A CONSTRAINT ON BROWN DWARF FORMATION VIA EJECTION: RADIAL VARIATION OF THE STELLAR AND SUBSTELLAR MASS FUNCTION OF THE YOUNG OPEN CLUSTER IC 2391

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ABSTRACT

We present the stellar and substellar mass function (MF) of the open cluster IC 2391, plus its radial dependence, and use this to put constraints on the formation mechanism of brown dwarfs (BDs). Our multi-band optical and infrared photometric survey with spectroscopic follow-up covers 11 deg², making it the largest survey of this cluster to date. We observe a radial variation in the MF over the range 0.072–0.3 $M_\odot$, but no significant variation in the MF below the substellar boundary at the three cluster radius intervals is analyzed. This lack of radial variation for low masses is what we would expect with the ejection scenario for BD formation, although considering that IC 2391 has an age about three times older than its crossing time, we expect that BDs with a velocity greater than the escape velocity have already escaped the cluster. Alternatively, the variation in the MF of the stellar objects could be an indication that they have undergone mass segregation via dynamical evolution. We also observe a significant variation across the cluster in the color of the (background) field star locus in color–magnitude diagrams and conclude that this is due to variable background extinction in the Galactic plane. From our preliminary spectroscopic follow-up, to confirm BD status and cluster membership, we find that all candidates are M dwarfs (in either the field or the cluster), demonstrating the efficiency of our photometric selection method in avoiding contaminants (e.g., red giants). About half of our photometric candidates for which we have spectra are spectroscopically confirmed as cluster members; two are new spectroscopically confirmed BD members of IC 2391.

Key words: open clusters and associations: individual (IC 2391) – stars: low-mass, brown dwarfs – stars: luminosity function, mass function

Online-only material: machine-readable table

1. INTRODUCTION

The origin and evolution of brown dwarfs (BDs) remains a fundamental open question. BDs have masses bridging the lowest mass hydrogen-burning stars and giant planets, so any picture of star and planet formation is incomplete if it cannot account for BDs. Several formation mechanisms have been proposed, including star-like formation from the compression and fragmentation of a dense molecular cloud, planet-like formation in a circumstellar disk, and the dynamical interruption of a star-like accretion process.

There are observational signatures which may be used to distinguish between these scenarios, such as the distribution of binaries, the presence and properties of circumstellar disks, the (initial) mass function (MF) and kinematics (see Luhman et al. 2007 for a review of observational signatures on the formation of BDs). Work over the past ten years has seen considerable success in measuring the MF into the BD regime in several clusters, including $\sigma$ Orionis (González-García et al. 2006; Caballero et al. 2007; Lodieu et al. 2009), the Orion Nebula Cluster (ONC; Hillenbrand et al. 2000; Slesnick et al. 2004), IC 2391 (Barrado y Navascués et al. 2004; Platais et al. 2007), and the Pleiades (Moraux et al. 2003; Lodieu et al. 2007). These are only examples among many other analysis of stellar and substellar populations.

The comparison of the MF in clusters with different properties (e.g., the different density clusters Taurus and ONC; clusters with different ages, e.g., Chabrier 2003) has led some workers to draw conclusions about the relative efficiency of possible BD formation mechanisms (e.g., Kroupa & Bouvier 2003). While some observations (Luhman et al. 2007) and theoretical works (Padoan & Nordlund 2004; Hennebelle & Chabrier 2008) conclude in a common formation mechanism for BDs and stars, some studies has suggested that BDs could form by massive disc fragmentation (Stamatellos & Whitworth 2008), photoevaporation of the accretion envelope (Hester et al. 1996), or interruption of the accretion process (Reipurth 2000; Reipurth & Clarke 2001). For instance, Bate & Bonnell (2005) have performed hydrodynamic simulations of star formation from fragmentation of molecular clouds. They concluded that objects which end up as BDs stop accreting before they reach the hydrogen burning limit because they are ejected from the dense gas soon after their formation by dynamical interaction in unstable multiple systems.

This ejection scenario in some cases predicts a higher velocity dispersion and spatial spread of BDs in comparison to stellar objects, which in turn may be observed as a variation in the MF with radius (Kroupa & Bouvier 2003). On the other hand, other works have shown that if BDs are formed by ejection, the velocity distribution could be the same for BDs and stars (Bate 2009). Muench et al. (2003) observed a radial variation in the MF of IC 348 measured over 0.5 to 0.08 $M_\odot$, but no variation was detected in the BD regime. In a study of the spatial distribution of substellar objects in IC 348 as well as Trapezium in the ONC, Kumar & Schmeja (2007) observed the stellar objects to be more clustered than the substellar ones, which they took as evidence in favor of the ejection scenario. By looking at the spatial distribution of the Taurus stellar and substellar population, Guieu et al. (2006) observed a gradient in the BD abundance relative to stars, which they conclude as in favor of the ejection scenario.

In this paper, we present the results of a program to study, in detail, the MF of one of the nearest and richest open clusters, IC 2391. This has an age of 50 Myr measured...
from lithium depletion (Barrado y Navascués et al. 2004) or 40 Myr from main-sequence fitting (Platais et al. 2007). The Hipparcos distance is 146.0^{+4.3}_{-1.8} pc (Robichon et al. 1999) and the metallicity and extinction are [Fe/H] = −0.03 ± 0.07 and $E(B−V) = 0.01$, respectively (Randich et al. 2001). Because of its proximity and youth, this cluster has been subject to several studies (e.g., Barrado y Navascués et al. 2004, 2001, 1999; Koen & Ishihara 2006; Siegler et al. 2007; Platais et al. 2007). Barrado y Navascués et al. (2004) and Dodd (2004) measured the MF down to the substellar limit, but the MF for confirmed member with a completeness limit at lower masses has not yet been determined.

Since IC 2391 is not as young as IC 348 (age ∼2 Myr from Muench et al. 2003) and Trapezium (age ∼0.8 Myr from Muench et al. 2002), one may expect it has already lost a significant fraction of its substellar population to evaporation by dynamical evolution. Using the tidal radius and mass of IC 2391 estimated by Piskunov et al. (2007; 7.4 pc and 175 $M_\odot$), we compute the escape velocity as $v_e = 0.4 \text{ km s}^{-1}$ and the crossing time as $t_{\text{cross}} = 17 \text{ Myr}$ (We stress that the crossing time is just an order-of-magnitude quantity, $2R/v$, where we have adopted for $R$ the tidal radius of 7.4 pc from Piskunov et al. 2007 and the velocity dispersion of $\sim 0.85 \text{ km s}^{-1}$ from Platais et al. 2007). Assuming a minimum value for the number of cluster members as the objects reported by Dodd (2004) and Barrado y Navascués et al. (2004; 125 and 33, respectively, together a total lower limit of 158 objects), we estimate that the lower limit of the relaxation time for this cluster is $t_{\text{relax}} \sim 105 \text{ Myr}$. Furthermore, in a numerical simulation of open clusters and the population of BDs members, Adams et al. (2002) shows that there would still be more than 80% of the original BD population in the cluster even after about 10 crossing times, assuming that BDs and stars have a similar velocity dispersion. Therefore, IC 2391 is still young enough for a radial study of its very low mass star (VLMS) and BD populations, considering the fact that mass segregation occurs on a timescale of order one relaxation time (Bonnell & Davies 1998; although recent work by Allison et al. 2009 suggest that mass segregation can occur on a smaller time than a relaxation time, at least for more massive stars).

The paper is structured as follows. We will first present the data set, reduction procedure, and calibration in Section 2. We then discuss our candidate selection procedure in Section 3, present the survey results in Section 4, and then discuss the radial variation of the MF in Section 5. The preliminary spectroscopic follow-up is presented in Section 6 followed by our conclusions in Section 7.

2. OBSERVATIONS, DATA REDUCTIONS, AND CALIBRATIONS

2.1. Observations

The survey consists of 35 $34' \times 33'$ fields extending to $3'$ from the center of the cluster and centered on R.A. = 08h40m36s and decl. = −53°02'00" (Figure 1). The central four fields will be referred to as the deep fields, while the other 31 fields will be referred as the radial fields and outward fields. (We make a distinction since they were observed with different exposure times and different filters, as will be specified below) The fields were chosen to extend preferentially along lines of constant Galactic latitude in an attempt to reduce systematic errors in any established cluster MF gradient, which could arise from contamination by a Galactic disk population gradient. The total coverage of our survey is 10.9 deg$^2$. This compares to 2.5 deg$^2$ in the survey of Barrado y Navascués et al. (2001).

The optical observations were carried out in four runs with the Wide Field Image (WFI) on the 2.2m telescope at La Silla (Baade et al. 1999) in: 1999 January 24–February 9, 2000 January 20–24, 2007 March 10–23, and 2007 May 15–18. The WFI is a mosaic camera comprising 4 × 2 CCDs each with 2k × 4k pixels delivering a total field of view of 34' × 33' at 0.238 arcsec per pixel. The deep fields in our survey were observed in four medium bands filters, namely, 770−625−316 nm (the filter name notation is central wavelength on the full width at half-maximum, FWHM, in nm) and one broadband filter, $R_c$. The radial fields were observed in $R_c$, 815/20, and 914/27 while the five outward fields were not observed in $R_c$.

These filters were chosen to sample the spectra of late M and early L dwarfs to improve selection over, say, $R_c−I_c$, and to minimize the Earth–sky background plus any nebular emission (as the filters are in regions of low emission). The pass band function for all filters are shown in Figure 2. For all radial fields, we have used an exposure time of 15, 10, and 25 minutes for the 815/20, 914/27, and $R_c$ filters, respectively. For each deep field, we obtained an integration time of 65 minutes for each of 770/19 and $R_c$, from 50 to 155 minutes for 815/20, from 25 to 261 minutes for 856/14, and from 50 to 80 minutes for 914/27. We additionally obtained short exposures for all fields to extend the dynamic range to brighter objects. The photometry from the short exposures were combined with the photometry of our long exposures for our analysis. In order to improve the determination of their low-mass status (via a better determination of spectral type and luminosity), we also observed all radial fields, including the outward fields, in the $J$ band using the CPAPIR on the 1.5 m telescope at Cerro Tololo, Chile (runs on 2007 February 28–March 3 and 2007 March 10). However, we did not get $J$-band photometry for the deep fields. CPAPIR consists of one Hawaii II detector of 2k × 2k pixels for a field of view of...
35′ × 35′ with a pixel scale of 1.03 arcsec per pixel. All fields were observed with a total exposure time of 30 minutes. The J filter of CAPIR is centered at 1250 nm with a FWHM of 160 nm. A detailed list of the fields observed with pointing, filter used, exposure time, and 10σ detection limit, is given in Table 1.

Our 10σ detection limit is \( J = 17.7 \) and 914/27 = 20.5 for the radial and deep fields, respectively (which corresponds to \( \sim 0.03 \) \( M_\odot \) for both cases). However, we cannot expect to detect all objects down to these magnitudes. The completeness spanning from the brightest objects without saturation down to the 10σ detection limit is estimated by taking the ratio of the number of objects detected to the predicted number of detections and assuming a uniform distribution of stars along the line of sight in the fields of our survey. The predicted number of detections is derived very simply by extrapolating to the detection limit a linear fit to the histogram of the number of detections as a function of magnitude (Figure 3). The completeness of the radial part of the survey is 91.8% while for the deep part it is 82.7%.

The spectroscopic observations were carried out with HYDRA, a multi-object, fiber-fed spectrograph on the 4m telescope at Cerro Tololo on the nights of 2007 January 6 and 7. For the deep part it is 82.7%.

2.2. Reduction and Astrometry

The standard CCD reduction steps (overscan subtraction, trimming, and flat-fielding for the WFI data and dark subtraction, flat-fielding for CAPIR data) were performed on a nightly basis using the ccdred package under IRAF. For WFI data, we used the dome flat both for pixel-to-pixel variation correction and to correct the global illumination, while for CAPIR data we used superflat (obtained by combining science image frames for each night). For WFI data, we reduced each of the eight CCDs in the mosaic independently and in the final step scaled them to a common flux response level. We made an initial sky subtraction via a low-order fit to the optical data, and for the infrared data by subtracting a median combination of all (unregistered) images of the science frames. Images were fringe subtracted when fringes were visible, which was the case for all medium bands filters used, in a similar way as described by Bailer-Jones & Mundt (2001). Finally, the individual images of a given field were registered and median combined. We calculated magnitudes via aperture photometry together with an aperture correction following the technique used in Howell (1989). An astrometric solution was achieved using the IRAF package imcoords and the tasks ccsynmatch, ccmap, and ccctran. For each field, this solution was computed for the 815/20 band image using the Two Micron All Sky Survey (2MASS) catalog as a reference. The rms accuracy of our astrometric solution is within 0.15″–0.20″ for WFI data and within 0.3″–0.4″ for CAPIR data. For WFI data, the astrometry was also performed on a CCD-by-CCD basis.

We only retained images for this study which were taken under photometric conditions, as determined by our monitoring of conditions during the observations and, moreover, by our data reduction procedure.

2.3. Photometric Calibration

To correct for Earth-atmospheric absorption on the photometry, we solved by least squares fitting the equation,

\[
m_A = m_{A,\text{raw}} + Z_A + C_A(m_A - m_B) + \kappa_A X_A,
\]

for observations of the standard stars at a range of air masses, where the spectrophotometric standard stars observed were Hiltner 600, HR 3454, and LTT 3864. (In order to obtain the observed magnitude from Equation (1), the fluxes of each standard star, \( f_\lambda \), were taken from Hamuy et al. 1992, 1994.) The parameters \( m_A \) and \( m_B \) are the apparent magnitudes of our spectrophotometric standard in two particular bands (\( A \) and \( B \)), where \( m_{A,\text{raw}} \) is the instrumental magnitude of our spectrophotometric standard stars, \( Z_A \) is the zero-point offset, \( C_A \) is the color correction, \( \kappa_A \) is the extinction coefficient for band \( A \), and \( X_A \) is the air mass at which \( m_{A,\text{raw}} \) was obtained.

We calibrated the infrared data using the J-band values of 2MASS objects, which were observed in the science fields. By determining a constant offset between the magnitude of 2MASS and our instrumental magnitude, we obtained the zero-point offset. Since this zero-point offset was obtained with objects in the same field of view in each science frame, we did not perform a color or air-mass correction when reducing our NIR photometry.

2.4. Mass and Effective Temperature Based on Photometry

We used the spectral energy distribution to derive the mass and effective temperature, \( T_{\text{eff}} \), assuming that all our photometric candidates belong to IC 2391. We used evolutionary tracks from Baraffe et al. (1998) and atmosphere models from Hauschildt et al. (1999a) (assuming a dust-free atmosphere; the NextGen model) to compute an isochrone for IC 2391 using an age of

\footnote{A fringe correction frame was created, which is a median combination of all science in a same filter with same exposure time. This fringe correction frame was scaled by a factor—determined manually for each science frames—and subtracted from the science image.}
non-photometric nights were reported for the 2000 January observation run. The reddening ($E(B-V) = 0$). These models and assumptions provide us with a prediction of $f_\lambda$, the spectral energy distribution received at the Earth (in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) from the source. We need to convert these spectra to magnitudes in the filters we used. Denoting as $S_\lambda(\lambda)$ the (known) total transmission function.
of filter $A$ (including the CCD quantum efficiency and assuming
telescope and instrumental throughput is flat), then the flux
measured in the filter is

\[ f_A = \frac{\int_0^\infty f_\lambda S_\lambda(\lambda) d\lambda}{\int_0^\infty S_\lambda(\lambda) d\lambda}. \]  

(2)

The corresponding magnitude $m_A$ in the Johnson photometric
system is given by

\[ m_A = -2.5 \log f_A + c_A, \]  

(3)

where $c_A$ is a constant (zero point) that remains to be deter-
mined in order to put the model-predicted magnitude onto the
Johnson system. We determine this constant for each of the
bands $R_c$, $770/19$, $815/20$, $856/14$, $914/27$, and $J$ in the stan-
dard way, namely by requiring that the spectrum of Vega pro-
duce a magnitude, $m_A$, of zero in all bands. Using the Vega
spectrum from Colina et al. (1996), we derive values of $c_{Rc} =
-21.6607$, $c_{770/19} = -22.2517$, $c_{815/20} = -22.4391$, $c_{856/14} =
-22.6341$, $c_{914/27} = -22.8353$, and $c_J = -23.6865$ mag.

Applying the two equations above to a whole set of model spec-
tra produces a theoretical isochrone in color–magnitude space.

Note that this procedure only provides us with the “true” mag-
nitudes of the model spectra, not their instrumental ones. The
photometric calibration procedure applied to the data converts
the measured, instrumental magnitudes to the “true” magnitude
plane where we can compare them.

Assuming that all our photometric candidates belong to
IC 2391, we derive masses and effective temperatures in
the following way. We first normalize the measured spectral
energy distribution (multi-band photometry) of each object to
the energy distribution of the model using the $815/20$ filter.
Then we estimate the mass and effective temperature (which are
not independent of course) via a least squares fit between the
measured spectral energy distribution and the model spectral
energy distribution from the isochrone.

There are several sources of error in the mass and $T_{\text{eff}}$
estimates. These come from the photometry, the photometric
 calibration, the least squares fitting (imperfect model), and the
uncertainties on the age of IC 2391 (we use 5 Myr). This last
and most significant error gives $0.075 \pm 0.006 M_\odot$ and $2914 \pm
43$ K for an object at the hydrogen burning limit and $1.000 \pm
0.027 M_\odot$ and $5270 \pm 70$ K for a solar-type object.

2.5. Spectroscopic Data Reduction and Calibration

The standard CCD reductions (overscan subtraction and
trimming) were performed on each image using the ccdred
package under IRAF. We then used the IRAF package dohydra
to perform flat-fielding (using dome flats), throughput correction
(with the skyflats), and scattered light corrections. The spectra
were wavelength calibrated using the PENRAY comparison
lamp with 2 s exposure time. Sky subtraction was performed
in a similar manner as fringe subtraction in photometry: a
standard sky spectrum (shown at Figure 4) was obtained
from the median of our sky spectra (more than 20 fibers
were assigned for sky subtraction in each HYDRA pointing)
and scaled to optimize the sky subtraction for each science
spectrum individually. However, this sometimes resulted in H\alpha
apparently being in absorption for some objects. We attribute
this to H\alpha emission from the background itself. This is spatially
variable and so subtracting the sky spectrum (which includes H\alpha)
sometimes results in a over-subtraction of this feature.

![Figure 4. Spectrum used for sky subtraction of our spectroscopic data. Note the H\alpha (nebula) emission line with equivalent width of $W(H\alpha) = 48 \AA$.](image-url)

We discuss this contamination problem and the danger of
determining membership status based on H\alpha in Section 6.1.

Finally, flux calibration was performed with the spectropho-
tometric standard Hiltner 600, which was observed three times
a night, at three different air masses.

2.6. Spectral Type, Effective Temperature, and Mass
Determination

For the objects for which spectra is available, we estimated
in addition the spectral type using the PC3 index from Martín
et al. (1999). The distinction between M dwarf and background
M giants and M supergiants was achieved using a CaH index
(Jones 1973). We visually inspected all spectra in order to
confirm the spectral-type and luminosity class estimation. We
estimated a spectroscopic $T_{\text{eff}}$ from the spectral type using the
temperature scale of Luhman (1999) for objects between M1V
and M9V and of Martín et al. (1999) for objects from L0V
and later. We then use our isochrone of IC 2391 to obtain the mass
based on $T_{\text{eff}}$.

3. CANDIDATE SELECTION PROCEDURE

The selection procedure discuss here concerns only our
photometric data while the discussion of the selection of our
spectroscopic candidates is done in Section 6. The candidate
selection procedure is as follows (and explained in more
detail in the remainder of this section). Candidates were first
selected based on color–magnitude diagrams (CMDs). A second
selection was performed using color–color diagrams. Third,
astrometry was used to remove objects with high proper motion.
Finally, non-candidates were rejected based on a discrepancy
between the observed magnitude in 815/20 and the magnitude
in this band computed with the isochrone of IC 2391 and our
estimation of $T_{\text{eff}}$. To be a cluster member in this work, an object
has to satisfy all four of these steps.

3.1. First Candidate Selection: CMDs

Candidates were first selected from our CMDs by keeping all
objects which are no more than 0.15 mags redder or bluer than
the isochrone in all CMDs (this number accommodates errors in the magnitudes and uncertainties in the model isochrone), plus errors from age estimation and distance to IC 2391 reflected on the isochrone. We additionally include objects brighter than 0.753 mag the isochrone in order to include unresolved binaries. In Figure 5, we show two CMDs for field 01 where candidates were selected based on \( \frac{R_c}{20} \) versus \( \frac{R_c}{20} - \frac{J}{27} \) (top two panels). We also present two CMDs from the deep field 32 using the medium band \( \frac{770}{19} \), \( \frac{856}{14} \), and \( \frac{914}{27} \) (lower two panels). From a total of 20,008,114 objects detected, 174,511 are kept (99.2% are rejected).

We also present in this figure low-mass cluster member candidates from previous work, which we detected in our survey (Patten & Pavlovsky 1999; Barrado y Navascués et al. 2004; Dodd 2004; and X-ray sources detected by XMM-Newton where some are also presented in Marino et al. 2005). Some candidates from previous studies are simply not detected in our work. This is the case with Platais et al. (2007) where the faintest candidates have \( V \sim 15 \), which corresponds to 0.6 \( M_\odot \) (close to the saturation limit of the radial and outward fields at \( \sim 0.9 M_\odot \) and at the saturation limit of the central deep fields, also at \( \sim 0.6 M_\odot \)). Also, no objects in our sample match the 34 members studied by
Figure 6. Two color–color diagrams of objects that are candidates based on our first selection (from field 01). Isochrones and objects from Barrado y Navascués et al. (2004; triangles), Dodd (2004; squares), and XMM-Newton (circle) are as shown in Figure 5. The thin lines represent the color of possible background red giant contaminants. The color–color diagram on the left is therefore not suited for further candidate selection since the isochrone is spanned by the color grid of the red giants (which is not the case for the color–color diagram on the right panel). In each panel, the thin solid lines next to the isochrone represent the selection curve.

Siegler et al. (2007) because either our images are too deep so bright stars saturate (e.g., HD74275, HD74374, and VXR22a, which saturate in the short exposures), or the objects are not in our fields (e.g., VXR06, SHJM10, and PP07, which are between fields 32 and 37). Also, no objects match within 4′′ between our objects and the 17 cluster candidates from Rolleston & Byrne (1997) for similar reasons: the bright stars saturate (e.g., object ID 162, 311, and 362, which are brighter then our saturation limit in R_c), or the objects are not in our fields (e.g., object ID 729 and 955, which are in the central part of the cluster between fields 20 and 27).

Finally, we point out that the survey of IC 2391 based on proper motion done by Dodd (2004) only covers an area of 1° diameter in the central part of the cluster.

3.2. Second Candidate Selection: Color–Color Diagrams

The second stage of candidate selection was achieved by taking all objects within 0.15 mag of the isochrone of the NextGen model in selected color–color diagrams. In Figure 6, we present two color–color diagrams where only the objects from the first selection are plotted. Considering that many color–color diagrams are possible (we have four to five filters), the variation of color as a function of T_{eff} was used to reject the use of colors for which the NextGen model shows small variation in the M and L dwarf regime (this is illustrated in Figure 7 with the 815/20–914/27 colors).

Because one source of contamination are background red giants, we show theoretical colors for such objects using the atmosphere models of Hauschildt et al. (1999b), assuming that all objects have a mass of 5 M_{⊙}, 0.5 < log g < 2.5, and 2000 K < T_{eff} < 6000 K. We can see that R_c – J versus R_c – 815/20 is not best suited for selecting candidates since the isochrone is overlapped by red giant contaminants. However, in 815/20–J versus 914/27–J, we see a clear distinction between the isochrone and the red giant contaminant in the BD regime (by more than 0.2 mag). This procedure definitely helps to remove red giant contaminants, and is further discussed in Section 6.3. From a total of 174,511 objects, 33,794 are kept (80.6% are rejected).

3.3. Rejection of Contaminants Based on Proper Motion

Although the rms error of our astrometry is 0.15″–0.20″ (WFI) and 0.3″–0.4″ (CPAPIR), we nonetheless estimated proper motions per year using the motion between the 1999/2000 WFI data and the 2007 CPAPIR data in an attempt to reject objects which deviate significantly from the mean cluster proper motion in the literature. The typical error on our proper-motion measurement is 24 milliarcsec per year (mas yr^{-1}). The values
of \((\mu_\alpha \cos \delta, \mu_\delta)\) for IC 2391 in mas yr\(^{-1}\) from the literature are \((-25.04 \pm 1.53, +23.19 \pm 1.23)\), \((-25.05 \pm 0.34, +22.65 \pm 0.28)\), \((-24.64 \pm 1.13, +23.25 \pm 1.23)\), and \((-25.06 \pm 0.25, +22.73 \pm 0.22)\) from Dodd (2004), Loktin & Beshenov (2003), Sanner & Geffert (2001), and Robichon et al. (1999), respectively. For our selection procedure, we use the average of these, \((-25.0 \pm 2.0, +23.0 \pm 1.7)\).

We first investigated whether the cluster itself could be identified in the proper-motion plane. To do this, we retained only those objects detected from our observation that run with WFI (1999, 2000, and 2007) and CPAPIR (2007) which have a match within 1\(^{\prime}\). We then examined the distribution in the \((\mu_\alpha \cos \delta; \mu_\delta)\) plane for any feature at \((-25.0; +23.0)\). However, we see no clump in the distribution of the proper motion (Figure 8). Considering the large errors and the absence of any structure at the expected location, we decided not to perform any selection using the proper motion of IC 2391. However, astrometry is used to remove all objects with a proper motion higher than 72 mas yr\(^{-1}\) (3\(\sigma\)) away from the cluster proper motion.

3.4. Rejection of Objects Based on Observed Magnitude versus Predicted Magnitude Discrepancy

As indicated in Section 2.4, our determination of \(T_{\text{eff}}\) is based on the energy distribution of each object and is independent of distance. The membership status is determined by comparing the observed magnitude of a given object in a band with the magnitude predicted based on its derived \(T_{\text{eff}}\) and IC 2391’s isochrone. (The premise is that the predicted magnitude of a background contaminant would be lower—brighter—than its observed magnitude and higher for a foreground contaminant.) In order to avoid removing unresolved binaries that are real members of the cluster, we keep all objects with a computed magnitude of up to 0.753 mag brighter than the observed magnitude. In this procedure, we are also taking into account photometric errors and uncertainties in the age and distance determinations of IC 2391. This is represented in Figure 9. Combined with the rejection of contaminants based on proper motion, this selection step reject 89.2% of the 33,794 candidates obtained from the CMD and color–color diagrams.

4. RESULTS OF THE SURVEY

The final selection gives us 954 photometric candidates for outward fields (namely fields 43, 46, 47, 48, and 49), 499 photometric candidates for the four deep fields (15, 20, 27, and 32, with filters \(R_c, 770/19, 815/20, 856/14,\) and 914/27) and 1734 for all other radial fields (observed with filters \(R_c, 815/20, 914/27,\) and \(J\)). (We present in Section 5.3 a discussion of the contamination of the radial fields.) All our photometric candidates are presented in Table 2. Objects are given the notation IC 2391-WFI-ZZ-YYY where ZZ is the field number and YYY a serial identification number (ID). Only the first 10 rows of the tables are shown, the remainder available
in our survey (object number 155, also identified as CTIO-061), and was detected by our survey (source number 86 and CTIO-130), but neither objects is recovered by our photometric selection. The values of $t_{\text{eff}}$, $(R - I)_{\text{c}}$, and $I_{\text{c}}$ were given in the last three columns are taken from each of the previous studies.

online. We also compare in Table 3 all objects in our sample, which are also confirmed as cluster members from Barrado y Navascués et al. (2004) and Dodd (2004) and was detected by the X-ray Multi-Mirror Mission (XMM-Newton). We see a good agreement between $t_{\text{eff}}$ from our photometric data and from Barrado y Navascués et al. (2004), where only the color $(R - I)_{\text{c}}$ was used to compute $t_{\text{eff}}$.

Not all candidate members from previous studies, detected in our survey, are members of IC 2391 based on our photometric selection. As pointed above, a cluster member presented in this work is an object that satisfies all four steps of our selection procedure. For instance, between the two objects detected in our survey, which are also cluster candidates by Patten & Pavlovsky (1999), one is recovered by our selection (object number 8). From 10 objects classified as candidate members from spectroscopy and photometry by Barrado y Navascués et al. (2004), 5 are recovered in our selection: objects CTIO-038 and −091 fail the color−color diagrams test and objects CTIO-041, −049, and −091 fail the predicted magnitude versus observed magnitude test. One possible source of disagreement could be the use of Hz by Barrado y Navascués et al. (2004) as a membership criteria (see Section 6.1 for further discussion of this issue).

A total of 53 objects classified as cluster members by Dodd (2004) based on proper motion and photometry were detected in our survey. However, one of Dodd objects is recovered in our survey (object number 155, also identified as CTIO-152). This is also the only matches, within 4", with the cluster members of Barrado y Navascués et al. (2004). Considering the size of the window used for their proper-motion selection (in milliarcsecond, $-28 \geq \mu_{\alpha} \cos \delta \geq -20$ and $+20 \leq \mu_{\delta} \leq +28$) and the order of the error on the known proper motion of IC 2391 ($\lesssim 2$ mas in $\mu_{\alpha} \cos \delta$ and $\mu_{\delta}$, see Section 3.3 below), one could suspect some contamination by field stars. This can be confirmed by the large scatter in the CMDs of IC 2391 presented by Dodd (2004) below $R \sim 12$ and $K \sim 10$ in Figures 3 and 4, respectively. Another survey on IC 2391 based on proper motion was performed recently by Platais et al. (2007). However, as discussed in Section 3.1, no objects from this work were detected in our survey.

Only two objects listed Table 2 from Marino et al. (2005; IC 2391 members observed with XMM-Newton) were also detected by our survey (source number 86 and CTIO-130), but neither objects is recovered by our photometric selection. The first one is a source that overlaps2 with VX 53 from Patten & Simon (1996) and was identified as a suspected cluster member, and also overlaps with CTIO-126 from Barrado y Navascués et al. (2001) and was classified as a cluster member (however, there was no spectroscopic follow-up of CTIO-126 by Barrado y Navascués et al. 2004). This object is not recovered in our selection because this candidate fail the observed magnitude versus predicted magnitude test. Another object presented by

2 The EPIC cameras on XMM-Newton have an angular resolution of 6". Two of the cameras are MOS (Metal Oxide Semiconductor) CCD arrays (referred to as the MOS cameras) and on camera at the focus of this telescope uses pn CCDs (referred to as the pn camera).
Marino et al. (2005; observed only by the MOS cameras onboard XMM-Newton, but not by the pn camera) is CTIO-130, but they noted that this star has $J$ and $(J-K)$ values incompatible with the IC 2391 main sequence.

4.1. Effect of Background Contamination on Candidate Selection

In comparing the CMDs for different fields, we discovered something peculiar (Figure 10, top three panels). We see a shift in the colors of the bulk of the (field) stars from field to field, something we also observe in other colors. The comparison of the amplitude of this shift (for a given magnitude interval) with observational parameters such as nights, air mass, seeing, and 10$\sigma$ detection limit shows no correlation and there is no other indication of reduction problems. We did, however, find a correlation of the color shift with the Galactic longitude, $b$.

However, in order to verify that these shifts where real, we obtained DENIS photometry in $I$ and $J$ band for the same fields presented in Figure 10, which are field 01, 09, and 40. We can see that the shift in the colors of the bulk of the (field) stars is also observed in the DENIS data (Figure 10, lower three panels).

Although reddening is negligible for objects in IC 2391, this is not the case for background objects, and these constitute most of the stars in our sample. Due to the high variation of the background extinction in this direction of the Galactic disk (Schlegel et al. 1998)—the cluster is centered at $l = 270.4 \ b = -6.9$—some variation in the CMD locus could be extinction-induced variations in the background stars. In Figure 11 (left panel), we plot the reddening $E(B-V)$ in our fields against the median of the color 815/20-914/27 (in a bin of magnitude of $15 < 815/20 < 16$) for all our fields. The colors vary by as much as 0.25 mag. To better illustrate the spatial variation of the background extinction, Figure 11 (right panel) shows the position of the fields of our survey overlaid with the $E(B-V)$ extinction map of Schlegel et al. (1998). This color gradient of the background stars has not been reported in previous surveys of IC 2391 (Dodd 2004; Barrado y Navascués et al. 2001; Patten & Pavlovsky 1999).

4.2. Mass Function

The MF, $\xi(\log_{10} M)$, is generally defined as the number of stars per cubic parsec ($pc^3$) in the logarithmic mass interval $\log_{10} M$ to $\log_{10} M + d\log_{10} M$. Here, we do not compute the volume of IC 2391 so instead we present a MF using the total number of objects in each 0.1 log $10^M$ bin per 1000 arcmin$^2$, starting at the mass bin $\log_{10} M = -1.65$ ($\sim$0.02 $M_\odot$). The MFs computed here are all system MFs since we do not make any corrections for binaries. We analyze the radial variation of the MF using the fields with photometry with the filters $R_c$, 815/20, 914/27, and $J$ (Figure 12). MFs were computed over three regions: for fields from 0.5 to 1.5 of the cluster center (which corresponds to 1.3 pc and 3.8 pc, respectively); for the annulus from 1.5 to 2.1 (which corresponds to 5.4 pc); for fields outside
Figure 11. Left panel: $E(B - V)$ toward all our fields (from the Schlegel et al. 1998 extinction map) plotted against the median 815/20-915/27 stellar color in those fields. Right panel: position of the fields of our survey overplotted by the $E(B - V)$ extinction map of Schlegel et al. (1998). The contour separation is 0.2 mag.

Figure 12. MF based on photometry for all radial fields. The 10σ detection limit is shown as a vertical dashed line. Dots in each panel represent the MF of (left panel) fields within 1.5 of the cluster center, (center panel) fields within the annulus from 1.5 to 2.1, and (right panel) fields outside of 2.1. Error bars are Poissonian arising from the number of objects observed in each bin. The histogram is the MF for all fields within 2.1 of the cluster center. The vertical thin dotted line is the mass for which saturation start to occur in the short exposures. (The total area covered for each panel, from left to right, is 6637, 9539 and 5609 arcmin².) Just for reference, the ordinate value of 1.13 for the bin at log10 $M = -0.85$ (0.14 $M_{\odot}$)—the histogram peak—corresponds to 109 objects.

We have also computed a MF for all fields within 2.1 of the cluster center to help radial variation analysis and present this as our estimation of the MF for IC 2391. Furthermore, we have measured the MF for the five outward fields and also for the four deep fields (Figure 13).

Since the radial fields were also observed with $R_c$ in addition to the filters used for both the radial and outward fields, we use this to estimate the (additional) contamination in outward fields relative to the radial fields for each mass bin. To do so, we performed a photometric selection for our radial fields using only the filters available in the outward fields (815/20, 915/27, and $J$). We compared the MF computed from this with the MF from the outward fields and obtained, for each mass bin, the number of object that would have been rejected if we would had an additional $R_c$-band observation. (Here, we make the assumption that the true MF should be the same in the radial and outward fields.)

In Figure 13 (left panel), we present the uncorrected MF of the outward fields and the corrected MF of the outward fields (right panel). It is not possible to perform such corrections for the deep fields.

Useful (and simple) parameterizations of the MF include the power law of Salpeter (1955) and a lognormal

$$
\xi(\log_{10} M) = k \cdot \exp\left[-\frac{(\log_{10} M - \log_{10} M_0)^2}{2\sigma^2}\right],
$$

where $k = 0.086$, $m_0 = 0.22 M_{\odot}$, and $\sigma = 0.57$ was derived for the Galactic field by Chabrier (2003). Fitting the lognormal MF to our data for all fields within 2.1 of the cluster center, we obtain $k = 10.7 \pm 3.2$, $m_0 = 0.13 \pm 0.03 M_{\odot}$, and $\sigma = 0.46 \pm 0.07$. This is overplotted in Figure 13.

If we assume that the lognormal fit of the MF describe the behavior of the population in the mass range 0.02–0.9 $M_{\odot}$ in IC 2391, the total number of object expected is 3985 for a total

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3 For reference, the core and tidal radius of IC 2391 estimated by Piskunov et al. (2007) are 1.2 pc and 7.38 pc, respectively, which corresponds to 0.35 and 2.89 from the cluster center.
mass of 679 $M_{\odot}$. (In Section 5.3, we will discuss again the total number of object and total mass, following an estimation of the contamination for each mass bin in the MF of the radial fields.)

We present in Figure 14 the MF for all fields within 2ʰ1 of the cluster center and from other open clusters with similar ages (NGC 2547, ∼30 Myr; IC 4665, 28±7Myr based on Li depletion boundary; Manzi et al. 2008). We also show on Figure 14 the MF of IC 2391 as determined in previous work (i.e., from Barrado y Navascués et al. 2004 and Dodd 2004). All were normalized to the Galactic field star MF at 0.3 $M_{\odot}$.

5. ANALYSIS AND DISCUSSION OF THE MASS FUNCTIONS

In the following subsection, we discuss the MF derived from the deep fields and from outward fields only. The other fields are used to study the radial variation of the MF and are subject of further discussion in the following two subsections. We complete this section with a discussion of the contamination rate by non-cluster members.

5.1. MF of the Outward Fields and of the Deep Fields

Considering the fact that only three bands were used for the outward fields, and thus fewer constraints imposed, we expect that the number of photometric candidates would be larger per unit area than the other fields. The MF (Figure 13, left panel) shows more low-mass objects (compared to the MF of the radial field, for masses below ∼0.15 $M_{\odot}$), a similarity with the radial MF from 0.15 to 0.3 $M_{\odot}$, and again more stellar objects in the mass range 0.5–0.8 $M_{\odot}$. The corrected MF (Figure 13, right panel) shows a better agreement with the radial MF.

The MF from the deep fields (Figure 13) agrees with the MF of the radial fields within 2ʰ1 from cluster center in the mass range 0.05–0.1 $M_{\odot}$ and above 0.2 $M_{\odot}$. However, there is more substellar objects below 0.05 $M_{\odot}$.

The rise of the MF for objects below 0.05 $M_{\odot}$ was also observed in IC 2391 by Barrado y Navascués et al. (2004). In their work, the MF was computed with objects that were selected as cluster members based on $R_c$, $I_c$, $J$, $H$, and $K$ photometry. Since their NIR photometry was taken from 2MASS, no data are available for objects fainter than $I_c \lesssim 19$ (10σ detection limit of 2MASS is at $J \sim 15.8$). As a result, their selection for fainter objects was based on $R_c$ and $I_c$ photometry only. In our case, although $J$-band photometry is available for the outward fields, no $R_c$ photometry is available. Thus, Barrado y Navascués et al. (2004) used a relatively short baseline ($R_c - I_c$) for their selection, as did we in our outward fields (815/20, 914/27, and $J$), both of which are considerably shorter than the baseline we used in the radial fields ($R_c$, 815/20, 914/27, and $J$). This situation is also observed in the MF of the deep fields (where $R_c$-band photometry is available, but no $J$-band photometry). Only the fields observed with $R_c$ and $J$ as well (i.e., a longer baseline) show no significant rise of the MF below 0.05 $M_{\odot}$ (Figure 13, left panel). Since no red giants were observed in our spectroscopic follow-up of the two deep fields 15 and 20 (Section 6), we conclude that this increase is an artifact due to contamination by M dwarfs. In this low-mass regime (for objects with mass $\lesssim 0.05 M_{\odot}$), a long spectral baseline (including, for instance, $R_c$ and $J$) is needed to efficiently remove contaminations, as it allows a better determination of the energy distribution. This is confirmed when we compare the corrected and uncorrected MFs of the outward fields (Figure 13).

The rise in the MF over 0.5–1.0 $M_{\odot}$ is observed in the outward fields but not in the deep fields (Figure 13). Jeffries et al. (2004) present the MF of the open cluster NGC 2547 and also noticed a rise in the 0.7–1.0 $M_{\odot}$ interval (Figure 14). This rise, also observed in the luminosity function as a large peak at 12 $\lesssim I_c \lesssim 14.5$, they attribute to contaminating background giants. This would be consistent in the fact that we see this in the radial fields (see Figure 12) but not in the deep fields (Figure 13). Indeed, as we discuss later in Section 6, no red giants were found in our spectroscopic follow-up, confirming that the use of medium bands such as 770/19, 815/20, 856/14, and 914/27, and theoretical colors (Hauschildt et al. 1999b) are...
effective in removing background red giants. However, from the MF of the radial fields (including the outward fields), the medium filters 815/27 alone, combined with wide band $R_c$ and/or $J$, are less efficient at removing background giants. Therefore, the rise in the MF of the outward fields over $0.5–1.0 \, M_\odot$ is related to the filters used, but is not a baseline issue.

We also observe on Figure 13 that two mass bins at $\sim0.11$ and $\sim0.18 \, M_\odot$ are significantly high compared to the other mass bins in the mass range $0.05–0.3 \, M_\odot$. Considering that this is not observed in the MF of the radial field and in the corrected/uncorrected MF of the outward fields, we suspect that this is due to the selection procedure related to the deep fields so no conclusion should be made based on these two mass bins.

5.2. Radial Variation of the MF at the Stellar and Substellar Regimes

From a first glance at Figure 12, we see that the two MFs within 2′1 (the points in the two left-hand panels) are somewhat similar. While there is some differences, these are not very significant compared to the difference between their common MF within 2′1 (plotted as the histogram) and the MF in the outskirts of IC 2391 (beyond 2′1) as shown in the right-hand panel. Indeed, the MF for $\theta > 2′1$ shows a significant deficiency of stellar objects from 0.1 to 0.3 $M_\odot$ ($\log_{10} M = -0.6$) compared to the MF from the inner part of the cluster, whereas outside of this mass range there is no significant change with radius. Although we observe a number of objects in the highest mass bins at $0.5–0.7 \, M_\odot$ ($\log_{10} M = -0.3$ to $-0.15$), we concluded (in Section 5.1) that this range of masses is subject to significant contamination by red giants, so no conclusion should be drawn from the radial variation of the MF in this mass interval.

In Figure 15, we present the cumulative MF for the same three regions of the cluster presented in Figure 12. We again see the relative absence of objects from 0.1 to 0.3 $M_\odot$ ($\log_{10} M = -0.6$) for the inner radii. A Kolmogorov–Smirnov test performed on these distributions indicates that there is only a $1.1 \times 10^{-5}$ probability of getting such a difference under the null hypothesis that the population at $\theta > 2′1$ is the same as that at $\theta < 2′1$, thus reinforcing the suggestion that the MFs are significantly different.

To help the analysis of the radial variation as a function of mass, we also present on Figure 16 the radial profile of IC 2391 using the radial fields for four different mass bins: $M < 0.072 \, M_\odot$, $0.072 \, M_\odot < M < 0.15 \, M_\odot$, $0.15 \, M_\odot < M < 0.3 \, M_\odot$, and $0.3 \, M_\odot < M$. (It is not surprising that a fit for the most massive stars is not possible since the core radius is at 0.35 and we do not have any radial fields closer than 0.8.) For the second and third radial profile, we fit a King profile (King 1962), where the fit give us a maximal number density at the center of $2^{\circ7+2}{^{\circ9}}$ and $2^{\circ6+2}{^{\circ3}}$ members per 1000 arcmin$^2$ and a full width at half maximum of $1^{\circ39+0}{^{\circ4}}$ (or 3.5 pc$^{\circ1+0}{^{\circ3}}$) and $1^{\circ45+0}{^{\circ7}}$ (or 3.7 pc$^{\circ1+0}{^{\circ5}}$), respectively. This is purely for illustration purposes, as it is clear that this is not a good model for this mass profile.

Figure 14. MF of IC 2391 from our present work (empty dots, from all fields within 2′1 from the cluster center), for IC 4665 (filled triangles) from de Wit et al. (2006), and for NGC 2547 (filled dots) from Jeffries et al. (2004). We also show the galactic field stars MF from Chabrier (2003) as a dashed line. We also present the MF of IC 2391 from Barrado y Navascués et al. (2004; empty triangles) and from Dodd (2004; empty squares).

Figure 15. Cumulative number of cluster members within 1′5 (dash-dotted line), within the annulus from 1′5 to 2′1 (dotted line) and outside of 2′1 (thick line). The 10σ detection limit is shown as an horizontal dash line. The vertical thin dotted line is the mass for which saturation starts to occur.
In Figure 12, we do not see any significant radial variation of the MF in the substellar regime. The radial profile of the substellar population in Figure 16 also indicates no significant radial variation. On the other hand, we do see reasonable evidence for a radial variation for masses above $0.072 M_\odot$. From this radial profile and the MFs already discussed, we can conclude that the spatial distribution of the BD population is uniform compared to the stellar population (from 0.072 to $0.3 M_\odot$), which is more clustered within $\theta \sim 2^\circ$.

Kumar & Schmeja (2007) also found the stellar population to be more clustered than the substellar population in the clusters IC 348 and Trapezium. This would favor the ejection scenario for forming BDs if the BDs have a higher velocity dispersion than the stars (Kroupa & Bouvier 2003), because the higher velocity from ejection creates a more uniform spatial distribution for the BDs compared to the stars. However, the two clusters of Kumar & Schmeja (2007) are both younger than 3 Myr, while IC 2391 has an age of 50 Myr, some $\sim$3 times older than its crossing time ($t_{\text{cross}} = 17 \text{ Myr}$). We can expect that if BDs have a higher velocity dispersion than stars, then in an older cluster most of the BDs with velocity dispersion greater than the escape velocity could have escaped the cluster already (Moraux & Clarke 2005).

The homogeneous distribution of the substellar objects compared to the more clustered stellar population could be instead a signature of mass segregation through dynamical evolution or of primordial origin. We have indicated previously that mass segregation via dynamical evolution could occur on a timescale of order one relaxation time (Bonnell & Davies 1998), or even less (Allison et al. 2009). Considering that the cluster is only three times older than its crossing time, which may be insufficient for significant dynamical evolution, it is difficult to make an inference on the BD formation mechanism from the radial MF variation given the uncertainty about to what extent the cluster has evolved dynamically. If it could be demonstrated that the cluster is dynamically unevolved and that the BDs have a higher velocity dispersion than the stars, then our observations are consistent with BD formation by the ejection hypothesis.

5.3. Contamination by Non-members

Possible point source contaminants other than field M dwarfs include red giants and high redshift quasars (Caballero et al. 2008). However, as pointed out in Section 5.1 and in our spectroscopic follow-up (see below in Section 6.3), the use of medium band filters and theoretical colors is efficient at removing potential background red giant contaminants. As for the high redshift quasars (for instance at $z \sim 6$), their spectral energy distribution is similar to mid-T dwarfs and, moreover,
they are rare (Caballero et al. 2008). Considering that our faintest targets are early L dwarfs, the MF should not be affected by contamination by quasars.

Here, we present an estimation of the contamination in our photometric survey based on the radial fields. First, we used the radial profile of IC 2391 using the radial fields for four different mass bin (Figure 16). We assumed that near the tidal radius (∼2.89), the number of objects per 1000 arcmin² should be zero. From this, we computed that we can expect a contamination of ∼8.8 objects per 1000 arcmin² for masses above 0.3 $M_\odot$, ∼8.8 objects per 1000 arcmin² in the mass range of $0.15 M_\odot < M < 0.3 M_\odot$, ∼16.7 objects per 1000 arcmin² in the mass range of $0.072 M_\odot < M < 0.15 M_\odot$, and ∼9.8 objects per 1000 arcmin² in the substellar regime. If we use the same assumptions about the lognormal fit of the MF, the new total number of object expected in IC 2391 is 1954 for a total mass of 308 $M_\odot$.

6. PRELIMINARY SPECTROSCOPIC FOLLOW-UP

Here, we present the results of a preliminary spectroscopic follow-up of some photometric candidates. As explained in the previous section, the main sources of contamination in our photometric selection are background red giants and field M dwarfs. We have also shown in Section 4.1 that, because of extinction, background contamination is non-uniform. We therefore need to refute or confirm membership status with optical spectra. For this task, we used the fiber spectrograph
HYDRA. It is not possible to cross fibers with this instrument, so we have not yet been able to observe all candidates in a given field. (It is our intention to eventually obtain spectra of all candidates.) The data reduction was described in Section 2.5, while the spectral type and luminosity class determination was presented in Section 2.6. The spectroscopic $T_{\text{eff}}$ was obtained using the spectral type and the temperature scales of Luhman (1999), while each mass was derived from $T_{\text{eff}}$ using our isochrone for IC 2391. We discuss membership determination based on optical spectra below in Section 6.2.

Among the spectra obtained, 17 had a signal-to-noise ratio (S/N) higher than 5. These are presented in Figure 17. Table 4 provides the derived parameters (spectral type, $T_{\text{eff}}$ and mass) and the S/N. Objects are given the same notation as the photometric candidates: IC 2391-WFI-ZZ-YYY where ZZ is the field number and YYY a serial identification number (ID). Table 5 gives details of an object confirmed as cluster members by Barrado y Navascués et al. (2004), including their SpT and $T_{\text{eff}}$ determination, for which we also have a spectra.

6.1. Contaminating Hα Nebula Emission

We mentioned in Section 2.5 the presence of contamination at Hα in sky spectra. As these spectra are used for background subtraction (we have fiber spectra), there are potential difficulties in measuring the stellar Hα line. We now discuss this issue.
We must therefore question its use by Barrado y Navascués et al. (2004) to draw any conclusions on membership status based on this line.

Significant variation of the Hα emission line of our background spectra for field 20. While there done by Carpenter et al. (1997), where the same fibers for the ground subtraction to be performed in a similar way as the one of IC 2391 using fiber-fed spectrograph, we recommend background subtraction to be performed in a similar way as the one typically used for sky subtraction but shifted 6′′ away.

The SpT and $T_{\text{eff}}$ given in the last two columns are based on the spectra from Barrado y Navascués et al. (2004).

### Table 5
Object from Barrado y Navascués et al. (2004), which we also Observed in Our Spectroscopic Follow-up

| Field | ID | R.A. | Decl. | S/N | SpT | $T_{\text{eff}}$ | $M$ | Name | SpT | $T_{\text{eff}}$ |
|-------|----|------|-------|-----|-----|---------------|----|------|-----|---------------|
| 20    | 022 | 8:38:47.282 | −52:44:32.61 | 17.0 | M6.0 | 2840 | 0.065 | CTIO-062 | M6.0 | 2800 |

Note. The SpT and $T_{\text{eff}}$ given in the last two columns are based on the spectra from Barrado y Navascués et al. (2004).

### Table 6
Spectroscopic Data, Photometric and Spectroscopic Membership Status

| Field | ID | S/N | SpT | EW(Hα) | EW(Na i 8182 Å) | EW(Na i 8194 Å) | RV (km s$^{-1}$) | EW(Li) | Spec Member ? |
|-------|----|-----|-----|--------|----------------|----------------|-----------------|--------|---------------|
| 15    | 003 | 6.1 | M2.0 | …      | 1.21           | …              | …               | …      | No            |
| 15    | 004 | 20.7 | M3.5 | 7.38    | 3.12           | 2.43           | …               | …      | No            |
| 15    | 005 | 8.3 | M7.5 | 4.30    | …              | …              | …               | …      | Yes           |
| 15    | 010 | 8.0 | M7.5 | 2.80    | 0.75           | …              | …               | …      | No            |
| 15    | 011 | 9.0 | M7.0 | −6.80   | 2.15           | 1.77           | …               | …      | No            |
| 15    | 041 | 35.2 | M5.5 | 12.66   | 1.02           | 1.75           | …               | …      | No            |
| 20    | 001 | 32.0 | M5.0 | …      | 1.21           | 2.88           | 15.11(8.39)     | 0.8    | Yes           |
| 20    | 009 | 20.2 | M5.0 | −17.56  | 2.65           | 2.19           | −18.28(12.37)   | <0.1   | Yes           |
| 20    | 012 | 9.2  | M4.5 | 15.16   | …              | …              | 11.31(77.0)     | …      | Yes           |
| 20    | 014 | 27.6 | M5.0 | 13.24   | …              | …              | 23.33(6.88)     | <0.1   | Yes           |
| 20    | 018 | 22.0 | M5.0 | 21.36   | 1.91           | 3.32           | 19.32(7.78)     | …      | Yes           |
| 20    | 022 | 17.0 | M6.0 | 13.03   | 1.55           | 2.61           | 14.95(8.14)     | …      | Yes           |
| 20    | 023 | 20.0 | M2.0 | −6.12   | …              | 1.72           | 94.74(6.90)     | …      | No            |
| 20    | 024 | 21.8 | M6.5 | …      | 1.29           | …              | 27.91(7.35)     | …      | Yes           |
| 20    | 028 | 26.5 | M7.5 | …      | 1.23           | …              | 11.78(7.48)     | …      | No            |
| 20    | 029 | 21.4 | M6.5 | …      | 2.38           | 2.33           | 16.25(6.59)     | 1.3    | Yes           |
| 20    | 033 | 13.1 | M6.5 | 5.80    | …              | 1.96           | 6.23(7.04)      | …      | No            |

Note. A value of <0.1 as equivalent width of lithium indicates the presence of a feature at 6708 Å, but no reliable measurement of equivalent width can be done.

### Table 7
Stellar Parameters Obtained from Spectra

| Field | ID | R.A. | Decl. | S/N | $R_e$ | $R_e$−815/20 | SpT | $T_{\text{eff}}$ | $M$ | $T_{\text{eff}}$(phot) | $M$ (phot) |
|-------|----|------|-------|-----|-------|--------------|-----|-----------------|----|---------------------|------|
| 15    | 005 | 8:36:18.241 | −53:25:57.60 | 8.3 | 21.048 | 3.245 | M7.5 | 2660 | 0.049 | 2654 | 0.048 |
| 20    | 029 | 8:40:16.671 | −52:36:58.32 | 21.4 | 20.076 | 2.505 | M6.5 | 2780 | 0.056 | 2740 | 0.055 |

6.2. Membership Determination

We use the Li I line at 6708 Å to help confirm substellar status of photometric candidates and to establish membership of IC 2391. Lithium can be observed in young, more massive stars with radiative interiors because of less efficient mixing than in fully convective low-mass stars (e.g., Manzi et al. 2008). Lithium may still even be present in the atmospheres of young, fully convective low-mass stars, if they are young enough that not yet all the lithium has been “burned” (Manzi et al. 2008). Older, lower mass BDs ($\geq 0.065$ $M_\odot$) never achieve core temperatures high enough to burn lithium and so preserve their initial lithium content (Rebolo et al. 1996). Here, we assume that field stars (with $M \gtrsim 0.072$ $M_\odot$) are too old to still retain lithium in their atmospheres. Hence, we take the presence of the Li I line in candidates with $M \lesssim 0.072$ $M_\odot$ as an indicator of membership in IC 2391, as only cluster members fainter than the lithium depletion boundary ($L = 16.2$ mag; Barrado y Navascués et al. 2001) are young enough to retain lithium.

The sodium doublet at 8200 Å is a gravity indicator, so is sometimes used to exclude field stars. Specifically, its equivalent width (EW) is sensitive to log g (Martín et al. 1996) and because BDs contract as they age, log g will increase. Because field late M dwarfs (which have similar colors to M dwarf cluster members) will generally be much older and so more evolved, they will have larger EWs in this line (for a given chemical
Figure 19. Spectra of the eight newly discovered brown dwarf members of the IC 2391 cluster found in our survey. We also present, for each spectra, a new close-up on the Li and the Na\textsc{i} doublet.

Figure 20. Finding charts of the two new brown dwarf members of IC 2391 (from 815/20 images). The panels are 3.5′ × 3.5′ with north up and east to the left.

composition). We use the EW measurement of CTIO-046 from the Barrado y Navascués et al. (2004) survey as a lower limit on EW values for M dwarfs to be non-members. (This object was defined as a non-member based on various criteria and had \( W(\text{Na}\textsc{i})=7.3 \pm 0.2 \, \text{Å} \).) It can be argued that, since surface gravity changes with mass, the limit \( EW(\text{Na}\textsc{i})=7.3 \, \text{Å} \) could also change with mass. Based on our isochrone of IC 2391, from 0.04 to 0.2 \( M_\odot \) (which is the mass range of our spectroscopic follow-up), the surface gravity will vary only from \( \log g = 4.65 \) to 4.72 (\( \delta \log g = 0.07 \)).

The spectral resolution is sufficient to provide an estimate of the radial velocity.\(^4\) As for the radial velocity criteria, we exclude candidates which differ significantly (\( \pm 3 \sigma \)) from a recent determination of the cluster’s radial velocity (16 ± 3 km s\(^{-1}\); Kharchenko et al. 2005, where \( \sigma \) is the error of the radial velocity of IC 2391 added in quadrature with the error of our candidates). We did not use radial velocity measurement for which errors exceed 30 km s\(^{-1}\), which is ten times the error on the radial velocity of IC 2391.

Finally, we use the SpT determination to obtain \( T_{\text{eff}} \) and masses for each spectrum. In order to be confirmed as a (spectroscopic) cluster member, the spectroscopic \( T_{\text{eff}} \) and must agree with the photometric \( T_{\text{eff}} \) to within 200 K.

In Table 6, we again present all objects from Table 4, but with physical parameters and with membership status based on photometry and spectroscopy (i.e., which satisfy our spectroscopic criterion). We do not reject objects below which does not present a feature of Li\textsc{i} due to low S/N if the other criteria are satisfied (e.g., IC2391-WFI-15-005).

6.3. Discussion of the Spectral Data

Of the 17 photometric candidates observed with a S/N higher than 5, 9 are spectroscopic members of the cluster. We find no red giants in our spectral sample, which demonstrates that our choice of filters and selection procedure is efficient at minimizing this contamination. Since our spectroscopic follow-up covers only part of the mass range used for the MF calculation in Section 5, it is not possible to compute a new MF with corrections applied at each mass bin. It is expected that the contamination rate would be different for other mass range and fields (for different filter combinations). One of our spectral targets was observed by Barrado y Navascués et al. (2004): CTIO-62, which has the label IC2391-WFI-20-067 in our survey. We agree with Barrado y Navascués et al. (2004) on the status (cluster member) of this object.

Another of our spectral targets, IC2391-WFI-20-001, shows lithium even though this object has an inferred mass above the stellar/substellar boundary (spectroscopic mass of 0.079 \( M_\odot \) and a photometric mass of 0.089 \( M_\odot \)). The lithium depletion boundary has been estimated to be at \( I_c = 16.2 \, \text{mag} \) (Barrado y Navascués et al. 2001), which corresponds to an effective temperature of about 3000 K based on our isochrones of IC 2391. As the cluster is not that old, the lithium depletion boundary lies well above the substellar boundary, so it is not surprising to see

\(^4\) The radial velocity measurement was performed with the IRAF task \texttt{xcsao}. This task perform cross correlation against a spectrum with known radial velocity and makes the barycentric correction.
a trace of lithium in the spectrum of this object (which has a magnitude of $I_\alpha = 16.681$ mag).

Although we obtained for IC2391-WFI-20-024 the same spectral type as for IC2391-WFI-20-029, we consider this object as a member of IC 2391, but to have a mass slightly above the substellar. Its photometry gives $T_{\text{eff}} = 2958 \text{ K}$ and $M = 0.081 M_\odot$, with a predicted magnitude of $815/20 = 16.445$ mag. If this object were an unresolved binary, we would expect its observed magnitude to be brighter than its predicted one, which is not the case (observed magnitude of $815/20 = 16.520$ mag). Also, it should be noted that this object was observed with a fiber with poor spectral response below 6800 Å (which is why we do not show it in Figure 17). Although this does not affect the PC3 index used for the SpT determination (which covers 7540 Å to 7580 Å, and 8230 Å to 8270 Å), it does influence the reduction process (including the throughput correction, illumination correction, extraction of the spectra, and flux calibration). Therefore, we consider its SpT uncertainty to be larger (two subtypes rather than one).

6.4. Discovery of New Brown Dwarf Members of IC 2391

Of the 17 spectral targets, we assign two in IC 2391 as BDs, on the basis of spectroscopic confirmation, and having both photometric and spectroscopic masses below $0.072 M_\odot$. These are new discoveries. These objects are IC2391-WFI-15-005 and IC2391-WFI-20-029. Table 7 lists their parameters. Figure 19 shows their spectra and Figure 20 contains the finding charts. We can see in Figure 19 that $\alpha$ is not visible in IC2391-WFI-20-029, so it would be designated as non-members by Barrado y Navascués et al. (2004). Considering that the MF from our radial fields is similar to that of the deep fields in the mass range of these two new objects (from $0.045$ to $0.072 M_\odot$), then if we used the same selection method, then statistically we would expect to find two BDs in the same mass range in the other two deep fields, and about 31 in all of the radial fields.

7. CONCLUSIONS

We have performed a multi-band photometric survey over 10.9 deg$^2$ of the open cluster IC 2391, and completed a preliminary spectroscopic follow-up of BDs and VLMs candidates from two of the WFI fields. Our objective was to study the MF of this cluster, and in particular its radial dependence. We observed a radial variation in the MF from 0.072 to 0.3 $M_\odot$, but we do not observe a significant radial variation in the MF in the substellar regime. This comparative lack of radial variation of the substellar MF is in favor of the ejection scenario for forming BDs, but considering that IC 2391 is $\sim 3$ times older than its crossing time, we might expect that most of the BDs with velocity dispersion greater than the escape velocity could have already escape the cluster. On the other hand, the rather homogeneous distribution of the substellar objects and the clustered distribution of stellar objects within $\theta \sim 2\arcsec$ could be a signature that mass segregation via dynamical evolution has occurred in IC 2391, or that this mass segregation is of primordial nature. We have concluded that if this cluster is dynamically unevolved and if the BDs have a higher velocity dispersion than the stars, then our observations are consistent with BD formation by the ejection hypothesis.

In addition to the radial study, we derived an MF from four central deeper fields as well as from five fields near the edge of the cluster observed with only three filters (the outward fields). In both cases, we see an apparent rise in the number of objects below $0.05 M_\odot$ ($\log_{10} M = -1.3$), but we concluded that this is an artifact of residual contamination by field M dwarfs. This was also seen by Barrado y Navascués et al. (2004). The fact that we do not see this rise in the radial fields is because they were observed with both the $J$ and $R_c$ filters in addition to the medium band filters. This longer spectral baseline permits a better determination of the energy distributions and thus helps the rejection of objects (in particular field M dwarfs) based on observed magnitude versus predicted magnitude from models.

Another apparent rise in the MF over the $0.5–1.0 M_\odot$ interval (also observed by Jeffries et al. 2004 for NGC 2547) is due to background giants. Red giant contamination may be reduced by using medium bands such as $770/19, 815/20, 856/14$, and $914/27$, and theoretical colors of red giants (Hauschildt et al. 1999b). Our spectroscopic follow-up has confirmed that selection based on these filters resulted in no red giant contaminants among our sample of spectra.

We see some variation in the colors of the main (field star) locus, which we attribute to variable extinction affecting the background stars. This underlines the need for spectroscopic observations in this cluster in order to confirm membership and/or BD status in individual cases.

We have performed a preliminary spectroscopic follow-up of photometric candidates in two of our deep fields (0.5 deg$^2$). Of 17 photometric candidates, we confirm 9 objects (i.e., half) as true cluster members. Of these, two are new BD members of IC 2391 (in the sense that they fulfill our spectroscopic and photometric criteria). Using our derived MFs for the deep and radial fields, we expect there to be two more BDs in the mass range 0.045–0.072 $M_\odot$ in the other deep fields and up to 31 in all the other radial fields in the same mass range.

Finally, we find that the $\alpha$ line cannot be used as a membership criterion from fiber spectroscopy at low spectral resolution (spectral dispersion of 1.14 Å per pixel) because of spatially variable diffuse $\alpha$ emission. This prevents reliable sky subtraction around this line when using a fiber spectrograph with fibers assigned for sky subtraction.

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