S Ori 70: still a strong cluster planet candidate

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In this paper I show that the coolest σOrionis cluster planet S Ori 70 is still a strong candidate member despite recent claims by Burgasser et al. that it could be a brown dwarf interloper. The main point of my argument is that the colors of S Ori 70 are significantly different to those of field dwarfs. This object has in fact the reddest $H-K$ color of all known T dwarfs, a clear indication of low gravity according to all published models. In a $J-H$ versus $H-K$ diagram, S Ori 70 lies in the region where models of ultracool dwarfs predict that low gravity objects should be located. I conclude that S Ori 70 is still a strong candidate member of the σOrionis open cluster. I briefly discuss additional observational tests that can be carried out with existing facilities to verify the σOrionis membership of this cluster planet candidate.

Keywords: stars: very low mass stars and brown dwarfs.

1 Introduction

The term brown dwarf (BD) refers to objects with masses below the limit for stable hydrogen fusion in stellar interiors. For solar composition, this limit was calculated to be 0.08 $M_\odot$ by Kumar (1963) and Hayashi & Nakano (1963). Modern calculations have changed the value of this boundary only slightly. For example, Baraffe et al. (1998) give 0.072 $M_\odot$ for solar metallicity.

There is no consensus in the community about the minimum mass of brown dwarfs (Boss et al. 2003). Some argue for the deuterium burning limit at 13 Jupiter masses (for solar composition). Some prefer a limit at around 10 Jupiter masses, where there appears to be a sharp rise in the number of extrasolar planets detected by high-precision radial velocity surveys around main-sequence stars. Finally, it has also been proposed to use a limit at 5 Jupiter masses where the mass-radius relationship of substellar objects changes its sign. In this paper we continue to use the deuterium limit as the mass boundary between brown dwarfs and planets because we do not have any strong reason to change the nomenclature adopted in our previous papers.

Another term used in this paper is that of ultracool dwarf, which refers to small objects with very cool effective temperatures. Since 1997, two new ultracool spectral classes have been adopted to extend the classical OBAFGKM system into cooler temperatures. The L dwarfs are characterized by weak or absent TiO bands, and very broad NaI and KI lines in the optical spectrum (Martín et al. 1997, 1999; Kirkpatrick et al. 1999, 2000). The T dwarfs are characterized by methane bands in the near-infrared spectra (Oppenheimer et al. 1995; Burgasser et al. 2002; Geballe et al. 2002). Current estimates of the temperatures of ultracool dwarfs range from about 2400 K to 1400 K for L dwarfs, and from 1400 K to 700 K for T dwarfs (Basri et al. 2000; Vrba et al. 2004).

Most of the known ultracool dwarfs have been identified in the general field by the wide area surveys 2MASS and SDSS. These objects consist of a mixed population of very low-mass stars, brown dwarfs and free-floating planets formed in different star-formation events during the lifetime of the Milky Way. Their individual ages, chemical compositions and masses are not known. Our best chance to study a population of ultracool dwarfs of known age, chemical composition, and uniform distance is to find them in open clusters where the stellar populations are well characterized. Two of the first brown dwarfs identified were located in the Pleiades open cluster (PPl 15 and Teide 1, Stauffer et al. 1994; Basri et al. 1996; Rebolo et al. 1995). Now, we know several dozens of bona fide brown dwarfs in the Pleiades and in other open clusters.

The σOrionis open cluster has been a region where our group has concentrated many efforts to reveal the substellar population (see Zapatero Osorio et al. 2003 for a recent review). It offers several advantages: (1) It is young (3-8 Myr) and, thus, the substellar objects are relatively bright and hot (Béjar et al. 2001), but not so young that the theoretical models cannot be reliably used to obtain masses (Baraffe et al. 2001). (2) It has very little extinction (Lee 1968), probably because the parental cloud has been blown away by the O-type star at the center of the cluster. (3) It is relatively nearby (distance 350 pc). (4) It is moderately rich and dense. Béjar et al. (2004, in preparation) estimate a peak central density of 0.2 members per square arcminute.

So far the coolest and faintest candidate member that we have found in the σOrionis cluster is the T dwarf candidate S Ori 70 (Zapatero Osorio et al. 2002). It was found in a pencil-beam deep mini-survey of only 55 square arcminutes with a sensitivity of 21 magnitude in the J and H-bands carried out with the 4.2-meter William Herschel Telescope in the Observatorio del Roque de los Muchachos. Follow-up near-infrared photometry and low-resolution spectroscopy were obtained with NIRC at the 10-meter Keck I telescope. The photometry is summarized in Table 1, together with the data for field T dwarfs of similar spectral type obtained from the literature. A mid-resolution spectrum in the K-band obtained with NIRSPEC on Keck II was presented in Martín & Zapatero Osorio (2003). We have claimed that both the NIRC and the NIRSPEC spectra are best fitted with synthetic spectra with low gravity (log g=3.5), which is consistent with membership in the σOrionis open cluster. We have estimated a mass of 3 Jupiter masses for an age of 3 Myr, making S Ori 70 the least massive object observed directly outside the solar system.

2 A critique of Burgasser et al.'s paper

Burgasser et al. (2004) have carried out an independent analysis of our Keck NIRC and NIRSPEC data of S Ori 70. We sent them our raw and reduced spectra. Burgasser et al. reprocessed our spectra using their own software and found the same results as us for S Ori 70 but not for the comparison object 2MASS J055919-1404. Apparently, our NIRSPEC data reduction for the 2MASS comparison object was incorrect, and it turned out to be a field star rather than a T dwarf.

Table 1: Comparison of photometric data of field T4-T8 dwarfs with S Ori 70

Name	SpT	J	$J-H$	$H-K$	Ref.
2MASS 2254+3123	T4	15.01±0.03	0.06±0.04	-0.08±0.04	K04
SDSS 0000+2554	T4.5	14.73±0.05	-0.01±0.06	-0.08±0.04	K04
SDSS 0207+0000	T4.5	16.63±0.05	-0.03±0.07	0.04±0.07	L02
SDSS 0926+5847	T4.5	15.47±0.03	0.05±0.04	-0.08±0.04	L02
2MASS 0559-1404	T4.5	13.57±0.03	-0.07±0.04	-0.09±0.04	L02
SDSS 0742+2055	T5	15.60±0.03	-0.35±0.04	-0.11±0.04	K04
SDSS 0830+0128	T5.5	15.99±0.03	-0.18±0.04	-0.21±0.04	K04
SDSS 0741+2351	T5.5	15.87±0.03	-0.25±0.06	0.00±0.07	K04
2MASS 2339+1352	T5.5	15.81±0.03	-0.19±0.04	-0.17±0.04	K04
SOri70	T5.5	20.28±0.10	-0.14±0.15	0.64±0.25	MZO02
Gl 229B	T6	14.33±0.05	-0.02±0.07	-0.07±0.07	L99
SDSS 1231+0847	T6	15.14±0.03	-0.26±0.04	-0.06±0.04	K04
SDSS 2124+0100	T6	15.88±0.03	-0.24±0.04	0.05±0.04	K04
2MASS 0937+2931	T6	14.29±0.03	-0.38±0.04	-0.72±0.04	K04
2MASS 1225-2739	T6	14.88±0.03	-0.29±0.04	-0.11±0.04	L02
SDSS 1110+0116	T6	16.12±0.05	-0.10±0.07	0.17±0.07	L02
2MASS 1047+2124	T6.5	15.46±0.03	-0.37±0.04	-0.37±0.04	K04
SDSS 1758+4633	T7	15.86±0.03	-0.34±0.04	0.08±0.04	K04
2MASS 1217-0311	T8	15.56±0.03	-0.42±0.04	0.06±0.04	L02
Gl 570D	T8	15.33±0.05	0.05±0.10	0.01±0.19	B00
2MASS 0727+1710	T8	15.19±0.03	-0.48±0.04	-0.02±0.04	K04

Burgasser et al. compared the spectra of S Ori 70 with spectra of field T brown dwarfs (bdTs) obtained by them, and claimed to find a good match between our object and old brown dwarfs. In their Figure 2, they showed a comparison of their reduction of our NIRSPEC spectrum of S Ori 70 and their NIRSPEC spectrum of the field bdT7 2MASS1553+1532. In their Figure 4, they showed a comparison of our NIRC spectrum of S Ori 70 with their NIRC spectrum of the field bdT6.5 2MASS1047+2124. From these comparisons they claimed that S Ori 70 is a field brown dwarf that coincidentally lies in the line of sight of the cluster. If the interpretation of Burgasser et al. is correct, S Ori 70 should be at a distance of only 75 to 100 pc, instead of 350 pc.

We note that contrary to the claims of Burgasser et al., there are significant differences between S Ori 70 and field T dwarfs. The KI doublet at 1.25 microns is stronger in S Ori 70 than in 2MASS1553+1532, the pseudocontinuum bump between 1.57 and 1.62 microns is narrower in SOri70 than in 2MASS1047+2124, and the pseudocontinuum bump between 2.0 and 2.2 microns is higher and redder in SOri70 than in 2MASS1047+2124. All these three features are consistent with the model predictions for gravity effects as also noted by Lucas et al. (2001) in their analysis of infrared spectra of L dwarfs in the Trapezium cluster and by Knapp et al. (2004) in their analysis of field T dwarfs. Burgasser et al. neglected to comment on the NIRC spectra mis-matches between SOri70 and field T dwarfs, and dismissed the detection of the KI doublet because the NIRSPEC spectrum is too noisy.

Knapp et al. (2004) have proposed that the spread of $H-K$ colors observed in field T dwarfs could be due to differences in gravities, expected for a sample of brown dwarfs with a wide range of ages and masses. The models indicate that objects with red H-K colors have low gravities due to weaker pressure-induced H_2 absorption in the K-band. This effect was first predicted by Saumon et al. (1996), and can also be noticed in the models published by Allard et al. (2001). It seems to be a robust prediction of all models. In Figure 1, I display a color-color diagram comparing the position of S Ori 70 with that of field T4-T8 dwarfs. The S Ori 70 photometry was calibrated in the same system as that of Leggett et al. (2002). The plot includes six bdTs with photometry from Leggett et al. (2002). The MKO system used by Knapp et al. (2004) is very close to the Leggett et al. system, and hence I have made no corrections. I also show the models used by Knapp et al. Full explanation of these cloudless models can be found in Marley et al. (2002). All the field bdT objects are located in the region where the models give gravities in the range log g=4.0-5.5, consistent with their presumed old ages. S Ori 70, on the other hand, is located outside the locus of the field bdTs, even taking into account the photometric error bars. Its red $H - K$ color indicates lower gravity than the field objects according to the models. In fact, Martín & Zapatero Osorio (2003) derived log g=3.5 for S Ori 70, which implies a mass of 3 Jupiters. The red $H - K$ color cannot be due to insterstellar reddening because extinction is very low in this line of sight, and because reddening would also affect the $J - H$ color.

3 Where do we go from here?

The differences in colors and spectral energy distribution between SOri70 and field bdTs strongly suggest that S Ori 70 has lower gravity, consistent with young age and low mass. We conclude that, despite Burgasser's claims, S Ori 70 is still a strong cluster planet candidate. Nevertheless, more data is necessary to improve our understanding of this object and to confirm its cluster membership in σOrionis. In this section, I discuss future observations that will provide crucial information about S Ori 70.

- **The proper motion:** Zapatero Osorio et al. (2002) compared images with a 3 year baseline of the field around S Ori 70. They placed an upper limit of 0.1 arcsec per year on the proper motion of S Ori 70. If S Ori 70 is a bdT at 75-100 pc, the proper motion should be about 0.05 arcsec per year. The last images of S Ori 70 were obtained at Keck I on December 2001. We plan to obtain new images in winter 2004 in order to improve the limit on the proper motion of S Ori 70 by a factor of two. Unfortunately, proposals to obtain accurate astrometry of S Ori 70 with HST in Cycles 11, 12 and 13 have not been successful.

- **The KI near-infrared lines:** The detection of the KI doublet at 1.25 microns reported by Martín & Zapatero Osorio (2003) needs to be confirmed with higher signal to noise ratio. A proposal to reobserve S Ori 70 with Keck/NIRSPEC was rejected by the NASA TAC given "the extensive study of S Ori 70 by Burgasser and his colleagues". In this paper we have shown that the Burgasser et al. study did not provide the final word on the nature of this object, and that S Ori 70 clearly deserves further investigation.

- **The spectral energy distribution (SED):** The SED coverage of S Ori 70 is still incomplete and the error bars in the photometry should be reduced. A proposal to obtain the JH spectrum with Keck/NIRC, and to improve the HK spectrum was rejected by the NASA TAC. A proposal to obtain mid-infrared photometry with SIRTF/IRAC was also turned down. We plan to insist on applying for telescope time to observe S Ori 70 so that we can obtain an excellent SED of this benchmark cluster planet, which can be a reference for future studies of planetary-mass objects in star-forming regions and young open clusters. In parallel with more detailed observations of S Ori 70, there should also be theoretical efforts to improve the synthetic spectra of T dwarfs. The best fit of the J-band NIRSPEC spectrum found by Martín & Zapatero Osorio (2003) has a T_{eff}=1,100 K,

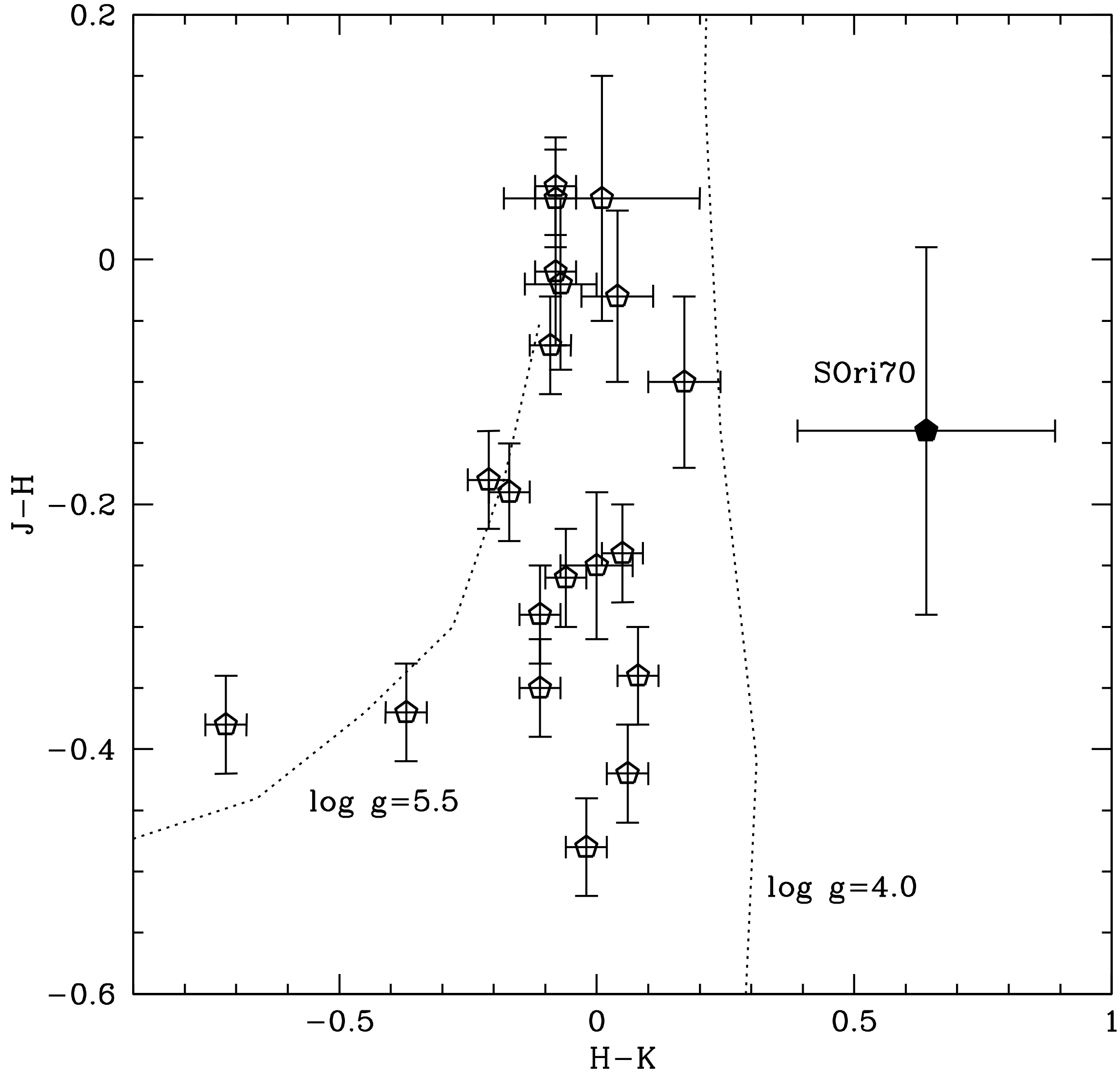

Figure 1: Comparison of S Ori 70 with field bdT4-T8 objects. Theoretical models from Marley et al. (2002) are also shown with dotted lines for two different gravities. Note that S Ori 70 is located in a region outside the locus of field T dwarfs, consistent with having lower surface gravity. All the known field T dwarfs are bracketed by the models.

significantly hotter than the best fit of the HK NIRC spectrum for $T_{\rm eff}$=800 K obtained by Zapatero Osorio et al. (2002). Burgasser et al. (2004) correctly pointed out this inconsistency in the comparison of observations with theory and also showed that this fitting technique provides gravities that are too low for bdT7-bdT8 field objects. However, the gravities obtained from the models are reasonable for bdT6 field objects, which is closer to the spectral type of S Ori 70.

Last but not least, I would like to note that our efforts to find more cluster planets similar to S Ori 70 have met with poor weather in several observatories (Calar Alto, Canaries, Hawaii and Paranal). We do not have a reliable database to search for these objects yet. Nevertheless, we have found a few candidates that await spectroscopic observations. I showed one of them at the Moriond meeting, a possible planetary mass companion to an M dwarf member in the σOrionis open cluster. Follow-up observations of these objects with several telescopes are planned. Stay tuned!

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