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Young Brown Dwarfs and Giant Planets as Companions to Weak-Line T Tauri Stars

Wolfgang Brandner[1], Sabine Frink[2], Rainer Köhler[3], and Michael Kunkel[3]

Abstract:

Weak-line T Tauri stars, contrary to classical T Tauri stars, no longer possess massive circumstellar disks. In weak-line T Tauri stars, the circumstellar matter was either accreted onto the T Tauri star or has been redistributed. Disk instabilities in the outer disk might result in the formation of brown dwarfs and giant planets.

Based on photometric and spectroscopic studies of *ROSAT* sources, we have selected an initial sample of 200 weak-line T Tauri stars in the Chamaeleon T association and the Scorpius-Centaurus OB association. In the course of follow-up observations, we identified visual and spectroscopic binary stars and excluded them from our final list, as the complex dynamics and gravitational interaction in binary systems might aggravate or even completely inhibit the formation of planets (depending on physical separation of the binary components and their mass ratio). The membership of individual stars to the associations was established from proper motion studies and radial velocity surveys.

Our final sample consists of 70 single weak-line T Tauri stars. We have initiated a program to spatially resolve young brown dwarfs and young giant planets as companions to single weak-line T Tauri stars using adaptive optics at the ESO 3.6 m telescope and *HST*/NICMOS. In this poster we describe the observing strategy and present first results of our adaptive optics observations. An update on the program status can be found at
http://www.astro.uiuc.edu/~brandner/text/bd/bd.html.

1. Extrasolar Planets and the Brown Dwarf Gliese 229 B

Only two years ago, the century-old paradigm that other planetary systems would be similar to our own solar system started to change. The discovery of extrasolar giant planets and brown dwarfs by monitoring radial velocities of nearby stars revealed that giant planets are not necessarily 5 to 30 AU away from their sun but may orbit at much smaller ($\ll 1$ AU) separations (Mayor & Queloz 1995; Marcy & Butler 1996).

While radial velocity surveys are most successful for discovering close companions, direct imaging allows one to probe systems with larger separations for which radial velocity methods are not sensitive. Indeed, Gl 229B, the first brown

[1]Astronomy Department, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[2]Astronomisches Rechen-Institut, Heidelberg, Germany
[3]Max-Planck-Institut für Astronomie, Heidelberg, Germany

dwarf to be identified unambiguously, has a separation of 45 AU from the central star. It was discovered with an adaptive optics coronograph at the Palomar 1.5m telescope (Nakajima et al. 1995; Oppenheimer et al. 1995). Direct imaging of resolved objects also allows one to study their spectral features in detail.

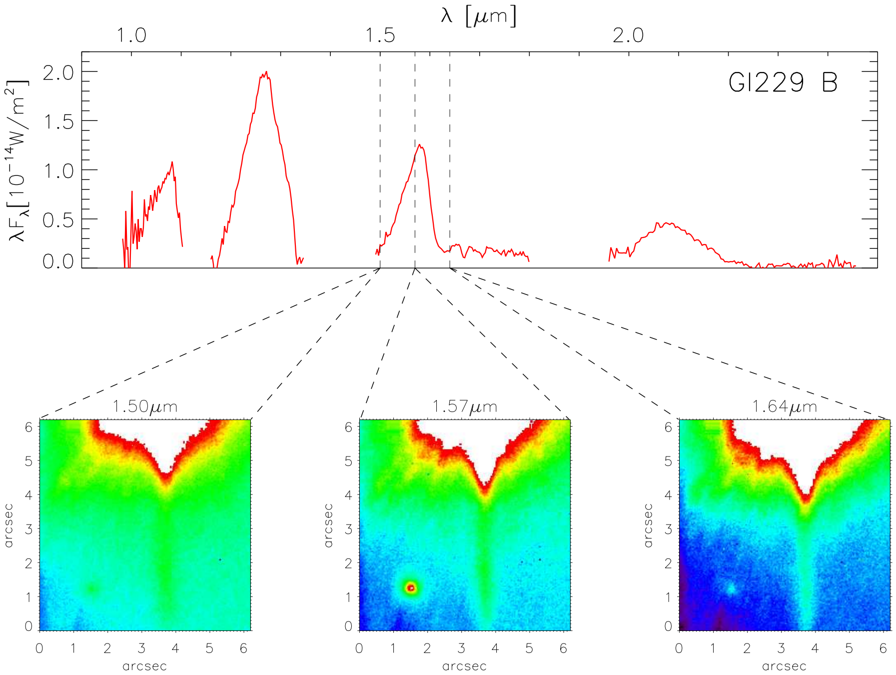

Figure 1. Top: Low-resolution spectrum of Gl 229 B (Oppenheimer et al. 1995). Bottom: Gl 229 B observed with adaptive optics (ADONIS) at the ESO 3.6m telescope on March 24 1997 in wavelength bands centered on molecular absorption bands and in the continuum. At the wavelength of a strong CH_4 absorption band (1.64 μm), Gl 229 B is about 2 mag fainter than in the nearby "continuum" (1.57 μm). North is up and east is to the left.

In Figure 1 we show on top a low-resolution spectrum of Gl 229B (Oppenheimer et al. 1995). Below, adaptive optics images obtained with ADONIS/SHARP and the circular variable filter ($\lambda/\Delta\lambda \approx 60$) at three distinct wavelength bands on and off molecular absorption bands are shown. The image scale was $0\farcs035$/pixel. Four two-minute exposures were coadded for each frame. No image deconvolution has been applied.

As stated by Allard & Hauschildt (1995), the energy distribution of late-type dwarfs and thus of young brown dwarfs and giant planets is very peculiar. The molecular opacities which globally define the continuum cause the spectral energy distribution to peak around 1.1 μm for solar metallicities, almost independently of the effective temperature (cf. Figure 2). This has recently been confirmed by Burrows et al. (1997) on the basis of their first non-gray calculations. With decreasing effective temperature the peak of the spectral energy distribution does not move redward as one would expect for a blackbody.

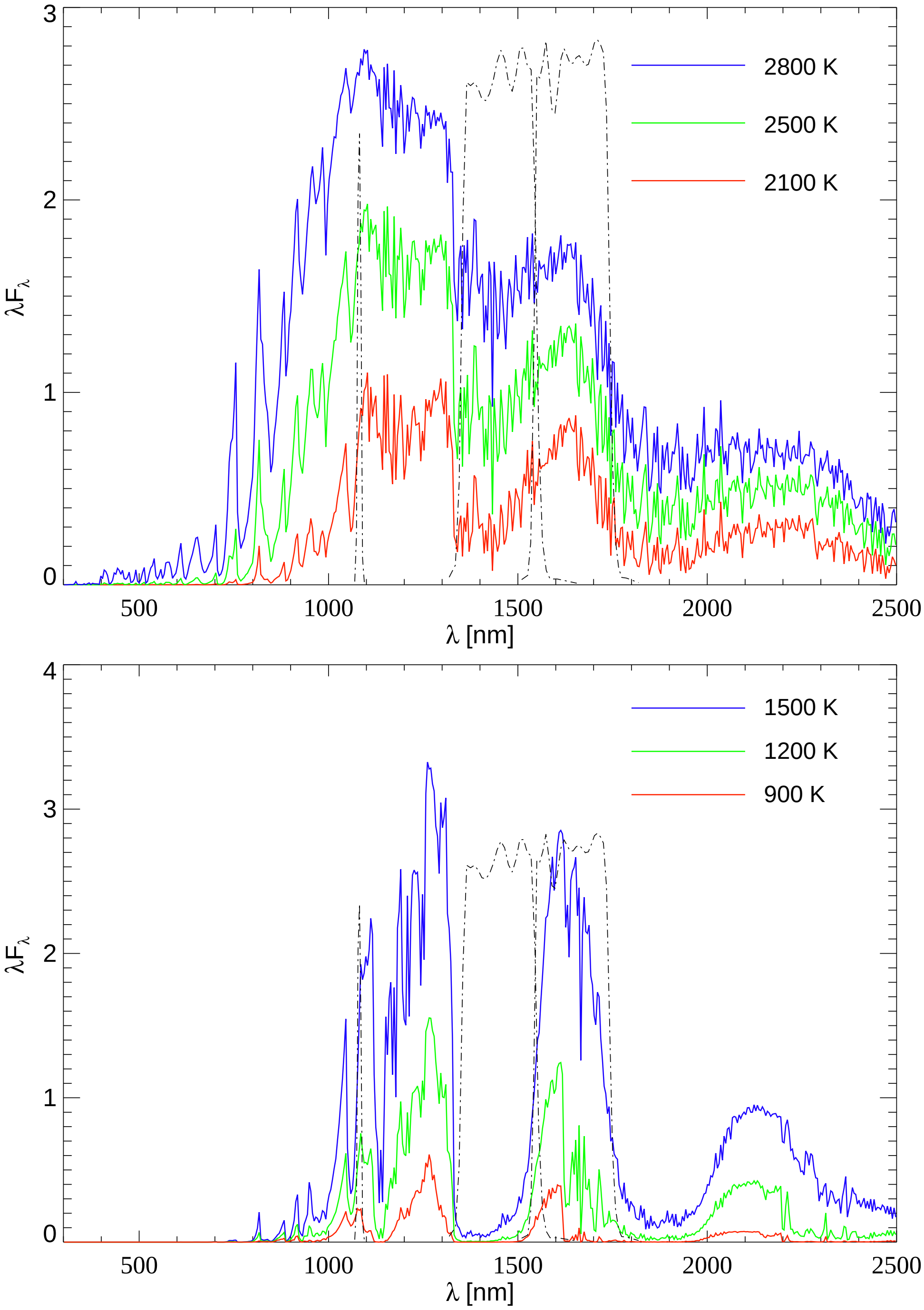

Figure 2. Model atmospheres for M dwarfs (left) and brown dwarfs (right) by Allard & Hauschildt (1995) rebinned to a spectral resolution of 4 nm. The dashed-dotted lines indicate the transmission curves of the *HST*/NICMOS F108N, F145M, and F165M filters.

2. The Luminosity Evolution of Young Brown Dwarfs and Giant Planets

Younger brown dwarfs will have a higher luminosity, their bolometric luminosity $L_{\rm BD}$ evolves with time t as $L_{\rm BD} \propto t^{-1.2}$ (Black 1980; Burrows et al. 1995 [4]). Pre-main-sequence stars exhibit a temporal luminosity evolution similar to brown dwarfs. However, their luminosity $L_{\rm PMS}$ decreases much slower than that of brown dwarfs (e.g., $L_{\rm PMS} \propto t^{-0.7}$ for a pre-main-sequence star with a mass of 0.5 $M_\odot$ and an age between 10^5 and 10^8 yr, D'Antona & Mazzitelli 1994).

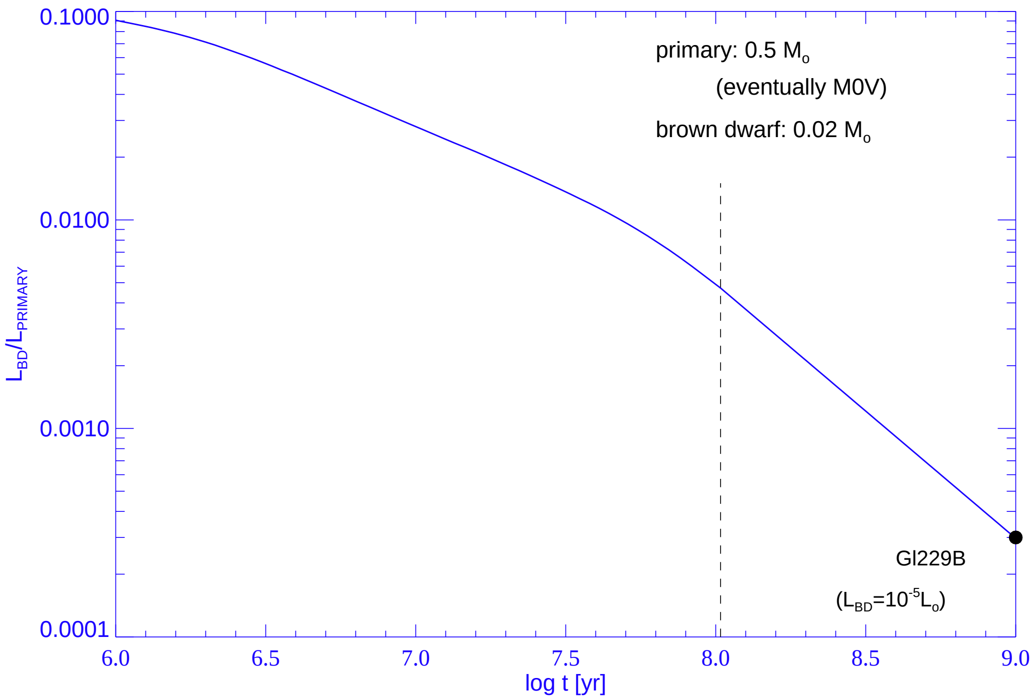

Figure 3. Temporal evolution of the luminosity ratio of a $0.02\,M_\odot$ brown dwarf and a $0.50\,M_\odot$ star ("primary"), which after $\approx 10^8$ yr (dashed line) eventually settles on the main sequence as a M0 type star. The current location of Gl 229 B is indicated by a black dot.

Figure 3 illustrates the evolution of the luminosity ratio of a $0.02\,M_\odot$ brown dwarf and a $0.50\,M_\odot$ star. Whereas at an age of 10^6 yr to 10^7 yr the luminosity ratio is in the range of ≈ 0.1 to 0.03, it will be two orders of magnitude smaller at an age of 10^9 yr. It will become increasingly harder to detect a brown dwarf next to an "older" pre-main-sequence star or even a main-sequence star than next to a young pre-main-sequence star — always assuming that the star and the brown dwarf are coeval. Studies of the individual components of pre-main-

[4] Note that these calculations did not consider the fact that brown dwarfs with masses $\geq 13 M_{\rm Jupiter}$ will start deuterium burning and might be considerably brighter over a short period of time.

sequence binaries revealed that most of them are indeed coeval (Hartigan et al. 1994; Brandner & Zinnecker 1997).

Because of the smaller brightness difference, it should be much easier to detect and resolve young brown dwarfs and young giant planets as companions to T Tauri stars than their more evolved (older) counterparts. As explained above, observations in the near-infrared between 1.0 μm and 2.5 μm are suited best!

3. The Sample

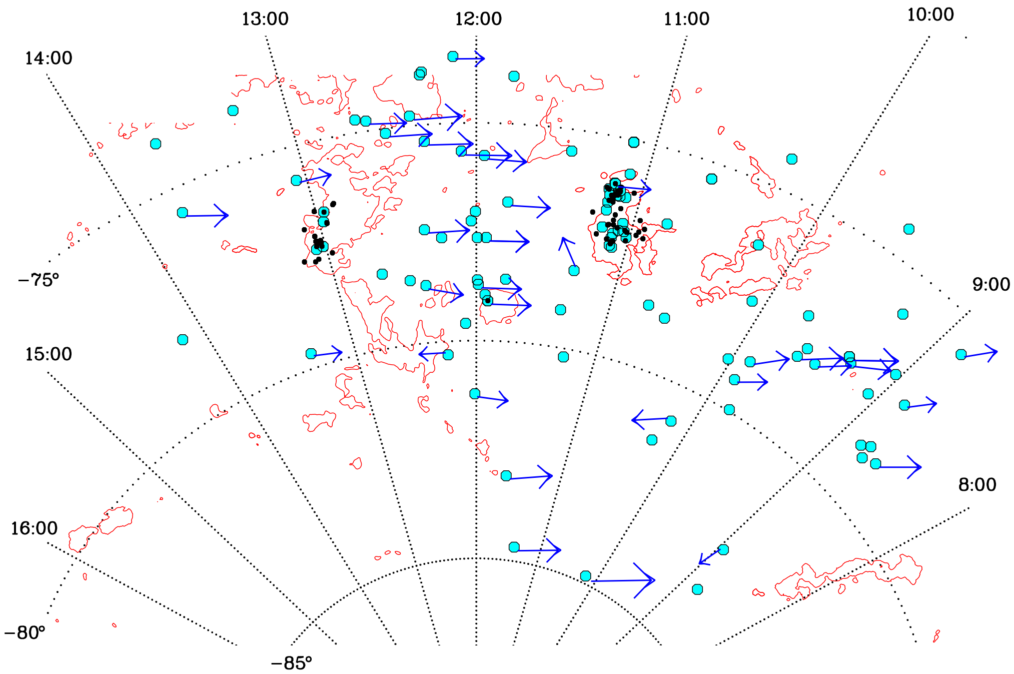

Figure 4. Spatial distribution of classical (black dots) and weak-line (turquoise dots) T Tauri stars in the Chamaeleon T association. Proper motions are indicated by blue arrows. *IRAS* 100 μm contours indicate the location of the dark clouds.

Contrary to classical T Tauri stars weak-line T Tauri stars no longer possess massive circumstellar disks (e.g., Beckwith et al. 1990; Henning et al. 1993). In weak-line T Tauri stars, the circumstellar matter was either accreted onto the central star or redistributed to form planetesimals or – via disk fragmentation – to form directly giant planets or brown dwarfs.

Based on photometric and spectroscopic studies of *ROSAT* sources (Alcalá et al. 1995; Kunkel et al. in prep.) we have selected an initial sample of 200 weak-line T Tauri stars in the Chamaeleon T association (Figure 4) and the Scorpius-Centaurus OB association (Figure 5). Proper motion studies (Frink et al. 1997; Frink et al. in prep.) as well as radial velocity measurements (e.g., Covino et al. 1997) helped to select member stars of the associations. In the course of follow-

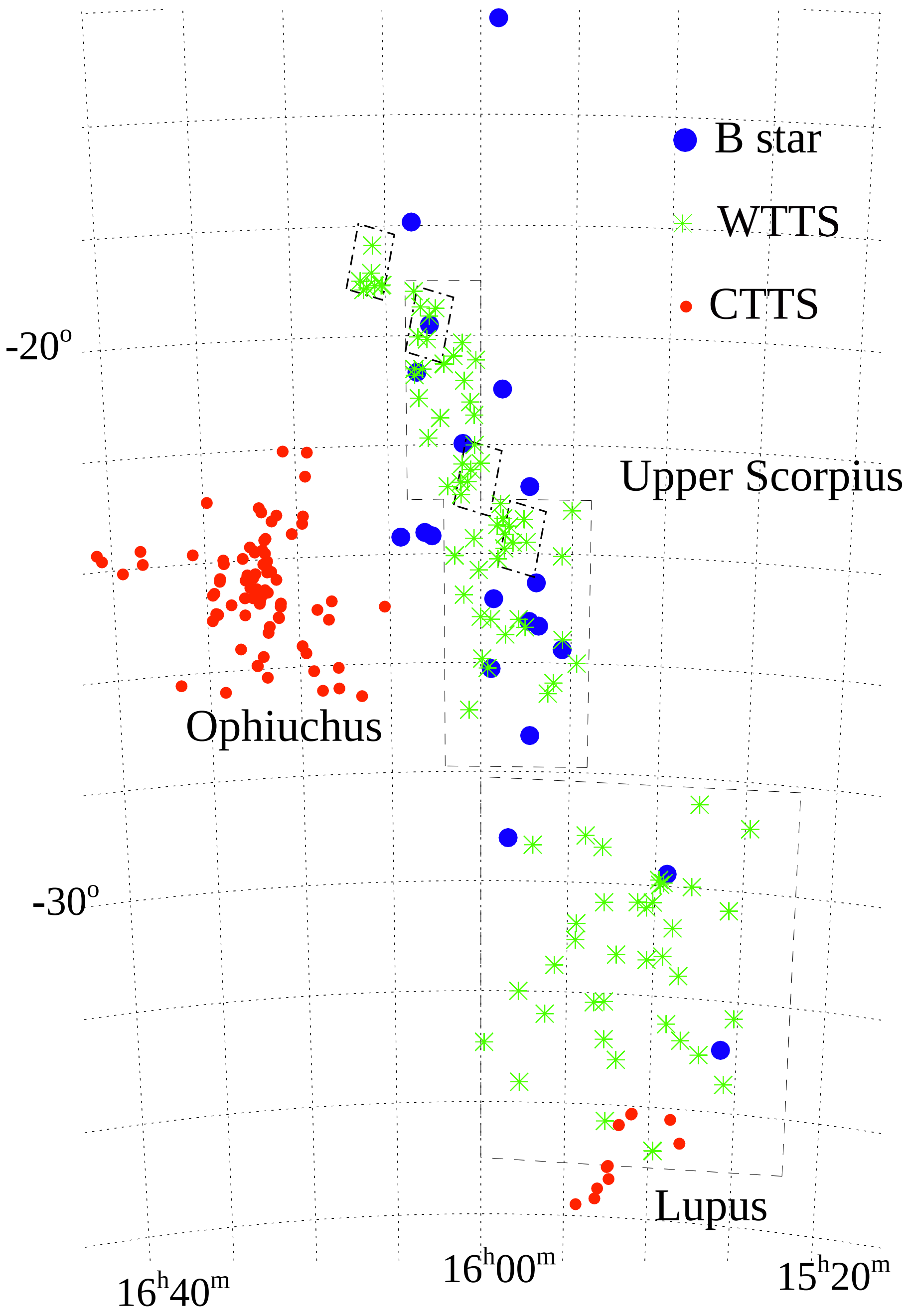

Figure 5. Spatial distribution of classical (red dots) and weak-line (green asterisks) T Tauri stars in the Upper Scorpius subgroup of the Scorpius-Centaurus OB association. B type stars are indicated by blue dots.

up observations visual and spectroscopic binary stars were identified (Brandner et al. 1996; Covino et al. 1997; Köhler et al. in prep.) and excluded from our final list as the complex dynamics and gravitational interactions in binary systems might aggravate or even completely inhibit the formation of planets (depending on physical separation of the binary components and their mass ratio). We ended up with a final sample of about 70 presumably single weak-line T Tauri stars.

4. Observations with Adaptive Optics and *HST*

The *$ 1,000,000 questions* are:

- What are the time scales for disk dissipation?
- When does planet formation take place?
- How common are young planetary systems?
- What type of environment encourages the formation of planetary systems? (T or OB associations?)

In order to estimate the expected brightness differences between a weak-line T Tauri star and its substellar companion, we convolved model atmospheres (Allard & Hauschildt 1995) with the transmission curves of the NIC1 filters. Table 1 summarizes the results and allows us to choose the best filter combination. F108N gives us the highest spatial resolution (diffraction limited + well defined PSF) and the optimal contrast (smallest brightness difference between star and companion), while F145M and F165M give us color information, albeit at 30% reduced spatial resolution. A brown dwarf should be bright in F165M, but faint in F145M (see Fig. 1 & 2).

By comparing the color information with our model spectra we then can derive the object's effective temperature and obtain a first mass estimate.

In March 1997 we started a systematic search for substellar companions to single weak-line T Tauri stars using adaptive optics (ADONIS/SHARP) at the ESO 3.6m telescope. In total, about 50 G and K type weak-line T Tauri stars will be observed. In August/September 1997 24 M type weak-line T Tauri stars have been surveyed for faint brown dwarf or giant planet companions with *HST*/NICMOS.

First results of our adaptive optics survey are shown in Figure 6. Follow-up observations are necessary in order to verify that the T Tauri star and its presumed companion form a common proper motion pair. Adaptive optics images in and out of molecular bands (cf. Figure 1, see also Rosenthal et al. 1996) will then provide a first estimate of the effective temperature of the companion. Check out our WWW pages for the latest results[5], or to learn more about the status of our *HST* program[6]. Our *HST* data should become public in November/December 1997.

[5] http://www.astro.uiuc.edu/~brandner/text/bd/bd.html

[6] http://presto.stsci.edu/cgi-bin/get-proposal-info?7412

Filter	$\Delta m_{T2800K/T900K}$	$\Delta m_{T3800K/T900K}$
F095N	$7\overset{\text{m}}{.}9$	$9\overset{\text{m}}{.}3$
F097N	$7\overset{\text{m}}{.}8$	$9\overset{\text{m}}{.}2$
F108N	$\mathbf{5\overset{\text{m}}{.}2}$	$\mathbf{6\overset{\text{m}}{.}2}$
F113N	$8\overset{\text{m}}{.}9$	$9\overset{\text{m}}{.}9$
F164N	$6\overset{\text{m}}{.}0$	$6\overset{\text{m}}{.}9$
F166N	$5\overset{\text{m}}{.}5$	$6\overset{\text{m}}{.}5$
F187N	$8\overset{\text{m}}{.}5$	$10\overset{\text{m}}{.}0$
F090M	$7\overset{\text{m}}{.}6$	$9\overset{\text{m}}{.}1$
F110M	$5\overset{\text{m}}{.}9$	$7\overset{\text{m}}{.}0$
F145M	$\mathbf{7\overset{\text{m}}{.}0}$	$\mathbf{8\overset{\text{m}}{.}2}$
F165M	$\mathbf{5\overset{\text{m}}{.}1}$	$\mathbf{6\overset{\text{m}}{.}1}$
F170M	$5\overset{\text{m}}{.}8$	$6\overset{\text{m}}{.}9$
F110W	$5\overset{\text{m}}{.}6$	$6\overset{\text{m}}{.}7$
F140W	$5\overset{\text{m}}{.}5$	$6\overset{\text{m}}{.}6$
F160W	$5\overset{\text{m}}{.}6$	$6\overset{\text{m}}{.}7$
WFPC2:		
F1042M	$6\overset{\text{m}}{.}1$	$7\overset{\text{m}}{.}4$

Table 1. The expected brightness in various NIC1 filters for a M-type primary with an effective temperature of 2800 K (M6) or 3800 K (M0), respectively, and a young brown dwarfs with $T_{\rm eff}$=900K. Wide-band filters smear out the diffraction pattern and thus result in a reduced sensitivity for faint companions. F108N will give us the highest spatial resolution (diffraction limited + well defined PSF) combined with the optimal contrast (smallest brightness difference between star and companion), while F145M and F165M should give us color information, albeit at 50% worse spatial resolution. For comparison, we also show the expected brightness difference in the WFPC2 F1042M filter.

Depending on the brightness difference between the primary and the low-mass companion our survey will be sensitive to separations down to $0\overset{''}{.}20$, i.e., 30 AU (comparable to the semi-major axis of the orbit of Neptune) at a distance of 150 pc.

The new generation of 8m to 10m class telescopes in combination with adaptive optics will enable us to extend this survey to substellar companions situated even closer to their central star. From 1998 on, the Keck II telescope will be equipped with adaptive optics (diffraction limited at 2 μm) and thus be able to resolve separations as small as 15 AU at a distance of 150 pc. Adaptive optics at the first VLT telescope should become online in 2000. Diffraction limited imaging at 1 μm would give a spatial resolution for faint companions of about 8 AU at 150 pc.

Also in 2000, the first segment of the VLTI as well as the Keck interferometer (equipped with adaptive optics) should become operational. Both interferometers will ultimately provide a resolution of 3 mas at 2μm (less than 1 AU at 150

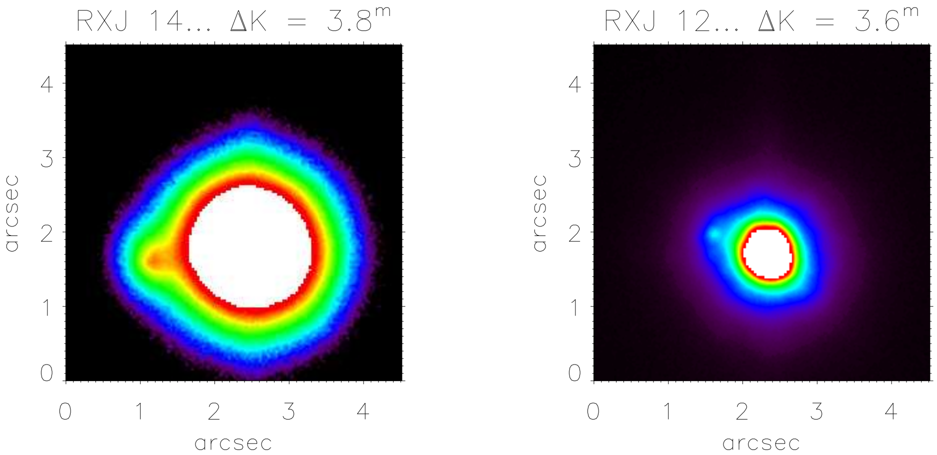

Figure 6. Candidates for substellar companions of two weak-line T Tauri stars in Chamaeleon (ADONIS/ESO 3.6m, March 1997). Follow-up observations are necessary to discern physical companions from chance projections and to probe the physical properties of the companions. North is up and east is to the left.

pc). Thus, also the inner region of young planetary systems will finally become resolvable.

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