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# FIRST HIGH-CONTRAST SCIENCE WITH AN INTEGRAL FIELD SPECTROGRAPH: THE SUBSTELLAR COMPANION TO GQ LUPI

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## ABSTRACT

We present commissioning data from the OSIRIS integral field spectrograph (IFS) on the Keck II 10 m telescope that demonstrate the utility of adaptive optics IFS spectroscopy in studying faint close-in substellar companions in the halos of bright stars. Our $R \approx 2000$ *J*- and *H*-band spectra of the substellar companion to the 1–10 Myr old GQ Lup complement existing *K*-band spectra and photometry and improve on the original estimate of its spectral type. We find that GQ Lup B is somewhat hotter (M6–L0) than reported in the discovery paper by Neuhäuser and collaborators (M9–L4), mainly due to the surface gravity sensitivity of the *K*-band spectral classification indices used by the discoverers. Spectroscopic features characteristic of low surface gravity objects, such as lack of alkali absorption and a triangular *H*-band continuum, are indeed prominent in our spectrum of GQ Lup B. The peculiar shape of the *H*-band continuum and the difference between the two spectral type estimates is well explained in the context of the diminishing strength of $H_2$ collision-induced absorption with decreasing surface gravity, as recently proposed for young ultracool dwarfs by Kirkpatrick and collaborators. Using our updated spectroscopic classification of GQ Lup B and a reevaluation of the age and heliocentric distance of the primary, we perform a comparative analysis of the available substellar evolutionary models to estimate the mass of the companion. We find that the mass of GQ Lup B is 0.010–0.040 $M_\odot$. Hence, it is unlikely to be a wide-orbit counterpart to the known radial velocity extrasolar planets, whose masses are $\lesssim 0.015\ M_\odot$. Instead, GQ Lup A/B is probably a member of a growing family of very low mass ratio widely separated binaries discovered through high-contrast imaging.

*Subject headings:* binaries: general — instrumentation: adaptive optics — stars: individual (GQ Lupi) — stars: low-mass, brown dwarfs

## 1. INTRODUCTION

After more than a decade of precision radial velocity surveys, we know that extrasolar giant planets exist around at least 5%–15% of Sun-like stars (Marcy & Butler 2000; Fischer et al. 2003). Unfortunately, these planets lie at small angular separations ($<0.5''$) with high contrast ($>10^6$) from their host stars, and therefore, every known radial velocity extrasolar planet is beyond the current technical limitations for direct imaging. As a result, the physical properties of these radial velocity planets (except for several transiting planets) remain largely unknown. However, recent efforts in high-contrast imaging with adaptive optics (AO) have lead to the discovery of two distinct substellar companions, 2MASSW J1207334−393254 B (Chauvin et al. 2005a) and GQ Lup B (Neuhäuser et al. 2005), at wider ($>0.7''$) angular separations from their primary stars and with estimated masses comparable to those of known radial velocity planets ($\lesssim$15 Jupiter masses [$M_{\rm Jup}$]). Unlike the close-in ($\lesssim$6 AU) radial velocity planets, whose (minimum) masses are inferred directly from the orbital periodicity of the Doppler signal, the masses of these two wider (>40 AU) companions have not been established dynamically due to their much longer orbital periods. Instead, the estimated masses are based entirely on theoretical models of substellar evolution (Burrows et al. 1997, 2001; Chabrier et al. 2000; Baraffe et al. 2003; Wuchterl & Tscharnuter 2003). At present, such models have very few empirical constraints, and at the young ($\lesssim$10 Myr) ages of the two directly imaged planetary-mass companions, their predictions are very sensitive to the initial conditions. A larger sample of empirical data on such young low-mass objects is thus necessary to calibrate and fully understand the evolution of these objects at such young ages.

In the present paper we discuss the younger of the two resolved candidate planetary-mass companions, GQ Lup B. The secondary was discovered and confirmed as a proper-motion companion to GQ Lup A by Neuhäuser et al. (2005). Being one of the youngest low-mass substellar objects discovered to date, there is considerable uncertainty in estimating the mass of GQ Lup B. Neuhäuser et al. argue that the widely adopted substellar evolutionary models of Burrows et al. (1997) and Chabrier et al. (2000), which assume an initial postformation internal structure for substellar objects, are inadequate at the young age of GQ Lup because of the arbitrariness in their assumptions for the initial conditions. Instead, Neuhäuser et al. advocate a different set of models (Wuchterl & Tscharnuter 2003), which take into account the conditions and processes in the parent molecular cloud and may be more adequate at very young ($\sim$1 Myr) ages. Using the models of Wuchterl & Tscharnuter and assuming an age of $\sim$1.1 Myr, Neuhäuser et al. find that the mass of GQ Lup B may be as low as 1–2 $M_{\rm Jup}$ and hence that it is potentially the first extrasolar planet to be directly imaged around a star.

We present new near-IR spectroscopic data on GQ Lup B obtained with the recently commissioned OSIRIS (OH Suppressing Infra-Red Imaging Spectrograph) IFS (Larkin et al. 2006) on

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Keck (§§ 2 and 3), recalculate the age of GQ Lup, and address recent empirical calibrations of the substellar models (§ 4). We find that the mass of GQ Lup B is near, or more likely higher than, $13M_{\rm Jup}$ and thus should not be considered an extrasolar planet. Finally, we place GQ Lup B in the context of other young substellar objects and discuss the implications from its coevolution with the primordial circumstellar disk around GQ Lup (§ 5).

## 2. OBSERVATIONS

### 2.1. *Integral Field Spectroscopy*

GQ Lup was observed on 2005 June 26 (UT) as a commissioning target for the OSIRIS instrument at the W. M. Keck Observatory. OSIRIS is a medium-resolution ($R = 3700$) infrared (IR) integral field spectrograph (IFS) that was designed and constructed to operate behind the Keck Observatory's AO System (Wizinowich et al. 2000). An IFS is an instrument that takes contiguous spectra over a rectangular field of view (FOV). In the case of OSIRIS, a microlens array is placed in the focal plane of the instrument to separate the field points, where each lenslet becomes a spatial pixel element (spaxel) in the final data cube. Each lenslet focuses the incident light to a pupil plane located directly behind the lenslet array. These pupils are dispersed by a diffraction grating and subsequently focused onto a detector in such a way that each spectrum lies 2 pixels above its neighbor on the detector. The OSIRIS IFS employs a Rockwell Hawaii II HgCdTe detector ($2048 \times 2048$ pixels, 32 channel output) to achieve high quantum efficiency in the *z*, *J*, *H*, and *K* bands with low read noise (13 $e$ pixel$^{-1}$). The actual near-IR filters are spectroscopic filters and do not correspond exactly to any near-IR standard. These broad bands correspond to different orders of the diffraction grating, as defined by the blaze angle. Larkin et al. (2006) present a comprehensive review of the OSIRIS instrument design.

We made natural guide star (NGS) AO observations of GQ Lup in the *J* and *H* broad bands over a $0.32'' \times 1.28''$ FOV at $0.020''$ spaxel$^{-1}$. In each of the observations, the position angle of the long-axis FOV was set to 90° in order to align the rectangular FOV along the separation axis of the GQ Lup A and B components. The *J*-band images were obtained in a three-point raster scan pattern with a $0.15''$ dither to the east between each of the 600 s integrations, thus moving GQ Lup A from the center of the field to just off the FOV in the final frame. The science frames were followed by a sky of similar integration time. A single 600 s *H*-band image was obtained of the GQ Lup system, with a $3''$ dither to a sky position. Observing conditions were photometric, with the Keck AO system running on-axis using GQ Lup A ($R = 11$ mag) as the reference star. We measure the AO point-spread function (PSF) full width at half-maximum of GQ Lup A to be $0.06''$ and $0.05''$ at *J* and *H* band, respectively. Afterward, we observed the A0 V star HD 152384 in the *J* and *H* band, with a similar instrument configuration and at an air mass (1.78) comparable to the science frames, in order to calibrate the telluric and instrumental absorption profile.

The OSIRIS data reduction pipeline (DRP) was used to process and extract the raw, two-dimensional (2D) spectra and place them back into their spatial positions, producing a data cube of two spatial dimensions ($x$, $y$) and one wavelength dimension ($\lambda$; Krabbe et al. 2004). As explained in Krabbe et al. (2004), the DRP consists of a main processing routine that calls data reduction modules in a sequential order to fully reduce the data from the raw frames into a final data product. The 2D raw data were first processed by performing a pairwise sky subtraction, a removal of the spectral cross talk associated with extremely bright spectra on one row of the detector, an adjustment of the 32 individual channels on the detector to remove any systematic bias, a rejection of electronic glitches that occur during the readout of the detector, and a cleaning of pixels overexposed by cosmic rays. The above procedures eliminate instrumental artifacts prior to the spectral extraction. The truly unique step within the OSIRIS pipeline is the extraction of the spectra from the 2D raw frames. This process requires that the PSF of every lenslet position as a function of wavelength has been mapped using a white-light calibration lamp. These PSFs appear to be stable over many months, and the calibration is performed infrequently, either by the instrument team or Keck staff. The extraction routine uses the spectral PSFs to iteratively assign flux from a particular pixel into its corresponding lenslet spectrum. Once the spectra are assigned to the appropriate lenslet, each individual spectrum is resampled onto a regular wavelength grid using linear interpolation and a global wavelength solution determined from 19 spectral arc lines. Finally, the extracted spectra are inserted into their respective spatial locations in a data cube.

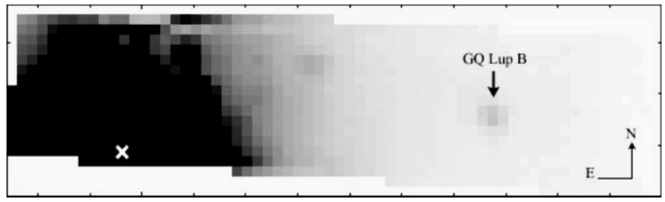


Fig. 1.—Median collapsed *H*-band data cube of the GQ Lup system obtained on 2005 June 26. The cross marks the position of GQ Lup A, and $0.1''$ tick marks border the image. GQ Lup B appears $7.5 \pm 0.5$ mag fainter $0.73'' \pm 0.01''$ away, with a position angle of $276.2° \pm 0.3°$.

A visual inspection of the *J*- and *H*-band data cubes confirmed the companion GQ Lup B in the position identified by Neuhäuser et al. (2005). The reduced *H*-band image of the GQ Lup system is displayed in Figure 1. The fully reduced data cube exhibits the effects of differential atmospheric dispersion, as demonstrated by the spatial motions of the stellar location as a function of wavelength. Therefore, the profile of the differential dispersion was calculated by measuring the centroid in each of the spectral channels and fitting these data with a second-order polynomial. The telluric spectra were obtained by measuring their centroids at the front of the data cube (shortest observing $\lambda$) and extracting from this center along the dispersion direction using a 2 spaxel ($0.040''$) radius circular aperture. We correct for the intrinsic features in the A0 V spectra by fitting Lorentzian profiles to each of the hydrogen Paschen and Brackett lines and subtracting these fits from the original telluric spectrum. The telluric and instrument absorption profiles were removed from the final data cube by dividing each spatial location by the normalized telluric spectrum and multiplying by a normalized blackbody curve of $T_{\rm eff} = 10{,}000$ K (corresponding to spectral type A0 V).

The spectra of GQ Lup A and B were extracted from the telluric-corrected data cubes using the same technique that was applied to the telluric standard. However, at a separation of just $0.7''$ the spectrum of GQ Lup B was significantly contaminated by the bright halo of its host star. We approximated the background at the companion location by extracting spectra of the halo of GQ Lup A at 1 spaxel ($0.020''$) intervals along a radial line connecting the host and companion. We then fit a third-order polynomial to each spectral bin as a function of radial separation and used the interpolated halo spectrum at the distance of the companion as an estimate of the halo contamination in the spectrum of GQ Lup B. The halo contamination was subsequently

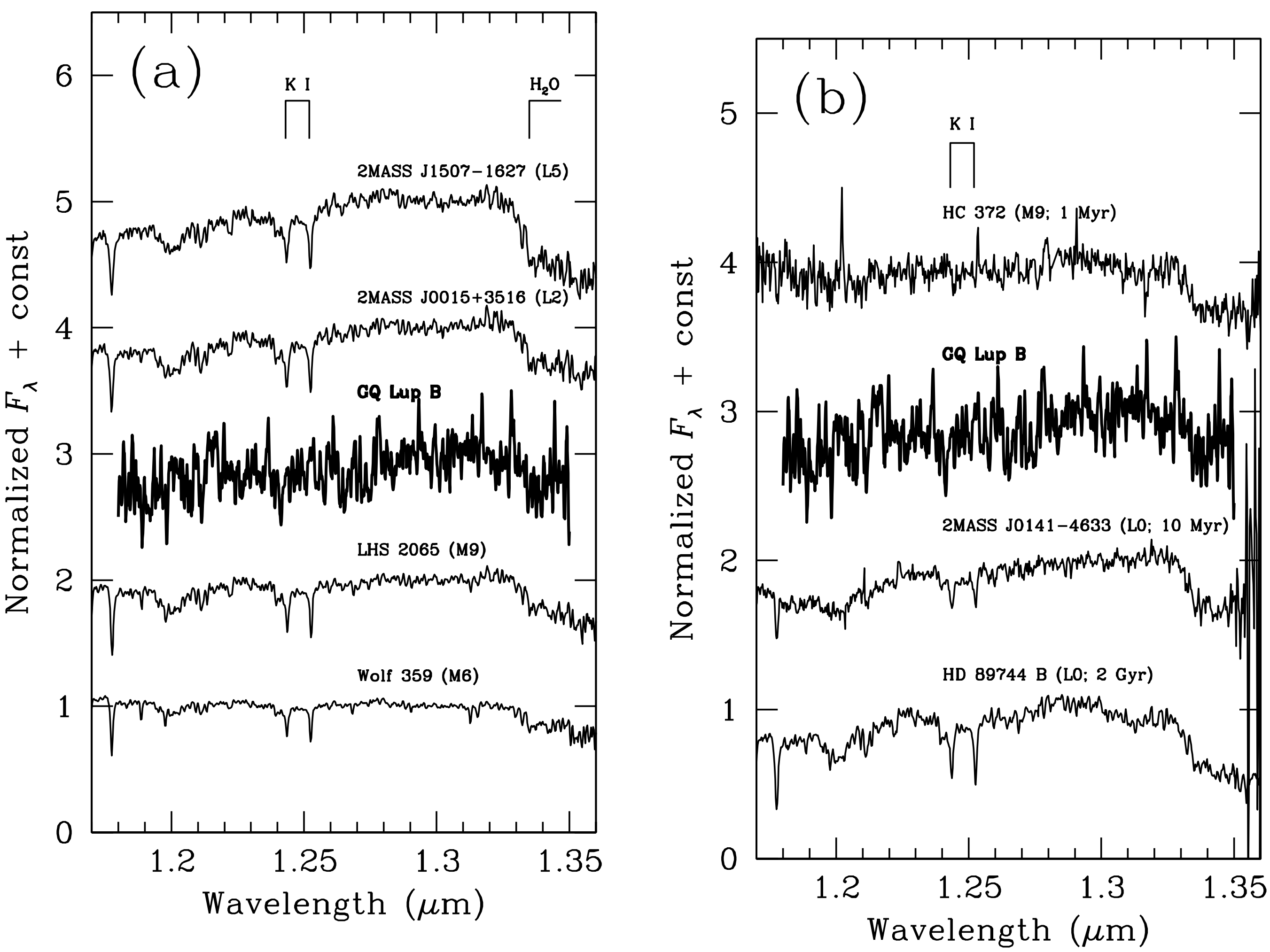


FIG. 2.—Comparison of our 1.20–1.35 $\mu$m spectrum of GQ Lup B to the spectra of dwarfs of a range of (*a*) spectral types and (*b*) ages. The comparison spectra in (*a*) are of field dwarfs from the NIRSPEC brown dwarf spectroscopic survey of McLean et al. (2003). The comparison spectra in (*b*) are from McLean et al. (2003; HD 89744B), Kirkpatrick et al. (2006; 2MASS J01415823−4633574), and Slesnick et al. (2004; HC 372). The strength of the $H_2O$ absorption longward of 1.33 $\mu$m indicates a spectral type of M6–L0 (§ 3.1). Unlike older field dwarfs, but similar to the 1 Myr old Orion Nebular cluster dwarf HC 372, GQ Lup B does not exhibit any K I absorption at 1.243 and 1.252 $\mu$m, an indication of low surface gravity and youth. All spectra are normalized to unity at 1.30 $\mu$m.

subtracted from the extracted spectrum of GQ Lup B. The reduced *J*- and *H*-band spectra of GQ Lup B are shown in Figures 2 and 3, respectively.

## 3. RESULTS

### 3.1. *The Spectrum of GQ Lup B*

#### 3.1.1. *J Band*

We compare our *J*-band spectrum of GQ Lup B to the spectra of field M6–L5 dwarfs from the NIRSPEC brown dwarf spectroscopic survey of McLean et al. (2003) in Figure 2*a*. Our $R \approx 3700$ spectrum from OSIRIS has been smoothed to the $R \sim 2000$ resolution of the comparison NIRSPEC spectra. The spectrum of GQ Lup B exhibits a depression due to water absorption longward of 1.33 $\mu$m consistent with the spectra of other M6–L5 dwarfs in the field. However, unlike the several Gyr old field dwarfs, GQ Lup B does not show K I absorption at 1.243 and 1.254 $\mu$m—an indication that GQ Lup B has low surface gravity. A comparison with $R \approx 2000$ *J*-band spectra of M9–L0 dwarfs of various ages exemplifies this point (Fig. 2*b*). With its lack of K I absorption at *J* band (3 $\sigma$ upper limit of 1.2 Å on the equivalent width at 1.244 and 1.253 $\mu$m), GQ Lup B closely resembles the $\sim$1 Myr old M9 dwarf HC 372 in the Orion Nebular cluster (Slesnick et al. 2004), but not the older L0 dwarfs 2MASS J01415823−4633574 [$\sim$10 Myr;[5] Kirkpatrick et al. 2006; EW(K I) $= 3.5 \pm 0.5$ Å at each of the two central wavelengths] and HD 89744B ($\sim$2 Gyr; Wilson et al. 2001). The low surface gravity of GQ Lup B indicates that it is a very young brown dwarf, as we later confirm from an age analysis of its pre–main-sequence primary (§ 4.3).

A visual comparison of the *J*-band continuum shapes of GQ Lup B and the M6–L5 dwarfs in Figure 2*a* indicates that the spectral type of GQ Lup B is intermediate between those of mid-M and early L dwarfs. We test this result by calculating the *J*-band $H_2O$ indices of McLean et al. (2003) and Slesnick et al. (2004), which measure the onset of water absorption at 1.34 $\mu$m. The strength of water absorption has been reported to be gravity-sensitive in the *H* band, as displayed in the peaked shapes of *H*-band continua of young ultracool dwarfs (Lucas et al. 2001;

[5] Kirkpatrick et al. (2006) report an age of 1–50 Myr for 2MASS J01415823−4633574, but they compare their derived values of $T_{\rm eff}$ and log $g$ to the theoretical models of Baraffe et al. (2001) and find their best-guess age estimate is 5–10 Myr.

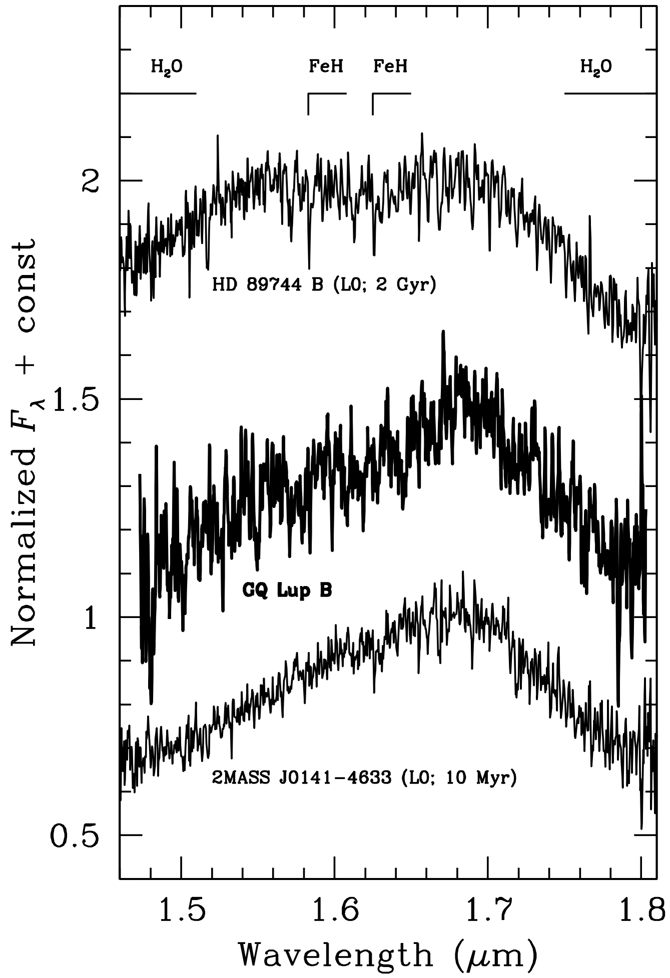


FIG. 3.—*H*-band spectrum of GQ Lup B compared to the spectra of L0 dwarfs of different ages. The peaked continuum shape of the spectrum of GQ Lup B strongly resembles that of the ∼10 Myr old 2MASS J01415823−4633574, indicating similarity in low surface gravity and spectral type. All spectra are normalized to unity at 1.68 $\mu$m.

Luhman et al. 2004). However, Slesnick et al. find that at 1.34 $\mu$m water absorption is unaffected by surface gravity in ultracool dwarfs and is thus an adequate indicator of effective temperature. We verify this claim by applying the *J*-band $H_2O$ index of Slesnick et al. to the low-gravity L dwarf 2MASS J01415823−4633574 (Kirkpatrick et al. 2006) and obtain a formal spectral type estimate of *M*9.5 ± 1.1 for that object, fully consistent with the ∼L0 classification of Kirkpatrick et al. (2006). Thus, using the *J*-band $H_2O$ indices of McLean et al. and Slesnick et al., we infer a spectral type of M6–L0 for GQ Lup B. The range in spectral type is determined by observing the variations in the inferred spectral type as a result of small shifts (up to 50 Å) in the centers of the spectral windows used in the index definitions. This method allows a better sampling of the noise in our spectrum.

### 3.1.2. *H Band*

The *H*-band spectrum of GQ Lup B is shown in Figure 3, where it is compared to the spectra of the ∼10 Myr old 2MASS J01415823−4633574 (Kirkpatrick et al. 2006), and the ∼2 Gyr old HD 89744B (Wilson et al. 2001). The sharply peaked, triangular continuum of the spectrum of GQ Lup B strongly resembles that of the young L0 object, while both differ from the plateau-shaped continuum of the older L0 dwarf. Similarly shaped *H*-band continua have been reported in 1–10 Myr old late M/early L dwarfs before and are now known to be indicators of low surface gravity and youth (Lucas et al. 2001; Luhman et al. 2004). The strong gravity dependence of the *H*-band continuum shape and the lack of other obvious spectroscopic features (although FeH absorption at 1.625 $\mu$m can be seen in the higher signal-to-noise ratio spectrum of 2MASS J01415823−4633574; Kirkpatrick et al. 2006) prevent us from using the *H*-band spectrum of GQ Lup B for accurate spectroscopic classification. We only note that the overall similarity between the spectra of GQ Lup B and 2MASS J01415823−4633574 indicates proximity in spectral type, in agreement with our *J*-band spectroscopic classification (§ 3.1.1).

### 3.2. *Astrometry and Photometry of GQ Lup A and B*

In addition to the spectral information obtained from the OSIRIS data cube, typical imaging measurements can be performed on the three-dimensional data cube. Relative astrometry of the binary was calculated through measurements of the component centers in collapsed narrowband (100 spectral channel bins) images for each of the two *J*-band frames that contained both GQ Lup A and B. We fit 2D Gaussian profiles to the clearly resolved cores of the PSFs of each component in order to attain their respective location in the frame. We measure the separation between the components to be $0.73'' \pm 0.01''$ with a position angle of $276.2° \pm 0.3°$. Our astrometric observations are fully consistent with the values reported in Neuhäuser et al. (2005), and we agree that GQ Lup A and B compose a common proper motion system.

The *J*-band magnitudes for the system components were obtained by comparing the relative spectral intensities of the 2 spaxel radius extracted spectra. It was necessary to derive a flux for GQ Lup A instead of using the published 2MASS value, because this source is variable at many wavelengths (§ 4.3). We calibrate our photometry with the 2MASS value for the telluric standard (HD 152384); however, since the telluric standard was intrinsically brighter than GQ Lup A, the AO performance on the telluric standard was better, and therefore the core of the PSF was narrower. Consequently, we could not directly compare the total flux of the 2 spaxel radius extracted spectrum of the telluric standard with that of GQ Lup A. We derive a radial profile curve of growth for both GQ Lup A and the telluric standard, and we approximate the total enclosed flux by assuming circular symmetry. The magnitudes were estimated from 30 spaxel radius apertures, which alleviates the effect of different PSF shapes. Our derived *J*-band magnitude for GQ Lup A is $J = 8.69 \pm 0.04$ mag, which is consistent with the quoted 2MASS value of $8.605 \pm 0.021$. We find that GQ Lup B has $J = 14.90 \pm 0.11$ ($\Delta J = 6.21 \pm 0.12$ mag). Following Stephens & Leggett (2004), we estimate that for an object of spectral type M6–L0, an error of ∼0.1 mag is necessary to translate to the standard near-IR standard filters in the *J* band, and this error has been added to our uncertainty. As mentioned above, the near-IR magnitudes are unique to the OSIRIS instrument, in which each filter corresponds to a different order of the diffraction grating. We refrain from reporting the *H*-band photometry for the system because the center of GQ Lup A straddles a spaxel at the edge of the field of view (see Fig. 1), which complicates the the relative photometry and results in a ∼1 mag uncertainty in our measurements.

## 4. DISCUSSION

In order to determine the luminosity and model-dependent mass of GQ Lup B, we need accurate estimates of its distance from the Sun and its intrinsic age. We assume throughout this discussion that GQ Lup B is gravitationally bound to GQ Lup A, which implies that it resides at the same heliocentric distance as the primary. We also assume that physical association in the binary implies coeval formation.

### 4.1. *Comparison with the Spectral Type Inferred by Neuhäuser et al.*

The final spectral type of GQ Lup B is consistent with, albeit somewhat earlier than, the M9–L4 determination from *K*-band spectroscopy in Neuhäuser et al. (2005) and Guenther et al. (2005). The estimates in these two papers are primarily based on the continuum slope around 2.0 $\mu$m, where spectra of ultracool dwarfs exhibit $H_2O$ absorption. The effect of surface gravity on this absorption band has not been empirically determined, and it is possible that enhanced water absorption in low surface gravity photospheres may be depressing the continuum near 2 $\mu$m, thus making objects appear cooler. Such an interpretation draws an analogy with the perceived role of water absorption in creating the peaked *H*-band continua of young ultracool dwarfs (Luhman et al. 2004). However, the lack of sensitivity to surface gravity of the 1.34 $\mu$m water absorption band (Slesnick et al. 2004) is perplexing in this context.

A more self-consistent picture of the spectral shapes of young ultracool dwarfs in the near-IR has been recently offered by Kirkpatrick et al. (2006). These authors argue that, rather than due to enhanced water absorption, the triangularly shaped continua at *H* band are caused by a reduction in $H_2$ collision-induced absorption (CIA) at low surface gravity (Borysow et al. 1997). Borysow et al. (1997) show that at the temperatures of late M and early L dwarfs ($\sim$2300–2500 K) CIA $H_2$ peaks in strength near 2.5 $\mu$m and weakens toward shorter wavelengths or with decreasing surface gravity. Kirkpatrick et al. (2006) find that the theoretical picture of Borysow et al. (1997) correctly predicts two main features of young late M/early L dwarfs, namely, redder $J - K_s$ colors and peaked *H*-band continua. Indeed, employing the $K_s$ magnitude from Neuhäuser et al. (2005) with the photometry presented herein, we find a $J - K_s$ color of $1.8 \pm 0.1$ mag, significantly redder than the $J - K_s = 1.0$–1.2 for typical field M6–L0 dwarfs (Leggett et al. 2002). Given the decreasing strength of CIA $H_2$ toward shorter wavelengths, this interpretation also explains the diminished sensitivity to surface gravity in the depth of the 1.34 $\mu$m water absorption band in ultracool dwarfs. The effect is strongest at *K* band, where the decreasing strength of CIA $H_2$ with decreasing surface gravity makes the continuum redder. In particular, *K*-band spectroscopic classification of young ultracool dwarfs based on the water band continuum slope near 2 $\mu$m will produce later spectral types than other classification schemes (e.g., spectral types based on the strength of the 1.34 $\mu$m water band). Hence, this scenario offers an explanation of the slightly later spectral type obtained for GQ Lup B by Neuhäuser et al. (2005) and Guenther et al. (2005).

A comparison of the absolute magnitude of GQ Lup B with other similiarly young brown dwarfs suggests that GQ Lup B is, in fact, of an earlier spectral type than $\sim$L0. At an $M_{K_s} = 7.2 \pm 0.3$ mag (adopting a distance of $150 \pm 20$ pc to GQ Lup; § 4.2), GQ Lup B is 1–2 mag brighter than the 1–10 Myr old $\sim$M9.5 dwarfs OTS 44 ($M_{K_s} = 8.48$ mag) and Cha 110913-773444 ($M_{K_s} = 9.6$ mag) in Chamaeleon (Luhman et al. 2004, 2005), and the 1–5 Myr old M9/L0 binary Oph 162225$-$240515 A/B ($M_{K_s} = 8.19/8.75$ mag; Jayawardhana & Ivanov 2006) in Ophiuchus. In addition, GQ Lup B is also of approximately the same bolometric luminosity ($\log L/L_\odot = -2.2$; § 4.4) and age as the 3–5 Myr old M7–M7.5 dwarfs USco 128 and USco 130 ($\log L/L_\odot = -2.4$; Mohanty et al. 2004) in Upper Scorpius. Therefore, our mean spectral type estimate of M8 for GQ Lup B is in agreement with expectations when compared to the spectral types of similar objects from the literature.

A different explanation for the discrepancy between the spectral types of GQ Lup B inferred in the present work and in Neuhäuser et al. (2005) may be suggested as a result of previously noted difficulties in reproducing the correct continuum slopes of objects observed with AO long-slit spectroscopy (Goto et al. 2003). The width of spectroscopic slits used with AO is often 1–2 times the FWHM of the PSF ($\sim$60 mas at 2.2 $\mu$m on 8–10 m class telescopes) and of order of the accuracy ($\approx$20 mas) with which an object can be positioned and maintained on the slit during dithers. Because the PSF possesses a strong radial chromatic gradient, any misalignment of the target on the slit can lead to an artificial change in the measured continuum. Furthermore, in high-contrast observations of binary systems (i.e., when one object is much fainter than the other), it is desirable to have the slit oriented along the binary axis to allow accurate determination of the contamination of the secondary spectrum by the halo of the primary. As a result, spectroscopy of binaries rarely benefits from having the slit oriented along the parallactic angle and can suffer additional slit losses due to differential atmospheric refraction (DAR), especially at high ($\gtrsim$1.5) air masses and short ($\lesssim$1.5 $\mu$m) wavelengths.

Given that Neuhäuser et al. (2005) observed GQ Lup at *K* band and at low ($<$1.1) air mass, the slit losses described above due to DAR are negligible. However, the effect of potential misalignment of GQ Lup B and the slit could be significant. Goto et al. (2003) find that a misalignment equal to half the slit width changes the measured continuum slope by 7%–8% $\mu m^{-1}$ at *H* band. The effect is likely less pronounced at *K* band, and the width of the slit used by Neuhäuser et al. (2005; 172 mas) is larger than that of the one used by Goto et al. (2003; 100 mas) in their experiment. Hence, maintaining adequate alignment on the slit should have been easier to achieve in the case of the *K*-band spectroscopic observations of GQ Lup B by Neuhäuser et al. Therefore, we conclude it is improbable that slit losses have significantly altered their *K*-band continuum shape and that the likely reason for the discrepancy between the spectral types of GQ Lup B inferred by Neuhäuser et al. and in the present work remains CIA $H_2$.

### 4.2. *The Heliocentric Distance to GQ Lup*

GQ Lup A is a T Tauri star located in the Lupus 1 star-forming region (Schwartz 1977). With a visual magnitude of $V \approx 12$ (Covino et al. 1992; Gregorio-Hetem et al. 1992), it is too faint to have a trigonometric parallax measurement from *Hipparcos*. However, its heliocentric distance can be inferred from the distance to its parent molecular cloud as determined from interstellar reddening, polarization, or Na I absorption in the spectra of objects along the same line of sight, or from the mean distance to brighter early-type members of the cloud. Neuhäuser et al. (2005) and Guenther et al. (2005) summarize the available distance estimates for GQ Lup from the literature and converge on a value of $140 \pm 50$ pc. The adopted distance correctly represents the entire range of published distances to the overall Lupus star-forming region (100–190 pc; Hughes et al. 1993; Wichmann et al. 1998; Knude & Hog 1998; Teixeira et al. 2000). A more precise estimate can be obtained from a joint comparative analysis of the techniques employed in the various studies and by discriminating among the four subgroups (Schwartz 1977) of the Lupus molecular cloud complex. Such a comprehensive analysis is presented by Franco (2002), who concludes that the mean distance to the entire molecular cloud complex, and to Lupus 1 in particular, is

≈150 pc. According to Franco (2002), the near edge of the Lupus 1 cloud is at least 130–140 pc away, based on studies of interstellar polarization (Rizzo et al. 1998) and Na I absorption (Crawford 2000) toward Lupus 1. Hence, we conservatively adopt a 20 pc uncertainty in the inferred 150 pc distance to Lupus 1.

### 4.3. *The Age of GQ Lup*

From a comparison to stellar evolutionary models, Neuhäuser et al. (2005) find that the age of GQ Lup A is between 0.1 and 2 Myr. While this is less than the median age (3 Myr) of the Lupus star-forming region (Hughes et al. 1994), this region contains both classical and weak-line T Tauri populations that may have different ages. The Lupus 1 and 2 subregions, in particular, have the highest concentration of classical T Tauri stars and are considered to be the youngest (0.1–1 Myr; Hughes et al. 1994). The location of GQ Lup in Lupus 1 indicates that, indeed, an age younger than 3 Myr may be warranted. However, we note that GQ Lup has been classified both as a weak-line T Tauri star (H$\alpha$ equivalent width of 2.8 Å; Herbig & Bell 1988) and as a classical T Tauri star (H$\alpha$ equivalent width of 38.6 Å; Appenzeller et al. 1983; Hughes et al. 1994). The variation in the strength of its H$\alpha$ emission precludes a conclusive association with either the classical or weak-line populations in Lupus. Therefore, we derive an independent estimate of the age of GQ Lup.

We use *R*- and Cousins *I*-band photometry from the literature to place GQ Lup on a $M_I$ versus $R - I$ color-magnitude diagram and compare its position to the predictions of theoretical models for pre–main-sequence stars. The *R* and *I* bands are not strongly affected by excess UV and IR emission and are thus suitable proxies for the bolometric luminosities and effective temperatures of pre–main-sequence stars. *R*- and *I*-band photometry of pre–main-sequence stars is also often obtained simultaneously[6] and thus allows self-consistent measurements of the color of variable stars. This is a particularly important consideration in the case of GQ Lup, which is strongly variable (up to 2 mag at *V*; Covino et al. 1992). GQ Lup is further known to have nonnegligible visual extinction, for which reports vary in the literature: $A_V = 0.4 \pm 0.2$ mag (Batalha et al. 2001), $A_V = 0.95$ mag (Hughes et al. 1994), or $A_V = 1.6$ mag (Bertout et al. 1982). Barring systematic differences in the approaches used to determine the visual extinction in the three cases, the variability in visual extinction may be linked to the photometric variability of GQ Lup, pointing to a probable circumstellar origin for the extinction. Such a conclusion is supported by simultaneous *UBVRI* monitoring observations of GQ Lup, from which Covino et al. (1992) find that the changes in the optical colors approximately follow a standard interstellar extinction law. We adopt the mean of the above extinction values and their standard deviation, i.e., $A_V = 1.0 \pm 0.6$ mag, as representative of the extinction toward GQ Lup at any given time and use the interstellar extinction law of Cardelli et al. (1989) to convert $A_V$ to *R*- and *I*-band extinction. GQ Lup is also known to exhibit variable veiling in its optical spectrum (Batalha et al. 2001), with the amount of excess emission ($F_{ex}$) being 0.5–1.5 times the photospheric level ($F_{phot}$) at *V* band and 1.0–4.5 times that at *B* band. Veiling of the optical continuum in T Tauri stars occurs as a result of excess emission at the location where the accretion column collides with the stellar surface in a radiative shock. Adopting a simple blackbody model for the veiling with the derived effective temperatures in Batalha et al. (2001), we find that the veiling of GQ Lup makes, on average, the *I*-band photometry 0.35 mag brighter (amplitude of variation ±0.24 mag) and the $R - I$ color 0.15 mag bluer (amplitude of variation ±0.07 mag).

Figure 4 shows the photometric measurements of GQ Lup from each of four separate optical data sets. Solid circles and solid triangles show the original data, without dereddening and deveiling, whereas the open circles and open triangles correspond to the dereddened and deveiled data. The error bars on the photometry and colors correspond to the quadrature sum of the amplitude of the observed variability and the 1 $\sigma$ uncertainty (0.32 mag) in the distance modulus. For the dereddened and deveiled data we also include the full ranges of the inferred reddening and veiling. Also overlaid are isochrones (*solid curves*) and evolutionary tracks (*dashed curves*) from Baraffe et al. (1998) with the mixing length parameter $\alpha = 1.0$. In a comparative analysis of theoretical evolutionary tracks, Hillenbrand & White (2004) find that this set of models most accurately predicts the dynamical masses of pre–main-sequence stars.

As is evident in Figure 4, the photometric data reveal that the age of GQ Lup is ≈3 Myr, although ages from 1 to ∼50 Myr are within the allowed $M_I$ and $R - I$ locus. An age >10 Myr can be excluded if we treat GQ Lup A as one of the classical T Tauri stars, which are not typically found in associations older than ∼10 Myr (the approximate age of the TW Hydrae association; Kastner et al. 1997; Mamajek 2005). Indeed, we argue that because circumstellar extinction probably contributes significantly to the observed variability, we need to weigh the data in Figure 4 more heavily toward higher luminosities (i.e., younger ages), which likely represent the unextincted state. We therefore conclude that GQ Lup is ≈3 Myr old, with a possible age range of 1–10 Myr, i.e., marginally older than the 1 ± 1 Myr estimate of Neuhäuser et al. (2005).

#### 4.3.1. *A Need to Revise the Age of Lupus?*

Our age estimate for GQ Lup from the evolutionary tracks of Baraffe et al. (1998) suggests an older age for the Lupus 1 star-forming region as a whole than the currently quoted value of 0.1–1 Myr. The latter age range was derived by Hughes et al. (1994) based on models from D'Antona & Mazzitelli (1994), which have now been shown to systematically underestimate the masses of pre–main-sequence stars (Hillenbrand & White 2004). Indeed, at an inferred age of 0.1 Myr, GQ Lup is ranked as one of the youngest stars in Lupus, according to Hughes et al. Our updated, older age for GQ Lup indicates that the entire region is probably ≈10 times older than Hughes et al. (1994) found, i.e., 1–10 Myr. The color-magnitude diagram in Figure 4 contains all 14 Lupus 1 members listed in Hughes et al. (1994). For all stars we have adopted the photometry and extinctions listed in Table 3 of Hughes et al. (1994) and the same veiling as for GQ Lup. Figure 4 demonstrates that the majority of the Lupus 1 members are at least 3 Myr old, with an age scatter of 1–100 Myr. However, ages of >10 Myr would be highly unusual for any members in this molecular cloud, which has a high incidence of classical T Tauri stars. Barring major inaccuracies in the Baraffe et al. (1998) models, the old appearance of some of the stars could be explained by local deviations from the adopted interstellar extinction law. Indeed, because of dust grain growth in primordial circumstellar disks, extinction and reddening due to circumstellar dust is not always described adequately by the standard interstellar medium (ISM) extinction law, which holds for grains 0.01–0.1 $\mu$m in size. Instead, circumstellar extinction is often more neutral in color ("gray"), especially in systems with close to edge-on viewing geometries, where the light from

[6] *I*- and *J*-band photometry are another suitable filter pair for estimating bolometric luminosities and effective temperatures, but these filter complements require two different detectors.

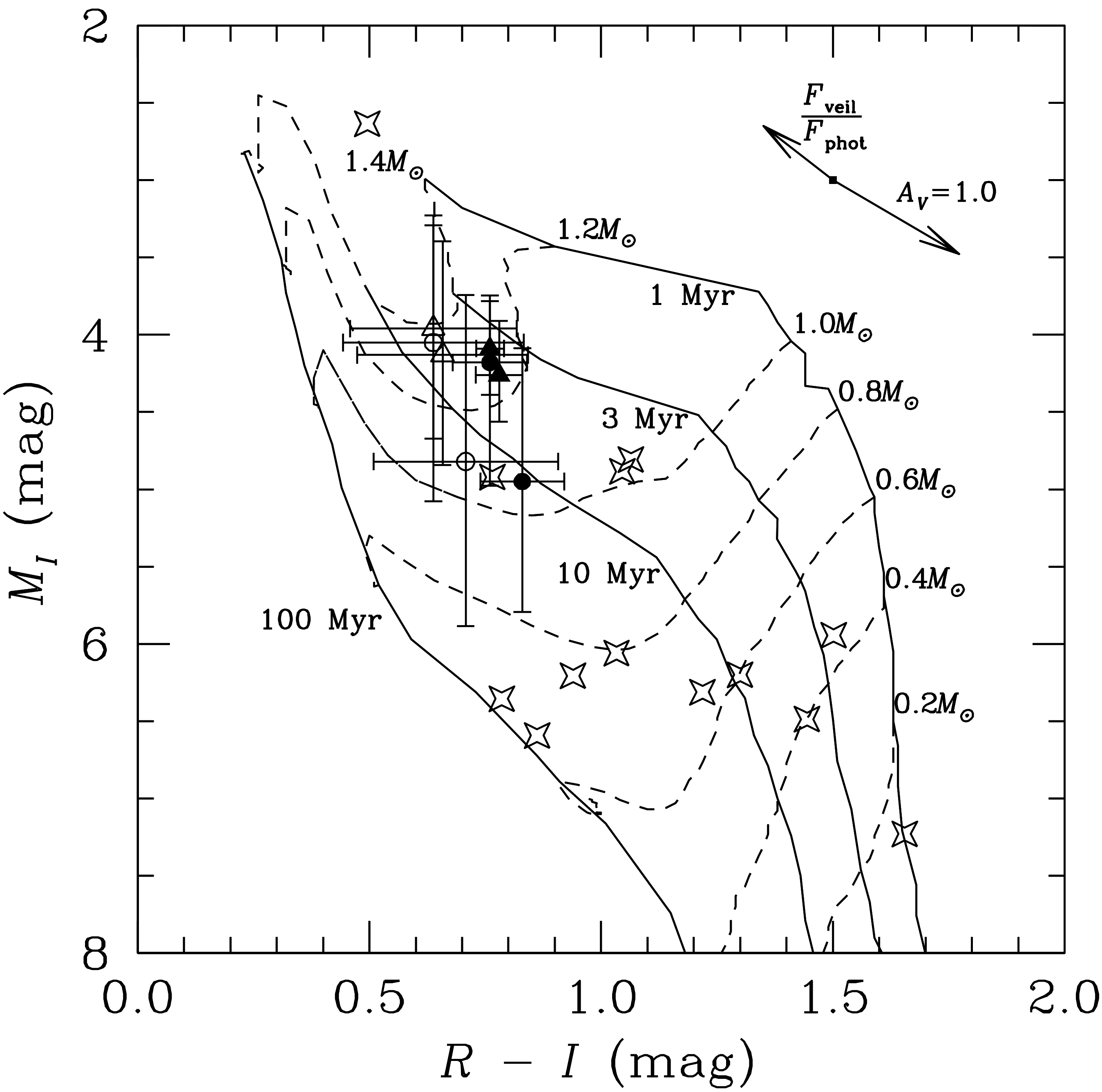


FIG. 4.—Color-magnitude diagram of GQ Lup (*data points with error bars*) and other Lupus 1 members (*open stars*) with evolutionary tracks from Baraffe et al. (1998). The filled symbols represent the observed data from four photometric data sets before dereddening and deveiling. The solid circles show the mean magnitudes and colors of long-period (>10 days) photometric campaigns from Covino et al. (1992) and W. Herbst (2007, unpublished; available at ftp://ftp.astro.wesleyan.edu/ttauri). The solid triangles show single-epoch measurements from Gregorio-Hetem et al. (1992) and Hughes et al. (1994). The error bars on the solid symbols denote the quadrature sum of the full range of observed photometric variation and the 1 $\sigma$ uncertainty (0.32 mag) in the distance modulus of GQ Lup. The open circles and triangles indicate the dereddened and deveiled data for GQ Lup, using the mean reddening and veiling estimates from § 4.3 (*vectors at upper right*). The error bars on the open symbols include the full amplitudes of the inferred reddening and veiling. The starlike symbols represent other dereddened and deveiled Lupus 1 members from Hughes et al. (1994). For these, we have adopted visual extinctions from Hughes et al. (1994) and the veiling vector for GQ Lup.

the central source passes through a nonnegligible part of the disk (e.g., Throop et al. 2001). Hence, because Hughes et al. (1994) determine extinctions based on observed $R - I$ colors and a priori known spectral types, the inferred ISM-like extinctions may underestimate the actual ones. As a result, on a color-magnitude diagram the stars would appear fainter, but not redder. That is, the stars would appear older. It is possible that some of the dereddened and deveiled data points in Figure 4, especially along the older isochrones, underestimate the actual unextincted stellar luminosities and ages. An upper age limit of $\sim$10 Myr can be inferred by comparing to the TW Hydrae association, which is the oldest stellar association known to harbor classical T Tauri stars. Considering the upper envelope of the data, which presumably are least affected by gray extinction, there is a strong reason to believe that the stellar population in the Lupus 1 molecular cloud is $\geq$1 Myr old.

The above reasoning leads us to infer that the age of Lupus 1 is 1–10 Myr, or 10 times older on average than previously

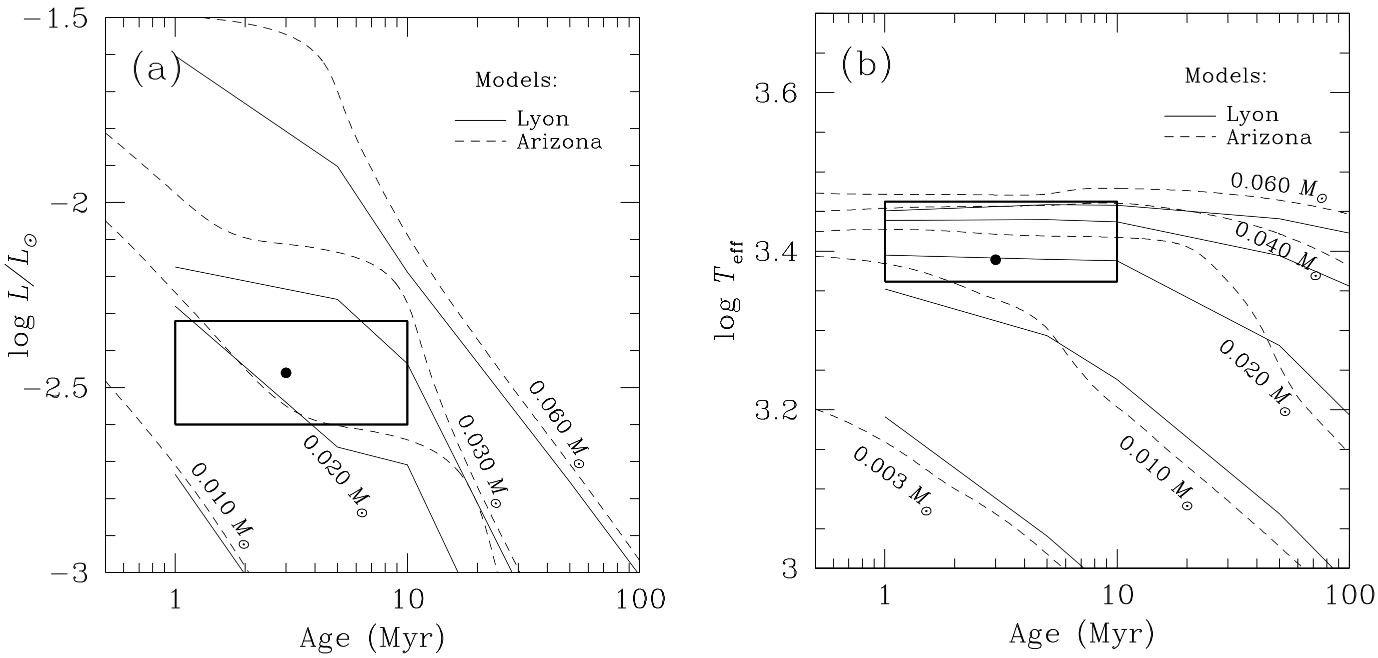


Fig. 5.—(*a*) Luminosity-age and (*b*) effective temperature–age evolution diagrams for GQ Lup B, with models from Chabrier et al. (2000; Lyon group) and Burrows et al. (1997; Arizona group) overlaid. The dot in each panel represents the mean estimate of the parameters of GQ Lup B, while the rectangle delimits the allowed range of their variation. The predictions for the mass of GQ Lup B based on its bolometric luminosity and effective temperature are consistent.

presumed. Similar analysis leads to an analogous conclusion for the ages of other young star-forming regions of ages comparable to that of Lupus 1 (e.g., Taurus). In view of the continuous improvement in stellar evolutionary models, a broad reanalysis of stellar ages in star-forming regions may indeed be necessary in the future. However, given the remaining uncertainties in the theory at ~1 Myr ages, we cannot claim a need for a significant reevaluation of pre–main-sequence ages, despite the relative success of the Baraffe et al. (1998) models of the Lyon group in reproducing dynamical masses of pre–main-sequence stars. We adopt these models to estimate the age of GQ Lup (and Lupus 1) in the present analysis to ensure self-consistency with the evolutionary models (Chabrier et al. 2000; also from the Lyon group) that we use to estimate the mass of GQ Lup B (§ 4.4). In addition to being some of the most widely used and successful (§ 4.4) substellar evolutionary models to date (the other set coming from the Arizona group; Burrows et al. 1997), the substellar evolutionary models of Chabrier et al. (2000) allow us to estimate the mass of GQ Lup B based on the same theoretical framework used in estimating the age of the primary.

### 4.4. *The Mass of GQ Lup B*

We base our estimate of the mass of GQ Lup B on the models of Burrows et al. (1997) and Chabrier et al. (2000). We obtain its bolometric luminosity using the derived $J$ magnitude, our distance estimate (§ 4.2), and $K$-band bolometric corrections for M6–L0 dwarfs from Golimowski et al. (2004). Although based solely on optical–near-IR data, the values of the bolometric corrections have been largely confirmed by recent 5.5–38 $\mu$m *Spitzer* IRS spectra of ultracool dwarfs (Cushing et al. 2006). The bolometric corrections are translated from the $K$ to $J$ band assuming the $J - K$ color for M6–L0 dwarfs is $1.1 \pm 0.1$ mag (Leggett et al. 2002). We note that the bolometric corrections in Golimowski et al. (2004) are compiled from data for >1 Gyr old high surface gravity field dwarfs and may need to be corrected for the expected ≈1 dex lower surface gravity of GQ Lup B. The sense and magnitude of this correction is unknown empirically, as the body of data on young ultracool dwarfs is extremely limited. We use the models of Chabrier et al. (2000) to infer that the correction to $BC_J$ for a +1 dex change in surface gravity is ≈0.15 mag. We adopt ±0.10 mag as an error estimate for the surface gravity correction to $BC_J$, i.e., of the same order as the precision of empirical bolometric corrections. We have not applied an extinction correction to our $J$-band photometry. At $J$ band the amount of extinction is only one-third of the visual extinction (for an ISM extinction law; Cardelli et al. 1989), and given the adopted $A_V = 1.0 \pm 0.6$ mag toward GQ Lup A, it would be $A_J = 0.28 \pm 0.17$ mag; i.e., the estimated luminosity of GQ Lup B would increase by ≈30%. However, we chose not to apply this correction, because we concluded that the extinction toward GQ Lup A is probably circumstellar in origin (§ 4.3). Given the relatively wide separation (≈110 AU) between the primary and the secondary and the lack of evidence (e.g., much higher circum–primary extinction) for a high optical depth edge-on viewing geometry for the system, we believe that near-IR light from the secondary is negligibly extincted by dust in the circum–primary disk.

The resulting estimate for the bolometric luminosity of GQ Lup B is $\log L/L_\odot = -2.46 \pm 0.14$. The effective temperature estimate is 2450 K, with a range of 2300–2900 K, corresponding to the spectral type M8 ± 2, according to the $T_{\rm eff}$–spectral type relation from Golimowski et al. (2004). Comparisons of these values with substellar evolutionary models from Burrows et al. (1997) and Chabrier et al. (2000) are presented in Figure 5. We estimate the mass of GQ Lup B at ~0.012–0.040 $M_\odot$ based on its bolometric luminosity, or ~0.010–0.040 $M_\odot$ based on its effective temperature. Despite the use of the same photometry, our mass estimate for GQ Lup B is a factor of ~1.5–2 higher than that of Neuhäuser et al. (2005) based on the same models, largely because of the older age that we estimate for the primary (§ 4.3).

We have not performed a detailed estimate of the mass of GQ Lup B based on the models of Wuchterl & Tscharnuter (2003) as done by Neuhäuser et al. (2005), because these models are not publicly available. Nevertheless, if we overlay the values for the effective temperature and luminosity of GQ Lup B on an

H-R diagram containing tracks from Wuchterl & Tscharnuter (e.g., Fig. 4 in Neuhäuser et al. 2005), we confirm the 1–2 $M_{Jup}$ mass estimate of Neuhäuser et al. This result is favored by Neuhäuser et al., who argue that at the very young age of GQ Lup the models of Wuchterl & Tscharnuter provide a more realistic account of the collapse and formation of substellar objects. Burrows et al. and Chabrier et al. model substellar evolution only postcollapse, by assuming a preexisting fully convective internal structure that is adiabatic at all stages of evolution (i.e., a "hot start"). Such models are thus uncertain at ages up to a few Myr (Baraffe et al. 2002) and may be inadequate for the ~3 Myr old GQ Lup B. However, Janson et al. (2006) argue that the version of the Wuchterl & Tscharnuter models used by Neuhäuser et al., based on a core-accretion–gas-capture scenario within a circumstellar disk, are also inappropriate at the young age of GQ Lup because they may not allow sufficient time for the formation of the secondary.

The decision of which models to use in this scenario is therefore best made in the context of existing empirical constraints on the models. Dynamical masses of very young substellar objects did not exist at the time of the investigation of Neuhäuser et al. (2005), but the first dynamical masses were recently reported for the ~1 Myr old eclipsing substellar binary 2MASS J05352184−0546085 A/B (Stassun et al. 2006). We use this young brown dwarf binary to decide which set of models more accurately predicts the mass of the objects in this system. We find that the hot-start models reproduce the individual component masses at an age of 1 Myr to within 30% of their dynamically measured values. Wuchterl & Tscharnuter's evolutionary tracks, on the other hand, underpredict the dynamical masses by a factor of ~3—too large a discrepancy to be explained by, e.g., a potential 1–5 Myr underestimate of the age of the binary. While we acknowledge that 2MASS J05352184−0546085 A/B provides only two empirical data points and that a broader comparison between data and theory will be needed to conclusively test the models, we consider the above test a sufficient demonstration that the hot-start models are more accurate at ages of 1–3 Myr and favor their predictions for the mass of GQ Lup B. Hence, we conclude that GQ Lup B is not a Jupiter-like object in its initial phase of contraction, but rather a ≥10 times heavier brown dwarf.

## 5. GQ LUP: A SUBSTELLAR COMPANION AND A DISK

From *Infrared Astronomical Satellite* (*IRAS*; Weaver & Jones 1992) data, GQ Lup is known to possess a strong IR excess (Fig. 6) that signals the presence of an optically thick circumstellar disk. The coexistence of this disk with a low-mass substellar companion is highly relevant for theories of planet and brown dwarf formation. The initial claim of Neuhäuser et al. (2005) that the mass of GQ Lup B could be as small as 1$M_{Jup}$ posed significant difficulties for planet formation theories. The existence of such a young planet at >100 AU from its host star required that the planet formed in the denser inner reaches (~30 AU) of the stellar system and was then ejected through a dynamical interaction with a more massive third body (Boss 2006). While realizing the obvious bias in favor of discovering such ejected planets through direct imaging, a conceptually simpler account of the formation of GQ Lup B may offer a more viable solution. In view of our present results, the requirement that GQ Lup B must have formed near its present separation can be satisfied given the higher inferred mass for the companion. At a minimum mass of 10$M_{Jup}$, GQ Lup B is more massive than the opacity mass limit for turbulent fragmentation (~5$M_{Jup}$; Bate et al. 2003). Therefore, the GQ Lup A/B system probably formed through direct collapse and fragmentation of the parent molecular cloud into a binary.

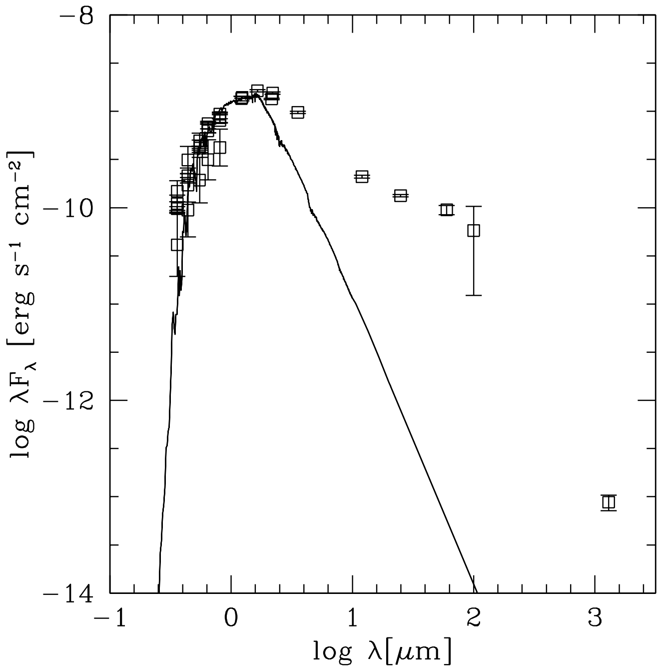


Fig. 6.—Spectral energy distribution of GQ Lup. A 4200 K (spectral type ≈ M0) NextGen model (Hauschildt et al. 1999) with solar metallicity and surface gravity log $g = 4.0$ has been overplotted. An extinction of $A_V = 1.0$ mag has been assumed (§ 4.3). The empirical data (*squares with error bars*) are from Mundt & Bastian (1980), Covino et al. (1992), Gregorio-Hetem et al. (1992), Hughes et al. (1994), Appenzeller et al. (1983), unpublished Las Campanas data contained in W. Herbst's T Tauri star photometry database, 2MASS, *IRAS* (Weaver & Jones 1992), and Nuernberger et al. (1997). Given the high optical variability of GQ Lup (§ 4.3) and the nonsimultaneity of the different data sets, we have made no attempt to fit the data. Instead, the model photosphere is simply normalized to the 2MASS flux at 1.2 μm.

Moreover, as pointed out by Janson et al. (2006), GQ Lup A/B is far from unique in the realm of wide (>100 AU) very low mass ratio ($M_2/M_1 \lesssim 0.03$) binaries, where it is joined by systems such as HR 7329 A/B (Lowrance et al. 2000), AB Pic A/B (Chauvin et al. 2005b), HN Peg A/B (Luhman et al. 2006), and HD 203030 A/B (Metchev & Hillenbrand 2007). The characteristics of these objects suggest formation through cloud fragmentation, and we infer that GQ Lup A/B followed the same formation scenario.

## 6. CONCLUSION

We have presented near-IR integral field spectroscopic AO observations of the GQ Lup A/B binary system obtained with the OSIRIS IFS on Keck. Our results demonstrate the utility of adaptive optics IFS spectroscopy in studying faint close-in substellar companions buried in the complex speckle-dominated halos of bright stars. Our *J*- and *H*-band spectra of GQ Lup B show the typical characteristics of very young ultracool dwarfs, such as the lack of alkali absorption and triangularly shaped *H*-band continua. From our *J*-band spectra, we determine a spectral type of M6–L0 for GQ Lup B, in marginal agreement with previous *K*-band spectroscopy from Neuhäuser et al. (2005), who find M9–L4. We argue that the difference in the spectral type estimates from the *J*- and *K*-band spectroscopy arises from the sensitivity to surface gravity of the 2 μm continuum slope indices used by Neuhäuser et al. (2005) and that the true spectral type of GQ Lup B is indeed earlier. This claim is sustained by a comparison of GQ Lup B to other substellar objects of similar luminosities in young stellar associations of similar ages. Following a careful analysis of the age and heliocentric distance of GQ Lup A, we conclude that the mass of GQ Lup B is 0.010–0.040 $M_\odot$. The mass estimate is based on the hot-start models from Burrows et al. (1997) and Chabrier et al. (2000) and is $\geq$5–10 times higher than the mass predicted by the core-accretion–gas-capture models of Wuchterl & Tscharnuter (2003). We favor the hot-start models because they more accurately predict the dynamical masses of the newly discovered (Stassun et al. 2006) 1 Myr brown dwarf binary 2MASS J05352184−0546085 A/B. The inferred mass of GQ Lup B makes it an improbable wide-orbit analog of the present population of $<15 M_{\rm Jup}$ radial velocity extrasolar planets. Instead, we conclude that GQ Lup A/B is a member of a growing population of wide (>100 AU) binary systems with very low mass ratios ($M_2/M_1 \lesssim 0.03$), the identification of which has only recently been possible, through high-contrast imaging.

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*Facilities:* Keck:II(OSIRIS)

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