A DYNAMICAL MASS OF 70 ± 5 $M_{\text{Jup}}$ FOR GLEIES 229B, THE FIRST IMAGED T DWARF

TIMOTHY D. BRANDT$^1$, TRENT J. DUPUY$^2$, BRENDAN P. BOWLER$^3$, DANIELLA C. BARDALEZ GAGLIUFFI$^4$, JAQUELINE FAHERTY$^4$, G. MIRED BRANDT$^1$, AND DANIEL MICHALIK$^5$

Draft version October 7, 2019

ABSTRACT

We combine Keck/HIRES radial velocities, imaging with HiCIAO/Subaru and the Hubble Space Telescope, and absolute astrometry from Hipparcos and Gaia to measure a dynamical mass of 70 ± 5 $M_{\text{Jup}}$ for the brown dwarf companion to Gl 229. Gl 229B was the first imaged brown dwarf to show clear signs of methane in its atmosphere. Cooling models have been used to estimate a mass in the range of 20–55 $M_{\text{Jup}}$, much lower than our measured value. We argue that our high dynamical mass is unlikely to be due to perturbations from additional unseen companions or to Gl 229B being itself a binary, and we find no evidence of a previously claimed radial velocity planet around Gl 229A. Future Gaia data releases will confirm the reliability of the absolute astrometry, though the data pass all quality checks in both Hipparcos and Gaia. Our dynamical mass implies a very old age for Gl 229, in some tension with kinematic and activity age indicators, and/or shortcomings in brown dwarf cooling models. Gl 229B joins a small but growing list of T dwarfs with masses approaching the minimum mass for core hydrogen ignition.

Subject headings:

1. INTRODUCTION

Brown dwarfs’ physical and atmospheric properties bridge giant planets to stars (Burrows et al. 1997). They can have masses of up to ~80 $M_{\text{Jup}}$, depending on metallicity (e.g., Burrows et al. 2001), as degeneracy pressure prevents the core from reaching a temperature necessary to sustain hydrogen fusion. This lack of an internal energy-generating mechanism causes substellar objects to continuously contract, cool, and dim: objects of very different masses can have the same luminosity and temperature if they were born at different times. To test models of brown dwarfs, we need to know both mass and age together with other observable properties like luminosity.

Although ~10$^3$ brown dwarfs are now known (e.g., Smart et al. 2017), only ~20 brown dwarf binary systems have fully determined orbits and dynamical mass measurements for their individual components (Dupuy & Liu 2017). Such dynamical masses have typically relied on a combination of high-angular resolution imaging to measure relative astrometry and flux ratios and absolute astrometry from wide-field imaging to measure the parallax and photocenter orbit. While current adaptive optics (AO) imaging techniques can resolve most brown dwarf binaries down to separations of ~1 AU, such systems are very rare, and in practice dynamical masses have more typically relied on 2–4 AU binaries. The correspondingly long orbital periods of such systems, 10–30 years, have required a major effort spanning over a decade of patient orbit monitoring. And in the very small subset of cases where brown dwarf binaries orbit solar-type stars, the stellar age and metallicity have provided the strongest tests of substellar evolutionary models (e.g., Dupuy et al. 2009, 2014; Crepp et al. 2012; Cardoso 2012).

The first dynamical mass measurement of the components of an L/T transition binary showed that some of the most widely used models (e.g., Baraffe et al. 2003) fail to reproduce coevality (Dupuy et al. 2015). Recent age estimates and dynamical mass measurements of the old ultracool dwarfs Gl 758B, HD 4747B, and HR 7672B, however, showed generally good agreement with models (Brandt et al. 2019) and resolved some earlier discrepancies (Bowler et al. 2018; Calissendorff & Janson 2018).

Most T dwarfs have dynamical masses that are relatively low (30–50 $M_{\text{Jup}}$), as expected given their low temperatures (950–1250 K) and the typical ages of field dwarfs (1–5 Gyr). There have been some notable exceptions, with measured T dwarf masses at the very high end of, and possibly at odds with, expectations. WISE J0720–0846B (T5.5, 66 ± 4 $M_{\text{Jup}}$; Dupuy et al. 2019) and Gl 758B (~T8, 38.1$^{+1.7}_{-1.5}$ $M_{\text{Jup}}$; Vigan et al. 2016) both require ages of several Gyr, according to evolutionary models, in order to have masses as high as observed given their luminosities. According to Cardoso (2012), the case of i Ind BC is similar, with masses of 68±0.9 $M_{\text{Jup}}$ and 53.1±0.3 $M_{\text{Jup}}$ for the T1.5 and T6 components (Kasper et al. 2009; King et al. 2010). However, Dieterich et al. (2018) find the masses to be much higher, 75.0±0.8 $M_{\text{Jup}}$ and 70.1±0.7 $M_{\text{Jup}}$. This would present a severe challenge to most evolutionary models, which predict that such massive objects cannot cool sufficiently to display methane absorption. Another highly problematic case for models is the late-T dwarf HD 4113C. Its dynamical mass of 66$^{+5}_{-4}$ $M_{\text{Jup}}$ (Cheetham et al. 2018) is significantly higher than the maximum mass of ≈40 $M_{\text{Jup}}$ predicted from models for such a low luminosity object ($\approx 10^{-6} L_\odot$).
Anomalously high masses could always be due to unresolved multiplicity. Ruling out this scenario can be difficult, especially at older ages where a lower-mass companion would contribute little to the integrated spectrum or colors. A larger sample of dynamical masses for well-characterized objects is needed to determine whether discrepancies with models are due to shortcomings in the models themselves, unresolved multiplicity or to other observational biases.

In this paper we present a precise dynamical mass measurement for the T7 dwarf Gl 229B, the very first object of its type (and one of the first brown dwarfs ever) to be discovered (Nakajima et al. 1995) Oppenheimer et al. (1995). We use the Hipparcos–Gaia Catalog of Accelerations (HGCA; Brandt et al. 2018), combined with relative astrometry from direct imaging and 17 years of precision radial velocities, to precisely determine its mass and constrain its orbital parameters. We find that this object joins the short, yet growing, list of “massive” T dwarfs.

2. SYSTEM AGE AND METALLICITY

Some of the earliest age analyses of Gl 229 accompanied the discovery of its brown dwarf companion. Nakajima et al. (1995) noted that the star’s kinematics are cold, consistent with youth, but that its observed Hα absorption rules out very young ages (<500 Myr). Those authors adopted the wide range of 0.5–5 Gyr. Leggett et al. (1999) derived a consistent age of 0.5–1 Gyr and a mass of 25–35 M_Jup for Gl 229B by fitting the brown dwarf’s colors and luminosity to evolutionary models. However, Leggett et al. (2002) derived a younger age of ~30 Myr and a metallicity of [M/H] ~ −0.5 dex by simultaneously fitting low-resolution spectra of both Gl 229A and B with AMES-Cond models (Allard et al. 2001).

Gl 229A is an M1V dwarf (Kirkpatrick et al. 1991; Cushing et al. 2006), a class of star for which age is difficult to determine (West et al. 2008). Nevertheless, we can use the star’s rotation, activity, and kinematics to provide some constraints on the age. We revisit the age of the system here using only the properties of the primary star, Gl 229A. We also review literature measurements on the star’s composition, particularly given the fit by Leggett et al. (2002) at a strongly subsolar metallicity.

2.1. Metallicity

Recent measurements of Gl 229A’s metallicity from medium- and high-resolution spectra yield approximately solar values. Gaidos & Mann (2014) derived a spectroscopic metallicity of [Fe/H] = 0.12 ± 0.10 dex from medium-resolution SpEX spectroscopy across the JHK bands; they fit for T_{\text{eff}} using an optical spectrum. Gaidos et al. (2014) used high signal-to-noise ratio, medium-resolution optical spectra calibrated to M dwarfs using wide binaries to obtain [Fe/H] = 0.02 ± 0.11 dex, consistent with the previous measurement.

Neves et al. (2013) published two metallicities from HARPS spectra: [Fe/H] = 0.11 dex and [Fe/H] = −0.05 dex using the Johnson & Apples (2009) and Neves et al. (2012) photometric metallicity relations, respectively; they reported a final value of [Fe/H] = −0.01 dex. Neves et al. (2014) slightly revised this value to [Fe/H] = −0.04 ± 0.09 dex, again based on HARPS high signal-to-noise ratio, high-resolution optical spectroscopy. Nakajima et al. (2015) inferred approximately solar abundances of carbon and oxygen (depending on the adopted solar abundance pattern) and a slightly super-solar C/O ratio from a high-resolution IRCS spectrum (Nakajima et al. 2015).

There are also two older spectroscopically determined metallicities: Schiavon et al. (1997) obtained Fe/H ≈ −0.2 dex from the ~1-µm FeH band, while Mould (1978) derived M/H ≈ 0.15 dex from Fourier transform spectroscopy of aluminum, calcium, and magnesium lines. None of the spectroscopic measurements support the very low metallicity of −0.5 dex suggested by some of the early spectroscopic fits to either the host star or Gl 229B (Leggett et al. 2002).

2.2. Rotation and Activity

Gl 229A shows chromospheric and coronal activity associated with its magnetic dynamo. Astudillo-Defru et al. (2017) calibrated log R_{\text{HK}} = −4.69; the method of Brandt et al. (2014) gives log R_{\text{HK}} = −4.84. Adopting the higher activity index would push the age slightly lower, but well within the uncertainties. Gl 229A was also detected by ROSAT (Voges et al. 1999). The observed X-ray counts imply an activity index, the logarithmic ratio of X-ray to bolometric flux, of log R_X = −5.14. There is no measured rotation period for Gl 229A; Astudillo-Defru et al. (2017) inferred a period of 25 days from measured chromospheric emission.

Gyrochronology for Gl 229A requires an extrapolation of the Mamajek & Hillenbrand (2008) relations, where R_{\text{HK}} and R_X are poorly calibrated. Still, Figures 9 and 10 of Mamajek & Hillenbrand (2008) suggest that gyrochronology remains viable down to early-M stars like Gl 229A. We use the Bayesian age dating described in Brandt et al. (2014) to obtain our activity-based age constraints; this method is based on the relations of Mamajek & Hillenbrand (2008). We first convert R_{\text{HK}} and R_X to the Rossby number, and then to a rotation period using the convective overturn time as a function of color given in Noyes et al. (1984). The rotation period implied by log R_X = −5.14 is 30 days, while log R_{\text{HK}} = −4.84 implies 47 days. We then use the gyrochronological relations of Mamajek & Hillenbrand (2008) together with the weighted average of these rotation periods, 42 days, as described in Brandt et al. (2014).

Angus et al. (2019) have re-calibrated gyrochronology down to early-M dwarfs, below the mass of Gl 229A. Unfortunately, Gl 229A lacks a measured rotation period, and recalibrated coronal and chromospheric activity proxies for stellar rotation are not available. The gyrochronology relations in Mamajek & Hillenbrand (2008) give an age of 3.6 Gyr for B−V = 1.48 and P = 42 days, while those of Angus et al. (2019) give an age of 2.5 Gyr for Gaia BP − RP = 2.08 and the same rotation period. We propagate an uncertainty of 0.16 in Rossby number, as [Mamajek & Hillenbrand (2008) suggest for Solar-type dwarfs with only R_{\text{HK}} to obtain P_{\text{rot}} = 42 ± 5 days. Fixing the mass of Gl 229 to 0.54 M_⊙ as we determine in our dynamical fit, and fixing BP − RP = 2.08, the gyrochronological relations of Angus et al. (2019) give an age of 2.6 ± 0.5 Gyr.

Figure 1 shows our age posterior based on the Brandt et al. (2014) methodology. It is broad, ranging from ~2 Gyr to ~6 Gyr. Adopting the inferred rotation...
rate and/or \( R'_{\text{HK}} \) measurements of Astudillo-Defru et al. (2017) would exclude the older ages in our distribution. The PARSEC stellar models (Bressan et al. 2012) are consistent with Gl 229A lying on the main sequence, and do not provide meaningful age constraints.

2.3. Kinematics

Gl 229A is a member of the kinematic thick disk, with \( UVW \) velocities of \((12, -12, -12)\) km s\(^{-1}\), and a vertical height \( Z \approx 2 \) pc below the Solar position (Lindgren et al. 2018; Soubiran et al. 2013; Rodriguez 2016). The Sun itself is within \(~20–25\) pc of the disk midplane; its exact position depends on the adopted definition of the midplane and the tracers used (Bland-Hawthorn & Gerhard 2016; Kann & Mamajek 2017; Yao et al. 2017; Anderson et al. 2019). Relative to the local standard of rest, Gl 229’s \( UVW \) velocities are approximately \((23.0, -5)\) km s\(^{-1}\) (Schönrich et al. 2010).

The stellar disk increases in scale height and velocity dispersion as a function of age (e.g. Holmberg et al. 2007), likely due to interactions with molecular clouds and transient spiral structures (Binney & Tremaine 2008 and references therein). We use the power-law fits of Holmberg et al. (2007) to model the dynamical heating of the disk, taking the zero-age velocity dispersions to be 15, 10, and 5 km s\(^{-1}\) in \( U, V, \) and \( W \), respectively. We add the power-law components in quadrature such that we match the \( UVW \) dispersions of 50, 30, and 30 km s\(^{-1}\) at 10 Gyr. We take the velocity distribution near the disk midplane to be a multivariate Gaussian with these dispersions as individual measurements of the separation. The radial velocities for Gl 229 show a shallow linear trend of \( \pm 0.1 \) km s\(^{-1}\) yr\(^{-1}\). Tuomi et al. (2014) reported a planet-mass companion at a radial velocity semi-amplitude of \( 4 \) km s\(^{-1}\) and a period of \(~470\) days using \(~7\) years of HARPS and UVES spectra. As we discuss in Section 4 we see no evidence for this planet in our longer HIRES time series.

3. RADIAL VELOCITIES AND ASTROMETRY

3.1. Radial Velocity Monitoring

Gl 229 was observed using the HIRES échelle spectrograph (Vogt et al. 1994) at Keck Observatory as part of the Lick-Carnegie Exoplanet Survey (LCES, Butler et al. 2017). Butler et al. (2017) published 47 radial velocity measurements taken between December 1996 and December 2013 with a median uncertainty of \( 1.33 \) km s\(^{-1}\). These spectra were reduced and calibrated using the same method and pipeline as the California Planet Survey (Howard et al. 2010).

The radial velocities for Gl 229 show a shallow linear trend of \( 0.3 \pm 0.1 \) km s\(^{-1}\) yr\(^{-1}\). Tuomi et al. (2014) reported a planet-mass companion at a radial velocity semi-amplitude of \( 4 \) km s\(^{-1}\) and a period of \(~470\) days using \(~7\) years of HARPS and UVES spectra. As we discuss in Section 4 we see no evidence for this planet in our longer HIRES time series.

3.2. Relative Astrometry from HST WFC2

Gl 229B was observed between 1995 and 2000 using the planetary camera (PC) of the Wide Field and Planetary Camera 2 (WFC2) aboard the Hubble Space Telescope (HST). Golinowski et al. (1998) presented astrometry from the first three epochs (1995–1996). The 1999–2000 measurements (from Proposal 8290, PI Christopher Burrows) have never been published but are available in the HST archive. We have (re-)derived all of the astrometry, as described below, and used the latest distortion correction provided in archival headers.

HST data were taken in a combination of short, 1.6-second exposures (to avoid saturating Gl 229A) and long, 400- to 500-second exposures to achieve a good signal-to-noise ratio on Gl 229B. Nearly all of these exposures were taken with the F1042M filter centered at \( 1.02 \) \( \mu \)m; a few images taken with the F835W filter produce consistent results. The frames were dithered by \( \approx5 \) pixels in both the horizontal and vertical directions. Figure 2 shows a composite HST/WFPC2 image from 1999 produced using four dither offsets; Gl 229B is visible in the lower-left. We have replaced the saturated core of Gl 229A with data from a short, unsaturated image. We measure relative astrometry using the point-spread function (PSF) of Gl 229A as our template to fit Gl 229B.

We fit for the relative positions of Gl 229A and Gl 229B in pairs of exposures with one object unsaturated in each. We use all such pairs from a given sequence of observations as individual measurements of the separation. The best fit solution was determined by maximizing the cross-correlation between the interpolated PSF of Gl 229A and the PSF of Gl 229B as sampled by the PC pixels. We do not subtract the faint outer PSF halo of Gl 229A when fitting for the location of Gl 229B. We also checked reversing the object whose PSF we interpolated; the results do not change, implying that the slightly undersampled PSF is not a limiting factor in our analysis (at \( \lambda = 1.02 \) \( \mu \)m a PC pixel is \( 1.93\lambda/D \)). Subtracting the saturated PSF of Gl 229A rotated by \( 180^\circ \) changes our derived astrometry by no more than 0.4 mas in separa-
must also address a possible underestimation of the uncertainty due to the poor subpixel sampling of the PSFs (and hence, of the pixel response function). We do this using a sample of 32 low-mass stars observed in the same filter and instrument configuration as Gl 229. These 32 stars had -to-noise ratios ranging from values slightly lower than that of Gl 229B to values approaching that of Gl229A. Our sample produces 32 $\times$ 31 pairs of images to which we can fit 31 relative offsets using the same method we apply to Gl 229AB. The root-mean-square scatter of the individual offsets against these fitted offsets is 1 mas in both horizontal and vertical directions. As one last consistency check, we computed the root-mean-square scatter in the positional difference $\Delta x_{ab} + \Delta x_{bc} - \Delta x_{ac}$; the result is consistent with $\sqrt{3}$ times the 1 mas root-mean-square scatters we found when comparing single offsets with average offsets. We adopt 1.4 mas in separation uncertainty to account for the uncertain distortion correction and the effects of pixel sampling, combining 1 mas for each in quadrature.

We obtain our uncertainties in the position angle in a similar way as for separation. We first divide the extra 1.4 mas in separation uncertainty by the measured separation to produce an uncertainty in position angle. We then need to correct the orientation of the field. For this purpose, we use the drizzled images from the HST archive, which incorporate all known offsets between the chips, geometric distortions, and artifacts. We then identify between five and seven stars in each field that are present in Gaia DR2 (Lindegren et al. 2018). Propagating the Gaia positions back to the HST epochs provides an astrometric reference field with typical positional uncertainties of $\sim$1 mas across the 2.5 WFPC2 field. We do not apply a correction for parallactic motion. All but one of the reference stars have parallaxes $\lesssim$1 mas, while the last one has a parallax of 4 mas. We fit two-dimensional Gaussians to the stellar positions on the drizzled images and compute the best-fit rotation and translation between the coordinates of the stars in Gaia DR2 and those measured on WFPC2. After applying this rotation and translation, the remaining positional residuals between WFPC2 and Gaia are a few mas, which projects to an angle of $\sim$0.002 arcsec. We include an additional uncertainty of 0.01" to account for any variations in chip positions or orientations (though these are expected to be very small, Gonzaga et al. 2010) and for possible systematic offsets resulting from spatial variations in the point-spread function.

Four of the HST epochs—1996 May, 1999 May, 2000 May, and 2000 November—used the same pair of guide stars. The other two observations each used different pairs of guide stars, and might be misaligned with one another and/or with the other four epochs even after the drizzling correction. Our position angle uncertainties could be underestimated for these two epochs, 1995 November and 1996 November. The observations from 1995 November have an especially large angular offset of 0.17 implied by the field stars in the drizzled images (the angular offsets are $\lesssim$0.03 for the other epochs). The systematic differences between our relative astrometry and that of Golinowski et al. (1998) are $\sim$15 mas in separation and $\sim$0.3 in position angle. The separation differences are $\sim$1.5σ-significant, but the po-

![Image](image-url)

Fig. 2.—Image of Gl 229AB as seen in 1999 by WFPC2 on HST through the $\sim$1 $\mu$m filter F1042M. The observations consisted of short exposures (with Gl 229A unsaturated) and long exposures (with a good signal-to-noise ratio on Gl 229B). The figure shows a composite of four dithered long exposures. The inner, saturated region has been replaced by data from a short exposure.
Table 1

| Date       | ρ     | σρ   | PA   | σPA  | Instrument       |
|------------|-------|------|------|------|-----------------|
| 1995-11-17 | 7777.0| 1.7  | 163.224 | 0.015 | HST WFPC2      |
| 1996-05-25 | 7732.0| 2.0  | 163.456 | 0.019 | HST WFPC2      |
| 1996-11-09 | 7687.7| 1.5  | 163.595 | 0.015 | HST WFPC2      |
| 1999-05-26 | 7458.3| 1.6  | 164.796 | 0.015 | HST WFPC2      |
| 2000-05-26 | 7362.8| 1.6  | 165.244 | 0.016 | HST WFPC2      |
| 2000-11-16 | 7316.9| 1.6  | 165.469 | 0.016 | HST WFPC2      |
| 2011-03-26 | 6210  | 10   | 171.2 | 0.1   | HiCIAO          |

† Data from 1995 November and 1996 November used different guide stars from one another and from the other four HST epochs.

3.3. Relative Astrometry from HiCIAO

After intensive monitoring by HST between 1995 and 2000, Gl 229 has little published astrometry. Geißler et al. (2008) did obtain 8.6-μm images in 2006 using VLT/NACO, but the astrometric precision of these measurements is poor (σρ = 50 mas, σPA = 0.9′). Gl 229 was also briefly observed as part of the SEEDS survey (Brandt et al. 2013). Visually, the center of the saturated star is consistent with its position in unsaturated images. We therefore adopt 1 pixel (or 10 mas) as our uncertainty in the separation of the star and its companion. A 10 mas uncertainty projects to our adopted uncertainty of 0.1 in position angle. The precision of the distortion corrected value of true north is ~0′.005; its value was stable to ~0′.03 during the SEEDS survey (Brandt et al. 2013).

The last line of Table 1 lists our HiCIAO measurements from March of 2011. Despite its lower precision, the long time baseline between the HiCIAO observation and the HST images makes it a valuable constraint on the companion’s orbit. We omit the 2006 VLT/NACO astrometry from our analysis, as its precision is a factor of 5–10 worse than that of HiCIAO and it offers no additional time baseline.

3.4. Absolute Astrometry from the HGCA

We take our absolute stellar astrometry from the HGCA. This catalog gives nearly instantaneous proper motions at the Hipparcos and Gaia DR2 epochs, along with the difference in positions between the two catalogs divided by the time baseline. Each measurement also has a central epoch similar to, but slightly distinct from, the catalog epochs of 1991.25 and 2015.5.

Table 2 lists the catalog astrometry for Gl 229A. The HGCA performs a full cross-calibration of Hipparcos and Gaia DR2 (Gaia Collaboration et al. 2016, 2018; Lindegren et al. 2018) including locally variable frame rotation, an optimized linear combination of the two Hipparcos reductions (ESA 1997; van Leeuwen 2007), and error inflation. We refer the reader to Brandt (2018) for a detailed discussion of the catalog.

Gl 229A appears to be an excellent fit in both Hipparcos and Gaia DR2. It has no rejected data in either Hipparcos reduction, and has slightly negative goodness-of-fit metrics (i.e. better than expected on average for Gaussian errors) in both the ESA (1997) and van Leeuwen (2007) catalogs. Gl 229A likewise has no rejected astrometric data in Gaia DR2 and has a renormalized unit weight error of 0.98. Gl 229B is not present in Gaia DR2: its I-band brightness of ~19.5 (Golimowski et al. 1998) and proximity to the bright star Gl 229A may have placed it just beyond Gaia’s reach. The T dwarf companion might be present in future Gaia data releases; its position relative to Gl 229A (and potentially even its relative proper motion) would further constrain the system’s orbit.
TABLE 2

**Absolute Stellar Astrometry**

| Mission               | \(\mu_G\) (mas yr\(^{-1}\)) | \(\sigma[\mu_G]\) (mas yr\(^{-1}\)) | \(\mu_B\) (mas yr\(^{-1}\)) | \(\sigma[\mu_B]\) (mas yr\(^{-1}\)) | Corr[\(\mu_G\),\(\mu_B\)] | \(t_{\alpha*}\) (year) | \(t_\delta\) (year) |
|-----------------------|-----------------------------|-------------------------------------|-----------------------------|-------------------------------------|---------------------------|---------------------|---------------------|
| Hipparcos             | -127.34                     | 0.58                                | -713.35                     | 0.83                                | -0.33                      | 1911.05            | 1911.29            |
| Hipparcos–Gaia DR2    | -136.514                    | 0.020                               | -714.967                    | 0.031                               | -0.18                      | ...                | ...                |
| Gaia DR2              | -135.99                     | 0.19                                | -719.09                     | 0.27                                | -0.25                      | 2015.04            | 2015.26            |

4. ORBITAL FIT

4.1. Single-Epoch Approximation

As a first step, we use the method described in Section 5 of [Brandt et al. (2019)] to compute Gl 229B’s dynamical mass. This method fits the relative astrometry and radial velocity using quadratics in space and time, respectively. It then computes the instantaneous projected separation and radial velocity acceleration at a characteristic epoch for the absolute astrometry of the HGCA. We then calculate the companion mass using

\[
M = \frac{\rho^2 (a_{\alpha B}^2 + a_{RV}^2)^{3/2}}{\pi^2 G a_{\alpha B}^2},
\]

where \(\rho\) is the projected separation, \(\alpha_{\text{B}}\) and \(a_{\text{RV}}\) are the astrometric and radial velocity accelerations, respectively, and \(G\) is the gravitational constant.

[Tuomi et al. (2014)] reported a periodic radial velocity signal with a semi-amplitude of \(\sim 4 \text{ m s}^{-1}\), a period of \(\sim 470\) days, and near-zero eccentricity. However, fitting a linear trend plus a zero-centricity planet to our HIRES radial velocities does not improve the fit significantly over a linear trend alone. Fitting for a zero-centricity planet of \(4 \text{ m s}^{-1}\) semi-amplitude greatly degrades the quality of the fit, increasing the required “jitter” from about \(3 \text{ m s}^{-1}\) to nearly \(4 \text{ m s}^{-1}\) even after optimizing over the planet’s phase. [Butler et al. (2017)] did not see any periodic signal in their own analysis of the HIRES data.

Without independent confirmation of the planet reported by [Tuomi et al. (2014)], and with a significant degradation of our residuals at the best-fit orbital parameters reported by [Tuomi et al. (2014)], we exclude this companion from our analysis. The 17-year baseline of our data and its uneven sampling limit the effect to excluding a real planet with these properties to \(\lesssim 0.5 \text{ m s}^{-1} \text{ yr}^{-1}\).

Table 3 shows the results of the single-epoch approximation to the mass of Gl 229B. We obtain a value of \(72 \pm 5 \text{ M}_{\text{Jup}}\) that is much higher than previously estimated mass ranges, but marginally consistent with the maximum mass derived from theoretical considerations assuming an age of \(\sim 10\) Gyr (e.g., [Allard et al. 1996], [Marley et al. 1996]). The Gl 229AB system traced out a small fraction of an orbital arc in 15 years of astrometric monitoring; the assumptions required to compute a single-epoch mass are well-satisfied. We perform a self-consistent orbital analysis to verify the single-epoch result, obtain full posterior probability distributions on orbital parameters, and to check for goodness-of-fit.

4.2. A Full Orbital Fit

We fit the orbit of Gl 229AB using the method described in [Brandt et al. (2019)], with a few significant modifications. As previously, we perform a parallel-tempering Markov Chain Monte Carlo (MCMC) analysis using [emcee] [Earl & Deem 2005], [Foreman-Mackey et al. 2013]; our likelihood is calculated by comparing the measured separations, position angles, absolute astrometry, and radial velocities to those of a synthetic orbit and assuming Gaussian errors. This method includes several nuisance parameters, including the precise proper motion and radial velocity of the system barycenter and the radial velocity jitter. To reduce the number of parameters fit by emcee, we explicitly marginalize out the proper motion of the barycenter, the systemic radial velocity, and the parallax (adopting the Gaia DR2 value of 173.6955 \pm 0.0457 mas as our prior).

Our most important modification to the method of [Brandt et al. (2019)] is our use of epoch astrometry from both Hipparcos and Gaia, as described in Brandt et al. (in preparation). The epochs and scan angles of both Hipparcos and Gaia are publicly available. For the original Hipparcos reduction [ESA 1997], they are contained in the intermediate astrometric data hosted by the European Space Agency. The intermediate data of the [van Leeuwen 2007] re-reduction were distributed on compact disc and are more difficult to obtain, but are available on request. Predicted Gaia observations may be obtained from the Observation Forecast Tool.

The scan angles and uncertainties provided with the intermediate Hipparcos astrometric data are sufficient to construct the covariance matrices used to fit for proper motion. For Gaia, we assume that the along-scan uncertainties are the same for all observations. We can then sample our synthetic orbits at the observed epochs and fit linear motion exactly as the processing teams did, using either the real covariance matrices or a close approximation. We then compare the resulting positions and proper motions with the values given in [Brandt 2018]. This approach allows us to accurately reproduce the Hipparcos and Gaia measurements, even though Gaia epoch astrometry is currently unavailable and will not be published for several years.

Figures 3, 4, 5, and 6 show our orbital fits. Figures 3 and 4 use black lines to show the orbit with the maximum posterior probability density. The colored lines show 100 orbits randomly drawn from the MCMC posterior probability distributions, color-coded by Gl 229B’s

https://www.cosmos.esa.int/web/hipparcos/

intermediate-data

https://gaia.esac.esa.int/gost/
mass. Figures 5 and 6 show the posterior probability distributions and covariances of the fitted parameters; Table 4 lists the median, 1σ, and 2σ posterior intervals on all parameters.

Our best-fit orbit has a χ² of 3.0 for seven separation measurements, and χ² = 11.8 for seven position angles. The χ² for position angles is dominated by the 1995 November and 1996 November epochs, which used different sets of guide stars than the other HST astrometric measurements. Doubling the error bars on these two position measurements to 0′03 reduces the χ² on position angle to 4.9, and has a negligible effect on the posterior distributions of any of the fitted parameters.

Our maximum posterior probability orbit has a χ² of 7.4 for six absolute astrometry measurements. We marginalize out two parameters for the proper motion of the system barycenter, reducing the number of degrees of freedom to four. Our use of the proper motion to constrain the orbit further reduces the number of degrees of freedom, making a value of 7.4 somewhat higher than we would expect. The probability of obtaining χ² ≥ 7.4 is 12% assuming four degrees of freedom, and 6% assuming three degrees of freedom. Future Gaia data releases will enable additional consistency checks on the absolute astrometry. However, as discussed in Section 3.4 the astrometry of Gl 229A passes every internal consistency check in both Hipparcos and Gaia.

5. EVOLUTIONARY MODEL ANALYSIS

We derive mass-calibrated fundamental parameters for Gl 229B by performing rejection sampling analysis with evolutionary models in the same fashion as in Dupuy & Liu (2017) and Dupuy et al. (2019). Briefly, we start with randomly drawn masses and luminosities from the measured distributions and combine these with ages randomly drawn from a uniform prior. We use masses drawn from our MCMC posterior and normally distributed values of log(Lbol/L⊙) = −5.208±0.007 dex from Filippazzo et al. (2015). Each random draw corresponds to a measured luminosity as well as a model-derived luminosity (from mass and age), and the rejection probability is computed from the difference between these two luminosities. Over three iterations we adjust the range over which ages are drawn as needed to ensure a well-sampled posterior on model-derived properties.

Table 5 gives the results of our evolutionary model analysis, which we performed for three different sets of models: the “hybrid” version of the Saumon & Marley (2008) models, that transitions from cloudy to cloud-free atmospheres as objects cool from 1400 K to 1200 K; the “Cond” models of Baraffe et al. (2003), that are intended to match the condensate-free atmospheres of T dwarfs like Gl 229B; and the “heritage” Tucson models (Burrows et al. 1997) that use the cloudless atmospheres of Marley et al. (1996). Every Monte Carlo trial preserved in our rejection sampling analysis corresponds to a part of parameter space actually covered by models, so the posterior mass of 63.1±1.6 M Jup from hybrid models is significantly lower, with smaller errors, than our input measurement. The modest tension between the posterior mass and the dynamical mass is partially responsible for the small error bar: two incompatible distributions can combine to give a deceptively narrow joint distribution. The Cond and hybrid models give somewhat different radii (the Cond radius is 4% smaller), which propagates to gravity and temperature (Cond is higher for both). Even the smaller values of T eff = 850 K and log(g) = 5.0 dex from the hybrid models are quite high compared to the typical best-fit model atmospheres in the literature, such as T eff = 850 K and log(g) = 5.0 dex from Nakajima et al. (2015). However, these values are consistent with the highest-gravity fits of Saumon et al. (2000). As noted by Saumon & Marley (2008), the Tucson models give a lower luminosity than hybrid models at a given mass and age because they lack many of the opacity sources included in more recent work and Lbol ∝ κR eff 0.35 (where κR is the Rosseland mean opacity; Burrows & Liebert 1993). As a result, the Tucson models provide a younger age estimate (6.8±1.5 Gyr) and mass posterior closely matching the input measured value for Gl 229B.

6. DISCUSSION

Gl 229B provided the first spectrum of a methane-bearing compact source outside our solar system (Nakajima et al. 1995; Oppenheimer et al. 1995) and helped define the “T” spectral class (Burgasser et al. 1999, 2002). Atmospheric models were developed or refined shortly after Gl 229B’s discovery in order to fit its spectrum and estimate its surface gravity, effective temperature, age, and mass (Tsuji et al. 1996; Allard et al. 1996; Marley et al. 1996). These models suggested a mass of ∼20–55 M Jup, significantly lower than our dynamical measurement of 70±5 M Jup. Models of T dwarfs have been tested and refined since then, and molecular line lists have improved (e.g., Saumon et al. 2012; Yurchenko & Tennyson 2014). Although Gl 229B itself lacks an analysis with modern models, the mass range generally implied by spectroscopically-derived gravities for late-T dwarfs has remained broadly similar, consistent with ages of 1–5 Gyr (e.g., Line et al. 2017).
Fig. 4.— Astrometry and RVs as a function of time for the Gl 229 system. The line colors and thicknesses have the same meaning as Figure [3]. Green lines correspond to lower companion masses, and pink lines are higher masses. Left: astrometry of Gl 229B relative to its host star from direct imaging. Middle: astrometric acceleration induced by Gl 229B on its host star, where $\Delta \mu$ is the difference between the Hipparcos and Gaia proper motions compared to the scaled positional difference between the two catalogs (i.e., the 25-year proper motion). Right: RVs of the host star measured from Keck (top) and the full RV orbit over three centuries.

| Property                               | Median ±1σ | 95.4% c.i. | Prior          |
|----------------------------------------|-------------|------------|----------------|
| Fitted parameters                      |             |            |                |
| Companion mass $M_{\text{comp}}$ ($M_{\text{Jup}}$) | $70.4 \pm 4.8$ | 61, 80     | $1/M$ (log-flat) |
| Host-star mass $M_{\text{host}}$ ($M_{\odot}$) | $0.54_{-0.03}^{+0.04}$ | 0.48, 0.61 | $1/M$ (log-flat) |
| Semimajor axis $a$ (AU)                | $34.7_{-1.9}^{+1.3}$ | 31.7, 40.1 | $1/a$ (log-flat) |
| Inclination $i$ (°)                    | $13_{-12}^{+10}$ | 1, 41      | sin($i$), $0° < i < 180°$ |
| $\sqrt{\sin \omega}$                 | $-0.21_{-0.29}^{+0.75}$ | $-0.54, 0.93$ | uniform |
| $\sqrt{\cos \omega}$                 | $0.80_{-0.22}^{+0.13}$ | $-0.75, 0.93$ | uniform |
| Mean longitude at $t_{\text{ref}} = 2455197.5$ JD, $\lambda_{\text{ref}}$ (°) | $-60_{-26}^{+49}$ | $-80, 103$ | uniform |
| PA of the ascending node $\Omega$ (°)  | $335_{-48}^{+13}$ | 171, 347   | uniform |
| RV jitter $\sigma_{\mu}$ (m s$^{-1}$)  | $3.2 \pm 0.4$ | 2.4, 4.1   | $1/\sigma_{\mu}$ (log-flat) |

Computed properties

| Property                               | Median ±1σ | 95.4% c.i. | Prior          |
|----------------------------------------|-------------|------------|----------------|
| Orbital period $P$ (yr)                | $263_{-29}^{+21}$ | 217, 336   | ...            |
| Semimajor axis (mas)                   | $6030_{-330}^{+220}$ | 5510, 6970 | ...            |
| Eccentricity $e$                       | $0.846_{-0.015}^{+0.014}$ | 0.764, 0.864 | ...            |
| Argument of periastron $\omega$ (°)   | $-10_{-40}^{+50}$ | $-40, 150$ | ...            |
| Time of periastron $T_0 = t_{\text{ref}} - P \frac{\lambda_{\text{ref}} - \omega}{360°}$ (JD) | $2467400_{-500}^{+400}$ | $2466500, 2468900$ | ...            |
| Mass ratio $q = M_{\text{comp}}/M_{\text{host}}$ | $0.123_{-0.013}^{+0.012}$ | 0.101, 0.150 | ...            |

Note. — The $\chi^2$ of relative astrometry is 3.0 for separations and 11.8 for PAs, with 7 measurements for each. The $\chi^2$ of the Hipparcos and Gaia proper motion differences is 7.4 for four measurements (after marginalizing out the barycenter’s proper motion).
Fig. 5.— Joint posterior distributions for selected orbital parameters. Dark dashed contours indicate 1σ ranges and lighter dotted contours indicate 2σ ranges. The top right panel shows the posterior distribution of the companion’s mass.
Fig. 6.— Marginalized posterior distributions for fitted orbital parameters (dark gray histograms) and select parameters computed from these (light gray histograms).

### TABLE 5

**Evolutionary Model-Derived Parameters**

| Property                  | Cond (B03)     | Hybrid (SM08) | Tucson (B97) | Prior            |
|---------------------------|----------------|---------------|--------------|------------------|
| Mass ($M_{Jup}$)          | $64.5^{+1.7}_{-1.1}$ | $63.1^{+1.7}_{-0.9}$ | $70.1^{+4.6}_{-2.1}$ | $70 \pm 5$       |
| log($L_{bol}$) [$L_{\odot}$] | $-5.208 \pm 0.007$ | $-5.208 \pm 0.007$ | $-5.208 \pm 0.007$ | $-5.208 \pm 0.007$ |
| Age (Gyr)                 | $8.2^{+1.8}_{-0.9}$ | $8.6^{+1.4}_{-0.6}$ | $6.8^{+1.2}_{-1.7}$ | $U(\leq 10)$     |
| $T_{\text{eff}}$ (K)      | $1039^{+5}_{-5}$  | $1011^{+5}_{-5}$  | $1023^{+0}_{-7}$  | $\cdots$         |
| log($g$) [cm s$^{-2}$]    | $5.451^{+0.016}_{-0.014}$ | $5.400^{+0.018}_{-0.010}$ | $5.467^{+0.044}_{-0.019}$ | $\cdots$         |
| Radius ($R_{Jup}$)        | $0.754^{+0.003}_{-0.009}$ | $0.788^{+0.003}_{-0.006}$ | $0.770^{+0.006}_{-0.013}$ | $\cdots$         |

**References.** — B03—Baraffe et al. (2003); B97—Burrows et al. (1997); SM08—Saumon & Marley (2008).
As shown in Figure 10, Gl 229B has the highest measured mass of any known brown dwarf with a luminosity $< 3 \times 10^{-5} L_\odot$, though within the errors it is consistent with two other massive T dwarfs ε Ind B (68.0±0.9 $M_{\text{Jup}}$) and WISE J0720−0846 B (66 ± 4 $M_{\text{Jup}}$). Figure 9 compares the dynamical mass that we measure to the predictions of the Saumon & Marley (2008), Baraffe et al. (2003), and Burrows et al. (1997) model grids. The left panel assumes a uniform distribution of ages from 1−5 Gyr; the right panel assumes 5−10 Gyr. At the very oldest ages, the mass is in good agreement with the Burrows et al. (1997) models and in marginal agreement with the others. If the system is younger as suggested by its kinematics and activity indicators, then its dynamical mass of 70 ± 5 $M_{\text{Jup}}$ is surprisingly high for a late-type T dwarf.

In the following, we examine our unexpectedly high dynamical mass measurement in the context of substellar evolutionary models and the empirical information available on the age of the system. But first, we consider both observational and astrophysical systematic uncertainties that could have impacted our measurement.

6.1. Potential Systematics

6.1.1. Incorrect or Corrupted Host-Star Astrometry

It is possible that the astrometry for Gl 229A in the Hipparcos and/or Gaia DR2 catalogs is incorrect. A slightly high astrometric $\chi^2$ gives some support to this hypothesis (Table 3). However, the star passes every goodness-of-fit test in both catalogs, and our orbital fit accounts for the individual scanning epochs and scan angular.

Dieterich et al. (2018) reported a mass of 75.0 ± 0.8 $M_{\text{Jup}}$ for ε Ind B, which would make it the most massive known T dwarf. We adopt the mass of 68.0 ± 0.9 $M_{\text{Jup}}$ from Cardoso (2012) here because, as discussed in Dupuy et al. (2019), it agrees better with the total system mass from the relative orbit measured with VLT/NACO.

6.1.2. Unresolved Multiplicity of Gl 229B

One solution to an anomalously high mass is to make Gl 229B itself a binary, e.g., a 45-$M_{\text{Jup}}$ object that contributes the vast majority of the observed flux and a much fainter 25-$M_{\text{Jup}}$ object. Evidence of this might ap-
pear in high-contrast imaging or in relative astrometry. Figure 8 shows the HiCIAO images from 2011: the upper panels show the PSF of Gl 229A, while the lower panels show Gl 229B. None of these near-infrared images show any evidence for binarity. The full width at half maximum of the PSF in these cases is $\sim 60$ mas, or $\sim 0.3$ au at the distance of Gl 229A.

At smaller orbital separations, the precise HST astrometry strongly constrains the presence of additional companions. The typical separation uncertainties of 1.5 mas project to 0.009 AU at the system's distance from Earth, and a typical photocenter orbit for Gl 229B due to a faint companion would be a factor $\sim 0.3$ of the semimajor axis. The small $\chi^2$ of 3.0 for our seven relative separation measurements thus provides strong evidence against a massive companion to Gl 229B beyond $a > 0.03$ AU ($P > 7$ days), up to orbital periods comparable to the time baseline of the measurements (about 5 years). Even smaller orbital separations, inside 0.01 AU or 20 $R_{\text{Jup}}$, would have placed Gl 229B in contact with its putative companion when young (Allard et al. 2001). Future measurements with VLTI/Gravity, as were obtained for HR 8799e (Gravity Collaboration et al. 2019), could offer even better astrometric constraints on a hypothetical companion.

A companion of nearly equal flux and very small separation would evade these astrometric constraints. However, Gl 229B's absolute magnitude is normal relative to other objects of comparable spectral type and color. For example, the mean T7 dwarf has $M_J = 15.54 \pm 0.25$ mag (error is the root-mean-square of four objects Dupuy & Liu 2012), compared to $M_J = 15.21 \pm 0.05$ mag for Gl 229B. It is also unremarkable on color–magnitude diagrams, with a very typical absolute magnitude of $M_V = 13.44 \pm 0.05$ mag at its color of $K - J' = 2.12 \pm 0.07$ mag (Dupuy & Liu 2012).

6.1.3. Age of Gl 229A

Gl 229A is an early-M star and does not possess any well-calibrated age indicators. Its chromospheric and coronal activity seem to favor an intermediate age of 2–6 Gyr, but this relies on modest extrapolations of relations derived for more massive stars. Its cold, thin-disk kinematics provide another weak constraint disfavoring very old ages. An age of 7–10 Gyr would bring our mass measurement into agreement with all cooling models (Figure 9). Our age analysis (Section 2) disfavors this possibility, but with caveats.

6.2. Peculiar Spectral Classification

Although Gl 229B began as the prototypical T dwarf, once a sufficient sample of spectra for other T dwarfs became available it was ultimately classified as peculiar (Burgasser et al. 2006). Most T dwarfs show a consistent sequence of increasing H$_2$O and CH$_4$ absorption across the near-infrared, but Gl 229B has unusually weak absorption at some wavelengths, primarily in the Y and K bands, given the strong CH$_4$ absorption seen at other wavelengths, especially the deep feature on the red side of the H band (Geballe et al. 1996; Oppenheimer et al. 1998). Early studies proposed that Gl 229B is of subsolar metallicity (e.g., Griffith et al. 1998; Griffith & Yelle 2000; Leggett et al. 2002), which is one possible explanation for the spectral peculiarity. There is, however, a well-known degeneracy between metallicity and gravity in T dwarfs due to collision-induced absorption by molecular hydrogen, the most abundant species in the atmosphere (e.g., see Saumon et al. 2012). As noted by Saumon et al. (2000), this degeneracy implies that Gl 229B would have a high surface gravity if it was also of solar metallicity.

As recently pointed out by Nakajima et al. (2015), previous detailed studies of Gl 229B were done before modern calibrations for empirical M dwarf abundances were established. While it was once plausible for Gl 229A to have a significantly sub-solar metallicity, that is no longer the case (Section 2.1). Our dynamical mass measurement suggests that the spectral peculiarity of Gl 229B, compared to other T dwarfs, is instead a reflection of its high surface gravity $\log(g) = 5.4$–5.5 dex (Section 5).

7. CONCLUSIONS

In this paper we have combined radial velocity, imaging, and absolute astrometry to measure a mass of $70 \pm 5 \, M_{\text{Jup}}$ for the T dwarf Gl 229B. We fit Keplerian orbits using an MCMC to derive posterior probability distributions for all of the orbital parameters. In addition to the high companion mass, we derive an eccentricity of $0.846^{+0.014}_{-0.015}$, a semimajor axis of $34.7^{+1.3}_{-1.9}$ AU, and an orbital period of $263^{+29}_{-25}$ years. Despite the fact that our observations cover only a small fraction of the orbit (<10%), the combination of absolute astrometry and radial velocities establish Gl 229A’s three-dimensional acceleration in an inertial reference frame and enable us to

![Figure 9](image-url)
determine a precise companion mass. The uncertainty in our mass measurement is chiefly limited by the proper motion errors of Gaia DR2; it will improve with upcoming Gaia data releases.

Early analyses of the Gl 229 system generally favored an intermediate age and T dwarf companion mass of $\sim 20 - 55 \, M_{\text{Jup}}$ (Nakajima et al. 1995; Oppenheimer et al. 1995; Leggett et al. 1999, 2002). Evolutionary models are marginally or fully compatible with the higher mass that we measure if the system is old (7–10 Gyr). We revisit Gl 229A's age using both kinematics and stellar activity. Both disfavor such old ages, but with caveats: kinematics provide only limited precision while the activity relations must be extrapolated from mid-K to early-M spectral types. If the brown dwarf cooling models are reliable, then the dynamical mass that we measure could instead be used to calibrate stellar activity relations for M dwarfs at very old ages.

Given the disagreement between our measurement and earlier mass estimates, we address factors that could inflate our measured mass of Gl 229B. Our radial velocity time series comes from the HIRES échelle spectrograph on Keck as released by Butler et al. (2017); it shows no evidence of the inner planet reported by Tuomi et al. (2014). Positing another massive companion would induce a trend that Gl 229B would have to cancel, further increasing its inferred mass. Relative astrometry also disfavors another massive companion in the system, as it would perturb the archival HST imaging that we re-analyzed to achieve uncertainties of 1.5 mas. High-contrast imaging using HI CI AO on the Subaru Telescope shows no evidence for a luminous companion beyond $\gtrsim 0.3$ AU. While the $\chi^2$ of the absolute astrometry is somewhat high, at 7.4 for roughly three degrees of freedom, Gl 229A is well-fit as a single star in both Hipparcos and Gaia. Future Gaia data releases will provide a definitive answer on the absolute astrometry. Overall, we conclude that our measured mass should accurately reflect the true mass of Gl 229B, and while this is somewhat higher than expected, it is consistent with Gl 229B being an old and commensurately massive T dwarf.

With our mass measurement, Gl 229B joins a short but growing list of ultracool dwarfs just below stellar/substellar boundary. Gl 229B is the lowest-luminosity brown dwarf known to have such a high mass, thereby providing a critical test of substellar evolution theory.

This research is based in part on data collected at the Subaru telescope, which is operated by the National Astronomical Observatories of Japan. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. T.D.B. and J.F. gratefully acknowledge support from the Heising-Simons foundation. T.D.B. acknowledges support from NASA under grant #80NSSC18K0439. T.J.D. acknowledges research support from Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., on behalf of the international Gemini partnership of Argentina, Brazil, Canada, Chile, the Republic of Korea, and the United States of America. B.P.B. acknowledges support from the National Science Foundation grant AST-1909209. D.M. gratefully acknowledges support from the European Space Agency (ESA) Research Fellow programme.

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