Ground-based Imaging for Direct Detection of Substellar Companions to Nearby Stars

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Adaptive Optics

The achievable resolution of a ground-based telescope is limited by atmospherical properties, quantified by the atmospheric seeing. This means that an ordinary telescope does not gain anything in terms of resolution by an increased size beyond the limit set by the seeing. This problem is partly solved by including an adaptive optics (AO) system. AO is a technique in which the wavefront distortions caused by the atmosphere are monitored and used as input to a deformable mirror which is distorted so as to counteract the wavefront effects from the atmosphere and send wavefront-corrected light to the scientific camera. In this way, a certain fraction of the light will make up a diffraction-limited PSF "core" with the rest of the light remaining in the seeing-limited PSF "halo", which greatly improves the achievable resolution for large telescopes. AO is a necessity for efficient low-mass companion searches from the ground.

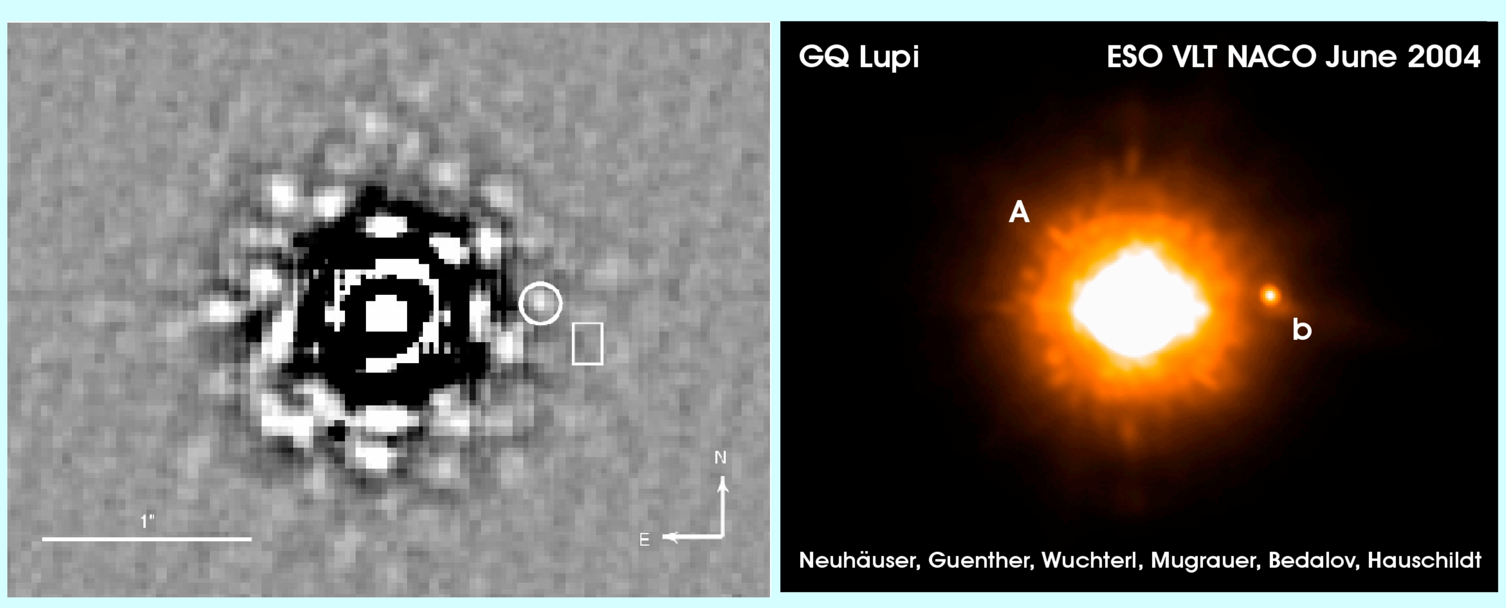

Figure 1. Left: High-pass filtered image of the GQ Lup system from 1994 taken with ComeOn+ at La Silla (Janson et al., 2006). Right: The same system from 2004 imaged with NACO by Neuhäuser et al. The square in the left panel marks where GQ lup B would be expected if it was a background source.

Spectral Differential Imaging

The main limiting factor in high-contrast imaging with AO is generally not photon noise, but speckle noise from the halo. This is a particularly nasty kind of noise since it forms a coherent structure in the image space which can mimick a companion signal. To get rid of speckle noise, we use spectral differential imaging (SDI). SDI takes advantage of the fact that cool objects (T-dwarfs and giant planets) exhibit atmospheric methane absorption, whereas stars do not. Thus by subtracting simultaneous narrow spectral band images from inside and ouside the spectral methane absorption feature at 1.6 um (after rescaling to a mutual λ/D scale), we can get rid of most of the primary PSF, including the speckle noise, whereas the companion PSF will be virtually unaffected.

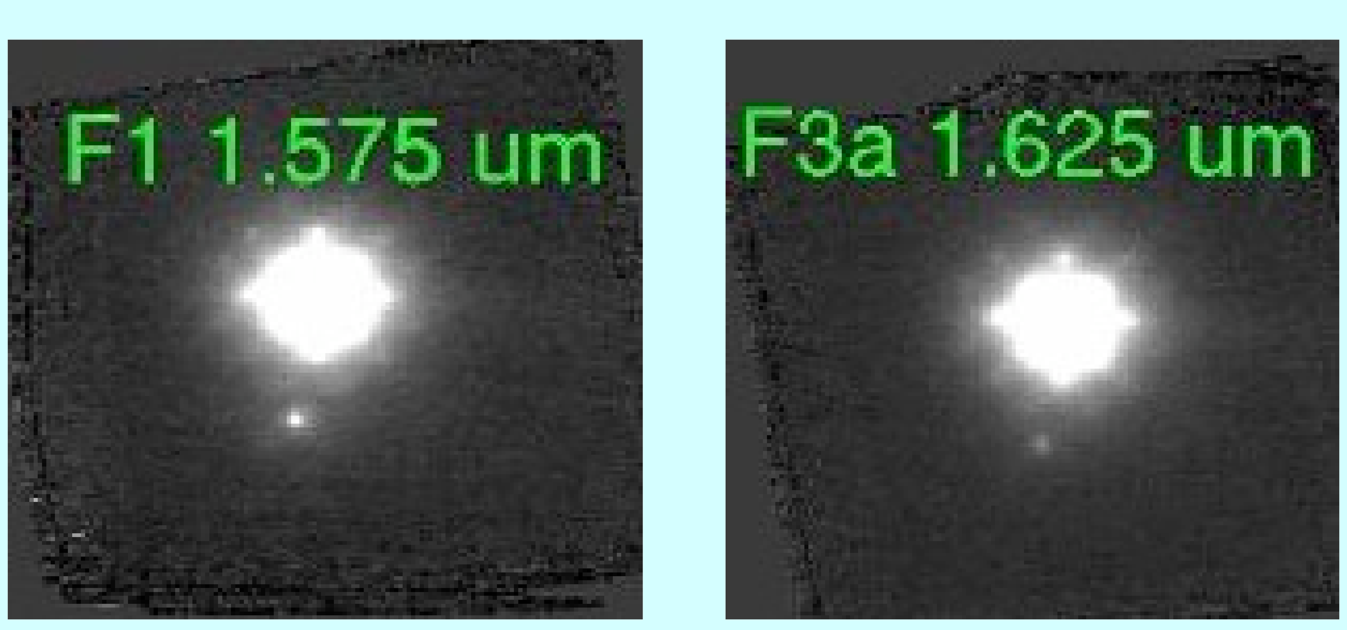

Figure 2 NACO-SDI images of SCR1845 (Biller et al., 2006). Left: Narrow-band image at 1.575 um. Right: Narrow-band image at 1.625 um. The companion is brighter in the left image than in the right one, indicating that it exhibits methane absorption.

Angular Differential Imaging

A residual speckle pattern will remain even after applying SDI, due to non-common path aberrations. This noise can be strongly mitigated by taking exposures at different rotator angles (we use 0 and 33 degrees), and subtracting the results. This is called angular differential imaging (ADI). The idea behind the technique is that if the camera is rotated, the companion will rotate with respect to the primary, whereas the non-common path aberrations will remain the same. Thus the noise will be subtracted to a large degree in the resulting image, and the companion will get a very particular signature of one positive and one negative peak, separated by 33 degrees with respect to the primary.

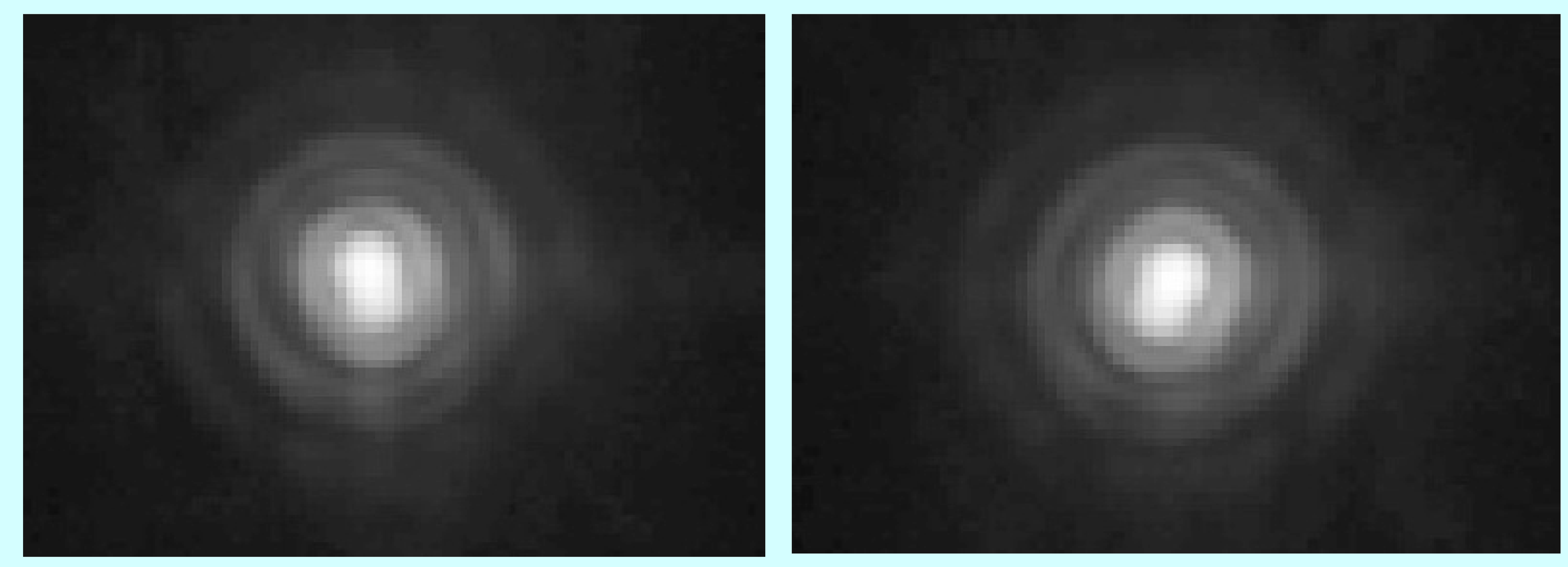

Figure 3 GJ 3305 is a previously unresolved binary with a projected separation of about 1.7 AU. The left image is taken at a rotation of 0 degrees, and the right image at 33 degrees. Here, instead of using SDI, direct L-band images were taken with NACO due to the excellent achievable Strehl ratio.

Some Results

In 2005, Neuhäuser et al. reported the discovery of GQ Lup B. Upon reexamination of GQ Lup data from 1994 taken with the first-generation AO system ComeOn+ (at 3.5m, La Silla), we found a posteriori a candidate which matches the expected position and flux of GQ Lup B (the position is expected to be very close to the later epoch data, due to the ~1000 yr orbit). We could also exclude the hypothesis that GQ Lup B is a background object. As is readily seen from the image (Figure 1), a priori detection of GQ Lup B based only on that data set would be impossible. This underlines the importance of using better AO systems, as well as SDI and ADI.

Using NACO at VLT, we have performed several searches for BDs and planets. In 2005, we presented the results of a survey (see Masciadri et al., 2005) which to date give the most stringent upper limits for masses of possible non-detected objects in the examined systems. Using theoretical mass-luminosity relationships (Masciadri et al., 2005), it was e.g. found that no 5 Mjup objects at more than 14 AU were detected for 50% of the systems. Subsequent surveys using the rather recent SDI capacity of NACO have been performed, yielding even more stringent limits, in particular for the well known ϵ Eri system (e.g. Kellner et al., in preparation).

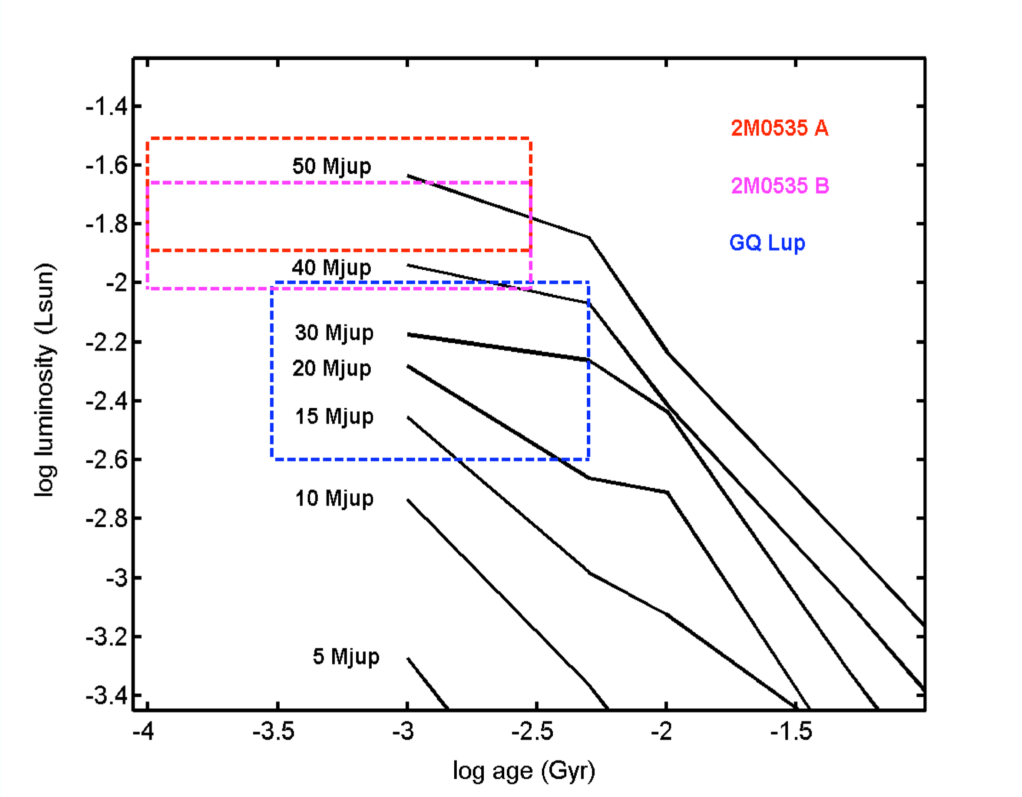

Figure 4 Evolutionary mass-tracks from Baraffe et al. (2003). The red and purple squares correspond to properties of brown dwarf binary 2M0535 A and B (Stassun et al., 2005). For these sources, the dynamical masses are also known (54 Mjup for A and 34 Mjup for B), and agree quite well with the theoretical tracks.

Goals and Prospects

The main problem in substellar science to date is the lack of a well calibrated mass-luminosity relationship. By imaging very low mass companions close enough to their star that a dynamical mass can be determined within a reasonable timeframe, we can achieve such a calibration. The mass range of around 13 Mjup is a particularly interesting regime. While this is the traditional border between planets and BDs, there may be an overlap in which a certain mass can be aquired both from planet and star formation scenarios. Direct imaging is likely to give clues about the origin of such objects; the mass/luminosity relationship may be different for the two origins, as well as atmospheric spectra (e.g. through enrichment of heavy elements in disk-formed objects), and most certainly the orbital characteristics (e.g. a disk-formed object would tend to be co-inclined with a remnant disk or the rotation of the star). Thus, while this mass domain certainly constitutes a desert where many sources have to be observed per detection, it is a physically interesting domain where observations can trim both the planet and star formation models at their extremes.