TIMESCALES OF DISK EVOLUTION AND PLANET FORMATION: 
HST, ADAPTIVE OPTICS, AND ISO OBSERVATIONS OF WEAK-LINE AND POST-T TAURI STARS

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ABSTRACT

We present high-spatial resolution HST and ground-based adaptive optics observations, and high-sensitivity ISO (ISOCAM & ISOPHOT) observations of a sample of X-ray selected weak-line (WTTS) and post (PTTS) T Tauri stars located in the nearby Chamaeleon T and Scorpius-Centaurus OB associations. HST/NICMOS and adaptive optics observations aimed at identifying substellar companions (young brown dwarfs) at separations $\geq$ 30 A.U. from the primary stars. No such objects were found within 300 A.U. of any of the target stars, and a number of faint objects at larger separations can very likely be attributed to a population of field (background) stars. ISOCAM observations of 5 to 15 Myr old WTTS and PTTS in ScoCen reveal infrared excesses which are clearly above photospheric levels, and which have a spectral index intermediate between that of younger (1 to 5 Myr) T Tauri stars in Chamaeleon and that of pure stellar photospheres. The difference in the spectral index of the older PTTS in ScoCen compared to the younger classical and weak-line TTS in Cha can be attributed to a deficiency of smaller size (0.1 to 1 $\mu$m) dust grains relative to larger size ($\approx$5 $\mu$m) dust grains in the disks of the PTTS. The lack of small dust grains is either due to the environment (effect of nearby O stars and supernova explosions) or due to disk evolution. If the latter is the case, it would hint that circumstellar disks start to get dust depleted at an age between 5 to 15 Myr. Dust depletion is very likely related to the build-up of larger particles (ultimately rocks and planetesimals) and thus an indicator for the onset of the period of planet formation.

Subject headings: circumstellar matter — stars: low-mass, brown dwarfs — planetary systems — stars: pre-main sequence — open clusters and associations: individual (Scorpius-Centaurus, Chamaeleon)

1. INTRODUCTION

In the solar system, the coplanarity of planetary orbits and their moons, and the preferentially prograde rotation direction led Kant (1755) to the suggestion that the solar system evolved out of a flattened, disk like structure (“Urnebel”). Kant also proposed that planetary systems similar to the solar system might be common around other stars. Two of the major observational breakthroughs in astronomy in the 1990s were the direct imaging detection of circumstellar disks around young stars in nearby star-forming regions with the Hubble Space Telescope (O’Dell et al. 1993; McCaughrean & O’Dell 1996; Burrows et al. 1996), and the indirect detection of giant planets in close orbits around nearby stars (Mayor & Queloz 1995; Marcy & Butler 1996). These important observational findings provide strong support for Kant’s hypotheses. Still uncertain, however, are the timescales of disk evolution and the exact physical processes leading to the formation of giant and terrestrial planets.

Giant planets in the solar system possess a core of higher density material surrounded by a shell of metallic hydrogen and an outer atmosphere. According to one model, a
higher density (rocky) core with a mass of \( \approx 10 M_\oplus \) has to form first, before noticeable amounts of nebular gas can be accreted by the proto-giant planet. Simulations indicate that at least \( 10^6 \) yr are necessary to form a 10 \( M_\odot \) rocky core (Lissauer 1987), and that another \( 10^7 \) yr are required for the 10 \( M_\odot \) core to accrete 300 \( M_\odot \) of nebular gas. It is still unknown if massive circumstellar disks can indeed survive for such an extended period. A second model, recently reinstated by Boss (1999), suggests that gravitational instability of a protoplanetary disk leads directly to the formation of a giant gaseous protoplanet on time scales as short as \( 10^3 \) yr. The rocky core then forms due to the settling of dust grains initially acquired, and by further accretion of solid bodies in the course of the following \( 10^5 \) yr. The difference in timescales for the formation of giant planets in the two models provides observational means to decide for or against either model by studying the circumstellar environment of stars with ages \( \leq 15 \) Myr.

Weak-line (WTTS) and the even more evolved post-T Tauri stars (PTTS) are prime targets since – contrary to the very young classical T Tauri stars – they lack strong 1.3 mm dust continuum emission. This suggests that WTTS (and PTTS) no longer possess massive cold circumstellar dust disks (Beckwith et al. 1990, Henning et al. 1993). In WTTS and PTTS, the (dusty) circumstellar matter was either already partially accreted onto the central star or redistributed to form planetesimals or – via disk fragmentation – to form directly giant planets.

We devised a twofold strategy in order to study disk evolution and the timescales of the formation of planetary systems. First, taking advantage of the high sensitivity of the Infrared Space Observatory (ISO, Kessler et al. 1996), we searched for evidence of circumstellar disks around the presumably diskless WTTS and PTTS. Secondly, using high-spatial resolution imaging, we aimed at directly detecting faint substellar companions to the WTTS and PTTS.

Section 2 describes the sample selection. In Section 3 we explain the observing strategies and give an overview of the data reduction and analysis. Section 4 describes the attempt to detect substellar companions using the NASA/ESA Hubble Space Telescope (HST) and ground-based adaptive optics (AO). The results of the ISO observations and their implications are discussed in Section 5. An overall summary of the findings is presented in Section 6.

2. SAMPLE SELECTION

2.1. Selection of star forming regions

We selected the nearby (\( \approx 150 \) pc) Chamaeleon T association and the Scorpius-Centaurus OB association for our study. Young low-mass stars in OB associations are of particular interest, as most stars – including our Sun (see Vanhall, 1998, and references therein) – are believed to have originated in OB associations (e.g., Miller & Scalo 1978). In the course of photometric and spectroscopic follow-up studies of ROSAT sources, an initial sample of about 150 young, X-ray active late-type stars was identified in the Chamaeleon T association (Alcalá et al. 1995, 1997; Covino et al. 1997) and the Scorpius-Centaurus OB association (Kunkel et al. 2000).

2.2. Classification of evolutionary status

Traditionally, ages for pre-main sequence stars are derived based on their location above the main-sequence and by comparison with theoretical evolutionary tracks and isochrones in an HR-diagram. This approach relies on precise distance estimates in order to derive luminosities. In ScoCen and Cha, however, parallax measurements are only available for a handful of the X-ray active low-mass stars (see Frink et al. 1998; Neuhäuser & Brandner 1998; Kunkel et al. 2000). Furthermore, the individual parallax measurements indicate a relatively large spread in distance among various members of these associations. Hence it would be disadvantageous to determine the evolutionary status of the X-ray active low-mass stars using properties which are independent of the distance, like, e.g., spectral features.

In general, the X-ray active low-mass stars in Chamaeleon exhibit higher lithium equivalent widths than their counterparts in Scorpius-Centaurus. As lithium is continuously destroyed near the bottom of the convections zone, the photospheric lithium abundance decreases with increasing stellar age (Herbig 1965; Bodenheimer 1965). Therefore the lower lithium abundance indicates that the low-mass stellar population in ScoCen is older than in Chamaeleon.

Martín (1997, 1998) suggested a refined classification, based on \( H\alpha \) and lithium equivalent widths as a function of spectral type to distinguish between CTTS, WTTS and PTTS. In a diagnostic diagram, late-type PTTS occupy a region intermediate between WTTS and stars in young open clusters like the Pleiades or \( \alpha \) Per with ages of 60 to 120 Myr. Unfortunately, the lithium criterion can only be applied to stars of spectral type K0 and later, and does not allow to discriminate pre-main-sequence from zero-age-main-sequence (ZAMS) stars of earlier spectral types. Thus the number of stars located in the PTTS region of the diagnostic diagram represents only a lower limit to the total number of PTTS in a stellar population (Martín 1997). Therefore additional criteria like stellar kinematics (e.g., Feigelson 1996; Frink et al. 1997, 1998) are needed in order to distinguish between pre-main-sequence and ZAMS stars of spectral type K0 and earlier.

In order to avoid a contamination of our sample by ZAMS field stars, unclassified stars according to the diagnostics by Martín (1997, 1998) were largely rejected. In Chamaeleon, the majority of the young late-type stars are CTTS and WTTS and have typical ages between 1 Myr and 5 Myr (Alcalá et al. 1995). In the Scorpius-Centaurus OB association, a total of 76 TTS were detected. 49 of them can be classified as PTTS, 20 as WTTS and 7 as CTTS. 42 X-ray active stars in ScoCen remain unclassified. Typical ages for the WTTS and PTTS in ScoCen are of the order of 5 Myr to 15 Myr (Kunkel et al. 2000).

The sample was narrowed down to about 50 WTTS and PTTS by selecting preferentially late-type stars with lithium equivalent width \( \geq 0.1 \) to 0.6 Å.

2.3. Preselection against binary systems

As we aimed for the search for faint (substellar) companions and the study of disk evolution, it is important to consider the effect of binary stars. In binary systems, the complex dynamics and gravitational interactions between the individual components and their circumstellar and circumbinary disks might influence the evolution of circum-
stellar disks and aggravate or even completely inhibit the formation of substellar companions (Papaloizou & Pringle 1977; Artymowicz & Lubow 1994). Recent observations of circumstellar disks in multiple systems support these theoretical predictions (e.g. HK Tau, Stapelfeldt et al. 1998, Koaresko 1998; HV Tau, Monin & Bouvier 2000). All stars in the sample were therefore surveyed for visual and spectroscopic binary companions (Brandner et al. 1996; Covino et al. 1997; Köhler et al. 2000; Kunkel et al. 2000). None of the detected companions was faint enough to be classified as a substellar source. Binary and multiple systems with separations less than $3''$ (450 A.U. at a distance of 150 pc) were excluded from the final target list. Table 3 gives an overview on the physical properties of the stars which were observed with HST and ISO.

3. OBSERVATIONS AND DATA REDUCTION

3.1. HST/NICMOS observations

3.1.1. Observing Strategy

Young substellar companions are still relatively hot, and are thus considerably more luminous and much easier to spot than evolved (older and cooler) substellar companions (Brandner et al. 1997; Malkov, Piskunov, & Zinnecker 1998). Maybe somewhat counterintuitive is the fact that the best wavelength region to search for substellar companions is the near-infrared between 1 $\mu$m and 2 $\mu$m. The spectral energy distribution of late-type dwarfs and thus of spectral energy distribution of late-type dwarfs and thus of $\mu_2$ corresponds to 30 A.U., i.e. comparable to the semimajor axis of Neptune’s orbit.

3.1.2. Observations

The NICMOS camera aboard HST was installed in February 1997 (Thompson et al. 1998). HST/NICMOS observations (see Table 2) of 24 M-type WTTS and PTTS in Chamaeleon and Scorpius-Centaurus were carried out between 1997 Aug 14 and Sep 22 using NICMOS camera 1 (NIC1, 0.043/pixel). The observations were obtained in the F108N filter using MULTIACCUM mode. 18 of the targets were also observed in the F110M filter in order to obtain additional color information. Exposure times were between 2560s to 3072s in F108N, and between 64s to 192s in F110M.

3.1.3. Data reduction and analysis

The data reduction was carried out using the IRAF/STSDAS package CALNICA V3.1. For the data reduction, we replaced the model dark frames (as provided by STScI) with darks derived from archived on-orbit measurements. The photometric accuracy of the flux measurements for the faint sources is limited by the uncertainties in the dark/bias subtraction, flatfield errors, and the resulting uncertainties in the local background. The overall photometric uncertainties are of the order of 0.05 for the brighter objects, and 0''1 to 0''2 for the fainter sources. Figures 1 and 2 show examples of the reduced frames.

As the NICMOS PSF can vary significantly from one HST orbit to the next, the HST/NICMOS observations of all target stars were used to build up a library of HST/NIC1 PSFs in the F108N and F110M filters. For each set of observations, we then identified the best matching PSF in the library. Sub-pixel offsets between target and PSF were computed by cross-correlating the individual frames. The PSF was then Fourier-shifted, scaled, and subtracted. The resulting difference frames were searched for faint, close companions. Figure 3 shows the typical detection limit (solid line) in terms of brightness difference versus separation. It would have been possible to detect a 4''7 fainter companion at a separation of 0''2, and a 8'' fainter companion at a separation of 1''. This detection limit is in good agreement with the detection limit derived from the simulations based on TinyTim PSFs.

Three of the “single” stars turned out to be close binaries, and two of the three wide binaries turned out to be hierarchical triple systems (Figure 4). A number of faint objects, which were found close to some of the target stars, are shown in Figure 5.

3.2. Adaptive Optics Observations

The observing strategy for the adaptive optics observations with ADONIS/SHARP at the ESO 3.6m telescope was similar to that of the HST/NICMOS observations. Because of the need for a star sufficiently bright for wavefront sensing, only bright G- and K-type stars could be observed. The observations were carried out in the broadband H and K filter, with the intent to gather additional data with the circular variable filter (CVF) for good candidates for substellar companions.

In two observing nights in March 1997, a total of 17 WTTS and PTTS in Chamaeleon and Scorpius Centaurus were observed, and two 4'' to 5'' fainter companions were identified (RXJ 12253-7857 and RXJ 14150-7822, see
Brandner et al. 1997). Unfortunately, unfavorable weather conditions during the second half of the second observing night prevented any immediate follow-up using the CVF.

3.3. **ISOcam & ISOpHOT observations**

3.3.1. **Observing Strategy**

ISO offered the unique opportunity to search for subtle infrared excesses from circumstellar disks and substellar companions with unprecedented sensitivity. As the temperature of circumstellar disks changes with radial distance from the star, one can probe the radial surface density and temperature profile of circumstellar disks by observing them at a wide range of wavelengths. If for example in the course of disk evolution the inner disk is depleted first, it should still be possible to detect the cooler, outer parts of the disk at longer wavelengths. Consequently, the observing strategy was to observe the sample stars both with ISOcam (Cesarsky et al. 1996) at 6.7 μm and 15 μm, and with ISOpHOT (Lemke et al. 1996) at 60 μm and 90 μm.
3.3.2. Observations and Data Reduction

The ISO observations with ISOCAM and ISOPHOT were carried out between 1997 Aug 04 and 24. Of the 30 WTTS and PTTS in the initial target list, only twelve were actually observed with ISOPHOT. The ISOPHOT observations of twelve stars were carried out as $3 \times 3$ maps using the PHT C100 detector in mode PHT22 and the C100$_{60\mu m}$ and C100$_{90\mu m}$ filters. NTTS155436-2313 was only observed with ISOPHOT. The other eleven stars were also observed with ISOCAM. The ISOCAM observations were obtained with a scale of 3"/pixel as $2 \times 2$ rasters using the LW2 (6.75 $\mu$m) and LW3 (15 $\mu$m) filters. No color information could be obtained for RXJ 15460-2920, as it was observed in LW2 only. Total exposure times were of the order of 200s to 240s per filter and object.

The data reduction was carried out using the software packages CAM Interactive Analysis and PHOT Interactive Analysis. The standard processing includes dark subtraction, deglitching, transient correction, flatfielding and mosaicing. None of the sources was detected at 60 $\mu$m and 90 $\mu$m down to a limiting flux of $\approx 400$ mJy.

Figure 3 shows the pipeline reduced ISOCAM data in
the LW2 filter. All eleven target stars (8 PTTS, 1 WTTS, 2 unclassified stars) are clearly detected (Moneti et al. 1999). On several occasions additional foreground (field) stars are also detected. Foreground stars can easily be distinguished from the WTTS and PTTS based on their LW3-LW2 colors (see below). Aperture photometry was performed using IRAF and 4.5 pixel and 5.5 pixel apertures for LW2 and LW3, respectively. Random uncertainties should be of the order of a few percent, but systematic errors might be as large as 20% due to uncertainties in the transient correction and the uncertain color terms. Table 3 summarizes the results of the ISOCAM observations.

3.4. Ground-based NIR follow-up

Ground-based near-infrared spectroscopy of the target stars and the faint sources detected with HST/NICMOS
and adaptive optics was attempted in the course of two nights in April 1998 using the CTIO 4m Blanco telescope and the near infrared spectrograph. Due to fog and clouds, no useful data were obtained.

4. PHYSICAL COMPANIONS AND BACKGROUND SOURCES

4.1. Faint (Substellar?) Sources

The PSF subtraction of the HST/NICMOS data did not reveal any faint objects which would qualify as a candidate for a substellar companion within 2″ of the WTTS and PTTS. A total of five point sources at projected separations >2″ and 6 to 8 mag fainter than their primary were detected in the 24 fields (Figure 3). Photometric and astrometric measurements for the faint sources are summarized in Table 4, and a plot of brightness difference between the primary and a possible companion vs. separation is shown in Figure 3.

The probability \( P(\Theta, m) \) for an unrelated source to be located within a certain angular distance \( \Theta \) from a particular target is given by

\[
P(\Theta, m) = 1 - e^{-\pi\rho(m)\Theta^2}
\]

(1)

where \( \rho(m) \) is the cumulative surface density of background sources down to a limiting magnitude \( m \). The probability for chance alignments increases with increasing angular distance and decreasing brightness. Therefore, in order to derive an estimate of \( P(\Theta, m) \), one has to determine the local density of background sources first.

For the sources in Scorpius-Centaurus, parallel NIC2 observations of adjacent fields were obtained in the F110W filter. The eleven NIC2 fields cover an area of about 4000 square arcsec. 68 sources with brightness values between 16\(\text{m}4 \) and 23\(\text{m}2\) were detected. Figure 4 shows the cumulative brightness function \( \rho(m) \) scaled to an area of 1 square degree. The number counts in the observed cumulative brightness function are in good agreement with the number counts expected according to the Galactic model by Wainscoat et al. (1992). No NIC2 parallel observations in F110W were obtained for the targets in Chamaeleon, but a cumulative brightness function can again be derived from the model by Wainscoat et al. (1992).

As the probability for physical association decreases with increasing angular separation, our best candidate for a true substellar companion is the faint source ≈2″ northwest of RXJ12319-7848. According to equation (1) the bare-bone probability for it being an unrelated background source is only ≈5%. In other words, equation (1) yields a 95% probability for a physical association between the RXJ12319-7848/c and RXJ12319-7848. Similar reasoning has in the past frequently been cited as supporting evidence for the substellar nature of faint objects near a brighter star (e.g., 0918-0023B, Jones et al. 1994; TMR-1C, Terebey et al. 1998; TWA-7B, Neuhäuser et al. 2000a).

In many cases, follow-up observations helped to establish the true nature of the faint object, and the object turned out to be an unrelated background star (e.g., TMR-1C, Terebey et al. 2000; TWA-7B, Neuhäuser et al. 2000b) or a distant galaxy (0918-0023B, Becklin et al. 1995).

It is therefore advisable to refrain from assigning probabilities to individual sources. Instead one should compute

![Graph showing the distribution of the brightness difference between the target stars and their possible companions versus the angular separation. The solid line indicates the detection limit after PSF subtraction. It would have been possible to detect a 4″7 fainter companion at a separation of 0″2 and an 8″8 fainter companion at a separation of 1″, but none were found. The region preferentially occupied by background objects is also shown (dotted line). Note that the lack of nearly equal brightness binaries with separation between 0″2 and 2″5 is due to the preselection against binaries identified in the ground-based speckle and direct imaging observations.](image-url)
Fig. 5.— Background star counts as measured on the NIC2 parallel observations in the general direction of ScoCen (l≈345°, b≈+15°) and scaled to 1 square degree. Based on these star counts, we expect on average 0.37 objects with $16^{m}75 \leq m_{F110M} \leq 19^{m}15$ per NIC1 frame, or 4.0 background sources in total on the 11 NIC1 frames towards ScoCen.

Fig. 6.— Color magnitude diagram for target stars (WTTS and PTTS) and faint sources. Most of the M-type TTS show $m_{F108N}-m_{F110M}$ colors close to 0 (with the exception of the PTTS RXJ 12046-7731). Because of their faintness, the colors of the suspected background objects have relatively large uncertainties, but all fall clearly outside the region occupied by substellar objects. The dashed line indicates the expected color for a brown dwarf with $T_{\text{eff}}$=900 K.

The ensemble statistics. While the probability for finding a background object similar to RXJ12319-7848/c within 2″ of RXJ12319-7848 is only 5%, the probability for finding any such object within 2″ of one of the 24 HST/NICMOS targets is ≈70%. It is thus not unlikely that RXJ12319-7848/c is an unrelated background source.

Based on the observed cumulative brightness function for Scorpius-Centaurus, one would expect to detect on av-
verage 4.0 sources with F110W magnitudes between 16.0 and 19.0 would be expected on average in a field equivalent in size to the area covered by the 13 NIC1 frames. Four faint sources were detected on the NIC1 frames towards Chamaeleon, which is in good agreement with the theoretical expectation.

The agreement between the $m_{F108}$ - $m_{F110}$ colors of the faint objects and the M-type WTTS and PTTS (Figure 3) provides additional evidence that the faint objects are unrelated background sources and not substellar companions.

4.2. Binary and multiple systems

In addition to 21 stars which were assumed to be single stars, also three wide binaries with separations $\geq 3.5$ were included in the sample. Three of the “single” stars turned out to be close binaries, and two of the three wide binaries turned out to be hierarchical triple systems (see Figure 4). RXJ 11088-7519 constitutes an additional triple system, with RXJ 11088-7519a being a spectroscopic binary (Covino et al. 1997). The relatively high incidence of triple systems (see Figure 4) can be attributed to the selection effect in favor of multiple systems in ROSAT selected samples of young X-ray active late-type stars (see Brandner et al. 1996; Kunkel et al. 2000).

The adaptive optics observations led to the identification of two faint companions to X-ray active stars in Chamaeleon. The relatively small lithium equivalent widths of RXJ 12253-7857 and RXJ 14150-7822 (see Alcalá et al. 1997) indicates that both stars could be either pre-main-sequence stars with ages of up to 20 Myr or ZAMS stars. In all cases the brightness of the secondary suggests that it is a stellar companion (i.e., not substellar).

4.3. Implications

It seems likely that all five faint sources are background objects, and not physically related to the PTTS and WTTS. The lack of brown dwarf companions at separations larger than 30 A.U. (0.2 at 150 pc) indicates that wide brown dwarf companions are rare (less than 4% of all cases). This is in good quantitative agreement with the surveys for brown dwarf companions to white dwarfs (Probst 1983; Becklin & Zuckerman 1988) and M-dwarfs (Oppenheimer 1999; Burgasser et al. 2000) in the solar neighborhood. It implies that fragmentation of collapsing molecular cloud cores in general does not produce extremely unequal mass pairs. Alternatively, the density of circumstellar disks at radii greater than 30 A.U. appears to be too small to allow for the formation of massive substellar companions.

5. EVOLVED (REMNANT) CIRCUMSTELLAR DISKS

5.1. ISOCAM survey of low-mass star forming regions

A large scale ISOCAM survey of low-mass star forming regions in the solar neighborhood was carried out by Nordh and collaborators (Nordh et al. 1996, 1998; Olafsson et al. 1999; Persi et al. 1999). The first part of Nordh’s survey included the dark clouds Chamaeleon I, Ophiuchus, Serpens, and Corona Australis and covered an area of 2.3 square degree. A total of 402 sources in Oph, Cha, and CrA were detected both in LW2 and LW3 (Nordh et al. 1998). When placed on a log $F_\nu$/($F_\nu$/LW3) vs. log($F_\nu$/LW3)/$F_\nu$/LW2) magnitude-color diagram, the sources cluster in two distinctive groups. As discussed by Nordh et al. (1996), the two groups can be identified with disk-less main-sequence stars (stellar photospheres), and pre-main sequence stars with circumstellar disks.

The expected value of $R = \log F_\nu$/($F_\nu$/LW2) for disk-less main-sequence stars is approx. $-0.68$ and it is rather insensitive to the effective temperature of the star. For T Tauri stars with circumstellar disks, $R$ can be derived from simple disk models. Kenyon & Hartmann (1995) computed the spectral index

$$\alpha_{12} = \frac{\log(\lambda_2 F_\lambda) - \log(\lambda_1 F_\lambda)}{\log \lambda_2 - \log \lambda_1}$$

for flat and flared disk models. According to their models, $\alpha = -0.7$ for a flared disk and $\alpha = -1.3$ for a flat disk at 10 $\mu$m. This corresponds to $R = -0.1$ and $R = +0.1$, respectively. About 90% of the 402 sources in the sample by Nordh et al. (1998) have either $R < -0.5$ or $R > -0.2$, and are thus either (disk-less) main-sequence stars or young pre-main sequence stars with circumstellar disks. Only about 10% of the sources fall in the transitional region with $-0.5 \leq R \leq -0.2$.

5.2. ISOCAM mini-survey of Scorpius-Centaurus

Our ISOCAM mini-survey in Scorpius-Centaurus covers only 10 stars (1 WTTS, 7 PTTS, and 2 unclassified stars) which were observed both with LW2 and LW3. Two stars (1 WTTS, 1 PTTS) have ISOPHOT observations, but no ISOCAM observations in LW3 (see Table 5). Figure 5 shows one of the above mentioned log $F_\nu$/($F_\nu$/LW3) vs. log($F_\nu$/LW3)/$F_\nu$/LW2) magnitude-color diagrams for the sources detected towards Chamaeleon I by Nordh et al. (1996). Overplotted are the sources from the present survey. Interestingly, the majority of the stars in our sample (seven out of ten) have R in the range of $-0.2$ to $-0.5$, whereas the large majority of the sources in Chamaeleon and other low-mass star forming regions have R values outside this range. The values of $R$ measured for our sample of PTTS are on average higher than the values for a pure stellar photosphere, but significantly less than the typical value measured for CTTS and WTTS in low-mass star forming regions.

5.3. Implications

The non-detection with ISOPHOT at 60 $\mu$m and 90 $\mu$m confirms the absence of cold, massive dust disks around the low-mass WTTS and PTTS in ScoCen. The ISOCAM observations, however, indicate the presence of circumstellar material (presumably in form of a circumstellar disk). The physical properties of the disks in ScoCen appear to be different from the disks typically found around CTTS and WTTS in low-mass star forming regions. The difference in R (or spectral index $\alpha$) can be explained by differences in the global dust opacities at 6.5 $\mu$m and 15 $\mu$m in both types of disks.

Suttner, Yorke & Lin (1999) studied dust coagulation in the envelopes around young stellar objects. They simulated the effect of grain size on the specific extinction
coefficient. Figure 1 in their paper indicates that a change in the average dust grain size from 0.1 µm to 5 µm leads to an increase of the specific extinction coefficient $\kappa_{\text{ext}}$ at 6.5 µm by a factor of $\approx 5$, whereas $\kappa_{\text{ext}}$ at 15 µm remains virtually unchanged. Such an increase in $\kappa_{\text{ext}}(6.5 \mu m)$ is equivalent to an increase in the spectral index $\alpha$. A “flat” spectral index $\alpha = 0$, e.g., corresponds to $R=-0.35$. Thus any mechanism which preferentially removes or destroys smaller grains can provide a viable explanation for the observed differences in the spectral index of PTTS in ScoCen and WTTS and CTTS in low-mass starforming regions such as Chamaeleon.

The higher ratio of PTTS to WTTS in Scorpius-Centaurus compared to Chamaeleon suggests that the X-ray active low-mass stars in Scorpius-Centaurus are on average older than their counterparts in Chamaeleon. Alcalá et al. (1997) assign ages less than 5 Myr to the majority of the X-ray active stars in Chamaeleon, whereas Kunkel et al. (2000) find average ages in the range of 5 to 15 Myr for the WTTS and PTTS in Scorpius-Centaurus. Disk evolution and grain growths in circumstellar disks would lead to a deficiency in smaller grains. Such a deficiency in smaller grains should only last until a critical number of massive particles like rocks and planetesimals has formed. Collisions between individual planetesimals will then replenish the disk with smaller grains. During the initial build-up period, however, there should be a phase in which a disk is almost devoid of smaller grains.

Apart from the age difference, the PTTS in ScoCen are located in an OB association, and thus – unlike the WTTS and CTTS in T-associations – subject to the effects of nearby O stars and supernova explosions. Both impacting shock fronts (Dwek et al. 1996) and high energy photons from nearby O stars and occasional supernova explosions (Voit 1991) could change the distribution of grain sizes. Overall, however, the contribution of Lyman continuum radiation to dust destruction should be negligible as only grains with sizes of $\lesssim 0.001 \mu m$ are affected (see discussion in Richling & Yorke 1997).

Thus disk evolution appears to be the more likely explanation for the difference in spectral index between CTTS and WTTS in Chamaeleon and the PTTS in Scorpius-Centaurus.

6. SUMMARY

High-spatial resolution HST and ground-based adaptive optics observations, and high-sensitivity ISO (ISOCAM & ISOPHOT) observations of a sample of X-ray selected weak-line (WTTS) and post (PTTS) T Tauri stars located in the nearby Chamaeleon T and Scorpius-Centaurus OB associations were obtained and analyzed.

The HST/NICMOS and adaptive optics observations aimed at identifying substellar companions (young brown dwarfs) at separations $\geq 30$ A.U. ($0'.2$ at 150 pc) from the

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**Figure 7.** (adapted from Nordh et al. 1996) Color-magnitude diagram based on ISOCAM observations of young stars in Chamaeleon (circles) and Scorpius-Centaurus (squares). Black filled circles indicate previously known YSOs and CTTSs, circles with a central dot previously known WTTS, and open circles new sources detected with ISO by Nordh et al. (1996). The dashed line indicates the location of pure stellar photospheres, the dotted and solid line the location of flat and flared circumstellar disks, respectively, as predicted by the models from Kenyon & Hartmann (1995). WTTS and PTTS in ScoCen show a spectral index intermediate between main-sequence stars and CTTS and WTTS in Chamaeleon.
primary stars. While the sample was preselected against binary stars with $0''2 \leq \text{sep.} \leq 3''$, we detected 5 binary stars with separations $<0''2$. The largest brightness difference between a primary and a secondary in these close binaries is $1''75$. The relatively small brightness difference indicates that all five secondaries at separations $<0''2$ are low-mass stars with masses clearly above the hydrogen burning limit. Even though it would have been possible to detect a $4''7$ fainter object at a separation of $0''2$ from the primary star, or a $8''$ fainter object at a separation $\geq 1''$ from the primary star, no such objects were found within 300 A.U. (2'') of any of the target stars. 5 objects at separations larger than 2'', and 6 mag to 8 mag fainter than the target stars can very likely be attributed to a population of field (background) stars. We conclude that the formation of massive substellar companions at separations larger than 30 A.U. from the primary star is very unlikely.

ISOCCAM observations of WTTS and PTTS in ScoCen reveal infrared excesses which are clearly above photospheric levels, and which have a spectral index intermediate between that of younger (1 to 5 Myr) T Tauri stars in Chamaeleon and that of pure stellar photospheres. The difference in the spectral index of the older WTTS and PTTS in ScoCen compared to the younger classical and weak-line TTS in Cha can be understood in terms of disk evolution, and could hint that circumstellar disks start to get dust depleted at an age around 5 to 15 Myr. Dust depletion is very likely related to the build-up of larger particles (ultimately rocks and planetesimals) and thus an indicator for the onset of the period of planet formation.

In evolved disks, the presence of larger grains resulting from dust coagulation and the gradual build-up of larger bodies should manifest itself both in the scattering properties at longer wavelengths and in spectral features. In the near future, using SIRTF/IRS and SOFIA, it will become possible to study the mid- and far-infrared properties of the circumstellar disks around the PTTS and WTTS in ScoCen and other nearby star forming regions. Furthermore, high-sensitivity CO surveys with the Atacama Large Millimeter Array will be able to detect also the gaseous component of the disks around the PTTS and WTTS in ScoCen and Chamaeleon. These surveys will provide the final answer to the question whether massive gaseous disks can survive long enough to allow for slow accretion of gas onto proto-giant planets over timescales of $10^7$ yr, or if giant planets have to form on much shorter time scales by disk instabilities.

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The expected brightness difference in various NIC1 filters between an M-type primary with an effective temperature of 2800 K (M6) or 3800 K (M0), respectively, and a young brown dwarf with $T_{\text{eff}}=900$ K. F145M and F165M provide color information, albeit at worse spatial resolution than F108N. For comparison, the expected brightness difference in the WFPC2 F1042M filter is shown.

| Filter | $\Delta m_{T2800K/T900K}$ | $\Delta m_{T3800K/T900K}$ |
|--------|--------------------------|--------------------------|
| F095N  | 7.9                      | 9.3                      |
| F097N  | 7.8                      | 9.2                      |
| F108N  | 5.2                      | 6.2                      |
| F113N  | 8.9                      | 9.9                      |
| F164N  | 6.0                      | 6.9                      |
| F166N  | 5.5                      | 6.5                      |
| F187N  | 8.5                      | 10.0                     |
| F090M  | 7.6                      | 9.1                      |
| F110M  | 5.9                      | 7.0                      |
| F145M  | 7.0                      | 8.2                      |
| F165M  | 5.1                      | 6.1                      |
| F170M  | 5.8                      | 6.9                      |
| F110W  | 5.6                      | 6.7                      |
| F140W  | 5.5                      | 6.6                      |
| F160W  | 5.6                      | 6.7                      |
| WFPC2: |                          |                          |
| F1042M | 6.1                      | 7.4                      |
Table 2
Target List. Coordinates are presented in columns 2 and 3. Column 4 lists whether the object has been observed with HST or ISO. Column 5 list aliases when available.

| Target          | \( \alpha \) (2000) | \( \delta \) (2000) | HST/ISO | Alias |
|-----------------|----------------------|---------------------|---------|-------|
| RXJ08480-7854\(^1\) | 08 47 57.21          | -78 54 54.0         | HST     |       |
| RXJ09029-7759\(^1\) | 09 02 51.85          | -77 59 35.2         | HST     |       |
| RXJ10053-7749\(^1\) | 10 05 20.54          | -77 48 42.8         | HST     |       |
| RXJ11088-7519B\(^1\) | 11 08 52.92          | -75 19 03.1         | HST     |       |
| RXJ11498-7850\(^1\) | 11 49 32.60          | -78 51 00.7         | HST     |       |
| RXJ11585-7754B\(^1\) | 11 58 27.57          | -77 54 44.8         | HST     |       |
| RXJ12028-7718\(^1\) | 12 02 55.25          | -77 18 37.7         | HST     |       |
| RXJ12046-7731\(^1\) | 12 04 36.78          | -77 31 34.2         | HST     |       |
| RXJ12077-7953\(^1\) | 12 07 48.96          | -79 52 42.3         | HST     |       |
| RXJ12197-7403\(^1\) | 12 19 44.24          | -74 03 56.9         | HST     |       |
| RXJ12319-7848\(^1\) | 12 31 56.61          | -78 48 32.0         | HST     |       |
| RXJ12436-7834\(^1\) | 12 43 37.21          | -78 34 07.4         | HST     |       |
| RXJ13033-7706\(^1\) | 13 03 04.84          | -77 07 02.0         | HST     |       |
| RXJ15241-3030B\(^2\) | 15 24 12.99          | -30 30 56.0         | HST     |       |
| RXJ15409-3024\(^2\) | 15 40 56.50          | -30 24 23.3         | HST, ISO|       |
| RXJ15419-3019\(^2\) | 15 41 57.49          | -30 19 04.5         | HST, ISO|       |
| RXJ15438-3306\(^2\) | 15 43 51.58          | -33 06 29.4         | HST     |       |
| RXJ15460-2920\(^2\) | 15 46 05.26          | -29 20 52.1         | HST, ISO|       |
| RXJ15489-3045\(^2\) | 15 48 57.30          | -30 45 02.4         | HST, ISO|       |
| RXJ15549-2347\(^2,3\) | 15 54 59.9           | -23 47 18           | ISO     | Sco005|
| NTT155421-2330\(^3\) | 15 57 20.0           | -23 38 49           | ISO     | Sco015|
| NTT155436-2313\(^3\) | 15 57 34.4           | -23 21 11           | ISO     | Sco017|
| RXJ15598-2556\(^2\) | 15 59 50.05          | -25 55 57.9         | HST, ISO|       |
| RXJ16002-2417\(^2\) | 16 00 13.32          | -24 18 10.2         | HST, ISO|       |
| RXJ16043-2130B\(^2\) | 16 04 21.07          | -21 30 41.9         | HST     |       |
| RXJ16047-1930\(^2,3\) | 16 04 47.8           | -19 30 23           | ISO     | Sco027|
| RXJ16056-2152\(^2\) | 16 05 39.40          | -21 52 34.0         | HST, ISO|       |
| RXJ16070-2043\(^2\) | 16 07 03.75          | -20 43 07.3         | HST, ISO|       |

\(^1\)Alcalá et al. 1995, 1997; \(^2\)Kunkel et al. 2000; \(^3\)Walter et al. 1994
Table 3  
Physical Parameters: Spectral type, Lithium equivalent width, V magnitude and V-J color are from Alcalá et al. (1995, 1997), Kunkel et al. (2000) and Walter et al. (1994), except where mentioned ootherwise.

| Target          | TTS-class | SpT | EW(Li) [Å] | V | V-J | m$_{F108N}$ | m$_{F108N}$-m$_{F110M}$ | F$_{ν}$ (F108N) [mJy] |
|-----------------|-----------|-----|------------|---|-----|-------------|-------------------------|----------------------|
| RXJ08480-7854  | W         | M2  | 0.61       | 13.19 | 3.89 | 9.60        | -0.005                  | 296.5                |
| RXJ09029-7759  | P         | M3  | 0.50       | 13.99 | ... | 10.50       | 0.012                   | 129.8                |
| RXJ10053-7749  | W         | M1  | 0.57       | 13.41 | 3.59 | 10.21       | -0.016                  | 169.5                |
| RXJ11088-7519B | P         | M3  | 0.50       | 14.78 | ... | 10.97       | 0.065                   | 83.7                 |
| RXJ11498-7850  | P         | M1  | 0.50       | 14.37 | ... | 9.81        | 0.010                   | 243.4                |
| RXJ11585-7754B | W         | M3  | 0.60       | 14.29 | 3.97 | 10.69       | 0.002                   | 108.6                |
| RXJ12028-7718  | W         | M0  | 0.60       | 14.38 | ... | 10.85       | 0.000                   | 93.5                 |
| RXJ12046-7731  | P         | M2  | 0.47       | 13.78 | ... | 10.11       | -0.147                  | 185.3                |
| RXJ12077-7953  | W         | M4  | 0.60       | 14.52 | ... | 10.85       | 0.002                   | 94.9                 |
| RXJ12197-7403  | W         | M0  | 0.56       | 13.12 | ... | 10.09       | ...                     | 189.5                |
| RXJ12319-7848  | W         | M1  | 0.60       | 14.17 | 3.90 | 10.60       | 0.002                   | 117.8                |
| RXJ12436-7834  | W         | M0  | 0.70       | 13.13 | 3.75 | 9.72        | -0.008                  | 265.0                |
| RXJ13033-7706  | W         | K7/M0 | 0.60 | 13.23 | ... | 10.07       | 0.01                    | 192.5                |
| RXJ15241-3030B | P         | M1  | 0.38       | 13.58 | ... | 10.95       | ...                     | 85.8                 |
| RXJ15409-3024  | P         | M2  | 0.11       | 14.53 | 3.89$^1$ | 11.02       | ...                     | 80.2                 |
| RXJ15419-3019  | P         | M4  | 0.19       | 16.06 | 4.29$^1$ | 12.18       | ...                     | 27.6                 |
| RXJ15438-3306S | ?         | M3  | 0.04       | 14.86 | 4.20 | 11.56       | ...                     | 48.6                 |
| RXJ15438-3306N | ...       | ... | ...        | ...   | ... | ...         | ...                     | ...                  |
| RXJ15460-2920  | P         | M0  | 0.42       | 13.46 | ... | 10.76       | 0.044                   | 101.6                |
| RXJ15489-3045  | P         | M2  | 0.09       | 15.28 | 4.03$^1$ | 11.66       | ...                     | 44.5                 |
| RXJ15549-2347  | ?         | G2  | 0.28       | 8.93  | 1.36 | ...         | ...                     | ...                  |
| NTT155421-2330 | P         | M0  | 0.28       | 12.78 | 3.09 | ...         | ...                     | ...                  |
| NTT155423-2133 | W         | M0  | 0.58       | 13.63 | 3.77 | ...         | ...                     | ...                  |
| RXJ15598-2556A | P         | M2  | 0.31       | 14.21 | 3.61 | 10.94       | 0.003                   | 86.4                 |
| RXJ15598-2556BC | ...       | ... | ...        | ...   | ... | 14.32       | -0.002                  | 3.8                  |
| RXJ16002-2417  | P         | M0  | 0.47       | 13.66 | 3.20$^1$ | 10.87       | 0.053                   | 92.2                 |
| RXJ16043-2130B | P         | M2  | 0.38       | 15.06 | 4.62 | 10.85       | -0.047                  | 93.9                 |
| RXJ16047-1930  | ?         | K3  | 0.32       | 11.17 | 2.25 | ...         | ...                     | ...                  |
| RXJ16056-2152  | P         | M1  | 0.50       | 14.26 | ... | 10.86       | 0.016                   | 92.7                 |
| RXJ16070-2043  | W         | M1  | 0.55       | 14.51 | ... | 11.05       | 0.012                   | 77.6                 |

$^1$J magnitudes based on 2MASS Second Incremental Release data products.
### Table 4
Separation, position angle, and photometric measurements for components of multiple systems and faint field (background?) sources

| Target                  | separation ["] | PA ["] | \(m_{\text{F108N}}\) [mag] | \(m_{\text{F108N}}-m_{\text{F110M}}\) [mag] | \(F_{\nu}(\text{F108N})\) [mJy] |
|-------------------------|-----------------|--------|-----------------------------|---------------------------------|--------------------------------|
| RXJ11088-7519Ba         | ...             | ...    | 11.45                       | 0.066                           | 53.7                           |
| RXJ11088-7519Bb         | 0.160±0.010     | 2.8±0.4| 12.08                       | 0.065                           | 30.0                           |
| RXJ12436-7834a          | ...             | ...    | 10.39                       | ...                             | 84.9                           |
| RXJ12436-7834b          | 0.05: 155.3±1.8 | 10.53  | 0.02: 123.0                 |                                 |                                |
| RXJ15241-3030Ba         | ...             | ...    | 10.94                       | ...                             | 19.7                           |
| RXJ15241-3030Bb         | 3.467           | 300.5±0.1| 12.52                      | 30.0                            |                                |
| RXJ15438-3306Na         | ...             | ...    | 12.03                       | ...                             | 30.9                           |
| RXJ15438-3306Nb         | 0.05:           | 17.8:  | 12.68                       | 17.0                            |                                |
| RXJ15598-2556Ca         | ...             | ...    | 14.53                       | -0.03                           | 3.0                            |
| RXJ15598-2556Cb         | 0.112±0.005     | 211.0±0.3| 16.28                      | 0.08                            | 0.60                           |
| RXJ16043-2130Ba¹        | ...             | ...    | 11.38                       | 0.02                            | 56.5                           |
| RXJ16043-2130Bb¹        | 0.089±0.005     | 342.5±0.2| 12.05                      | 0.02                            | 30.5                           |
| RXJ11088-7519B/c        | 3.352±0.030     | 142.44±0.39| 19.16±0.18                | -0.22±0.25                    | 0.04                           |
| RXJ12028-7718/c         | 6.980±0.008     | 335.69±0.01| 18.63±0.15                | 0.23±0.21                     | 0.07                           |
| RXJ12319-7848/c         | 1.992±0.002     | 290.83±0.14| 18.73±0.15                | 0.26±0.21                     | 0.07                           |
| RXJ13033-7706/c         | 7.243±0.002     | 10.19±0.11| 16.73±0.05                | -0.16±0.07                    | 0.42                           |
| RXJ15460-2920/c         | 2.928±0.021     | 50.37±0.31| 19.15±0.18                | -0.03±0.25                    | 0.05                           |

¹Comparison to Köhler et al. (2000) indicates that RXJ16043-2130B rotates counterclockwise with a rate of approx. 5° yr⁻¹.

### Table 5
Flux values derived from ISOCAM observations for 8 PTTS, 2 WTTS, and 2 unclassified stars. The unclassified star RXJ 15549-2347 (Sco005), which is the only G-type star in the sample, is also the only star with \(R<−0.5\), and thus very likely a disk-less main-sequence star. Two stars have \(R>−0.2\). RXJ 15598-2556 is a triple system which is unresolved by ISO. RXJ 15419-3019 has a spectral type of M4.

| Target                  | \(F_{\nu}(6.75 \mu m)\) [mJy] | \(F_{\nu}(15 \mu m)\) [mJy] | \(R\)      | TTS class | Alias   |
|-------------------------|--------------------------------|--------------------------------|------------|-----------|---------|
| RXJ15409-3024           | 12.5                           | 4.5                            | -0.45      | P         |         |
| RXJ15419-3019           | 4.4                             | 11.7                           | +0.42      | P         |         |
| RXJ15460-2920           | 11.3                            | ...                            | ...        | P         |         |
| RXJ15489-3045           | 6.9                             | 3.8                            | -0.26      | P         |         |
| RXJ15549-2347           | 114.7                           | 32.8                           | -0.54      | ? Sco005  |         |
| NTTS155421-2330         | 24.4                            | 9.6                            | -0.40      | P Sco015  |         |
| NTTS155436-2313         | ...                            | ...                            | ...        | W Sco017  |         |
| RXJ15598-2556           | 14.5                            | 9.6                            | -0.18      | P         |         |
| RXJ16002-2417           | 14.4                            | 9.1                            | -0.20      | P         |         |
| RXJ16047-1930           | 49.2                            | 16.9                           | -0.46      | ? Sco027  |         |
| RXJ16056-2152           | 15.9                            | 7.2                            | -0.34      | P         |         |
| RXJ16070-2043           | 14.0                            | 7.5                            | -0.27      | W         |         |