COOL YOUNG STARS IN THE NORTHERN HEMISPHERE: \( \beta \) PICTORIS AND AB DORADUS MOVING GROUP CANDIDATES

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ABSTRACT

As part of our continuing effort to identify new, low-mass members of nearby, young moving groups (NYMGs), we present a list of young, low-mass candidates in the northern hemisphere. We used our proven proper-motion selection procedure and ROSAT X-ray and GALEX-UV activity indicators to identify 204 young stars as candidate members of the \( \beta \) Pictoris and AB Doradus NYMGs. Definitive membership assignment of a given candidate will require a measurement of its radial velocity and distance. We present a simple system of indices to characterize the young candidates and help prioritize follow-up observations. New group members identified in this candidate list will be high priority targets for (1) exoplanet direct imaging searches, (2) the study of post-T-Tauri astrophysics, (3) understanding recent local star formation, and (4) the study of local galactic kinematics. Information available now allows us to identify eight likely new members in the list. Two of these, a late-K and an early-M dwarf, we find to be likely members of the \( \beta \) Pic group. The other six stars are likely members of the AB Dor moving group. These include an M dwarf triple system, and three very cool objects that may be young brown dwarfs, making them the lowest-mass, isolated objects proposed in the AB Dor moving group to date.

Key words: open clusters and associations: individual (Beta Pictoris, AB Doradus) – stars: kinematics and dynamics – stars: pre-main sequence

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Well-characterized samples of low-mass, pre-main sequence (PMS) stars are important for understanding star formation and evolution, the circumstellar environment, and planetary system formation. These stars are attractive targets for exoplanet searches by direct imaging because young, massive planets are expected to be self-luminous from gravitational contraction and the contrast between host star and planet is more favorable when the star is intrinsically faint. The nearest and youngest stars in clusters lie in the Taurus and Ophiuchus star-forming regions (SFRs) with ages \( \sim 1-5 \) Myr and distances 120–145 pc. Their distances limit the detail with which they can be studied. Nearby, low-mass PMS stars that are no longer associated with their SFRs have long been sought following Herbig’s (1978) suggestion that they may exist in large numbers mingled with field stars. Post-T-Tauri stars (PTTSS), with ages \( \sim 10^7 \) to \( \sim 10^8 \) yr, exhibit properties associated with stellar youth, such as chromospheric activity, lithium absorption, and rapid rotation, which provide the means to distinguish them among older field stars.

Stellar counterparts to ROSAT (Voges et al. 1999, 2000; hereafter V99, V00) X-ray sources and the compilation of precision astrometric catalogs (e.g., the Hipparcos catalog; Perryman et al. 1997) have yielded the identification of nearby, young stars as members of coeval groups characterized by the common motion of their members through the Galaxy. These groups of stars are known as nearby, young moving groups (NYMGs; see Zuckerman & Song 2004, hereafter ZS04; Torres et al. 2008, hereafter T08). Members of NYMGs have ages \( \lesssim 100 \) Myr and lie at distances \( \lesssim 100 \) pc (T08). The ages, space motions, and sky distributions of stars in the NYMGs suggest that they share a common origin. Kinematic traceback studies show that they may be related to a star formation event in the Sco–Cen region (Mamajek & Feigelson 2001; Fernández et al. 2008).

Most members of the known moving groups are concentrated in the south. However, we began our search for new, low-mass NYMG members in the \( \beta \) Pictoris moving group (BPMG; Lépine & Simon 2009, hereafter LS09) and expanded it to the AB Doradus moving group (ABDMG; Schlieder et al. 2010, hereafter S10) because they have known members in the north. The northern hemisphere presents a relatively untapped resource in the search for moving group members.

To date, confirmed members of the BPMG and ABDMG show a marked deficiency in low-mass stars between spectral subtypes M0 to M6. If those moving groups have a mass function consistent with field stars (see Bochanski et al. 2010), then astronomers are currently missing the bulk of the \( \beta \) Pic and AB Dor members. There are two primary factors contributing to the observed deficiency of known low-mass members: (1) low-mass stars are intrinsically faint, thus the majority are beyond the magnitude limits of the Hipparcos and Tycho-2 astrometric catalogs which, along with the ROSAT catalogs, have so far been used as the primary sources for identifying new group members. (2) The lowest-mass stars lack reliable youth diagnostics from which the missing stars could be easily identified. Traditional activity indicators, X-ray and H\( \alpha \) emission, are increasingly less reliable for spectral types (SpTy) later than M4 because most older, field stars are active in that spectral range (West et al. 2008, 2011, hereafter W11). This is probably a consequence of the transition to fully convective interiors. Lithium is also depleted for most low-mass stars at the ages of the NYMGs (Palla & Randich 2004) which makes the detection/non-detection of the...
Li 6708 Å line an unreliable indicator of age. Furthermore, Baraffe & Chabrier (2010, hereafter BC10) have also shown that Li depletion may be strongly affected by stellar accretion history in low-mass stars.

LS09 developed an astrometric technique to identify low-mass candidates of NYMGs in proper-motion catalogs. The projected mean motion vector of a known moving group is used to identify candidates based on their proper motion and optical/IR photometry. The visual magnitude of the proper-motion samples to which LS09 applied this technique (V < 12) limited the identification of likely new members (LNMs) to stars earlier than approximately M2 SpTy (LS09). S10 expanded the technique to a preliminary version of the deeper (V < 19) SUPERBLINK catalog (SBK; S. Lépine et al. 2012, in preparation) to probe into the mid-M range.

Several other efforts are underway to identify low-mass NYMG members. Shkolnik et al. (2009, hereafter Sh09) use ROSAT X-ray data and spectroscopic follow-up to identify nearly 150 nearby, young M dwarfs in a < 25 pc sample, at least some of which are likely to be NYMG members. Shkolnik et al. (2011, hereafter Sh11) present an analysis of M dwarfs in the HST Guide Star Catalogue (Lasker et al. 2008) and the Two Micron All Sky Survey (2MASS) All-Sky Catalog of Point Sources (Skrutskie et al. 2006) having Galaxy Evolution Explorer (GALEX) counterparts to calibrate UV emission as a youth indicator in low-mass stars. UV emission was then used as a basis to identify two new members of the ~10 Myr old TW Hydrae association. Kiss et al. (2011) use a selection technique similar to T08 and data from The Radial Velocity Experiment (Steinmetz et al. 2006) to identify new NYMG members in the south. Rice et al. (2010) report the first isolated brown dwarf member of the BPMG as a result of a large-scale astrometric and spectroscopic survey of brown dwarfs. Others have started to use GALEX data to identify cool young stars as well, focusing on UV excess as a diagnostic (Findels & Hillenbrand 2010, hereafter FH10; Rodriguez et al. 2011, hereafter R11). A program is also underway that uses a selection technique very similar to LS09, S10, and this work but assigns membership probabilities to candidates using Bayesian analysis techniques. This search focuses on β Pic, AB Dor, and Tuc/Hor candidates (Malo et al. 2012, in preparation; see Rice et al. 2011).

In Sections 2 and 3 of this paper we apply the techniques described in LS09 and S10 to search for BPMG and ABDMG candidates in the Tycho-2 catalog (Hog et al. 2000, hereafter H00), the LSPM-North catalog (Lépine & Shara 2005, hereafter LSO5), and the now complete northern hemisphere SBK catalog. This extension permits identification of moving group candidates with SpTy’s beyond M4, which raises the problem of identifying the young stars among them. For mid-M dwarfs and later, the gravity sensitive alkali lines, such as the neutral sodium doublet at 8200 Å, can serve as proxies for youth. At a few tens of Myrs age, these stars are still contracting to the main sequence (MS) and have lower photospheric gravities than they will have later; this makes the Na i doublet at ~8200 Å a useful indicator of age in low-mass stars (Schlieder et al. 2011). The extensive spectroscopic observations required to study this feature are however beyond the scope of this paper. We therefore describe in Section 4 our list of young β Pic and AB Dor candidates in the north identified using our selection technique and the X-ray/UV youth criteria described in Sh09 and Sh11. We also carry out a preliminary study of the candidates to determine those for which these youth indicators are most reliable. In Section 5, we investigate the bulk properties of the sample to guide follow-up priority. In Section 6, we describe LNMs identified in the analysis presented and we summarize our results in Section 7.

2. CANDIDATE SELECTION

T08 lists 50 BPMG members with membership probability ≥90% for all but three stars. The membership probabilities were calculated using the full, six-dimensional galactic kinematics of the group in a k-NN model (T08). We include all 50 known members in our analysis. The known BPMG members lie at a median distance of ~35 pc and have ages 10–20 Myr (T08). The motion of the group through the galaxy is defined using U, V, and W space velocities (Johnson & Soderblom 1987) with means (UBPMG, VBPMG, WBPMG) = (−10.1 ± 2.1, −15.9 ± 0.8, −9.2 ± 1.0) km s⁻¹ relative to the Sun (T08). In this coordinate system, U is positive toward the galactic center, V is positive in the direction of solar motion around the Galaxy, and W is positive toward the north galactic pole. The group shows extension in the direction toward the galactic center (Figure 1), a feature common to all NYMGs younger than 30 Myr (T08).

The 89 known members of the ABDMG lie at a median distance of ~30 pc and have ages of ~70 Myr (T08). All of these stars have a membership probability in T08 ≥85%. The mean velocities of AB Dor group members are (UABDMG, VABDMG, WABDMG) = (−6.8 ± 1.3, −27.2 ± 1.2, −13.3 ± 1.6) km s⁻¹. These space velocities are comparable to those of Pleiades open cluster members. Luhman et al. (2005) and Ortega et al. (2007) argue that the ABDMG may be remnant of the star formation event that formed the Pleiades. Possibly coincidentally, the space velocities of some AB Dor stars are similar to β Pic stars in the U and W plane. The group lacks the X-direction extension of younger NYMGs and exhibits a more uniform galactic distance distribution (see Figure 2).

LS09 and S10 have described the proper-motion selection algorithm in detail. To produce a list of young candidates in the northern hemisphere we performed only the first 3 steps in the

5 Proposed BPMG members HD 203, HD 15115, and HD 199143 have probabilities 75%, 60%, and 75%, respectively.

6 XYZ distances are defined positive in the same directions as UVW velocities.
search procedure: (1) isolate a sample of stars in a proper-motion catalog whose proper-motion vectors are consistent with moving group membership (see LS09 Equations (1)–(4)); (2) identify stars in that subsample whose photometric distance \((d_{\text{phot}})\) is consistent with the kinematic distance \((d_{\text{kin}})\), which is derived from the proper motion assuming group membership (see LS09 Equations (5)–(7)); and (3) trim this sample to include only stars exhibiting indicators of youth. After this, all that will be required is a confirmation that the radial velocity (RV) and astrometric distance are consistent with NYMG membership. This follow-up work is now in the planning stages. We follow the labeling convention introduced in S10.

1. **Candidate.** A low-mass star having proper motion and photometry consistent with NYMG membership.
2. **Probable young candidate (PYC).** A candidate exhibiting indicators of youth.
3. **Likely new member (LNM).** A PYC having an RV or distance consistent with NYMG membership.

Because the search parameters govern the candidates selected, we describe the parameters in detail and define the limits used in this search.

**Lower proper motion limit**, \(\mu_{\text{min}}\). A lower limit that is very small will introduce contamination from field stars whose proper motions align with the projected mean motion of the group by chance. We chose \(\mu_{\text{min}} = 40 \text{ mas yr}^{-1}\) as a lower limit because the majority of known BPMG and ABDMG members have \(40 \text{ mas yr}^{-1} \lesssim \mu \lesssim 200 \text{ mas yr}^{-1}\) (see Figure 3).

**Dispersion about average space motion**, \(\phi\). The scalar product of the mean projected motion of the group with the proper motion of a catalog star, calculated in the plane of the sky local to the star, defines \(\cos \phi\) (LS09, Equation (3)). Stars that are actual NYMG members will have \(\phi\) close to 0. The largest acceptable value of \(\phi\), called \(\phi_{\text{max}}\), depends on the \(U/V/W\) velocity dispersion of known moving group members and can be assessed by calculating \(\phi\) for each known member (see Figure 4). We choose \(\phi_{\text{max}} = 10^\circ\) because it includes most of the known BPMG and ABDMG members and limits contamination from kinematic interlopers.

**Kinematic distance**, \(d_{\text{kin}}\). If one assumes that a candidate selected by its proper motion actually belongs to the moving group considered, then its \(d_{\text{kin}}\) can be calculated from the magnitude of the proper vector (LS09, Equation (6)) and used as a selection parameter in two ways. First, a comparison of candidate and known member \(d_{\text{kin}}\) can act as a selection cut. The range of \(d_{\text{kin}}\) accepted when searching for candidates of an NYMG is again determined from the distribution of known members (Figure 5). Both \(d_{\text{kin}}\) distributions peak between 30 and 40 pc with an upturn at 70 pc. Three of the five stars in the 70–80 pc range in the BPMG are later than SpTy K4, and only one has a measured parallax. The upturn at 70 pc in the ABDMG is more drastic, with more than three times the stars in the previous bin. All 15 of the proposed ABDMG members in the 70–80 pc bin are earlier than mid-K type. However, only two have measured parallaxes. Since most of the stars in the 70–80 pc bins and beyond do not have measured distances we conservatively choose \(d_{\text{kin}} \leq 70 \text{ pc}\) as the cutoff in the candidate search.
Second, the $d_{\text{kin}}$ is used to calculate a pseudo-absolute $K$ magnitude ($M_K$) in an $M_V$ versus $(V - K_s)$ color–magnitude diagram (CMD). Candidates that are true NYMG members will be positionally and photometrically consistent with the cluster sequence of known group members in the CMD (see Figure 6). Any candidate remaining in the sample after previous cuts that falls outside of the cluster-sequence locus is presumed to have its true distance over or underestimated by $d_{\text{kin}}$ and is rejected from the sample.

$(V - K_s)$ color. A lower limit on the $(V - K_s)$ color determines the upper bound on the mass of the candidates. A 0.7 $M_\odot$ dwarf with an age of 40 Myr will be SpTy $\sim$K7 and have $(V - K_s) \approx 3.2$ (Siess et al. 2000, hereafter SDF2000). We used this value to concentrate our search on M dwarf candidates and avoid a high level of giant contamination (see Figure 6).

Proper-motion catalogs are magnitude and proper motion limited. Thus, searching several catalogs with complementary limits allows for the identification of all candidates within the combined limits of the search parameters and catalogs. The combined properties of the catalog subsamples we searched for northern hemisphere candidates are $\delta \geq 0^\circ$, $\mu \geq 40$ mas yr$^{-1}$, and complete to $V = 19$ mag. The individual catalogs we searched are as follows.

The Tycho-2 catalog contains positions, proper motions, and photometric data for $\sim$2.5 million stars. The catalog is $\approx$99% complete to $V \approx 11.0$, with a limiting magnitude of $V \approx 13.0$, and has proper-motion accuracy of 2.5 mas yr$^{-1}$ (H00). We selected a subsample of northern hemisphere Tycho-2 stars with $\mu \geq 40$ mas yr$^{-1}$ ($\sim$120,000 stars) which is cross correlated with 2MASS to obtain near-IR $J$, $H$, and $K_s$ magnitudes. Our previous results show that searches in the Tycho-2 catalog return candidates that are mostly earlier than SpTy $\sim$M3 (S10), a result of the $V$ magnitude limit of the catalog.

The LSPM-North catalog is an astrometric catalog of positions, proper motions, and multi-band photometry of $\sim$62,000 high proper-motion stars produced by data mining the Digitized Sky Surveys using specially developed software (LS05). The catalog contains stars with $\mu > 150$ mas yr$^{-1}$ ($\mu_{\text{err}} \approx 8$ mas yr$^{-1}$) north of the celestial equator and is $\approx$99% complete for $12.0 < V < 19.0$ with a faint limit of $V = 21.0$ (LS05). LSPM-North complements the magnitude range of Tycho-2, overlapping it in some cases, and allows access to NYMG candidates down to $\sim$0.1 $M_\odot$. SUPERBLINK (SBK) is the smaller proper-motion (40 mas yr$^{-1}$ $\leq \mu \leq$ 150 mas yr$^{-1}$) counterpart of the LSPM-North catalog and was produced using the same technique and thus retains the same limits (S, Lépine 2011, private communication). This database contains $\sim$1.5 million stars with $\delta > 0^\circ$. The lower proper-motion limit of SBK allows access to a larger spatial volume and hence more potential NYMG candidates unavailable in the Tycho-2 or LSPM-North catalogs.

3. $\beta$ Pic AND AB DOR GROUP CANDIDATES

We apply the search algorithm to the proper-motion catalogs using the search parameter limits discussed in Section 2 to identify candidates of the BPMG and ABDMG. We emphasize that our technique is statistical in nature; it can identify candidates only within the limits chosen to characterize a group. The resulting list of candidates includes recovered known members,
stars previously investigated in this project (LS09, S10), contaminants, and many new NYMG candidates, some of which will eventually become LNMs. We describe here the subsamples in the initial candidate list before presenting the final young sample.

The search for BPMG candidates returns 132 stars (see Figure 6). Only two previously known BPMG members are recovered (Table 1). We expected to recover four members based on their declinations and colors. The two not recovered, BD+30 397B and HIP 23418, are missing from the catalogs searched and fall outside of the BPMG sequence locus defined in Figure 6, respectively. The remaining known BPMG members in T08 are not recovered because they lie in the southern hemisphere or have \((V-K_s)\) colors that are too blue. Nineteen of the candidates were already investigated (LS09, S10), we therefore delete these from the present list, leaving 111 BPMG candidates.

The search for ABDMG candidates identifies 582 stars. Compared to the BPMG this is a much larger number of candidates and is a consequence of the older age of the ABDMG. For a given SpTy, a member of the ABDMG is fainter than one in the BPMG, thus the cluster sequence of the ABDMG lies lower in the CMD and the search algorithm picks up more contaminants (see Figure 6). The candidate search recovered four known ABDMG members (Table 1). The declinations and colors of known ABDMG members allow for the recovery of six in the search. The two not recovered are HD 21845B, a close companion lacking sufficient photometric data in the catalogs, and BD+01 2447, which lies outside of the ABDMG sequence locus defined in Figure 6. S10’s search included nine of the candidates, we remove them from the sample leaving 569 ABDMG candidates.

After removal of known members and previously investigated stars, the candidate searches in the BPMG and ABDMG result in a sample of 680 low-mass moving group candidates. These remaining stars represent a mixture of different populations including old and young dwarfs and evolved stars such as late-type giants. We may identify some of the interlopers by considering their locations in an \((J-H)\) vs \((H-K_s)\) color–color diagram. Figure 7 shows the candidate diagram. We overplotted the expected sequences for A0 to M6 dwarfs and K to M giants (Bessell & Brett 1988; Bessell 1991). Nearly all of the candidates occupy the region expected for late-type dwarfs. A few fall outside of this region; two align with the expected giant sequence at \((J-H)\) \(\approx 0.8\) and fewer than 10 are coincident with the expected sequence for earlier dwarfs \((J-H) \lesssim 0.55\) and \((H-K_s) \approx 0.1\). These candidates are not included in further analyses. The seven candidates in the solid box have \((H-K_s)\) colors redder than MS dwarfs, they are the ultracool candidates discussed in Section 6.

indicators of youth. We follow the procedures outlined in Sh09 and Sh11 and perform a very similar analysis of X-ray and UV flux to identify PYCs.

4. PROBABLE YOUNG CANDIDATES

4.1. X-Ray Analysis

We perform a positional cross-correlation of known (T08) and new (LS09, S10) late-type \(\beta\) Pic and AB Dor members and our candidate sample with the ROSAT All-Sky Survey Bright Source and Faint Source catalogs (RASS-BSC and RASS-FSC; V99, V00). All known late-type \(\beta\) Pic and AB Dor members and 147 candidates have ROSAT counterparts within 50\(''\). If a candidate had a counterpart outside of 25\(''\) they were individually checked for crowded fields and unreliable matches were removed. X-ray fluxes \(F_X\) were calculated from count rates and hardness ratios (Schmitt et al. 1995). Figure 8 shows log\(F_X/F_{K_s}\) as a function of \((V-K_s)\) color for the previously mentioned subsamples. We choose to take the ratio \(F_X/F_{K_s}\) to be consistent with the use of \(K_s\) throughout our analysis, and because \(F_{K_s}\) varies little with activity. We compare to Sh09, who takes the flux ratio using \(F_J\), and see an average difference of \(\sim 0.1\) dex between

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**Table 1**

| Cat ID         | Hipparcos ID | Tycho2 ID | \(\alpha\) (ICRS) (2000.0) | \(\delta\) (ICRS) (2000.0) | \(V\) (mag) | \(K_s\) (mag) | \(d_{\text{visual}}\) (pc) | SpTy\(^a\) | Membership |
|---------------|--------------|-----------|----------------------------|----------------------------|-------------|-------------|-----------------|------------|------------|
| PM I02414+0559 | 12545        |           | 40.357864                  | 5.988454                   | 10.3        | 7.1         | 38.5 ± 3.7     | K6Ve      | BPMG       |
| PM I04595+0147 | 23200        | 85 1075 1 | 74.895126                  | 1.785355                   | 10.3        | 6.3         | 25.8 ± 2.9     | M0Ve      | BPMG       |
| PM I17386+6114 | 86346        | 4199 1286 1 | 264.665100                 | 61.237804                  | 10.3        | 6.8         | 24.2 ± 5.1     | K7Ve      | ABDMG      |
| PM I21521+0537 | 107948       | 556 1289 1 | 328.043396                 | 5.626641                   | 12.1        | 7.4         | 29.9 ± 2.0     | M2Ve      | ABDMG      |
| PM I22234+3227 | 110526       | 2738 1390 1 | 335.871185                 | 32.459461                  | 10.7        | 6.1         | 15.0 ± 1.1     | M3e       | ABDMG      |
| PM I12060+3355 | 114066       | 4286 212 1 | 346.520111                 | 63.926220                  | 10.9        | 7.0         | 23.7 ± 2.0     | M1e       | ABDMG      |

**Note.** \(^a\) SpTy’s from T08.
known NYMG member data points. This reflects the difference in $J$ and $K_s$ band magnitudes, we thus choose $\log(F_X/F_{K_s}) \geq -2.6$ as the cut for PYCs to be consistent with Sh09’s youth cut and the observed flux ratio difference. This choice includes $\sim 90\%$ of the known late-type NYMG members. We identify 114 PYCs having $F_X/F_{K_s}$ comparable to or larger than known late-type NYMG members. The remaining 33 candidates that fall below the cut are removed from the sample. However, the strong X-ray flux detected in some of these PYCs may be unreliable as a youth indicator since they are later than mid-M; these stars will be discussed later in this section.

The dashed gray line in Figure 8 represents a ROSAT All-Sky Survey detection limit for the candidate sample. The detection limit was estimated using the limiting count-rate in the RASS-BSC scaled to the source photon limit of the RASS-FSC.\footnote{The RASS-BSC limit is 0.05 counts s$^{-1}$ in the 0.1–2.4 keV energy band, or $\geq 15$ source photons in the exposure time. For the RASS-FSC the detection limit is $\geq 6$ source photons in the exposure time.} This limiting count-rate was combined with an average sample exposure time of $\sim 500$ s, the average X-ray hardness ratio (HR1) of the known NYMG members, and model derived magnitudes from SDF2000 evolutionary models for 40 Myr late-K to mid-M dwarfs at 40 pc to generate the curve.

4.2. UV Analysis

The NASA GALEX is a space based 0.5 m UV telescope sensitive to 1350 Å $\leq \lambda \leq 2750$ Å (Martin et al. 2005). Part of the mission is to produce an All-Sky Imaging Survey (AIS) in two bands: the near-UV (NUV, 1750–2750 Å) and far-UV (FUV, 1350–1750 Å). Sh11 showed that GALEX NUV and FUV data can be used to effectively identify young M-dwarfs beyond 100 pc, far surpassing the sensitivity of ROSAT and providing a new resource in the search for cool, young stars in the solar neighborhood (see also FH10 and R11).

We used Galex View\footnote{A webtool for accessing GALEX data available at http://galex.stsci.edu/galexview/} to cross-correlate the known late-type NYMG subsample and our candidate list with the sixth data release of the GALEX AIS, which covers $\sim 75\%$ of the sky. We obtained NUV and FUV data when available for stars with counterparts within 5°, the resolution of GALEX FUV channel. All known NYMG members are detected in NUV and all except one are detected in FUV.\footnote{Likely new $\beta$ Pic member PM 04439+3723 is not detected in the FUV. S10 estimate the star to be SpTy M3 and lie at a distance of $\sim 80$ pc.} Three hundred eighty-nine candidates have a detection in at least one GALEX band.

Figure 9 shows $\log(F_{\text{NUV}}/F_{K_s})$ as a function of $(V-K_s)$ for the 304 NUV active candidates and known group members. Comparing to Sh11 we see the same $\sim 0.1$ dex difference between our UV/$K_s$ flux ratios and their UV/$J$ ratios as in the X-ray analysis. We thus choose $\log(F_{\text{NUV}}/F_{K_s}) \geq -4.1$ and $\log(F_{\text{FUV}}/F_{K_s}) \geq -5.1$ as our cuts for PYCs, again to be consistent with Sh11 and include the flux difference between $J$ and $K_s$ bands. We identify 149 PYCs with strong NUV flux. Many candidates with strong NUV flux also have strong X-ray flux. There are 14 PYCs with both NUV and FUV flux and no ROSAT detection that would have been missed if GALEX data were unavailable. Candidates having a GALEX NUV detection in Figure 9 but falling below the PYC cut are removed from the sample.

The estimated detection limit of the GALEX AIS is shown as the gray dashed line in Figure 9. The limit was estimated...
using the GALEX AIS 5σ limiting NUV magnitude for a 100 s exposure (Morrissey et al. 2005) and the same SDF2000 models as the X-ray limit. Some candidates that we consider PYCs due to strong UV emission fall below the curve. This can be attributed to two factors: (1) the exposure time, many of the candidates have actual exposure times >100 s and (2) the model distance and age; this was chosen for simplicity to be representative of the two NYMGs. Individual candidates have a range of distances and ages. Nonetheless, the detection limits in both Figures 8 and 9 correspond to a model derived limiting magnitude of $V \sim 16$ for the lowest mass candidates.

**4.3. Undetected Candidates**

Three hundred sixty-one candidates are undetected by either ROSAT or GALEX. Figure 10 shows the $V$ (top) and $d_{\text{kin}}$ (bottom) distributions of these candidates. Solid, black and hashed, gray curves represent the undetected candidates (UCs) in the ROSAT and GALEX catalogs, respectively. The $V$ distributions show that most UCs have $13 \lesssim V \lesssim 15$ and $d_{\text{kin}} \gtrsim 50$ pc. These are most likely MS stars with kinematics similar to those of the NYMGs selected by chance. It is likely that the faintest UCs are beyond the detection limits of the surveys. It was expected that $\sim 25\%$ of the candidate sample would be undetected by GALEX because of the sky coverage of the AIS. However, the greater sensitivity of the GALEX satellite is apparent from the distributions. There are fewer UCs overall, the peak of the $V$ distribution is shifted to fainter magnitudes by $\sim 1$, and the $d_{\text{kin}}$ distribution is approximately flat at large distances. The faintest UCs in the sample could be pursued for individual follow-up to check spectroscopic youth indicators, such as gravity sensitive alkali lines, to verify their suspected MS ages. However, most of the UCs appear to be within the estimated limits of the ROSAT and GALEX surveys and likely represent older stars which only appear to be co-moving with the BPMG and ABDMG by chance.

Since the ROSAT and GALEX catalogs do not have uniform coverage of the entire sky we cannot be certain that we have not missed some potentially young stars but the analyses presented are the best way to identify young stars quickly without intensive observation. We recognize that the chosen activity indicators may introduce contamination to the PYC sample in the form of flaring dwarfs, unresolved white dwarf-M dwarf systems, and unresolved, tidally interacting binaries and that the reliability of these indicators decreases substantially after $\sim M4$ SpT y. To address this problem we devise a simple system to prioritize follow-up observations to measure radial velocities and parallaxes.

**4.4. Activity, Color, and Priority Indices**

*Activity index*, $\alpha$. The 204 PYCs have varying levels of activity as indicated by their X-ray, NUV, and FUV flux ratios. The $\alpha$ index shows these variations in a simple way. It is a three digit binary number where each digit represents whether a youth diagnostic is positive (1) or not (0). $\alpha$’s first digit represents the X-ray flux ratio, 1 indicates that the ratio is at or above the PYC cut, 0 means that the ratio is either below the cut or X-ray flux is not detected. The second and third digits represent the NUV and FUV flux ratios, respectively. Their value is selected following the same prescription as the first digit. Example activity indices for PYCs are listed in Table 2.

*Color index*, $C$. The reliability of the indicators described by $\alpha$ is dependent on PYC mass. W11 used Sloan Digital Sky Survey (SDSS) M-dwarf spectroscopic data to show that the fraction of stars with H\textalpha emission increases substantially around mid-M type and nearly all late Ms are active. This is probably the result of convection throughout their interiors and a strengthening of their magnetic dynamos. Since H\textalpha traces activity in a way similar to X-ray and UV emission this activity trend can be applied to the indicators described here. Thus, $C$ is a single digit binary number indicating whether a star has $(V - K_s) \lesssim 5$, approximately earlier than M4 according to SDF2000 models, and hence whether $\alpha$ is reliable (1) or not (0). We henceforth designate PYCs with $C = 1$ as candidates with reliable youth (CWRYS) and candidates with $C = 0$ as candidates with ambiguous youth (CWAYs). PYC color indices are listed in Table 2. The PYC sample is comprised of 113 CWRYS and 91 CWAYs. Even though some CWAYs may actually be active older stars they are still worthy of follow-up since the activity cuts have been chosen via comparison to known, young, late-type stars. These candidates are prime targets for studies of gravity sensitive spectral features.
### Table 2
Northern PYC List

| PYC ID         | Hipparcos ID (2000.0) | Tycho2 ID (2000.0) | \(\alpha\) (mag) | \(\delta\) (mag) | \(V\) (mag) | \(J\) (mag) | \(H\) (mag) | \(K_s\) (mag) | \(\mu_\alpha\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(d_{\text{kin}}\) (pc) | \(\delta d_{\text{kin}}\) (pc) | \(RV_p\) (km s\(^{-1}\)) | \(\delta RV_p\) (km s\(^{-1}\)) | \(|X|^a\) (dex) | \(|N|^b\) (dex) | \(|F|^c\) (dex) | A | C | P | Candidate\(^d\) |
|----------------|------------------------|---------------------|------------------|------------------|-------------|-------------|-------------|---------------|-------------------------------|-------------------------------|------------------|-------------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| J00025+3422N   | 0.645568               | 34.381161           | 13.6             | 10.4             | 9.7          | 9.5         | 67.0        | -52.0         | 68.8                          | 7.4                           | -14.11           | 1.31                          | 0.00             | -3.80           | -4.23            | 011             | 1               | 3               | 2                |
| J00197+1951    | 4.929336               | 19.853241           | 15.7             | 10.7             | 10.1         | 9.9         | 59.0        | -45.0         | 59.4                          | 7.9                           | -1.73            | 1.05                          | -1.74            | -3.86           | 0.00             | 110             | 0               | 2               | 1                |
| J00270+6630    | 6.761791               | 66.510834           | 13.2             | 9.6              | 8.9          | 8.7         | 66.0        | -23.0         | 56.9                          | 8.3                           | -9.16            | 1.27                          | -2.36            | 0.00             | 0.00             | 100             | 1               | 2               | 1                |
| J00270+6630    | 6.761791               | 66.510834           | 13.2             | 9.6              | 8.9          | 8.7         | 66.0        | -23.0         | 69.5                          | 9.0                           | -20.81           | 1.23                          | -2.36            | 0.00             | 0.00             | 100             | 1               | 2               | 2                |
| J00325+0729    | 8.145008               | 74.90874            | 12.8             | 8.4              | 7.8          | 7.5         | 92.0        | -55.0         | 41.1                          | 4.4                           | 1.70             | 1.05                          | -1.60            | -3.86           | -4.47            | 111             | 0               | 3               | 1                |
| J00390+1330    | 9.764313               | 13.504687           | 15.7             | 10.9             | 10.4         | 10.1        | 66.0        | -70.0         | 67.7                          | 6.4                           | -3.45            | 1.45                          | -1.97            | -3.79           | -3.96            | 111             | 0               | 3               | 2                |
| J00411+5523    | 10.296559              | 55.399475           | 16.6             | 11.4             | 10.8         | 10.6        | 84.0        | -61.0         | 51.7                          | 4.9                           | -17.76           | 1.24                          | -1.60            | 0.00             | 0.00             | 100             | 0               | 1               | 2                |
| J00450+2634    | 11.250682              | 26.569508           | 12.5             | 9.5              | 8.9          | 8.7         | 85.0        | -100.0        | 48.2                          | 3.7                           | -8.06            | 1.37                          | -2.02            | -3.65           | 0.00             | 110             | 1               | 3               | 2                |
| J00484+3632    | 2288 758 1             | 12.119358           | 11.7             | 9.2              | 8.6          | 8.5         | 59.0        | -40.0         | 61.4                          | 8.4                           | -3.14            | 1.25                          | 0.00             | -3.90           | 0.00             | 010             | 1               | 2               | 1                |
| J00489+4435    | 12.242649              | 44.585823           | 13.9             | 9.1              | 8.5          | 8.2         | 116.0       | -136.0        | 32.6                          | 2.2                           | -14.15           | 1.27                          | -1.65            | 0.00             | 0.00             | 100             | 0               | 1               | 2                |
| J00495+0356    | 12.394575              | 3.938275            | 14.8             | 10.9             | 10.3         | 10.0        | 71.0        | -88.0         | 57.9                          | 4.8                           | 1.35             | 1.51                          | 0.00             | -3.90           | 0.00             | 010             | 1               | 2               | 2                |
| J00546+3434    | 13.671499              | 34.575741           | 15.4             | 10.9             | 10.3         | 10.1        | 60.0        | -68.0         | 68.1                          | 6.8                           | -10.30           | 1.32                          | 0.00             | -3.89           | 0.00             | 010             | 0               | 1               | 2                |
| J01028+1856    | 15.712469              | 18.948402           | 14.4             | 9.5              | 8.9          | 8.7         | 94.0        | -53.0         | 40.9                          | 4.4                           | 1.53             | 1.23                          | 0.00             | -3.90           | -4.36            | 011             | 0               | 2               | 1                |
| J01036+4051W   | 4967                   | 2803 800 1          | 15.917160        | 40.858143       | 10.9          | 8.1         | 7.5         | 7.3          | 122.0           | 29.2                          | 1.8                           | -11.93           | 1.29                          | -2.05            | -3.51           | -4.38            | 111             | 1               | 4               | 2                |
| J01037+4051W   | 15.925412              | 40.854427           | 13.5             | 9.4              | 8.8          | 8.5         | 132.0       | -164.0        | 28.7                          | 1.8                           | -11.93           | 1.29                          | -1.57            | -3.83           | -4.44            | 111             | 1               | 4               | 2                |

Notes.

\(^a\) \(\log(F_X/F_{K_s})\).
\(^b\) \(\log(F_{NUV}/F_{K_s})\).
\(^c\) \(\log(F_{FUV}/F_{K_s})\).
\(^d\) Candidate of (1) BPMG and (2) ABDMG.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
Priority index, \( P \). The observing priority of a PYC can be quickly determined by summing the digits of \( A \) and \( C \). This leads to a new, one digit index \( P \), which ranges between 1 and 4 (see Table 2). The most promising candidates, with strong, reliable indication of youth, have \( P = 4 \). We discuss the statistical properties of the PYCs and illustrate the use of their indices when selecting stars for follow-up studies in Section 5.

4.5. Northern PYC List

The youth indicator analysis has reduced the number of candidates by nearly 70% to 204 PYCs. Inevitably, it still contains contaminants in the form of active stars whose kinematics align with the NYMGs by chance. Their removal will require follow-up observations that are beyond the scope of this paper. Three stars are candidates for both the BPMG and ABDMG. Dual candidacy was expected for some stars due to the overlap of the two groups in \( U \) and \( W \) velocity space. We present an example of the format of the northern PYC list in Table 2 and explain the column designations in the following subsections. The entire list is available in the electronic version of the journal in machine readable format.

Columns 1–3 list our internal ID and Hipparcos and Tycho-2 IDs if available. The internal ID is based on the star’s coordinates in the ICRS epoch 2000.0 system. The final letter (N, S, E, W) is optional and distinguishes pairs of stars that would otherwise have the same coordinates. The choice depends on the orientation of the pair. If the separation in declination is larger, the stars are appended N and S. If the separation in right ascension is larger, the pair is given E and W. Candidates with NS or EW are not necessarily common proper-motion pairs, although they may be. If only one star appears with a directional designation, its counterpart was cut from the sample during the search, usually because it fails to meet the \((V-K_s)\) cut.

Columns 4 and 5 list the coordinates in the ICRS epoch 2000.0 system. Columns 6–9 give the \( V, J, H, \) and \( K_s \) photometry of the candidate. If the star is in the Hipparcos or Tycho-2 catalogs the \( V \) magnitudes from those sources are used. If the star is missing from those catalogs the \( V \) mag is a combination of the USNO-B1.0 \((B_j, R_p, 1_p)\) photographic magnitudes following the conventions of LSO15. \( J, H, \) and \( K_s \) magnitudes are from 2MASS. Columns 10 and 11 list the proper motions of the PYCs. Proper motions are taken from the Hipparcos and Tycho-2 catalogs if the candidate has a counterpart, otherwise the LSPM/ SBK derived proper motions are used. We adopt the \( \pm 8 \) mas yr\(^{-1} \) uncertainty of the LSPM and SBK catalogs as the proper-motion uncertainty in the list.

Columns 12 and 13 list the \( d_{\text{kin}} \) of the candidate and its uncertainty. Columns 14 and 15 list the predicted radial velocity \((R_V, \text{see LS09 and S10})\) of the candidate and its uncertainty which includes the intrinsic spread in BPMG or ABDMG \( UVW \) velocities quoted in Section 2. Columns 16–18 list the logarithm of the X-ray, NUV, and FUV flux ratios described in Section 4. Columns 19–21 are the activity (\( A \)), color (\( C \)), and priority (\( P \)) indices, respectively (see Section 4) and Column 22 identifies whether a star is a PYC of the BPMG (1) or the ABDMG (2). Stars with dual candidacies are listed with identical IDs, coordinates, proper motions, and photometry and differ only in their \( d_{\text{kin}} \) and \( R_V \), which are specific to the particular NYMG.

5. STATISTICAL PROPERTIES

The PYC sample is comprised of 49 BPMG and 155 ABDMG candidates. Figure 11 shows the distributions of the PYC \( V \) mags and \( d_{\text{kin}} \) with the BPMG and ABDMG PYCs shown in hashed, gray and solid, black histograms, respectively. In the \( V \) magnitude distributions BPMG candidates appear brighter on average and there are fewer at large predicted distances. Because of its older age, the ABDMG suffers from greater contamination as search volume increases. The distributions indicate that BPMG candidates are more promising targets for follow-up and may yield a higher success rate.

Figure 11. Northern probable young candidate (PYC) \( V \) mag (top) and \( d_{\text{kin}} \) (bottom) distributions. BPMG (hashed, gray) and ABDMG (solid, black) histograms exhibit differences in both distributions. BPMG candidates are brighter on average and there are fewer at large predicted distances. Because of its older age, the ABDMG suffers from greater contamination as search volume increases. The distributions indicate that BPMG candidates are more promising targets for follow-up and may yield a higher success rate.

5.1. Index Distributions

In this subsection, we break the PYC sample into subgroups as defined by the \( A, C, \) and \( P \) indices. We first discuss the color index (\( C \)) subgroups and compare their cumulative activity index \((\Sigma A)\) distributions. Figure 12 shows the \( V \) mag (top) and \( d_{\text{kin}} \) (bottom) distributions for CWRYs. The three histograms plotted represent CWRYs with \( \Sigma A = 1 \) (solid, gray), 2 (hashed, dark gray), or 3 (open, red). The largest contribution to the CWRY sample are candidates having only one strong activity indicator.
Figure 12. Candidates with reliable youth (CWRY) activity index ($\Sigma A$) $V$ mag (top) and $d_{\text{kin}}$ (bottom) distributions. Histograms represent CWRYs with $\Sigma A = 1$ (solid, gray), 2 (hashed, dark gray), and 3 (open, red). Many of the CWRYs are candidates having only one strong activity indicator; typically only strong X-ray or NUV. There are more CWRYs with $\Sigma A = 3$, those with the strongest indication of youthful activity, than $\Sigma A = 2$. The $\Sigma A = 3$ distance distribution also peaks at smaller $d_{\text{kin}}$. This combination of multiple strong activity indicators, relatively bright $V$ mag, and smaller predicted distances makes these candidates high priority for follow-up investigations.

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

These candidates typically have only strong X-ray or NUV. It is striking that there are more CWRYs with $\Sigma A = 3$, those with the strongest indication of youthful activity, than $\Sigma A = 2$. The $\Sigma A = 3$ distance distribution also peaks at smaller $d_{\text{kin}}$. The larger number of $\Sigma A = 3$ candidates at smaller predicted distances makes follow-up of these CWRYs particularly pertinent.

The same distributions using the same color designations in Figure 12 for the CWAYs are shown in Figure 13. The $V$ magnitude distributions are systematically shifted to fainter magnitudes. The $d_{\text{kin}}$ distribution of the $\Sigma A = 3$ CWAY subsample is approximately flat. This feature is an indication that contamination does not increase as volume increases in this subsample. Thus these candidates are prime for follow-up.

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

Figure 13. Candidates with ambiguous youth (CWAYs) activity index ($\Sigma A$) $V$ mag (top) and $d_{\text{kin}}$ (bottom) distributions. The three histograms represent CWAYs with the same cumulative $A$ values described in Figure 12. Because CWAYs are candidates with redder ($V - K_s$) colors the $V$ magnitude distributions are systematically shifted to fainter magnitudes. The $d_{\text{kin}}$ distribution of the $\Sigma A = 3$ CWAY subsample is approximately flat. This feature is an indication that contamination does not increase as volume increases in this subsample. Thus these candidates are prime for follow-up.

As a final guide to prioritize follow-up, Figure 14 shows the $P = 1$ and $P = 2$ and 3 index $V$ mag and $d_{\text{kin}}$ distributions of the young candidates. The $P = 1$ sample consists entirely of candidates with ($V - K_s$) > 5.0 (CWAYs) that have only one strong activity indicator. These candidates are the lowest priority for immediate RV follow-up, but are prime targets for the study of gravity sensitive spectral features. The $P = 2$ and 3 distributions are a mixture of CWRYs and CWAYs that may have multiple strong activity indicators. The $P = 4$ distribution consists only of candidates with ($V - K_s$) $\leq$ 5.0 (CWRYs) that have strong X-ray, NUV, and FUV flux. These candidates have the strongest indication of reliable youth and are the highest priority for follow-up. The $P = 3$ and 4 distance distributions (Figure 14, bottom) do not have strong flat distance distribution is indication that contamination does not increase as volume increases in the $\Sigma A = 3$ CWAY sample. Thus these candidates are also prime for follow-up.
5.2. Survey Completeness and Moving Group Densities

Our search for low-mass stars in the BPMG and ABDMG is effectively complete for stars within 70 pc to within the proper-motion limit of the SBK catalog. Because the SBK catalog is complete to $V \approx 20$ and has a proper-motion limit $\mu > 40$ mas yr$^{-1}$, all low-mass stars within 70 pc will be detected if their absolute $V$ magnitude $M_V < 15.5$ and if their velocity in the plane of the sky $v_{\text{tran}} > 13.3$ km s$^{-1}$. Regardless of how much contamination there is in our sample, the fact remains that virtually all moving group members that have absolute magnitudes and velocities within the limits above are to be found in our list.

Not all stars in the BPMG and ABDMG will have proper motions large enough to be detected. To estimate the fraction of stars detected as a function of their distance, we have performed a simple Monte Carlo simulation which assumes a uniform density of moving group members in the solar vicinity and estimates how many stars in the synthetic sample would have proper motions large enough to be detected. In addition to the kinematic selection, we add a 5% probability that any star may be overlooked, consistent with the estimated >95% completeness of the SBK catalog. Results are displayed in Figure 15 (upper panels) for both the BPMG and ABDMG; one finds that >75% of the BPMG stars at $\approx 70$ pc from the Sun should be on our list, and larger fractions of more nearby objects for a total of $\approx 86.8$% of all BPMG within 70 pc. For the ABDMG, the search is significantly more complete due to the larger systemic velocity of the group, which yields larger proper motions on average than BPMG stars. The simulation suggests that >85% of the ABDMG low-mass stars at $\approx 70$ pc should be in the list and $\approx 94.4$% of all the members within that range.

With this high level of completeness, it is possible to place firm upper limits on the volume density of BPMG and ABDMG stars in the northern hemisphere based on the number of stars we identified. We separate the candidates in 10 pc distance bins, count the number of stars with absolute magnitudes $8.0 < M_V < 15.5$ within each bin, and divide this number by the detected fraction as estimated above. Then calculate the density of stars $\rho_*$ in that distance range by dividing by the volume enclosed by each of the corresponding hemispheric shell, and express the result in stars per cubic parsec (stars pc$^{-3}$). Results are displayed in Figure 15 (lower panels). We calculate $\rho_*$ as a function of distance for the complete list of low-mass star candidates (open triangles) and for the subset of candidates which show strong evidence of youth (PYCs, filled squares).

If we believe that all group members should display indicators of youth, while allowing that some non-members might show signs of youth as well, then the mean density of young candidates sets an upper limit for the density of the group. Under this assumption, we find that in the northern sky volume within 70 pc of the Sun, the BPMG has a maximum number density of low-mass stars of $\approx 6.7 \times 10^{-5}$ stars pc$^{-3}$, which means that the same volume should be host to at most $\approx 36$ low-mass (M dwarf) members of the BPMG. For the ABDMG, we find that the group has a maximum density of $\approx 2.2 \times 10^{-5}$ stars pc$^{-3}$ for low-mass stars, which suggests that the 70 pc volume should contain at most $\approx 119$ low-mass (M dwarf) members. We expect that most of the true low-mass, north-sky members of the BPMG and ABDMG should be in our Table 2.

6. PRELIMINARY RESULTS

6.1. Ultracool Candidates

Seven candidates in Figure 7 are redder in $(H - K_s)$ than the expected dwarf sequence (black box). These stars are potential ultracool candidates with SpTy’s M7 and later. We perform a literature search for pertinent youth and kinematic data regarding these candidates since they are not expected to exhibit strong activity. The literature reveals three LNMs, another three stars that require further follow-up, and one that is ruled out on the basis of inconsistent RVs (see Table 3).

6.2. PYCs with Hipparcos Distances

Five stars in the PYC sample have distances measured by Hipparcos, this allows us to directly test group membership by verifying that $d_{\text{kin}}$ is consistent with the parallax distance ($d_p$). We have calculated distances for all stars listed in the Hipparcos catalog based on measured parallaxes from the recent new reduction by van Leeuwen (2007). Table 4 compiles...
| Cat ID               | 2MASS ID              | α(ICRS) (2000.0) | δ(ICRS) (2000.0) | V (mag) | J (mag) | H (mag) | Ks (mag) | \(d_{\text{kin}}\) (pc) | \(d_{\text{phot}}\) (pc) | \(RV_p\) (km s\(^{-1}\)) | \(RV_m\) (km s\(^{-1}\)) | SpTy | Candidate | Notes                                      |
|---------------------|-----------------------|-----------------|-----------------|---------|---------|---------|-----------|----------------|----------------|-----------------|-----------------|------|-----------|-------------------------------------------|
| **Likely new members** |                       |                 |                 |         |         |         |           |                 |                 |                 |                 |      |           |                                           |
| PM I00194+4614      | J0019262+461407       | 4.859472        | 46.235477       | 20.0    | 12.6    | 11.9    | 11.5      | 39.6 ± 3.1   | 19.5 ± 1.6\(^a\) | −16.5 ± 1.3     | −19.5 ± 2.0\(^b\) | M8\(^a\) | ABDMG    | RV\(_p\) \(\approx\) RV\(_m\), youth\(^b,c\) |
| PM I04436+0002      | J0443376+000205       | 70.906723       | 0.034731        | 19.6    | 12.5    | 11.8    | 11.2      | 39.5 ± 3.1   | 16.2 ± 1.0\(^a\) | 19.0 ± 1.4     | 17.1 ± 2.0\(^b\) | M9\(^d\) | ABDMG    | RV\(_p\) \(\approx\) RV\(_m\), youth\(^b,d\) |
| PM I13143+1320      | J1314203+132001       | 198.584839      | 13.333536       | 15.9    | 9.8     | 9.2     | 8.8       | 20.1 ± 1.0   | 16.4 ± 0.8\(^e\) | 9.7 ± 3.0\(^f\) | −10.3 ± 1.6    | M7\(^e\) | ABDMG    | d\(_{\text{kin}}\) \(\approx\) d\(_{\text{phot}}\), youth\(^e\) |
| **Require further follow-up** |                       |                 |                 |         |         |         |           |                 |                 |                 |                 |      |           |                                           |
| PM I03010+4416      | J0301032+441656       | 45.263393       | 44.282410       | 18.0    | 12.1    | 11.4    | 11.0      | 50.6 ± 3.9   | 24.5 ± 4.2\(^a\) | −6.4 ± 1.3     | 14.0 ± 1.4     | M6\(^a\) | ABDMG    |                                           |
| PM I09069+0301      | J0906955+030117       | 136.733276      | 3.021399        | 14.6    | 11.1    | 10.5    | 10.1      | 65.6 ± 6.8   | 14.0 ± 2.1\(^f\) | 27.6 ± 1.4     | 27.4 ± 0.4\(^f\) | M9\(^f\) | ABDMG    | RV\(_p\) \(\neq\) RV\(_m\)                 |
| **Ruled out**       |                       |                 |                 |         |         |         |           |                 |                 |                 |                 |      |           |                                           |
| PM I08109+1420      | J0810586+142039       | 122.744370      | 14.344112       | 19.6    | 12.7    | 12.1    | 11.6      | 46.0 ± 3.6   | 13.8 ± 2.1\(^f\) | 11.9 ± 1.3     | 27.4 ± 0.4\(^f\) | M9\(^f\) | ABDMG    |                                           |

**Notes.**
\(^a\) Cruz et al. (2003).
\(^b\) Reiners & Basri (2009).
\(^c\) Reiners & Basri (2010).
\(^d\) Cruz et al. (2007).
\(^e\) Lépine et al. (2009).
\(^f\) Reid et al. (2002).
\(^g\) Gizis et al. (2000).
Figure 15. Estimated completeness of the search and predicted number densities of northern, low-mass stars in each of the β Pic and AB Dor moving groups. Upper panels: expected rate of detection for stars with absolute magnitudes $8.0 < M_V < 15.5$, typical for young M dwarfs. The main source of incompleteness comes from the proper-motion limit ($\mu > 40 \text{ mas yr}^{-1}$) of the source catalog; the incompleteness increases with distance. Lower panels: volume densities of β Pic (left) and AB Dor (right) moving group candidates, corrected for incompleteness. Estimates based on the full candidate list (open triangles) are compared to estimates using only probable young candidates with strong activity (PYCs, filled squares). The latter provide an upper limit estimate for the density of the group in the surveyed volume.

Table 4
Candidates With Consistent Hipparcos Distances

| PYC ID   | Hipparcos ID | $\alpha$(ICRS) (2000.0) | $\delta$(ICRS) (2000.0) | V (mag) | $K_s$ (mag) | $d_{\text{kin}}$ (pc) | $d_{\text{sys}}$ (pc) | $RV_p$ (km s$^{-1}$) | $RV_m$ (km s$^{-1}$) | SpTy | Candidate | Notes |
|----------|--------------|-------------------------|-------------------------|---------|------------|-----------------|-----------------|-----------------|-----------------|------|-----------|-------|
| J01036+4051 | 4967        | 15.917160               | 40.858143               | 10.9    | 7.3        | 29.2 ± 1.8     | 29.9 ± 2.1     | −11.9 ± 1.3     | 2.7 ± 0.1d     | M1b | BPMG      | VTb   |
| J09362+3731 | 47133       | 144.066330              | 37.529320               | 11.1    | 7.2        | 33.0 ± 2.9     | 33.7 ± 2.6     | 1.0 ± 1.6       | 2.7 ± 0.1d     | K5c | BPMG      |       |
| J10143+2104 | 50156       | 153.579926              | 21.074898               | 10.0    | 6.3        | 20.7 ± 1.7     | 23.1 ± 1.0     | 2.8 ± 1.3       | 2.7 ± 0.1d     | M1b | BPMG      |       |

Notes.

* Distance from Hipparcos new reduction parallax (van Leeuwen 2007).
* VT: visual triple, VB: visual binary; Shkolnik et al. (2009).
* SpTy from SIMBAD.
* López-Santiago et al. (2010).
* Upgren & Harlow (1996).
* This work, using CSHELL at the NASA-IRTF (Greene et al. 1993).
literature data on these five stars and lists their ID, *Hipparcos* ID, coordinates in the ICRS system, *V* mags, 2MASS *K_s* mags, predicted *d_HK* and measured *d_\text{parallax}* distances, predicted and measured RV, NYMG candidacy, and if the star was removed from the sample. Five LNMs (one triple system and two singles) are identified, and two are ruled out on the basis of inconsistent measured RV (see Table 4). All of the candidates with *Hipparcos* distances are CWRYS with *P* = 3 or 4.

### 6.3. Likely New Members

**PYC J09362+3731 = HIP 47133.** HIP 47133 is a late-K dwarf at a distance of 31 pc, consistent with our predicted distance. The star exhibits strong NUV and FUV emission, consistent with known late-type BPMG members. We identify HIP 47133 as an LNM of the BPMG on the basis of consistent distance and strong activity. RV measurements should be performed to confirm membership.

**PYC J10143+2104 = HIP 50156.** HIP 50156 is an M1 dwarf at a distance of ∼20 pc. Strong X-ray flux, moderate H\alpha emission, possible low surface gravity from CaH indices, but no 6708 Å lithium line are described by Sh09. We identify strong NUV and FUV fluxes as well. López-Santiago et al. (2010, hereafter L10) measure an RV of 2.7 ± 1.0 km s\(^{-1}\), which matches well with our predicted RV, and calculate (UVW) = (−6.8, −18.3, −8.2). L10 classify the star as a member of the local association and also report a Li non-detection. However, the (UVW) velocities are more consistent with those of the BPMG than those of the local association (Montes et al. 2001). The lack of detected Li in both Sh09 and L10 is contrary to expectations for ∼10 Myr old early-M dwarfs. But, BC10 suggest that Li content is not a reliable youth indicator since it is strongly affected by stellar accretion history. We therefore identify HIP 50156 as a likely member of the BPMG based on consistent UVW kinematics and strong activity and suggest further follow-up for confirmation.

**PYC J01036+4051 = HIP 4967.** HIP 4967 is a visual triple system at a distance of ∼30 pc. Sh09 identify indicators of youth in the spectra of the M3 secondary and M4 tertiary components, including H\alpha emission, and estimate the ages to be 20–300 Myr. We also identify strong activity in components of the system. Based on evidence of youth and consistent distance we identify HIP 4967 as a likely member of the ABDMG. RV measurements should be pursued to verify membership.

**PM J00194+4614 = 2MASS J0019262+461407.** 2MASS J0019262+461407 (hereafter 2MASS J0019) was identified by Cruz et al. (2003) as an M8 dwarf in a search for nearby ultracool objects in the 2MASS catalog. Reiners & Basri (2009, 2010, hereafter RB09, 10) measure an RV of −19.5 ± 2.0 km s\(^{-1}\), which is consistent with our predicted RV, and a remarkably large *v sin i* of 68 ± 10 km s\(^{-1}\). In their high resolution optical spectra they also identify lithium at 6708 Å in absorption, indicating that 2MASS J0019 is most likely a young brown dwarf (*M_\text{Jup} \lesssim 65 M_\text{Jup}, \text{Age} < 0.5 \text{ Gyr})*. We identify 2MASS J0019 as an LNM of the ABDMG on the basis of indicators of youth and consistent RV. Assignment as a true group member awaits parallax measurement to verify that *d_\text{parallax}* is the true distance and a more detailed analysis of youth indicators.

**PM J04436+0002 = 2MASS J0443376+000205.** 2MASS J0443376+000205 (hereafter 2M0443) was identified as an M9 dwarf by Hawley et al. (2002). Cruz et al. (2007) identified indicators of low surface gravity in its spectrum and propose that the object is a young brown dwarf. The RV and *v sin i* of 2M0443 were measured by RB09 and RB10 to be 17.1 ± 2.0 km s\(^{-1}\) and 13.5 ± 2.0 km s\(^{-1}\), respectively. The RV measurement is consistent with our predicted RV. Reiners and Basri also identify lithium absorption in the dwarf, strengthening the argument that 2M0443 is a young brown dwarf. Thus, we identify 2M0443 as an LNM of the ABDMG and will pursue a parallax measurement to verify membership.

PM J1314+1320 = 2MASS J1314203+132001. 2MASS J1314203+132001 (hereafter 2M1314) was first identified as the high proper-motion star NLT1 33370 by Luyten (1979). Based on its photometry, LS05 estimate its distance to be 9.7 ± 3.0 pc. Lépine et al. (2009, hereafter L09) measure strong H\alpha emission (EW = 54.1 Å) and a parallactic distance of 16.4 ± 0.8 pc. This is nearly twice the photometric distance but in agreement with our predicted distance. Since *d_\text{phot}* significantly underestimates the true distance to 2M1314 the star could be an unresolved binary or very young. Either of these scenarios can be consistent with the strong H\alpha emission. If 2M1314 is < 100 Myr old its mass would be very close to the substellar limit. We identify 2M1314 as an LNM of the ABDMG based on the evidence in the literature and will pursue RV measurements and follow-up on further indicators of youth in order to verify group membership.

If these three ultracool LNMs are verified to be bona fide members of the AB Dor group they will be the lowest mass, isolated members and represent important benchmarks.

### 7. SUMMARY

We have presented a list of 204 young moving group candidates in the northern hemisphere. These stars are candidates of the ∼10 Myr old BPMG and ∼70 Myr old ABDMG. Candidates were selected from the Tycho-2, *LSPM-North*, and *SBK* catalogs using the search algorithm first described in LS09 and S10. Selection criteria used in choosing candidates were derived from the known members of the NYMGs. X-ray, NUV, and FUV activity indicators were used to trim the initial sample to only the young stars following the convention of Sh09 and Sh11. Identification of true moving group members in the list requires RV and parallax measurements to verify consistent group kinematics. We have devised a simple system of indices based on activity and color to help prioritize follow-up observations.

From detailed inspection and data gathered in the literature, we can identify two LNMs of the BPMG and six of the ABDMG (three in a triple system). Three of the LNMs of the ABDMG are possible young brown dwarfs. The identification of three LNMs as possible brown dwarfs is particularly valuable because if follow-up proves them true members of the group they will be the lowest-mass, isolated members of the group yet identified. Not only are these objects interesting for assessing the substellar mass function of the ABDMG, they may represent benchmark young substellar objects which are crucial for understanding substellar formation and evolution. Our proper-motion search technique has now yielded at least 24 likely new moving group members (LS09, S10, this work).

This paper concerns only candidates of the BPMG and ABDMG north of the celestial equator. Since 80%–90% of the known β Pic and AB Dor group members lie in the south (see T08), we can expect that extension of our identification procedures to the south will yield similarly greater numbers of PYCs and LNMs. A complete census of NYMG members including the low-mass stars will allow for the study of: (1) the origins of the moving groups, (2) stellar evolution in a relatively nearby sample of PTTSs and young brown dwarfs, and (3) exoplanets and their formation.
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Note added in proof. Likely AB Dor member PM I13143+1320 was resolved as a tight binary by Law et al. (2006) using lucky imaging. The components are separated by 0.13" and have a z' band contrast ratio of ∼1 magnitude.

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