

HUBBLE SPACE TELESCOPE NICMOS OBSERVATIONS OF NGC 1333: THE RATIO OF STARS TO SUBSTELLAR OBJECTS

JULIA GREISSL AND MICHAEL R. MEYER

Steward Observatory, University of Arizona, Tucson, AZ, USA; jgreissl@as.arizona.edu, mmeyer@as.arizona.edu

BRUCE A. WILKING AND TINA FANETTI

Department of Physics and Astronomy, University of St. Louis, St. Louis, MO, USA

GLENN SCHNEIDER

Steward Observatory, University of Arizona, Tucson, AZ, USA

THOMAS P. GREENE

NASA Ames Research Center, Moffet Field, CA, USA

AND

ERICK YOUNG

Steward Observatory, University of Arizona, Tucson, AZ, USA

Received 2006 June 5; accepted 2006 November 14

ABSTRACT

We present an analysis of NICMOS photometry and low-resolution grism spectroscopy of low-mass stars and substellar objects in the young star-forming region NGC 1333. Our goal is to constrain the ratio of low-mass stars to substellar objects down to $20M_{\text{Jup}}$ in the cluster, as well as constrain the cluster initial mass function (IMF) down to $30M_{\text{Jup}}$, in combination with a previous survey of NGC 1333 by Wilking et al. Our survey covers four fields of $51.2'' \times 51.2''$, centered on brown dwarf candidates previously identified in Wilking et al. We extend previous work based on the use of a water vapor index for spectral typing to wavelengths accessible with NICMOS on the *Hubble Space Telescope*. Spectral types were derived for the 14 brightest objects in our fields, ranging from $\leq M0$ to M8, which, at the age of the cluster (0.3 Myr), correspond to a range in mass of $\geq 0.25\text{--}0.02 M_{\odot}$. In addition to the spectra, we present an analysis of the color-magnitude diagram using pre-main-sequence evolutionary models of D’Antona & Mazzitelli. Using an extinction-limited sample, we derive the ratio of low-mass stars to brown dwarfs. Comparisons of the observed ratio to that expected from the field IMF of Chabrier indicate that the two results are consistent. We combine our data with those of Wilking et al. to compute the ratio of intermediate-mass stars ($0.1\text{--}1.0 M_{\odot}$) to low-mass objects ($0.03\text{--}0.1 M_{\odot}$) in the cluster. We also report the discovery of a faint companion to the previously confirmed brown dwarf ASR 28, as well as a possible outflow surrounding ASR 16. If the faint companion is confirmed as a cluster member, it would have a mass of $\approx 5M_{\text{Jup}}$ (mass ratio 0.15) at a projected distance of 350 AU, similar to that of 2MASS 1207–3923B.

Key words: infrared: stars — ISM: individual (NGC 1333) — stars: formation — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — stars: pre-main-sequence

1. INTRODUCTION

The shape of the initial mass function (IMF) and its connection to the initial physical conditions in molecular clouds remains one of the fundamental questions in star formation. More specifically, does the young cluster IMF mimic the integrated field-star IMF, even to very low masses? Is there a low-mass cutoff to the substellar mass function?

The IMF over the full range of stellar masses has been extensively studied in past decades, starting with Miller & Scalo (1979), with updates by Kroupa et al. (1993) and Chabrier (2003). It is generally accepted that young clusters exhibit a Salpeter-like IMF above $1 M_{\odot}$, flattening out toward low-mass stars. Studies of the IMF have been concentrated on young clusters, because they offer several beneficial characteristics. Their populations are less likely to have undergone significant dynamical mass segregation compared to older clusters, which means that a small field can yield a sample representative of the whole cluster. In addition, young low-mass stars are still located significantly above the main sequence and are thus several times brighter than their main-sequence counterparts. Finally, young clusters are fairly compact, meaning that they occupy a small area in the sky, and they are often situated

in front of a large amount of extinction. This minimizes both foreground contamination by field stars and background contamination by giants.

Recent studies of Galactic young clusters have been extended down to the hydrogen-burning limit, to a distance of 1 kpc (Luhman et al. 1998; Hillenbrand 1997; Carpenter et al. 1997). These studies suggest that the IMF is universal above $0.1 M_{\odot}$ (Meyer et al. 2000). The shape of the IMF in the substellar regime is less well constrained, and we are only now beginning to probe it in great detail (Hillenbrand & Carpenter 2001; Briceño et al. 2002). Several clusters have been studied down to $30M_{\text{Jup}}$ in both photometric and spectroscopic studies, among them the Orion Nebula cluster (Slesnick et al. 2004), IC 348 (Najita et al. 2000; Luhman et al. 2003), the Taurus star-forming region (Luhman 2004a; Guieu et al. 2006), the Chameleon I star-forming region (Luhman 2004b), and the Pleiades (Moraux et al. 2003).

Searching for IMF variations at the lowest masses can tell us about possible low-mass cutoffs in the IMF, which might be associated with the minimum mass for opacity-limited fragmentation ($\approx 10M_{\text{Jup}}$; Rees 1976). Evidence presented by Briceño et al. (2002; see also Luhman 2004b) showed the Taurus star-forming region to exhibit a dearth of brown dwarfs, by as much as a factor

TABLE 1
LOG OF OBSERVATIONS

| Obs. Field | R.A. (J2000.0) | Decl. (J2000.0) | F110 Exp. Time (s) | F160 Exp. Time (s) |
|-------------------------|----------------|-----------------|-----------------------|-----------------------|
| S1 | 03 28 56.41 | +31 15 33.1 | 766 | 383 |
| S2 | 03 29 03.16 | +31 16 58.7 | 766 | 383 |
| S3A | 03 29 11.97 | +31 16 58.2 | 766 | 383 |
| S3B..... | 03 29 12.38 | +31 17 25.2 | 766 | 383 |
| N2..... | 03 29 11.65 | +31 23 19.5 | 510 | 256 |
| N7..... | 03 29 04.1 | +31 25 29.5 | 255 | 128 |
| Roque 25..... | 03 48 30.6 | +22 44 50 | 256 | 128 |
| Roque 33..... | 03 48 49.0 | +24 20 25 | 256 | 128 |
| Teide 1 | 13 05 40.18 | -25 41 06.0 | 256 | 128 |
| J0205.5-1159..... | 02 05 29.40 | -11 59 29.7 | 256 | 128 |
| σ Ori 60 | 05 39 37.62 | -02 30 45.64 | 256 | 128 |
| σ Ori 47/27..... | 05 38 16.00 | -02 40 23.80 | 256 | 128 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

of 2, when compared to the denser region of the Orion Nebula cluster. However, newer studies covering a larger area of Taurus suggest that this deficiency is not as marked as previously reported (Luhman et al. 2007). Nonetheless, the low-mass IMF remains a strong candidate for variations with cluster characteristics. This suggests a possible connection between stellar density and the shape of the low-mass IMF. NGC 1333 is a young star-forming region intermediate in density between Taurus and Orion, making it an ideal test bed to search for variations in the low-mass IMF and explore differences based on the star-forming environment.

The NGC 1333 reflection nebula is part of the Perseus molecular cloud complex at an estimated distance of 300 pc (de Zeeuw et al. 1999; Belikov et al. 2002). The proximity of the cluster allows us to study the IMF down to very low masses. It was first identified as a star-forming region in Herbig & Rao (1972; see also Herbig 1974; Strom et al. 1976). Infrared surveys have since revealed a large population of low-mass objects (Aspin et al. 1994; Lada et al. 1996; Wilking et al. 2004). These studies have characterized the young stellar population over large areas of the cloud, but have not fully probed the very lowest masses because of a lack of sensitivity.

We have performed a new, deep ($J < 21$ mag) near-infrared survey over a limited area in NGC 1333 using the *Hubble Space Telescope* (*HST*) NICMOS. This study is complete to magnitudes fainter than those used in previous studies, thus allowing the characterization of a significant extinction-limited sample of brown dwarfs. This enables us to study the population of very low mass objects in detail. We obtained photometry as well as infrared spectroscopy. The spectra enable estimates of stellar masses and ages for individual objects by comparing their positions in the H-R diagram with pre-main-sequence (PMS) evolutionary models. The spectra further help us adopt models to interpret our flux-limited survey by constraining a mass-luminosity relation appropriate for the cluster. We construct an extinction-limited sample to explore the shape of the mass function in the cluster.

The paper is structured as follows. Section 2 describes the observations and data reduction, followed by a description of the photometric and spectroscopic analysis in § 3. Section 4 details the results, and places them in context with recent literature. A summary and conclusions are presented in § 5.

2. OBSERVATIONS AND DATA REDUCTION

We obtained images of the young cluster NGC 1333, using camera 3 of NICMOS (NIC3) as part of *HST* program 9846. Six fields, each $51.2'' \times 51.2''$ with a plate scale of $0.2'' \text{ pixel}^{-1}$, were obtained between 2004 January 15 and 2005 August 11, using

12 *HST* orbits. In addition to the six NGC 1333 fields, we also obtained observations for seven additional objects. Six of these are previously confirmed brown dwarfs from older star-forming regions and the field. We obtained these observations in order to explore the surface gravity dependence of our spectral typing technique. The coordinates for each of the fields, in addition to the total exposure times, are listed in Table 1. For the position of our fields with respect to molecular line maps of the region, please see Figure 1 in Wilking et al. (2004). Each field was observed in F110W, F160W, and the grism G141, which cover $0.8\text{--}1.4 \mu\text{m}$ (broadband), $1.4\text{--}1.8 \mu\text{m}$ (broadband), and $1.1\text{--}1.9 \mu\text{m}$ (dispersed), respectively. F110W is roughly equivalent to the *J* band, and F160W is roughly equivalent to the *H* band. The fields were observed in a 2×2 dither pattern, with an offset of 1.75 pixels. The observations were subdivided into visits, with each visit covering one field in G141, F160W, and F110W, in that order. Since the grism G141 is slitless, stars that are close in either the *x*- or the *y*-direction can have overlapping spectra for each individual visit. To minimize this overlap, we observed each photometric and spectroscopic field in three visits, at roll angles offset $30^\circ\text{--}75^\circ$ and $105^\circ\text{--}150^\circ$ between subsequent visits. We were unable to obtain three separate roll angles for the fields N2 and N7, causing their final photometry to be less deep than that of the other four fields. For this reason, they are excluded from the photometric analysis and used only in the spectroscopy section. All four of these fields lie in the southern half of the cluster, and the complete area covered by our photometric survey is 2.9 arcmin^2 . Compared to the combined areas of the surveys by Wilking et al. (2004) and Aspin et al. (1994), which surveyed both the north and south components of the cluster and covered 79 and 81 arcmin^2 , respectively, our photometric survey covers $\approx 2\%$ of the area of NGC 1333. Total integration times for the fields with three roll angles, including dithers and multiple roll angles, were 383 s for F160W, 766 s for F110W, and 4608 s for G141 per field.

2.1. Photometry

Data reduction was carried out using a combination of IRAF and custom IDL routines. The methods described below closely follow those used in Liu et al. (2003b). The images were dark- and sky-subtracted using combined dark plus sky frames created with the routine NICKYDARK in the NICRED package for IRAF (McLeod 1997). Cosmic rays and bad pixels were located and removed using the routine FULLFITBAM, by searching for discontinuities in the flux in each pixel over time. After dark and sky subtraction and cosmic-ray reduction, there did not appear to

TABLE 2
PHOTOMETRY OF SOURCES DETECTED IN *J* OR *H* BAND

| Object ID | R.A. (J2000.0) | Decl. (J2000.0) | <i>J</i> | <i>J</i> _{err} | <i>H</i> | <i>H</i> _{err} | ASR ID ^a | Notes |
|-----------|----------------|-----------------|----------|-------------------------|----------|-------------------------|---------------------|---------------------------|
| S1-1 | 03 28 54.938 | +31 15 29.65 | 16.09 | 0.14 | 14.96 | 0.05 | 109 | |
| S1-2 | 03 28 55.334 | +31 15 53.83 | N/A | N/A | 20.00 | 0.23 | N/A | |
| S1-3 | 03 28 56.020 | +31 15 49.28 | 20.62 | 0.25 | 19.05 | 0.10 | 16 | Possible outflow |
| S1-4 | 03 28 56.959 | +31 15 50.93 | 15.10 | 0.13 | 14.06 | 0.04 | 15 | |
| S1-5 | 03 28 57.162 | +31 15 35.19 | 15.28 | 0.15 | 13.95 | 0.05 | 17 | |
| S1-6 | 03 28 57.388 | +31 15 36.72 | 17.83 | 0.18 | 16.30 | 0.07 | N/A | |
| S1-7 | 03 28 57.990 | +31 15 50.36 | N/A | N/A | 21.03 | 0.39 | N/A | |
| S1-8 | 03 28 58.058 | +31 15 48.65 | 19.24 | 0.32 | 16.67 | 0.10 | N/A | |
| S2-1 | 03 29 01.673 | +31 17 12.25 | 20.44 | 0.31 | 18.96 | 0.16 | N/A | |
| S2-2 | 03 29 01.876 | +31 16 43.98 | 21.79 | 0.62 | 19.79 | 0.24 | N/A | |
| S2-3 | 03 29 01.929 | +31 16 53.22 | 16.77 | 0.15 | 15.47 | 0.06 | 11 | |
| S2-4 | 03 29 02.654 | +31 17 14.84 | 22.44 | 0.66 | 21.45 | 0.48 | N/A | |
| S2-5 | 03 29 04.077 | +31 16 59.71 | 20.95 | 0.39 | 19.36 | 0.19 | N/A | |
| S2-6 | 03 29 04.114 | +31 17 07.46 | 13.25 | 0.10 | 12.67 | 0.03 | 8 | |
| S2-7 | 03 29 04.179 | +31 16 50.93 | 18.74 | 0.28 | 16.56 | 0.09 | 9b | |
| S2-8 | 03 29 04.229 | +31 16 50.60 | 17.15 | 0.24 | 14.80 | 0.09 | 9a | |
| S2-9 | 03 29 04.713 | +31 16 59.03 | 15.00 | 0.17 | 13.44 | 0.06 | 105 | |
| S2-10 | 03 29 05.413 | +31 17 02.57 | 20.56 | 0.41 | 18.33 | 0.14 | N/A | |
| S3B-6 | 03 29 10.716 | +31 17 21.34 | 21.36 | 0.44 | 20.04 | 0.25 | N/A | |
| S3A-1 | 03 29 10.787 | +31 16 43.99 | 16.07 | 0.17 | 14.55 | 0.06 | 23 | |
| S3A-2 | 03 29 11.272 | +31 17 18.85 | 13.95 | 0.10 | 13.30 | 0.04 | 24 | Both in frame S3A and S3B |
| S3B-3 | 03 29 11.353 | +31 17 17.52 | 13.99 | 0.09 | 13.31 | 0.03 | 24 | Both in frame S3A and S3B |
| S3A-3 | 03 29 12.923 | +31 17 08.34 | 15.94 | 0.11 | 15.38 | 0.04 | 25 | Both in frame S3A and S3B |
| S3B-4 | 03 29 13.008 | +31 17 07.01 | 16.02 | 0.15 | 15.40 | 0.04 | 25 | Both in frame S3A and S3B |
| S3A-4 | 03 29 13.014 | +31 16 41.12 | 18.19 | 0.22 | 16.30 | 0.08 | 26 | |
| S3B-7 | 03 29 13.034 | +31 17 37.34 | 20.39 | 0.32 | 18.80 | 0.13 | 28b | |
| S3B-1 | 03 29 13.078 | +31 17 38.24 | 15.24 | 0.10 | 14.62 | 0.04 | 28a | |
| S3A-5 | 03 29 13.269 | +31 17 17.35 | 20.21 | 0.41 | 17.54 | 0.12 | 27 | Both in frame S3A and S3B |
| S3A-6 | 03 29 13.283 | +31 16 45.91 | 23.37 | 2.38 | 19.47 | 0.37 | N/A | |
| S3B-5 | 03 29 13.351 | +31 17 16.01 | 20.14 | 0.39 | 17.55 | 0.12 | 27 | Both in frame S3A and S3B |
| S3B-2 | 03 29 13.655 | +31 17 43.48 | 16.14 | 0.20 | 14.19 | 0.07 | 29 | |
| S3A-7 | 03 29 14.285 | +31 17 00.58 | 21.05 | 0.36 | 19.37 | 0.19 | N/A | |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a ASR refers to Aspin et al. (1994).

be any bias offsets or “pedestal effects” between the different quadrants of the NICMOS chip, which is a common problem experienced with NICMOS (e.g., Liu et al. 2003b). This is because our fields were not very crowded and did not show significant nebulosity, as the pedestal is also dependent on the total charge of the quadrant. The only field that shows any nebulosity is S2. Finally, the images were flat-fielded using the routine NICFLATTEN and the appropriate epoch on-orbit flat fields from the Space Telescope Science Center Institute (STScI) Web site. The dithers were then combined using the IDL software IDP3 (Lytle et al. 1999), aligning the different frames by their world coordinate system, as well as resampling the images by a factor of 2 using a bicubic sinc to increase the resolution of the images. The three roll angles were combined using IDP3, first by rotating the images to align in angle and then by shifting the images to correct for offsets in *x* and *y*. For both of these routines, flux was conserved.

All sources presented in the color-magnitude diagram (CMD; § 3.3) were detected in both the F160W and F110W filters using the IRAF routine DAOFIND, with a 10σ detection threshold. Even with the low amount of nebulosity, every image still had some spurious detections that were removed by visual inspection. We took advantage of the three roll angles for each field in order to help identify false detections. If a source appeared in the same position for each roll angle, it was assumed to be genuine. False detections were located at their position on the chip for only one roll angle.

Since the fields were not crowded, the photometry was performed using the IRAF routine APPHOT. The optimal aperture size was calculated to be 8 pixels in radius, with the sky background measured using an annulus between 10 and 12 pixels around each object. Aperture corrections were calculated out to 25 pixels using several bright, nonsaturated stars and applied to the photometry. The aperture corrections derived were 0.054 ± 0.008 mag for m110 and 0.073 ± 0.008 mag for m160, where m110 and m160 refer to the magnitudes associated with F110W and F160W, respectively. Errors in the photometry were computed using PHOT and agreed with errors computed by comparing photometry derived from each separate roll angle. Two objects, ASR 9 and ASR 28, showed close companions. For these, an aperture radius of 3 pixels was used, with appropriate aperture corrections of 0.32 ± 0.03 mag for m110 and 0.38 ± 0.02 mag for m160, and a sky annulus of 20–24 pixels, so as to exclude flux from the companion. In addition, one object, ASR 16, appears to have extended nebulosity associated with it. Because of this, photometry was extracted for this object in the same manner as for the binaries, to minimize contamination from the nebulosity. This source is further discussed in § 4.2. A total of 25 unique sources were detected, which are listed in Table 2.

NICMOS magnitudes were calibrated using zero points of 1775 and 1093 Jy and were calibrated to the Vega system using the conversions of 2.873×10^{-6} and 2.776×10^{-6} Jy ADU⁻¹ s⁻¹ for F110W and F160W, respectively. Detection limits were

TABLE 3
SPECTRAL STANDARDS

| ID | R.A. (J2000.0) | Decl. (J2000.0) | Spectral Type ^a | Q^b | Prop ID |
|-------------------|----------------|-----------------|----------------------------|-------------|---------|
| GL 328..... | 08 55 07.62 | +01 32 47.4 | M0 | 0.87 | 7322 |
| GL 908..... | 23 49 12.53 | +02 24 04.4 | M1 | 0.98 | 7830 |
| GJ 623..... | 16 24 09.32 | +48 21 10.5 | M2.5 | 1.25 ± 0.01 | 7322 |
| GL 388..... | 10 19 36.50 | +19 52 10.6 | M3 | 1.38 | 7322 |
| GL 569a..... | 15 43 02.12 | +26 16 36.0 | M3 | 1.50 | 7322 |
| GJ 748..... | 16 24 09.32 | +48 21 10.5 | M3.5 | 1.15 | 7830 |
| GL 896a..... | 23 31 52.18 | +19 56 14.1 | M3.5 | 1.46 | 7830 |
| GL 213..... | 05 42 09.27 | +12 29 21.6 | M4 | 1.56 | 7322 |
| GJ 699..... | 17 57 48.50 | +04 41 36.2 | M4 | 1.16 ± 0.01 | 7322 |
| GJ 473a..... | 12 33 16.3 | +09 01 26 | M4 | 1.26 | 7830 |
| GL 83.1..... | 16 36 21.45 | -02 19 28.5 | M4.5 | 1.56 | 7322 |
| GJ 1245a..... | 19 53 54.48 | +44 24 53.3 | M5.5 | 1.23 ± 0.01 | 7830 |
| GL 406..... | 10 56 28.99 | +07 00 52.0 | M6 | 1.16 ± 0.02 | 7322 |
| GJ 1111..... | 08 29 49.35 | +26 46 33.7 | M6.5 | 1.59 | 7322 |
| GJ 473b..... | 12 33 19.1 | +09 01 10 | M7 | 1.67 ± 0.01 | 7830 |
| LHS 3003..... | 14 56 38.31 | -28 09 47.4 | M7 | 2.03 | 7322 |
| VB 8..... | 16 55 35.29 | -08 23 40.1 | M7 | 1.68 | 7322 |
| VB 10..... | 19 16 57.66 | +05 09 00.4 | M8 | 2.10 | 7322 |
| Teide 1..... | 13 05 40.18 | -25 41 06.0 | M8 | 1.69 ± 0.03 | 9846 |
| GL 569b..... | 15 43 03.8 | +26 15 59 | M8.5 | 2.29 | 7322 |
| LHS 2924..... | 14 28 43.33 | +33 10 37.9 | M9 | 2.42 | 7322 |
| Roque 33..... | 03 48 49.0 | +24 20 25 | L0 | 1.52 ± 0.06 | 9846 |
| Roque 25..... | 03 48 30.6 | +22 44 50 | L0 | 2.16 ± 0.22 | 9846 |
| Kelu-1..... | 13 05 40.18 | -25 41 06.0 | L2 | 2.79 | 7830 |
| J1228-1547..... | 12 28 15.23 | -15 47 34.2 | L5 | 3.51 | 7830 |
| J0205.5-1159..... | 02 05 29.40 | -11 59 29.7 | L7 | 3.71 ± 0.22 | 9846 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Spectral types are from Kirkpatrick et al. (1991), Henry et al. (1994), Martín et al. (2000), and Kirkpatrick et al. (1999).

^b Errors for Q are only given for objects with four or more spectra.

assessed using artificial-star tests. Artificial stars were added to the images in 0.5 mag steps, using a point-spread function (PSF) derived from bright, nonsaturated sources. The recovery fraction of these stars was then computed using the same detection technique as described above. The 90% completeness limits were found to be $m160 \approx 20.5$ mag and $m110 \approx 21.0$ mag. The NICMOS magnitudes $m110$ and $m160$ were transformed to the California Institute of Technology (CIT) system, J and H , by comparing magnitudes for sources in the survey that also had Two Micron All Sky Survey (2MASS) photometry (a total of 12 objects). The 2MASS photometry was converted to the CIT system using the transformations of Carpenter (2001). A linear regression was then performed to obtain color transformations between the HST magnitudes and the CIT system. The following color corrections were determined:

$$\begin{aligned}
 H &= m160 + (0.189 \pm 0.030) \\
 &\quad + (0.120 \pm 0.025)(m110 - m160), \\
 J - H &= (0.132 \pm 0.073) + (0.760 \pm 0.060)(m110 - m160).
 \end{aligned}$$

These color transformations were used to transform the NICMOS magnitudes to CIT, with the J magnitudes calculated as $J = (J - H) + H$.

Relative astrometry for each object was determined using the world coordinate system in the header of the NICMOS images, together with the XY2SKY routine in the WCSTools package (Mink 2002). The derived astrometry was compared with previously determined coordinates from 2MASS and showed no systematic offset. All coordinates presented in Table 3 are estimated to be accurate to $\leq 1.5''$.

2.2. Spectroscopy

The spectroscopic observations were performed with the grism G141, which is centered at $1.4 \mu\text{m}$, with a wavelength coverage between 1.2 and $1.9 \mu\text{m}$ and a resolution of $\approx 200 \text{ pixel}^{-1}$. This covers the water-band feature at $1.4 \mu\text{m}$ that is expected in the atmospheres of cool objects and is difficult to observe from the ground, making HST ideal for these observations. To reduce these data, the images were first run through the HST pipelines CalnicA and CalnicB. These pipelines perform the dark subtraction, using artificial dark frames from the STScI Web site, as well as cosmic-ray reduction. The pipelines were not used to co-add either the dithers or the roll angles, because this did not improve the quality of the spectra over extracting them from individual images. This means that for each object in the NGC 1333 sample, there can be a maximum of 12 extracted spectra. The spectra were extracted using the custom IDL routine NICMOSlook (Pirzkal et al. 1998), which was designed to deal specifically with NICMOS grism data. NICMOSlook reduces spectra in a standard way, by tracing the spectrum across the chip and summing the flux in the spatial dimension as well as subtracting a background region set by the user at each wavelength. To extract spectra, NICMOSlook needs a spectroscopic as well as a photometric image in order to perform the wavelength calibration. The photometric image gives the true location of the object's position, which then gives the zero point for the wavelength of the spectrum. The photometric image used was the F160W image because its central wavelength is closer to the central wavelength of G141. The spectra were extracted with an extraction width of roughly 2 times the FWHM of the spectra, in general ≈ 4 pixels. The background size was varied, depending on the crowding of the field. NICMOSlook

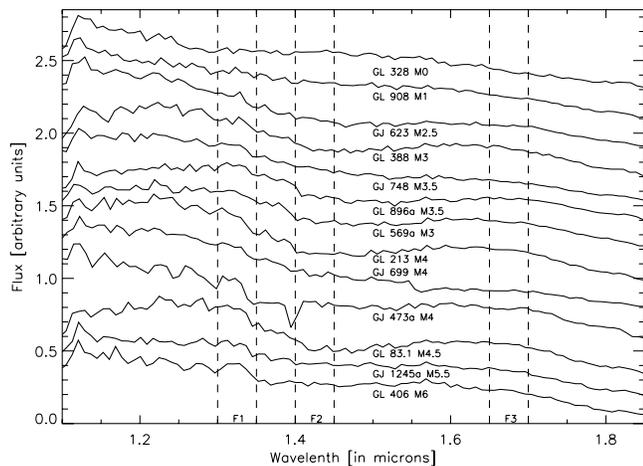


FIG. 1.—NICMOS G141 spectra of field dwarf standards from M0 to M6.

also flat-fields the spectra during the extraction. This is necessary because the quantum efficiency of the detector changes with both wavelength and position. For this reason, the spectra cannot be flat-fielded before extraction. NICMOSlook flat-fields the spectra using a set of narrowband flat-field images, which are chosen according to the date of the observations, from which the software constructs a three-dimensional calibration data cube.

Signal-to-noise ratios (S/Ns) were estimated for all extracted spectra in two ways. First, a third-order polynomial was fitted to the combined average spectrum in the spectral region between 1.5 and 1.8 μm , and the rms of the difference between the observed continuum and the fit per pixel was calculated. Second, a S/N was calculated for each individual pixel in the spectrum, by estimating the signal as the mean of each pixel and the noise as the error in the mean from the ensemble of individual spectra for each source. Since there are only four independent extractions for some of the spectra, the error in the mean is not necessarily a high-fidelity estimate for the noise in each pixel. This means that the S/N estimated in this way may overestimate the real S/N of the spectra. The S/N of the spectrum is then the average of the S/Ns for all the pixels.

2.3. Spectral Standards

To help calibrate our method for spectral typing, we obtained spectra of seven objects with previously known spectral types (see Table 1), six of which are brown dwarfs. These objects are older than the NGC 1333 sources and were observed to explore the surface gravity dependence in our spectral-typing technique. Of the seven objects, only four had a high enough S/N to be included in the spectral sequence. They span a spectral range from M8 to L7. In addition, we extracted spectra from archival *HST* grism data (program IDs 7322 and 7830; see also Najita et al. 2000) of old low-mass field dwarfs with known spectral types. They span a spectral range from M0 to L5. The spectra are plotted in Figures 1 and 2. All standards used in the spectroscopic analysis are listed in Table 3.

2.4. NGC 1333 Spectra

Spectra were extracted for a total of 14 objects in NGC 1333 from six fields. Depending on the position of the spectra on the chip, such as proximity to other objects and position with respect to the edge of the chip, between 4 and 12 spectra were extracted for each source. The spectra were then combined in a sigma-clipped way, excluding pixels that deviated by more than 3σ . For the

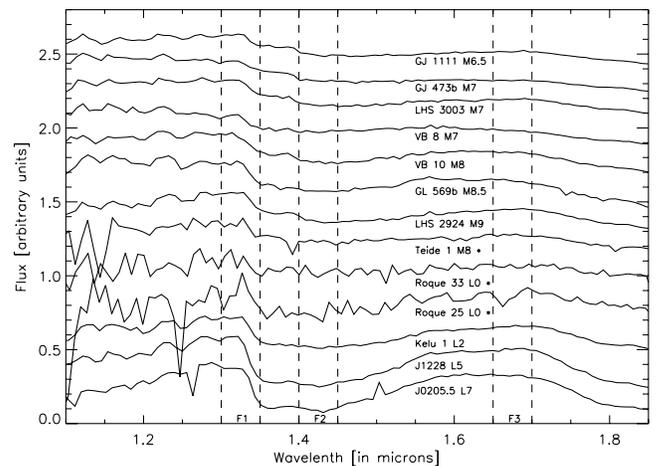


FIG. 2.—NICMOS G141 spectra of field dwarf standards, as well as younger brown dwarfs confirmed through visible spectroscopy between M6.5 and L7. The younger brown dwarfs are denoted by an asterisk.

NGC 1333 objects, the S/N ranged from ≈ 30 to ≈ 100 , and the different S/N estimates agreed well with one another. We compared these values with the expected S/N from the STScI exposure time calculator. In general, these theoretical S/Ns tended to be higher than those estimated from the real spectra. We chose to adopt the S/N estimates from the polynomial fits. Spectra of all NGC 1333 objects are plotted in Figure 3.

3. ANALYSIS

3.1. Spectroscopic Analysis

Spectral typing was performed using a water vapor absorption index centered on the water band at 1.4 μm . This band is sensitive to temperature in cool stars later than M0 (Jones et al. 1994) but not strongly dependent on surface gravity (Gorlova et al. 2003; Wilking et al. 2004). The method described here is similar to the one detailed in Wilking et al. (1999, 2004). We define a Q index that is independent of reddening, using the reddening law of Cohen et al. (1981):

$$Q = \left(\frac{F1}{F2} \right) \left(\frac{F3}{F2} \right)^{0.567},$$

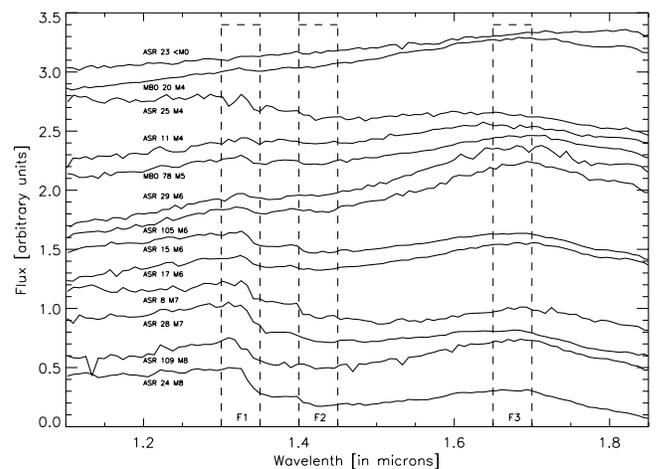


FIG. 3.—NICMOS G141 spectra for candidate brown dwarfs located in NGC 1333, arranged from earliest to latest spectral type.

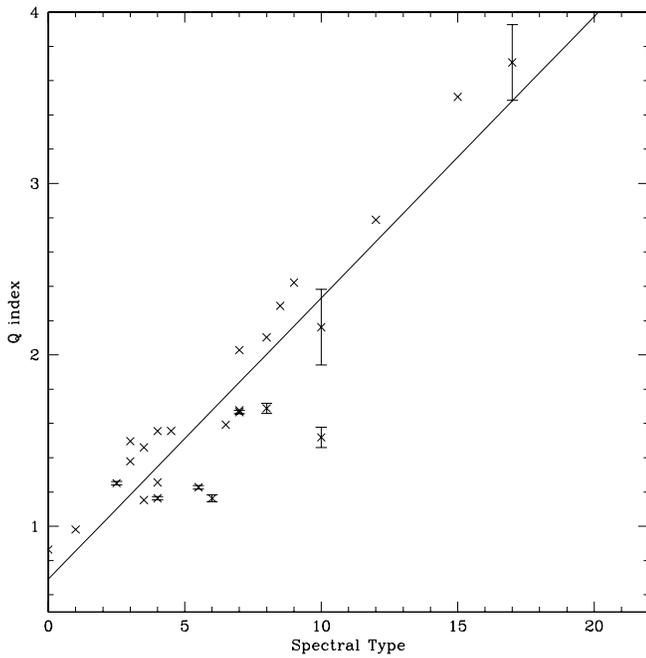


FIG. 4.—Plot of Q vs. spectral type, showing the fit derived for the old field dwarfs and young brown dwarfs.

where F_1 , F_2 , and F_3 are the averaged fluxes in the bands 1.30–1.35, 1.40–1.45, and 1.65–1.70 μm , respectively. The index is independent of reddening because it includes only a ratio of flux bands that have been scaled by an exponent directly related to the applicable reddening law. This accounts for any inherent slope in the spectrum due to interstellar reddening and corrects for it. To optimize our spectral-typing technique, we chose among several different combinations of flux bands and determined which fit of Q versus spectral type for our spectral standards showed the lowest combined error in slope and intercept and at the same time showed the strongest evolution with spectral type. This index was chosen because of its tight fit and its strong evolution with spectral

type, as it directly measures the evolution in the depth of the water-band feature at 1.4 μm . The evolution of Q with spectral type for the NGC 1333 objects is shown in Figure 3. The uncertainty in Q was estimated by calculating Q for each individual spectrum of an object and then deriving the error in the mean of those values from the multiple spectra that were available for each object. To calibrate the relation between Q and spectral type, a weighted linear fit of Q versus spectral types for the old field dwarf standards and the young confirmed brown dwarfs was performed. Together, these standards have spectral types ranging between M0 and L7 (see Table 3). Spectra with types earlier than M0 were excluded because they show no water-band absorption. This fit gives the relation

$$M \text{ V(subclass)} = (-5.04 \pm 0.31)Q + (-2.22 \pm 0.47).$$

The fit, together with the Q -values for the field dwarfs, is plotted in Figure 4.

We tried to assess the surface gravity dependence of the Q index by deriving a fit of Q versus spectral type for the young brown dwarfs with known spectral types observed as part of our program. Field stars in general have $\log g = 5.0$ – 5.5 , while younger PMS stars have lower surface gravities, between $\log g = 3.0$ and 4.2 (Gorlova et al. 2003). Thus, it is important to explore whether our spectral-typing technique is valid across a range of $\log g$. We performed a fit using only the young confirmed brown dwarfs and compared it to the fit derived using the field dwarf standards. Comparing these two fits, we estimate that assigning spectral types using the old M dwarfs might underestimate their temperature by ≈ 200 K (too late by one subclass). This means that the temperatures we derive are lower limits, similar to previous findings by Gorlova et al. (2003) and Wilking et al. (2004). However, we only have high-S/N spectra for three young brown dwarfs, so these are preliminary results at best.

Table 4 shows the derived spectral types for the NGC 1333 objects. The spectral types derived for the NGC 1333 objects range from $<M0$ to M8. Stars with no water-band absorption features were assigned a spectral type of $<M0$. Uncertainties in Q were between ± 0.01 and 0.17 , which leads to uncertainties in spectral types of approximately one subclass, comparable to the potential

TABLE 4
PROPERTIES OF NGC 1333 OBJECTS, WITH SPECTRAL TYPES

| Object Name ^a | Spectral Type | $\log(T_{\text{eff}})^b$ | $J-H^c$ | $H-K$ | K | A_v^d | $\log(L/L_{\odot})^e$ | r_k^f | Q | Notes ^g |
|--------------------------|-----------------|--------------------------|---------|-------|-------|---------|-----------------------|---------|-----------------|--------------------|
| ASR 24 | M8 \pm 0.8 | 3.38 | 0.60 | 0.42 | 12.94 | 0.0 | -1.52 | 0.02 | 2.02 \pm 0.05 | M8.2 |
| ASR 25 | M4 \pm 0.6 | 3.51 | 0.70 | 0.70 | 15.33 | 0.7 | -2.31 | 0.42 | 1.36 \pm 0.09 | |
| ASR 29 | M5 \pm 0.8 | 3.46 | 2.08 | 1.16 | 13.05 | 13.7 | -1.02 | -0.04 | 1.57 \pm 0.07 | |
| ASR 109 | M8 \pm 0.8 | 3.40 | 1.01 | 0.67 | 13.24 | 3.6 | -1.92 | -0.01 | 1.93 \pm 0.05 | |
| ASR 11 | M4 \pm 0.6 | 3.50 | 1.15 | 0.58 | 14.89 | 4.8 | -2.05 | 0.00 | 1.27 \pm 0.02 | |
| ASR 105 | M6 \pm 0.8 | 3.45 | 1.56 | 1.19 | 12.69 | 8.5 | -1.21 | 0.29 | 1.62 \pm 0.07 | |
| ASR 17 | M6 \pm 0.7 | 3.44 | 1.36 | 0.75 | 13.21 | 4.8 | -1.37 | 0.08 | 1.67 \pm 0.02 | M7.4 |
| ASR 26 | $<M0$ \pm 0.7 | 3.58 | 1.59 | 0.85 | 15.54 | 8.8 | -1.83 | 0.18 | 0.90 \pm 0.01 | |
| ASR 8 | M7 \pm 1.1 | 3.43 | 0.63 | 0.33 | 12.34 | 0.1 | -1.26 | -0.07 | 1.76 \pm 0.17 | |
| ASR 28 | M7 \pm 0.8 | 3.41 | 0.64 | 0.39 | 14.18 | 0.2 | -2.00 | -0.02 | 1.89 \pm 0.05 | Binary |
| ASR 15 | M6 \pm 0.7 | 3.44 | 0.99 | 0.53 | 13.49 | 3.3 | -1.60 | -0.04 | 1.66 \pm 0.03 | M7.4 |
| ASR 23 | $<M0$ \pm 0.6 | 3.58 | 1.48 | 0.76 | 13.33 | 7.8 | -1.04 | 0.16 | 0.89 \pm 0.07 | |
| MBO 20 | M3 \pm 0.6 | 3.51 | 1.75 | 0.88 | 10.91 | 10.9 | -0.17 | -0.05 | 1.19 \pm 0.02 | |
| MBO 78 | M5 \pm 0.7 | 3.47 | 1.78 | 1.18 | 13.37 | 10.8 | -1.35 | 0.16 | 1.45 \pm 0.05 | |

^a ASR designations are from Aspin et al. (1994); MBO designations are from Wilking et al. (2004).

^b Typical errors are ≈ 0.1 .

^c 2MASS photometry for the objects listed. This was used to derive r_k .

^d Typical errors are ≈ 1 .

^e Typical errors are ≈ 0.15 .

^f Typical errors are ≈ 0.1 .

^g Spectral types derived by Wilking et al. (2004).

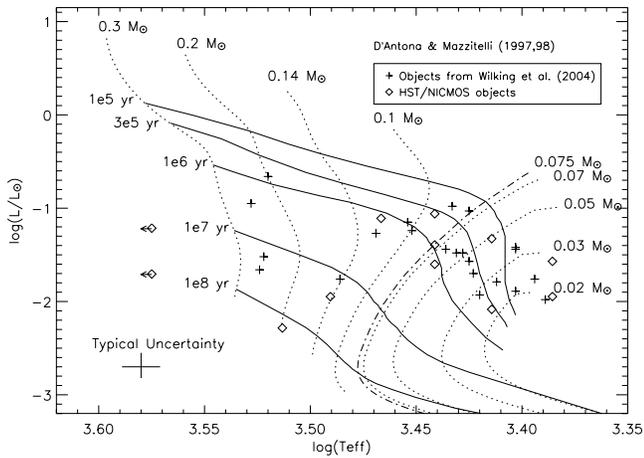


FIG. 5.—H-R diagram of the NGC 1333 objects from our survey, overplotted on DM98 isochrones and tracks, as well as sources from Wilking et al. (2004). For sources in common between the two studies, we defer to this study. Four objects show unusual positions in the H-R diagram. They are commented on in detail in § 3.2.

error in our calibration mentioned above. From this relation, we classify seven objects with spectral types of M6–M8 that are likely brown dwarfs. Three of the objects for which we have derived spectra—ASR 24, ASR 15, and ASR 17—have previous spectral classifications using K -band H_2O absorption bands (Wilking et al. 2004). Both derived spectral types are listed in Table 4 and agree to within the errors. While we did not detect cooler young brown dwarfs than Wilking et al. (2004), we were able to observe similar objects with greater obscuration. Alternative methods of the spectroscopic reduction, as well as a method of spectral typing, are also addressed in detail in Fanetti (2005).

3.2. H-R Diagram

To estimate the age of the cluster, we compared the positions of the NGC 1333 PMS objects in the H-R diagram to theoretical evolutionary tracks by D’Antona & Mazzitelli (1997; F. D’Antona & I. Mazzitelli 1998, private communication, hereafter DM98), as is appropriate for the median cluster age characterizing the low-mass population. First, we converted spectral types derived for the NGC 1333 objects to temperatures, using empirical relations derived from Dahn et al. (2002) and Leggett et al. (1996). The typical uncertainties in temperatures due to uncertainties in spectral types were ≈ 200 K. Luminosities were derived from the dereddened J -band magnitudes. To determine \mathcal{M}_J , we first calculated visual extinctions using the standard relation $A_v = 9.09[(J - H)_{\text{obs}} - (J - H)_0]$ (Cohen et al. 1981), where $(J - H)_0$ is the intrinsic color for a given spectral type. The values of A_v derived for NGC 1333 sources lie between 0 and 14 mag, with six sources having an extinction higher than 5 mag. Values for $\log(L_{\text{bol}}/L_{\odot})$ were calculated from the dereddened J -band magnitudes, after bolometric correction, as $\log(L_{\text{bol}}/L_{\odot}) = 1.89\mathcal{M}_{\text{bol}} - 0.4\mathcal{M}_{\text{bol}}$. We adopt intrinsic colors and bolometric corrections following Wilking et al. (2004). Typical errors in $\log(L_{\text{bol}}/L_{\odot})$ are ± 0.2 dex and are derived based on errors in the J -band magnitude, the distance modulus, and the bolometric correction. The H-R diagram is presented in Figure 5. The luminosities and temperatures for the NGC 1333 objects with spectral types are listed in Table 4. The positions of the brown dwarfs are compared to the theoretical tracks and isochrones from the models of DM98. In addition to our sample, objects in NGC 1333 for which unique spectral types were derived in Wilking et al. (2004) are plotted on the H-R diagram. From these objects, we estimated the cluster to be younger than 1 Myr and chose the DM98 0.3 Myr tracks as ap-

propriate for the median cluster age. It is noteworthy that these ages are relative ages, as absolute ages are model dependent. The objects in the H-R diagram show a scatter around the median age with an overall trend to younger ages for lower mass objects. The scatter is due in part to errors in the luminosities of the objects introduced by errors in the photometry and dereddening. The overall trend toward younger ages for lower mass objects is an effect often observed in H-R diagrams of young stellar clusters. This is most likely an effect of imperfect PMS models and not a real effect of an age-mass relation for the cluster. The median age of 0.3 Myr for our H-R diagram corresponds to the break point of the mass bins for our analysis ($0.1 M_{\odot}$), thus ensuring that we are using the correct mass-luminosity relationship at that mass.

Four objects exhibit unusual positions in the H-R diagram, with ages much older than 1 Myr, appearing underluminous compared to their PMS counterparts. Two of these objects have spectral types earlier than M0, meaning they show no water-band absorption feature in their spectra. These two objects could be background stars. The other two objects, both of spectral type M4, also appear fainter than expected but could still be cluster members. Note also three objects from Wilking et al. (2004) that lie below the expected locus for the majority of the PMS objects. These objects are specifically addressed in Wilking et al. (2004), but the following reasoning applies to them as well. The sources could have an infrared excess, causing a dilution of the water absorption bands, leading us to assign a spectral type that is too early. They could also exhibit unresolved scattered light due to a surrounding disk, which would result in bluer colors and could cause us to underestimate extinction and thus luminosity. There is evidence that disks around young brown dwarfs are ubiquitous. Liu et al. (2003a), for example, found that 77% of a sample of young brown dwarfs in IC 348 and Taurus showed evidence of a circumstellar disk. To establish whether any of these objects show signs of a disk and thus confirm their youth, in § 3.3 we attempt to assess whether they show an infrared excess. This method is described in detail in Wilking et al. (1999). Since we cannot rule out either solution at this point, it is impossible to assign a mass to the two M4 sources, or an age, if they are not cluster members. For these reasons, all four sources have been excluded from the mass function analysis. It is possible that other objects in our sample also possess circumstellar disks. However, for most objects, we can expect the effect of the disks on spectral typing to be small (Meyer et al. 1997; Muzerolle et al. 2003). Even if objects show a strong infrared excess, only those with special viewing geometry would be dominated by scattered light, leading us to underestimate the reddening. Further observations will be required to test whether these objects suffer from the effects mentioned.

3.3. K-Band Excess

For NGC 1333 objects with 2MASS photometry, we have estimated the amount of excess emission at K band, defined as $r_k = F_{K_{\text{ex}}}/F_K$,¹ where $F_{K_{\text{ex}}}$ is the flux contribution at K band due to circumstellar material, and F_K is the inherent stellar flux at K band (Wilking et al. 1999, 2004). Values of r_k are listed in Table 4. These estimates are lower limits, since we have assumed no excess at the J or H bands. Two objects, ASR 25 and ASR 105, show moderate K -band excesses. ASR 25 has a peculiar position on the H-R diagram, as mentioned above. The measured K -band excess makes it a likely cluster member; in addition, it may indicate that we have assigned it a spectral type that is too early, which would make

¹ The value of $r_k = F_{K_{\text{ex}}}/F_K = [(1 + r_{\lambda})(10^{(H-K)-(H-K)_0 - 0.065A_v})^{2.5} - 1]$. We have assumed that $r_j = r_h = 0$.

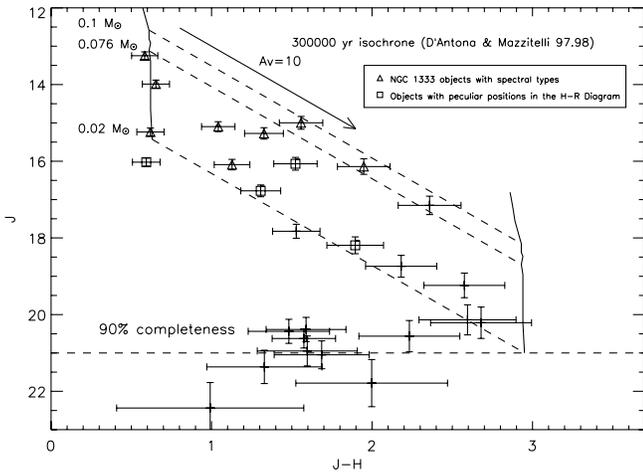


FIG. 6.—NICMOS photometry of sources detected in NGC 1333, transformed into the CIT system together with a 0.3 Myr (D’Antona & Mazzitelli 1997; DM98) isochrone and the reddening vector, also in the CIT system. The 90% completeness limit, derived from artificial-star tests, is also shown. The objects with derived spectral types are marked.

it a brown dwarf, and that it may possess a disk. Most of the other objects show little or no excess emission. It is possible that the lowest mass objects possess disks that are too cool to cause an excess in the K band, as the inner disk temperature is expected to be correlated with stellar luminosity (Pascucci et al. 2003).

3.4. Color-Magnitude Diagram and Extinction-limited Sample

In Figure 6 we present a CMD for the cluster. Also shown is the 0.3 Myr isochrone of DM98, which we adopted based on the H-R diagram discussed above. The isochrone was converted to the CMD by using a set of colors and bolometric corrections, with colors taken from Leggett (1992) and bolometric corrections adopted from Leggett et al. (1996), similar to Wilking et al. (1999). All but 3 out of 25 objects in the CMD appear to lie below the hydrogen-burning limit for a cluster age of 0.3 Myr. This number changes to 5 if we instead assume a cluster age of 1 Myr. The photometry, isochrone, and reddening vector (Cohen et al. 1981) are all presented in the CIT system, and the completeness limit discussed above is also shown. For the age derived above, we define an unbiased sample of low-mass objects in order to constrain the IMF for the cluster. We begin by creating an extinction-limited subsample to ensure that we are sampling the stellar population uniformly and not overrepresenting more luminous (massive), deeply embedded objects. The extinction limits used are $A_v \leq 21.1$ mag and ≤ 18.3 mag for the 0.3 and 1 Myr DM98 isochrones, respectively, corresponding to a mass range of $0.02\text{--}0.1 M_\odot$. For both isochrones, this led to a total sample of 13 (17 – 4) objects, excluding the 4 objects mentioned in § 3.2.

We are sensitive to a mass range lower than $20M_{\text{Jup}}$, albeit for a smaller range of extinctions. However, the DM98 tracks do not extend below this mass limit. Thus, no objects lower than $20M_{\text{Jup}}$ were considered for the cluster mass function. This means that compared to the survey of Wilking et al. (2004), we probe to a higher A_v but not to a lower mass range. There are six objects lying in the region below $20M_{\text{Jup}}$ for an assumed age of 0.3 Myr, two of them very close to the 90% completeness limit. One of them, ASR 28b, is a suspected companion to a brown dwarf primary and will be dealt with in more detail in § 4.3. Another object has been previously classified as ASR 16 and appears to have extended nebulosity associated with it. There are tracks available that extend below $20M_{\text{Jup}}$, such as Baraffe et al. (1998) and Burrows

et al. (1997). However, the NGC 1333 objects lie above the youngest tracks available for both sets of models (1 Myr) in the H-R diagram. Thus, these tracks are most likely not appropriate for NGC 1333, making the DM98 tracks the most appropriate choice for NGC 1333, with a median age of 0.3 Myr. Typical errors in assigning masses from different tracks are approximately a factor of 2 (Hillenbrand & White 2004), although this is only well tested down to $\approx 0.3 M_\odot$.

It is also worth noting that while the rapid drop in the number of objects below $20M_{\text{Jup}}$ looks striking, a fairly large area in the CMD in that region is covered by a small range in mass, namely between $5M_{\text{Jup}}$ and $20M_{\text{Jup}}$, with the masses defined according to tracks by Baraffe et al. (1998) and Burrows et al. (1997). However, it is curious that the objects we do detect seem clustered toward the lower end of this mass range, which is close to our 90% completion limit. We detect no objects between $10M_{\text{Jup}}$ and $20M_{\text{Jup}}$ with low A_v . Due to our small sample size and survey area, this does not allow us to rule out that such objects exist in the cloud. It is, however, suggestive that NGC 1333 could lack objects below $20M_{\text{Jup}}$.

It is possible that at least some of the objects are background contaminants. We have tried to assess the amount of background contamination by adjusting the number counts measured by Lucas et al. (2003) in the Hubble Deep Field–South (HDF-S) using F160W. Using their estimates for number counts, one expects $1.7^{+0.4}_{-1.1}$ objects between 19 and 21 mag in our survey. However, the HDF-S points out of the Galaxy and thus this number should be a lower limit, since NGC 1333 lies closer to the Galactic plane. On the other hand, our NGC 1333 fields lie in front of a large amount of extinction, which will reduce the number of contaminants.

4. DISCUSSION

4.1. Cluster IMF

To constrain the slope of the IMF down to the lowest masses in the cluster, we derive the ratio of very low mass stars ($0.076\text{--}0.1 M_\odot$) to brown dwarfs ($0.02\text{--}0.076 M_\odot$) in our survey. We calculate this ratio to be $R = 3/10 = 0.30 \pm 0.20$, assuming a 0.3 Myr isochrone, with the errors computed due to Poisson statistics. For a 1 Myr isochrone, this ratio increases to $R = 5/8 = 0.625 \pm 0.356$. Both cluster ages give ratios consistent with having been drawn from a Chabrier (2003) system IMF, which gives a most likely ratio (mode) of $R = 0.30$. This corresponds to a slope of $dN/dM \propto M^{-1.1}$ over this range. For the older isochrone, there is a larger number of low-mass stars but still more brown dwarfs, due to the hydrogen-burning limit shifting to a fainter magnitude for a higher cluster age. Both ratios are lower limits, since the low-mass bin has objects for which we do not have spectra, and thus contamination by field stars may lead us to overestimate the number of brown dwarfs relative to low-mass stars in the sample. Above $0.076 M_\odot$, all objects but one have assigned spectral types, which allow us to assess their cluster membership. The object without a spectral type is ASR 9a, which is a previously identified cluster member (Aspin et al. 1994) that we have resolved to be a binary. Below $0.076 M_\odot$, however, there are four objects without spectral types that could be possible field stars, excluding ASR 9b. Thus, these ratios imply upper limits for the slope of the cluster mass spectrum below $0.1 M_\odot$ of $\alpha \leq 1.1$ and ≤ 0.55 for 0.3 and 1 Myr isochrones, respectively, where $dN/dM \propto M^{-\alpha}$ and $\alpha = 2.35$ is the Salpeter slope.

Where does our result stand with regard to comparable clusters and studies? Wilking et al. (2004) have explored the mass spectrum of NGC 1333 using an extinction-limited sample down to $0.04 M_\odot$, finding the ratio of substellar ($0.04\text{--}0.1 M_\odot$) to stellar

TABLE 5
RATIOS OF INTERMEDIATE-MASS STARS TO LOW-MASS OBJECTS

| Region | $N(0.1-1 M_{\odot})/N(0.03-0.1 M_{\odot})$ |
|-------------------------------|---|
| Pleiades ^a | $3.3^{+2.2}_{-1.0}$ |
| Chamaeleon ^b | $5.6^{+2.4}_{-4.5}$ |
| Mon R2 ^c | 5.3 ± 3.35 |
| Taurus ^d | 4.0 ± 1.2 |
| IC 348 ^e | 3.0 ± 0.5 |
| Orion ^f | 3.3 ± 0.6 |
| NGC 1333 | $R_1 = 0.14 \pm 0.047$ $R_2 = 0.64 \pm 0.38$ |

^a Data from Moraux et al. (2003).

^b Data from Luhman (2004a).

^c Data from Andersen et al. (2006).

^d Data from Luhman (2004b).

^e Data from Luhman et al. (2003).

^f Data from Hillenbrand & Carpenter (2000).

objects ($0.1-1 M_{\odot}$) to be $R_{SS} = 1.11^{+0.8}_{-0.4}$. They used this to estimate an upper limit for the slope of the lower end of the mass function of $\alpha \leq 1.6$. This compares well with slopes in the solar neighborhood below the hydrogen-burning limit, which Reid et al. (1999) found to be $1 < \alpha < 2$. Allen et al. (2005) have further attempted to constrain the shape of the field-star IMF below $0.1 M_{\odot}$ and found $-0.6 < \alpha < 0.6$ with 60% confidence and a best fit of $\alpha = 0.3$.

To derive a broader estimate of the cluster mass function, we attempted to combine this survey with that of Wilking et al. (2004) to make the cluster mass function more easily comparable to ratios published for other regions. We combined all objects between 0.1 and $1 M_{\odot}$ from Wilking et al. (2004) with an extinction limit of $A_v \leq 12.8$ mag, with the *HST* objects between 0.03 and $0.1 M_{\odot}$ with an extinction limit of $A_v \leq 21.1$ mag, scaling the number of *HST* objects by the ratios of the survey areas, which is 26.3, as well as the extinctions, which is 0.61. We chose not to include the objects below $0.1 M_{\odot}$ from Wilking et al. (2004), as that survey was estimated to have a large field-star contamination below $0.1 M_{\odot}$. We compute this ratio as $R_1 = N(0.1-1 M_{\odot})/N(0.03-0.1 M_{\odot}) = 0.14 \pm 0.047$, with errors again due to Poisson statistics, using the same cluster age and models for both surveys. This ratio is abnormally low when compared to other published results in this mass range, even within the errors. We have recomputed this ratio for five different young star clusters based on previously published data sets, and results range between ≈ 3 and 6. All surveys either were extinction-limited surveys or were normalized to make them as close to extinction-limited surveys as possible. See Table 5 for computed results and errors.

We then tried to compensate for possible differences in stellar density between the two surveys by introducing a normalization factor in an overlapping mass range between 0.07 and $0.1 M_{\odot}$. This normalization factor was computed to be 3.5 ± 2.0 . This increases the ratio to $R_2 = 0.64 \pm 0.38$, which is higher but still significantly lower than the result for any other cluster. This survey was centered on known brown dwarf candidates. Could this bias our result toward an artificially high number of brown dwarfs? Each of our fields was centered on one brown dwarf candidate, with S3A and S3B having the same candidate but offset from each other. If we remove these three candidates from our ratio, the normalized ratio increases to $R_3 = 0.83 \pm 0.41$, which is consistent with the ratio previously determined. Thus, the inclusion of these objects does not fundamentally change our results.

Due to the expected field-star contamination in Wilking et al. (2004), both ratios are lower limits. However, if the observed

density of brown dwarfs is constant over the molecular core previously surveyed at near-infrared wavelengths, this would imply that brown dwarfs outnumber low-mass stars in the cloud. This may be some indication that brown dwarfs form in a clustered environment within the cloud or are spatially segregated from stars due to dynamical evolution.

4.2. Pre-Main-Sequence Activity

Getman et al. (2002) have conducted a *Chandra* X-ray study of young stellar objects in NGC 1333. Two objects in our study, ASR 8 and ASR 24, show signs of X-ray activity. Both are spectroscopically confirmed brown dwarfs and have virtually no extinction. This means that two of our eight (excluding the four sources discussed in § 3.2), or 25%, of our spectroscopically confirmed brown dwarfs are detected in the X-ray. However, most of the other spectroscopic brown dwarfs in our survey have higher extinctions, decreasing the chance of detecting existing X-ray activity (Preibisch et al. 2005).

One of the objects in our survey, ASR 16, appears to have extended nebulosity associated with it, which is detected only in the F160W image. We were not able to obtain a spectrum for the object or the associated nebulosity. Extended emission in the infrared can be associated with emission-line Herbig-Haro objects or scattered-light envelopes. Since the nebulosity is seen only in the *H* band and not at the *J* band, we explore the possibility of a Herbig-Haro outflow associated with this brown dwarf candidate in NGC 1333, contrary to expectations from scattered-light models (Gomez et al. 1997). Since the nebulosity emission is bright in the F160W filter that covers $1.4-1.8 \mu\text{m}$, it seems that the emission is likely due to $[\text{Fe II}]$ at $1.644 \mu\text{m}$. Such outflows are thought to be associated with accretion onto the central object. Muzerolle et al. (2005) found that signs of accretion are common in the spectra of brown dwarfs. Outflows have also recently been detected around brown dwarfs (Whelan et al. 2005). We tentatively identify this as a candidate outflow around the brown dwarf ASR 16.

4.3. Binaries

There are two sources in our fields that have possible close companions. One was previously identified as ASR 9, which is now resolved into ASR 9a and ASR 9b, with a separation of $0.8''$. The other is ASR 28a, which we have determined has a close companion, ASR 28b. ASR 28a is one of our brown dwarf candidates with a spectral type of M7. ASR 28a and ASR 28b have a separation of $1.2''$ (≈ 350 AU at the distance of NGC 1333), and ASR 28b is 4.2 mag fainter in *H*. If ASR 28b is indeed a cluster member, its colors and apparent *J*-band magnitude (assuming the same A_v as ASR 28a) suggest a temperature of ≈ 1800 K (spectral type L4; Dahn et al. 2002) and a corresponding mass of $5M_{Jup}$ (Burrows et al. 1997) (with an approximate mass ratio of 0.15). If confirmed, this object would be very similar to the reported planetary mass companion of 2MASS 1207-3923 (hereafter referred to as 2MASS 1207). ASR 28b is too faint to extract a spectrum from this survey, and *J*- and *H*-band photometry are not enough to rule out the possibility that it is a background object earlier than M4. To ascertain that it is indeed a cluster member, we hope to obtain a *J*- and *H*-band spectrum of ASR 28b in the near future.

5. SUMMARY AND CONCLUSIONS

We present NICMOS photometry and spectroscopy for six regions in NGC 1333 centered on previously detected brown dwarfs from Wilking et al. (2004). We also analyze spectra of brown dwarf standards from this program and that of Najita et al. (2000). Our results are as follows.

1. We detect a total of 27 sources at H band and 25 sources at J band down to $M_J \leq 21$ mag and $M_H \leq 20.5$ mag over a region of $4 \times (51.2'' \times 51.2'')$.

2. Following Wilking et al. (1999, 2004), we develop a reddening-independent water-band index to estimate spectral types within one subclass from $S/N \geq 30$ NICMOS G141 spectra. With this method, we derive spectral types for 14 sources in NGC 1333, from $\leq M0$ to $M8$. Seven objects have spectral types $\geq M6$, suggesting that they are young brown dwarfs. While we were also sensitive to objects lower in mass than those surveyed by Wilking et al. (2004), we detected only objects of comparable mass but with much higher extinction.

3. Using the CMD and an assumed age of 0.3 Myr for the cluster, we define an extinction-limited sample of 13 sources between 0.02 and $0.1 M_\odot$ with $A_v \leq 21.1$ mag. Although we are sensitive to lower A_v objects, between $10M_{Jup}$ and $20M_{Jup}$, none were detected. Although we are limited by the small number of objects in our survey, this may be indicative of a lack of objects below $20M_{Jup}$ in the cloud.

4. We compute the ratio of low-mass stars to brown dwarfs in the cluster as $R = N(0.076-0.1 M_\odot)/(0.02-0.076 M_\odot) = 0.30 \pm 0.20$, which is consistent with having been drawn from a field-

star IMF (Chabrier 2003). We also compute the ratio of stars to low-mass objects in the cluster, in conjunction with the survey by Wilking et al. (2004), as $R = N(0.1-1 M_\odot)/(0.03-0.1 M_\odot) = 0.64 \pm 0.38$, which lies below published results for other regions. This may indicate that brown dwarfs form in a segregated environment compared to stars in this cluster.

5. Our survey includes several unusual objects, including a possible companion to the spectroscopically confirmed brown dwarf ASR 28, which, if it is a cluster member, would have a mass of $5M_{Jup}$. In addition, one of the brown dwarfs (ASR 16) might have an outflow associated with it, which could be confirmed through follow-up spectroscopy.

This work was supported by a Cottrell Scholar's Award to M. R. M. from the Research Corporation and NASA grant HST13-9846. We would like to thank Morten Andersen for sharing data in advance of publication, as well as for helpful suggestions. We thank Wilson Liu and Wolfram Freudling for assistance with data reduction, and Angela Benoist for preliminary work on spectral reduction.

REFERENCES

- Allen, P. R., Koerner, D. W., Reid, I. N., & Trilling, D. E. 2005, *ApJ*, 625, 385
 Andersen, M., Meyer, M. R., Oppenheimer, B., Dougados, C., & Carpenter, J. 2006, *AJ*, 132, 2296
 Aspin, C., Sandell, G., & Russell, A. P. G. 1994, *A&AS*, 106, 165
 Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
 Belikov, A., Kharchenko, N., Piskunov, A., Schilbach, E., & Scholz, R.-D. 2002, *A&A*, 387, 117
 Briceño, C., Luhman, K., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, *ApJ*, 580, 317
 Burrows, A., Marley, M., Hubbard, W., Lunine, J., Guillot, T., Saumon, D., Freedman, R., Sudarsky, D., & Sharp, C. 1997, *ApJ*, 491, 856
 Carpenter, J. M. 2001, *AJ*, 121, 2851
 Carpenter, J. M., Meyer, M. R., Dougados, C., Strom, S. E., & Hillenbrand, L. 1997, *AJ*, 114, 198
 Chabrier, G. 2003, *PASP*, 115, 763
 Cohen, J. G., Frogel, J. A., Persson, S. E., & Elias, J. H. 1981, *ApJ*, 249, 481
 Dahn, C. C., et al. 2002, *AJ*, 124, 1170
 D'Antona, F., & Mazzitelli, I. 1997, in *Cool Stars in Clusters and Associations*, ed. G. Micela, R. Pallavicini, & S. Sciortino (Florence: Societa Astronomica Italiana), 68
 de Zeeuw, P. T., Hoogerwerf, R., & de Bruijne, J. H. J. 1999, *AJ*, 117, 354
 Fanetti, T. 2005, M.S. thesis, Univ. Missouri, St. Louis
 Getman, K. V., Feigelson, E. D., Townsley, L., Bally, J., Lada, C. J., & Reipurth, B. 2002, *ApJ*, 575, 354
 Gomez, M., Whitney, B. A., & Kenyon, S. J. 1997, *AJ*, 114, 1138
 Gorlova, N., Meyer, M. R., Rieke, G. H., & Liebert, J. 2003, *ApJ*, 593, 1074
 Guieu, S., Dougados, C., Monin, J.-L., Magnier, E., & Martín, E. L. 2006, *A&A*, 446, 485
 Henry, T. J., Kirkpatrick, J. D., & Simons, D. A. 1994, *AJ*, 108, 1437
 Herbig, G. H. 1974, *Lick Obs. Bull.*, 658, 1
 Herbig, G. H., & Rao, N. 1972, *ApJ*, 174, 401
 Hillenbrand, L. 1997, *AJ*, 113, 1733
 Hillenbrand, L., & Carpenter, J. 2000, *ApJ*, 540, 236
 Hillenbrand, L., & White, R. 2004, *ApJ*, 604, 741
 Jones, H. R. A., Longmore, A. J., Jameson, R. F., & Mountain, C. M. 1994, *MNRAS*, 267, 413
 Kirkpatrick, J. D., Henry, T. J., & McCarthy, D. W. 1991, *ApJS*, 77, 417
 Kirkpatrick, J. D., et al. 1999, *ApJ*, 519, 802
 Kroupa, P., Tout, C. A., & Gilmore, G. 1993, *MNRAS*, 262, 545
 Lada, C., Alves, J., & Lada, E. 1996, *AJ*, 111, 1964
 Leggett, S. K. 1992, *ApJS*, 82, 351
 Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, *ApJS*, 104, 117
 Liu, M. C., Najita, J., & Tokunaga, A. T. 2003a, *ApJ*, 585, 372
 Liu, W. M., Meyer, M. R., Cotera, A. S., & Young, E. T. 2003b, *AJ*, 126, 1665
 Lucas, R. A., et al. 2003, *AJ*, 125, 398
 Luhman, K. 2004a, *ApJ*, 602, 816
 ———. 2004b, *ApJ*, 617, 1216
 Luhman, K., Briceño, C., Stauffer, J. R., Hartmann, L., Barrado y Navascues, B., & Caldwell, N. 2003, *ApJ*, 590, 348
 Luhman, K., Joergens, V., Lada, C., Muzerolle, J., Pascucci, I., & White, R. 2007, in *Protostars and Planets V*, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 443
 Luhman, K., Rieke, G., & Lada, C. 1998, *ApJ*, 508, 347
 Lytle, D., Stobie, E., Ferro, A., & Barg, I. 1999, in *ASP Conf. Ser. 172, Astronomical Data Analysis Software and Systems VIII*, ed. D. M. Mehringer, R. L. Plante, & D. A. Roberts (San Francisco: ASP), 445
 Martin, E. L., Brandner, W., Bouvier, J., Luhman, K. L., Stauffer, J., Basri, G., Zapatero Osorio, M. R., & Barrado y Navascues, D. 2000, *ApJ*, 543, 299
 McLeod, B. A. 1997, in *The 1997 HST Calibration Workshop with a New Generation of Instruments*, ed. S. Casarteno et al. (Baltimore: STScI), 281
 Meyer, M. R., Adams, F. C., Hillenbrand, L. A., Carpenter, J. M., & Larson, R. B. 2000, in *Protostars and Planets IV*, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 121
 Meyer, M. R., Calvet, N., & Hillenbrand, L. 1997, *AJ*, 114, 288
 Miller, G. E., & Scalo, J. M. 1979, *ApJS*, 41, 513
 Mink, D. J. 2002, in *ASP Conf. Ser. 281, Astronomical Data Analysis Software and Systems XI*, ed. D. A. Bohlender, D. Durand, & T. H. Handley (San Francisco: ASP), 169
 Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C. 2003, *A&A*, 400, 891
 Muzerolle, J., Calvet, N., Hartmann, L., & D'Alessio, P. 2003, *ApJ*, 597, L149
 Muzerolle, J., Luhman, K. L., Briceño, C., Hartman, L., & Calvet, N. 2005, *ApJ*, 625, 906
 Najita, J. R., Tiede, G. P., & Carr, J. S. 2000, *ApJ*, 541, 977
 Pascucci, I., Apai, D., Henning, T., & Dullemond, C. P. 2003, *ApJ*, 590, L111
 Pirzkal, N., Freudling, W., Thomas, P., & Dolensky, M. 1998, in *ASP Conf. Ser. 145, Astronomical Data Analysis Software and Systems VII*, ed. R. Albrecht, R. N. Hook, & H. A. Bushouse (San Francisco: ASP), 188
 Preibisch, T., et al. 2005, *ApJS*, 160, 582
 Rees, M. 1976, *MNRAS*, 176, 483
 Reid, I. N., et al. 1999, *ApJ*, 521, 613
 Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, *ApJ*, 610, 1045
 Strom, S., Vrba, F., & Strom, K. 1976, *AJ*, 81, 314
 Whelan, E. T., Ray, T. P., Bacciotti, F., Natta, A., Testi, L., & Randich, S. 2005, *Nature*, 435, 652
 Wilking, B., Greene, T. P., & Meyer, M. R. 1999, *AJ*, 117, 469
 Wilking, B., Meyer, M. R., Greene, T. P., Mikhail, A., & Carlson, G. 2004, *AJ*, 127, 1131