The low-mass companion of GQ Lup

E.W. Guenther 1, R. Neuhaus 2, G. Wuchterl 2, M. Mugrauer 2, A. Bedalov 2, P.H. Hauschildt 3

1 Thüringer Landessternwarte Tautenburg, 07778 Tautenburg, Germany
2 Astrophysikalisches Institut und Universitäts-Sternwarte Schillergäßchen 2-3, 07745 Jena, Germany
3 Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg Germany

Received 2.8.2005; accepted 21.10.2005; published online

Abstract. Using NACO on the VLT in the imaging mode we have detected an object at a distance of only 0.7 arcsec from GQ Lup. The object turns out to be co-moving. We have taken two K-band spectra with a resolution of \( \lambda/\Delta \lambda = 700 \). In here, we analyze the spectra in detail. We show that the shape of spectrum is not spoiled by differences in the Strehl ratio in the blue and in the red part, as well as differential refraction. We reanalyze the spectra and derive the spectral type of the companion using classical methods. We find that the object has a spectral type between M9V and L4V, which corresponds to a \( T_{\text{eff}} \) between 1600 and 2500 K. Using GAIA-dusty models, we find that the spectral type derivation is robust against different \( \log(g) \)-values. The \( T_{\text{eff}} \) derived from the models is again in the range between 1800 and 2400 K. While the models reproduce nicely the general shape of the spectrum, the \( ^{12} \text{CO} \)-lines in the spectrum have about half the depth as those in the model. We speculate that this difference might be caused by veiling, like in other objects of similar age, and spectral class. We also find that the absolute brightness of the companion matches that of other low-mass free-floating objects of similar age and spectral type. A comparison with the objects in USco observed by Mohanty et al. (2004b) shows that the companion of GQ Lup has a lower mass than any of these, as it is of later spectral type, and younger. The same is as true, for the companion of AB Pic. To have a first estimate of the mass of the object we compare the derived \( T_{\text{eff}} \) and luminosity with those calculated from evolutionary tracks. We also point out that future instruments, like NAHUAL, will finally allow us to derive the masses of such objects more precisely.

Key words: exo-planets, brown dwarfs

©2000 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1. Introduction

Now more than 160 extrasolar planets have been discovered indirectly by means of precise the radial velocity measurements of the host stars. At least for the 6 transiting planets the planetary nature of these objects is confirmed (e.g. Charbonneau et al. 2000). In two additional cases the planetary nature of the orbiting objects is confirmed astrometrically (Benedict et al. 2002). In many other cases, astrometric measurements are at least precise enough to rule out binary star viewed almost face on.

A statistical analysis shows that the observed frequency of solar-like stars having planets with a minimum mass \( \geq 0.3 \, M_{\text{Jupiter}} \) orbiting at distances of \( \leq 5 \, \text{AU} \) is 9\% (Lineweaver & Grether 2003). It is thus quite surprising that brown dwarfs are very rare as close companions to normal stars, in contrast to planets and stellar companions. The lack of brown dwarfs as companions is thus often referred as the brown dwarf desert. Marcy et al. (2003) estimate from their radial velocity (RV) survey of old, solar-like stars that the frequency of brown dwarfs with 3 AU of the host stars is only \( 0.5 \pm 0.2\% \), and thus much smaller than the frequency of planets, or the frequency of binaries. This result is recently confirmed by a radial velocity survey of stars in the Hyades which, combined with AO-imaging also shows that the number of companions with masses between 10 \( M_{\text{Jupiter}} \) and 55 \( M_{\text{Jupiter}} \) at distances \( \leq 8 \, \text{AU} \) is \( \leq 2\% \) (Guenther et al. 2005). Studies by Zucker & Mazeh (2001) show that the frequency of close companions drops off for masses higher than 10 \( M_{\text{Jupiter}} \), although they suspect there is still a higher mass tail that extends up to probably 20 \( M_{\text{Jupiter}} \). From the currently known “planets” 15 have an \( \text{m sin i} \) between 7 and 18 \( M_{\text{Jupiter}} \). It has been argued by Rice et al. (2003) that
these massive planets do not form by core accretion, because the host stars do not show enhanced metallicity, unlike stars hosting planets of lower mass. Wide companions (e.g. \( d \geq 50 \) AU) are detected by means of direct imaging. Unfortunately this means that their masses can only be estimated by comparing their temperature and luminosities with evolutionary tracks. In the case of these pairs, the situation is possibly different, as direct imaging campaigns probably have turned up 11 brown dwarfs orbiting normal stars. The result of all search programs for objects in TWA-Hydra, Tucanae, Horologium and the \( \beta \) Pic region is that the frequency of brown dwarfs at distances larger than 50 AU is \( 6 \pm 4\% \) (Neuh"auser 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, or it means that there are serious problems with the tracks.

Recently, three very low-mass companions have been identified that could possibly even have masses below 13 \( M_{\text{Jupiter}} \). 2MASSWJ 1207334-393254 is a brown dwarf with a spectral type M8V. A co-moving companion has been found which is located at a projected distance of 70 AU (Chauvin et al. 2005a). The companion has a spectral type between L6 and L9.5. Assuming that 2MASSWJ 1207334-393254 is a member of the TW Hydra association, and assuming an age \( 8^{+4}_{-3} \) Myr, the mass of the primary is \( 25 M_{\text{Jupiter}} \). Using the non-gray models from Burrows et al. (1997), the authors estimate the mass of the companion as 3 to 10 \( M_{\text{Jupiter}} \). AB Pic also has a very low-mass companion (Chauvin et al. 2005b). AB Pic is a K2V star in the Tucana-Horologium association. The age is estimated as \( \sim 30 \) Myr. The co-moving companion with a spectral type of L0 to L3 is located at the projected distance of 260 AU from the primary. The K-band spectrum of the companion shows the NaI doublet at 2.205 and 2.209 \( \mu m \). For this object, the authors give a mass estimate between 13 and 14 \( M_{\text{Jupiter}} \). The third such object is GQ Lupi which will be discussed here.

2. GQ Lup

GQ Lup is a classical T Tauri star 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) find 140 \( \pm 20 \) pc, Knude & Heg 1998 100 pc, Nakajima et al. (2000) 150 pc, Satori et al. (2005) 147, Franco et al. (2002) 150 pc, de Zeeuw et al. (1999) 142 \( \pm 2 \) pc, and Teixeira et al. (2000) 85 pc but note that 14 stars of this group have measured parallax-distances, which are are on average 138 pc. The most likely value for the distance thus is 140 pc, which will be used in the following. The spectral type of GQ Lup is K7V. Batalla et al. (2001) find a veiling of 0.5 and 4.5 and an extinction \( A_V \) of 0.4 \( \pm 0.2 \) mag, which implies an \( A_K = 0.04 \pm 0.02 \) mag, and \( A_L = 0.02 \pm 0.01 \) mag. Using spectra taken with HARPS, we derive a \( \nu \sin i \) of \( 6.8 \pm 0.4 \) km s\(^{-1}\), assuming a Gaussian turbulence velocity of 2 km s\(^{-1}\), and assuming a solar-like center to limb variation. The broadband 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 spectrum of the companion

We detected a faint companion at a distance of \( 732.5 \pm 3.4 \) mas with a positional angle of \( 275.45 \pm 0.30^\circ \) (Neuh"auser et al. 2005). As described in more detail in Mugrauer & Neuh"auser (2005), using our own imaging data, as well as data retrieved from the HST and SUBARU archive, it was shown that the pair has common proper motion at significants-level of larger than \( 7 \sigma \).

After this question is solved, the next question to solve is, what the companion is. Using NACO, we obtained two spectra of the companion. The first spectrum was taken on August 25, 2004, the second on September 13, 2005. 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. For our 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 \( \mu m \).

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 et al. (2003) which is simply the flux ratio between 1.964 to 2.075 \( \mu m \), we derive spectral types in the range between L2V.

---

**Fig. 1.** The figure show 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 GQ Lup b, and a K7V star with a diameter of 1.5 \( R_{\odot} \) located at a distance of 140 pc.
Unfortunately, there is a telluric band between 2.198 and 2.208 µm. Another piece of evidence is the NaI lines at 2.2056 and 2.2094 µm. The depth of the CO-lines is also similar. We assign a spectral type M9 to L4.

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 mag 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 \( m_K = 13.1 \pm 0.1 \), and \( m_L = 11.7 \pm 0.3 \), absolute magnitudes of \( M_K = 7.4 \pm 0.1 \) and \( M_L = 6.0 \pm 0.3 \) mag for the companion (Fig. 4). 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 T Tauri stars. 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⊙yr^{-1} (Liu, Najita, Tokunaga 2003; Natta et al. 2004; Mohanty et al. 2004a; Mohanty et al. 2005a; Muzerolle et al. 2005). Clear signs of accretion are observed even down to the planetary-mass regime at young ages (Barrado y Navascués 2002). The fact that we do not see the Brγ-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⊙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, Najita, Tokunaga 2003; Luhmann 2003). The absolute magnitudes of the companion of AB Pic of \( M_J = 12.8 \pm 0.7 \), \( M_H = 11.3 \pm 1.0 \), \( M_K = 10.8 \pm 0.9 \) are also quite similar to the of the companion of GQ Lup. Thus, the companion of GQ Lup is quite a normal for an object of its age, and we should keep in mind that it is likely that there is a disk, and accretion.

4. Comparing the spectrum with GAIA-dusty models

Up to now we have compared the spectrum of the companion of GQ Lup 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 \( T_{eff} \) 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.

Fig. 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 \(^{12}C\)O-lines and to the NaI doublet at 2.205 and 2.209 µm, it does fit to the \( H_2O \)-band in the spectrum. Clearly, the object must be cooler than this. Also, if the \( T_{eff} \) were 2900 K, the radius of the ob-
5 PUTTING THE OBJECT INTO PERSPECTIVE

Fig. 4. Flux calibrated spectrum of the companion of GQ Lup. The thick line is the observed spectrum, the thin lines are models calculated for \( T_{\text{eff}} = 2900 \) K and \( \log(g) = 0 \), and \( \log(g) = 4.0 \). Clearly, these model do not fit to the data. The object must be cooler than that.

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

The problem in giving a mass for the companion is that there is not a single object with an age of about one Myr and such a late spectral type where the mass has been determined directly. Mohanty et al. (2003) attempted to do this by deriving the \( \log(g) \) and \( T_{\text{eff}} \)-values for late type objects on USco. These objects have an age of about 5 Myr. For the analysis they used spectra with \( \Delta \lambda / \lambda = 31000 \) in the wavelength-range between 6400 and 8600 Å. For USco 128 and USco 130, which have a spectral type of M7 and M7.5, they find \( \log(g) \)-values of 3.25 (Mohanty et al. 2003). Mohanty, Jayawardhana, Basri 2004c). With these values, they find masses for these objects of 9 to 14 \( M_{\text{Jupiter}} \). However, during this meeting it was discussed by the authors that the \( \log(g) \)-values are possibly too small by 0.5 dex (Mohanty 2003b). This would increase the masses of these objects to \( \geq 20 M_{\text{Jupiter}} \). In any case, the mass of the companion of GQ Lup must be lower than that of USco 128 and USco 130, as it has a later spectral type and is younger than these (Fig. 6). Because the companion of GQ Lup has the same spectral type as the companion of AB Pic but is younger, it must have lower mass than it.

Given the cross-talk between \( \log(g) \) and \( T_{\text{eff}} \), and given that we have a spectrum with a resolution of only \( \lambda / \Delta \lambda = 700 \), it is currently not possible to constrain the \( \log(g) \) sufficiently well to give a mass. For a radius of 1.2 to 1.3 \( R_{\text{Jupiter}} \), a \( \log(g) \) of \( \leq 3.7 \) would imply a mass \( \leq 13 M_{\text{Jupiter}} \). Similarly, if we assume that there is no veiling, a \( \log(g) \) of \( \leq 3.4 \) would imply a planetary mass.

The problem when using evolutionary tracks for objects at very young ages is that the brightness and temperature of the objects depend on the history of the accretion. This means that in principle, the evolutionary tracks from Burrows et al. (1997) and Baraffe et al. (2002) should not be used at such a young age. However, it is still worthwhile to have a look at these in order to have a idea. Although an isochrone for 10\(^6\) years is not even shown in Burrows et al. (1997), the 3\(10^6\) year-isochrone leads to a mass of 3 to 9 \( M_{\text{Jupiter}} \), with a \( T_{\text{eff}} \) of 1800 and 2400 K. Similarly, we read of a mass between 3 to 16 \( M_{\text{Jupiter}} \) from the Fig. 2 in Baraffe et al. (2002).

Burrows et al. (1997) and Baraffe et al. (2002) also give the luminosity for objects at different ages. We may also try to use this result for estimating the masses. According to Golimowski et al. (2004) the bolometric correction \( BC_K \) is \( 3.17 \pm 0.06 \) and \( 3.38 \pm 0.06 \) 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. If we assume 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 $log(L/L_\odot) = -3.0$. For these three assumptions, we derive masses of about 20, 15 and 7 $M_{jupiter}$, using Burrows et al. (1997), for the three hypothesis respectively. Using Baraffe et al. (2002) we find values of about 30, about 15, and 10 $M_{jupiter}$, or so.

Now in progress are models which take the formation of the objects into account. Hubickjy, Bodenheimer, and Lissauer (2003) model the formation of giant planets via the accretion of planetesimals and subsequent capture of an envelope from the solar nebula gas. They show that for a short time, a massive planet can be very bright. Unfortunately, no evolutionary tracks giving $T_{eff}$ are shown. Evolutionary tracks for GQ Lup and its companion calculated by Wuchterl were presented in (Neuh"au er et al. 2005) and at this conference (see Wuchterl these proceedings). These tracks give masses between 1 and 2 $M_{jupiter}$ for the companion of GQ Lup.

### References

Barrado y Navascués, D., Zapatero Osorio, M. R., Martín, E.L., Béjar, V.J.S., Rebolo, R., Mundt, R.: 2002, A&A 393, L85

Baraffe, I.; Chabrier, G.; Allard, F.; Hauschildt, P.: 2002, A&A 382, 563

Basri, G., Mohanty, S., Allard, F., Hauschildt, P.H., Delfosse, X., Martin, E.L., Forveille, Th., Goldman, B.: 2000, Apj 538, 36

Batalha, C., Lopes, D.F., Batalha, N.M.: 2001: ApJ 548, 377

Benedict, G.F., McArthur, B.E., Forveille, T., Delfosse, X., Nelson, E., Butler, R. P., Spiesman, W., Marcy, G., Goldman, B., Perrier, C., Jefferys, W.H., Mayor, M.: 2002: ApJ 581, L115

Burrows, A., Marley, M., Hubbard, W. B., Lunine, J. I., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D., Sharp, C.: 1997, Apj 491, 856

Charbonneau, D., Brown, T.M., Latham, D.W., Mayor, M.: 2000, Apj 529, L45

Chauvin, G., Lagrange, A.-M., Dumas, C., Zuckermand, B., Moutlet, D., Song, I., Beuzit, J.-L., Lawrance, P.: 2005: A&A 438, 25

Chauvin, G., Lagrange, A.-M., Zuckermand, B., Dumas, C., Moullet, D., Song, I., Beuzit, J.-L., Lawrance, P., Bessel, M.: 2005: A&A 438, L29

Franco, G. A. P.: 2002: MNRAS 331, 474

Guenther, E.W., Paulson, D.B., Cochran, W.D., Patience, J., Hatzes, A.P., Macintosh, B.: 2005: A&A 442, 1031

Golimowski, D.A., Leggett, S.K., Marley, M.S., Fan, X., Geballe, T.R., Knapp, G.R. et al.: 2004, AJ 127, 3516

Hubickjy, O., Bodenheimer, P., & Lissauer, J. J.: 2004: Revista Mexicana de Astronomia y Astrofisica Conference Series 22, 83

Hughes, J., Hartigan, P., Clampitt, L.: 1993, AJ 105, 571

Kirkpatrick, J., Reid, I.N., Liebert, J., Cutri, R.M., Nelson, B., Beichman, Ch.A., Dahn, C.C., Monet, D.G., Gizis, J.E., Skrutskie, M.F.: 1999; ApJ 519, 802

Kirkpatrick, J.D., Reid, I. N., Liebert, J., Gizis, J.E., Burgasser, A.J., Monet, D.G., Dahn, C.C., Nelson, B., Williams, R.J. 2000: AJ 120, 447

Knude, J., Hag, E. 1998: A&A 338, 897

Lineweaver, Ch. Grether, D. 2003: ApJ 598, 1350L

Liu, M.C., Najita, J., Tokunaga, A.T.: 2003, ApJ 585, 372

Luhman, K.L.: 2004, ApJ 617, 1216

Marcy, G., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2003, in ASP Conf. Ser., Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming, & S. Seager (San Francisco: ASP)

Mayor, M., Queloz, D.: 1995, Nature 378, 355
Mohanty, S., Jayawardhana, R., Natta, A., Fujiiyoshi, T., Tamura, M., 
Barrado y Navascués, D. 2004a: ApJ 609, L33
Mohanty, S., Basri, G., Jayawardhana, R., Allard, F., Hauschildt, P., 
Ardila, D. 2004b: ApJ 609, 854
Mohanty, S., Jayawardhana, R., Basri, G.: 2004c, ApJ 609, 885
Mohanty, S., Jayawardhana, R., Basri, G.: 2005, ApJ 626, 498
Mohanty, S. these proceedings
Muzerolle, J., Luhman, K.L., Briceño, C., Hartmann, L., Calvet, N.: 
2005, ApJ 625, 906
McLean, I.S., McGovern, M.R., Burgasser, A.J., Kirkpatrick, J.D., 
Prato, L., Kim, S.S. 2003: ApJ 596, 561
Mugrauer, M., Neuhäuser, R., AN submitted
Nakajima, Y., Tamura, M., Oasa, Y., Nakajima, T.: 2000, AJ 119, 
873
Neuhäuser, R., Guenther, E.W., Alves, J., Huélamo, N., Ott, Th., 
Eckart, A. 2003: AN 324, 535
Neuhäuser, R., Guenther, E.W., Wuchterl, G., Mugrauer, M., Be-
dalov, A., Hauschildt, P.H., 2005: A&A 435, L13
Natta, A., Testi, L., Muzerolle, J., Randich, S., Comerón, F., Persi, 
P.: 2004, A&A, 424, 603
Reid, I. N., Burgasser, A.J., Cruz, K.L., Kirkpatrick, J. D., Gizis, 
J.E.: 2001, AJ 121, 1710
Rice, W.K.M., Armitage, P.J., Bonnell, I.A., Bate, M.R., Jeffers, 
S.V., Vine, S.G.: 2003, MNRAS 346, L36
Sartori, M.J., Lepine, J.R.D., Dias, W.S.: 2003, A&A 404, 913
Teixeira, R., Ducourant, C., Sartori, M. J., Camargo, J. I. B., Périé, 
J.P., Lépine, J.R.D., Benevides-Soares, P., 2000: A&A 361, 
1143
de Zeeuw, P.T., Hoogerwerf, R., de Bruijne, J.H.J., Brown, A.G.A., 
Blaauw, A.: 1999, AJ 117, 354
Zucker, Sh., Mazeh, T.: 2001, ApJ 562, 1038