Discovery and spectroscopy of the young Jovian planet 51 Eri b with the Gemini Planet Imager

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Directly detecting thermal emission from young extrasolar planets allows measurement of their atmospheric composition and luminosity, which is influenced by their formation mechanism. Using the Gemini Planet Imager, we discovered a planet orbiting the ~20 Myr-old star 51 Eridani at a projected separation of 13 astronomical units. Near-infrared observations show a spectrum with strong methane and water vapor absorption. Modeling of the spectra and photometry yields a luminosity of $L/L_{\odot}$=1.6-4.0 × 10^{-6} and an effective temperature of 600-750 K. For this age and luminosity, "hot-start" formation models indicate a mass twice that of Jupiter. This planet also has a sufficiently low luminosity to be consistent with the "cold-start" core accretion process that may have formed Jupiter.

Several young self-luminous extrasolar planets have been directly imaged (*1*–*8*) at infrared wavelengths. The currently known directly imaged planets are massive (estimated 5-13 M_J) and at large separations (9-650 AU) from their host star, compared to our solar system. Photometry and spectroscopy probe the atmospheres of these young Jovians, providing hints about their formation. Several unexpected results have emerged. The near-infrared colors of these planets are mostly red, indicating cloudy atmospheres reminiscent of brown dwarfs of spectral type L. Methane absorption features are prominent in the near-infrared spectra of T dwarfs (Teff <1100K), as well as the giant planets of our solar system, but so far weak or absent in the directly imaged exoplanets (*4*, *9*–*11*). Most young planets appear to be methane-free even at temperatures where equivalent brown dwarfs show methane, suggesting non-equilibrium chemistry and persistent clouds that are likely age and mass dependent (*1*, *12*–*15*).

In spite of uncertainties in their atmospheric properties, the luminosities of these planets are well constrained. Luminosity is a function of age, mass and initial conditions (*16*, *17*) and hence can provide insights into a planet's formation. Rapid formation, e.g., through global disk instabilities acting on a dynamical timescale, yields high-entropy planets that are bright at young ages – referred to as "hot-start". Alternatively, two-stage formation, first of a dense solid core followed by gas accretion through a shock, as likely in the case of Jupiter, can produce a range of states including lower-entropy planets that are cooler, and slightly smaller in radius ("cold start"). The young directly imaged planets are almost all too bright for "cold-start" except for very specific accretion shock properties, though their formation is also difficult to explain through global instability which should operate preferentially at higher masses and large semi-major axis separation (*18*, *19*). These planets are also close to the limit of sensitivity for first-generation large-telescope adaptive optics (AO) systems. The goal of the latest generation of surveys using dedicated high-contrast adaptive optics coronagraphs (*20*–*23*) such as the Gemini Planet Imager (GPI) and its counterparts is to expand this sample to closer separations, lower masses and temperatures, a crucial empirical step toward investigating these modes of formation.

The Gemini Planet Imager Exoplanet Survey (GPIES) is targeting 600 young, nearby stars using the GPI instrument. The star 51 Eridani (51 Eri) was chosen as an early target for the survey due to its youth and proximity. Stellar properties are given in Table 1. The star has weak mid- and far-IR excess emission indicating low-mass inner (5.5 AU) and outer (82 AU) dust belts (*24*, *25*). It also has two distant (~2000 AU) stellar companions—the 6 AU separation M-dwarf binary GJ3305AB (*26*). 51 Eri and GJ 3305 were classified in 2001 as members of the β Pictoris moving group (*27*) and subsequent measurements (*28*) support this identification. The estimated age of the β Pictoris moving group in the literature ranges from 12 to 23 Myr (*27*, *29*–*32*). Giving strong weight to the group's lithium depletion boundary age, we adopt an age of 20 ± 6 Myr for all four components of the 51 Eri system (*28*).

We observed 51 Eri in *H* band (1.65 μm) in December 2014 as the 44th target in the GPIES campaign. GPI observations produce spectroscopic cubes with spectral resolving power of 45 over the entire field of view. A companion, designated 51 Eri b, was apparent after point spread function subtraction. The planet is located at a projected separation of 13 AU and showed distinctive strong methane and water vapor absorption (Figs. 1 and 2). We observed 51 Eri in January 2015 to broaden the wavelength coverage using GPI (*J* band; 1.25 μm), and NIRC2/W. M. Keck 2 (*Lp*; 3.8 μm) and recovered the planet in both observations. The observed spectrum is highly similar to a field brown dwarf of spectral type T4.5-T6 (Fig. 2). The *J*-band spectrum confirmed methane absorption at this wavelength and the extremely red *H*-*Lp* color is also similar to other cool, low-mass objects (Fig. 3). The signal-to-noise at *J*-band is inferior to that at *H*, and extraction introduces additional systematic effects. The *J*-band detection is reliable (> 6-σ), but the fluxes in individual spectral channels are less certain. However, the methane feature is robustly detected at both bands (*28*).

Demonstrating common proper motion (e.g., *34*) or showing that the probability of a foreground or background contaminant is extremely low establishes the nature of directly imaged planets. The interval between the December 2014 and January 2015 observations is too brief given our astrometric accuracy (*28*) to show that 51 Eri b and 51 Eri share proper motion and parallax. However, non-detection of 51 Eri b in archival data from 2003 (*28*) excludes a stationary background source and requires proper motion within ~0.1 arcsec/yr of 51 Eri. The strong methane absorption seen in 51 Eri b is found only in T-type or later brown dwarfs. We determined the probability of finding a T dwarf in our field by merging the observed T-dwarf luminosity functions (*27*, *28*) and adopting the spectral types and absolute magnitudes for T dwarfs (*34*) from which we calculate a false alarm rate of 1.72×10^{-7} methane objects (i.e., types T0-T8.5) per GPI field (> 5- σ). The proper motion constraint eliminates a further 66% of likely background T dwarf proper motions. The total false alarm probability after observing 44 targets is that for a T spectrum object to appear in 44 Bernoulli trials, given by the binomial distribution, yielding a final probability of 2.4×10^{-6}. While the occurrence rates of planetary companions is not known with precision, the detection of planetary objects such as β Pic b and HR8799 e at similar physical separations to 51 Eri b indicate that the rate is $>10^{-3}$ per star. Hence, with the high-quality spectrum available to us, it is vastly more likely that 51 Eri b is a bound planetary companion than a chance alignment.

We use planetary atmosphere and evolution models to estimate the properties of 51 Eri b. We first fit the observed *J* and *H* band spectra using standard cloud-free equilibrium-chemistry models, constrained to have radii for a given mass as given by evolutionary tracks, similar to those in

(*35*). This constrained fit gives an effective temperature of 750K, with a radius (0.76 R_J) and surface gravity similar to an old (10 Gyr), high-mass brown dwarf. A similar though less extreme result – small radii and hence high masses and old ages – is found in several model fits to the HR8799 observations (*13*, *15*, *16*), even though high masses are clearly excluded by dynamical stability considerations (e.g., *32*). This model was not constrained to fit the *Lp* observation but does within 1.6σ.

We next fit a model to the *JH* spectra and *Lp* photometry using a linear combination of cloudy and cloud-free surfaces and non-equilibrium chemistry and allowed the planet's radius to vary independently of the radii given by evolutionary tracks. Models of this type generally produce reasonable fits to other directly imaged planets (*11–13, 15, 37, 38*). This model produces a slightly lower effective temperature. The spectral shape and colors only weakly constrain gravity but do favor lower masses, while the radius (~1 R_{Jup}) is consistent with evolutionary tracks given the age of the system. Table 2 summarizes the results of the modeling. With the spectral and atmospheric uncertainties, a wide range of other models (including temperatures as high as ~1000K) are also broadly consistent with the observations. The low temperature is supported by the presence of strong methane absorption that is not seen in other planets of similar age.

The luminosity of $\log(L/L_{\odot})$ of -5.4 to -5.8 is similar in all models regardless of temperature or clouds. Combined with the age, that luminosity can be used to estimate the mass of the planet. For a hot-start model, this corresponds to a mass of $\sim 2\ (t/20\mathrm{My})^{0.65}\ (L/2\times10^{-6})^{0.54}\ M_{\mathrm{Jup}}$ – the lowest-mass self-luminous planet directly imaged to date. 51 Eri b, unlike other young (<100 Myr) planetary-mass companions, has a low enough luminosity low to be consistent with cold-start core accretion scenarios. In cold-start evolution, luminosity at 20 Myr age is nearly independent of mass, so the mass of 51 Eri b would be between 2 and 12 M_{Jup}.

51 Eri b and the GJ 3305 binary form a hierarchical triple configuration (*28*), but the companion pair is far enough away that the planet is expected to be dynamically stable in its current orbit (*13*). Moreover, the young age of the system suggests that while long-term dynamical effects such as secular Lidov-Kozai oscillations might have altered the planet's eccentricity and inclination, it is unlikely they have had time to produce the extreme eccentricities required for tidal friction to alter the planet's semi-major axis (*39*). The formation of a ~2 M_{Jup} planet at an orbital distance of ~15 AU around a Sun-like star can be explained by modest extensions to the core accretion theory. Early versions of the theory (*40*) found that accretion of the core at larger orbital distances is in danger of taking too long, failing to capture the natal gas before it dissipates. 51 Eri b is close enough to the star that this may be less of a problem, and the addition of migration (*41*) or pebbles that experience gas drag (*42*) also help overcome this timescale difficulty.

The transition from L-type to T-type planets appears to occur over a narrow range of temperatures between the ~1000K HR8799b or PSO J318.5-22 (*42*) and the 700K 51 Eri. Direct determination of the object's mass – either through spectral surface gravity indicators, or reflex astrometry of the primary star – could determine whether it formed through hot- or cold-start processes; 51 Eri b provides an opportunity to study in detail a planet that is still influenced by its formation initial conditions. With a methane-dominated spectrum, low luminosity and potentially low-entropy start, 51 Eri b is a bridge from wider-orbit, hotter and more massive planets to Jupiter-like scales.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aac5891/DC1
Materials and Methods
Figs. S1 to S3
Tables S1 to S3
References (*47*–*90*)

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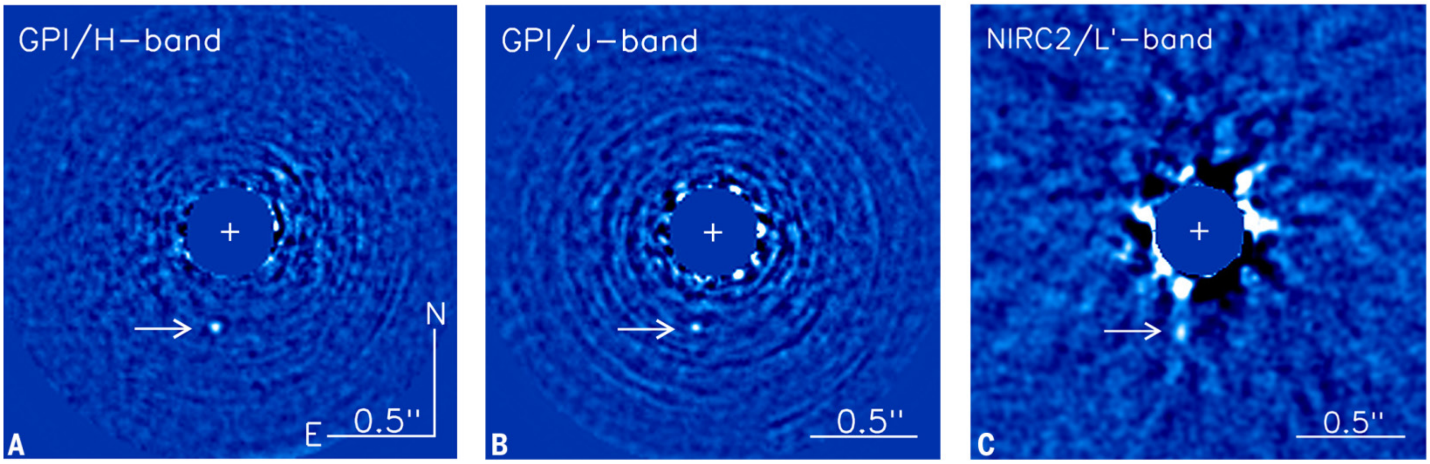

Fig. 1. Images of 51 Eri and 51 Eri b (indicated by arrow) after point spread function (PSF) subtraction. (**A**) *H*-band GPI image from December 2014. (**B**) *J*-band GPI image from January 2015. (**C**) *Lp*-band Keck image using the NIRC2 camera from January 2015.

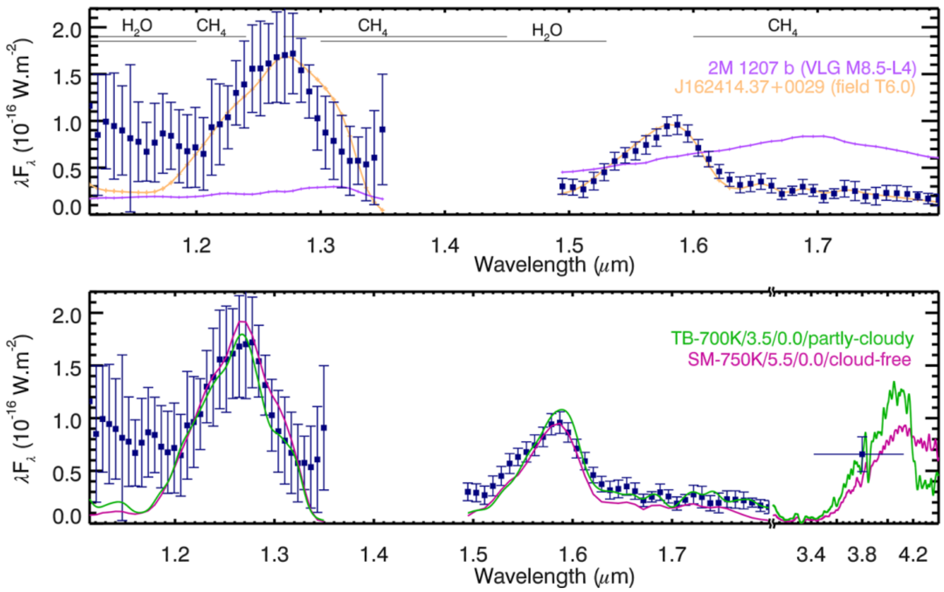

Fig. 2. 51 Eri b J and H band spectrum from GPI data after PSF subtraction. Strong methane absorption, similar to Jupiter, is readily apparent. Top: The hotter young planetary object 2M1207b and a high-mass field T6 brown dwarf from the SpeX library (*43*) are overplotted. Bottom: Observed *J* and *H* spectrum and *Lp* photometry with two model fits overlaid, a young low-mass partly-cloudy object (TB-700K) and a higher-mass cloud-free object (SM-750K). Note that the main source of error in the extracted spectrum is residual speckle artifacts, so errors in neighboring spectral channels are strongly correlated; error estimation is discussed in (*28*).

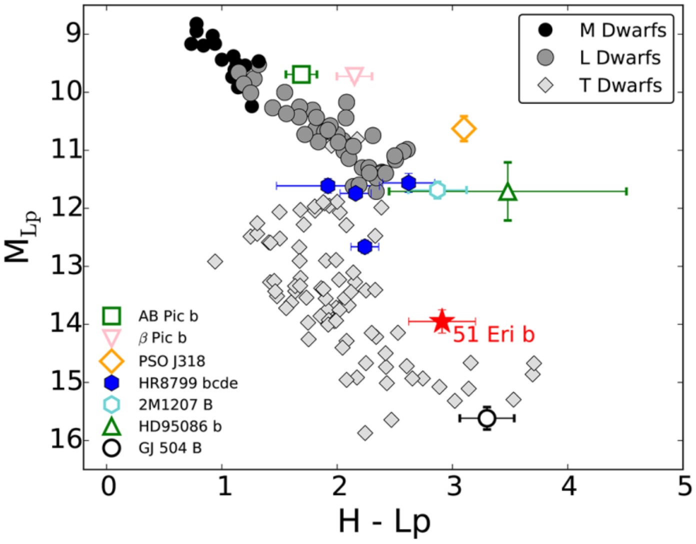

Fig. 3. Color-magnitude diagram of brown dwarfs (grey and black) and planetary-mass objects (colors). 51 Eri b is indicated with a red star, distinct from most other planets in the methane-dominated T-dwarf region of the diagram. The *Lp* field brown dwarf photometry is taken from (*45*, *46*) or converted from WISE W1 (*49*) using an *Lp* vs. W1 linear fit. Parallaxes are available for all objects plotted (*46*).

Table 1. Properties of 51 Eridani A and 51 Eridani b.

51 Eridani	
Spectral Type	F0IV
Mass ($M_{\odot}$)	1.75 ± 0.05
Luminosity ($L_{\odot}$)	7.1 ± 1
Distance (pc)	29.4 ± 0.3
Proper Motion (mas/yr east, mas/yr north)	[44.22 ± 0.34, -64.39 ± 0.27] (*44*)
Age (Myr)	20 ± 6
Metallicity (M/H)	-0.027 (*45*)
J, *H*, *K*s, *L*p (mag.)	4.68, 4.60, 4.56, 4.54
F_{dust}/F_{bol}	~10^{-6}
51 Eri b	
Projected separation (mas)	449 ± 7 (31 January 2015; *33*)
Projected separation (AU)	13.2 ± 0.2 (31 January 2015)
M_J	16.75 ± 0.40
M_H	16.86 ± 0.21
M_{Lp}	13.85 ± 0.27

Table 2. Modeling results for 51 Eri b.

	Cloud-free equilibrium model SM-750K	Partial-cloud model TB-700K
M_J	16.82	16.64
M_H	17.02	16.88
M_L	14.3	13.96
T_{eff} (K)	750	700
R (R_J)	0.76	1
log $L/L_\odot$	-5.8	-5.6
log(g)	5.5	3.5
Age (Myr)	10,000	20 (assumed to match stellar age)
Mass (M_J)	67	2 (from luminosity, assuming high-entropy start)