

DISCOVERY OF A VERY NEARBY BROWN DWARF TO THE SUN: A METHANE RICH  
BROWN DWARF COMPANION TO THE LOW MASS STAR SCR 1845-6357B.A. BILLER<sup>1</sup>, M. KASPER<sup>2</sup>, L.M. CLOSE<sup>1</sup>, W. BRANDNER<sup>3</sup>, & S. KELLNER<sup>4</sup>  
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## ABSTRACT

We present VLT/NACO SDI images of the very nearby star SCR 1845-6357 (hereafter SCR 1845). SCR 1845 is a recently discovered (Hambly et al. 2004) M8.5 star just 3.85 pc from the Sun (Henry et al. 2006). Using the capabilities of the unique SDI device, we discovered a substellar companion to SCR 1845 at a separation of 4.5 AU ( $1.170'' \pm 0.003''$  on the sky) and fainter by  $3.57 \pm 0.057$  mag in the  $1.575 \mu\text{m}$  SDI filter. This substellar companion has an H magnitude of  $13.16_{-0.26}^{+0.31}$  (absolute H magnitude of  $15.30_{-0.26}^{+0.31}$ ), making it likely the brightest mid-T dwarf known. The unique Simultaneous Differential Imager (SDI) consists of 3 narrowband filters placed around the  $1.6 \mu\text{m}$  methane absorption feature characteristic of T-dwarfs ( $T_{\text{eff}} < 1200$  K). The flux of the substellar companion drops by a factor of  $2.7 \pm 0.1$  between the SDI F1( $1.575 \mu\text{m}$ ) filter and the SDI F3( $1.625 \mu\text{m}$ ) filter, consistent with strong methane absorption in a substellar companion. We estimate a spectral type of  $T5.5 \pm 1$  for the companion based on the strength of this methane break. The chances that this object is a background T dwarf are vanishing small – and there is no isolated background T-dwarf in this part of the sky according to 2MASS. Thus, it is a bound companion, hereafter SCR 1845-6357B. For an age range of 100 Myr - 10 Gyr and spectral type range of T4.5-T6.5, we find a mass range of 9 - 65  $M_{\text{Jup}}$  for SCR 1845B from the Baraffe et al. (2003) COND models. SCR 1845AB is the 24th closest stellar system to the Sun (at 3.85 pc); the only brown dwarf system closer to the Sun is the binary brown dwarf Eps Indi Ba-Bb (at 3.626 pc). In addition, this is the first T-dwarf companion discovered around a low mass star.

*Subject headings:* instrumentation: adaptive optics — binaries: brown dwarfs

## 1. INTRODUCTION

After decades of little change in the number of known stellar systems within 5 pc, numerous previously unknown low mass stars have recently been discovered in the solar neighborhood (e.g. Scholz et al. 2003; Henry et al. 2004; Hambly et al. 2004). Because they are extremely nearby and intrinsically low luminosity, these objects are ideal targets to search for low mass companions, since even a close companion will appear reasonably separated on the sky. For example during commissioning of the Simultaneous Differential Imager (SDI) at the VLT (Close et al. 2005a; Lenzen et al. 2004), one such object,  $\epsilon$  Indi B was resolved into a binary T dwarf (McCaughrean et al. 2003).  $\epsilon$  Indi Ba,Bb are the closest brown dwarfs to the Earth ( $3.626 \pm 0.009$  pc). At a distance of  $3.85 \pm 0.02$  pc (Henry et al. 2006), the recently discovered M8.5 star SCR 1845-6357 is just slightly further away than  $\epsilon$  Indi Ba,Bb (Hambly et al. 2004) and is the 24th closest stellar system from the Earth. We report the discovery of SCR 1845-6357B (hereafter SCR1845B), a methane rich substellar companion to this star. This companion object is the third closest brown dwarf to the Sun. It is also the only example of a T dwarf companion to a low mass star and one of the tightest known brown dwarf companions to a star.

## 2. OBSERVATIONS AND DATA REDUCTION

Data were taken on the night of 2005 May 28 (UT)<sup>1</sup> at the 8.2m VLT-UT4 with the unique Simultaneous Differential Imager (SDI) in the facility AO system NACO (Lenzen et al. 2003; Rousset et al. 2003). To guide on this faint red object, the infrared wavefront sensor (IR-WFS) was used with the “K” dichroic, sending all of the K band light to the WFS. SDI can be used to calibrate and remove the “speckle noise” in AO images, while also isolating the light from a substellar methane companion from the starlight. This method was pioneered by Racine et al. (1999), Marois et al. (2000), Marois et al. (2002), and Marois et al. (2005). It exploits the fact that all cool ( $T_{\text{eff}} < 1200$  K) substellar objects have strong CH<sub>4</sub> (methane) absorption redwards of  $1.62 \mu\text{m}$  in the H band infrared atmospheric window (Burrows et al. 2001, 2003). The NACO SDI device obtains four images of a star simultaneously through three slightly different narrowband filters (sampling both inside and outside of the CH<sub>4</sub> features – Close et al. 2005a; Lenzen et al. 2004). These images are then differenced. This subtracts out the halo and speckles from the bright star to reveal any substellar methane objects orbiting that star. Since a substellar methane object will be brightest in one filter and absorbed in the rest, while the star is bright in all three, a difference can be chosen which subtracts out the star’s light and reveals the companion’s light. Thus, SDI also helps eliminate the large contrast difference between the star and substellar

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companions (Close et al. 2005a; Lenzen et al. 2004, 2005). The SDI device has already produced a number of important scientific results: the discovery of AB Dor C (Close et al. 2005b) – the faintest companion ever discovered within 0.16" of a star, detailed surface maps of Titan (Hartung et al. 2004), the discovery of the binarity of  $\epsilon$  Indi Ba-Bb, the nearest binary brown dwarf (Scholz et al. 2003; McCaughrean et al. 2003), and evidence of orbital motion for Gl 86B, the first known white dwarf companion to an exoplanet host star (Mugrauer & Neuhäuser 2005). Using the SDI device provides a marked advantage over single band imaging even in situations where the contrast difference between star and companion is not large – images in the 3 different SDI filters immediately provide spectral information about any substellar candidate, particularly regarding the amount of  $\text{CH}_4$  present.

SCR 1845 was observed for 15 minutes (with  $3 \times 30$  s subimages taken at 5 different dither positions) at a position angle of  $0^\circ$  and 15 minutes at a position angle of  $22^\circ$ . A base integration time (DIT) of 30 s was used and subimages were medianed. Observing the object at different roll angles allows us to immediately confirm if an object is real – an instrumental feature should not rotate with a change of rotator angle; however, a real object on the sky should appear to rotate by the change in rotator angle. Data were sky-subtracted, flat-fielded, and bad-pixel masked. Each data frame was then aligned to a master frame using the IRAF task xreg. After alignment, all frames were median combined. As a comparison, the data were also reduced using a custom IDL SDI pipeline which performs basic data reduction tasks and also precisely aligns images taken in each of the filters using a custom shift and subtract routine (Biller et al. 2006).

### 3. RESULTS AND DISCUSSION

Reduced data for the  $0^\circ$  dataset are presented in Fig. 1. SCR 1845B appears at a separation of  $1.170'' \pm 0.003''$  and at a position angle of  $170.20^\circ \pm 0.13^\circ$  from the M8.5 primary in all four of the SDI filters and rotates by  $22^\circ$  (as expected) between datasets. A three color image generated from the SDI filter images is presented in Fig. 2. For comparison, an image reduced using the SDI pipeline (Biller et al. 2006) is also presented in Fig. 2. While SCR 1845B is far from the primary and easily detected, we would also be capable of detecting similar or lower mass companions closer to the primary for this system (down to 0.1" separations).

Deacon et al. (2005) measured a trigonometric parallax to SCR 1845-6357 of  $282 \pm 23$  mas, corresponding to a distance of  $3.5 \pm 0.3$  pc. With additional epochs of observation, Henry et al. (2006) provide an updated distance of  $3.85 \pm 0.02$  pc. Thus, the candidate substellar object lies  $4.50 \pm 0.02$  AU from its primary. The candidate object is  $3.57 \pm 0.057$  mag fainter than the primary in the F1(1.575  $\mu\text{m}$ ) filter (all photometry performed with the IRAF DAOPHOT PSF fitting package).

#### 3.1. Spectral Type

The candidate object appears brightest in the F1(1.575  $\mu\text{m}$ ) filter, slightly fainter in the F2(1.6  $\mu\text{m}$ ), and then drops by a factor of  $2.7 \pm 0.1$  between the F1(1.575  $\mu\text{m}$ )

and F3(1.625  $\mu\text{m}$ ) filters. The spectral signature of this dropoff is consistent with methane absorption in the atmosphere of a substellar object (Geballe et al. 2002). Previous observations of the T6 spectral type brown dwarf  $\epsilon$  Indi Bb (McCaughrean et al. 2003) with the SDI device found that the flux of  $\epsilon$  Indi Bb also dropped by a similar factor between the F1(1.575  $\mu\text{m}$ ) and F3(1.625  $\mu\text{m}$ ) filters (see Fig. 3). To determine an accurate spectral type for SCR 1845B, we define an SDI methane spectral index calculated from our SDI F1(1.575  $\mu\text{m}$ ) and F3(1.625  $\mu\text{m}$ ) filter images (similar in concept to the methane spectral index defined by Geballe et al. 2002). The SDI device measures the location and strength of the 1.6  $\mu\text{m}$  methane absorption break, which is a principle spectral feature used to determine spectral types for T dwarfs – this SDI methane index should be sufficient to estimate an accurate spectral type for this object. The SDI methane spectral index is defined as:  $\text{index}(\frac{F1}{F3}) = \frac{\int_{\lambda_1}^{\lambda_2} S_\lambda F1(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} S_\lambda F3(\lambda) d\lambda}$

Each SDI filter was manufactured by Barr Associates to have a precise bandwidth of 0.025  $\mu\text{m}$ , so the wavelength intervals in the numerator and denominator have the same length for the SDI methane index.

We only possess SDI data on a limited number of T dwarfs (this object, Gl 229B,  $\epsilon$  Indi Ba (T1),  $\epsilon$  Indi Bb (T6)). In order to compare SCR 1845B to a wider range of L and T dwarf objects we calculated these same SDI spectral indices from spectra of 56 L dwarfs and 35 T dwarfs (Knapp et al. 2004). Spectra for these objects were obtained from Sandy Leggett's L and T dwarf archive<sup>2</sup>. In order to make an accurate comparison, SDI filter transmission curves were convolved into these calculations. Since we have full spectral data for these objects, we also calculated the 1.6  $\mu\text{m}$  methane spectral index defined by Geballe et al. (2002), which were found to be similar to our SDI methane spectral indices. In Fig. 3, SDI methane spectral indices are plotted for SCR 1845B, the T dwarfs Gl 229B,  $\epsilon$  Indi Ba,  $\epsilon$  Indi Bb, and 94 other L and T dwarfs. SCR 1845B appears to have a noticeable methane break with somewhat lower indices than the T6 dwarfs Gl 229B and  $\epsilon$  Indi Bb. However, Geballe et al. (2002) note that Gl 229B has an anomalously high methane index for its spectral type and assign a large uncertainty to Gl 229B's spectral type –  $T6 \pm 1$ . For our SDI methane indices, SCR 1845B has spectral indices similar to that of T4.5-T6.5 dwarfs. Thus, we determine an initial spectral type of  $T5.5 \pm 1$  for SCR 1845B.

#### 3.2. H magnitude

To determine an accurate H magnitude, the spectra of both the primary and secondary components of SCR 1845 must be taken into account. The M8.5 primary is extremely red – and will appear brighter in the H band than in our blue F1 band. Additionally, the  $T5.5 \pm 1$  companion is blue compared to the primary and will appear brighter in the F1 band than in the H band. To convert from our F1 filter magnitudes into calibrated H band magnitudes we must calculate the H band magnitude offsets for the M8.5 primary star and the T4.5-T6.5 companion (Offset<sub>M</sub> and Offset<sub>T</sub> respectively):  $\Delta H = H_T - H_M = (\text{Offset}_T + F1_T) - (\text{Offset}_M + F1_M) = (\text{Offset}_T - \text{Offset}_M) + \Delta F1$

<sup>2</sup> <http://www.jach.hawaii.edu/~skl/LTdata.html>

Using the spectrum of the star VB10 (an M8 template, and thus a reasonable approximation of an M8.5 spectrum), an H transmission curve, and our F1 filter transmission curve, we calculate a magnitude offset of  $\text{Offset}_M = -0.12 \pm 0.08$  mag. Assuming spectral types of T4.5-T6.5, we can perform a similar calculation for the companion. Offsets were calculated for 15 objects with spectral types of T4.5-T7 (spectra from Knapp et al. 2004), then averaged together by spectral type to derive an average offset for each spectral type. For instance, for a T5 companion,  $\text{Offset}_{T5} = 0.5 \pm 0.05$ . For a T6 companion,  $\text{Offset}_{T6} = 0.6 \pm 0.07$ . Magnitudes in the H filter for both primary and candidate object are presented in Table 1. Uncertainties are provided for a companion spectral type of  $T5.5 \pm 1$ . Background T4-T7 dwarfs possess absolute H magnitudes of  $\sim 14.5$ -16.0 (Burgasser et al. 2003), so our calculated absolute H magnitude of  $15.23_{-0.26}^{+0.31}$  for SCR 1845B is quite reasonable.

### 3.3. Likelihood of Being a Bound Companion and T Dwarf Number Densities

This object has not been observed at multiple epochs with the SDI device so we must consult other sources to determine if it is indeed truly bound, i.e. shares a common proper motion with its primary. SCR 1845 possesses a large proper motion of  $\sim 2.5''$ /year. A bound companion would possess a similar proper motion whereas a background object would appear to stay in the same spot on the sky. On 2000 January 1, SCR 1845A had an RA of  $18^h 45^m 05.2''$  and DEC of  $-63^\circ 57' 47.355''$  (J2000, Deacon et al. 2005). Taking proper motion into account, during the 2005 May 28 SDI observations, SCR 1845A therefore had an RA of  $18^h 45^m 07.21''$  and DEC of  $-63^\circ 57' 43.586''$ . SCR 1845B ( $1.17''$  separation at a PA of  $170.2^\circ$ ) had an RA of  $18^h 45^m 07.33''$  and DEC of  $-63^\circ 57' 42.786''$  during the 2005 May 28 SDI observations. If the faint companion is actually a background T dwarf, this RA and DEC should be reasonably correct for other epochs of observation. Checking the 2MASS point source catalog (2MASS images taken 2000 May 29), we found no objects within  $20''$  of this position and no objects with T dwarf colors in this part of the sky. Hence, it is impossible that this object is a background T-dwarf and it is highly likely to be a bound companion.

In the last few years, 3 new T dwarf companions have been discovered within 6 pc of the Sun – SCR 1845B and  $\epsilon$  Indi Ba-Bb. All three of the nearest T dwarfs are bound companions to stars. Combining these three new T dwarf companions with Gl 229B (5.8 pc) and Gl 570D (5.9 pc), we find a number density of T dwarf companions of  $5.5 \times 10^{-3} \text{ pc}^{-3}$  within 6 pc of the Sun. In contrast, only two isolated, field T dwarfs (2MASS J0415 and 2MASS J0937 from Vrba et al. 2004) are known within 6 pc of the sun, leading to a rough number density of field T dwarfs of  $\sim 2 \times 10^{-3} \text{ pc}^{-3}$  in this volume. Granted, this number of field dwarfs is somewhat

incomplete since there may be nearby T dwarfs without accurate trigonometric parallaxes, but the number is unlikely to change by more than a factor of 2 since this population of bright T-dwarfs is very well studied. The existence of 5 brown dwarfs within binary systems  $< 6$  pc of the Sun suggests that the number density of T dwarfs in binary systems may be higher than that of isolated, single T dwarfs. This may be difficult to explain with “ejection” theories of brown dwarf formation (Reipurth & Clarke 2002).

### 3.4. Mass Estimate for SCR 1845B

While the distance to SCR 1845 is well known, the age of the system is unconstrained. Ages between 100 Myr and 10 Gyr are all plausible for this system at this time. Future observations of lithium absorption might constrain the age of this system or at least rule out very young ages. However, with a  $v_{tan} = 41$  km/s it is unlikely that this system is very young. Using the Baraffe et al. (2003) COND models with this age range, an absolute H mag range of 15.1 to 15.6, and spectral types of T4.5-T6.5 ( $T_{eff} \sim 850 \text{ K} \pm 100 \text{ K}$ ), we find a mass range of 9 - 65  $M_{Jup}$ . While SCR 1845B is clearly substellar at any age, the uncertainty in the age of this system means that we cannot derive an unambiguous mass for this object from the COND models. However, since this object is so close to its primary (currently  $\sim 4.5$  AU), orbital motion should be evident within a few years. Both the primary and secondary mass can be measured accurately within a decade, making SCR 1845B a key T-dwarf mass-luminosity calibrator.

## 4. CONCLUSIONS

SCR 1845B is the brightest mid-T dwarf yet discovered. In addition, it is the first T dwarf companion found around a low mass star. At only  $\sim 4.5$  AU from its primary, it is one of the tightest known brown dwarf companions to a star and is a further piece of evidence that the brown dwarf desert does not exist for companions to very low mass stars (Close et al. 2003; Gizis et al. 2003). Both the primary and secondary mass can be accurately measured within a decade.

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TABLE 1  
SCR 1845 PHOTOMETRY

Spectral Type	H mag (primary)*	$\Delta F1$	H (companion)	absolute H
T5.5 $\pm$ 1	8.967 $\pm$ 0.027	3.57 $\pm$ 0.057	13.16 <sup>+0.31</sup> <sub>-0.26</sub>	15.30 <sup>+0.31</sup> <sub>-0.26</sub>

\* from 2MASS point source catalog

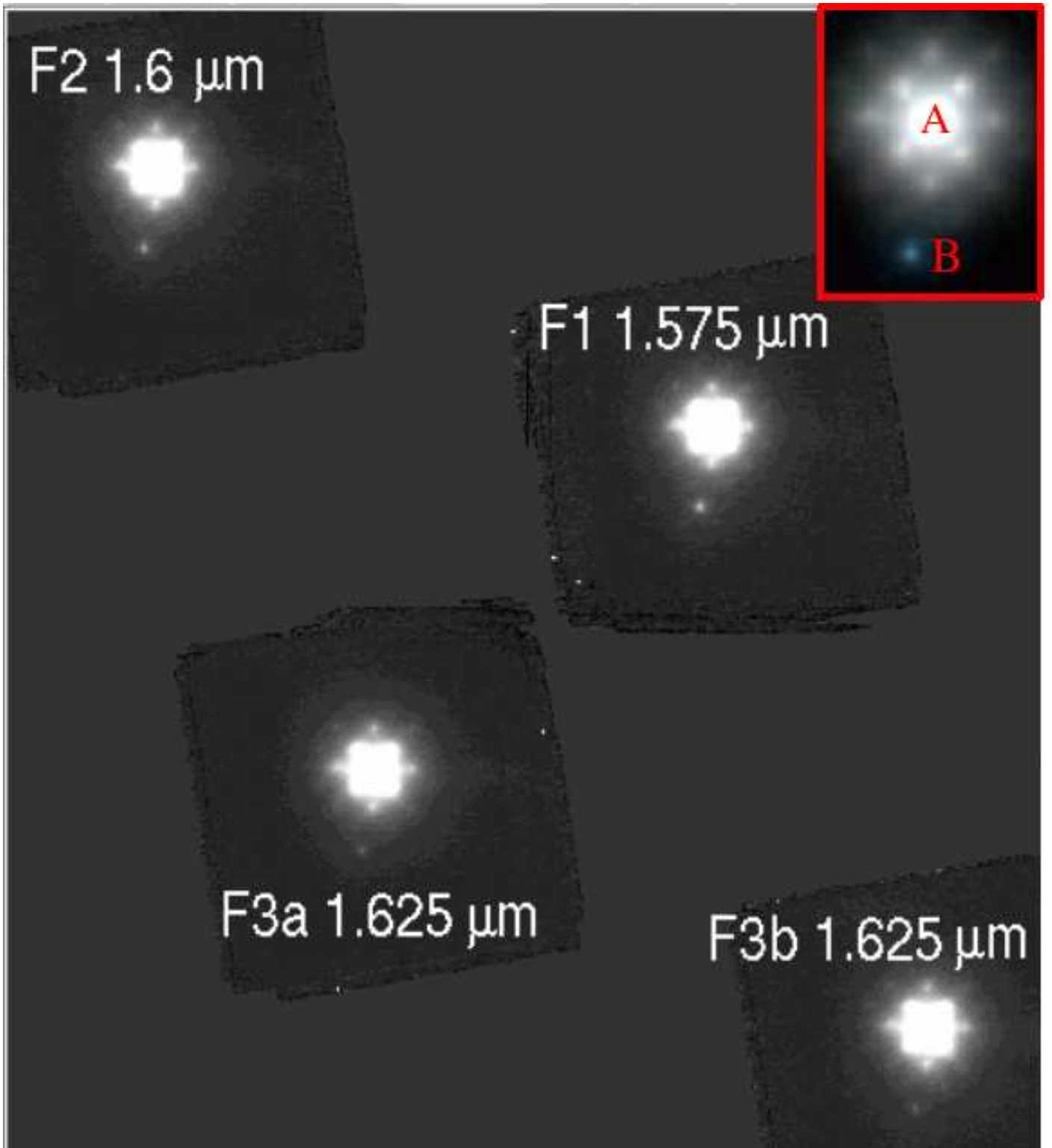


FIG. 1.— An SDI image of SCR 1845. This 15 minute long image was taken at a position angle of  $0^\circ$  and was reduced using a custom IDL pipeline and the IRAF xreg tool. A substellar companion appears at a separation of  $1.170'' \pm 0.003''$  (4.5 AU at 3.85 pc) from the primary and a position angle of  $170.20^\circ \pm 0.13^\circ$  in each of the 4 SDI filters. The platescale is  $(0.01725'' \pm 0.00025'')/\text{pix}$  (Nielsen et al. 2005). The companion appears brightest in the F1 filter (out of the  $\text{CH}_4$  absorption) and drops by a factor of 2.7 in the F3 filter (inside the  $\text{CH}_4$  absorption), consistent with a T5.5 dwarf spectral type. North is up and east is to the left. **Upper Right Inset:** Three color image of SCR 1845 A and B generated from the SDI filter images (blue= $1.575 \mu\text{m}$ , green= $1.600 \mu\text{m}$ , red= $1.625 \mu\text{m}$ ). The substellar companion appears blue in this image. This image was created with a log10 stretch and each filter is equally weighted. Note how similar in color (white) each of the PSF speckles are for the M8.5, while the faint companion SCR 1845B is considerably bluer due to strong  $\text{CH}_4$  absorption. The structure in the PSF is typical of the NACO IR WFS for a faint guide star such as SCR 1845A.

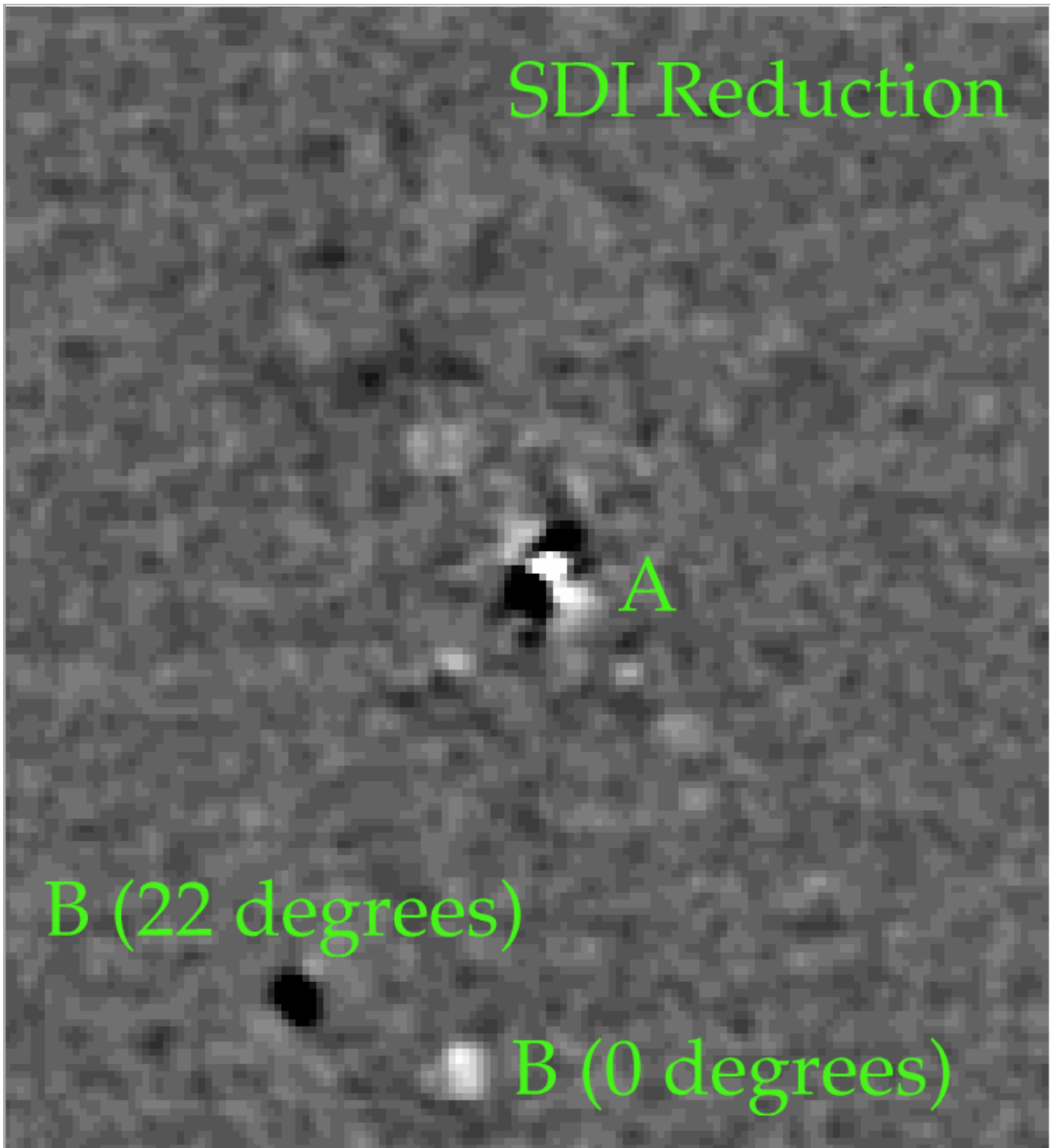


FIG. 2.— Images of SCR 1845 using the SDI device and reduced using a custom SDI pipeline (Biller et al. 2006). This 30 minute long image was taken at position angles of  $0^\circ$  (white) and  $22^\circ$  (black). Datasets from each roll angle were subtracted from each other and smoothed with a 1 pixel FWHM gaussian. A substellar companion appears at a separation of  $1.17''$  from the primary in each of the 4 SDI filters. Note that the speckles from the M8.5 are almost totally removed. With the high contrasts achievable by SDI, a methane object like SCR 1845B ( $\Delta H=4.2$  mag) could have been detected at  $10\sigma$   $10\times$  closer in at a separation of only  $\sim 0.1''$ .

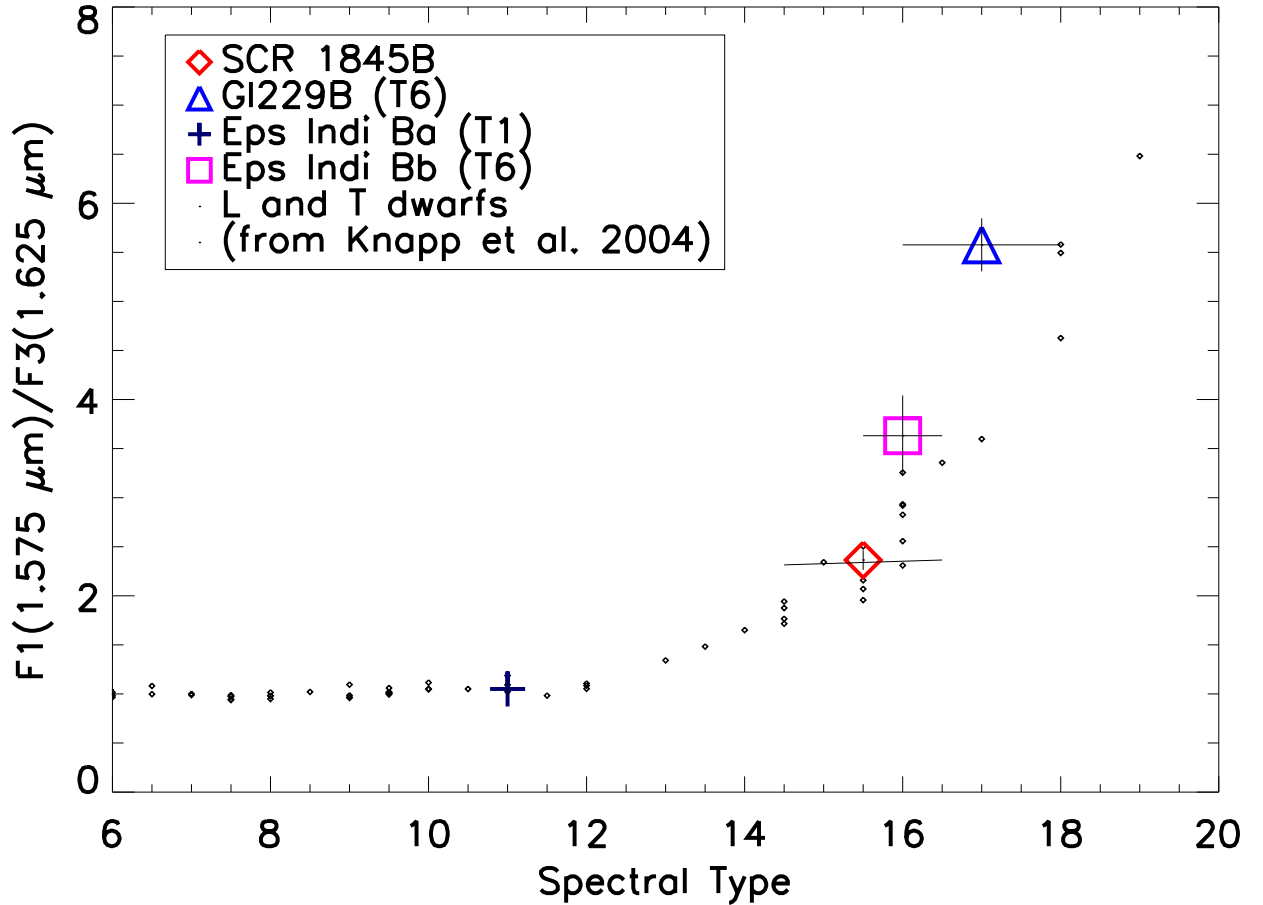


FIG. 3.— SDI methane spectral indices for SCR 1845B and the T dwarfs Gl 229B,  $\epsilon$  Indi Ba, and  $\epsilon$  Indi Bb. We plot numerical spectral types on the x-axis; a numerical type of 8 corresponds to a L8 spectral type, a numerical type of 16 corresponds to a T6 spectral type, etc. As a comparison, SDI methane spectral indices calculated from spectra for 94 L and T dwarfs (spectra from Knapp et al. 2004) are overplotted as small dots. SCR 1845B, Gl 229B, and  $\epsilon$  Indi Bb (T6) show strong methane indices, whereas  $\epsilon$  Indi Ba (T1) is relatively constant in flux across the SDI filters and has a much lower methane index. Geballe et al. (2002) note that Gl 229B has an anomalously high methane index for its spectral type. While Geballe et al. (2002) find an overall spectral type of  $T6 \pm 1$  for Gl 229B, they assign Gl 229B a spectral type of T7 based on this methane index. Note that the spectral indices for SCR 1845B are only consistent with spectral types of T4.5–T6.5.