New Candidates for Planetary-mass Brown Dwarfs in IC 348

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Abstract

We have used infrared images obtained with the Wide Field Camera 3 on board the Hubble Space Telescope to search for planetary-mass brown dwarfs in the star-forming cluster IC 348. In those images, we have identified 12 objects that have colors indicative of spectral types later than M8, corresponding to masses of \( \lesssim 30 \, M_{\text{Jup}} \) at the age of IC 348. The four brightest candidates have been observed with spectroscopy, all of which are confirmed to have late types. Two of those candidates appear to be young, and thus are likely members of the cluster, while the ages and membership of the other two candidates are uncertain. One of the former candidates is the faintest known member of IC 348 in extinction-corrected \( K_s \) and is expected to have a mass of \( 4–5 \, M_{\text{Jup}} \) based on evolutionary models and an assumed age of 3 Myr. Four of the remaining eight candidates have ground-based photometry that further supports their candidacy as brown dwarfs, some of which are fainter (potentially less massive) than the known members.

Unified Astronomy Thesaurus concepts: Brown dwarfs (185); Star forming regions (1565); Initial mass function (796); Hubble Space Telescope (761)

Supporting material: data behind figure, machine-readable table

1. Introduction

Over the last decade, searches for free-floating brown dwarfs have reached progressively deeper into the mass regime of planetary companions (\( \lesssim 15 \, M_{\text{Jup}} \)) in the solar neighborhood (Cushing et al. 2011; Luhman 2014; Kirkpatrick et al. 2019; Bardalez Gagliuffi et al. 2020; Meisner et al. 2020) and in the nearest young associations (Liu et al. 2013; Kellogg et al. 2015; Burgasser et al. 2016; Schneider et al. 2016; Best et al. 2017; Gagné et al. 2018) and star-forming regions (Scholz et al. 2012; Esplin et al. 2017; Zapatero Osorio et al. 2017; Lodieu et al. 2018; Esplin & Luhman 2019; Robberto et al. 2020). The IC 348 cluster in the Perseus molecular cloud (Herbst 2008) has been one of the most thoroughly surveyed examples of the latter because of several characteristics: young enough that its brown dwarfs are relatively luminous (2–6 Myr; Luhman et al. 2003; Bell et al. 2013); old enough that most of its members are not heavily obscured (\( A_V < 3 \)); among the nearest star-forming clusters (\( \sim 300 \, \text{pc} \)); sufficiently well-populated to provide good statistical constraints on the substellar mass function (\( N \sim 500 \)); compact enough to allow efficient imaging (\( \sim 0.2 \, \text{deg}^2 \)); and relatively low nebular emission because of the absence of an H II region. The latest census of IC 348 contains 67 objects likely to be brown dwarfs (\( \gtrsim 6.5 \, M_\odot \)), has a high level of completeness down to \( \sim 10 \, M_{\text{Jup}} \) (\( \sim 0.01 \, M_\odot \)), and reaches masses as low as \( \sim 5 \, M_{\text{Jup}} \) (Alves de Oliveira et al. 2013; Luhman et al. 2016; Esplin & Luhman 2017, references therein).

Brown dwarfs are typically identified using photometry or proper motions measured from wide-field surveys or deep imaging of small fields toward young clusters. Standard broadband filters at optical and infrared (IR) wavelengths have been successfully utilized in the photometric selection process, but filters that are designed to measure absorption bands from H\(_2\)O and CH\(_4\) produce particularly distinctive colors for brown dwarfs (Najita et al. 2000; Mainzer & McLean 2003; Tinney et al. 2005, 2018; Burgess et al. 2009; Haisch et al. 2010; Parker & Tinney 2013; Allers & Liu 2020; Jose et al. 2020; Robberto et al. 2020). In late 2016 and early 2017, portions of IC 348 were imaged by the Hubble Space Telescope in a medium-band filter aligned with H\(_2\)O and CH\(_4\) bands and in two neighboring broadband filters. In this paper, we present an analysis of those data in order to search for new members of the cluster at planetary masses.

2. WFC3 Imaging of IC 348

2.1. Data Collection

IC 348 was observed with the IR channel of Hubble’s Wide Field Camera 3 (WFC3; Kimble et al. 2008) on several dates between 2016 December and 2017 February through program 14626 (M. Barsony). The camera contains a 1024 \( \times \) 1024 HgCdTe array in which the pixels have dimensions of \( \sim 0.0135 \times 0.0121 \). The inner 1014 \( \times \) 1014 portion of the array detects light, which corresponds to a field of view of 136\(^\circ\) \( \times \) 123\(^\circ\). The observations were performed with the drift-and-shift (DASH) method of imaging multiple fields in a single orbit (Momcheva et al. 2017). After the guide star acquisition for the initial field in a given orbit, re-acquisitions for subsequent fields are omitted and guiding is performed with gyros alone. During the 25 s interval between a pair of nondestructive reads for an exposure, the telescope drift with gyros-only guiding is typically less than half of a WFC3 pixel, so the difference images between adjacent reads can be shifted and combined to produce a single image that has little smearing of the point-spread-function (PSF). For IC 348, the total exposure times were 250 or 275 s for a given field and filter. WFC3 observed 48 fields through three filters, consisting of F125W (1.1–1.4 \( \mu \)m), F139M (1.35–1.41 \( \mu \)m), and F160W (1.4–1.69 \( \mu \)m). In a given orbit, eight fields were imaged in a single filter, so the data were taken across a total of 18 orbits. The WFC3 fields are indicated on a map of the known members of IC 348 in Figure 1 (Luhman et al. 2016; Esplin & Luhman 2017). WFC3 observed the outskirts of the cluster to
measure aperture corrections between those apertures and radii of 0.4 using bright nonsaturated stars. When using gyroscopically guiding, the pointing of Hubble drifts and the rate of that drift varies with time. As a result, the sampling of the PSF is not identical among the different fields for a given filter, and hence the aperture corrections can vary among those fields. Therefore, we measured an aperture correction for each image if it contained a sufficient number of bright nonsaturated stars. For images with few stars of that kind, we applied the mean aperture correction among all of the images for a given filter that contain bright stars, which corresponded to 0.15, 0.16, and 0.195 mag for F125W, F139M, and F160W, respectively. We applied those corrections and the zero-point Vega magnitudes of 25.1439 (F125W), 23.2093 (F139M), and 24.5037 (F160W) for 0.4 apertures to the photometry. We adopted a minimum error of 0.02 mag for the photometry due to uncertainties in the aperture corrections.

Some of the WFC3 fields overlap (Figure 1), so we identified detections with matching coordinates among all images in a given filter and computed the mean coordinates and photometry for sources with multiple detections. The resulting catalogs for the three filters were then matched to each other to form a single catalog for the entire set of images. That catalog contains 1552 sources with nonsaturated detections in all three bands.

3. Identification of Brown Dwarf Candidates

The F139M filter of WFC3 is centered on absorption bands from H₂O and CH₄ while F125W and F160W encompass continuum at shorter and longer wavelengths. As a result, objects with strong absorption in those bands will exhibit blue colors in m₁₂₅ − m₁₃₉ and red colors in m₁₃₉ − m₁₆₀, which should be distinctive from most other astronomical sources. To use those colors to identify candidate brown dwarfs in IC 348, we have plotted a diagram of m₁₃₉ − m₁₆₀ versus m₁₂₅ − m₁₃₉ in Figure 2 for all sources from the WFC3 images that have photometric errors less than 0.1 mag in each of three bands. Since the WFC3 images are deeper in F125W and F160W than in F139M (Section 2.1), that sample is effectively limited by the sensitivity in F139M and all of the selected sources have small errors in F125W and F160W (no larger than 0.02 mag). To further refine our selection of brown dwarf candidates, we have included in Figure 2 a diagram of z′ − m₁₂₅ versus m₁₂₅ − m₁₃₉ in which the z′ data were measured by Luhman et al. (2016) using deep imaging from Alves de Oliveira et al. (2013). We also show m₁₆₀ versus m₁₂₅ − m₁₃₉ to illustrate the range of magnitudes spanned by any candidates that we identify. In each of the three diagrams in Figure 2, a reddening vector for A_K = 0–1 is shown for the extinction curve from Schlafly et al. (2016).

In Figure 2, we have indicated the known members of IC 348 that are within the WFC3 images and are not saturated. The members earlier and later than M₈ are shown with different symbols. A spectral type of M₈ is predicted to correspond to a mass of ~30 M_Jup for ages of a few megayears (Baraffe et al. 1998). As expected, the late-type members are blue in m₁₂₅ − m₁₃₉ and red in m₁₃₉ − m₁₆₀, making them distinctive from most other sources in the WFC3 images. To identify brown dwarf candidates based on colors of that kind,

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*Figure 1. Map of the known members of IC 348 (Luhman et al. 2016; Esplin & Luhman 2017) and the fields imaged by WFC3 in this study.*

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2. Data Reduction

We retrieved the raw WFC3/IR images of IC 348 from the Mikulski Archive for Space Telescopes: 10.17909/t9-d358-qj35. Each image was split into 25 s difference images using the python routine wfc3dash. The resulting frames were registered and combined using the tasks tweakreg and astrodizzle within the DrizzlePac software package. We adopted drop sizes of 1.0 native pixels and a resampled plate scale of 0′′.065 pixel⁻¹.

For each reduced image, we used the routine starfind in IRAF to identify detected sources and measure their pixel coordinates. We aligned the world coordinate system (WCS) of each F160W image to the astrometry of sources in the WFC3 images from Data Release 10 of the United Kingdom Infrared Telescope Infrared Deep Sky Survey (Lawrence et al. 2007). The WCS of each image in the other two filters was aligned to the updated WCS for F160W.

We measured aperture photometry for the sources in the WFC3 images using the IRAF task phot with an aperture radius of four pixels and radii of four and eight pixels for the inner and outer boundaries of the sky annulus, respectively. We

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*https://github.com/ghrammer/wfc3dash*
The reddening vector in the diagram of $m_{139} - m_{160}$ versus $m_{125} - m_{139}$ has been placed along the lower envelope of the known members later than M8. Twelve candidates appear above that vector, which are marked with open circles and triangles according to whether we have observed them with spectroscopy (Section 4). Six of the candidates have detections in $z'$, so they appear in the diagram in Figure 2 that contains $z' - m_{125}$. Four of those six candidates have similar positions in that diagram as the known late-type members, which supports their candidacy as cool objects. The other two candidates (LRL 60032 and LRL 91235) are somewhat bluer in $z' - m_{125}$ than the known $>$M8 members. Nine of the 12 candidates have detections in images at $J$, $H$, and $K_s$ from Luhman et al. (2016), so we have plotted them in a diagram of $K_s$ versus $H$.

Figure 3. Color–color and color–magnitude diagrams for known members of IC 348 with spectral types of $\leq$M8 and $>$M8 (filled circles and crosses) and candidate members selected from Figure 2 (Table 1) that have new spectroscopy (open circles, Figure 4) and that lack spectra (open triangles).
| IC 348 IRS          | LRL*  | Spectral Type/\(A_K\) | Young? | \(m_{125}\) (mag) | \(m_{139}\) (mag) | \(m_{160}\) (mag) | \(J\) (mag) | \(H\) (mag) | \(K_s\) (mag) |
|---------------------|-------|-----------------------|--------|-----------------|-----------------|-----------------|--------------|-------------|--------------|
| J03433364+3201037   | 61953 | …                     | ?      | 22.13 ± 0.03    | 21.53 ± 0.09    | 20.38 ± 0.02    | …            | 19.98 ± 0.10 | 18.78 ± 0.06 |
| J03433755+3201489   | 21460 | M9–L2/0.15            | N?     | 19.87 ± 0.02    | 19.91 ± 0.02    | 19.13 ± 0.02    | 19.80 ± 0.02 | 18.87 ± 0.04 | 18.07 ± 0.03 |
| J03433807+3208133   | 60101 | …                     | ?      | 21.19 ± 0.02    | 21.02 ± 0.05    | 20.15 ± 0.02    | 21.15 ± 0.09 | 19.68 ± 0.07 | 18.79 ± 0.04 |
| J03433941+3208131   | 60032 | …                     | ?      | 20.80 ± 0.02    | 20.75 ± 0.04    | 20.05 ± 0.02    | 20.80 ± 0.05 | 20.00 ± 0.12 | 19.09 ± 0.05 |
| J03434218+3212130   | 91235 | …                     | ?      | 21.62 ± 0.02    | 21.62 ± 0.08    | 20.94 ± 0.02    | …            | …           | …            |
| J03434453+3209113   | 60119 | L0–L4/0.20            | ?      | 20.56 ± 0.02    | 20.50 ± 0.03    | 19.60 ± 0.02    | 20.57 ± 0.03 | 19.29 ± 0.03 | 18.29 ± 0.02 |
| J03434526+3158556   | 61451 | …                     | ?      | 21.02 ± 0.02    | 20.99 ± 0.04    | 20.03 ± 0.02    | 20.91 ± 0.09 | 19.60 ± 0.06 | 18.60 ± 0.02 |
| J03441321+3200588   | 52542 | …                     | ?      | 21.46 ± 0.02    | 21.29 ± 0.07    | 19.84 ± 0.02    | …            | 19.30 ± 0.05 | 17.80 ± 0.02 |
| J03442211+3214105   | 40013 | M9.5–L2/0.10          | Y      | 18.82 ± 0.02    | 18.95 ± 0.02    | 18.12 ± 0.02    | 18.77 ± 0.02 | 17.77 ± 0.02 | 16.98 ± 0.02 |
| J03443946+3156549   | 60203 | …                     | ?      | 21.40 ± 0.02    | 20.86 ± 0.03    | 19.71 ± 0.02    | 21.33 ± 0.08 | 19.33 ± 0.03 | 18.40 ± 0.03 |
| J03444366+3158452   | 52142 | …                     | ?      | 21.55 ± 0.02    | 21.23 ± 0.05    | 19.97 ± 0.02    | 21.66 ± 0.12 | 19.76 ± 0.05 | 18.62 ± 0.02 |
| J03445439+3209485   | 52749 | LO-L4/0.10            | Y?     | 20.57 ± 0.02    | 20.38 ± 0.04    | 19.57 ± 0.02    | 20.30 ± 0.02 | 19.18 ± 0.03 | 18.25 ± 0.02 |

Note.  
* These source names are a continuation of the designation numbers from Luhman et al. (1998).  
(This table is available in its entirety in machine-readable form.)
versus $H - K_s$ in Figure 3 with all known members of IC 348. Five of those candidates (the four with spectroscopy and LRL 61451) have colors similar to those of the known >M8 members. Two candidates, LRL 60032 and LRL 60101, depart modestly from the known members in those colors. The two remaining candidates, LRL 52142 and LRL 60203, are significantly redder in $J - H$ than known late-type members near the same $H - K_s$.

In the diagram of $m_{160}$ versus $m_{125} - m_{139}$ in Figure 2, the 12 brown dwarf candidates range from $m_{160} \sim 18$–21 and are fainter than most of the known members of IC 348 that are within the WFC3 images. We compare 11 of the 12 candidates to all known members of the cluster in a diagram of $K_s$ versus $H - K_s$ in Figure 3. One of the candidates, LRL 91235, lacks photometry in those bands. Most of the candidates are fainter than the known members in $K_s$, although correcting the photometry for extinction would likely increase the overlap between the candidates and known members. If the candidates are dereddened to the intrinsic colors of the known late-type members (e.g., $m_{125} - m_{139} \sim 0$), roughly half of the candidates would be fainter than the known members in terms of extinction-corrected magnitudes.

We present the sample of 12 brown dwarf candidates in Table 1, which includes coordinate-based designations, the photometry that we measured from the WFC3 images, and photometry in $JHK_s$ measured from images in Luhman et al. (2016).

4. Spectroscopy of Brown Dwarf Candidates

We have performed near-IR spectroscopy on the four brightest brown dwarf candidates from the WFC3 images to measure their spectral types and check for evidence of youth, which would support their membership in IC 348. The spectra were obtained with the Gemini Near-Infrared Spectrograph (Elias et al. 2006) during nights in February and March of 2020. The instrument was operated in the cross-dispersed mode with the 1″ slit and the 31.7 $l/mm$ $^{-1}$ grating. That configuration provided a resolution of $\sim 600$ and a wavelength coverage of 0.8–2.5 $\mu$m. For each target, the slit was rotated to the parallactic angle and exposures were taken at two positions along the slit separated by 3″ in an ABBA pattern. The numbers of exposures and exposure times ranged from 8 × 180 to 12 × 250 s. The spectra were reduced and corrected for telluric absorption with routines in IRAF. The reduced spectra of the four candidates are presented in Figure 4. The spectra have been binned to a resolution of $\sim 100$ to improve their signal-to-noise ratios (S/Ns). The unbinned spectra are provided in an electronic file that accompanies Figure 4.
In Figure 4, we have included the spectra of a young L dwarf standard from Luhman et al. (2017) and a field L dwarf standard, 2MASS J11463449+2230527 (L2V; Kirkpatrick et al. 1999). Like those L dwarfs, the four brown dwarf candidates exhibit strong absorption bands from H$_2$O, which confirms their cool nature. The shape of the $H$-band continuum is sensitive to surface gravity and hence age (Lucas et al. 2001), as illustrated with the young and field L dwarf standards in Figure 4. LRL 40013 and LRL 52749 have triangular $H$-band continua, indicating that they are young, although the S/N for the latter is low enough that we treat its age classification as tentative. The S/Ns of the spectra for LRL 60119 and LRL 21460 are too low for definitive age classifications based on that feature, although the latter may have the $H$-band plateau found in field L dwarfs. We have measured spectral types and reddenings from the spectra of the four candidates through comparison to the young standard spectra from Luhman et al. (2017). Those classifications are listed in Table 1. If any candidate is a field dwarf rather than young object, then it should be classified through a comparison to a field standard, which would likely result in a different spectral type.

5. Discussion

Through spectroscopy, we have demonstrated that four of the 12 brown dwarf candidates in IC 348 have late spectral types, two of which appear to be young, and hence are likely to be members of the cluster. The spectra of the other two candidates have insufficient S/Ns for assessments of their ages and cluster membership. One of the candidates classified as young, LRL 52749, is the faintest known member (by a very small margin) in extinction-corrected $K_s$. We have estimated a mass of 4--5 $M_{\text{up}}$ for that object from a comparison of the luminosities predicted by evolutionary models at an age of 3 Myr (Chabrier et al. 2000; Baraffe et al. 2015) to the value derived by combining its $K_s$ photometry with a $K$-band bolometric correction for young L dwarfs (Filippazzo et al. 2015) and the distance of IC 348 (321 pc; Ortiz-León et al. 2018).

Among the remaining eight objects that lack spectroscopy, LRL 61451 is the most promising candidate for a late-type object based on its $J - H$ and $H - K_s$ colors (Section 3, Figure 3). If it is a member, it could be the faintest known member in extinction-corrected photometry. The near-IR colors of LRL 60032 and LRL 60101 are close enough to those of known late-type members of IC 348 that we consider them to be viable candidates. LRL 52542 has the reddest $H - K_s$ among the 11 candidates with measurements of that color (Figure 3), but it is only moderately red in $m_{125} - m_{139}$. The combination of those two colors suggests that LRL 52542 is a highly reddened brown dwarf. If its position in the diagram of $K_s$ versus $H - K_s$ in Figure 3 is dereddened to the sequence of lightly reddened members, it would have $A_K \sim 1.6$ and $K_s \sim 16.2$. LRL 60203, LRL 52142, and LRL 91235 are less likely to have late spectral types based on $z' - m_{125}$ or $JHK_s$ colors (Section 3). The last remaining candidate, LRL 61953, has too little photometry beyond the WFC3 bands (only $H$ and $K_s$) for further assessment of whether it might have a late spectral type.

We can examine the implications of our sample of brown dwarf candidates for the initial mass function (IMF) in IC 348. Since the positions of the WFC3 fields were selected to avoid brighter stars, the sample of cluster members within those fields is biased against more massive stars. For instance, the earliest known members within the WFC3 images have spectral types of M4 (~0.3 $M_{\odot}$). As a result, the WFC3 fields cannot be used to construct an IMF that is representative of the cluster’s stellar population for the full range of masses. Therefore, we can characterize the IMF only at lower masses in the WFC3 fields.

The current census of members of IC 348 is nearly complete for $K_s < 16.8$ at $A_J < 1.5$ ($A_K < 0.6$) in an area that encompasses most of the WFC3 images (Luhman et al. 2016), so we consider members and candidates within that extinction limit for the IMF sample in the WFC3 fields. That criterion is satisfied by 22 of the 38 known members that are within the WFC3 images and eight of the 12 WFC3 candidates. The four candidates that appear to have $A_K > 0.6$ based on their colors consist of LRL 52142, LRL 52542, LRL 61953, and LRL 60203. As done in some of our previous studies of the IMF in IC 348 and other young clusters (Luhman et al. 2016), we use a distribution of extinction-corrected near-IR magnitudes as an observational proxy for the IMF. In Figure 5, we show the distributions of extinction-corrected magnitudes in either $H$ or $m_{160}$ for the 22 known members of IC 348 that are within the WFC3 images and have $A_K < 0.6$ and the eight WFC3 candidates that appear to have $A_K < 0.6$. The extinctions for the known members are from Luhman et al. (2016) and the extinctions for the candidates are estimated from $m_{125} - m_{139}$ assuming an intrinsic value similar to that of the known late-type members. We use measurements of $m_{160}$ in the distributions when they are available and otherwise use $H$ for stars that saturated in F160W. The median value of $m_{160} - H$ is $\sim 0.31$ for late-type members of IC 348, so the two bands are...
sufficiently similar that they can be shown together in the distributions for Figure 5.

To interpret the distributions in Figure 5 in terms of a mass function, we have marked the magnitudes that are predicted to correspond to 0.1 $M_\odot$, 10 $M_{\text{Jup}}$, and 3 $M_{\text{Jup}}$ for an age of 3 Myr according to evolutionary models (Chabrier et al. 2000; Baraffe et al. 2015). Based on those theoretical magnitudes, Figure 5 contains 13 objects between 0.1 $M_\odot$ and 10 $M_{\text{Jup}}$, all of which are known members. If the substellar mass function is flat in logarithmic units ($dN/d\log M \propto M^{-\Gamma}$ where $\Gamma = 0$), the mass interval from 3 to 10 $M_{\text{Jup}}$ would contain ~6.5 objects. The distributions in Figure 5 contain four known members and seven candidates in the magnitude range corresponding to 3–10 $M_{\text{Jup}}$ and two of those candidates have been classified as members through our spectroscopy. Thus, the mass function in the WFC3 fields is consistent with $\Gamma \gtrsim 0$, although the uncertainties in the slope are large given the small numbers of objects in question and the unknown membership status of some of the candidates. Constraints on the mass function at planetary masses in IC 348 would be improved through spectroscopy of the remaining candidates and a survey of new areas of the cluster that contain larger numbers of members.

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