1. INTRODUCTION

Brown dwarfs form the low-mass, low-temperature end of the galactic stellar mass distribution. Optical and near-infrared (near-IR) surveys carried out over the past two decades have detected hundreds of objects with masses below the sustained hydrogen-burning threshold (about 0.07 $M_{\odot}$; Riaz & Gizis 2007). These brown dwarfs have effective temperatures $T_{\text{eff}} \lesssim 2500$ K in the spectral sequence from late M-stars through the L and T dwarfs. Although models of such low $T_{\text{eff}}$ brown dwarfs predict essentially no photospheric emission in the far-ultraviolet (far-UV; $1100 \leq \lambda \leq 1700$ Å), the far-UV spectra of these objects are mostly unresolved (see Hawley & Johns-Krull 2003; Gizis et al. 2005 for UV spectra of four late M-stars).

More massive M dwarfs (spectral types earlier than $\sim$M5) have strong magnetic fields that, through processes still not fully understood, produce hot plasma and non-thermal particles. The rich phenomenology includes chromospheres ($T \sim 10^4$ K), transition regions ($T \sim 10^3$ K), coronae ($T \sim 10^6$ K), flares, and other transient activity. We observe this phenomenology through X-ray, far-UV, optical, and non-thermal radio emission lines and continua. It is unclear if far-UV emission is common in brown dwarfs. Hα compared to $L_{\text{bol}}$ is observed to decrease in late M dwarfs (e.g., Berger et al. 2010), which would suggest less hot gas capable of producing far-UV emission. Alternatively, magnetically powered activity may extend through the late M dwarfs (and into the L and T classes), possibly with enhanced flaring relative to their more massive counterparts (Fleming et al. 2000; Berger et al. 2008). Using Hubble Space Telescope (HST)-STIS, Hawley & Johns-Krull (2003) found that M7–M9 stars show bright emission in C iv $\lambda 1550$ and other lines formed in high-temperature plasmas. Also, Welsh et al. (2006) found both near-UV and far-UV emission and flares on several late M dwarfs observed by Galaxy Evolution Explorer.

Far-UV emission from accretion shocks is another mechanism that could be important for young brown dwarfs where gas-rich accretion disks exist. 2MASS J12073346–3932539 (2M1207) is an M8 brown dwarf (M $\approx 0.024 M_{\odot}$; Riaz & Gizis 2007) located in the $\sim$10 Myr TW Hya association (Kastner et al. 1997; Webb et al. 1999), at a distance of 52.4 pc ($V = 20.15$; Ducourant et al. 2008). Initial evidence for a circumstellar disk in this system was inferred from the association with the TW Hya group and the detection of strong Hα emission, indicative of active accretion (Gizis 2002). More recently, photometric and spectroscopic observations of 2M1207 from the far-red to the mid-IR have allowed various groups to confirm the existence of a circumstellar dust disk (Riaz & Gizis 2007; Morrow et al. 2008). The accretion from this system has been shown to vary on timescales ranging from hours to weeks (Scholz et al. 2005; Scholz & Jayawardhana 2006), although the absolute level of the mass accretion rate ($M_{\text{acc}}$) is somewhat unclear (Herczeg et al. 2009).

While 2M1207 is an active accretor, searches for magnetic fields have returned only a surprisingly low 3σ upper limit. Reiners et al. (2009) constrain the total magnetic flux, $B_f < 1$ kG, where $B$ is the unsigned photospheric magnetic field.
and $f$ is the magnetic field filling factor. This object has the highest quality existing far-UV data set of any brown dwarf, obtained with HST-STIS (Gizis et al. 2005), where several lines produced in hot gas (most notably He I and C IV) were observed. The observation of these lines, combined with a non-detection of Si IV emission, led these authors to conclude that the UV emission is produced by accretion, and that the silicon in the 2M1207 disk has depleted into dust grains. If the hot gas lines were produced in a thermal plasma due to stellar activity, all astrophysically abundant species with similar emissivities should be present (for reasonable metallicities), the lack of Si IV implies that the hot gas is not primarily created in the stellar atmosphere, but at the shock interface between the accretion disk and the stellar surface.

Molecular hydrogen (H$_2$) emission was also detected in the STIS observations, although the low spectral resolution of the G140L mode ($\Delta \nu \sim 240$ km s$^{-1}$) prevented a conclusive determination of the location of the molecular gas in the system. The most likely origin of the H$_2$ emission is in a warm molecular layer of the circumstellar disk, in analogy to the warm disks seen around more massive classical T Tauri stars (CTTSs; Herczeg et al. 2008). It is worth noting in introducing the 2M1207 system that another reservoir of H$_2$ resides at the extrasolar giant planet companion, 2M1207b ($M_p \sim 6 M_J$, secondary/primary mass ratio $\sim 1.4$; Chauvin et al. 2004; Song et al. 2006). This object is at a radial distance of $\sim 40$ AU, although the orbit is poorly constrained due to the long temporal baseline necessary for orbital monitoring. The nature of 2M1207b is the subject of some debate (Mohanty et al. 2007; Mamajek & Meyer 2007; Ducourant et al. 2008).

In this paper, we present new far-UV observations of this interesting low-mass system. These data cover a similar spectral bandpass as the HST-STIS observations presented by Gizis et al. (2005), but with order of magnitude increases in sensitivity and resolving power. We describe the Cosmic Origins Spectrograph (COS) observations and data reduction in Section 2. A quantitative analysis of the far-UV spectrum is presented in Section 3, with a focus on the properties of the H$_2$ in the circumstellar disk and the hot gas produced in the accretion shock. In Section 4, we put these results in the context of other young objects in a stage of active disk accretion and argue that the similarities are evidence that accreting brown dwarfs are low-mass analogs to CTTSs. We conclude with a brief summary in Section 5.

2. HST-COS OBSERVATIONS AND DATA REDUCTION

2M1207 was observed with the medium-resolution far-UV modes (G130M and G160M) of HST-COS on 2009 December 8 for a total of 16,333 s. A description of the COS instrument and on-orbit performance characteristics are in preparation (J. C. Green et al. 2010, in preparation; S. N. Osterman et al. 2010, in preparation). In order to achieve continuous spectral coverage and minimize fixed pattern noise, observations in each grating were made at three central wavelength settings (G130M and G160M) of CTTSs. We conclude with a brief summary in Section 5.

Table 1

| Data Set | COS Mode | Central Wavelength | $T_{\text{exp}}$ (s) |
|----------|----------|--------------------|----------------------|
| lb4p02fm | G160M    | 1600               | 1410                 |
| lb4p02ft | G160M    | 1611               | 2975                 |
| lb4p02gn | G160M    | 1623               | 2975                 |
| lb4p02gr | G130M    | 1291               | 2967                 |
| lb4p02gx | G130M    | 1300               | 3000                 |
| lb4p02h6 | G130M    | 1309               | 3005                 |
| lb4p01s1 | G285M    | 2676               | 3050                 |
| lb4p01rx | G140L    | 1230               | 3015                 |
| lb4p01rv | G140L    | 1230               | 3015                 |
| lb4p01rt | G140L    | 1230               | 200                  |

Figure 1. Far-UV spectrum of 2M1207. The top plot is a weighted co-addition of the HST-COS G130M and G160M observations. The bottom plot highlights the 1480–1580 Å region with relatively strong lines of warm (H$_2$; $T \gtrsim 2500$ K) and hot (C IV; $T \approx 1 \times 10^5$ K) gas.

(A color version of this figure is available in the online journal.)

3. ANALYSIS AND RESULTS

3.1. Circumstellar Disk Profile from Warm H$_2$

Initial far-UV observations (Gizis et al. 2005) did not have sufficient velocity resolution to set meaningful constraints on the kinematics of the 2M1207 system. The COS observations analyzed here have a factor of $\approx 15$ higher resolving power than those acquired with STIS G140L. Gizis et al. (2005) noted the

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4. We refer the reader to the cycle 18 COS Instrument Handbook for more details: [http://www.stsci.edu/hst/cos/documents/handbooks/current/cos_cover.html](http://www.stsci.edu/hst/cos/documents/handbooks/current/cos_cover.html).
presence of H$_2$ lines pumped by H I Ly$\alpha$ photons, for which they assumed a circumstellar origin. We identify 14 clearly detected H$_2$ lines were detected, the signal-to-noise ratio (S/N) of the emission lines of H$_2$ (Table 2), all excited by Ly$\alpha$+, and assumed a circumstellar origin. We identify 14 clearly detected H$_2$ lines were detected, the signal-to-noise ratio (S/N) of the absorption transitions (Shull 1978; Valenti et al. 2000). These absorbing transitions are shifted from the Ly$\alpha$ absorption transitions (Shull 1978; Valenti et al. 2000). These absorbing transitions are shifted from the Ly$\alpha$ rest frame by $\approx$ +15 and +100 km s$^{-1}$, respectively.

The thermal width of a population of H$_2$ emitting gas will always be unresolved at the $\approx$15–20 km s$^{-1}$ velocity resolution of COS, hence evidence for a resolved velocity structure in the molecular lines can be attributed to kinematic broadening. The velocity structure can in turn be interpreted as a physical structure for the emitting gas. We found that while over a dozen H$_2$ lines were detected, the signal-to-noise ratio (S/N) in a given emission line made line-profile fitting highly uncertain. In order to improve the quality of the velocity fit, we created a normalized line profile from a co-addition of the six strongest H$_2$ lines ([(1–3) R(3), (1–6) R(3), (1–6) P(5), (1–7) R(3), (1–7) P(5), and (1–8) P(5)]. The line profile was fitted using a modified version of the IDL MPFIT function, customized to incorporate the COS line-spread function (LSF$^5$). The model LSFs used here are based on numerical simulations of the HST telescope and are qualitatively similar to a two-Gaussian fit. Our fitting routine convolves an underlying Gaussian profile with this LSF, and returns the amplitude, line center, and FWHM of the original Gaussian line shape (to measure the intrinsic H$_2$ line profile, the convolution with the Keplerian disk profile must also be taken into account). However, for the broad lines observed in 2M1207, the COS LSF is expected to be virtually indistinguishable from Gaussian (Ghavamian et al. 2009). For the H$_2$ lines described here, we find a $<2\%$ relative difference between Gaussian and COS LSF fitting.

In practice, the strongest H$_2$ lines fall near the center of the COS G160M segment B, so for the summed velocity profile, we employed the 1500 Å LSF (we note that the COS LSF only changes slowly with wavelength). It is immediately clear from a “by-eye” inspection of the resulting profile (Figure 2) that a single component is a poor representation of the H$_2$ velocity profile, and a $\chi^2$ analysis confirms this. A two-component fit is the most conservative assumption as there is no additional evidence to imply a more complicated velocity structure. Following the procedure described above, we found that the dominant velocity component was centered on $v_1 = +39$ km s$^{-1}$ (relative to the rest wavelengths of H$_2$), with a velocity width (FWHM) $\Delta v_1 = 79 \pm 11$ km s$^{-1}$. A weaker, narrower component was identified at $v_2 = +24$ km s$^{-1}$, with a velocity width $\Delta v_2 = 23^{+24}_{-23}$ km s$^{-1}$. We discuss possible origins for this second feature in Section 4.2. We note that while the relative velocities between different components should be robust, target acquisition errors cause zero-point uncertainties (0–30 km s$^{-1}$) in the COS wavelength scale as applied by the current version of CALCOS. However, none of the analysis presented here depends on the absolute velocity scale of the data.

We interpret the broad component as a tracer of the inner edge of the 2M1207 accretion disk (Morrow et al. 2008). The inner edge of the dust disk is set by the sublimation point of the grain population in the disk (Whitney et al. 2003, 2004). Riaz & Gizis (2007), using broadband mid-IR images from Spitzer and models of low-mass disks, find that ISM-like grains with a maximum size of $a \approx 0.25$ $\mu$m best approximate the observed properties of the 2M1207 disk (discussed further in Section 3.2.1). Using these parameters, and sublimation temperature of 1600 K, they find a sublimation radius of $\sim 3 R_*$ for a Keplerian disk profile, we find that our broad H$_2$ component is consistent with originating at this dust sublimation radius. This is somewhat surprising because around more massive young stars with gas-rich disks, the inner gas radius is often observed to extend inward to the corotation radius, where the gas disk is truncated by stellar magnetic fields (Najita et al. 2007). 2M1207 does not have a detectable magnetic field (Reiners et al. 2009; and see below for additional evidence.

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**Table 2**  
Ly$\alpha$-pumped H$_2$ Emission from the 2M1207 System

| Line ID$^a$ | $\lambda_{\text{rest}}$ ($\AA$) | $\lambda_{\text{obs}}$ ($\AA$) | Line Flux ($10^{-16}$ erg cm$^{-2}$ s$^{-1}$) |
|------------|-----------------|-----------------|-----------------|
| (1–2) P(8) | 1237.87 | 1237.92 | 0.26 $\pm$ 0.11 |
| (1–3) R(3) | 1257.83 | 1257.94 | 0.61 $\pm$ 0.12 |
| (1–3) R(6) | 1271.02 | 1271.12 | 0.28 $\pm$ 0.11 |
| (1–3) P(5) | 1271.93 | 1272.02 | 0.56 $\pm$ 0.07 |
| (1–6) R(3) | 1431.01 | 1431.23 | 1.10 $\pm$ 0.23 |
| (1–6) R(6) | 1442.87 | 1443.02 | 0.47 $\pm$ 0.14 |
| (1–6) P(5) | 1446.12 | 1446.28 | 1.47 $\pm$ 0.37 |
| (1–6) P(8) | 1467.08 | 1467.30 | 0.67 $\pm$ 0.60 |
| (1–7) R(3) | 1489.57 | 1489.76 | 1.21 $\pm$ 0.12 |
| (1–7) R(6) | 1500.45 | 1500.70 | 0.98 $\pm$ 0.14 |
| (1–7) P(5) | 1504.76 | 1504.91 | 2.43 $\pm$ 0.15 |
| (1–7) P(8) | 1524.65 | 1524.84 | 1.24 $\pm$ 0.18 |
| (1–8) R(3) | 1547.34 | 1547.63 | 1.35 $\pm$ 0.26 |
| (1–8) P(5) | 1562.39 | 1562.55 | 1.08 $\pm$ 0.25 |

Notes.

$^a$ Lyman band $(B^1 \Sigma_g^+ - X^1 \Sigma_g^+)$ transitions.

$^b$ $\lambda_{\text{obs}}$ fits based on a flux-weighted average of H$_2$ velocity component structure (Section 3.1).

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**Figure 2.** H$_2$ velocity profile created from a co-addition of the six strongest Ly$\alpha$-pumped lines in the far-UV spectrum of 2M1207. A minimum of two components (fitted with the appropriate COS LSF) are needed to achieve a reasonable fit to the H$_2$ profile. The broad component is representative of the kinematics of the circumstellar disk, indicating a pile-up of material at the inner wall of the disk at $\approx 3R_*$, corresponding to the disk sublimation radius. The second component is most likely unresolved, and may be located in a molecular outflow or near the accretion hotspot on the stellar surface. The solid line is the sum of the two components.

(A color version of this figure is available in the online journal.)

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$^5$ The COS LSF experiences a wavelength-dependent non-Gaussianity due to the introduction of mid-frequency wave-front errors produced by the polishing errors on the HST primary and secondary mirrors; http://www.stsci.edu/hst/cos/documents/issrs/.
against strong magnetic fields in this system), and it seems that the gas disk in 2M1207 is more closely tied to the dust disk relative to higher mass counterparts. We display the relevant velocity widths and radii on a hypothetical disk velocity profile in Figure 3.

The excitation conditions required for Lyα excitation also constrains the molecular phase of the disk. H2 requires appreciable occupation in the v = 2 level in order to absorb from the transitions coincident with Lyα, while at lower temperatures different pumping transitions will dominate the resultant fluorescence spectrum. At temperatures of a few hundred Kelvin, only the v = 0 level is significantly populated, and one expects Lyβ (via B−X (6−0) P(1)) to be the dominant excitation route. At intermediate temperatures, v = 1 is occupied, and O iv pumping becomes important (via C−X (1−1) Q(3); see the Appendix), assuming the shock/magnetically energized radiation field is capable of producing this ion (France et al. 2007). Observations of Lyα-pumped fluorescence indicate T(H2) \gtrsim 2500 K for the molecular component of the disk (Herczeg et al. 2004). The upper bound on the molecular disk temperature is set by the thermal dissociation threshold of H2, \approx 4000 K (Shull & Beckwith 1982). Thus, our observations imply that the 2M1207 disk has a warm molecular component with a temperature in the range 2500–4000 K.

3.2. Hot Gas (C iv and N v) Velocity Profiles

Emission from C iv λλ1548 and 1550 is the strongest feature in the far-UV spectrum of 2M1207 that is not contaminated by telluric airglow. The C iv λ1548 profile suggests a double-peak structure, however the S/N is not high enough to make a conclusive determination within the error bars. In order to obtain a more robust velocity profile of the hot gas (T \approx 10^5 K) in 2M1207, we follow the procedure outlined above for the H2 lines and co-add the lines of the C iv and N v doublets. Figure 4 shows this co-added profile, including a fit to the data. We see that the suggested line structure is real, however the S/N still prevents an unambiguous interpretation. We carried out a χ^2-minimization analysis to determine the most likely underlying line profile. We found that a two-component fit to the hot gas profile (Figure 4) produced a better fit (reduced χ^2 = 1.828) than either a single emission component (χ^2 = 1.992) or a single emission line with a superimposed absorption component (χ^2 = 2.370). While it may be possible to improve the fits by including additional component structure, the data do not support a more complicated interpretation. We find that the hot gas has velocity components v hot1 = +22, 41 km s\(^{-1}\), with Δv hot1 = 36, 76 km s\(^{-1}\). The broad component is most likely tracing material infalling along the accretion stream. It is interesting to note that the hot gas profile is qualitatively similar to the time-variable Hz profiles presented by Scholz et al. (2005). The Hz profiles show a broad emission line with a narrower, redshifted absorption component superimposed. This line profile may be present for the far-UV hot gas lines, but considerably higher S/N is needed to test this possibility.

Figure 5 shows a comparison of the warm (H2) and hot (C iv + N v) gas profiles described above. The COS LSF computed for λ = 1550 Å (λrest C iv) is shown overplotted in green. This clearly shows that the line profiles are fully resolved, and the LSF does not significantly alter the observed profiles, as expected for most emission lines observed with COS (S. N. Osterman et al. 2010, in preparation). While it is interesting that the H2 and hot gas profiles are qualitatively similar, we consider it most likely that this is coincidental and that the profiles are governed by different physical processes. While we favor the interpretation that the H2 is tracing the Keplerian rotation of the inner disk hole, it should be noted that the red wing of the H2 profile could include a contribution from the infalling accretion stream. This component would necessarily be in the outer regions of the accretion stream as H2 will be collisionally dissociated in a C iv emitting plasma.

In addition to C iv and N v, we observe a range of ionization states of carbon, including its neutral form, and He ii. These lines were fitted using the emission profile observed in the summed N v and C iv profiles as a proxy, and line strengths are presented in Table 3. The spectra also include emission from Lyα and the O i λ1304 multiplet, however, the large aperture of COS does not
permit us to separate the brown dwarf signal from geocoronal airglow emission.

### 3.2.1. Limits on Dust-depleted Species: Si and Mg

In a plasma with the range of temperatures necessary to excite C i as well as the three ionization states of carbon described above, one would expect strong line emission from other astrophysically abundant species with similar excitation energies, specifically silicon and magnesium. The COS observations presented here include wavelengths with strong emission lines of Si ii (λ1206), Si iv (λλ1394 and 1403), and Mg ii (λλ2796 and 2803). We do not detect any of these species (Figures 6 and 7), and the very low detection background of the COS micro-channel plate detector allows us to put tight limits on the flux in the silicon lines. Assuming the velocity width of the combined hot gas profile presented above, we can place 1σ integrated line flux limits of [0.18, 0.17, 0.19, 0.34, 0.29, 6.94, and 6.94] × 10\(^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) for the [Si iii λ1206, Si iv λλ1394, Si iv λ1403, Si ii λ1526, Si ii λ1533, Mg ii λ2796, and Mg ii λ2803] transitions, respectively (Table 3). Figure 6 shows the expected emission profiles from Si iii and Si iv based on the observed flux of the C iv emission and the relative emissivities of the relevant transitions (assuming collisional ionization and solar abundances; Dere et al. 1997, 2009). While the non-detection of silicon is highly significant, a direct comparison cannot be made between the observed C iv flux and the expected level of Mg ii emission as the species traditionally trace different atmospheric regions (chromosphere versus transition region) in low-mass stars. We note, however, that observations of more massive M dwarfs find Mg ii emission to be much stronger (× ∼ 10) than that of C iv (Byrne & Doyle 1989). The absence of Si iv emission was observed by Gizis et al. (2005) in the STIS observations of 2M1207, and COS allow us to set upper limits that are smaller by approximately an order of magnitude. We measure a C iv/Si iv ratio ≳ 35, very similar to the high ratios observed in some CTTSSs, but significantly different from the values of unity that are observed in higher mass cool star atmospheres (Ayres et al. 1997; and see Herczeg et al. 2002; Section 4 for discussion).

![Figure 5](image-url)  
*Figure 5.* Comparison of the warm (H\(_{\text{2}}\)) and hot (C IV + N v) gas profiles presented in Figures 2 and 4. The COS LSF (offset by +2.1 km s\(^{-1}\); Section 3.1) is shown as the dotted green line. While the warm and hot gas profiles are qualitatively similar, they are most likely created by different physical processes (rotation vs. accretion), and are not related to the instrumental profile. (A color version of this figure is available in the online journal.)

**Table 3**  
AtOMIC EMISSION FROM THE 2M1207 ACCRETION SHOCK

| Line ID | \(\lambda_{\text{rest}}\) (Å) | \(\lambda_{\text{obs}}\) (Å) | Line Flux \((10^{-16} \text{ erg cm}^{-2} \text{s}^{-1})\) |
|--------|-----------------|------------------|-------------------|
| O vi   | 1031.91         | ...              | \(\lesssim 5.1\)   |
| O vi   | 1037.61         | ...              | \(\lesssim 5.1\)   |
| C ii   | 1176            | ...              | 0.70 ± 0.34       |
| Si iii | 1206.50         | ...              | \(\lesssim 0.18\)  |
| H ii   | 1215.67         | 1215.66          | 2.3 × 10\(^{4}\)  |
| N v    | 1238.82         | 1238.94          | 1.28 ± 0.17       |
| N v    | 1242.80         | 1242.92          | 0.59 ± 0.16       |
| C ii   | 1280.33         | 1280.92          | 0.61 ± 0.12       |
| O iv   | 1302.17         | 1302.21          | 79.88 ± 1.59      |
| O ii   | 1304.86         | 1304.97          | 49.90 ± 3.96      |
| O ii   | 1306.03         | 1306.05          | 19.63 ± 1.75      |
| C ii   | 1334.53         | 1334.63          | 0.73 ± 0.40       |
| C ii   | 1335.71         | 1335.89          | 0.86 ± 0.09       |
| Si iv  | 1393.76         | ...              | \(\lesssim 0.17\)  |
| Si iv  | 1402.77         | ...              | \(\lesssim 0.19\)  |
| Si ii  | 1526.71         | ...              | \(\lesssim 0.34\)  |
| Si ii  | 1533.43         | ...              | \(\lesssim 0.29\)  |
| C iv   | 1548.19         | 1548.38          | 8.22 ± 0.37       |
| C iv   | 1550.77         | 1550.95          | 5.41 ± 0.21       |
| He ii  | 1640.40         | 1640.59          | 2.28 ± 0.54       |
| C i    | 1657           | 1657.69          | 4.83 ± 2.34       |
| Mg ii  | 2795.73         | ...              | \(\lesssim 6.94\)  |
| Mg ii  | 2802.70         | ...              | \(\lesssim 6.94\)  |

Notes.  
\(^{a}\) \(\lambda_{\text{obs}}\) fits based on a flux-weighted average of hot gas velocity component structure (Section 3.2).  
\(^{b}\) An alternative upper limit on O vi λ1032 derived from the absence of O vi-pumped H\(_{\text{2}}\) emission in the 2M1207 spectra is approximately 9.5 × 10\(^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) (see the Appendix for details).  
\(^{c}\) Lines labeled \(^\dagger\) are contaminated by geocoronal emission.  
\(^{d}\) Emission line flux decreased by interstellar absorption.

Silicon and magnesium can be heavily depleted into dust grains (Sembach & Savage 1996), and young circumstellar disks are known to exhibit grain growth (Apai et al. 2005) that can be a reservoir for refractory elements originally in the gas phase. Evidence for grain growth can be seen in mid-IR spectra of disks where the 10 \(\mu\)m silicate emission feature has broadened or disappeared. The mid-IR dust spectrum is somewhat ambiguous for 2M1207. Riaz & Gizis (2007) claim a detection of this feature, using ground-based and Spitzer (Infrared Array Camera and Multi-band Imaging Photometer for Spitzer) photometry to infer excess emission at 10 \(\mu\)m based on the ratio of 8.7/10.4 \(\mu\)m flux. However, Morrow et al. (2008) used direct spectroscopic observations with the Spitzer-IRS to rule out any emission from the 10 and 20 \(\mu\)m silicate features. The latter observation implies that the grains in the 2M1207 circumstellar disk have experienced significant evolution toward larger grains (\(a > 5 \mu\)m) and have most likely settled into the disk midplane (Dullemond & Dominik 2004). This scenario is consistent with our non-detection of dust depletion species in the COS spectra of 2M1207, and is not particularly surprising given the ~10 Myr age of the TW Hya association (Gizis 2002). Sargent et al. (2009) discuss a survey of 65 TTSs in the Taurus–Auriga star-forming region. These disks show evidence of grain growth in a population of more massive disks that are appreciably younger than those in TW Hya. In any event, this result presents an interesting constraint on the gas and dust composition in the disk, and provides additional evidence that accretion (and not magnetic activity) produces the hot gas in the 2M1207 system. Figure 8
produce the C\textsc{iv} the 2M1207 accretion disk has depleted into grains, and that accretion shocks C\textsc{iv} of Si\textsc{iii} atmosphere. The orange spectrum is the expected Si profile based on the ratio if the hot gas in the 2M1207 system is created by a magnetically active upper atmosphere. The (1–8) R(3) line of H\textsc{2} (λ = 1425 Å) on the spectroscopic analysis presented in Sections 3.1 and 3.2, presents a representation of the inner region of the system based on the variability of H\textsc{2} lines, this might warrant further attention, but as all of the features were approximately constant, this treatment conveys the accretion rate onto the stellar surface. The COS far-UV MCP presents a representation of the inner region of the system based on the two-dimensional spectral image and summing the photons in that region. We noted that the (1–8) R(3) line of H\textsc{2} (λ = 1425 Å, COS mode: G160M, segment B), C\textsc{iv} and N\textsc{v} observed in the system. (A color version of this figure is available in the online journal.)

3.3. Emission Line Variability

Scholz et al. (2005) and Scholz & Jayawardhana (2006) report on the variability of Hα emission from the 2M1207 system on timescales from hours to weeks, most likely due to variability in the accretion rate onto the stellar surface. The COS far-UV MCP is a photon-counting detector, and data are recorded in “time-tagged” mode: an [x, y, time] coordinate is recorded for each observed photon. This means that time variability in all spectral features can be tracked over the course of the observation, by isolating the appropriate x, y coordinates in a co-added two-dimensional spectral image and summing the photons in that region over a given time step. We isolated three spectral regions to explore time variability in the 2M1207 data: N\textsc{v} (COS mode: G130M, segment B), C\textsc{iv} (COS mode: G160M, segment B), and H\textsc{2} (λ = 1425 Å ≤ λ ≤ 1530 Å, COS mode: G160M, segment B). We note that the (1–8) R(3) line of H\textsc{2} (λ = 1457.34 Å) is included in the C\textsc{iv} region.

We do not find significant variations in the features tracked over the course of the observations. Figure 9 displays the emission line strengths as a function of exposure time. We also plot a time spectrum of the background level, obtained over an extraction box with the same dimensions as that used for H\textsc{2}, but offset by −50 pixels in the cross-dispersion direction. The time sampling was chosen to be 200 s, as this was the smallest interval that provided at least one background count in each time step. Figure 9 shows what might be variability in the relatively weak N\textsc{v} and H\textsc{2} lines, but a close inspection shows this change to simply be background variations, presumably related to the orbital position of HST. The background flux level is ≲ 10\textsuperscript{−4} counts s\textsuperscript{−1} pixel\textsuperscript{−1}, similar to the background level of the B-segment COS MCP reported by McCandliss et al. (2010).

For simplicity, we plot the N\textsc{v}, C\textsc{iv}, and H\textsc{2} on the same time axis, but in practice the G130M observations were acquired on the HST orbits following the G160M observations. The N\textsc{v} time sequence started roughly 3.6 hr (≈ 0.15 P\textsubscript{rot}) after the C\textsc{iv} and H\textsc{2} data. If significant changes were seen in any of the lines, this might warrant further attention, but as all of the features were approximately constant, this treatment conveys the relevant information. H\textsc{2} is a proxy for the strength of the Ly\alpha radiation field, and the constancy of the H\textsc{2} lines suggests that Ly\alpha was roughly constant over the ∼ 2.1 hr of the G160M observations. One might expect Ly\alpha to directly trace the other hot gas lines created in the accretion shock, and Figure 10 shows...
a comparison of the Lyα-pumped H₂ emission and that of the highest S/N hot metal emission, CIV. A correlation analysis finds a Pearson coefficient of 0.15, showing that correlated changes in the CIV and Lyα were not present during the G160M observations.

4. DISCUSSION

4.1. Mass Accretion Rate: CIV Luminosity

We do not have contemporaneous observations of 2M1207 in the optical or NUV, where traditional accretion diagnostics are located (Herczeg et al. 2009, and references therein). Johns-Krull et al. (2000) present empirical relations for determining the $M_{\text{acc}}$ of CTTSs, and while these relations were created for higher mass objects with larger mass accretion rates, it is interesting to compare an extrapolation of the CTTS relation to a more standard technique. For this purpose, we use Equation (2) of Johns-Krull et al. (2000). In addition to 2M1207 having over an order of magnitude smaller mass than any stars considered by Johns-Krull et al. (2000), we note they assume that the accretion emission is in excess of a saturated magnetic component that produces a surface CIV flux level of $F_{\text{CIV}} > 10^6$ erg cm$^{-2}$ s$^{-1}$. Taking a distance of 52.4 pc (Ducourant et al. 2008) and a stellar radius of 0.24 $R_\odot$, we find a total CIV surface flux of $F_{\text{CIV}} = 1.28 \times 10^5$ erg cm$^{-2}$ s$^{-1}$ (where no saturated magnetic component has been subtracted). While this is lower than the saturation threshold suggested by Johns-Krull et al. (2000), the combination of the low magnetic field at 2M1207 (<1 kG; Reiners et al. 2009) and the non-detection of Si and Mg species (Section 3.2.1) lead us to assert that essentially all of the CIV emission from 2M1207 is produced by accretion.

The empirical relation between the CIV luminosity ($L_{\text{CIV}}$, in units of erg s$^{-1}$) and $M_{\text{acc}}$ depends strongly on the method and values used for dereddening the observed fluxes, particularly at the wavelength of CIV ($\lambda 1550$), where the effects of interstellar extinction are large (Cardelli et al. 1989). The mass accretion rate is then

$$\log_{10}(M_{\text{acc}}) = 0.753 \log_{10}(L_{\text{CIV}}) - 29.89. \quad (1)$$

The $L_{\text{CIV}}$ is calculated to be $4.49 \times 10^{26}$ erg s$^{-1}$. We note that the 2M1207 sightline is generally assumed to suffer no interstellar extinction ($A_V = 0.0$; Herczeg et al. 2009), and no correction was applied to the CIV line fluxes presented in Table 3. We find $\log_{10} M_{\text{acc}} \approx -9.8$ ($M_{\text{acc}} = 1.6 \times 10^{-10} M_\odot$ yr$^{-1}$) from the CIV observations of the 2M1207 system. This value is consistent with the accretion level of 2M1207 derived from Hα observations ($\log_{10} M_{\text{acc}} = -10.1 \pm 0.7$) obtained in the “high” state (Scholz et al. 2005). Johns-Krull et al. (2000) note that alternative calibrations produce accretion rates that are about 10 times lower than those given in Equation (1) above. If that scaling is applied, we find that the $M_{\text{acc}}$ derived from the CIV line strengths is consistent with the lower values observed by Scholz et al. (2005; $\log_{10} M_{\text{acc}} = -10.8 \pm 0.5$).

Interestingly, while we find the CIV-based accretion rate to be in excellent agreement with that derived from Hα observations, our low values are approximately an order of magnitude greater than those measured using deep, low-resolution observations of the Balmer continuum ($\log_{10} M_{\text{acc}} = -11.9$; Herczeg et al. 2009). The accretion rate in the 2M1207 system is known to vary by at least an order of magnitude, and since none of the observations were acquired simultaneously, it is plausible that variability causes the discrepancy between the mass accretion rates measured by Hα, CIV, and Balmer continuum observations. Alternatively, absorption of Balmer continuum emission by the edge-on disk may lead to a lower estimation of the accretion rate by this method.

4.2. Physical Origin of the Narrow H₂ Component

In Figure 2, we displayed the co-added H₂ emission line profile of the six lines with the highest S/N in the COS M-grating data. In Section 3.1, we discussed the dominant broad component and identify it as emission from a pile-up of material at the inner wall of the circumstellar disk, approximately at the disk sublimation radius (Figure 8). The velocity width of the second component is poorly constrained as the fit is dominated by the broader, stronger component. The velocity width is consistent with being an unresolved feature. There are several possible physical origins for an unresolved H₂ population. The most likely scenario seems to be that this additional emission arises at the stellar surface. The photospheric temperature ($T_\text{p}$)
is 2550 K (Riaz & Gizis 2007), ideal for maintaining an H2 population that is capable of being pumped by Lyα photons in thermal equilibrium. If a photospheric origin is the correct interpretation, this would argue that the emitting molecules are near the accretion hotspot created at the interface of the infalling material from the disk, seen in our COS observations through several ionization states of He, C, and N. The relaxation time for the electronic transitions of H2 is very short (\( \tau_{\text{rot}} \) for (1–2) R(6) transition coincident with Lyα is 1.68 \times 10^5 \text{ s}^{-1}; Abgrall et al. 1993a), and the UV transitions of the H2 molecules would not be visible if they were not being actively excited.

The \( \approx 15 \text{ km s}^{-1} \) blueshift of this component relative to the bulk of the H2 emission from the disk suggests a possible outflow origin. The CTTSs T Tau and RU Lupi show narrow, blueshifted H2 emission that is thought to be indicative of a bipolar outflow (Herczeg et al. 2006). The blueshift of the outflow emission in these objects is roughly the same (\( v \approx -12 \text{ km s}^{-1} \)) as that found for 2M1207. If an outflow is the correct interpretation, the 15 km s\(^{-1}\) relative velocity of the narrow H2 component in 2M1207 is surprising because T Tau and RU Lupi host nearly face-on disks, where the outflow jet is pointed more directly at the observer. It seems unlikely that the edge-on orientation of the 2M1207 disk would permit the same magnitude of blueshift produced in more massive, face-on disks, however, 2M1207 is observed to have [O I] emission that is consistent with an outflow (Whelan et al. 2007). One final possibility is that the weak H2 emission originates in the dayglow or aurorae of the 6 MJ companion, 2M1207b (Chauvin et al. 2004; and see France et al. 2010 for a detailed discussion of the predicted UV emission properties of extrasolar giant planets). The far-UV spectrum of Jupiter is dominated by H2 emission, where the excitation is caused by electron impact where the magnetic field lines connect to the planetary surface near the poles and solar-induced Lyβ fluorescence in the equatorial regions (Feldman et al. 1993; Wolven & Feldman 1998). In the instance of an additional energy source (in this case the Shoemaker Levi 9 impact), the Jovian atmosphere supports Lyα-pumped H2 emission (Wolven et al. 1997) similar to that observed in 2M1207. The velocity shift due to the orbital motion of the planet would be undetectable at the COS resolution (\( v_{\text{orb}} \approx 0.7 \text{ km s}^{-1} \) at 40 AU, assuming a circular orbit), and this scenario would require both a mechanism to heat the 2M1207b atmosphere to \( T \gtrsim 2500 \text{ K} \), and produce a 15 km s\(^{-1}\) outflow. While we favor a photospheric origin for the narrow H2 component in 2M1207, we cannot conclusively rule out an outflow or the extrasolar giant planet companion as possible sources of the observed H2.

4.3. Young Brown Dwarfs: Low-mass Classical T Tauri Analogs

As mentioned in the previous subsection, 2M1207 displays metal depletions consistent with those seen in some CTTSs. The H2 disk emission is also reminiscent of that observed around more massive young stars. We therefore argue that 2M1207 is a low-mass analog to these systems. While TW Hya is a somewhat atypical pre-main-sequence object (with respect to the ages, accretion rates, and abundances of other CTTSs; we refer the reader to Section 1 of Herczeg et al. 2002 for a concise review), we use it for comparison with 2M1207 based on its well-studied far-UV spectrum (Herczeg et al. 2002). The H2 emission seen in our COS observations is qualitatively similar to that of TW Hya, however, there are quantitative differences in the far-UV spectra of these objects. The first is the wealth of lines observed in the spectrum of TW Hya compared to 2M1207.

While the 2M1207 observations are at a lower S/N than the STIS observations of TW Hya, there are numerous emission lines that would have been detected if they were present with the relative strengths seen in TW Hya (in particular, emission lines pumped by (0–2) R(0) 1217.21 Å and (0–2) R(1) 1217.64 Å). This implies that the Lyα emission profile in 2M1207 is considerably narrower than that observed in higher mass CTTSs. These “missing” fluorescent progressions are pumped by the wings of a broad stellar/shock Lyα emission profile, which are mostly inaccessible to COS due to contamination by geocoronal Lyα. The lack of a broad Lyα component in 2M1207 may be further evidence that Lyα is created in the accretion shock in this object (Herczeg et al. 2006).

We can make a quantitative comparison of the H2 flux from TW Hya and 2M1207. The total flux ratio between the two (\( R_{\text{2M}}^{\text{TW}}(\text{TOT}) \equiv I_{\text{H2}}(\text{TW Hya})/I_{\text{H2}}(2\text{M1207}) \)) is not the appropriate measure as TW Hya produces many more emission lines based on the broad stellar Lyα profile. We compare the total H2 emission from specific states observed in 2M1207, namely, those pumped by (1–2) R(6) 1215.73 Å and (1–2) P(5) 1216.07 Å. The distance-corrected flux ratios for the emission produced by pumping in those two lines are \( R_{\text{2M}}^{\text{TW}}(1–2 \text{ R}(6)) = 391 \) and \( R_{\text{2M}}^{\text{TW}}(1–2 \text{ P}(5)) = 350 \), respectively. The \( R_{\text{2M}}^{\text{TW}}(1–2 \text{ R}(6)) \) ratio is more susceptible to the effects of self-absorption by H1 in the circumstellar environment, though the ratios for both lines are similar. This implies that there is more Lyα flux per H2 in the disk of TW Hya compared to the disk of 2M1207, assuming that the disk masses are proportional to the mass of the primary (\( M_{\text{TW}}/M_{\text{2M}} = 0.7 \text{ M}_\odot/0.024 \text{ M}_\odot \approx 30 \)). The excess disk H2 emission in TW Hya can be interpreted as a stronger local Lyα radiation field, which we propose is due to the higher mass accretion rate in TW Hya (\( \approx 2 \times 10^{-9} \text{ M}_\odot \text{ yr}^{-1} \) as compared to \( \approx (1–150) \times 10^{-12} \text{ M}_\odot \text{ yr}^{-1} \) for 2M1207; Herczeg et al. 2006, 2009; Scholz et al. 2005; this work) as well as a larger surface flux contribution from the magnetic, non-accreting component on TW Hya.

While these differences may reflect lower mass accretion rates in lower mass objects, the general trends connecting CTTSs and 2M1207 seem clear. 2M1207 is actively accreting from its disk, retains a warm (2500–4000 K) layer of H2 in the inner disk, and shows evidence for depletion of Si and Mg into grains. Given the edge-on geometry of the 2M1207 system, a more direct comparison would be to the edge-on CTTS DF Tau. DF Tau was observed by COS as part of the HST Cycle 17 Guaranteed Time program, and a comparison with 2M1207 will be presented in a future work. If the additional H2 component described in Section 4.2 is attributable to an outflow, a better comparison might be made with the edge-on CTTS system DG Tau.

5. SUMMARY

We have presented far-UV spectroscopy of the young (\( \approx 10 \) Myr old) M8 brown dwarf/circumstellar disk system 2M1207. These data provide an order of magnitude increase in spectral resolution over existing far-UV observations of a brown dwarf system. We detect several emission lines of H2 that are excited by Lyα photons created in an accretion shock, and use these lines to constrain the kinematics and physical state of the disk. A second H2 component exists, and we discuss...
possibilities for the origin of this emission, including at the stell-
lar surface near the accretion shock and in an outflow. A third
possibility is that this H2 feature is dayglow emission from the
6 $M_J$ giant planet, 2M1207b, however the data do not allow us
to identify the exact location of the emitting region. We mea-
sure several emission lines that trace the hot gas produced in the
shock, including N v and C iv. Interestingly, we do not detect
ions of refractory elements such as silicon and magnesium, and
argue that these species have been depleted into grains. This
grain depletion scenario suggests that hot gas in the 2M1207
system is not significantly produced in a solar-type transition
region, rather the accretion shock is responsible for the majority
of the observed emission. Although there are quantitative dif-
ferences, these results suggest that young brown dwarfs harboring
circumstellar disks are low-mass analogs to CTTSs.

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APPENDIX

O vI FLUX LIMITS

O vI can be an important shock temperature diagnostic, par-
cularly when used in conjunction with the observed strengths of
N v and C iv (Danforth et al. 2001; Welsh et al. 2007, and ref-
ences therein). The production of these high ions in CTTSs is
not fully understood (Lamzin et al. 2007), hence in this appendix
we use the COS observations to constrain the O vI emission pro-
duced in the 2M1207 system as a reference for future studies of
low mass accreting systems.

During the Servicing Mission 4 Observatory Verification
period, it was discovered that the MgF2/AI mirrors of HST
have retained approximately 80% of their pre-flight reflectivity
(McCandliss et al. 2010). This (surprising) result has opened
the door for use of the short-wavelength response of the
G140L mode of COS to perform spectroscopic observations at
wavelengths inaccessible ($\lambda < 1100$ Å) to previous HST
instruments (McCandliss et al. 2010). The CALCOS pipeline
processing of the G140L, segment B (400 Å $\lesssim \lambda \lesssim 1150$ Å)
is not yet mature enough to produce one-dimensional spectra
appropriate for scientific analysis, however, we performed
a custom spectral extraction and reduction from the two-
dimensional spectrograms that allowed us to create a low-
resolution ($\Delta \lambda \sim 1.0$ Å) spectrum of 2M1207 from 912 to
1150 Å. We used this spectrum to set an upper limit on the
integrated line strengths of the O vI $\lambda\lambda1032, 1038$ resonance
doublet (Table 3). Assuming that any O vI produced in the
accretion shock has the same velocity structure observed in the
summed N v and C iv profile, we find a 1σ upper limit to the
O vI $\lambda\lambda1032$ and 1038 emission to be $5.1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$.

A more sophisticated approach to setting a limit on the level
of O vI is to use the absence of O vI-pumped H2 emission lines in
the higher sensitivity M-grating observations. We can set limits
on the amount of O vI emission that may be emitted from the
accretion shock by making rough assumptions about the total
column density of the emitting H2, $N$(H2). This method follows
the analysis of O vI-pumped H2 in the circumstellar disk around
the MIV star AU Microscopii presented by France et al. (2007).
The first step is to identify the COS band H2 lines that offer
the most stringent upper limits, which will be a combination of
intrinsic line strength and COS sensitivity at the corresponding
wavelength. For this purpose, the tightest limit is set by the non-
detection of the C–X (1–4) Q(3) H2 line at 1163.81 Å. Using
the measured upper limit on this O vI-pumped H2 emission line
flux ($1.1 \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$), we can calculate a limit to the
total fluorescent output from the O vI-pumped cascade. The
total emitted flux out of the electrovibrational state ($n', v', J'$),
$\sum_j F_{ij}$, is given by

$$\sum_j F_{ij} = F_{ik} \left( \frac{A_{i,j}}{\sum_k A_{i,k}} \right)^{-1} (1 - \xi_i)^{-1}, \quad (A1)$$

where $i$ refers to the upper state ($n', v', J'$). The indices $j$, $k$, and $l$
refer to the lower states ($n''v'', J''$). $F_{ik}$ is the upper limit of the flux in the COS band lines (in photons s$^{-1}$ cm$^{-2}$). The ratios of
individual to total Einstein A values (Abgrall et al. 1993b) are
the branching ratios, and $\xi_i$ is a correction for the efficiency of
predissociation in the excited electronic state (Liu & Dalgarno
1996). In the case of emission excited by coincidence with O vI,
we are concerned with Werner band emission ($n''-n'v''\rightarrow C-X \equiv C^1\Pi_g-X^3\Sigma^+_u$, $v'' = 1$, and $v' = 4$ for the 1163.81 Å
line. In general form, Equation (A1) must also be summed over the possible redistribution over rotational ($\Delta J = \pm 1$, 0) states,
however, the present case is simplified due to the parity selection
rules that forbid Q branch ($\Delta J = 0$) transitions to mix with R ($\Delta J = -1$) and P ($\Delta J = +1$) branches. The predissociation
fraction for the Werner bands is zero ($\xi_i = 0$; Ajello et al.
1984).

Following this procedure, we arrived at the total emitted photon
flux, derived from the observed (1–4) 1163.81 Å upper limit. Applying Equation (A1), we find that the limit to the total emitted
flux from the O vI-pumped H2 cascade is $\sum_j F_{ij} < 4.0 \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$. In order to convert this emission upper limit into a flux limit on the exciting O vI line, some assumptions must be made regarding the geometry and characteristics of the H2 population. The H2 covering fraction will likely be 0.5 or less, depending on the standoff distance
between the O vI emitting region and the inner edge of the
disk. We will use 0.5 for the purposes of this calculation. In
Section 3.1, we show that the temperature of the molecular
phase of the circumstellar disk has $2500 \lesssim T(H2) \lesssim 4000$ K,
so we assume a thermal width of 2500 K for the H2 absorption
at O vI. The upper limit to the exciting flux is found by balancing
the number of absorbed photons with the maximum line flux that
can be accommodated without producing a detectable level of
H2 emission. A total column density of $N$(H2) $\approx 3 \times 10^{16}$ cm$^{-2}$
is a rough estimate for the 2M1207 circumstellar disk value.
This is the value where the $[v, J] = [1, 3]$ absorption line begins
to saturate (for a 2500 K population), meaning that the total
number of absorbed photons rises slowly from this column until
damping wings become present, at the unrealistically large total
column of $\sim 10^{20}$ cm$^{-2}$. This total H2 column corresponds to a
column density in the $N(v, J) = N(1, 3)$ state of $5.7 \times 10^{14}$ cm$^{-2}$.
Using the peak of the O vI emission as a free parameter, we find
that the total number of photons absorbed reaches the upper
limit on the total number of emitted photons for an O vI $\lambda1032$
line strength of $I_{1032} < 9.5 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$. We see that
given the number of assumptions made, one cannot place a more
stringent limit on the O vi flux than using the G140L segment B observation. If one had an independent measure of the column density (from near- or mid-IR rovibrational emission lines, for example), this method would be far more robust, however, it is very unlikely that these lines could be detected with current IR instruments (e.g., Lupu et al. 2006; France et al. 2007).

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