GQ Lup and its companion

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Abstract

In 2005 Neuhäuser et al. published the discovery of a companion of the classical T Tauri star GQ Lup. The companion is co-moving an has a T_{eff} between 1800 and 2400 K. An analysis of the currently available data on young brown dwarfs and stars shows a large spread in temperature and luminosity even for objects of identical mass and age. The determination of the mass of a young object based on temperature and luminosity thus is difficult in general. This is especially the case, when only the temperature is used in order to determine the mass of a young low-mass object. A comparison of the luminosity and temperature of the companion of GQ Lup with objects of similar age nevertheless implies that the object possibly has a mass of $\leq$ 30 $M_{Jupiter}$. It is henceforth pointed out that because the object is young and has a low mass, it may help us understanding how such objects can form as companions to stars. Thus, in this article not only the basic properties of the object are described but also possible formation scenarios discussed.

1 Introduction

Classical T Tauri stars (henceforth called cTTSs) are young, low mass, optically visible pre-main sequence emission line stars, which, whilst formally classified in terms of the equivalent width of their $H\alpha$ emission, have an accretion disk. Weak-line T Tauri (WTTSs) stars are similar to the classical ones but at least have much smaller accretion rates, and less massive disks. Typical accretion rates of cTTSs are of the order of $10^{-8}\, M_{\odot}\, yr^{-1}$. Given their location above the main sequence in the Hertzsprung-Russell Diagram, their age has been estimated to be of the order of 1 Myr. Thus, while cTTSs represent the only late accretion phase in the formation of a star, they are excellent tools to study the formation of low-mass stars, because detailed studies at many different wavelength regions are possible. cTTSs are located in loose T- or R-associations as well as in dense OB associations.

As pointed out by Kouwenhoven et al. (2005), practically all (70–90%) stars form in clusters and within these clusters most stars are formed as binaries. The duplicity and multiplicity properties of newly born stars are among the most important

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clues for understanding the process of star formation. This is because the dynamical evolution is unable to pair stars efficiently, which leads to the conclusion that star-forming cores must usually fragment into ≥ 2 stars (Goodwin & Kroupa 2005). Studies of stars in the solar neighbourhood show that $13 \pm 3\%$ of the G stars, and 8.1% of the M stars are binaries with separation of $\leq$ 3 AU (Mazeh et al. 1992; Fischer & Marcy 1992).

The frequency of planets with a mass of $m\,sin\,i \geq 0.3\,M_{\rm Jupiter}$ orbiting at distances ≤ 5 AU is about 9% (Lineweaver & Grether 2003). It is thus quite surprising that in contrast to stellar and planetary companions brown dwarfs are very rare as close companions to normal stars. This lack of brown dwarfs as companions is thus often referred as the brown dwarf desert. Marcy et al. (2003) estimate from their radial velocity survey that the frequency of brown dwarfs with 3 AU of the host stars is only $0.5 \pm 0.2\%$. However, the population of planets does not drop off sharply at the 13 $M_{\rm Jupiter}$-boundary but tails off more slowly up to an $m\,sin\,i$ of 20 $M_{\rm Jupiter}$. From the currently known 170 "planets" 8 have an $m\,sin\,i$ between 10 and 18 $M_{\rm Jupiter}$ (Strictly speaking, most these objects will be brown dwarfs, or at least very likely so.). It is thus in the 20 to 80 $M_{\rm Jupiter}$-regime were the objects are missing, not in the 10 to 20 $M_{\rm Jupiter}$-regime. HD 137510 B is in fact one of the few brown dwarfs companion with a mass of about 30 $M_{\rm Jupiter}$ were the mass was determined by mean of radial velocity and astrometric measurements (Endl et al. 2004).

In the case of wide pairs consisting of a brown dwarf and a star, the situation is more complicated. These wide companions (e.g. $d \geq$ 50 AU) are detected by means of direct imaging. Direct imaging campaigns probably have turned up quite a number of brown dwarfs orbiting normal stars. The result of all search programs in TWA-Hydra, Tucanae, Horologium and the β Pic region is that the frequency of brown dwarfs at distances larger than 50 AU is $6 \pm 4\%$ (Neuhäuser et al. 2003). This result implies that the frequency of wide binaries consisting of a brown dwarf and a star is much higher than that of close binaries. One possible explanation for this result may simply be the difference in the methods used for detecting short and long period systems. In the case of the long-period systems, the masses of these objects were determined by combining the observed luminosity and temperature with evolutionary tracks. If for some reason the evolutionary tracks are off by a certain factor, a number of these brown dwarfs would be stars. There are in fact notable differences between evolutionary tracks published by different authors, especially for objects of low mass, and young ages. A recent determination of the dynamical mass of AB Dor C indicates that the true mass is a factor of two higher than the mass derived from evolutionary tracks, converting this brown dwarf into a star (Close et al. 2005). On the other hand, in the case of binary brown dwarf GJ 569 Bab the true mass and the mass derived from evolutionary tracks agree reasonably well (Zapatero Osorio et al. 2004). In contrast to the results obtained for young stars, a study of old, isolated G, K, and M stars indicates also a lack brown dwarf as wide companions. McCarthy & Zuckerman (2004) derive a frequency of $1 \pm 1\%$ for brown dwarfs orbiting old stars between 75 and 300 AU. Long period brown dwarf companions must also show up as trends in radial velocity surveys. Thus, a good strategy for finding long period brown dwarfs is to image with an AO-system all stars that show radial velocity trends. This approach was recently applied to the Hyades. After monitoring the radial velocity of 98 Hyades dwarf stars for 5 years, all stars that showed a trend were imaged with NACO on the VLT (Guenther et al. 2005a). The result was that all stars showing a trend were either binary stars, or active stars. From this survey, the number of companions with masses between 10 M_{Jupiter} and 70 M_{Jupiter} within 8 AU of the host stars in the Hyades was estimated to $\leq 2\%$.

In summary: we know that most stars form in binary-systems, which implies that star-forming cores must usually fragment into ≥ 2 objects. We also know that many stars have planets which presumably formed in a disk. In contrast to this, brown dwarfs as close companions to stars are rare but possibly not so rare as wide companion. Last not least, we also know that the population of planets does not stop at the 13 M_{Jupiter}-limit but extends up to ~ 20 M_{Jupiter} into the brown dwarf regime.

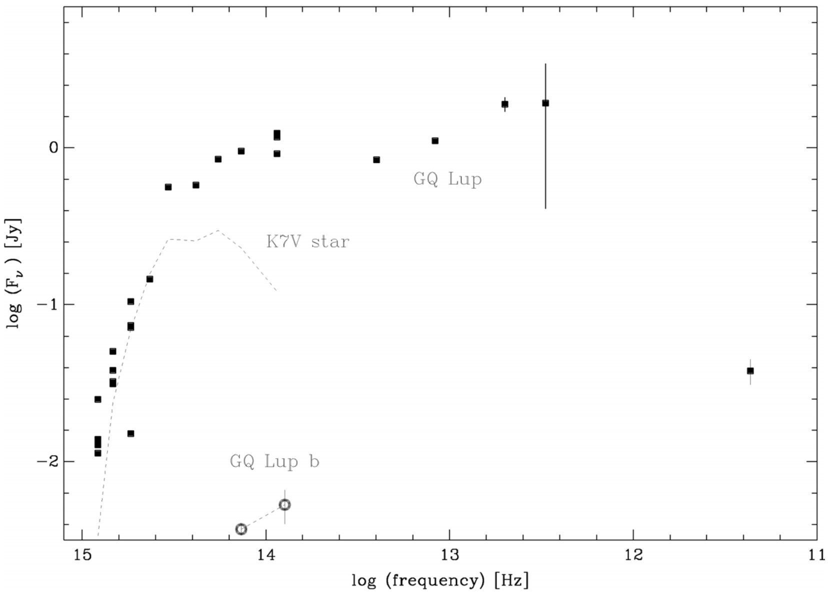

Figure 1: The spectral energy distribution of GQ Lup as derived by using all photometric measurements taken from the literature. Also shown are the two photometric measurements of the companion, and a K7V star with a diameter of 1.5 $R_\odot$ located at a distance of 140 pc.

The crucial question thus is, how do massive planets and brown dwarf form as companions to stars? Do they form via fragmentation like binary stars, or in a disk, like planets? Of course, it would be very interesting to learn more about how a massive planet, or brown dwarf forms. This will certainly help us understanding the formation of brown dwarfs and planets in general. Recently, Neuhäuser et al. (2005) has identified a companion of the cTTS GQ Lup which may help to better understand the formation of low-mass companions to young stars. In this article not only the previous knowledge on the object will be summarised but the data will be interpreted in the context of new results.

2 GQ Lup

GQ Lup is a cTTS of YY Orionis type located in the Lupus I star-forming region. Quite a number of authors have determined the distance to this star-forming region: Hughes et al. (1993) derive a distance of 140 ± 20 pc, Nakajima et al. (2000) 150 pc, Sartori et al. (2003) 147 pc, Franco et al. (2002) 150 pc, de Zeeuw et al. (1999) 142 ± 2 pc, and Teixeira et al. (2000) 85 pc but note that 14 stars of their sample have measured parallax-distances, which are on average 138 pc. In contrast

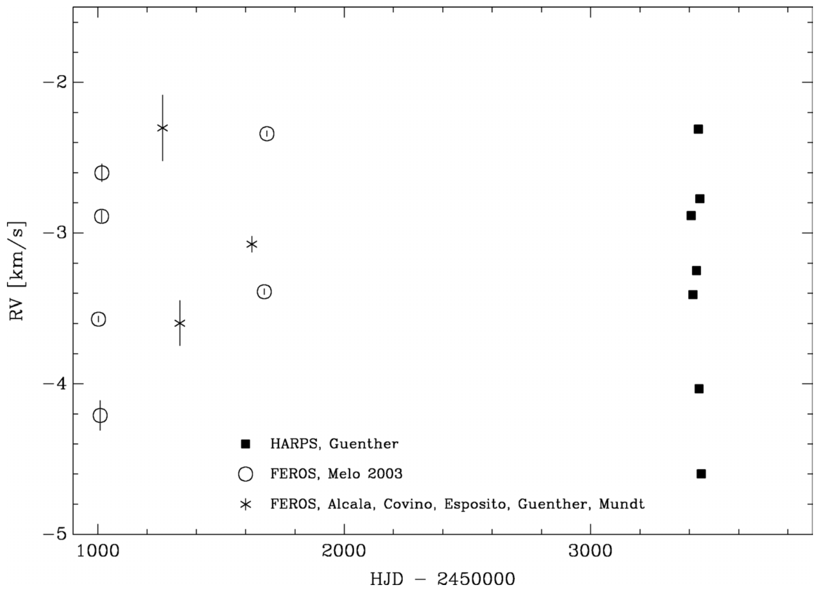

Figure 2: The radial velocity measurements of GQ Lup taken with FEROS and HARPS and taken from the literature (Melo 2003). The radial velocity variations are quite typical for a cTTS.

Figure 2 shows the radial velocity variations obtained for GQ Lup with HARPS and FEROS. The peak-to-peak variation is about 3 $km\,s^{-1}$. Such variation are quite typical for a T Tauri star, and usually interpreted as being caused by activity (Guenther et al. 2001a). No significant periodicity was found in the radial velocity data. Given the galactic coordinates of $l = 338.93°$ $b = +14.51°$, GQ Lup sits at the outer edge of the Lupus star formation region in the direction of the ρ Oph region. The average radial velocity is $-2.8 \pm 0.2\,km\,s^{-1}$ which is quite typical for an object in the Lupus star formation region (Sartori et al. 2003).

to this, Knude & Høg (1998) find a value of 100 pc. For the time being a distance of 140 pc will be assumed in the following but it will also be discussed how the picture changes for 100 pc. The spectral type of GQ Lup is K7V. Batalha et al. (2001) find a veiling between 0.5 and 4.5 and an extinction A_V of 0.4 ± 0.2 mag, which implies an $A_K = 0.04 \pm 0.02$ mag, and $A_L = 0.02 \pm 0.01$ mag. The $v\,sin\,i$ of GQ Lup is $6.8 \pm 0.4\,km\,s^{-1}$, assuming a Gaussian turbulence velocity of 2 $km\,s^{-1}$, and assuming a solar-like centre to limb variation. The broad-band energy distribution of

GQ Lup is shown in Fig. 1 together with a K7V star of 1.5 $R_\odot$ located at 140 pc. In the optical, the data fits nicely to a star with low to medium veiling, as observed. In the infrared, a huge excess due to the disk is seen.

3 The companion of GQ Lup

3.1 Astrometric and photometric measurements

As described in more detail in Neuhäuser et al. (2005), and Mugrauer & Neuhäuser (2005), the companion candidate is separated by 732.5 ± 3.4 mas with a positional angle of $275.45 \pm 0.30°$. Since the separation and positional angle did not change within five years, the pair seems to have a common proper motion, and thus is likely to be a real companion. The projected distance of the companion is about 100 AU.

Using the extinction to the primary, and assuming a distance of 140 pc, the observed brightness of $m_{K_s} = 13.1 \pm 0.1$, and $m_{L'} = 11.7 \pm 0.3$, gives an absolute magnitudes of $M_{K_s} = 7.4 \pm 0.1$ and $M_{L'} = 6.0 \pm 0.3$ mag for the companion. According to Golimowski et al. (2004) the bolometric correction BC_K is 3.17 ± 0.06 and 3.38 ± 0.06 for objects with spectral types of M9 and L4V, respectively. With $M_K = 7.4 \pm 0.1$, this gives an $M_{bol} = 10.7 \pm 0.2$, or $\log(L/L_\odot) = -2.38 \pm 0.08$, assuming a distance of 140 pc (that is, not taking the error of the distance into account), and assuming that there is no contribution from the disk, or accretion. As was already pointed out in Guenther et al. (2005b), the observed depths of the CO-lines are a factor of two smaller than those calculated with the GAIA-dusty models (Brott & Hauschildt, 2006). It is thus possible that there is a considerable amount of veiling. If we assume that 50% of the radiation is such a contribution, the luminosity goes down to $\log(L/L_\odot) = -2.7$. If we further assume that the distance would be only 100 instead of the canonical 140 pc, we would obtain only $\log(L/L_\odot) = -3.0$.

3.2 The spectrum of the companion

Using NACO, two spectra of the companion were obtained. The first spectrum was taken on August 25, 2004, the second on September 13, 2004. The first spectrum had a S/N-ratio of only 25, that is why it was repeated. The second spectrum has a S/N-ratio 45, and thus is noticeably better than the first. Figure 3 shows the averaged spectrum. For the observations we used $S54\,SK$-grism and a slit width of 172 mas which gives a resolution of about $\lambda/\Delta\lambda = 700$. Because the Strehl ratio, as well as the refraction depends on wavelength, the flux-loss in the blue and in the red part of the spectrum may differ if a very narrow slit is used. However, since we used a relatively wide slit, and observed airmass 1.24, and 1.30 respectively, this effect is only 1.5% for the wavelength region between 1.8 and 2.6 µm.

There are several classical methods as to derive the spectral types of late-type objects from spectra taken in the K-band. Using the K1-index from Reid et al. (2001) (K1=[2.10-2.18]-[1.96-2.04]/(0.5*[2.10-2.18]+[1.96-2.04]); Sp -2.8 + K1*21.8), we find spectral types in the interval M9V to L3V, using the two spectra and using different methods for the flux calibration. Using the $H_20 - D$-coefficient from McLean

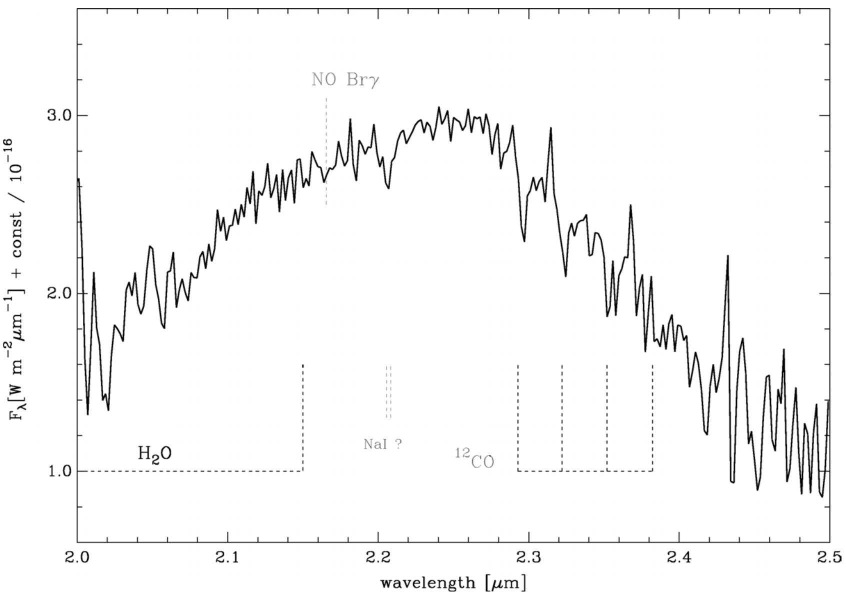

Figure 3: The K-band spectrum of the companion of GQ Lup.

et al. (2003) which is simply the flux ratio between 1.964 to 2.075 μm, we derive spectral types in the range between L2V to L4V. However, this coefficient is known to have an accuracy of only one spectral class. In order to be on the save side, we thus estimate the spectral type to be between M9V to L4V. Another piece of evidence is the NaI lines at 2.2056 and 2.2084 μm. These line vanishes at a spectral types later than L0V. Unfortunately, there is a telluric band between 2.198 and 2.200 μm, which is difficult to distinguish from the NaI lines in a low resolution spectrum. We thus can only give an upper limit of 3 Å for the equivalent width of the NaI doublet. Using the conversion from spectral type to $T_{\rm eff}$ from Basri et al. (2000), Kirkpatrick et al. (1999), and Kirkpatrick et al. (2000), this range of spectral types corresponds to $T_{\rm eff}$-values in the range between 1600 to 2500 K.

The expected K-L'-colours of an object with a spectral type M9V to L4V are between 0.5 and 1.2 mag, which matches reasonably well the derived K-L'-colour of 1.4 ± 0.3 of the companion (Golimowski et al. 2004). Using the extinction to the primary, and assuming a distance of 140 pc, we derive from the observed brightness of $m_{K_s} = 13.1 \pm 0.1$, and $m_{L'} = 11.7 \pm 0.3$, absolute magnitudes of $M_{K_s} = 7.4 \pm 0.1$ and $M_{L'} = 6.0 \pm 0.3$ mag for the companion (Fig. 1). Old M9V to L4V objects have M_K-values between 9.5 to 12 mag and $M_{L'}$-values between 9.8 and 10.5 mag. The companion thus is much brighter than old M, or L-dwarfs (Golimowski et al. 2004). When discussing the brightness of the companion, we have to keep in mind that there are three additional effects that may lead to large absolute magnitudes, apart from the young age of the object: The first one simply is that it could be a binary. The second is that the distance could be much smaller than 140 pc. The third possibility is that the brightness is enhanced due to accretion and a disk, like in cTTSs. In this respect it is interesting to note that objects of similar age and spectral type often have disks and show signs of accretion. Typical accretion rates are about $10^{-11}\ M_\odot yr^{-1}$ (Liu et al. 2003; Natta et al. 2004; Mohanty et al. 2005; Muzerolle et al. 2005). Clear signs of accretion are observed even down to the planetary-mass regime at young ages (Barrado y Navascués et al. 2002). The fact that we do not see the $Br\gamma$-line in emission does not speak against the accretion hypothesis, as the flux of this line is correlated with the accretion rate, and at $10^{-11}\ M_\odot yr^{-1}$, we do not expect to see it (Natta et al. 2004). The accretion hypothesis is further supported by the fact that objects with spectral types of late M in Taurus have $K_s - L'$-colours up to 1.2 mag, and absolute luminosities of $M_K = 6$ to 7, and $M_{L'} \sim 6.0$. The large luminosities and red colours of these objects are usually interpreted as being caused by disks and accretion (Liu, et al. 2003; Luhmann 2004). The absolute magnitudes of the companion of AB Pic of $M_J = 12.8^{+1.0}_{-0.7}$, $M_H = 11.3^{+1.0}_{-0.7}$, $M_K = 10.8^{+0.9}_{-0.7}$ are also quite similar to the companion of GQ Lup. Thus, the companion of GQ Lup is quite normal for a low-mass object of this age, and we should keep in mind that it is possible that there is a disk, and accretion.

3.3 Comparing the spectrum with GAIA-dusty models

Up to now the spectrum of the companion of GQ Lup was compared with spectra of old brown dwarfs which have a $\log(g) \sim 5.0$. Thus, one may wonder, whether this causes a problem for the determination of the spectral type. In order to derive $T_{\rm eff}$ it would be better to compare the observed spectrum with spectra of different $\log(g)$. The only way to do this, is to compare the observed spectrum with model calculations. To do this, we use the GAIA-dusty models (Brott & Hauschildt 2006).

Figure 4 shows the flux-calibrated spectrum together with two models. Both are calculated for a temperate of 2900 K. One is for $\log(g) = 0$ and the other for $\log(g) = 4.0$. While the model with $\log(g) = 4.0$ reproduces nicely the ^{12}CO-lines and to the NaI doublet at 2.205 and 2.209 μm, it does not fit to the H_2O-band in the blue part of the spectrum. The object thus is presumably cooler than this. Also, if the $T_{\rm eff}$ were 2900 K, the radius of the object would be only $\sim 1.0\ R_{\rm Jupiter}$.

Figure 5 shows the flux-calibrated spectrum together with two models calculated for a $T_{\rm eff}$ of 2000 K. Judging just from the shape of the spectrum, the three models almost perfectly match the observed spectrum. The fit seems to be better for the two models with $\log(g) = 2.0$ and $\log(g) = 4.0$. We can do this comparison a little more quantitatively. However, given the cross-talk between $\log(g)$ and $T_{\rm eff}$, and given that only a spectrum with a resolution of $\lambda/\Delta\lambda$ of 700 is available, the currently achievable accuracy of the determination of $\log(g)$ and $T_{\rm eff}$ is rather limited. The $T_{\rm eff}$-values in the range between 1800 and 2400 K give good fits, in excellent agreement with the previous temperature estimate. However, as can easily bee seen, the ^{12}CO-lines are always a factor two deeper in the model than in the spectrum. If we assume that this difference is caused by veiling due to the presence of the disk, the radius of the companion would be 1.2 to 1.3 $R_{\rm Jupiter}$. If we assume that there is no veiling, the object would have a radius of 1.7 to 1.8 $R_{\rm Jupiter}$. It is interesting to note that the depth of the ^{12}CO-lines in the spectrum of GQ Lup is the same as in the case of the companion of AB Pic. This means that either both have the same veiling, or the ^{12}CO-lines in the models are too deep.

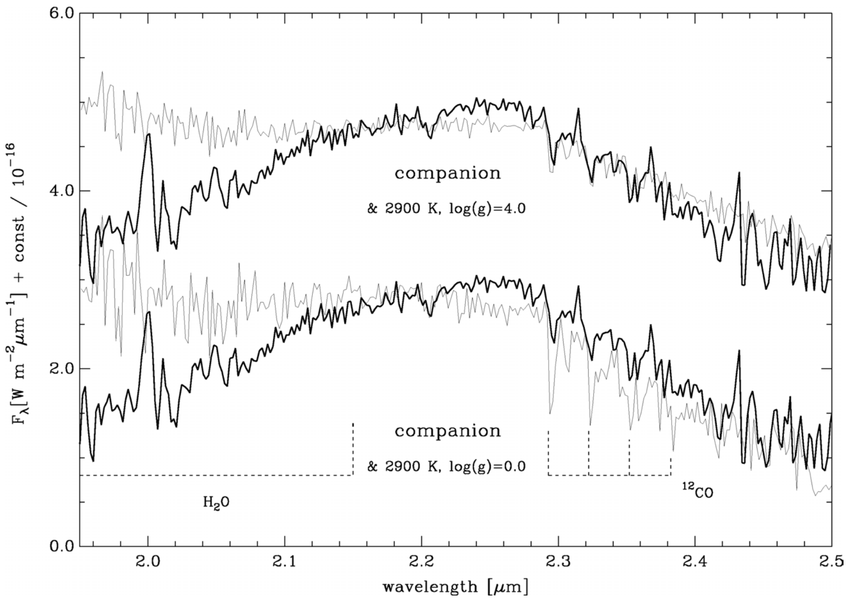

Figure 4: A flux calibrated spectrum of the companion of GQ Lup together with the GAIA-dusty models. The thick lines are the observed spectrum, the thin lines are models calculated for $T_{\rm eff} = 2900$ K and $\log(g) = 0$, and $\log(g) = 4.0$. For clearness the spectrum for $\log(g) = 4.0$ is moved upwards by $2\,10^{-16}\,{\rm Wm}^{-2}\,\mu{\rm m}^{-1}$. While this model fits nicely to the CO-lines, it does not reproduce the slope in the blue part of the spectrum.

3.4 Trying to get a mass

Using various evolutionary tracks, Neuhäuser (2005) gave a first mass estimate of GQ Lup in the range between 1 and 42 $M_{\rm Jupiter}$. Is it possible to narrow down the estimate a bit? In order to derive a mass for the companion of GQ Lup, one would ideally compare it with an object of known mass that has the same age, temperature and luminosity. The closest match is the eclipsing binary brown dwarf 2MASSJ 05352184-0546085 which was recently identified by Stassun et al. (2005). This binary is in the Orion Nebula cluster, so that the age of this object is roughly the same as that of GQ Lup. The mass of the two components are 0.00541 ± 0.0046 and $0.0340 \pm 27\ M_\odot$. Reading the values from their figure 3, the $T_{\rm eff}$ of the two brown dwarfs seem to be about 2700 ± 150 and 2800 ± 150 K, and thus a bit higher than that of the companion of GQ Lup. Interestingly, the more massive component is the cooler one. Figure 6 shows the masses and temperatures for stars and brown dwarfs in the Corona Australis, Orion, and upper Scorpius region for which the true masses have been derived. Also shown in this figure are the evolutionary tracks from Baraffe et al. (1998) for an age of 10 Myr, Baraffe et al. (2002) for an age of 1 Myr, and Burrows et al.

(1997) also for an age of 1 Myr. While the objects in Corona Australis, Orion should have about the same age as that of GQ Lup, the objects in upper Sco are a bit older (6–7 Myr). Shown as black squares in the figure are the eclipsing binaries, and one object were the mass was determined astrometrically, in the Corona Australis and Orion region (Casey et al. 1998; Steffen et al. 2001; Covino et al. 2004; Stassun et al. 2004). It is interesting to note that in general the eclipsing binaries are WTTSs so that there is little or no contribution from the disk, making the determination of the luminosity easier than in the case of cTTSs. Also, because WTTSs do not accrete matter (or at least much less than a cTTSs), these objects are less variable than the cTTSs. The data of the eclipsing binary AK Sco was taken from Alencar et al. (2003) and is shown as white square. The rest of the data for objects in upper Sco was taken from (Mohanty et al. 2004a, 2004b). The masses of theses objects were derived from the $\log(g)$ as derived from the spectrum, and not from eclipsing binaries. Masses of cTTSs can also be derived from the velocity of the matter in the disk. This was done by Simon et al. (2000) for objects in Taurus Auriga which again should have roughly the same age as Lupus. This data is shown as stars in Fig. 6. The most surprising feature seen in Fig. 6 is the large scatter in temperature for objects of similar mass. This scatter is not related to the accuracy of the measurements but must be a property of young objects. Another interesting feature is that for low-mass objects the temperature differences for objects of different masses are rather small. In the case of 2MASSJ 05352184-0546085 the higher mass object is even the cooler one. This implies that from temperature measurements alone it is rather difficult to assign a mass for an object like the companion of GQ Lup. For objects of low mass, plotting $\log(T_{\rm eff} n)$ against $\log(M_\odot)$ does not help either, because simply the difference in temperature for objects of different mass is small. Numerically, the $3\,10^6$ year-isochrone in Burrows et al. (1997) leads to masses between 3 to 9 $M_{\rm Jupiter}$, and Baraffe et al. (2002) to masses between 3 to 16 $M_{\rm Jupiter}$ for $T_{\rm eff}$-values between 1800 and 2400 K.

Figure 7 is similar to Fig. 6 but for luminosity. While the evolutionary tracks shown agree reasonably well with the observations, the scatter in luminosity is again large. Again this is not a problem of the measurements but a real feature of young objects. Take, for example the RXJ1603.8-3938: Both components have nearly the same masses but one star is constantly a factor of two brighter than the other, and this object is a WTTSs (Guenther et al. 2001b). The problem at very young ages is that the brightness and temperature of the objects depend on the history of the accretion. However, the relation between mass and luminosity seems to be more promising than the relation between temperature and mass. Given the large intrinsic scatter of the young objects, and given the fact that evolutionary tracks may have problems at young age, why not just draw a straight line through the observed data-points? If we do this, we find values around 10 $M_{\rm Jupiter}$, depending whether or not we assume a veiling contribution. For the three assumptions (no veiling, distance 140 pc; with veiling distance 140 pc; with veiling distance 100 pc), the masses derived from Burrows et al. (1997) are about 20, 15 and 7 $M_{\rm Jupiter}$, respectively. Using Baraffe et al. (2002) the masses are about 30, about 15, and 10 $M_{\rm Jupiter}$. The problem is not only the determination of the luminosity but also the large intrinsic scatter in luminosity of young objects. The companion of GQ Lup is a bit cooler, and fainter than the two

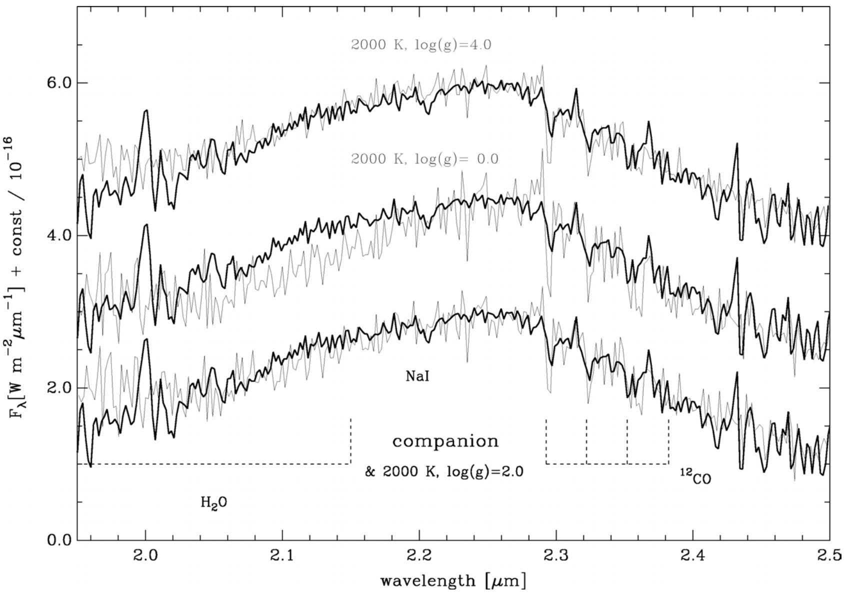

Figure 5: The flux calibrated spectrum of the companion of GQ Lup. The thick line is the observed spectrum, the thin lines are models calculated for $T_{\rm eff} = 2000$ K and $\log(g) = 0$, $\log(g) = 2.0$, $\log(g) = 4.0$. These models fit much better than the ones in Fig. 4.

components of 2MASSJ 05352184-0546085 which implies that the mass of the companion of GQ Lup might also be lower. Thus, for the time being it seem reasonable to assume that the mass of the companion is $\leq 30\ M_{\rm Jupiter}$.

4 Putting the object into perspective

The reader might now wonder why it is interesting to study an object were only a very rough estimate of the mass can be given. There are, several good reasons to do this. First of all, as was already pointed out in the introduction, there is no sharp break in the mass distribution function at 13 $M_{\rm Jupiter}$. Thus, it is reasonable to assume that the formation mechanism for massive planets and low-mass brown dwarfs could be the same. By studying the companion of GQ Lup, we can learn how such low-mass objects might have formed. Secondly, we know that the object has an age of only about 1 Myr, which implies that it must have formed rather quick. Thirdly, the object has currently a projected separation of 100 AU.

There are three basic scenarios for the formation of such an object:

- Formation in the disk at 100 AU.
- Formation in the dense inner part of the disk, and subsequent ejection.
- Formation via fragmentation.

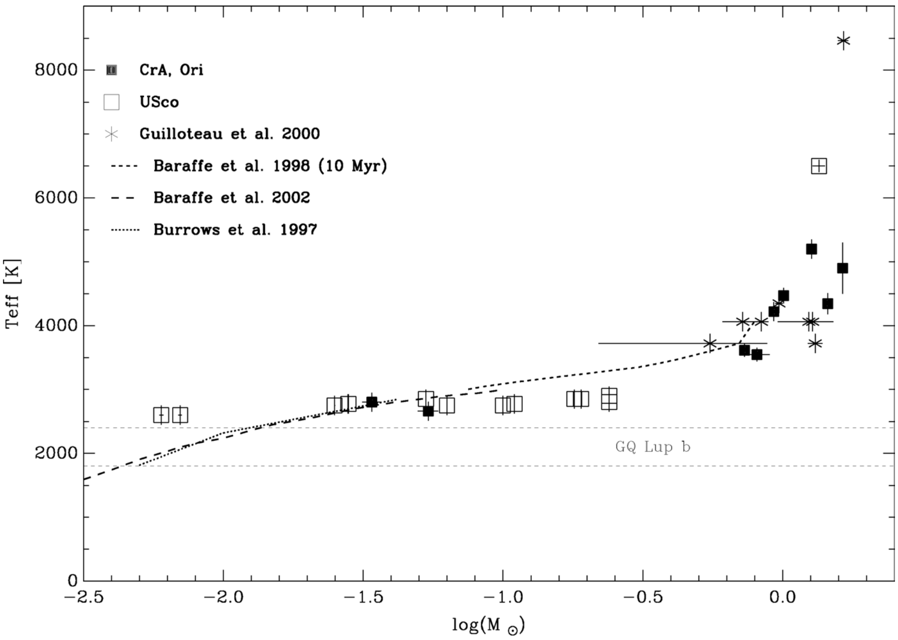

Figure 6: The temperature and true masses of young stars and brown dwarfs taken from the literature (see text). The black squares are objects in Orion and R Corona Australis that should have about the same age as GQ Lup. These objects are either eclipsing binaries, or the masses were derived astrometrically. Also shown are the values for objects in upper Sco. Except for one eclipsing binary, these values were derived from atmospheric models. It is interesting to note how large the scatter in temperature for objects of similar mass and age is. This scatter is not due to the accuracy of the measurements (note the small error bars) but a real property of young objects. Also shown are evolutionary tracks.

The first scenario certainly requires a large, massive disk ($d \gg 100\ AU$). While GQ Lup certainly has a disk, first models of the SED by Stecklum (2005) indicate that the radius of the disk is only in the range between 16 to 25 AU. The other constrain is the age of the object. At least models for the formation of planets via core-accretion in a disk by Hubickyj et al. (2004), Ida & Lin (2004a, 2004b, 2005), and Alibert et al. (2004) all lead to formation times of a several Myr even for objects at a distance of only a few AU from the host stars. The formation time scales ought to be even longer for an object at a larger distance from the host star. The formation of objects via a disk instability would be much quicker but requires a very massive disk (Boss 2003).

The formation of the object in the inner part of the disk with subsequent ejection is certainly possible. In this scenario, the companion should be in a highly eccentric orbit, and there has to be a massive third body that was responsible for the interaction. The radial velocity data allows to exclude a stellar companion with an orbital distance of ≤ 3 AU. Simulations by Hall et al. (1996) show that a close stellar encounter is likely to be rather destructive to the disk, so that it is unlikely that such

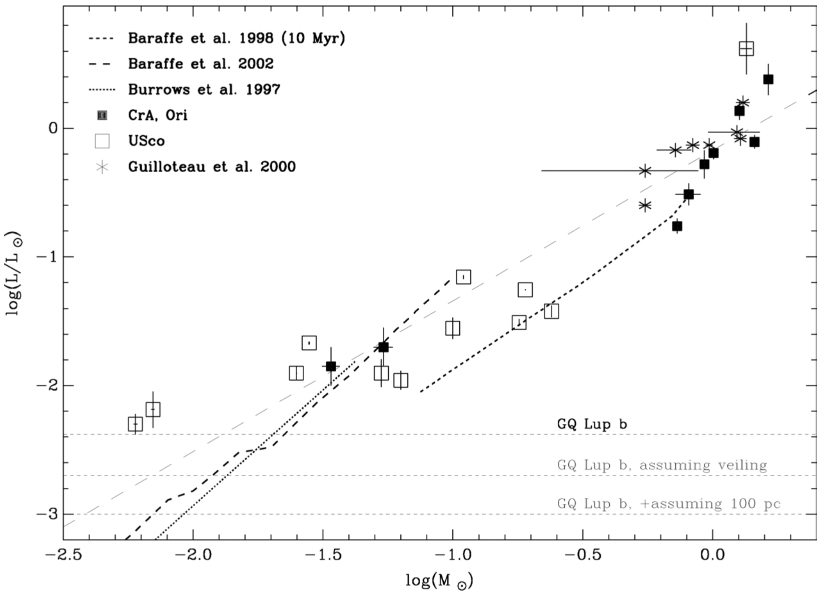

Figure 7: Similar to Fig. 6 but for luminosity instead of temperature. Again, we find large differences for objects of similar age an mass. However, using the luminosity instead of temperature seem to be better for determining the mass of young objects. The main problem in assigning a mass to the companion of GQ Lup is then the error of the distance, and the fact the lack of knowledge on the veiling contribution.

a process has happened. Thus, while this scenario is possible, there is currently at least no evidence for it.

Another possibility is the fragmentation scenario. There are many free-floating objects of similar luminosity and spectral type in star forming regions (e.g. Mohanty et al. 2004a]. If the companion of GQ Lup formed via fragmentation like a binary star, we would expected that the object should has disk. Whether this is the case remains however to be seen.

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