

## THE LOWEST-MASS MEMBER OF THE $\beta$ PICTORIS MOVING GROUP

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### ABSTRACT

We present spectral and kinematic evidence that 2MASS J06085283–2753583 (M8.5 $\gamma$ ) is a member of the  $\beta$  Pictoris Moving Group (BPMG, age  $\sim 12$  Myr), making it the latest-type known member of this young, nearby association. We confirm low-gravity spectral morphology at both medium and high resolutions in the near-infrared. We present new radial velocity and proper motion measurements, and use these to calculate galactic location and space motion consistent with other high-probability members of the BPMG. The predicted mass range consistent with the object's effective temperature, surface gravity, spectral type, and age is 15–35  $M_{\text{Jup}}$ , placing 2MASS 0608–27 well within the brown dwarf mass regime. 2MASS J06085283–2753583 is thus confidently added to the short list of very low mass, intermediate age benchmark objects that inform ongoing searches for the lowest-mass members of nearby young associations.

**Key words:** brown dwarfs – infrared: stars – open clusters and associations: individual ( $\beta$  Pictoris) – stars: individual (2MASS J06085283–2753583) – stars: late-type – techniques: spectroscopic

*Online-only material:* color figures

### 1. INTRODUCTION

Low-mass members of nearby clusters, moving groups, and loose associations are important objects of study for stellar and planetary astrophysics, formation, and evolution. These groups are older than regions of ongoing star formation (e.g., in Taurus and Orion, ages  $\sim 1$ –5 Myr) but younger than the disk population (ages  $\sim 1$ –10 Gyr). Such associations have only recently been discovered because they are low-density groups, and their members are spread out on the sky. Currently identified groups include the TW Hydrae Association (TWA, age  $\sim 10$  Myr), the  $\beta$  Pictoris Moving Group (BPMG,  $\sim 12$  Myr), and the Tucana/Horologium Association (Tuc–Hor,  $\sim 30$  Myr), along with several other clusters/associations with ages younger than  $\sim 500$  Myr (e.g., Zuckerman & Song 2004; Torres et al. 2008).

Young low-mass objects are hotter and have larger radii than older objects of the same mass (e.g., Chabrier et al. 2000), thus they are brighter and can be studied more efficiently than their older counterparts. Young associations and moving groups are closer to the Sun than the closest star-forming regions ( $d \sim 120$ –140 pc), allowing for more detailed study of their lowest-mass members. Furthermore, low-mass members of slightly older associations ( $> 20$  Myr) have typically ceased accretion and dissipated their primordial disks, making it easier to disentangle atmospheric and circumstellar properties. On the other hand, they still may show signs of youth, such as low-gravity spectral features and activity indicators. Eventually, a complete census of the low-mass members of nearby

associations will address outstanding questions in star formation, including the low-mass end of the initial mass function and its dependence on environment as well as the mass and age dependence of various processes in star and planet formation.

This Letter establishes 2MASS J06085283–2753583 (hereafter 2MASS 0608–27) as the lowest-mass confirmed member of the BPMG. Section 2 describes previous observations of 2MASS 0608–27, and Section 3 presents the observations analyzed herein. The kinematic and spatial properties of 2MASS 0608–27 are determined in Section 4, and its membership in the BPMG is discussed in Section 5. We present the conclusions of this Letter in Section 6.

### 2. PREVIOUS OBSERVATIONS OF 2MASS 0608–27

2MASS 0608–27 was discovered by Cruz et al. (2003) in a photometrically selected sample of ultracool dwarfs from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). They obtained a red-optical spectrum at 5.5 Å resolution with the RC Spectrograph on the Blanco 4 m telescope on Cerro Tololo. In addition to H $\alpha$  emission they observed enhanced VO absorption, suggesting low gravity (their Figure 10). They did not assign a spectral type but compared 2MASS 0608–27 to standard M8 and M9 objects and estimated a rough distance of 30 pc.

Kirkpatrick et al. (2008) included 2MASS 0608–27 in their study of field late-M through L dwarfs exhibiting signatures of youth. They obtained red-optical spectra at 10 Å resolution with LRIS on Keck I and noted weaker K I, Na I, and CaH and stronger VO than typically observed in field objects, indicative of low gravity (McGovern et al. 2004), as well as H $\alpha$  emission (their Figure 8). They assign a spectral type of M8.5 “peculiar” and estimate the age of 2MASS 0608–27 to be  $< 100$  Myr based on comparison of the spectrum to the Pleiades late-M dwarf Teide 1.

Luhman et al. (2009) reported *Spitzer*/IRAC observations of 2MASS 0608–27 and found that its [3.6]–[5.8] and [3.6]–[8.0]

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**Table 1**  
Observing log of 2MASS J06085283–2753583

UT Date of Observation	Telescope/ Instrument	Band	Resolving Power	Integration Time (s)	Reference
2003 Dec 4	Keck II/NIRSPEC	<i>J</i>	2000	600	1, 2
2007 Nov 13	IRTF/SpeX	<i>JHK</i>	1200	1600	3
2008 Dec 6	Keck II/NIRSPEC	<i>J</i>	20000	4800	2
2009 Oct 28	Gemini-S/Phoenix	<i>H</i>	40000	2400	3
2009 Dec 12	CTIO/ISPI	<i>J</i>	Imaging	200	4

**References.** (1) McGovern 2005; (2) Rice et al. 2010; (3) this work; (4) J. K. Faherty et al. 2010, in preparation.

colors showed no signs of infrared excess from a circumstellar disk. This generally suggests a lower age limit of 1–5 Myr, depending on the disk dissipation timescale for very low mass objects, although objects as young as 0.5 Myr have been observed without evidence for a disk.

Rice et al. (2010) included 2MASS 0608–27 in their 5–10 Myr age group (also containing Upper Scorpius and TWA members) based on medium-resolution ( $R \sim 2000$ ) *J*-band spectral features, namely weak  $K_1$  lines (McGovern 2005). Spectral fitting with models confirmed the object’s low gravity, consistent with an age of  $\sim 5$ –10 Myr. We present a more detailed analysis of the observed *J*-band spectra in Section 3.2.

The proper motion of 2MASS 0608–27 was measured by Caballero (2007) and Faherty et al. (2009). Both authors detected minor proper motion in right ascension (R.A.) ( $\mu_\alpha$ ) and declination (decl.) ( $\mu_\delta$ ) with relatively large error bars: ( $\mu_\alpha, \mu_\delta$ ) of ( $30 \pm 30, -30 \pm 30$ ) mas and ( $-13 \pm 11, -2 \pm 13$ ) mas, respectively. We present a new proper motion measurement in Section 4.1.

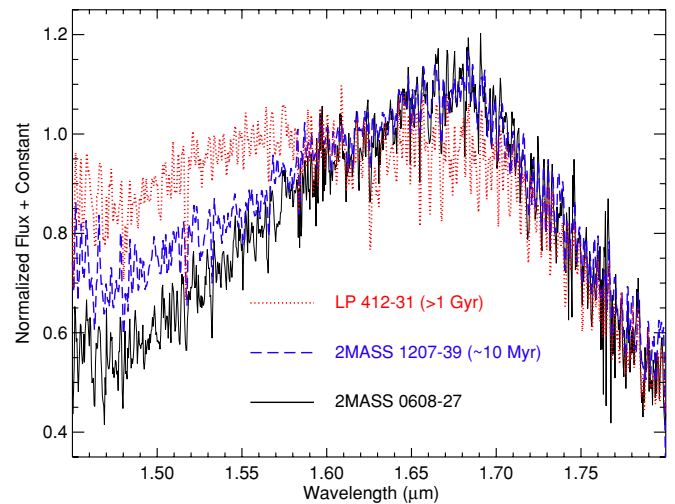
### 3. NEAR-INFRARED OBSERVATIONS

We analyzed near-infrared astrometric and spectroscopic observations of 2MASS 0608–27 to evaluate evidence of youth and membership in nearby stellar associations. Observations of 2MASS 0608–27 are summarized in Table 1 and described below.

#### 3.1. IRTF/SpeX *JHK*

2MASS 0608–27 was observed with SpeX on the NASA Infrared Telescope Facility (Rayner et al. 2003) as part of a larger investigation of field L dwarfs at low and moderate resolution in the near-infrared (K. L. Cruz et al. 2010, in preparation). The spectra were obtained in short-wavelength cross-dispersed mode, providing a wavelength coverage of 0.9–2.4  $\mu\text{m}$  in six orders. Use of the 0.5 slit provided a resolving power of  $R \sim 1200$ . The A0 V star HD 52487 was observed immediately following near a similar air mass as the target to provide both telluric correction and flux calibration. Data were reduced and corrected for telluric absorption using the SpeXtool package version 3.4 and standard methods (Vacca et al. 2003; Cushing et al. 2004, 2005).

In Figure 1, we compare the *H*-band SpeX spectrum with two late-type M dwarfs: the young M8 TWA member 2MASS J12073347–3932540 (hereafter 2MASS 1207–39, data from K. Allers 2010, private communication) and the field M8 dwarf LP 412-31 (Rayner et al. 2009). The spectrum of 2MASS 0608–27 shows a highly peaked *H*-band shape compared to the field dwarf LP 412-31, which is interpreted as stronger  $\text{H}_2\text{O}$  absorption on either side of the peak or weaker collisionally induced  $\text{H}_2$  absorption. Similar spectral



**Figure 1.** SpeX cross-dispersed *H*-band spectra ( $R \sim 1200$ ) of 2MASS 0608–27 (solid black line) compared to spectra of the field M8 object LP 412-31 (dotted red line) and the young M8 TWA member 2MASS 1207–39 (dashed blue line) normalized at 1.8  $\mu\text{m}$ . The highly peaked pseudo-continuum shape seen in 2MASS 1207–29 and 2MASS 0608–27 is typically interpreted as a hallmark of low gravity.

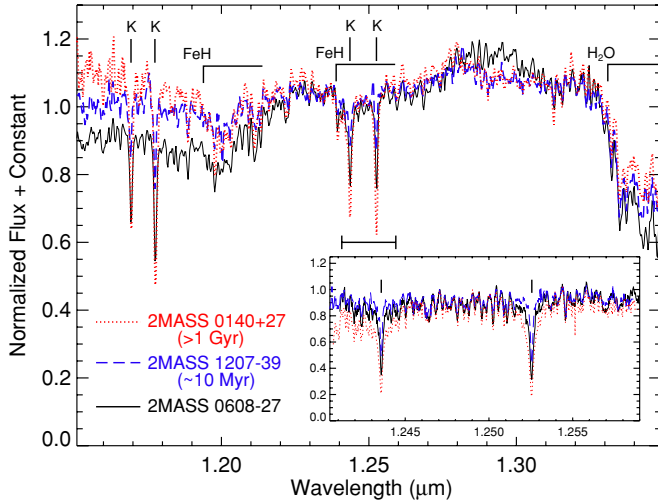
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morphology has been observed in  $\sim 1$  Myr old objects (Lucas et al. 2001; Allers et al. 2007) and M giants (e.g., Rayner et al. 2009, Figure 105), and is attributed to low surface gravity.

#### 3.2. Keck II/NIRSPEC *J* Band

*J*-band spectra of 2MASS 0608–27 were obtained at both medium ( $R \sim 2000$ ) and high ( $R \sim 20,000$ ) resolutions with NIRSPEC on Keck II (McLean et al. 1998, 2000) as part of the Brown Dwarf Spectroscopic Survey (BDSS; McLean et al. 2003, 2007). The observing procedure and data reduction methods are summarized in Rice et al. (2010).

Figure 2 shows spectra of 2MASS 0608–27 compared to a young M8 (2MASS 1207–39) and a field M9 (2MASS J01400263+2701505, hereafter 2MASS 0140+27). The widths and depths of the  $K_1$  lines of 2MASS 0608–27 are intermediate between those of the young M8 and the field M9. The  $K_1$  lines have been shown to increase in strength with increasing gravity (McGovern et al. 2004; Allers et al. 2007) and become pressure-broadened with both decreasing temperature and increasing surface gravity (McLean et al. 2007; Rice et al. 2010). Therefore, the  $K_1$  lines of 2MASS 0608–27 provide evidence for a cool temperature and low surface gravity. Interestingly, the pseudo-continuum shape of 2MASS 0608–27 is redder than the spectra of both 2MASS 1207–39 and 2MASS 0140+27, it has excess flux at 1.28–1.30  $\mu\text{m}$ , and the water band beginning at 1.33  $\mu\text{m}$  is slightly stronger. This could indicate that 2MASS 0608–27



**Figure 2.** NIRSPEC  $J$ -band spectra ( $R \sim 2000$ ) of 2MASS 0608–17 (solid black line) compared to the young M8 TWA member 2MASS 1207–39 (dashed blue line) and the field M9 dwarf 2MASS 0140+27 (dotted red line) normalized at  $1.25 \mu\text{m}$ . The inset plot shows the same objects observed at high resolution ( $R \sim 20,000$ ). The wavelength range of the inset plot is marked above it. 2MASS 0608–27 exhibits K I line strengths intermediate between those of the field and the young object, most apparent in the  $1.25 \mu\text{m}$  doublet.

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

has a cooler temperature than implied by its red-optical spectral type or a dustier atmosphere than the comparison objects.

Additional  $J$ -band echelle orders of 2MASS 0608–27 from Rice et al. (2010) and comparison spectra from the BDSS are used to measure radial velocity (RV, Section 4.2).

### 3.3. Gemini/Phoenix $H$ Band

Phoenix on the Gemini-South telescope was used to obtain a high-resolution ( $R \sim 40,000$ ) spectrum of 2MASS 0608–27 in the  $H$  band (H6420 filter centered near  $1.55 \mu\text{m}$ ). The observation was made as part of a larger project to measure RVs of late-M and L spectral type objects in the field that show signatures of low gravity (K. L. Cruz et al. 2010, in preparation). The spectrum was extracted, wavelength calibrated (using OH emission lines), and flat-fielded using the IDL-based REDSPEC software.<sup>7</sup> Observations of two late-type objects with stable RVs

<sup>7</sup> <http://www2.keck.hawaii.edu/inst/nirspec/redspeg.html>

were obtained with the same instrumental setup for the cross-correlation. The RV measurements are discussed in Section 4.2.

### 3.4. ISPI Imaging

We observed 2MASS 0608–27 with the Infrared Side Port Imager (ISPI) on the 4 m Blanco telescope as part of an ongoing brown dwarf astrometric program (J. K. Faherty et al. 2010, in preparation). 2MASS 0608–27 was observed in the  $J$ -band filter for a total of 40 s at each of five dither positions. Individual point sources were selected in each reduced image and matched to stars in the 2MASS Point Source Catalog. Once an initial World Coordinate System (WCS) was set, the distortion across the ISPI detector was corrected. The final WCS residuals against 2MASS were  $\sim 0.1$  pixels (30 mas) in both  $X$  and  $Y$ . Astrometry was performed on the final shifted and added image, and the results are described in Section 4.1.

## 4. KINEMATICS AND DISTANCE

Given its low gravity and implied youth, we calculate  $UVW$  velocities and  $XYZ$  location in order to test for membership in a young association.

### 4.1. Proper Motion

We determined a new proper motion for 2MASS 0608–27 by combining the R.A. and decl. position from ISPI with the 2MASS position. We calculated  $(\mu_\alpha, \mu_\delta)$  to be  $(-5 \pm 5, 10 \pm 5)$  mas yr<sup>-1</sup> using the 10.9 yr baseline between images (Table 2). Our measurement is consistent with previous measurements of Caballero (2007) and Faherty et al. (2009) with refined uncertainties from the longer time baseline of our observations.

### 4.2. Radial Velocity

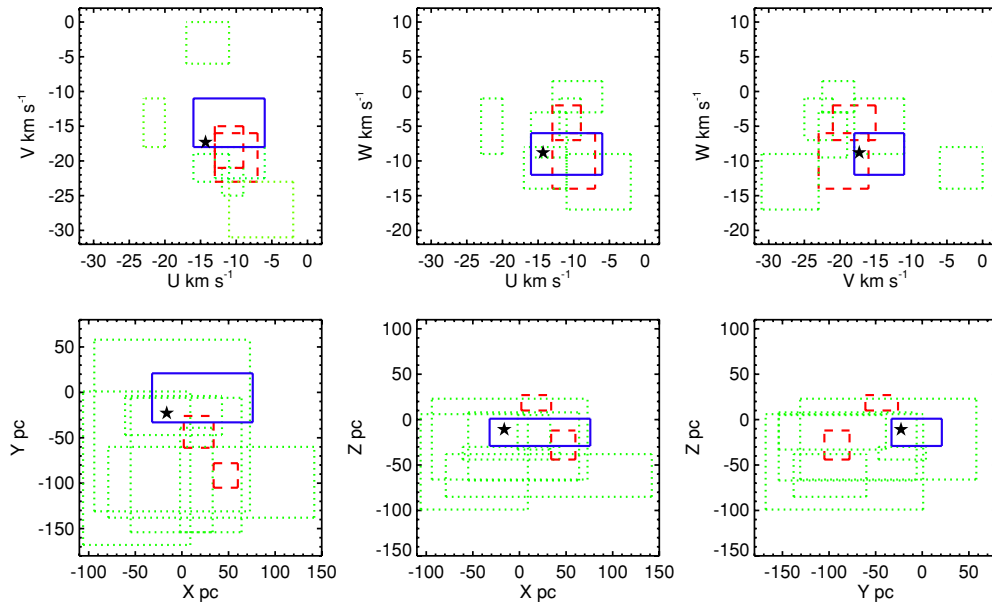
We measure the RV of 2MASS 0608–27 by cross-correlating the NIRSPEC echelle order 62 spectrum with multi-epoch spectra of RV standards G1 406 (M6; Nidever et al. 2002) and 2MASS 0140+27 (M9; Reid et al. 2002) from the BDSS. The mean measurement is  $23.4 \pm 0.5 \text{ km s}^{-1}$ . Cross-correlation of the reference spectra against one another provides an estimate of  $1.0 \text{ km s}^{-1}$  for the systematic uncertainty. We also measured the RV of 2MASS 0608–27 using the high-resolution ( $R \sim 40,000$ ) Phoenix  $H$ -band spectrum via cross-correlation with spectra of two L dwarfs from Blake et al. (2007), 2MASS

**Table 2**  
Properties of 2MASS J06085283–2753583

Parameter	Value	Reference
R.A., decl. (J2000)	06 <sup>h</sup> 08 <sup>m</sup> 52 <sup>s</sup> .8, $-27^\circ 53' 58''$	1
Optical spectral type	M8.5 $\gamma$	2
$J, H, K$	$13.595 \pm 0.028, 12.897 \pm 0.026, 12.371 \pm 0.026$	1
$\mu_\alpha, \mu_\delta$	$-5 \pm 5 \text{ mas yr}^{-1}, 10 \pm 5 \text{ mas yr}^{-1}$	2
RV	$24.0 \pm 1.0 \text{ km s}^{-1}$	2
$d_{\text{est}}$	$30 \pm 10 \text{ pc}$	2
$UVW$	$-14.3 \pm 1.4, -17.3 \pm 1.3, -8.8 \pm 1.4 \text{ km s}^{-1}$	2
$XYZ$	$-16.3 \pm 5.4, -22.8 \pm 7.6, -10.8 \pm 3.6 \text{ pc}$	2
$T_{\text{eff}}$	2555 K, 2529 K <sup>a</sup>	3, 4
$\log(g)$	3.98	4
Age	$\sim 10 \text{ Myr}$	2
Mass	15–35 $M_{\text{Jup}}$	2

**Note.** <sup>a</sup> The medium-resolution  $J$ -band spectrum of 2MASS 0608–27 is best fit by  $T_{\text{eff}} = 2200 \text{ K}$  (Rice et al. 2010), which is accounted for in the range of masses estimated here (see Section 5.4).

**References.** (1) 2MASS (Skrutskie et al. 2006); (2) this work; (3) Luhman et al. 2003; (4) Rice et al. 2010.



**Figure 3.** *UVWXYZ* properties of 2MASS 0608–27 (filled star) compared to those of nearby young associations presented in several sub-spaces. Top row: *UVW* velocity sub-space plots; bottom row: *XYZ* location sub-space plots. Rectangles surround the furthest extent of highly probable members from Torres et al. (2008), but their distribution does not necessarily fill the entire rectangle. Dashed lines (red) represent the younger moving groups TWA (~10 Myr) and  $\epsilon$  Cha (~6 Myr), the solid line (blue) represents the BPMG, and dotted lines (green) represent the older associations (Tuc–Hor, Columba, Carina, Octans, Argus, and AB Doradus) with ages of ~20–70 Myr. The space velocity and location of 2MASS 0608–27 are only coincident with the BPMG in all sub-spaces.

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

J05233822–1403022 and 2MASS J11553952–3727350. The result was  $24.5 \pm 1.5 \text{ km s}^{-1}$ . We adopt the average of these measurements,  $RV = 24.0 \pm 1.0 \text{ km s}^{-1}$ . This value is consistent with the previous measurement of  $RV = 22.6 \pm 1.5 \text{ km s}^{-1}$  by Rice et al. (2010).

#### 4.3. Distance Estimate

The distance to 2MASS 0608–27 was estimated by Faherty et al. (2009) to be  $27 \pm 4 \text{ pc}$ , based on the absolute 2MASS *J*-band magnitude and spectral type relation in Cruz et al. (2003). However, young objects at a given spectral type are typically brighter than their old counterparts. Indeed, initial parallax results for low surface gravity dwarfs demonstrate that distances are underestimated by up to 10% (J. K. Faherty et al. 2010, in preparation). Therefore, we adopt a distance of 30 pc and increase the estimated uncertainty to  $\pm 10 \text{ pc}$ .

## 5. DISCUSSION

### 5.1. The $\beta$ Pictoris Moving Group

Shortly after Barrado y Navascués et al. (1999) searched for kinematic companions to the young star  $\beta$  Pictoris in order to further constrain its age, Zuckerman et al. (2001) proposed 27 comoving stars as the BPMG. Proposed members were required to show some signature of youth, for example, large fractional X-ray luminosity, rapid rotation, large lithium abundance, or  $H\alpha$  emission. The age of the BPMG is typically quoted as ~12 Myr, which is consistent with age estimates from dynamical back-tracking models, age estimates for individual objects, and the distribution of lithium abundance (Fernández et al. 2008; Torres et al. 2008, and references therein). New members have been identified by several authors: Torres et al. (2008) included 48 stars as high-probability BPMG members, and Lépine & Simon (2009) added three members and one common proper

motion companion. The low-mass membership of the BPMG is certainly incomplete.

The high-probability members of the BPMG listed by Torres et al. (2008) include 21 objects with spectral types from M0 to M5, and the latest-type objects, three M4 and two M5 objects, are all in multiple systems. Other low-mass objects in the BPMG include the companion to  $\eta$  Tel (HR 7329), an M7.5 brown dwarf (Lowrance et al. 2000). In addition, Reiners (2009) and Reiners et al. (2010) determined that the young M6.5/M9 binary 2MASS J0041353–562112 could be an ejected member of BPMG, although they state that it is more likely a member of the ~20 Myr old Tuc–Hor Association.  $\beta$  Pictoris itself has a candidate planetary-mass companion, although the object has not been detected since the discovery observations (Lagrange et al. 2009a, 2009b; Fitzgerald et al. 2009).

### 5.2. Space Motion and Location

Based on the measured proper motion and RV, and the distance estimate described above, we calculate the *UVW* space motion of 2MASS 0608–27 (in a left-handed coordinate system with *U* positive toward the Galactic center) to be  $(-14.3 \pm 1.4, -17.3 \pm 1.3, -8.8 \pm 1.4) \text{ km s}^{-1}$ . The *XYZ* coordinates of 2MASS 0608–27 calculated from its R.A., decl., and distance are  $(-16.3 \pm 5.4, -22.8 \pm 7.6, -10.8 \pm 3.6) \text{ pc}$ . The *UVWXYZ* of 2MASS 0608–27 are shown relative to the loose associations from Torres et al. (2008) in Figure 3. Uncertainties on *UVWXYZ* values were estimated using Monte Carlo methods and are listed in Table 2. The results are most consistent with the BPMG, which has a mean *UVW* of  $(-10.1 \pm 2.1, -15.9 \pm 0.8, -9.2 \pm 1.0) \text{ km s}^{-1}$  (Torres et al. 2008). 2MASS 0608–27 is within  $2\sigma$  of the mean space velocity of high-probability BPMG members. The *XYZ* coordinates of confirmed BPMG members are centered around  $(20 \pm 50, -5 \pm 25, -15 \pm 14) \text{ pc}$  (Torres et al. 2008, Table 2 and Figure 8).



### 5.3. Membership of 2MASS 0608–27 in the BPMG

The spectral similarities of 2MASS 0608–27 and the TWA member 2MASS 1207–39 support a young age for 2MASS 0608–27, but low-mass objects vary drastically in their exhibition of youth signatures like X-ray emission and accretion indicators. The membership of 2MASS 0608–27 in the BPMG provides a tighter age constraint because a reliable age for the cluster has been determined with consistent results from different methods. Figure 3 shows the *UVWXYZ* distributions of young loose associations from Torres et al. (2008) in six sub-spaces; 2MASS 0608–27 is only coincident with the BPMG in all sub-spaces.

### 5.4. Physical Properties of 2MASS 0608–27

We revisit the spectral type estimation of Cruz et al. (2003) and Kirkpatrick et al. (2008) using the methods of Cruz et al. (2009) and assign a type of M8.5 $\gamma$  to 2MASS 0608–27, with the  $\gamma$  designation indicating low-gravity spectral features in the optical, intermediate between those of Pleiades members (designated  $\beta$ ) and Taurus members ( $\delta$ ). This is supported by the overall spectral similarity to the young M8 TWA member 2MASS 1207–39 in the near-infrared (Figures 1 and 2), but deeper H<sub>2</sub>O absorption and a redder *J*-band continuum could indicate a lower temperature and/or a dustier atmosphere for 2MASS 0608–27 (Sections 3.1 and 3.2).

Rice et al. (2010, their Figure 11) compared the effective temperature and surface gravity of 2MASS 0608–27 inferred from spectral fitting to DUSTY00 evolutionary models (Chabrier et al. 2000). The result supports an age of  $\sim 9$  Myr and a mass of  $\sim 25 M_{\text{Jup}}$  for 2MASS 0608–27. It is noteworthy that the Rice et al. (2010) high- and medium-resolution fits produced considerably different effective temperatures, 2529 K and 2200 K, respectively. This indicates the continued difficulty of inferring effective temperatures of cool objects from model fits. However, at the surface gravity inferred from the high-resolution fit, the implied age is relatively insensitive to temperature. Even an effective temperature of 2200 K would still imply an age older than 5 Myr with a mass above  $\sim 15 M_{\text{Jup}}$ , which we therefore include in the range of possible masses. The physical properties of 2MASS 0608–27 can also be inferred from its similarity to young TWA members 2MASS 1207–39 which has an estimated mass of  $25 \pm 5 M_{\text{Jup}}$  using photometry, trigonometric parallaxes, an age implied by TWA membership, and the DUSTY00 evolutionary models (Teixeira et al. 2008). As a member of the BPMG, 2MASS 0608–27 would be slightly older than the TWA members, which we account for with a larger range of masses than are typically quoted for 2MASS 1207–39. We therefore estimate a mass of 15–35  $M_{\text{Jup}}$ . The physical properties of 2MASS 0608–27 are assembled in Table 2.

## 6. CONCLUSIONS

Spectral features, kinematics, and the space location of 2MASS 0608–27 clearly confirm it as a member of the BPMG. 2MASS 0608–27 is the latest-type non-companion member by a substantial margin. Similarly, late-type objects in the BPMG are the M7.5 companion HR 7329B, possibly the M6.5/M9 binary 2MASS J0041353–562112, and the candidate planetary-mass companion to  $\beta$  Pictoris. Ongoing proper motion and RV measurements for apparently young M and L dwarfs in the field will likely confirm larger numbers of very low mass members of the BPMG and other young, nearby loose associations (Schlieder et al. 2010; K. L. Cruz et al. 2010, in preparation). The

identification of the M8.5 object 2MASS 0608–27 as a member of the BPMG provides an important late-type benchmark object for further studies.

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*Facilities:* Keck:II (NIRSPEC), IRTF (SpeX), Blanco (ISPI), Gemini:South (Phoenix)

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