Finding the Lower Stellar Mass Limit Observationally

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According to the Research Consortium on Nearby Stars (RECONS), the 100 nearest star systems contain 141 stars. Of these 141 stars, 109 of them are of the spectral type M or below. [**1**] Observing these low mass stars can be difficult due to their intrinsic low luminosities; nevertheless, they are an important part of determining the initial mass function. This paper will deal with the observational aspect of the lower mass limit. Although the scope of this paper is not on the theoretical aspect of the lower mass limit, I will go into some detail on exactly what the lower mass limit of a star is, and what significance it has physically. The remainder of the paper will deal with stars and sub-stellar objects above and below the lower mass limit, respectively. I will spend some time on the historical search for low mass objects, how these objects are detected, and some recent findings.

In 2006, the International Astronomical Union, in their infinite wisdom, decided to spend a great deal of time and publicity to define what a planet is. Unfortunately, this definition only pertains to planets within our own Solar System and mainly deals with reclassifying lower mass objects as dwarf planets. At this point, the reader is left to wonder what this has to do with a lower mass limit for stars. In 2003, the Working Group on Extrasolar Planets (WGESP) issued a statement saying:

> *"1. Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.*
>
> *2. Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.*

3. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate)."[**2**]

The upper mass limit of a planet dies at the deuterium burning limit. Objects that are oboe this limit, but below the hydrogen burning limit, are called brown dwarfs. These substellar objects do sustain nuclear fusion in some part of their lifetime. The cores of these objects do not get hot enough to burn hydrogen, but rather a heavier isotope of hydrogen. In a paper by Shiv Kumar in 1963, he discussed a type of low mass star that would become completely degenerate below a mass of $.09M_{\odot}$ for POPII stars, $.07M_{\odot}$ for POPI stars. He called these objects "black dwarfs". [**3**] These objects would burn deuterium, but never get hot enough to burn hydrogen. They would eventually cool and become degenerate at the core. This degeneracy would effectively halt stellar formation, and these objects would never go through a "normal stellar evolution". The term "black dwarf" was later changed to brown dwarf, but the idea of these objects being substellar has persisted. More recently, Oppenheimer et al. in 2000 defined brown dwarfs based on their internal physics, but the definition is best described in their analogy:

*"A main sequence star is to a candle as a brown dwarf is to a hot poker recently removed from the fire... Thus, like a candle, a star will burn constantly until its fuel source is exhausted. A brown dwarf's core temperature is insufficient to sustain the fusion reactions common to all main sequence stars. Thus brown dwarfs cool as they age. Cooling is perhaps the single most important salient feature of brown dwarfs..." [**4**]*

Despite the speculation of these substellar objects in 1963, they remained elusive for several decades. It was important for astronomers to find these objects at the time, because they were proposed to have filled in the “missing mass” problem of the Galaxy. If these objects were plentiful enough, they could solve some of the problems seen observationally with Galactic dynamics within the Milky Way, although this has since been discounted by MACHO. Still, as late as 1998, Kerins and Wyn Evans have suggested that brown dwarfs could account for the missing matter in the Galaxy.[**5**] Throughout the decades following Kumar’s 1963 paper, most of the searches for brown dwarfs were focused on clusters. Several surveys were launched in search of brown dwarfs. There have been IR surveys of the Pleiades and Orion to name a few.[**17**],[**18**],[**19**]

There were several claimed detections of brown dwarfs leading up to the launch of IRAS, but the detections were never substantiated, so the search continued. The principal goal of IRAS, launched in 1984, was to detect these objects. None were detected. Searches of nearby stars all failed to turn up any brown dwarfs. Henry et al. in 1990 used an infrared speckle technique to look for brown dwarfs within 8pc. [**7**] This also failed to turn up any brown dwarfs. Finally, in 1995 Nakajima et al. announced the detection of a cool brown dwarf, GL229B; it was later published in 1996. [**8**] This was a long awaited discovery that finally vindicated the idea that these objects must exists, and we should be able to detect them.

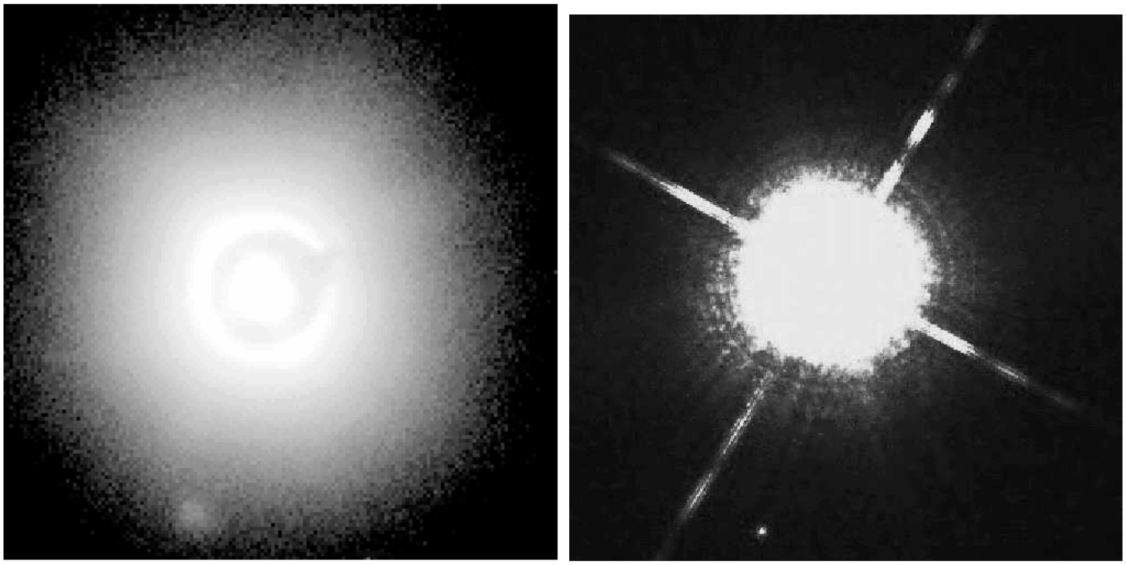

Fig. 1.— Two images of the Gliese 229 system. The right panel shows a direct image from HST's WFPC2. The brown dwarf is at the bottom left of the image. The left panel shows the discovery image from the Palomar 60 inch telescope fitted with a coronagraph. The coronagraphic stop is visible, obscuring most of the light from the primary star. The stop is 4 arcsec in diameter and is semi transparent. The brown dwarf is visible in the bottom left of the image. Both images are oriented with N up and E to the left and are approximately 17 arcseconds on a side. [**4**]

Historically, there are several ways to go about searching for low mass stars. The first method would be an indirect method of looking for a low mass companion. This can be done by astrometry, or by radial velocity. The idea is to study the apparent motion of a primary star and deduce the mass of a secondary, or if one exists. The search for low mass companions by astrometry has had limited success, with the exception of Wolf 424 which has .06 and .05 solar mass components. This was later shown in a paper by Torres et al., using the FGS on HST, that these were not substellar.[**20**] An astronomer having dinner at the January 2008 AAS meeting described the search for brown dwarfs and planets orbiting nearby stars as such: "The field is littered with the carcasses of those who have tried." Radial velocity studies have proved to be more successful.

Infrared speckle interferometry is another technique that has been used. IR speckle, in most basic terms, is a process that involves taking rapid images of a star with the hopes that you freeze out any distortions in the atmosphere. These images can then be added later to increase the visibility amplitude. This method can be done using shift-and-add or Fourier analysis, and can be useful if the primary and companion differ very little in magnitude. [**6**]

The previous two methods focused on finding a low mass companion. The next method deals with finding field stars of very low mass. This method involves looking at clusters for very faint stars. If one knows the distance to a cluster, one can infer the luminosities of the stars in that cluster. Looking for stars of very low luminosity would be a great way of finding low mass stars without knowing their dynamical masses.

Determining whether a cool object is a star or brown dwarf is based on the hydrogen burning mass limit (HBML). This limit puts constraints on the core temperature of the object. If it is massive enough to fuse hydrogen, then it is a cool red dwarf. If it cannot fuse hydrogen, then it is a brown dwarf. The luminosity can be used for brown dwarfs that have cooled from their formation. They are characterized by their luminosity $10^4 L_\odot$. [4] Using L T_{eff}^4, this corresponds to a temperature T_eff=1800K. If the distance to the object is known, this is a great way to determine if an object is a brown dwarf or a star. The problem with this is the uncertainty in the distance. For objects with parallax, this is not such a problem, but for objects with more uncertain distances, this can lead to misclassification.

The second test, called the lithium test, was described by Rebolo et al. in 1992. [**8**] The theory is such that the temperatures needed to destroy lithium were easily achieved in the cores of red dwarf stars, but that temperatures in brown dwarfs would be sufficiently low as to not deplete this element. Looking for lithium in the spectrum should identify an object as below the HBML. This is a key part of determining the lower mass limit. As the titanium oxide (TiO) bands subside at the end of the M spectral type, vanadium oxide (VO) reaches its maximum. Cooler down the L spectral sequence, the lithium begins to show, and lithium is present throughout the rest of the sequence.

The third test, for very low mass stars, is the molecular test. This test looks for molecular compounds such as methane. Methane is a key signature for the T spectral type. For very low mass brown dwarfs, the lithium test fails. The temperatures are not sufficient to show the Li signature, but molecules such as methane can form in the atmosphere of a brown dwarf if temperature T_eff=1500K [**4**]

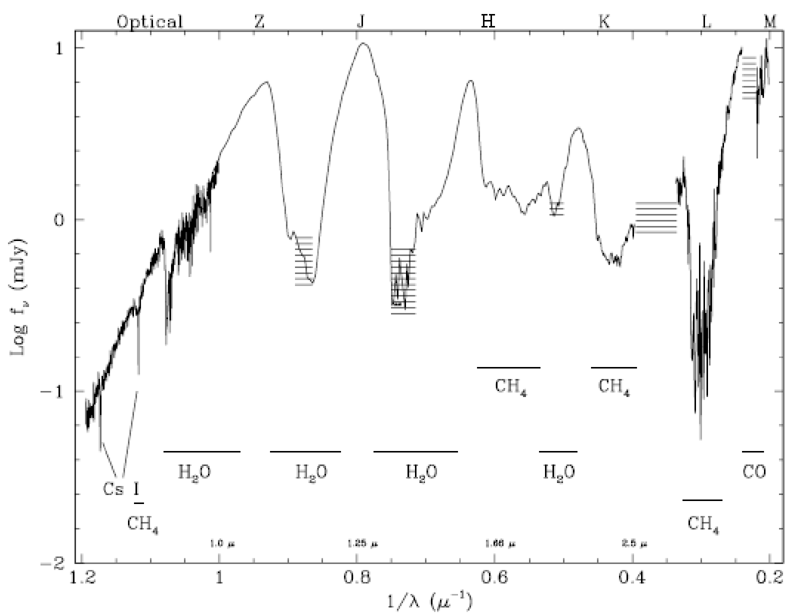

Fig. 2.— The spectrum of Gliese 229B from 0.8 μm to 5.0 μm. The principal absorption features are, as indicated, from water and methane, which is not present in stellar atmospheres. Additional features due to cesium and carbon monoxide are also marked. The relative smoothness of the 0.8 to 1.0 μm region indicates the presence of an unpredicted continuum opacity source. (From Oppenheimer et al. 1998a.) [4]

The three previous mentioned tests have their limits. They are all based on observed quantities that infer the structure and temperature of the core. If the models are correct, this is not a significant problem, but models have problems at such low masses. Age also plays a role in the uncertainty of the above three tests. A young brown dwarf can appear in the M spectral type. The object is still very hot from its formation and not reached a temperature position on the main sequence. These young hot low mass objects can masquerade as stars for a while. If an object is associated with a cluster, then the age can be reasonably determined. The big problem arises with young clusters, like Orion, where we may have very young brown dwarfs forming and mistake them for late M spectral types.

There have brown dwarf detection in clusters. In 1995, Rebolo et al. detected a brown dwarf in the Pleiades. More recently, Lucas et al. published a paper in 2000 that claims to have found several brown dwarf and free floating planet candidates in Orion. They claim that of the 515 objects surveyed, 32 percent of them were brown dwarf candidates. They used IJH band pass filters on UKIRT to search for these low mass objects.[**17**] They used the magnitudes and compared them to models. It is interesting to note that previous searches for such low mass objects in Orion have failed to turn up any. Lucas et al. notes that previous searches for such low mass objects in Orion failed to turn up any, but they are still confident that these objects are part of Orion and are in fact very low mass objects. This work was later followed up by Lucas et al. in 2006 to include spectroscopy using Gemini North and Gemini South.

At this point a discussion of spectral typing is useful. The lower mass end of the HR diagram ends with M spectral type stars. The spectral component that determines a star as an M type is titanium oxide. This is present as a large absorption in the spectrum of cool stellar atmospheres. Recently, the new suggested spectral classifications of L and T have been used to describe some very low mass objects. An M-type star is above the HBML, but a spectral type of L does not necessarily mean that it is stellar or substellar. The spectral types of L and T were described in an annual review by Kirkpatrick in 2005, but the L type was first proposed by Martin et al. in 1997.[**10**][**11**]

There was some trouble in choosing what letter to use to describe the two new spectral types. The argument made by Kirkpatrick for using L and T was based mostly on availability and an attempt to not confuse them with other designations used in astronomy. Table 1, below, lists the available letters and shows why each would be problematic. This left H, L, T, and Y. In the end, L and T were chosen. In a recent press release by Delorme et al., the spectral type Y has been proposed to describe "the coolest brown dwarf to date". This brown dwarf shows ammonia lines and has an estimated T_eff=620K. [**13**]

Summary of Letters to Guide Choice of New Spectral Type

Letter (1)	Status (2)	Notes (3)
A	In use	Standard spectral class
B	In use	Standard spectral class
C	In use	Standard carbon-star class
D	Ambiguous	Confusion with white dwarf classes DA, DB, DC, etc.
E	Ambiguous	Confusion with elliptical galaxy morphological types E0–E7
F	In use	Standard spectral class
G	In use	Standard spectral class
H	OK	
I	Problematic	Transcription problems with I0 (10, Io) and I1 (11, II, Il)
J	In use	Standard carbon-star class
K	In use	Standard spectral class
L	OK	
M......	In use	Standard spectral class
N	In use	Standard carbon-star class
O	In use	Standard spectral class
P	Problematic?	Incorrect association with planets?
Q	Problematic?	Incorrect association with QSOs?
R	In use	Standard carbon-star class
S.......	In use	Standard spectral class for ZrO-rich stars
T	OK	
U	Problematic?	Incorrect association with ultraviolet sources?
V	Problematic	Confusion with vanadium oxide (V0 vs. VO)
W......	Ambiguous	Confusion with Wolf-Rayet WN and WR classes
X	Problematic	Incorrect association with X-ray sources
Y	OK	
Z	Problematic?	Incorrect implication that we have reached "the end"?

Fig. 3.— This table from Kirkpatrick 2005 shows the current letters being used in astronomy and their respective use. This is how he claims to have chosen the spectral types of L and T.

At the middle of the M spectral type, the TiO bands become saturated and then weaken. This demanded a new spectral type. The T type describes a substellar object with methane. The L spectral type has no defining spectral features. In fact, it is defined, by default, as not having TiO or methane. It is within this spectral type that an object reaches the HBML and becomes a star. The key test for the lower mass limit is the lithium test stated above. An object can appear to be an M spectral type early on in its formation, but the detection of lithium will show it to be substellar.

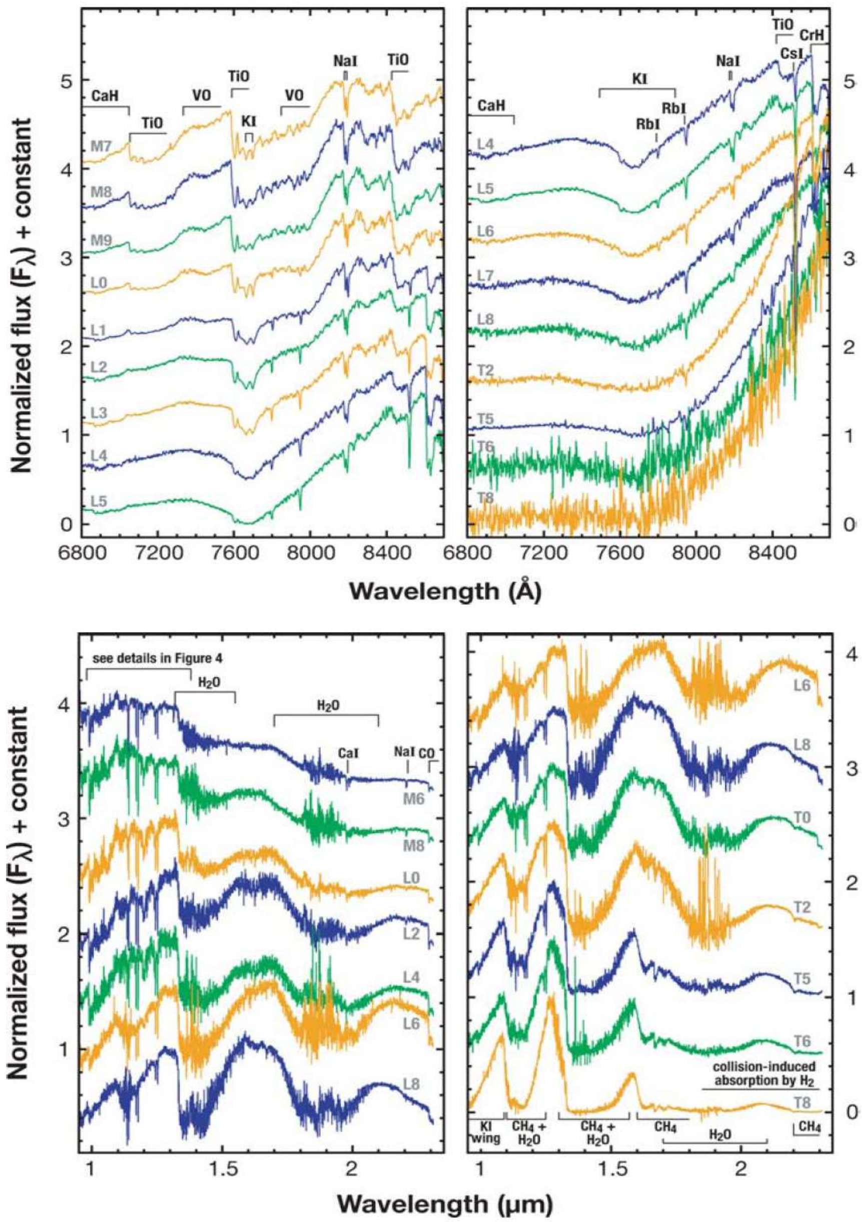

Fig. 4.— This figure from Kirkpatrick et al. shows the sequence from late M to late T. [12] This shows the disappearance of the TiO bands that define the M dwarfs. A brown dwarf will be a late M spectral type early on, and then cool to an L type, finishing its life as a T spectral type. This is why it is important to emphasize that a spectral type does not make an object a star.

In 1993, Henry et al. published a mass-luminosity relation for stars from 1-.08M. Infrared speckle was used to determine the component masses of several systems, and then their masses were used to determine masses empirically from V, J, H, and K magnitudes. These empirical relations can be used to get a rough estimate for the mass of an object. This would help determine if the object is near the HBML or above it without determining the mass through a companion. Henry et al. cautions the M-L relation is age dependant and should be used with caution. [**14**] This was later repeated in the optical from .08-.02$M_{\odot}$in a paper by Henry et al in 1999. It is important to note that this particular approach relies on accurate parallaxes. The equation for optical is as follows for mass from .08-.02$M_{\odot}$:
$Log\,(M/\,M_{\odot}= +0.005239M_v^2 - 0.2326M_v + 1.3785)$ [**15**]

With interferometers coming online in the astronomical community, it is now possible to test some of the properties of stellar models. Interferometry allows astronomers to get very high angular resolution on stars with the hope of resolving them. In a nod to CHARA, a paper by Berger et al. in 2006 produced radius measurements of low mass stars. Although these stars were early M type stars, it is worth noting that the radii measured for these stars did not match current models for the spectral type. If combined with some of the data out of the VLTI, and the PTI, a trend emerges that shows the models do need work. [**16**]

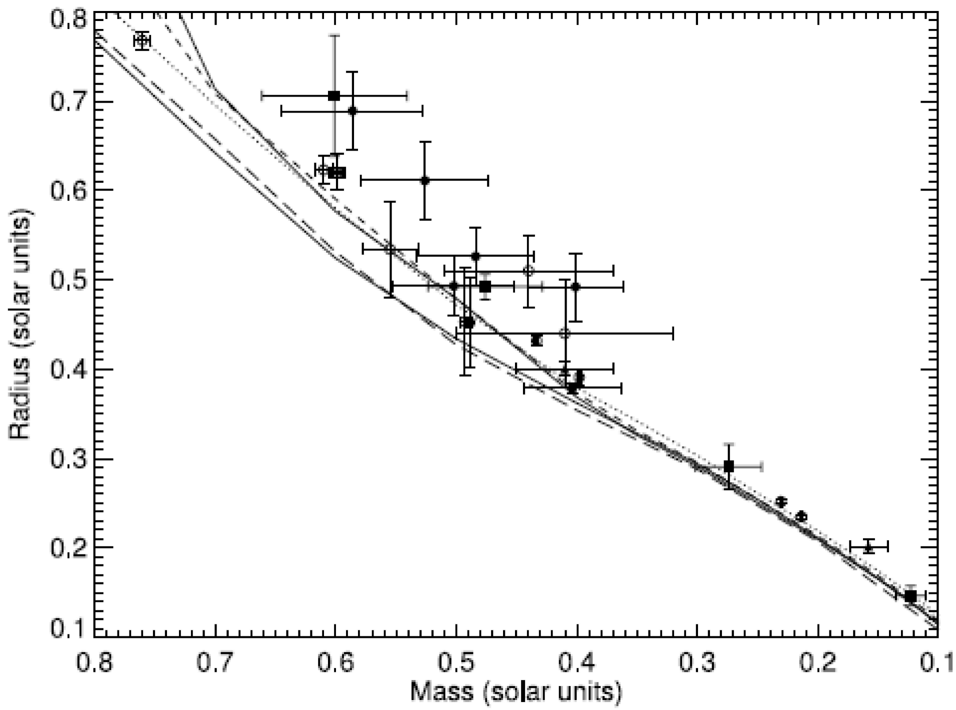

Fig. 5.— Figure 4: Mass-radius relation for low-mass dwarfs measured by long-baseline interferometry (filled symbols) and spectrophotometry of eclipsing binaries (open circles; see references in x 1). The interferometry data included are from this paper (circles), PTI (Lane et al. 2001, triangles), and VLTI (Segransan et al. 2003, squares). The lines represent models from Chabrier & Baraffe (1997) for different metallicities (dotted line: [M/H] 0:0; short-dashed line: [M/H] _0:5; double-dot-dashed line: [M/H] _1:0) and Siess et al. (1997) for similar metallicities (solid line: [M/H] 0:0; long-dashed line: [M/H] _0:3).

The conclusion that can be drawn from this paper is that there is still much to be done observationally in determining a lower mass limit. There has been some work done in determining radii for low mass stars, but currently the limiting magnitude is too low to reach down to the late M to early L spectral types. This would be of great use to theorists to nail down the radii of low mass stars and brown dwarfs. It is important to remember that the detection of these low mass objects is crucial to determining the IMF of the

Galaxy. Although they cannot account for the missing mass in the galaxy, they can help astronomers determine the initial mass function. This piece of information could greatly constrain the mass in the galaxy, as well as show how stars form and in what distributions.

This paper has discussed the different detection methods of brown dwarfs. It is important to remember that these detection methods are not without limits. Age, metallicity, and distance estimate play a very important role in using these tests. The HBML is the point quantity that determines if an object is a star or a brown dwarf. Henry et al. showed that if the object is not a binary and a mass cannot be easily determined, a mass-luminosity relationship can be used to determine the mass. Once again, age, metallicity, and distance errors can render the relationship less useful. A brown dwarf can appear to be a late M type star early in its infancy, but a detection of lithium can rule it out as being stellar in nature. An older brown dwarf is unmistakably substellar.

References

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