Results from BASS, the BANYAN All-Sky Survey

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Abstract.

We present results from the BANYAN All-Sky Survey (BASS), a systematic allsky survey for brown dwarf candidates in young moving groups. We describe a crossmatch of the 2MASS and ALLWISE catalogs that provides a list of 98 970 potential nearby dwarfs with spectral types later than M5 with measurements of proper motion at precisions typically better than 15 mas yr⁻¹, as well as the Bayesian Analysis for Nearby Young AssociatioNs II tool (BANYAN II) which we use to build the BASS catalog from this 2MASS–ALLWISE cross-match, consisting of more than 300 candidate members of young moving groups. We present the first results of a spectroscopic follow-up of those candidates, which allowed us to identify several new low-mass stars and brown dwarfs displaying signs of low gravity. We use the BASS catalog to show tentative evidence for mass segregation in AB Doradus and Argus, and reveal a new ~ 13 M_{Jup} co-moving companion to a young low-mass star in BASS. We obtain a moderate-resolution nearinfrared spectrum for the companion, which reveals typical signs of youth and a spectral type L4 γ .

1. INTRODUCTION

Nearby young moving groups (YMGs) such as TW Hydrae (TWA; 8 – 12 Myr; de La Reza et al. 1989; Zuckerman & Song 2004), β Pictoris (β PMG; 26 – 29 Myr; Zuckerman et al. 2001; Malo et al. 2014), Tucana-Horologium (THA; 20 – 40 Myr; Torres et al. 2000; Zuckerman & Webb 2000), Carina (20 – 40 Myr; Torres et al. 2008), Columba (20 – 40 Myr; Torres et al. 2008), Argus (ARG; 30 – 50 Myr; Makarov & Urban 2000) and AB Doradus (ABDMG; 70 – 120 Myr; Zuckerman et al. 2004) provide a unique opportunity for the study of young, age-calibrated very low-mass stars and brown dwarfs (BDs) in the Solar neighborhood. The current census of bona fide members of those groups is still limited to early-type (\leq M0) stars, whereas a small fraction of the expected M0–M5 population has been only recently explored (Shkolnik et al. 2012; Malo et al. 2013; Rodriguez et al. 2013; Kraus et al. 2014). The identification of the even fainter BD members is a challenging task which requires a kinematic and spectroscopic follow-up of a large number of faint targets: only a handful of such BD candidate members have been identified so far (Mamajek 2005; Looper et al. 2007; Rice et al. 2010; Delorme et al. 2012; Liu et al. 2013; Faherty et al. 2013; Gagné et al. 2014a; Gagné et al. 2014b).

The Banyan All-Sky Survey (BASS) was initiated to search for this missing > M5 population of young low-mass stars and BDs in nearby moving groups. Completing this population will open the door to answering a number of fundamental questions on the formation process of such low-mass objects, *e.g.* by constraining the low-mass end of the initial mass function and studying the physical properties of these objects in coeval populations of well-defined ages. A few results from the BASS survey were already published, including the discovery of a planetary-mass companion to a M5.5 binary low-mass star in THA (Delorme et al. 2013) and the first L dwarf candidate member to TWA (Gagné et al. 2014b).

We describe here the candidate selection process that was used to build a list of several hundreds of young, late-type candidate members to moving groups (Sections 2. and 3.); the status of our spectroscopic follow-up (Sections 4. and 5.); as well as a number of preliminary results from the BASS survey (Section 6.).

2. SELECTION OF CANDIDATES

Candidate members of YMGs in the BASS survey were selected from an initial cross-match of the Two Microns All-Sky Survey (2MASS; Skrutskie et al. 2006) with the ALLWISE survey (Wright et al. 2010; Kirkpatrick et al. 2014). All sources in ALLWISE were already matched with their 2MASS counterpart if it is located within an angular distance of 3". We used all unmatched sources in both catalogs to identify additional matches with angular distances up to 25", for all 173 443 sources outside of the Galactic plane and surviving a set of various quality and color filters. We rejected spurious matches for which colors were not consistent with late-type objects (*i.e.*, $K_S - W1 < 0.153$ or $K_S - W1 > 2$). We used the astrometric measurements in both catalogs to determine the proper motions with typical precisions of 5–15 mas yr⁻¹ for bright sources (J < 16) and 5–25 mas yr⁻¹ for fainter sources (Figure .1). We then selected all sources with a proper motion larger than 30 mas yr⁻¹ at a confidence level larger than 5 σ . This set of 98 970 objects corresponding to potential nearby, later-than-M5 dwarfs, was used as the input sample for the identification of new candidate members of nearby, young moving groups. Cross-matching this sample with the Initial Gaia Source List (Vizier catalog I/324/igsl3) revealed that our 2MASS–ALLWISE proper motions are consistent with those of UCAC4 (Zacharias et al. 2013) and PPMXL (Roeser et al. 2010), with reduced χ^2 values of 1.27 and 1.03 for $\mu_{\alpha} \cos \delta$ and μ_{δ} , respectively.



(a) 2MASS-ALLWISE $\mu_{\alpha} \cos \delta$ precision (b) 2MASS-ALLWISE μ_{δ} precision

Figure .1: Precision of 2MASS–ALLWISE proper motions derived in this work, as a function of 2MASS J apparent magnitude (pink dots). Pale green contour lines include 30%, 75% and 98% of our sample, respectively. We obtain typical precisions of 5–15 mas yr⁻¹ in the bright regime (J < 16) and 5–25 mas yr⁻¹ in the faint regime.

We used the Bayesian Analysis for Nearby Young AssociatioNs II tool¹ (BANYAN II; Gagné et al. 2014a) to identify candidate members of YMGs considered here, amongst the input sample of potential nearby $\geq M5$ dwarfs described above. This tool takes as inputs the sky position, proper motion and 2MASS J, H, K_S as well as ALLWISE W1 and W2 apparent magnitudes of a given source and compares them to spatial and kinematic models for the Galactic position XYZ and space velocity UVW of these associations and field stars, as well as field and young dwarf sequences in two distinct color-magnitude diagrams (CMDs; M_{W1} versus $J - K_S$ and M_{W1} versus H - W2). Young objects are expected to fall on the red side of the field sequence in these CMDs, due to their larger luminosity (a consequence of their inflated radius) and/or the enhanced presence of dust in their photosphere (in the case of L-type BDs; see Figure .2). The comparison with these models is performed using a naive Bayesian classifier, where different hypotheses consist in membership to the field or the YMGs considered here. Since radial velocity and distance are not known for the BASS catalog, those parameters are marginalized in Bayes' theorem (*i.e.*, a range of radial velocities and

¹Publicly available at http://www.astro.umontreal.ca/~gagne/banyanII.php.

distances are tested and the output probability density functions are integrated over those two parameters). The BANYAN II tool outputs a statistical prediction for the distance and radial velocity and a probability associated to each hypothesis. For more information, we refer the reader to Gagné et al. (2014a) and J. Gagné et al. (submitted to ApJ). All sources with a Bayesian probability lower than 10% or with a predicted position on the blue side of the field sequence in any of the two CMDs described above were rejected. All 273 sources with CMD positions at least 1σ redder than the field sequence were selected to define the BASS catalog (Figure .2), whereas the 275 sources with colors within the field scatter were selected to define the low-priority BASS (LP-BASS) catalog. In Figure .3, we show the sky position and proper motion of candidate members of β PMG in BASS, compared to its bona fide members. It can be seen that the proper motions of both samples are consistent and point towards the apex of the moving group.

3. THE BASS CATALOG

We performed a literature search for all 548 sources in the BASS and LP-BASS catalogs to gather any relevant information, such as multiplicity, age, radial velocity, trigonometric distance, spectral types or membership to associations, to refine Bayesian membership probabilities with the BANYAN II tool. We also determined an estimated maximal hit rate of 87% and 74% in the BASS and LP-BASS catalogs, respectively, which is obtained by calculating the fraction of candidates that were rejected by any additional information in the literature, compared to the number of candidates for which additional information was consistent with suspected membership.

We retrieve a total of 60/97 of all known candidates or bona fide members to the YMGs considered here in the BASS catalog, as well as an additional three in LP-BASS. Most (22/36) of the remaining objects were missed because of quality filters that were applied in the construction of our input list, whereas the 14 others were missed because of low Bayesian probabilities.

We used the BT-SETTL atmosphere models (Allard et al. 2013; Rajpurohit et al. 2013), AMES-Cond isochrones (Baraffe et al. 2003), the 2MASS and ALLWISE magnitudes, as well as the most probable statistical distances of BASS candidates to estimate their spectral types (Figure .4) and masses. We find that the BASS sample potentially contains 101 previously unknown young BDs, 22 of them having estimated masses below 13 M_{Jup} .

4. SIGNATURES OF YOUTH IN LOW-MASS STARS AND BROWN DWARFS

Young low-mass stars and BDs have a larger radius as a consequence of their gravitational contraction phase, which is still ongoing. The thermal energy released by this contraction makes them hotter than field dwarfs of the same mass: both effects conspire to make them more luminous than older objects of a similar mass. Since spectral types are mostly dependent on temperature, young dwarfs are less massive and more inflated than older objects of the same spectral type, and thus have a lower surface gravity. This in turn yields a lower pressure in their atmospheres, decreasing the effects of pressure broadening and collision-induced absorption of the H_2 molecule. These effects respectively cause young



Figure .2: 2MASS $J - K_S$ color versus ALLWISE absolute W1 magnitude for the field sequence (thick green line) and its scatter (dashed pale green lines), compared to candidate members of YMGs identified in the BASS survey (filled purple circles; using their most probable statistical distances from the BANYAN II tool). Objects in BASS were selected so that they fall on the red side of the field sequence in this CMD, which is typical of young, inflated (thus brighter) M-type dwarfs, as well as young L-type dwarfs which have thicker dust clouds in their photosphere (causing redder near-infrared colors).

objects to have a smaller equivalent width of atomic absorption lines such as K I, Na I, FeH and CrH (Lyo et al. 2004; McGovern et al. 2004; Cruz et al. 2009), as well as a triangular-shaped continuum in the H-band (Rice et al. 2010). Furthermore, atmospheric cloud thickness is enhanced in young L dwarfs, which causes stronger VO absorption and redder near-infrared (NIR) colors (Allers et al. 2007; Burgasser et al. 2008; Looper et al. 2008).



Figure .3: Proper motion and position of β PMG candidates from the BASS survey (red arrows) and their corresponding great circles (pink lines), compared to those of bona fide members of β PMG (green arrows and lines). It can be seen that bona fide members as well as candidates all point away from the antapex and towards the apex of β PMG (blue circles), which is known as the property of common proper motion, and is due to the similar space velocities UVW of the members of a moving group projected on the Celestial Sphere. The Solar apex and antapex are displayed as the black cross and plus symbols, respectively.

Kirkpatrick et al. (2006) suggest appending a Greek-letter suffix to the spectral type nomenclature, in order to differentiate field dwarfs with a normal surface gravity (α) from younger dwarfs with a mild low surface gravity (β) or those with a very low surface gravity (γ). Cruz et al. (2009) follow this nomenclature and assign a gravity classification to several new young L dwarfs, by visually comparing their optical spectra with those of various spectroscopic standards. Allers & Liu (2013) presents a quantitative method to assign a gravity classification to > M5 dwarfs using various spectroscopic indices and equivalent widths suitable for NIR spectroscopy with resolutions R > 75 or R > 750 (depending on individual indices). They find that young dwarfs do not display uniform signs of low gravity, in the sense that young objects of the same age and spectral type can reveal their low-gravity nature through distinct properties. For this reason, a set of several low-gravity indices must be considered altogether to assign a low-gravity classification. They build several sequences of spectral types – spectroscopic indices which are each used to assign a low-gravity score associated to a particular gravity-sensitive index, then all scores are combined together to a final gravity classification of either *field gravity* (FLD-G), *intermediate gravity* (INT-G) or very low gravity (VL-G). They report that the FLD-G, INT-G and VL-G classifications are consistent with the respective α , β and γ classifications used in the optical. For this reason,



Figure .4: Histogram of estimated spectral types for the BASS catalog (pink bars), compared with known bona fide members in the associations considered here (green bars). The vertical range has been truncated for visibility (the bar for spectral type M5 extends to a value of 91). This survey explores a yet poorly known population of very late-type and low-mass young objects in YMGs.

we follow the suggestion of Kirkpatrick et al. (2006) and use a Greek-letter classification in the remainder of this work.

5. SPECTROSCOPIC FOLLOW-UP

We initiated a low- to mid-resolution ($R \sim 75$ to $R \sim 6000$) spectroscopic follow-up of the BASS catalog to assign spectral types and identify signs of youth in the NIR and optical, using GMOS (Hook et al. 2004) and FLAMINGOS-2 (Eikenberry et al. 2004) at the Gemini-North and Gemini-South telescopes; SpeX (Rayner et al. 2003) at the IRTF; as well as FIRE

(Sincoe et al. 2013) and MAGE (Marshall et al. 2008) at the Magellan telescopes. We obtained more than 255 hours of queue observing and 15 nights of classical observing that were dedicated to this project in the 2012A to 2014B semesters.

6. RESULTS FROM THE BASS SURVEY

We present in this section preliminary results from the BASS survey: this includes a number of new young BDs (Section 6.1), a new planetary companion to a low-mass star (Section 6.2) and tentative indications of mass segregation in some YMGs (Section 6.3).

6.1 New Low-Mass Stars and Brown Dwarfs with Signs of Low-Gravity

We identified more than 45 new BDs displaying signs of low gravity (youth), some of which are presented in Figures .5 and .6. We used both a visual and an index-based classification to assess signs of low-gravity. Visual comparison was done using the method of Cruz et al. (2009) in the optical and K. Cruz et al. (in preparation; see also Cruz & Núñez 2007) in the NIR: the J, H and K bands are normalized individually to ensure that the classification is not affected by the large spread in NIR colors of BDs. We used the NIR classification scheme of Allers & Liu (2013) to confirm the visual classifications, and found that both methods agree very well. In Figures .7 and .8, we compare the gravity-sensitive indices of young BASS candidates to sequences defined by Allers & Liu (2013). These Figures demonstrate how the BASS survey represents a significant contribution to the set of currently known young BDs. More importantly, all these new young BDs are potentially age-calibrated members of nearby moving groups, which will be of crucial importance in understanding how their properties correlate with age. Allers & Liu (2013) note that their respective gravity classes FLD-G, INT-G and VL-G seem to correspond to respective ages of > 200 Myr, 50–200 Myr and 10–30 Myr, using 25 young BDs with age constraints.

In Figure .9, we compare various optical gravity-sensitive indices of M-type dwarfs from BASS to preliminary sequences built from field, young and giant M-type stars obtained from the DwarfArchives², the Sloan Digital Sky Survey (Abazajian et al. 2009) and the RIZzo spectral library³ (Kirkpatrick et al. 2000; Cruz & Reid 2002; Cruz et al. 2003; Cruz et al. 2007; Reid et al. 2008). This allowed us to identify several candidates with signs of low-gravity in the optical, however we find that it is challenging to differentiate young and old < M5 dwarfs using these spectroscopic indices.

6.2 A New Planetary-Mass Companion to a Young Moving Group Candidate Member

We used acquisition images from our spectroscopic follow-up to identify a large-separation co-moving companion to a young low-mass star in the BASS sample (Figure .10). A spectroscopic follow-up with the FIRE spectrometer revealed that the companion is young, with a spectral type L4 γ . This result will be presented in more detail in an upcoming paper (É. Artigau et al., in preparation).

²http://dwarfarchives.org

³http://www.astro.umontreal.ca/~gagne/rizzo.php



Figure .5: NIR relative spectral distributions of new young BDs discovered in the BASSurvey (thick black lines), compared to various field and young BDs of the same spectral types (colored lines). All spectra are normalized at their median value in the 1.27–1.33 μ m range. It can be seen that the new BASSiscoveries display hallmark signs of low-gravity such as a redder slope and a triangular continuum shape in the *H*-band (1.45–1.8 μ m).



Figure .6: NIR relative spectral distributions of new young BDs discovered in the BASSurvey, compared to various field and young BDs of the same spectral type (see Figure .5 for color codes). The young L4 β SIMP J2154–1055 (panel e) has been independently discovered (Gagné et al. 2014, ApJ in press) in the *Survey Infrarouge de Mouvement Propre* survey (SIMP Artigau et al. 2009; J. Robert et al., in preparation).



Figure .7: Panels (a)–(c): Gravity-sensitive NIR spectroscopic indices of new discoveries in the BASS survey (open black stars classified as INT-G and filled black stars classified as VL-G; see text), compared to the field sequence (thick blue line) and its scatter (pink region delimited by dashed pale blue lines) as defined in Allers & Liu (2013). The thick, dashed blue line represents the delimitation between the intermediate and very low-gravity regimes and known young BDs are represented with filled dots (green dots for INT-G and purple dots for VL-G). Random offsets with a standard deviation of 0.2 subtypes were added to spectral types for visibility. Panel (d): 2MASS $J - K_S$ colors as a function of spectral type of new young BD discoveries from the BASS survey (filled black stars), compared to the field sequence (blue line) and its scatter (pink region delimited by dashed pale blue lines). The field sequence was built from the DwarfArchive. Known young field BDs are displayed as green dots, whereas members of slightly older associations are displayed as open purple symbols; circles for the Pleiades (~ 125 Myr), downside triangles for Ursa Major (~ 400 Myr), right triangles for Coma Berenices (\sim 500 Myr) and left triangles for the Hyades (\sim 625 Myr). Young L dwarfs generally display redder NIR colors compared to their older equivalents due to an enhanced atmospheric dust thickness.



Figure .8: Gravity-sensitive spectroscopic indices (panels a–b) and equivalent widths (panels c–f) of new young BD discoveries in the BASS survey, compared to other young BDs and the field sequence. See Figure .7 (panels a–c) for a description of the symbols.

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6.3 Tentative Indications of mass segregation

The Virial theorem suggests that a group of isolated and gravitationally interacting stars should relax towards a state of equilibrium where every star possesses the same quantity of kinetic energy. For this reason, it is expected that the massive stars of such a group would have a smaller velocity spread compared to the less massive members. This effect has been observed in several associations of stars (Jeffries et al. 2004; Hasan & Hasan 2011; Olczak et al. 2011; Pang et al. 2013), however it has never been demonstrated for any of the YMGs considered here.

Olczak et al. (2011) introduced a quantitative method to measure mass segregation in associations of stars, based on the principle of Minimum Spanning Trees (MSTs). An MST is defined as the shortest network of lines that connects together a set of points, without creating any loop (see Figure .11 for an example). This offers the crucial advantage of measuring the typical length scale of a distribution without any prior knowledge on its geometry. For example, determining the MST of the spatial XYZ distribution of members of a YMG will yield its length scale without needing to determine its center of mass. This property is crucial in the case of YMGs, because we expect many of their members to be still missing, not to mention that the masses of those that we know are generally not well constrained.

We use a metric for the measurement of mass segregation that is defined by Allison et al. (2009); the total length of the MST is determined for a subset of the N most massive stars of a given association (we call this measurement l_{massive}), and then this is repeated for a large number of random subsets of N stars in the same association (which yields an array of lengths $l_{\text{norm};i}$). The Mass Segregation Ratio (MSR; not to be confused with MST) is then defined as :

$$\Lambda_{\rm MSR} = \frac{\langle l_{\rm norm;i} \rangle}{l_{\rm massive}},\tag{1}$$

where $\langle x_i \rangle$ denotes the mean value of an array x_i . The standard deviation of $l_{\text{norm};i}$ can be used in turn to assess the statistical signification of Λ_{MSR} .

We applied this method to the spatial XYZ and kinematic UVW distributions of bona fide members and BASS candidates of YMGs considered here, for all possible values of N. Instead of selecting subsets of stars based on their estimated masses which are uncertain, we rather use their absolute M_{W1} magnitudes, which should vary monotonically with mass for a coeval population. We present partial results in Figure .12: we find that objects in ARG have an MSR larger than unity at a 3σ significance when selecting the subset of stars more massive than $\sim 0.27 \ M_{\odot}$ (corresponding to a positive mass segregation, *i.e.* more massive stars being more concentrated), whereas we find positive dynamical mass segregation in ABDMG with a $\sim 1\sigma$ significance if we select stars more massive than $\sim 0.48 \ M_{\odot}$ or $\sim 0.22 \ M_{\odot}$. More detail on these results will be presented in J. Gagné et al. (submitted to ApJ), but we point out that measurements of radial velocity and parallax for all BASS candidates will be needed to corroborate these tentative results.

7. CONCLUSIONS

We present a description of the candidate selection method that we used to build the BASS catalog of very low-mass candidate members of YMGs, as well as a spectroscopic follow-up to identify signs of youth in their NIR and optical spectra. We present first results from this survey, including several new low-mass stars and BDs displaying telltale signs of youth such as a triangular H-band continuum or lower-than-normal atomic line equivalent widths. We adapt the method of minimum spanning trees to YMGs, and use it to identify tentative signs of spatial and dynamical mass segregation in YMGs, however we stress that a complete measurement of the kinematics of the BASS sample will be needed to verify these results.

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Figure .9: Gravity-sensitive optical spectroscopic indices of potentially young low-mass stars and BDs in the BASS sample (black stars), compared to the field sequence (thick blue line) and its scatter (pink region delimited by dashed pale blue lines). Young members of moving groups considered here (10–125 Myr) are displayed as upside, orange filled triangles, whereas very young objects from star-forming regions (0–3 Myr) are displayed as green, filled rightpointing triangles. Giant stars, which have an even lower surface gravity than those of very young low-mass stars and BDs, are displayed as open, purple left-pointing triangles. It can be seen that giants and young objects follow distinct sequences at spectral types later than M5, however the delimitation is not as clear as for NIR spectroscopic indices (see Figures .7 and .8), especially in the case of early-type young dwarfs.



(a) J-band image

Figure .10: Left Panel : Direct imaging of a planetary-mass companion to a young low-mass star in the BASS sample, using Flamingos-2 in the J band. Right Panel : Resolved FIRE spectrum of the L4 γ planetary-mass companion, compared to several field and low-gravity L4 BDs.



Figure .11: Minimum spanning tree (pale green lines) for bona fide members and BASS candidates of ABDMG (red spheres) in UVW velocity space. Red spheres are projected on the three planes for visibility. The minimum spanning tree is the network of minimal length that connects all points together (*i.e.*, all candidates and members of ABDMG), without creating any loop (see text).



Figure .12: Dynamical (UVW space) and spatial (XYZ space) mass segregation ratios ($\Lambda_{\rm MSR}$) for all bona fide members and BASS candidates in ABDMG and ARG (pale purple line; dark purple line is a smoothed version). A unit MSR indicates no mass segregation (*i.e.*, the MST length does not correlate with the absolute magnitude of the subset of objects used to define the MSR). An MSR larger (smaller) than one indicates that the brightest (faintest) stars are more concentrated in position or velocity space. A Monte Carlo simulation allowed us to delimit the region where $\Lambda_{\rm MSR}$ does not depart from unity with a statistical significance of 1 σ (pale blue region). Red lines indicate a positive departure from $\Lambda_{\rm MSR} = 1$ at significances of 1 σ (solid line), 2σ (dash-dotted line) and 3σ (dashed line), whereas green lines similarly indicate a negative departure from $\Lambda_{\rm MSR} = 1$. For example, panel (b) indicates that an MST built from only the 30% brightest stars in ARG (corresponding to $M_{W1} \leq 2.7$ or estimated masses $\geq 0.27 M_{\odot}$), has a larger total length than that of an MST build from random selections of 30% of stars in ARG at a $> 3\sigma$ significance. This indicates that the stars in this sample which are more massive than $\sim 0.27 M_{\odot}$ tend to be more concentrated in the XYZ space.