larger temperature range than in Chauvin et al. (2004, 2005b) [7] [9]. AB Pic b appears to be quite similar as GQ Lup b, but older. According to the Tucson and Lyon models, all three companions could either be planets or brown dwarfs. According to the Wuchterl formation model, the masses seem to be below the D burning limit. We discuss whether the three companions can be classified as planets, and whether the three systems are gravitationally bound and long-term stable.

1 Introduction: Direct imaging of exo-planets

Direct imaging of planets around other stars is difficult because of the large dynamic range between faint planets very close to much brighter primary stars. Few Myr young planets and young sub-stellar companions in general including both brown dwarfs are much brighter than Gyr old sub-stellar objects because of ongoing contraction and possibly accretion (e.g. Burrows et al. 1997 [4]; Wuchterl & Tscharnuter 2003 [30]).

Below, we will compile the observational evidence published for the three currently discussed exo-planets detected directly, namely around GQ Lup (Neuhäuser et al. 2005a [24]; henceforth N05a), 2M1207 (Chauvin et al. 2005a [8]; henceforth Ch05a), and AB Pic (Chauvin et al. 2005b [9]; henceforth Ch05b). From the published observables, we derive in a homogeneous way the parameters needed for placement in the H-R diagram, i.e. luminosity and temperature. Then, we compare the loci of these three planet candidates with different model tracks to determine the masses.

2 Observational evidence: Three candidates

N05a presented astrometric and spectroscopic evidence for a sub-stellar companion around the well-known classical T Tauri star GQ Lup, for which also radius and gravity could be determined. Chauvin et al. (2004) [7] presented a companion candidate near 2MASSWJ 1207334-393254 (or 2M1207 for short), JHK imaging and a low-resolution, low S/N spectrum (both with AO at the VLT), which still needed astrometric confirmation. Schneider et al. (2004) [26] also detected the companion candidate using the HST/Nicmos a few weeks later, too early for astrometric confirmation (2 σ only). Then, Ch05a published the astrometric confirmation for the two objects (companion candidate and primary object) to have the same proper motion. Also very recently, Ch05b presented evidence for another possibly planetary-mass companion around yet another young nearby star, namely AB Pic.

The directly observed parameters are presented in Table 1, keeping the preliminary designations (*A* for the primary object, *b* for the companion, always regarded as a planet candidate). We also would like to note that both GQ Lup A and AB Pic A are normal stars, while 2M1207 A is a brown dwarf.

Table 1. Observables published

Object	Spec type	J [mag]	H [mag]	K [mag]	L or L' [mag]	distance [pc]
GQ Lup A	K7	8.605 (21)	7.702 (33)	7.096 (20)	6.05 (13)	140 ± 50
GQ Lup b	M9-L4			13.10 (15)	11.7 (3)	
2M1207 A	M8	12.995 (26)	12.388 (27)	11.945 (26)	11.38 (10)	70 ± 20 (*)
2M1207 b	L5-9	≥ 18.5	18.09 (21)	16.93 (11)	15.28 (14)	
AB Pic A	K2	7.576 (24)	7.088 (21)	6.981 (24)		47.3 ± 1.8
AB Pic b	L0-3	16.18 (10)	14.69 (10)	14.14 (8)		

Note: Numbers in brackets are error margins on last digits. (*) Mamajek 2005 [20] give 53 ± 6 pc for 2M1207 A, within the Ch05a error.
Ref.: N05a, Ch05a, Ch05b, 2MASS, Jayawardhana et al. 2003 [15], Chauvin et al. 2004 [7].

3 Derived parameters

Based on the directly observable parameters listed in Table 1, we can now homogeneously derive some other parameters, which are not observable directly. Those other parameters are in particular luminosity and temperature, which are neccessary for placement into the H-R diagramm.

The derivation of temperature from the spectral type also needs the gravity as input (see e.g. Gorlova et al. 2003 [14]). For none of the six objects involved, the gravity is measured directly by high-resolution spectra; only for GQ Lup b, there is a measurement (from a low-resolution spectrum, R$\simeq$ 700). Only one of the six objects is already on the zero-age main-sequence, namely AB Pic A, so that we can assume dwarf gravity. GQ Lup A is a pre-MS star, 2M1207 A a brown dwarf, and the other companions are sub-stellar and, hence, above the main sequence, probably intermediate between dwarfs and giants. Hence, it is best to derive the full possible range in temperature, given several different spectral type to temperature scales. We list the temperature ranges for all available scales in Table 2 - together with the bolometric corrections used to estimate the luminosities, which are also given, as well as absolute K-band magnitudes.

The temperature mean and range for GQ Lup b is almost identical to the one given in N05a (mean $\sim$ 2050 K, range 1600 to 2500 K), where a few scales listed in Table 2 here were not included.

Table 2. Derived parameters for sub-stellar objects involved

Temp. scale below	GQ Lup b	2M1207A	2M1207 b	AB Pic b
Spectral type:	M9-L4	M8	L5-9	L0-3
Luhmann 1999 (a)	≤ 2550	≤ 2720	n/a	< 2550
Reid et al. 1999	2100-1800	~ 2200	2000-1850	2000-1850
Kirkpatrick et al. 2000	2050-1650	n/a	2000-1750	2000-1750
Basri et al. 2000	2500-1850	~ 2500	1750-1600	2250-1950
Stephens et al. 2001	2320-1820	~ 2400	1720-1320	2220-1920
Leggett et al. 2002 (b)	2500-1700	~ 2200	1650-1150	2350-1650
Burgasser et al. 2002	2300-1740	~ 2400	1625-1170	2190-1850
Dahn et al. 2002	2500-1900	~ 2550	1900-1300	2400-1950
Nakajima et al. 2004	2520-1830	~ 2650	1690-1140	2380-1970
Golimowski et al. 2004	2400-1600	~ 2500	1950-1100	2400-1600
mean	2060 ± 180	2425 ± 160	1590 ± 280	2040 ± 160
range	2520-1600	2650-2200	2000-1100	2400-1600
M_K [mag]	7.37 ± 0.96	7.72 ± 0.66	12.70 ± 0.75	10.77 ± 0.14
B.C.$_K$ (*)	3.3 ± 0.1	3.1 ± 0.1	3.25 ± 0.1	3.3 ± 0.1
log $L_{bol}/L_\odot$	-2.37 ± 0.41	-2.43 ± 0.20	-4.49 ± 0.34	-3.730 ± 0.039

Remarks: (a) Luhman 1999 [19] intermediate scale; (b) compilation in Leggett et al. (2002) [17]; n/a for not applicable; all temperatures are given in [K], (*) bolometric correction B.C.$_K$ in [mag] for the K-band according to Golimowski et al. (2004) [13].

Chauvin et al. (2004) [7] derive the age of 2M1207 A by assuming it to be co-eval with the mean TWA age and then assume that 2M1207 b has the same distance and age. For 2M1207 b, Chauvin et al. (2004) [7] give a temperature of only 1250 ± 200 K, obtained from the absolute magnitudes in H, K, and L' with Chabrier et al. (2000) [5] and Baraffe et al. (2002) [1]; apparently, this temperature range is obtained from *http://perso.ens-lyon.fr/isabelle.baraffe/DUSTY00* models for 10 Myrs, roughly the age of the TW Hya association. They also obtain 1000 to 1600 K from Burrows et al. (1997) [4] for 70 pc and 5-10 Myrs age. Hence, they have obtained the temperature from uncertain models tracks and an assumed distance and age, and not from converting the observed (distance-independant) spectral type to a temperature. Our temperature range is larger and its upper limit is shifted to higher values compared to Chauvin et al. (2004) [7]. The situation is similar for AB Pic b, for which we obtain a temperature of 2040 ± 160 K from its spectral type and considering all scales (table 2). Ch05b, however, only use the models by Burrows et al. (1997) [4] yielding 1513 to 1856 K and Chabrier et al. (2000) [5] and Baraffe et al. (2002) [1] giving 1594 to 1764 K. Hence, one could conclude that the models underestimate the temperature.

On the other hand, if one gives a correct absolute magnitude (or luminosity) as input (assuming a correct distance), and also taking into account that the Lyon models used in Ch05b were previously found to *under*estimate the radii (Mohanty et al. 2004 [21]), one would expect that the resulting temperature is an *over*estimate. This shows that the determination of the temperature should be done with great care under full consideration of the young age and, hence, low gravity of the involved objects.

4 Mass determination by model tracks

Once temperatures, absolute magnitudes, and luminosities are determined homogeneously, we can derive the masses of the objects, see Table 3.

Table 3. Masses of sub-stellar objects involved (masses in [M_{jup}])

Model Reference	Figure used	Input parameters	Object GQ Lup b	2M1207 A	2M1207 b	AB Pic b
		(age used:)	1-2 Myr	5-12 Myr	5-12 Myr	30-40 Myr
masses derived from temperatures and ages:						
Burrows et al. 1997	Fig. 9/10	T & age	4-15	14-25	4-14	13-25
Chabrier et al. 2000	Fig. 2	T & age (a)	≤ 20	15-25	≤ 15	15-30
Baraffe et al. 2002	Fig. 2	T & age (b)	3-16	15-25	2-12	12-50
Baraffe et al. 2002	Fig. 3	T & age	5-30	20-45	≤ 20	15-30
Wuchterl model	(f)	T & age	1-3	1-5	n/a (c)	n/a (c)
masses derived from luminosities and ages:						
Burrows et al. 1997	Fig. 7	L & age	12-32	20-30	2-10	14-15
Baraffe et al. 2002	Fig. 2	L & age	12-42	12-30	2-5	~ 20
Baraffe et al. 2002	Fig. 3	L & age	10-30	10-50	n/a (c)	n/a (c)
Baraffe et al. 2002	(b)	L & age	18-50	25-60	3-6	11-18
Wuchterl model	(f)	L & age	1-3	1-5	n/a (c)	n/a (c)
masses derived from luminosities and temperatures (H-R diagram):						
Burrows et al. 1997	Fig. 11	L & T	≤ 15	≤ 25	2-70 (d)	2-70 (d)
Baraffe et al. 2002	Fig. 1	L & T	≤ 20	≤ 20	n/a (d)	n/a (d)
Baraffe et al. 2002	Fig. 6	L & T	≤ 30	10-35	n/a (c)	n/a (e)
Wuchterl model	(f)	L & T	1-3	1-5	n/a (c)	n/a (c)

Remarks: n/a for not applicable, (a) Similar for Dusty, Cond, and NextGen, (b) see also http://perso.ens-lyon.fr/isabelle.baraffe/DUSTY00 models, (c) outside of range plotted or calculated, (d) full mass range possible; for additional contraint of assumed age, i.e. to be located on the correct isochrone, the mass would be ≤ 20 M_{jup}, (e) ≤ 60 M_{jup} from L & T in Fig. 8, (f) Fig. 4 in N05a.

Table 3 shows that for all three planet candidates, there is a large mass range when employing the full possible range of luminosities, temperatures, and age, at least when using the Lyon or Tucson models. For 2M1207 b, those models tend to give masses below ~ 20 M_{jup} from luminosities, temperatures, and age, but higher masses are not excluded.

For young objects as the ones considered here, one has to take into account the formation, i.e. initial conditions matter, so that models starting with an assumed internal structure are highly uncertain. Stevenson (1982) [28] wrote about such collapse calculations: *Although all these calculations may reliably represent the degenerate cooling phase, they cannot be expected to provide accurate information on the first* 10^5 *to* 10^8 *years of evolution because of the artificiality of an initially adiabatic, homolously contracting state.*

Baraffe et al. (2002) [1] also wrote that *assinging an age* (or mass) *to objects younger than a few Myrs is totally meaningless when the age is based on models using oversimplified initial conditions.*

Chabrier et al. (2005) [6] assertain that *both models and observations are hampered by nummerous uncertainties and great caution must be taken when considering young age (≤ 10 Myr) objects.*

Chauvin et al. (2004) [7] state in their section 3.5 ... *although the models are reliable for objects with age ≥ 100 Myr, they are more uncertain at early phases of evolution (≤ 100 Myr). As described by Baraffe et al. (2002), the choice of the initial conditions for the model adds an important source of uncertainty which is probably larger than the uncertainties associated with the age and distance of 2M1207. ... We then consider the new generation of models developed by Chabrier et al. (2000) and Baraffe et al. (2002) ...* (to determine the mass of 2M1207 b).

Table 4. Summary of parameters for the three planet candidates

Parameter	Objects		
	GQ Lup b	2M1207 b	AB Pic b
distance [pc]	140 ± 50	70 ± 20:	47.3 ± 1.8
membership	Lupus I	TWA (?)	TucHorA
age [Myr]	≤ 2	5-12:	30-40
epoch difference [yr]	5	1	1.5
separation	0.7", 100 AU	0.8", 54 AU	0.5", 258 AU
sign. for CPM (1) [σ]	$6+4+7$	$2+2+4+4$	$3+5$
remaining motion A/b [mas/yr]	1.4 ± 2.2	4.1 ± 8.2	6.9 ± 13.2
orbital motion exp. [mas/yr]	3.7 ± 1.5	1.9 ± 0.6	6.9 ± 0.4
escape velocity exp. [mas/yr]	5.2 ± 2.1	2.7 ± 0.9	9.8 ± 0.6
long-term stable ? (2)	yes	no	yes
SpecType	M9-L4	L5-L9.5	L0-3
spectrum resolution	700	< 700	700
spectrum S/N ratio	45	low	high
$T_{\rm eff}$ [K]	2520-1600	2000-1100	2400-1600
gravity $\log g$ [cgs]	2.0-3.3 (3)	unknown	unknown
radius [$R_{\rm jup}$]	1.2 ± 0.6 (4)	unknown	unknown
M_K [mag]	7.37 ± 0.96	12.70 ± 0.75	10.77 ± 0.14
$\log L_{bol}/L_\odot$	-2.37 ± 0.41	-4.49 ± 0.34	-3.730 ± 0.039
mass [$M_{\rm jup}$] Lyon/Tucson	1-42	2-70	11-70
mass [$M_{\rm jup}$] Wuchterl	1-3	n/a (5)	n/a (5)

Remarks: (1) significance for common proper motion in Gaussian σ; (2) according to criteria in Weinberg (1987) [29] and Close et al. (2003) [10] (3) from fit to theoretical GAIA-dusty template spectrum; (4) from fit to spectrum with flux and temperature known; (5) not applicable, because outside of plotted or calculated range.

Ref.: this paper, N05a, Mugrauer & Neuhäuser 2005 [22], Ch05a, Ch05b, Hipparcos.

Ch05b write in their section 5 ... *as described in Baraffe et al. (2002), model predictions must be considered carefully as they are still uncertain at early phases of evolution (≤ 100 Myrs; see also Mohanty et al. 2004 and Close et al. 2005). We then considered the most commonly used models of Burrows et al. (1997), Chabrier et al. (2000), and Baraffe et al. (2002) ...* (to determine the mass of AB Pic b).

It is surprising that Chauvin et al. (2004) [7] and Ch05b first ascertain that the Lyon (Chabrier et al. 2000 [5] and Baraffe et al. 2002 [1]) and Tucson (Burrows et al. 1997 [4]) models, which both do not take into account the collapse and formation, are not applicable for 2M1207 and AB Pic, and then use them. Given the fact that these models are not applicable, as correctly stated by Chauvin et al. (2004) [7] and Ch05b, one has to conclude that the temperatures and, hence, masses of 2M1207 b and AB Pic b were essentially undetermined.

The model by Wuchterl & Tscharnuter (2003) [30] for stars and brown dwarfs does take into account their formation, so that it can be valid for very young objects. The tracks for planets shown in Fig. 4 in N05a are calculated based on the nucleated instability hypothesis (Wuchterl et al. 2000 [31]).

Finally, we would like to point out, that neither distance nor age are directly derived parameters in the cases of the companions, and that only the distance towards AB Pic A is determined directly as parallaxe by Hipparcos. In all three cases, the age and distance of the companion is assumed to be the same as for the primary because of common proper motion. However, there are counter-examples.

5 Summary and discussion on planethood

We compile all information relevant for our discussion in Table 4.

Gravitationally bound ? While the remaining possible motion between GQ Lup A and b (change in separation and position angle) is smaller than both the expected orbital motion and the expected escape velocity, this system may well be gravitationally bound. This may be different for 2M1207 A+b: The remaining motion between the two objects may be larger than the expected escape velocity (Table 4), so that it is not yet shown to be bound. The GQ Lup system has a total mass and bounding energy sufficient for being long-term stable according to the criteria by Weinberg et al. (1987) [29] and Close et al. (2003) [10], while the 2M1207 system is not – too low in mass(es) for the given separation. See Mugrauer & Neuhäuser (2005) [22] for a discussion. 2M1207 A+b, if formed together and if still young, may be an interesting case as a low-mass binary just desintegrating. The remaining motion between the AB Pic A and b is not yet shown to be smaller than the expected escape velocity (Table 4), so that is not yet shown to be bound, but it could be stable.

Masses: Chauvin et al. (2004) [7] and Ch05b may have underestimated the range in possible temperatures of both 2M1207 b and AB Pic b by using models rather than spectral type to temperature conversions.

According to the Lyon and Tucson models, GQ Lup b and 2M1207 b may either be planet or brown dwarf, while AB Pic b would be a low-mass brown dwarf. According to both the Wuchterl model and our K-band spectrum compared with the Hauschildt GAIA-dusty model, GQ Lup b is a planet; the mass, age, and planethood of AB Pic b and 2M1207 b cannot yet be discussed using the Wuchterl model, because it is not yet available in the neccessary parameter range regarding temperatures, luminosities, and ages (outside the range in fig. 4 in N05a). An extrapolation would indicate that AB Pic b has a mass around one Jupiter mass, but it is probably much harder to form a one Jupiter mass object at 258 AU separation (AB Pic b) than at 100 AU separation (GQ Lup b). 2M1207 A, according to the Wuchterl model, appears to be below the D burning mass limit at roughly a few Jupiter masses. It would need to be more nearby and/or older to be above 13 M_{jup}.

Lodato et al. (2005) [18] argue that 2M1207 system may rather be seen as a binary pair of two very low-mass objects than a planet around a primary, due to the similar masses of both objects at the given relatively large separation. A several Jupiter mass object at 55 AU separation could not have formed by planet-like core accretion from a (low-mass) disk around a brown dwarf such as 2M1207 A. GQ Lup b may have been able to form as a planet at 100 AU separation around an almost solar-mass star (Lodato et al. 2005 [18]), while AB Pic b with 258 AU separation is again to far off.

The GQ Lup b K-band spectrum resembles well the spectra of isolated, free-floating young objects previously classified as brown dwarfs. However, the mass range of brown dwarfs and planets may well overlap: The Saturnian moon Titan has both a solid core and an atmosphere. It is regarded as a moon, because it orbits Saturn, a planet. If Titan would orbit the Sun directly (without other objects of similar mass in a similar orbit), it would be regarded a planet. The mass range of moons and planets overlaps. Analogously, if an object below 13 Jupiter masses with a solid or fluid core formed in a disk and orbits a star, then its a planet, otherwise a low-mass brown dwarf.

Those young objects with similar spectra as GQ Lup b were classified as 13 to 78 Jupiter mass brown dwarfs based on Tucson or Lyon models, which may not be valid until at least 10 Myrs, as recently specified in Chabrier et al. (2005) [6]. Hence, they may be lower in mass, maybe around a few to 10 Jupiter masses. If GQ Lup b has the same spectrum and mass as those young free-floating objects, the free-floating objects may be low-mass brown dwarfs (or planemos), because they are free-floating, while GQ Lup b with the same mass can be a planet, namely if formed with a core in a disk.

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