

S ORIONIS 70: JUST A FOREGROUND FIELD BROWN DWARF?

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ABSTRACT

We examine recent claims that the T-type brown dwarf S Ori 053810.1–203626 (S Ori 70) is a spectroscopically verified low-mass ($3_{-1}^{+5} M_{\text{Jup}}$) member of the 1–8 Myr σ Orionis cluster. Comparative arguments by Martín & Zapatero Osorio asserting that S Ori 70 exhibits low surface gravity spectral features indicative of youth and low mass are invalidated by the fact that their comparison object was not the field T dwarf 2MASS 0559–1404, but rather a nearby background star. Instead, we find that the 1–2.5 μm spectra of S Ori 70 are well matched to older (age \sim few Gyr) field T6–T7 dwarfs. Moreover, we find that spectral model fits to late-type field T dwarf spectra tend to yield low surface gravities ($\log g = 3.0\text{--}3.5$), and thus young ages (≤ 5 Myr) and low masses ($\leq 3 M_{\text{Jup}}$), inconsistent with expected and/or empirical values. Finally, we show that the identification of one T dwarf in the field imaged by Zapatero Osorio et al. is statistically consistent with the expected foreground contamination. Based on the reexamined evidence, we conclude that S Ori 70 may simply be an old, massive (30–60 M_{Jup}) field brown dwarf lying in the foreground of the σ Orionis cluster. This interpretation should be considered before presuming the existence of so-called “cluster planets.”

Subject headings: open clusters and associations: individual (σ Orionis) — planetary systems: formation — stars: formation — stars: individual (S Orionis 70) — stars: low-mass, brown dwarfs — techniques: spectroscopic

1. INTRODUCTION

The boundary between classical planets (e.g., Jupiter) and stars has been blurred by the discovery of brown dwarfs, which presumably form like stars but lack sufficient mass to sustain core hydrogen fusion (Hayashi & Nakano 1963; Kumar 1963). Known brown dwarfs exhibit a number of features similar to those of giant planets, including size⁵ ($R \sim R_{\text{Jup}}$), atmospheric composition (e.g., CH₄, condensate clouds), and possibly mass (of order 10 M_{Jup}), but are typically found in stellar environments as isolated field and cluster objects and as wide companions to main sequence stars. While brown dwarfs appear to be rare as close companions to stars (Marcy & Butler 2000), a regime occupied by solar and extrasolar planets. The possibility of planetary ejection (Li 2002; Nelson 2003) or brown dwarf capture (Bonnell et al. 2003) and the identification of low mass ratio binaries with substellar secondaries (e.g., HR 7329AB; Lowrance et al. 2000) makes it impossible to unambiguously deduce the origin of a particular substellar object. This situation has led to considerable debate over the definition of a planet and its distinction from a low-mass brown dwarf (Boss et al. 2003).

Recently, Zapatero Osorio et al. (2002a, hereafter Z02) have identified a brown dwarf in the direction of σ Orionis particularly relevant to this debate. The object, S Ori 053810.1–203626 (hereafter S Ori 70), is classified as a T dwarf based on the presence of CH₄ absorption in its near-infrared

spectrum (Burgasser et al. 2002b; Geballe et al. 2002) and therefore has an effective temperature T_{eff} less than $\sim 1200\text{--}1400$ K (Kirkpatrick et al. 2000; Leggett et al. 2001a; Stephens et al. 2001). Z02 identify this object as a candidate member of the young (age $\sim 1\text{--}8$ Myr) σ Orionis cluster and deduce an estimated mass of only $3_{-1}^{+5} M_{\text{Jup}}$, potentially the least massive brown dwarf known. Both Z02 and Martín & Zapatero Osorio (2003, hereafter MZ03) claim that cluster membership for S Ori 70 is verified by (1) comparative near-infrared spectroscopy with the presumably older (higher surface gravity) field T dwarf 2MASS J05591914–1404488 (Burgasser et al. 2000b), (2) spectral fits to theoretical models from Allard et al. (2001) that yield a low surface gravity consistent with a young, low-mass brown dwarf, and (3) low foreground contamination by field T dwarfs in the search area imaged by Z02.

In this article, we address flaws in each of these arguments. Specifically, in §§ 2–4, we show that (1) comparison with the spectrum of 2MASS 0559–1404 is invalidated by the fact that MZ03 observed the wrong comparison star, and in fact the spectrum of S Ori 70 is an excellent match to those of field T6–T7 dwarfs; (2) Allard et al. (2001) spectral model fits tend to be skewed toward lower surface gravities, and thus lower ages and masses, for late-type T dwarfs; and (3) the identification of one foreground T dwarf in the Z02 field is statistically consistent with the expected contamination. This analysis indicates that S Ori 70 may simply be a foreground field T dwarf with a much older age and higher mass than reported by Z02 and MZ03. We summarize our results in § 5.

2. COMPARISON OF THE J-BAND SPECTRUM OF S ORI 70 TO FIELD OBJECTS

Young, low-mass brown dwarfs have much lower surface gravities than their evolved field counterparts; $\log g$ (cgs) $\sim 3\text{--}4$ is typical for a 1–10 Myr, 1–50 M_{Jup} object, versus 4.5–5.5 for a ~ 1 Gyr field brown dwarf with similar T_{eff} (Burrows

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⁵ We adopt the Jupiter-based units $R_{\text{Jup}} = 7.15 \times 10^9$ cm and $M_{\text{Jup}} = 1.90 \times 10^{30}$ g = 0.00095 M_{\odot} throughout this article (Tholen, Tejfel, & Cox 2000).

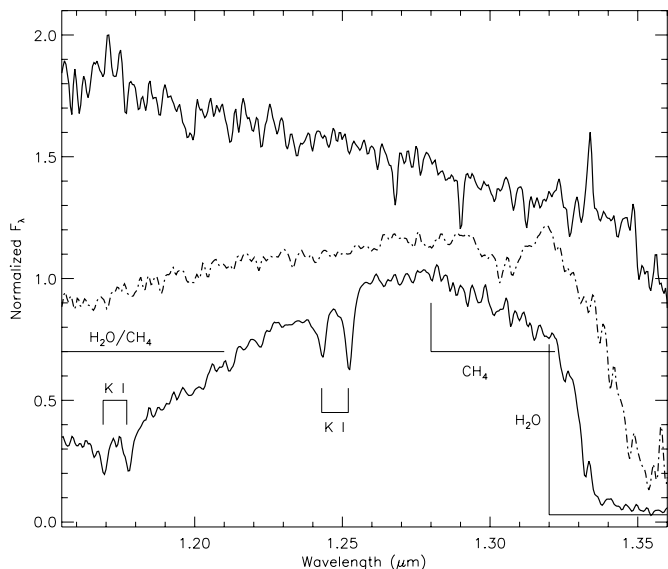


Fig. 1.—Comparison of the reported J -band spectrum of 2MASS 0559–1404 from MZ03 (*middle spectrum, dot-dashed line*) to BDSS data for the same object (*bottom spectrum*) and our re-reduction of the raw data from MZ03 using REDSPEC (*top spectrum*). All three spectra are normalized at $1.27 \mu\text{m}$ and offset by a constant for clarity. The object observed by MZ03 is a background star, and the features present in their reported spectrum are likely due to a saturated flat field. None of the indicated features typical of T dwarf spectra are seen in the MZ03 data.

et al. 1997; Baraffe et al. 2003). As the abundances and band strengths of molecular species that dominate the photospheric opacity of cool brown dwarfs (e.g., H_2O , CH_4 , collision-induced H_2 absorption) are pressure-sensitive, the photospheric gas pressure, and hence surface gravity, can substantially influence the emergent spectral energy distribution.

The J -band spectrum of S Ori 70 presented in MZ03 exhibits a distinct triangular-shaped spectral morphology, which those authors argue is due to its low surface gravity. They draw an analogy with the peaked spectral morphologies of low-gravity L dwarfs in the Trapezium cluster (Lucas et al. 2001), although the latter data were obtained at H and K bands and not at J . The low surface gravity argument of MZ03 is supported by a comparison with the spectrum of the presumably older, and hence higher surface gravity, field T dwarf 2MASS 0559–1404, which appears in their Figure 1 to have a very different J -band spectral morphology. However, their reported spectrum is not that of 2MASS 0559–1404, but rather an adjacent background source. Figure 1 compares the reported MZ03 spectrum of 2MASS 0559–1404 to data obtained as part of the NIRSPEC Brown Dwarf Spectroscopic Survey (McLean et al. 2003, hereafter BDSS) and to a re-extraction of the raw data from MZ03 using the REDSPEC package⁶ (Fig. 1). The re-reduced spectrum of the comparison object observed by MZ03 exhibits none of the hallmark features of mid- and late-type T dwarfs. Thus, the differences noted by MZ03 between S Ori 70 and their field comparison star have nothing to do with surface gravity effects.

In fact, the triangular shape of the J -band spectrum of S Ori 70, the result of H_2O and CH_4 absorption wings on either side of the J -band peak, is common among mid- and late-type T dwarfs (Burgasser et al. 2002b; Geballe et al. 2002).

⁶ See <http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html>. Data reduction procedures are fully described in McLean et al. (2003).

Figure 2 compares the MZ03 spectrum of S Ori 70 to BDSS data for the T7 field brown dwarf 2MASS J15530228+1532369 (Burgasser et al. 2002b). This object is presumably much older than the <10 Myr σ Orionis cluster given the similarity of its $1\text{--}2.5 \mu\text{m}$ spectrum to other T6–T7 field dwarfs (Burgasser et al. 2002b; McLean et al. 2003), which have space motions consistent with 1–5 Gyr disk dwarfs (Gizis et al. 2000; Dahn et al. 2002; Tinney, Burgasser, & Kirkpatrick 2003), and the absence of any star-forming regions in its vicinity. The match between the S Ori 70 and 2MASS 1553+1532 data is excellent, and similar good agreement is found with other T6 and T7 BDSS spectra. Hence, the J -band spectrum of S Ori 70 is consistent with that of an old, high-gravity, late-type field T dwarf.

3. SPECTRAL MODEL FITS: SKEWED AGES FOR MID-TYPE T DWARFS

Both Z02 and MZ03 determine the surface gravity and T_{eff} for S Ori 70 by fitting their spectra to the most recent theoretical models from Allard et al. (2001). In the absence of dynamical mass, radius, and bolometric flux measurements, the use of spectral models is required to derive these physical parameters, as the complexity of the spectra prohibit classical techniques such as curve of growth (Pavlenko & Magazzù 1996). However, despite substantial improvements over the past decade, these models do not yield reliable fits to the observed data, particularly when disentangling T_{eff} and gravity (Saumon et al. 2000; Geballe et al. 2001). These limitations are largely due to incomplete or inaccurate molecular line lists and the uncertain treatment of photospheric condensates (Allard et al. 2001; Burgasser et al. 2002a). For instance, Leggett et al. (2001a) find T_{eff} discrepancies as high as 400 K between spectral model fits and luminosity-determined temperatures for the latest type field L dwarfs.

To assess whether similar discrepancies occur in the T dwarf regime, we performed minimum χ^2 fits of BDSS J -band data for seven T6–T7 field dwarfs using the same Allard et al. (2001) COND models as those used by MZ03.

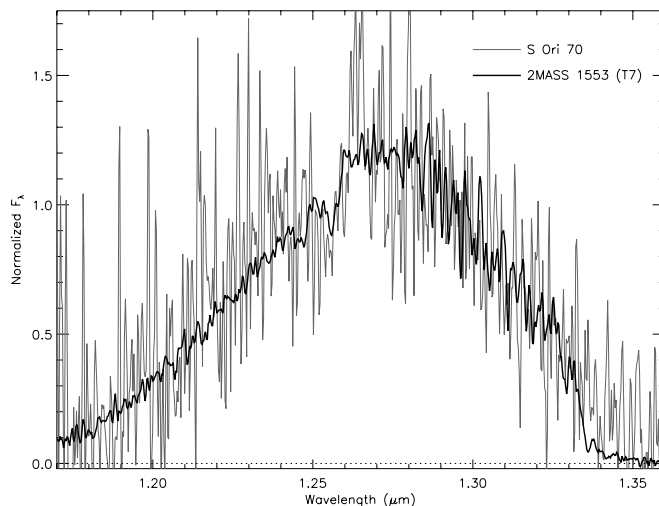


Fig. 2.—Comparison of the J -band spectrum of S Ori 70 from MZ03 (*dotted line*) to NIRSPEC BDSS data for the field T7 brown dwarf 2MASS 1553+1532 (*black line*). Data are normalized at $1.27 \mu\text{m}$. The excellent match between these spectra and other presumably old, and therefore high-gravity, field T6–T7 dwarfs belie arguments that S Ori 70 exhibits low-gravity signatures.

TABLE 1
COMPARISON OF MODEL FITS TO EXPECTED PARAMETERS FOR FIELD T6–T8 DWARFS

OBJECT (1)	SpT ^a (2)	MODEL FIT PARAMETERS ^b				EXPECTED FIELD PARAMETERS ^c		
		T_{eff} (K) (3)	$\log g$ (cgs) (4)	Age (Gyr) (5)	Mass (M_{\odot}) (6)	T_{eff} (K) (7)	$\log g$ (cgs) (8)	Mass (M_{\odot}) (9)
2MASS J23565477+1553111.....	T6	1100	5.0	0.8	0.03	1000	5.0	0.03–0.06
SDSSp J162414.37+002915.6.....	T6	900	5.0	2	0.03	1000	5.0	0.03–0.06
2MASS J12373919+6526148.....	T6.5	900	5.0	2	0.03	950	5.0	0.03–0.05
2MASS J15530228+1532369.....	T7	1200	3.5	0.004	0.003	900	5.0	0.03–0.05
2MASS J07271824+1710012.....	T7	1200	3.5	0.004	0.003	900	5.0	0.03–0.05
Gliese 570D.....	T8	1100	3.0	<0.001	<0.001	784–824 ^d	5.0–5.3 ^d	0.03–0.05 ^d
2MASS J04151954–0935066.....	T8	700	4.5	0.7	0.014	800	4.5–5.0	0.02–0.04

^a Near-infrared spectral types from Burgasser et al. (2002b).

^b T_{eff} and $\log g$ (cgs) for the best (lowest χ^2) Allard et al. (2001) model fits to BDSS J -band data; ages and masses are derived from the evolutionary models of Baraffe et al. (2003).

^c T_{eff} estimated from the empirical relation $T_{\text{eff}} \approx 1600 - 100\text{SpT}$, where $\text{SpT}(T0) = 0$, $\text{SpT}(T5) = 5$, etc (Burgasser 2001); $\log g$ (cgs) and masses from Baraffe et al. (2003) assuming an age of 1–5 Gyr.

^d Empirical parameters from Geballe et al. (2001) assuming an age of 2–5 Gyr, estimated from the system’s K4 V primary star.

We sampled a grid of models spanning $2.5 < \log g < 6.0$ and $600 < T_{\text{eff}} < 1400$ K in intervals of 0.5 dex and 100 K, respectively. Both empirical and model spectra were Gaussian smoothed to the instrumental resolution ($R \sim 2000$) and interpolated onto identical wavelength scales. As parallax measurements are unavailable for most of these objects and S Ori 70, we performed the fits by normalizing the empirical and theoretical spectra at the $1.27 \mu\text{m}$ spectral peak. The χ^2 deviation between the spectra was computed over the range 1.16–1.34 μm , minimizing over relative scalings of 0.8–1.2. This procedure is similar to that employed by MZ03 for S Ori 70.

Table 1 lists the best-fit model parameters for the spectral data, along with associated mass and age estimates from the Baraffe et al. (2003) evolutionary models. Given that the objects examined in these fits are all field dwarfs, it is apparent that the derived parameters tend to be skewed toward lower

gravities, and hence younger ages and lower masses, particularly for the T7 dwarfs. The most deviant case is that of Gliese 570D, a widely separated T8 brown dwarf companion to the nearby Gliese 570 triple star system (Burgasser et al. 2000a). Assuming coevality, Gliese 570D has a well-defined age of 2–5 Gyr (Geballe et al. 2001). On the contrary, the spectral model fits predict an age of less than 1 Myr and mass $< 1 M_{\text{Jup}}$. Figure 3 compares the minimum χ^2 fit model for this object to one based on the more widely adopted parameters $\log g = 5.0$ and $T_{\text{eff}} = 800$ K (Geballe et al. 2001). The lower gravity model matches the overall J -band morphology better than the higher gravity model but predicts spiked features around 1.255 μm . These features do not coincide with (presumably noise) spikes seen at 1.265 μm in the S Ori 70 spectrum, as is evident in Figure 3 of MZ03. The inferior fit of the high-gravity model is generally confined to the spectral peak and may be the result of deep condensate opacity in this

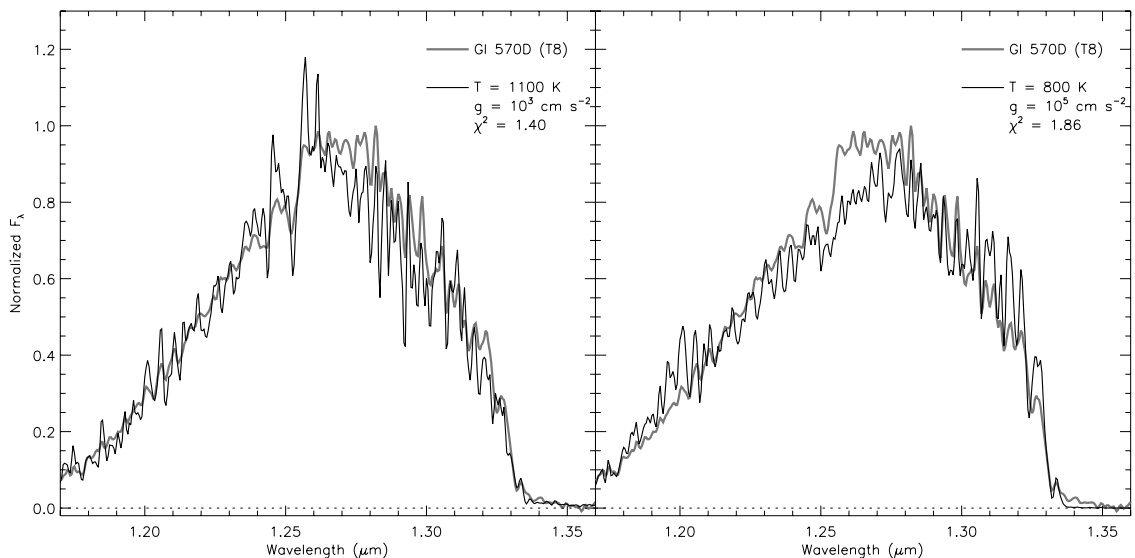


FIG. 3.—Spectral model fits (black lines) for NIRSPEC BDSS data of the T8 companion dwarf Gliese 570D (gray lines) to Allard et al. (2001) models of $T_{\text{eff}} = 1100$ K and $\log g$ (cgs) = 3.0 (left) the best-fit spectral model (minimum χ^2); and $T_{\text{eff}} = 800$ K and $\log g$ (cgs) = 5.0 (right) the most widely adopted empirical parameters for this object (Geballe et al. 2001). The best-fitting model predicts an age < 1 Myr and mass $< 1 M_{\text{Jup}}$, grossly inconsistent with this object’s membership in the 2–5 Gyr Gliese 570 system.

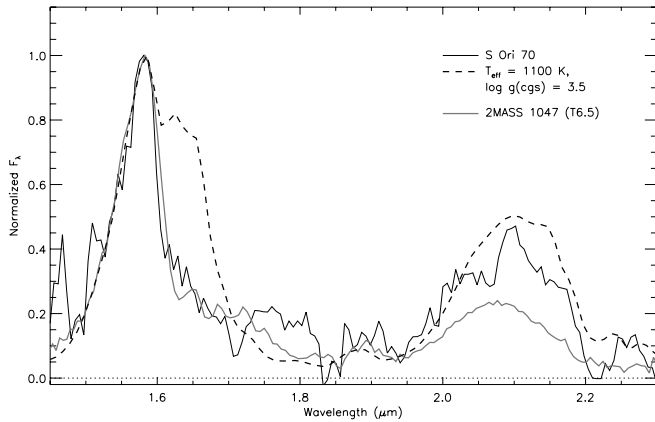


FIG. 4.—Comparison of the *HK* spectrum of S Ori 70 from Z02 (solid black line) to a Gaussian smoothed $T_{\text{eff}} = 1100$ K, $\log g(\text{cgs}) = 3.5$ model from Allard et al. (2001) (dashed line). The model parameters are those determined by MZ03 as the best fit to the *J*-band spectrum of this object. Also shown are *HK* data for the field T6.5 2MASS 1047+2124 obtained with the same instrument (Burgasser et al. 2002b, gray line). All spectra are normalized at $1.57 \mu\text{m}$.

relatively transparent spectral region (Burrows et al. 2002). Regardless of the reason, it is clear that the best-fit spectral models can yield skewed gravities for late-type field T dwarfs, resulting in underestimated ages and masses. Hence, the spectral fit parameters for S Ori 70, which itself appears to be a late-type T dwarf, must be considered with skepticism.

There are also inconsistencies between the *J*-band spectral model fits for S Ori 70 from MZ03 and the *HK* spectral model fits from Z02. The latter yield a substantially lower T_{eff} (800 vs. 1100 K) and a somewhat higher surface gravity (4.0 vs. 3.5 dex), which is consistent with a 50, not 8 Myr, brown dwarf (Baraffe et al. 2003). While the differences between the parameter fits are within the reported uncertainties, they yield significantly incompatible spectral morphologies. Figure 4 demonstrates this, comparing the *HK* spectrum from Z02 to a smoothed Allard et al. (2001) model using the best-fit parameters from MZ03. It is clear that this model grossly underestimates the strength of the $1.6 \mu\text{m}$ CH_4 band and somewhat overestimates the flux at *K* band. On the other hand, empirical spectral data for the field T6.5 2MASS J10475385+2124234 (Burgasser et al. 1999, 2002b), obtained with identical instrument settings, does fairly well at matching the *H*-band region, although it somewhat underestimates the flux at *K* band. The latter disagreement, possibly due to differences in collision-induced H_2 opacity, may be indicative of a somewhat lower surface gravity for S Ori 70 relative to 2MASS 1047+2124 (Leggett et al. 2001b),⁷ although signal-to-noise ratio (S/N) may also be an issue. Nevertheless, the fact that empirical data for field T6–T7 dwarfs reproduce the $1.1\text{--}1.3 \mu\text{m}$ and $1.5\text{--}2.4 \mu\text{m}$ spectra for S Ori 70 more consistently than the theoretical models indicates both the unreliability of physical parameters derived from the model fits and the likelihood that S Ori 70 is a foreground brown dwarf.

4. THE STATISTICAL SIGNIFICANCE OF FOREGROUND CONTAMINATION

A third argument used by Z02 to establish cluster membership for S Ori 70 is the low foreground contamination

by field T dwarfs (0.08–0.3 objects) expected in their 55.4 arcmin^2 search area. We have computed an independent estimate of the foreground contamination using substellar luminosity function simulations from Burgasser (2001), absolute photometry from Dahn et al. (2002) and Tinney et al. (2003), and an assumed limiting magnitude of $J \sim 21$ (Z02). For a substellar mass function $dN/dM \propto M^{-\alpha}$ and $0.5 \leq \alpha \leq 1.5$, we find 0.1–0.2 T dwarfs with $700 \leq T_{\text{eff}} \leq 1100$ K (typical for late-type T dwarfs; Burgasser 2001) expected in the Z02 field, consistent with their estimates and certainly less than unity.

However, the relevant quantity is the likelihood of detecting one foreground object in the imaged area given the expected contamination rate. This confidence limit (CL) can be derived from Poisson statistics,

$$\text{CL} = \sum_{x=0}^{n-1} \frac{\lambda^x e^{-\lambda}}{x!} = e^{-\lambda} \quad (1)$$

(Gehrels 1986) for $n = 1$ source detected and an expected contamination of λ . For $0.08 < \lambda < 0.3$, equation (1) yields $0.74 < \text{CL} < 0.92$, equivalent to $0.6\text{--}1.4 \sigma$ on a Gaussian scale. Hence, the presence of one foreground T dwarf in the Z02 field is a 1σ event, and cannot be ruled out statistically.

5. DISCUSSION

Based on the arguments above, we find compelling evidence that S Ori 70 is not a member of the σ Orionis cluster but rather a foreground field brown dwarf. This is not an unexpected result, given the predicted $\sim 30\%$ contamination rate amongst L dwarfs in the σ Orionis sample (Zapatero Osorio et al. 2000). Indeed, quite a few σ Orionis brown dwarf candidates have been ruled out as foreground objects in follow-up observations (Béjar et al. 2001; Martín et al. 2001; Kenyon, Jeffries, & Naylor 2001;⁸ Zapatero Osorio et al. 2002b; Barrado y Navascués et al. 2003; Muzerolle et al. 2003; McGovern et al. 2004), and Kenyon et al. (2001) find the fraction of spectroscopically verified candidates in σ Orionis decreases toward fainter magnitudes. It should come as no surprise that the faintest candidate to date, S Ori 70, may be a contaminant field source.

Uncertainties in the spectral models and difficulty in obtaining high S/N spectra for this faint T dwarf ($J = 20.28 \pm 0.10$; Z02) imply that unambiguous verification of cluster membership for S Ori 70 will require measurement of its parallax and proper motion to establish spatial and kinematic association. Such observations are hindered by the distance of this object even if it is a foreground brown dwarf. Z02 measure an upper limit proper motion of $\mu \leq 0''.1 \text{ yr}^{-1}$ for S Ori 70, which only restricts its distance to $\gtrsim 40$ pc, roughly half the spectrophotometric distance if it is a field T6–T7 dwarf ($\sim 75\text{--}100$ pc; Tinney et al. 2003).

We conclude that S Ori 70 has not been rigorously proven to be a member of the young σ Orionis cluster. Rather, observations obtained thus far are consistent with this object being a massive ($M \sim 30\text{--}60 M_{\text{Jup}}$, assuming an age of 1–5 Gyr) foreground field brown dwarf. This interpretation should be seriously considered before assuming the existence of a “cluster planet” population in the σ Orionis cluster.

⁷ Available at <http://origins.colorado.edu/cs12/>.

⁸ Available at <http://origins.colorado.edu/cs12/>.

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