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Research Experience for Undergraduates Program 2005
Final Research Paper

A Wide Field Optical and Near-Infrared Search for Brown Dwarf Candidates

I. Introduction

Bridging the gap between the traditional stellar and planetary realms, brown dwarfs are an exciting reminder of the physical significance behind many seemingly archaic or arbitrary astronomical classifications. With core temperatures and pressures far too low to sustain hydrogen fusion, these "failed stars" are believed to be products of star-formation processes – yet they approach the planetary realm in mass and size. Some of these objects may have such low masses that, like planets, they cannot even initiate deuterium burning. This ambiguous transition will be greatly illuminated through continued study of the observational and physical properties of the two populations.

Once a young brown dwarf has exhausted the energy provided by its gravitational contraction and any deuterium burning, it enters a state of perpetual cooling. Late spectral types are representative of these ultra-cool temperatures. Although brown dwarfs cannot be confirmed through photometry alone, one can fairly confidently identify late-type dwarf candidates from optical and near-infrared colors. M, L, and T dwarfs candidates are excellent candidates for follow up spectroscopic analysis to authenticate brown dwarf suspicions as all brown dwarfs evolve from M to L to T dwarfs. This paper details a search of th*i*s kind: locating late-type dwarf candidates for further spectral consideration.

These objects are not so easily detected. However, since its initial data release in 1999, the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) has shown itself to be an incredible asset to the search for M, L, and T dwarfs. The survey's J, *H*, and *K* band photometry has proven very useful for identifying low mass stars and brown dwarf candidates. There are 404 L dwarfs and 58 T dwarfs currently confirmed (dwarfarchives.org), at least thirty percent of which owe their discoveries to 2MASS.

There is nothing novel about utilizing 2MASS photometry to locate brown dwarf candidates; many searches have already examined the survey successfully (notably, Cruz et al. 2003 and Hawley et al. 2002 in conjunction with the Sloan Digital Sky Survey). In order to continue to mine the low mass wealth of 2MASS, we have employed its photometry in conjunction with archival Kron-Cousins *I*-band data taken with the CFH12K wide field imager on the Canada-France-Hawaii Telescope on Mauna Kea. By utilizing the combined datasets to derive *I-J* colors for objects in the CFH12K field and comparing those values with corresponding 2MASS *J-K* colors, we attempted to identify a collection of previously unidentified candidates whose locations in color space imply late spectral types.

The following sections will describe the steps taken to limit the dataset of over 24 thousand CFH12K images consisting of about 11.6 million celestial objects to a reasonable subset of possible late-type dwarfs, detail the features of my final list of candidates, and discuss some possible routes for continuing the project.

II. Data and Analysis

IIa. 2MASS and CFHT

The Two Micron All Sky Survey is the product of observations from two 1.3-meter telescopes, one at Mt. Hopkins in Arizona and the other in Chile. The two telescopes made simultaneous observations at *J*, *H*, and *K* for over 99 percent of the sky between 1997 and 2001. The 2MASS survey had magnitude limits of 15.8 for *J*, 15.1 for *H*, and 14.3 for *K* for point sources with S/N = 10.

In addition to the All-Sky 2MASS data release, we utilized archival CFH12K *I*-band (centered at .822 microns) observations obtained while the telescope was in queue-mode during the period from 2001 to mid 2002 and in classical observing mode from September 1999 to December 2000. CFH12K is a 12,288 by 8,192 pixel mosaic CCD - the largest in use at the time of these observations. The images had an *I* magnitude limit around 23.5 for a one second exposure. The exposure times ranged from a few to a few hundred seconds. The objects of interest, however, were faint enough that saturation was not an issue. Many of the available images covered overlapping regions on the sky, with the total archive covering less than 1% of the sky. Consequently, robust averages were computed to be employed in the color analysis. The relative photometry program utilized was sensitive to the location of measurements on the chip, disregarding the unreliable measurements at the edges.

This CFH12K data was used to test and develop the Elixir data processing system. (Magnier and Cuillandre 2004) As the proprietary period has concluded for these observations, the Elixir-processed data is now public domain. The initial dataset, therefore, consisted of the relatively small region encompassed by the CFH12K observations along with overlapping 2MASS data in *J*, *H*, and *K*. (1.25, 1.65, and 2.17 microns, respectively).

These two datasets were effectively merged and analyzed through the use of Desktop Virtual Observatory (DVO), a component of the Elixir system. DVO provided the means for matching measurements from the different bands to single objects (with a two arc second matching radius) and consequently extracting all necessary information to select dwarf candidates via a graphical sky navigation interface.

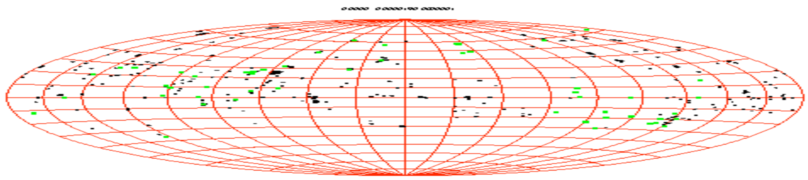

Figure 1. The DVO full sky navigation window. CFH12K images are shown in black. The locations of the final candidates are shown in green.

IIb. Known Dwarfs

Due to the wide range of dwarf detection techniques and the steadily expanding list of confirmed objects, a standardized means of reporting discoveries is necessary. Dwarfarchives.org (maintained by Chris Gelino, Davy Kirkpatrick, and Adam Burgasser) fills this much needed role. With detailed information about L and T dwarfs accessible in a single location, we were able to determine if our dataset included any previously detected objects. We found that 20 known L dwarfs and 4 known T dwarfs had coordinates covered by the CFH12K data, although only 10 were detectable. This information was useful on two levels. First, we would be able to exclude these objects from our own list of candidates. Even more valuable, however was the second use. We created a subset of the full dataset consisting of regions overlapping these known dwarfs. This subsection was a convenient tool for the development of our search methods (discussed below). Our confidence in our methods was greatly increased by returning the known objects in preliminary queries of the known dwarf subset.

IIc. Candidate Selection

Before deciding on criteria for candidate selection, the quality of the two datasets was addressed. Certain regions of the sky were immediately excluded due to cumbersome image densities. 2MASS photometric quality flags were considered to ensure low photometric errors and high scan S/N when available. Remaining 2MASS measurements with S/N less then 10 were ultimately excluded as well. A measurement quality assessment from DVO was also considered to select only measurements suggestive of non-extended and non-saturated point sources. These measures greatly reduced the volume of viable measurements to be considered in the candidate selection.

Hawley et al. (2002) published a list of average colors and absolute *J* magnitudes for spectral types M0 through T6 based on dwarfs discovered in the Sloan Digital Sky

Survey. Although these averages are based on a limited number of measurements, they provided the most relevant color information for comparison with the combined CFH12K and 2MASS data set. Most notably, they reported that an I - J range from around 4 to 8 encompasses spectral types L0 through T6. This information directly influenced my first selection criteria: $4 < I - J < 10$.

Unfortunately, L and T dwarfs are not the only astronomical bodies that reside in that color range. Background giant stars affected by extinction can have very similar $I – J$ colors. In order to differentiate between the two populations, the effects of extinction in color-color space must be considered. Using methods presented by Cardelli, Clayton and Mathis (1989), I calculated the extinction vector in I - J vs. $J – K$ color space. It can be assumed that the detectable brown dwarf candidates are sufficiently close that they are not subject to extinction. The background giants, however, should show a noticeable effect. Figure 3, a color-color diagram of the $I – J$ selected data, reveals two distinct populations: one affected by extinction and one that is not. The two groups correspond to theoretical and observational L and T dwarfs and giant stars adjusted by the extinction vector.

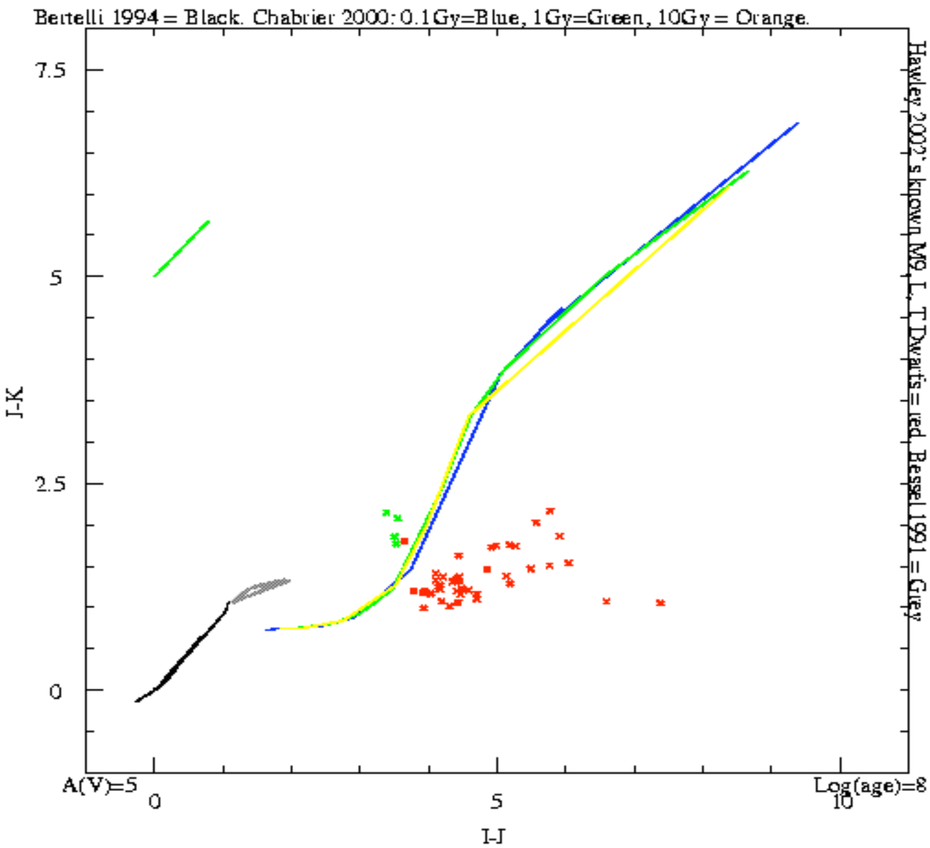

Figure 2. A color-color diagram depicting theoretical color-space locations of different types of objects. The extinction vector for A(v) = 5 is shown in green on the upper left. Isochrones for low-mass stars at various ages are shown in blue, green, and yellow. The main sequence and giants are shown in black. The red crosses represent the locations of a few known late-M, L, and T dwarfs. This plot reveals that the known dwarfs are a better guideline for color-space restrictions than theoretical predictions.

The separation between the giants and dwarfs is so easily distinguishable in color-color space that a restriction in $J - K$ is sufficient to exclude all background giants. I chose $J - K <= 1.5$ as a criteria for inclusion in the set of candidates. It is worth noting that a previous study with 2MASS data (Cruz et al., 2003) successfully selected brown dwarf candidates using a criterion of $J - K > 1.0$. Although these two restrictions seem contradictory, the existence of known dwarfs on both sides of these cutoffs illustrates the validity of our choice.

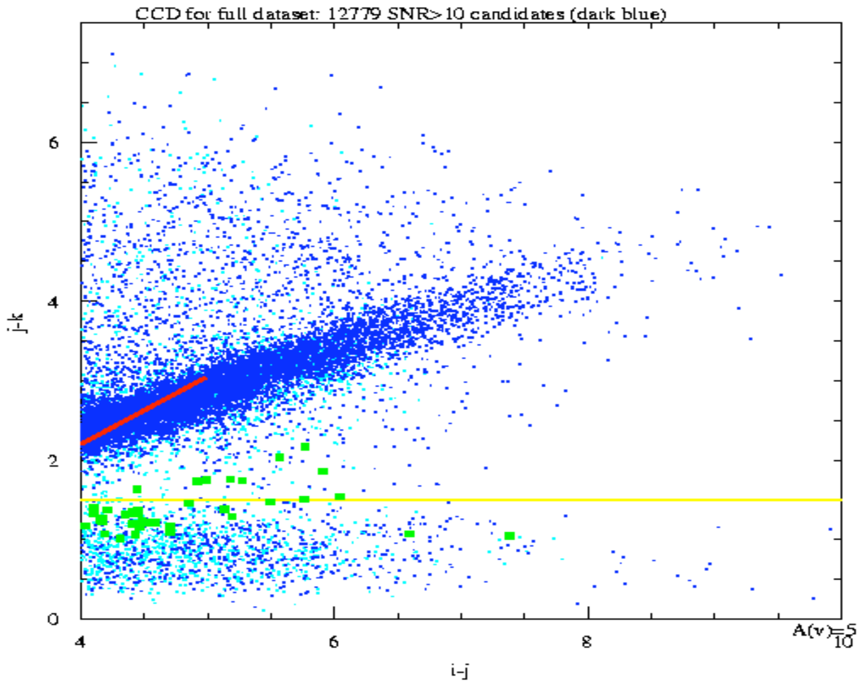

Figure 3. Color-Color Diagram displaying the difference between background giants and dwarf candidates. Dark blue dots have S/N > 10. Light blue dots have S/N > 5. Green squares are examples of known dwarfs reported by Hawley et al.. The A(v) = 5 extinction vector is shown in red. The yellow line represents the J-K < 1.5 cutoff.

There were also artifacts in color space resembling unexpected densities at various *I – J* values that revealed a further source of error in the CFH12K data. We believe the culprit to be clouds affecting the observations, although instrumental errors have not been ruled out. An example of a color-color diagram for a patch of the sky which had images affected by clouds is shown in Figure 4. This region was observed at four different times. At one time, clouds were not present and the main sequence is seen at a low *I-J*. The concentrations at redder *I-J* values are echoes of the main sequence that have been shifted in color space due to varying levels of clouds. The shift is exclusively in *I*-J because it is only the CFH12K I-band image that is affected. The *I*-J color of the main sequence was measured for every CFH12K image. A detail of a histogram of these values can be seen in Figure 5. The main sequence *I-J* values actually extend out to redder than 8 for a few images. We chose to eliminate any images with the main sequence shifted past *I*-J = 1.66 from further consideration, effectively cutting out 25% of the available data.

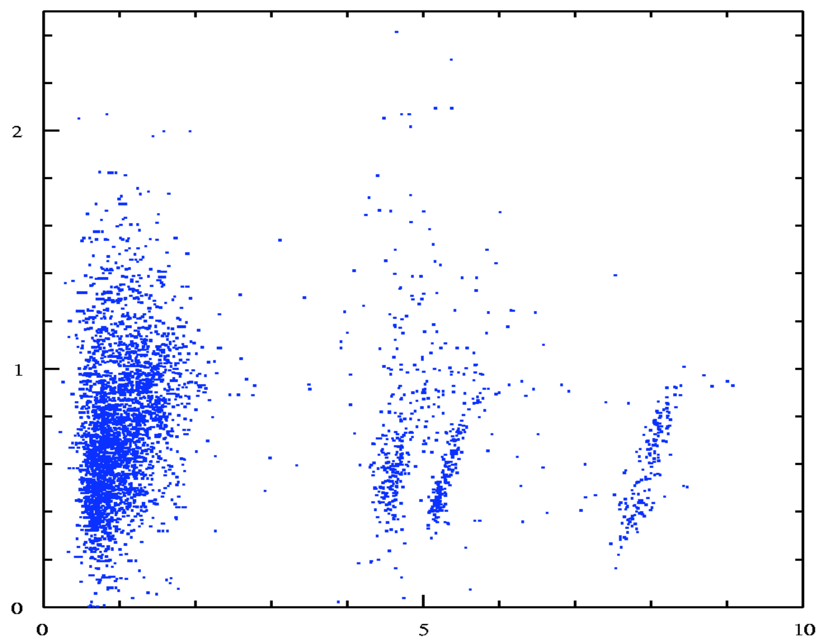

Figure 4. An I-J vs J-K color-color diagram for one patch of the sky. The region was imaged 4 times and each concentration of data points in color-space corresponds to the main sequence as reddened by different levels of clouds.

The product of these criteria was a list of 1,437 brown dwarf candidates with S/N > 5, which was further reduced to 645 candidates with S/N > 10 for both *J* and *K* measurements. Of these objects, 30 had counterparts in the SIMBAD database within ten arc seconds. Some of the counterparts were bright stars that may have contaminated the magnitude measurements and others were true overlaps. Six of the thirty were members of clusters that have been the subject of localized brown dwarfs surveys. The resulting list of 615 candidates was then compared to the USNO-B catalog. Most of the candidates had bright USNO-B counterparts in the red and blue bands and were excluded. The final list of candidates consists of 217 objects which were not detected in the USNO-B data, or had fainter blue and red magnitudes than their CFH12K and 2MASS measurements.

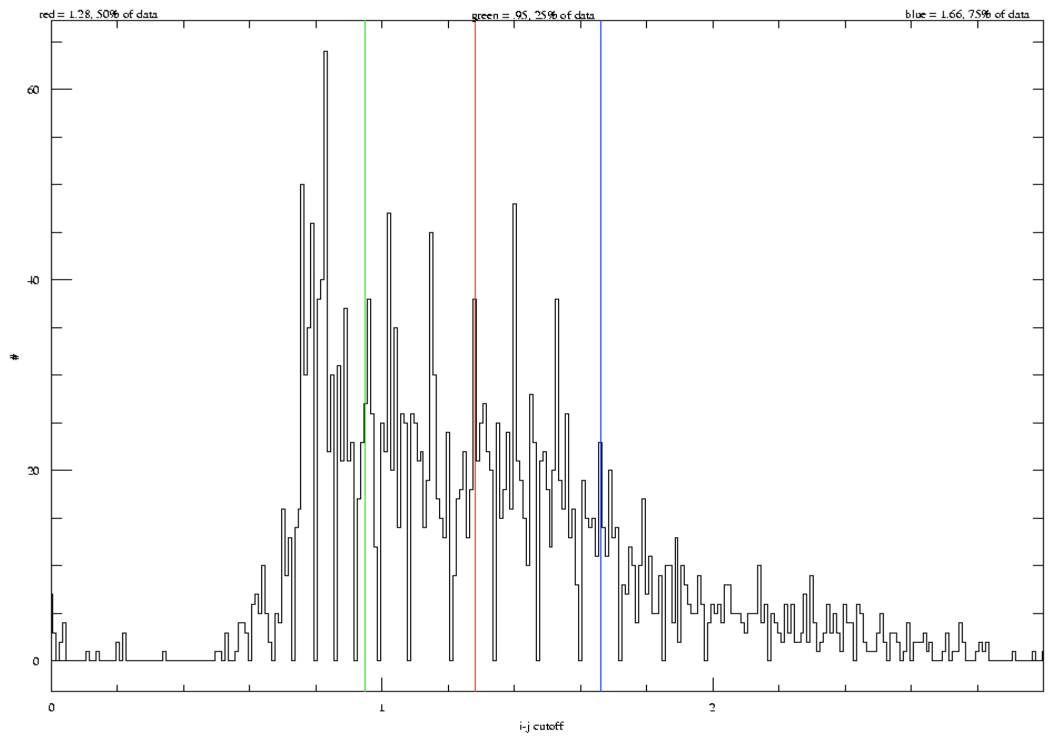

Figure 5. A histogram of the recorded I-J color of the main sequence for every CFH12K image. The full range of colors extends past I-J = 8. The red line represents the median main sequence color, I-J=1.28. The blue line represents the chosen cutoff for acceptable main sequence colors, I-J = 1.66.

III. Results and Discussion.

The 217 final brown dwarf candidates presented here have been matched to the average spectral types reported by Hawley et al. (2002) via their 2MASS *J* and *K* magnitudes and their CFH12K *I* –band measurements. The spectral type distribution can be seen in Figure 6. These spectral types are not very robust, as they are subject to both Hawley's error in averaging them, and the error in the 2MASS and CFH12K data. Nonetheless, the application of these average spectral type characteristics to the final candidates permits further analysis of the population. For instance, Hawley computed an average absolute *J* magnitude for spectral types from M0 to T6, which allowed us to estimate the distances of the candidates. For limiting 2MASS magnitudes of *J* = 15.8 and *K* = 14.3, we found that the candidate list is complete out to 61.37 parsecs for estimated spectral types M9 – L2, to 32.66 parsecs for estimated spectral types L3 – L6, to 14.65 parsecs for estimated spectral types L7 – T0, and to 15.34 parsecs for estimated spectral types T1-T6.

These candidates were derived from a dataset spanning 165 square degrees.

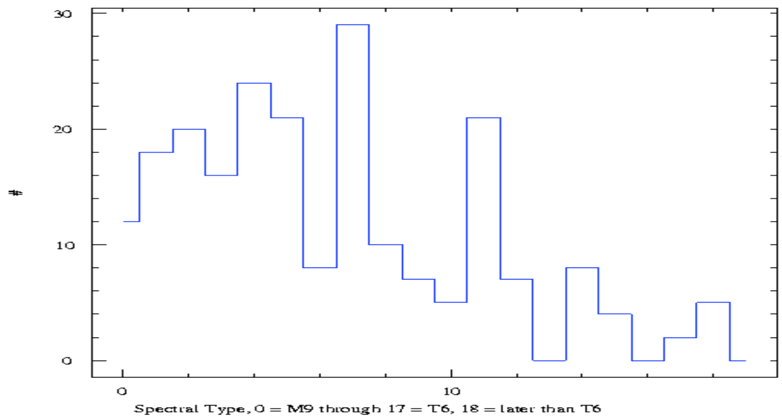

Figure 6. HIstogram of the estimated spectral types derived from Hawley et al.'s averages for the 217 final candidates.

Computing the volumes for the above mentioned completeness limits results in estimates of brown dwarf spatial densities. However, the computed densities were much larger than previous estimates. We found densities of about 0.017 M9-L2 dwarfs per cubic parsec, 0.1405 L3-L6 dwarfs per cubic parsec, 0.5258 L7-To dwarfs per cubic parsec, and 0.6594 T1-T6 dwarfs per cubic parsec. The increase in density for later spectral types is also peculiar. It is possible that an unidentified source of contamination remains in the dataset. The distribution of detections in galactic latitude shows a surprisingly high number of candidates within 10 degrees of the galactic plane. This effect would probably not be seen if all of the candidates were indeed late-type dwarfs as the magnitude limits suggest completeness to only 60 parsecs. The density of detections at the galactic plane is not caused by the distribution of observations on the sky, as shown in Figure 7. The source of these inconsistencies is a topic of continued consideration.

Further work will hopefully address these issues and ultimately present a revised list of candidates with higher confidence. Follow-up spectroscopic analysis of the final candidates will confirm the spectral types of the candidates and look for the tell-tale signs of brown dwarfs such as atmospheric methane. Any confirmed brown dwarfs resulting from this project will tell us a lot about the strength of our search methods as well as provide insight into questions of star formation by aiding in the constraint of the substellar initial mass function.

IV. Acknowledgments

This research makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work has also benefited from the M, L, and T dwarf compendium housed at DwarfArchives.org and maintained by Chris Gelino, Davy Kirkpatrick, and Adam Burgasser.

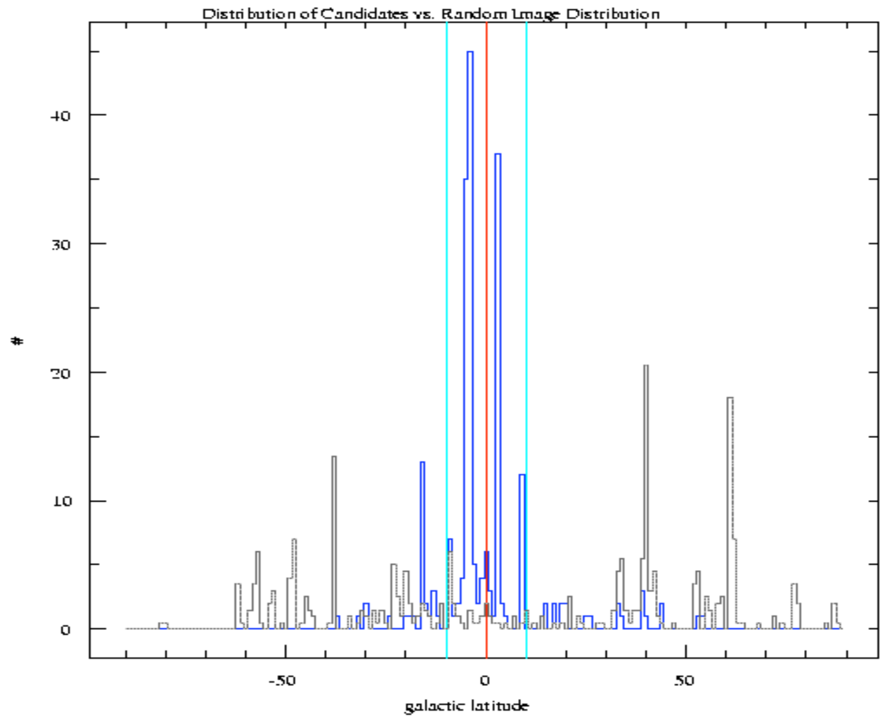

Figure 7. Histogram of the galactic latitudes of the 217 candidates shown in dark blue. The grey histogram represents the galactic latitudes of randomly selected CFH12K images. The lack of correlation between the two histograms reveals that there is a concentration of candidates within 10 degrees of the galactic plane that is not related to the density of images.

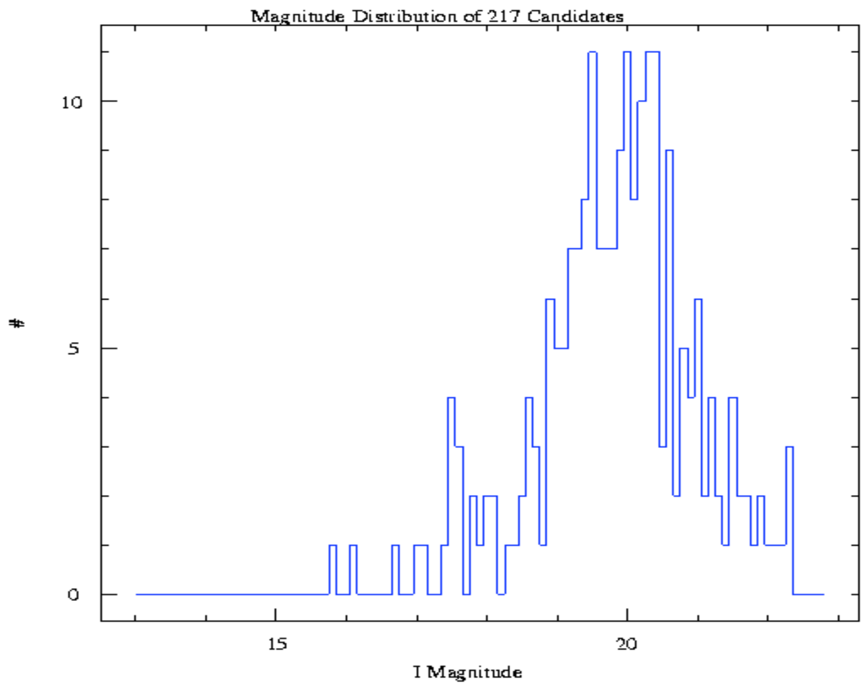

Figure 8. Histogram of measured CFH12K I magnitudes for the 217 candidates.

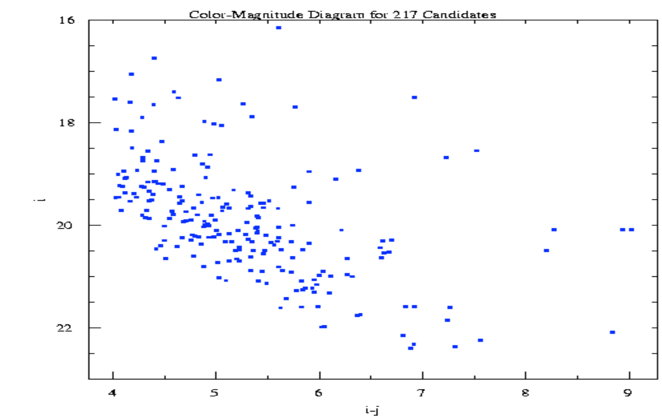

Figure 9. I-J vs. I color-magnitude diagram for the 217 final candidates.

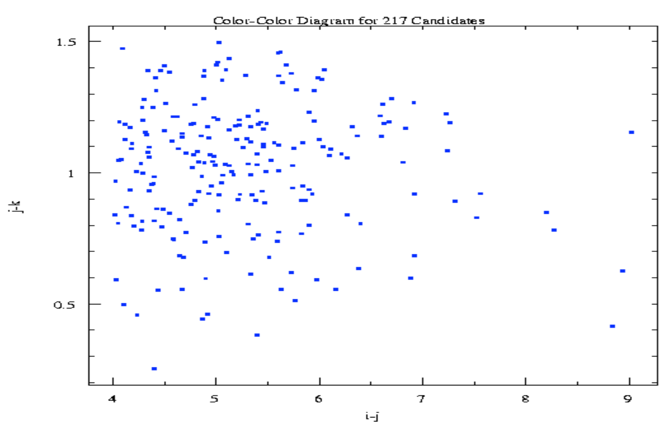

Figure 10. I-J vs. J-K color-color diagram for 217 final candidates.

V. References

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