Direct Imaging of Sub-Stellar Companions around Young Stars – Special Case: GQ Lup A + b

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In several years of direct imaging searches of sub-stellar companions around young nearby stars, first with plain and speckle imaging, now with Adaptive Optics (AO), we have found several brown dwarf companions – and most recently also an object with a mass estimate well below 13 Jupiter masses, so that it is probably a giant planet imaged directly, GQ Lup b. We were able to confirm all these companion candidates by common proper motion and spectroscopy showing a cool spectral type of late-M or early-L. They are only a few million years old and allow us to study the formation of planets and brown dwarfs observationally.

Objects below the hydrogen-burning mass limit of ~ 0.078 $M_\odot$ are called *sub-stellar objects*, which include brown dwarfs and planets. The definitions of *brown dwarfs* and *planets* and their distinction are still under dispute. Can the mass ranges of those two types of sub-stellar objects overlap? May only objects orbiting normal stars be called planets? The working definition of the IAU for planets accepts objects below the deuterium-burning mass limit of ~ 13 Jupiter masses orbiting around normal stars.

The formation mechanism of sub-stellar objects is also not yet clear. Do brown dwarfs form just like stars, or always as companions to normal stars, so that all free-floating, isolated brown dwarfs are ejected stellar embryos? Do planets form fast by direct gravitational collapse in a massive circumstellar disc or by a slow build-up of a solid core? Such questions can be studied observationally, just by observing young sub-stellar objects, in particular as companions to young stars. E.g., the youngest star found to be orbited by a planet gives the lower limit for the planet formation timescale. Migration of planets in a circumstellar disc can also be studied by comparing young planetary systems with old ones.

However, imaging detection of sub-stellar companions is difficult due to the problem of dynamic range: Sub-stellar objects are too faint and too close to much brighter stars. After a brief phase of deuterium burning, a few million years only, brown dwarfs cool down and fade away. Planets also get fainter as they age.

In 1993, it became clear that young sub-stellar objects are hotter and brighter than old sub-stellar objects by several orders of magnitude: young sub-stellar objects, still contracting and possibly even accreting, gain gravitational energy and become self-luminous in the infrared (Burrows et al. 1993). The magnitude difference between a sub-stellar companion of a given mass and its stellar primary gets worse as they age, because the stellar primary will reach stable hydrogen burning, i.e. constant luminosity, while the sub-stellar companion gets fainter. Hence, direct imaging of sub-stellar companions should be less difficult around young stars.

For a direct imaging detection of a faint companion next to a bright star, one also needs high angular resolution, i.e. nearby young stars. Without AO, we set our distance limit to roughly 70 to 100 pc. However, around the mid-1990s, basically no pre-main-sequence stars were known within 100 pc. All the well-known star-forming regions like Taurus, Lupus, Corona Australis, Chamaeleon are at roughly 140 pc. Hence, the first step should be a search for stars which are both *young* and *nearby*. That is what we did in the 1990s with optical follow-up observations of unidentified ROSAT X-ray sources, using mostly the B&C spectrograph at the ESO 1.5-m telescope, and Caspec at the 3.6-m for high-resolution spectra of good candidates (Neuhäuser 1997).

In the course of this survey, many new pre-main sequence stars were found, both within and around the star forming clouds. If some of them are tens of degrees, i.e. tens of pc, off the clouds, then they should partly be tens of pc closer than the clouds, but no parallaxes were available. Towards the end of the 1990s, newly available Hipparcos data gave the distances of many of those and previously known young stars, showing that some of them were indeed located within 100 pc (Neuhäuser and Brandner 1998), e.g. TW Hya and the stars of the group now called TW Hya Association (TWA) and many more. Hence, we could now start our direct imaging survey, namely deep, high angular resolution images of pre-main-sequence stars within 100 pc. For the southern sky, we used the MPE speckle camera SHARP at the ESO 3.5-m NTT.

Sub-stellar companions show up as faint objects close to the primary target star. Faint dots next to bright stars are not always companions, they are mostly background. However, they can all be regared as companion candidates. To confirm such a candidate as a real companion, one has to check for common proper motion and take a spectrum of the companion, which should be as cool as expected from the magnitude difference between primary and companion candidates, given the age and distance of the target. Given the known proper motion of the primary stars, the pixel scale of the detector used, and the actual astrometric precision achieved (primary sometimes saturated or in the non-linear regime, companion very faint with low S/N), one has to wait one to a few years before second-epoch images can be taken.

Once common proper motion is shown and the spectral type and, hence, temperature of the companion is determined, one can place primary and companion together in the H-R diagram to check whether they appear to be coeval, and to measure the mass of the companion from theoretical evolutionary tracks. Here, it becomes clear whether we are dealing with a low-mass stellar companion or, e.g., a brown dwarf.

Since brown dwarfs are both brighter than planets and may also be at larger separations, we first found a few brown dwarfs: Within our project, we found and/or confirmed three brown dwarfs as companions to young nearby stars within 100 pc by both common proper motion

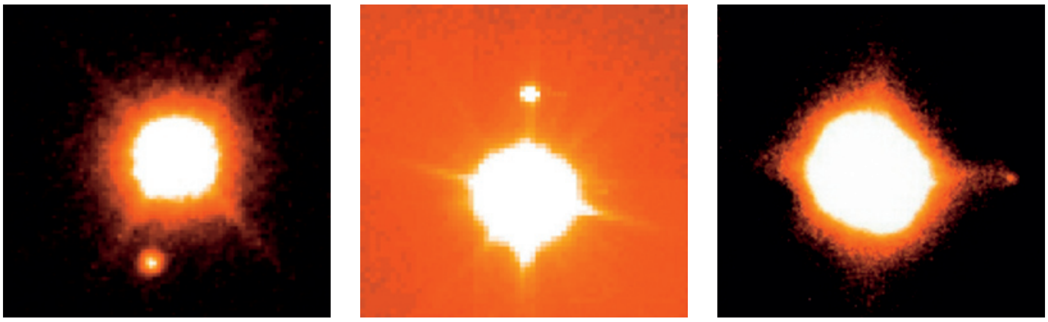

Figure 1: These three images show the three brown dwarf companions found so far by us around young nearby stars: HR 7329 B (left, VLT/ISAAC), TWA-5 B (middle, VLT/FORS1), and GSC 8047 B (right, NTT/Sharp). They show common proper motion with their primary star and a cool spectral type of M7-9, so that they have 15 to 40 Jupiter masses.

and spectroscopy (Figure 1). These were the first three brown dwarfs found and confirmed as companions to young stars.

With the advent of NACO, i.e. AO at the VLT, we (and other groups) were able to extend the sample of young stars to those in the nearby star forming regions at 140 pc including Lupus, and also reobserve those within 100 pc including TWA and other associations. We could now hope for both closer and fainter companions, i.e. giant planets.

About one year ago, we announced the detection of a sub-stellar companion to GQ Lup (Neuhäuser et al. 2005), which could well be a planet imaged directly. The direct evidence presented included the common proper motion (high significance after five year epoch difference), a cool spectral type (M9–L4), and apparently low gravity (log g = 2 to 3), however from a low-resolution NACO spectrum only. Given the location in the H-R diagram, the companion to GQ Lup could have a mass of 3 to 42 Jupiter masses according to calculations from the Tucson and Lyon groups (Neuhäuser et al. 2005), which do not take into account the formation of the objects, so that they are not valid in the first few million years, but only a few Jupiter masses according to more recent formation models (Wuchterl 2005).

Figure 2 shows our deepest image of GQ Lup so far, after shift-and-add of three NACO observations from June 2004 to August 2005. The dynamic range obtained is then shown in Figure 3. We can exclude all other companions outside of 0.2 arcsec (28 AU at 140 pc) with at least the mass of GQ Lup b.

Our NACO *K*-band spectrum of GQ Lup b shows a spectral type of M9 to L4, consistently obtained from comparison to standards and from spectral indices. Note in particular the water-steam absorption band in the blue part (Figure 4) of both GQ Lup b and the L2 dwarf, which is not present in the M8 brown dwarf, which is hotter. The spectral slope was corrected with both the GQ Lup primary (in the same slit) and a telluric standard (Neuhäuser et al. 2005).

From the *K*-band magnitude (~ 13.1 mag), the flux observed at ~ 140 pc (distance towards the Lupus clouds), and the best-fit temperature of ~ 2000 K, we obtain a radius of one to two Jupiter radii. With the gravity log g = 2 to 3, this results in ~ 0.5 to 6 Jupiter masses (Neuhäuser et al. 2005), so that GQ Lup b may very well be an object with mass below the deuterium-burning limit (13 Jupiter masses), i.e. a planet. Our mass determinations are model-dependent, not yet from orbital dynamics.

The companion to GQ Lup is younger in age and later in spectral type than the previously found brown dwarf companions to young stars, so that GQ Lup b is lower in mass. GQ Lup b is also cooler than the two components of the eclipsing double-lined spectroscopic brown dwarf – brown dwarf binary found in Orion (Stassun et al. 2005), and at about the same age, so that GQ Lup is lower in mass than those two brown dwarfs (Guenther 2006), which are 30-Jupiter-mass objects determined dynamically (Stassun et al. 2005).

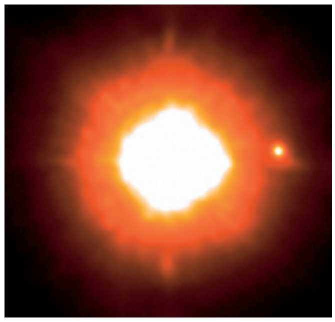

Figure 2: Deep, high S/N, high angular resolution VLT/NACO image of GQ Lup A (bright star in the centre) and b (0.7 arc sec west of it) after shift-and-add of three deep observations of ~ 20 to 30 min each (June 2004, May and August 2005). The FWHM is 68 mas, the field size shown is 2.2 arcsec × 2.2 arcsec, east is left, north is up.

Comparing the images obtained over the last few years, including the new observations from 2005, shows that the separation remains constant, no orbital motion is detected so far. Orbital motion would be detectable as a slight deviation from a constant separation (or position angle), but within about ± 5 mas/yr, the expected maximal orbital motion. We would have to wait at least until the detection of curvature in the orbit before we could determine the mass dynamically. This may take tens to hundreds of years.

GQ Lup b has a projected separation of ~ 100 AU (732 milliarcsec at 140 pc), which is three times further out than the outermost gaseous planet in the solar system. It could have formed further inwards, but got onto an highly eccentric orbit by a close encounter with another protoplanet (Debes and Sigurdsson 2006) or another star. For the time being, its formation remains unclear.

By now, we and other groups have observed roughly 100 young nearby stars, and two planet candidates were found, GQ Lupi b and 2M1207 b in the TWA group (Chauvin et al. 2005). For the latter case, it is not yet shown that the remaining motion between the two components is significantly smaller than the expected escape velocity for the companion, given the smaller epoch difference and/or the small total mass. In the case of GQ Lup A + b, this has been shown: The remaining motion seen between the two objects is 1.4 ± 2.2 mas/yr, the maximum orbital motion could be 3.7 ± 1.5 mas/yr, and the estimated escape velocity would be 5.2 ± 2.1 mas/yr.

Being located close to a star, common proper motion and a cool spectrum are not sufficient for an object to be considered a bound companion, however. The binding energy (total mass for the given separation) also needs to be large enough for the pair to remain bound and stable long-term. Figure 5 shows the total mass of stellar and brown dwarf binaries versus their separations: Binaries to the upper left of the line(s) should be long-term stable against encounters with other stars and clouds in the Galaxy. There are no old wide brown dwarf – brown dwarf pairs known, because they are probably not long-term stable. There is not even a young wide brown dwarf – brown dwarf pair with common proper motion known or observed.

While GQ Lup b (100 AU away from a 0.7 solar-mass star) seems to be long-term stable, 2M1207 (55 to 70 AU from a brown dwarf primary) might not be long-term stable (Mugrauer and Neuhäuser 2005). The 2M1207 system may be an interesting case, where we see two brown dwarfs formed together as a pair, but possibly separating from each other right now. Whether systems like GQ Lup and 2M1207 are rare or frequent, is still to be investigated. Many more young nearby stars can and should be observed with NACO.

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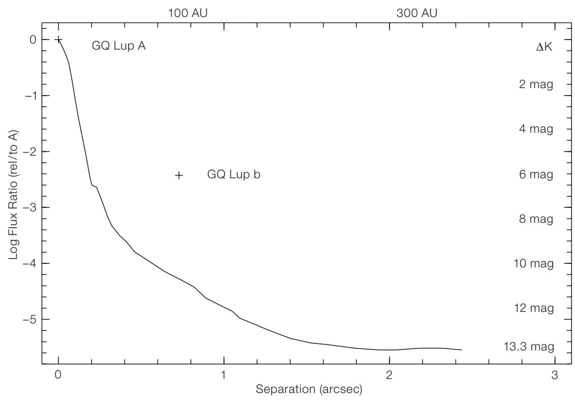

Figure 3: Dynamic range obtained from Figure 2 as flux ratio between background noise and primary GQ Lup A (at 0,0) versus separation. GQ Lup b is shown at 6.1 mag difference at 0.7325 arcsec separation. Projected separation at 140 pc is indicated at the top, magnitude difference in K at the right. Achieved dynamic range is ΔK = 13.3 mag outside of 2 arcsec, 12 mag at 1 arcsec, 10 mag at 0.5 arcsec, and 7 mag at 0.2 arcsec. No other companions are detected so far. We can exclude other companions with at least the mass of GQ Lup b outside 0.2 arcsec (28 AU).

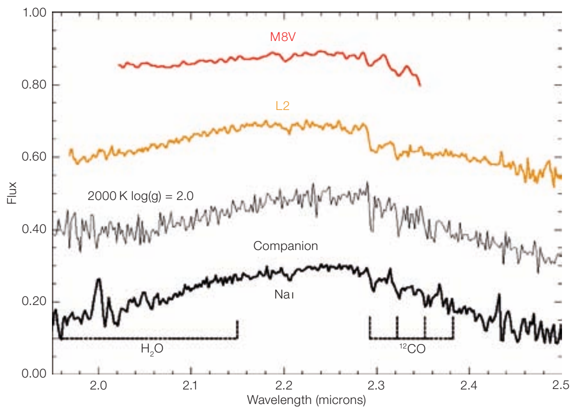

Figure 4: Our low-resolution *K*-band spectrum of GQ Lup b taken with NACO (bottom) compared to M8 (top), L2 (second from top), and a GAIA-Dusty template spectrum (Hauschildt et al., in preparation) for 2000 K and log g = 2, which compares well with the companion (Neuhäuser et al. 2005). One can see water-steam bands and CO absorption, possibly also Na.

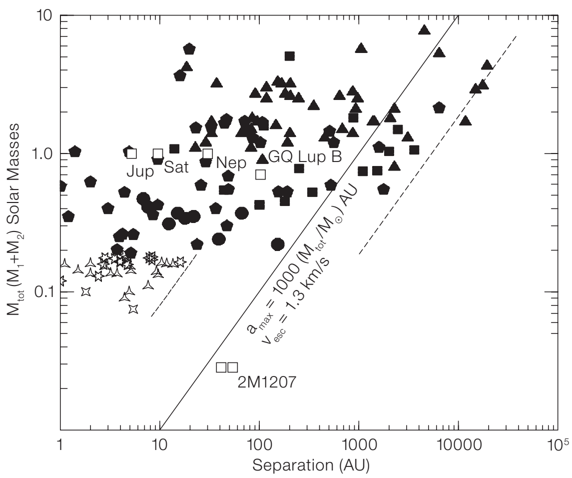

Figure 5: The total mass of binaries (binding energy) versus separation with very low-mass binaries as open stars and normal stellar binaries as filled symbols. There are no low-mass common proper-motion systems with separations larger than 16 AU. The solid line gives the stability limit: Bound in the upper left, unbound in the lower right. The companions of 2M1207 and GQ Lup and the giant planets in our Solar System are shown. The GQ Lup system seems bound and long-term stable (100 AU), 2M1207 does not (Mugrauer and Neuhäuser 2005), distance and, hence, projected separation are not well known for 2M1207, hence two symbols for 53 and 70 pc).