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32. We thank the many people that made this research possible: B. Clark, R. Schwartz, P. Wolken, and the staffs at the participating observatories, at NASA-JPL, and at the MPIfR, where all the data were correlated. We also thank K. W. Weiler for useful comments on our manuscript. This research was partly supported by the Dirección General de Investigación Científica y Tecnológica in Spain and by NSF in the United States. NRAO is a facility of NSF operated under cooperative agreement by Associated Universities, Inc. DSS14, DSS15, and DSS63 are operated by NASA-JPL. This work was carried out in part by JPL, California Institute of Technology, under contract to NASA. E.R. acknowledges receipt of a scholarship of the Generalitat-Valenciana. Partial support for the correlator operation from the European Union Access to Large Scale Facilities Programme is acknowledged.

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Infrared Spectrum of the Cool Brown Dwarf Gl 229B

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Spectroscopic measurements of a cool brown dwarf, Gl 229B, reveal absorption features attributable to methane in the near infrared much like those of Jupiter. These features are not seen in any star. The presence of methane indicates that the surface temperature of Gl 229B is below 1000 kelvin. Features attributed to water vapor also indicate that Gl 229B is much cooler than any known star.

Stars like our sun fuse hydrogen into helium and in the process produce energy, most of which appears as light. Current stellar models agree that objects less massive than $0.08M_{\odot}$ cannot sustain hydrogen fusion (*1*, *2*) (the sun is denoted by the symbol $\odot$, and $M_{\odot}$ is the mass of the sun). Such objects are called brown dwarfs. When young ($\lesssim 10^8$ years), they contract relatively rapidly, and the gravitational binding energy released makes these objects quite luminous. As they age, they rapidly cool, and grow dim, becoming increasingly harder to detect. At even lower masses, there exist giant planets, the only examples of which are the giant outer planets of our solar system, including Jupiter (mass $M_J \sim 10^{-3}\ M_{\odot}$). According to theory, the objects in the mass range $1M_J$ to $100M_J$ have similar characteristics. All of them have fully convective interiors and thin radiative atmospheres that radiate mostly between bands of molecular absorption. In addition, they all have about the same radius, $R \sim 0.1R_{\odot}$. Despite these similarities, brown dwarfs and giant planets are thought to form differently. It is believed that planets condense within a protoplanetary disk. In contrast, brown dwarfs are thought to form like stars through direct condensations of interstellar gas.

There are at least two reasons why the study of brown dwarfs, especially cool brown dwarfs, excites considerable attention. First, astronomers would like to investigate these objects because they lie in the unexplored mass range between stars and planets. Although these objects were predicted some 30 years ago (*1*), the lack of unambiguous specimens has been a major stumbling block in this field. Second, planetary scientists would like to study the atmospheres of cool brown dwarfs to understand how they are related to the atmospheres of planets. Such understanding is critical in the search for other planetary systems.

The emergent spectrum of radiation from a condensed object depends on the chemical composition, the surface gravity, and the effective surface temperature T_{eff}, which is defined here by the relation $\sigma T_{\mathrm{eff}}^4 = L/4\pi R^2$, where L is the luminosity of the object and σ is the Stefan-Boltzmann constant. The minimum luminosity of hydrogen-fusing stars (main-sequence stars) is $10^{-4}\ L_{\odot}$ (*2*). Thus, for these stars, $T_{\mathrm{eff}} \gtrsim 1800$ K. This is about equal to the temperature of GD 165B (*3*), the coolest condensed object known until the discovery of Gl 229B (*4*). As discussed above, old brown dwarfs do not generate nuclear power and thus can have very low T_{eff}.

At the low temperatures characteristic of planets and old brown dwarfs, molecules and possibly dust are readily formed. Molecules have a large number of energy levels, which drastically complicates detailed modeling of their atmospheres. To date, there exist no detailed models for T_{eff} below 2000 K (*5*, *6*). However, predictions do exist. For example, below T_{eff} of 1000 K, most of the carbon is predicted (*7*) to reside in methane (CH_4). In contrast, the cool, late-type stars (with $T_{\mathrm{eff}} > 1800$ K) have no CH_4. Their carbon resides mainly in CO, which has a distinctive appearance in spectra of these stars.

Observations of cool objects are crucial to any further progress in this field. As Stevenson (*8*) remarked in a review of high-mass planets and brown dwarfs, "The biggest challenges for the future lie not in theory but in observations: we need more than two colors. We need spectra. . . . Refinement of the theory does not seem to be a compelling task until this happens."

Here we report the first near-infrared (IR) spectroscopic observation of a cool brown dwarf, Gl 229B (*4*). This object has the same proper motion as that of Gl 229 and is thus most likely a companion of Gl 229 (hereafter Gl 229A). Nakajima *et al.* (*4*) obtained broadband photometric measurements from which they deduced $L \lesssim 10^{-5}\ L_{\odot}$. This is 1/10 of the minimum luminosity of any main-sequence star. Nakajima *et al.* concluded that Gl 229B is a cool ($T_{\mathrm{eff}} \lesssim 1200$ K) condensed object. At the present time, we are unable to determine the origin of this object. For simplicity, we will refer to Gl 229B as a brown dwarf.

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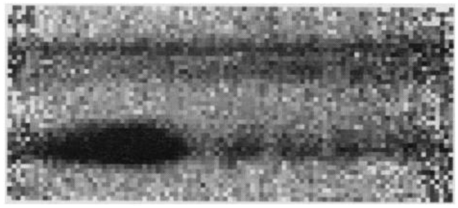

Fig. 1. Typical spectral image of Gl 229B in the H band. The vertical dimension covers 5.4 arc sec west along the slit. The upper dark stripe is the spectrum of the light from Gl 229A diffracted by the telescope spider, and the lower dark stripe is the spectrum of Gl 229B. These two stripes do not overlap; thus, the one-dimensional spectra must in fact be correct extractions from these spectral images. The wavelength coverage is from 1.5 μm (left) to 1.8 μm (right). The diffracted light from Gl 229A is separated from the light of Gl 229B by 2.4 arc sec. The spectrum of Gl 229A, a cool star of spectral type M1, is almost flat through the H band, whereas that of Gl 229B strongly peaks just below 1.6 μm. This spectral feature of Gl 229B distinguishes it from any previously known hydrogen-burning star.

Our IR spectra were obtained at the *f*/70 Cassegrain focus of the Hale 200-inch telescope with a grism spectrograph and an IR camera consisting of reimaging optics and a 256 pixel by 256 pixel InSb detector (Santa Barbara Research). For all of the observations reported here, a focal slit of 0.5 arc sec by 32 arc sec was used. The appropriate orders of the spectrum dispersed by the grism were selected with interference filters: Z (0.95 to 1.11 μm), J (1.15 to 1.40 μm), H (1.49 to 1.81 μm), and K (1.95 to 2.55 μm). For each of the spectra, the resolution was $\lambda/\Delta\lambda \sim 150$ (λ, wavelength). The detector pixel size was 0.125 arc sec in the spatial dimension and one-quarter of the resolution in the spectral dimension.

Spectra of Gl 229B were obtained in the K and H bands on the night of 14 September 1995, and in the Z, J, H, and K bands on the following night. We also obtained spectra of Jupiter for comparison. For atmospheric transmission calibration, G dwarf stars were observed at air masses similar to those of Gl 229B and Jupiter. For wavelength calibration, we observed the bright planetary nebula NGC 7027.

When obtaining the spectrum of Gl 229B, we oriented the long axis of the slit east-west to minimize the contamination of light from Gl 229A diffracted by the secondary mirror support. Data obtained with the star at three different positions on the slit allowed us to remove time-varying sky contributions by subtracting consecutive images. The data were then divided by the spectral image of the G star HR 683, which we uniformly scanned along the slit by tilting the secondary; for Jupiter, we used HR 6269. In addition, we subtracted the adjacent sky for Gl 229A, in order to remove atmospheric emission features, and obtained a spectral image (Fig. 1). This image demonstrates that the spectra of Gl 229A and Gl 229B are well separated and cannot be a combination of the two. By summing the data along the spatial dimension, we created one-dimensional spectra. Next, we removed the blackbody shape of the G star. The absolute flux calibration of the Gl 229B spectrum involved (i) the removal of the blackbody shape of the G star used, (ii) the normalization of the flux density to the photometry of Nakajima *et al.* (*4*), and (iii) the assumptions that Gl 229B has a radius of $0.1R_{\odot}$ and is 5.7 pc distant. The result, then, is the flux density at the surface of Gl 229B. The assumptions in step (iii) have no effect on the shape of the spectrum (Fig. 2).

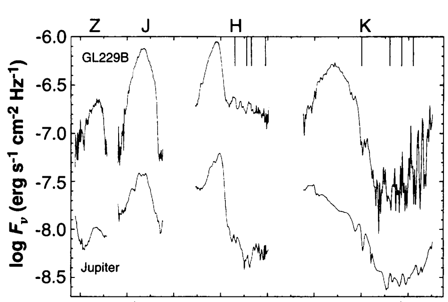

Fig. 2. Near-IR spectra of Gl 229B and Jupiter (in flux per unit frequency, wavelength, F_ν, plotted versus λ). The spectra of Jupiter are shifted vertically for ease of comparison. The spectral resolution is 150. The vertical bars at the top of the plot indicate the locations of CH_4 absorption features at 1.66, 1.71, 1.79, 2.20, 2.32, 2.37, and 2.4 μm.

The spectrum of Gl 229B is different from the spectra of late M stars, including that of GD 165B [figure 1 of (*9*)], but is similar to that of Jupiter. The striking features in the Gl 229B spectrum are the absence of any signal in one-half (1.62 to 1.80 μm) of the H band and one-half (2.25 to 2.40 μm) of the K band. However, these features are seen in Jupiter's spectrum (Fig. 2). In Jupiter, the H-band absorption is primarily attributed (*10*) to strong CH_4 bands, and the K-band depression is attributable to CH_4 and also collisionally induced absorption by molecular hydrogen. The similarity of the H-band spectra of Gl 229B to that of Jupiter is a clear indication that CH_4 is present in Gl 229B. Some similar features are observed in the dusty envelopes surrounding the bright asymptotic giant branch (AGB) stars. However, Gl 229B has a large proper motion (*4*). If it were an AGB star, with an intrinsic luminosity typical of such stars, Gl 229B would lie outside the galaxy and would be moving at a relativistic speed.

A deep absorption feature at 1.34 μm is seen in the spectrum of Gl 229B. Such a feature is also seen in all cool stars and GD 165B and is attributed to an H_2O absorption band. Jones *et al.* (*9*) argued that the depth of this absorption feature—defined as R_{H_2O}, the ratio of flux in the band 1.286 to 1.303 μm to the flux in the band 1.338 to 1.356 μm—is inversely related to T_{eff}. The absorption of GD 165B is much deeper than that of any of the M stars, and thus, the largest value of $R_{H_2O} \sim 1.9$. For Gl 229B, $R_{H_2O} \sim 10$. Jones *et al.* (*9*) also pointed out that the slope of the spectrum in the range 2.05 to 2.15 μm is inversely proportional to T_{eff}. The slope for Gl 229B is more than an order of magnitude larger than that for GD 165B.

Tsuji (*7*), on the basis of chemical equilibrium considerations, has argued that for atmospheres with T_{eff} less than 1000 K, almost all of the carbon is in the form of CH_4, rather than in CO. This explains why CH_4 is seen in Jupiter but not in any main-sequence star. The presence of CH_4 in Gl 229B is an independent indication that T_{eff} for Gl 229B is less than 1000 K. Further support for this conclusion comes from the extreme values of the two spectral diagnostics described above. These imply that Gl 229B is indeed a cool brown dwarf, with $T_{eff} \lesssim 1000$ K.

Our upper limit on T_{eff} is based purely on chemical thermodynamics and molecular excitation physics. In contrast, Nakajima *et al.* (*4*) used broadband photometric data and the assumption that Gl 229B is at the distance of Gl 229A to estimate that $T_{eff} \lesssim 1200$ K. Our upper limit on T_{eff} lends strong credence to the idea that Gl 229A and Gl 229B constitute a binary system at a distance of 5.7 pc.

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