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PROPERTIES OF M31. IV. CANDIDATE LUMINOUS BLUE VARIABLES FROM PANDROMEDA

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ABSTRACT

We perform a study on the optical and infrared photometric properties of known luminous blue variables (LBVs) in M31 using a sample of LBV candidates from the Local Group Galaxy Survey by Masset et al. We find that M31 LBV candidates show photometric variability ranging from 0.375 to 1.576 mag in r_{P1} during a 3 yr time span observed by the Pan-STARRS 1 Andromeda survey (PAndromeda). Their near-infrared colors also follow the distribution of Galactic LBVs as shown by Oksala et al. We use these features as selection criteria to search for unknown LBV candidates in M31. We thus devise a method to search for candidate LBVs using both optical color from the Local Group Galaxy Survey and infrared color from the Two Micron All Sky Survey, as well as photometric variations observed by PAndromeda. We find four sources exhibiting common properties of known LBVs. These sources also exhibit UV emission as seen from *Galaxy Evolution Explorer*, which is one of the previously adopted methods of searching for LBV candidates. The locations of the LBVs are well aligned with M31 spiral arms as seen in UV light, suggesting that they are evolved stars at a young age given their high-mass nature. We compare these candidates with the latest Geneva evolutionary tracks, which show that our new M31 LBV candidates are massive, evolved stars with ages of 10–100 Myr.

Key words: galaxies: individual (M31) – stars: early-type – stars: evolution – stars: massive

Online-only material: color figures

1. INTRODUCTION

Luminous blue variables (LBVs) are hot massive stars that undergo sporadic eruptions on timescales of years and decades (Humphreys & Davidson 1994). The prototype is S Doradus, as well as Hubble–Sandage variables in M31 and M33 (Hubble & Sandage 1953), which shows eruptions of 1–2 mag level over several decades. Other examples are η Carina and P Cygni, which show giant eruptions (>2 mag) over several centuries. Conti (1984) was the first to coin the name "luminous blue variables" for this type of star, and separated them from other type of bright blue stars, such as Wolf–Rayet stars.

LBVs play an important role in a very late stage of massive star evolution. They are considered as a transition phase where O stars evolve toward Wolf–Rayet stars (Meynet et al. 2011). LBVs were originally regarded as supernova (SN) impostors because they often show giant eruptions mimicking the explosion of SNe, but the central star remains after the ejecta have been expelled. However, a link between LBVs and SN progenitors was suggested by Kotak & Vink (2006) when interpreting the radio light curves of SNe. The radio emission seen after the SN explosion is induced by the interaction between SN ejecta and the progenitor's circumstellar medium, thus radio light curves bear information on the mass-loss history of the progenitor. Kotak & Vink (2006) suggested that radio light curves of SNe indicate high mass-loss histories of the progenitors, which matches well with LBVs.

Pre-eruption images of several SNe also suggest LBVs as their progenitor. For example, the progenitor of SN 1987A was recognized as a blue supergiant (Walborn et al. 1987) and Smith (2007) suggested that it could be classified as a low-luminosity LBV. Gal-Yam & Leonard (2009) identified the progenitor of SN 2005gl using *Hubble Space Telescope* (*HST*) and considered it to be a LBV. Recently, a previously known LBV, SN 2009ip, underwent its third eruption and has been linked to a true SN (Mauerhan et al. 2013). The nature of the recent eruption of SN 2009ip is under debate; subsequent follow-up has been carried out to verify or reject it as a core-collapse SN (Fraser et al. 2013). However, there are only a few known LBVs, either in our Galaxy or in M31 and M33, thus, increasing the number of known LBVs is essential for understanding their nature and evolution.

In addition to the pioneering decades-long photometric monitoring campaign conducted by Hubble & Sandage (1953), there are several methods to uncover LBVs. For example, LBVs are strong UV and Hα emitters (see Massey et al. 2007, and reference therein) and can be revealed, e.g., with observations of the *Galaxy Evolution Explorer* (*GALEX*) satellite or Hα surveys. Massey et al. (2007) conducted a Hα survey of M31 and M33 and spectroscopically followed up on a selected sample of strong Hα emitters. By comparing the spectra of their Hα emitter sample with known LBVs, they were able to identify candidate LBVs, which saved a substantial amount of time required to photometrically uncover LBVs. Because they have uncovered more than 2500 Hα-emitting stellar objects, they can only follow up on dozens of them, yet there are many more to be explored. Humphreys et al. (2013) are currently exploring other Hα-emitting sources on this list, in combination with infrared

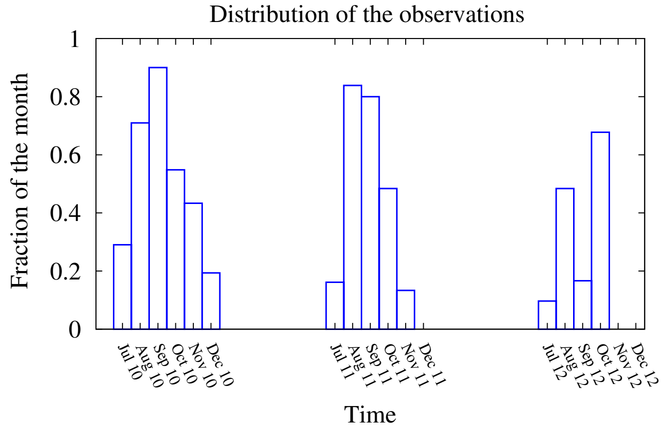

Figure 1. Distribution of the observations of PS1 toward M31. We plot the monthly fraction of nights in the r_{P1}-filter during the 2010, 2011, and 2012 seasons. In general, the observations cover most of the time in the second half of each year.

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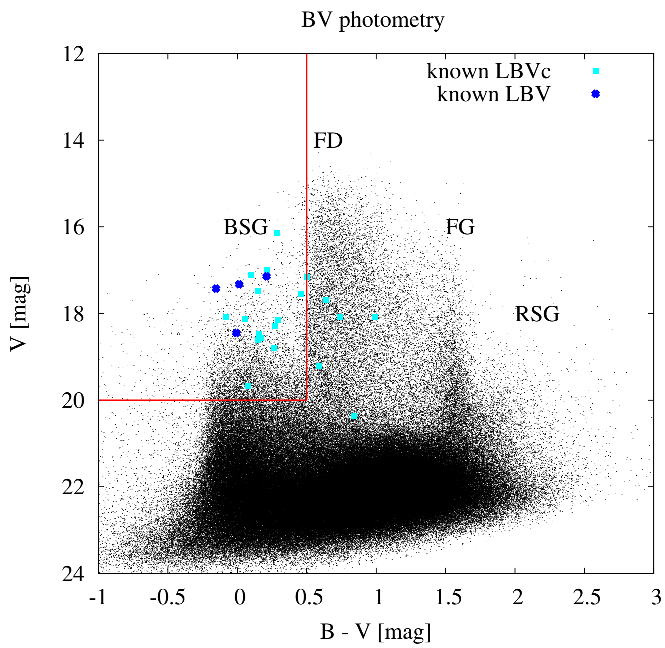

Figure 2. M31 color–magnitude diagram using the *B* and *V* photometry from Massey et al. (2006). All sources in their catalog are shown with black dots. The peaks at $B - V \sim 0.0$, 0.6, and 1.5 are from blue supergiants (BSGs), foreground dwarfs (FDs), and foreground giants (FGs), respectively. We thus make a cut at $B - V < 0.5$ and *V* brighter than 20 mag (marked with red lines) to avoid contamination from foreground stars and red supergiants (RSGs). The known LBVs in the LGGS sample are plotted with blue points and the LBV candidates listed in the LGGS sample are plotted with cyan points.

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photometry including Two Micron All Sky Survey (2MASS), *Spitzer*, and *WISE* to search for luminous and variable stars. Since LBVs undergo several eruptions and exhibit high mass-loss rates, they accumulate vast amounts of material in their circumstellar environment which could be detectable in the infrared (e.g., Gvaramadze et al. 2012). Khan et al. (2013) have made use of *Spitzer*/IRAC photometry and searched for η Carina analogs in nearby galaxies including M33 (but not M31). They estimate that 6 ± 6 of their candidates are true η Carina-like sources.

Here we outlined a novel approach utilizing mid-term photometric variation, as well as optical and infrared color to search

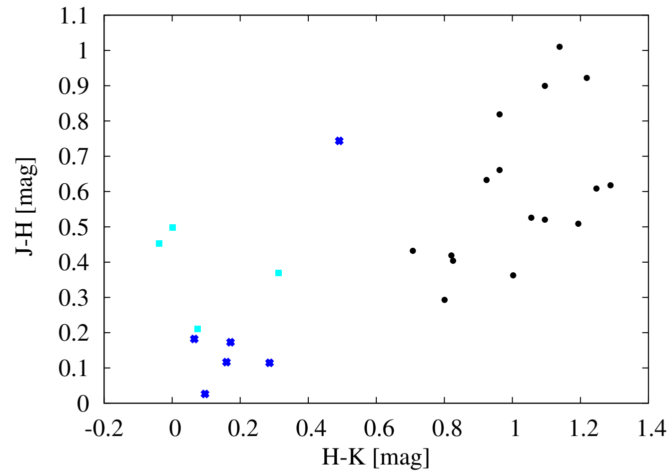

Figure 3. Infrared color–color diagram of LBVs and B[e]SGs using the 2MASS photometry from Skrutskie et al. (2006). Galactic LBVs in the Oksala et al. (2013) sample are shown in blue. Known M31 LBVs are shown in cyan. The Galactic B[e]SG sample from Oksala et al. (2013) is shown in black, which is distributed in a region at $H - K > 0.5$ and is distinct from the LBVs.

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

Table 1
Number of Stars Passed in Each Criterion

Criterion	Number of Passed Stars
Total LGGS sources	371781
$B - V < 0.5$ and $V < 20$	5928
Δ mag > 0.4	9
$H - K < 0.5$	7
Previously unknown	4

for LBVs using the Local Group Galaxy Survey (LGGS) optical and 2MASS infrared photometry, with the combination of the photometric variability from the PAndromeda monitoring campaign. Our paper is organized as follows. In Section 2, we describe the optical and infrared data we use. In Section 3, we outline our method. A discussion of our candidates is presented in Section 4, followed by an outlook in Section 5.

2. DATA SAMPLE

2.1. Optical Data

The time-series photometric data employed to search for variability are from the PAndromeda project. PAndromeda monitored the Andromeda galaxy with the 1.8 m PS1 telescope with a $\sim$7 deg^2 field-of-view (see Kaiser et al. 2010; Hodapp et al. 2004; Tonry & Onaka 2009, for a detailed description of the PS1 system, optical design, and the imager). Observations have been taken in the r_{P1} and i_{P1} filters on daily basis during July to December in 2010, 2011, and 2013 in order to search for microlensing events and variables. The distribution of the observations in the r_{P1}-filter is shown in Figure 1. Several exposures in g_{P1}, z_{P1}, and y_{P1} are also taken as complementary information for studies of the stellar content of M31.

The data reduction is based on the MDia tool (Koppenhoefer et al. 2013) and is explained in Lee et al. (2012) in detail.

We outline our data reduction steps as follows. The raw data are detrended by the image processing pipeline (Magnier 2006) and warped to a sky-based image plane (so-called skycells).

The images at the skycell stage are further analyzed by our sophisticated imaging subtraction pipeline *mupipe*

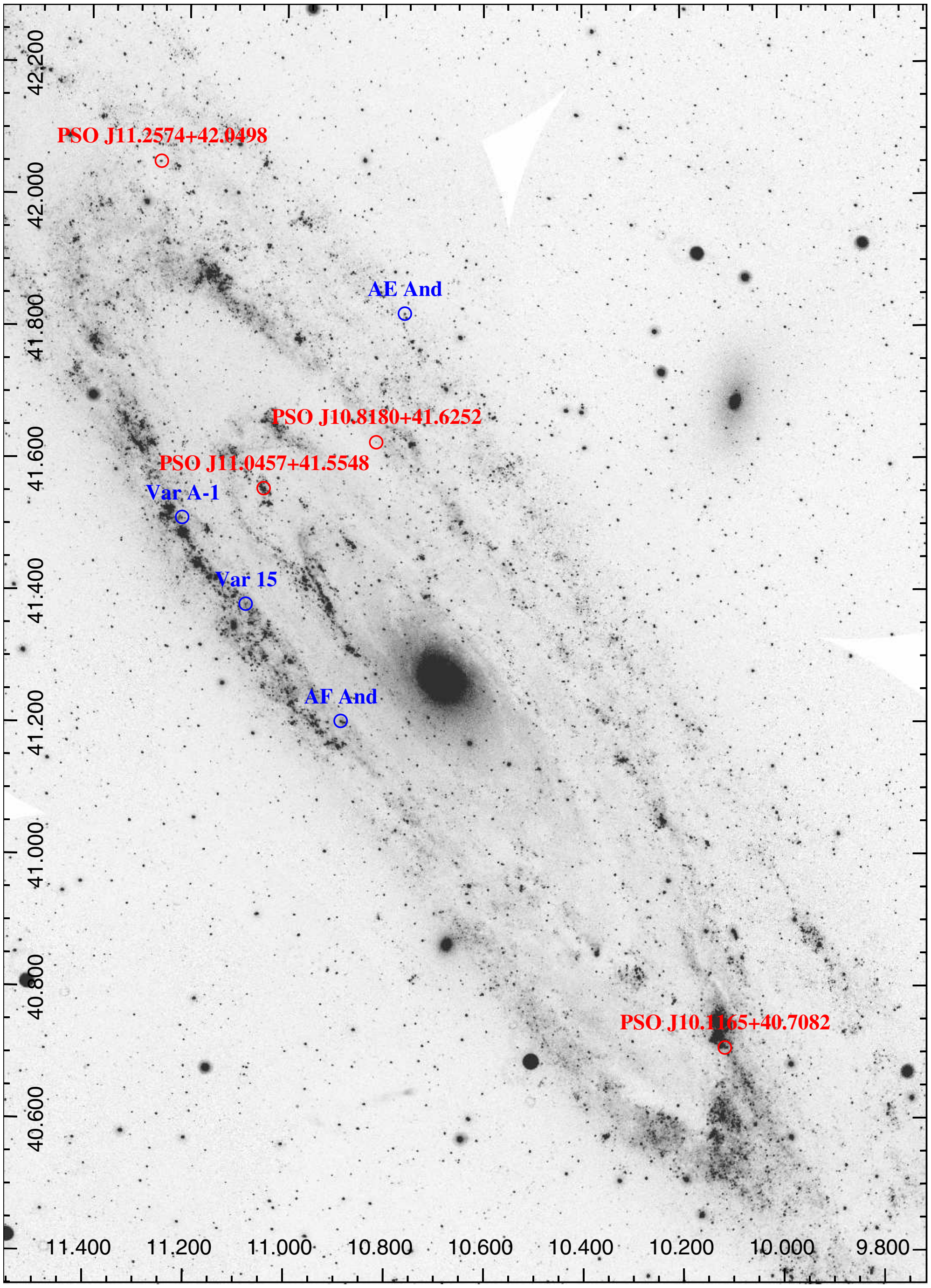

Figure 4. Spatial distribution of our LBV candidates (red circles) and the LBVs listed in Massey et al. (2007; blue circles). The underlying image is the *GALEX* near UV map by Gil de Paz et al. (2007).

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

Table 2
Optical and Infrared Photometry of Our LBV Candidates

Name	R.A. (J2000)	Decl. (J2000)	V	$B-V$	J	H	K_s
PSO J10.1165+40.7082	00:40:28.00	+40:42:29.1	19.513	0.027	15.617	14.729	14.319
PSO J10.8180+41.6265	00:43:16.33	+41:37:30.6	19.494	0.164	14.671	13.896	13.458
PSO J11.0457+41.5548	00:44:11.01	+41:33:17.6	17.300	0.042	16.483	15.085	14.884
PSO J11.2574+42.0498	00:45:01.84	+42:02:59.2	18.498	0.344	15.244	14.501	14.146

Note. B and V photometry are taken from the LGGS; JHK_s photometry are taken from the 2MASS catalog (Skrutskie et al. 2006).

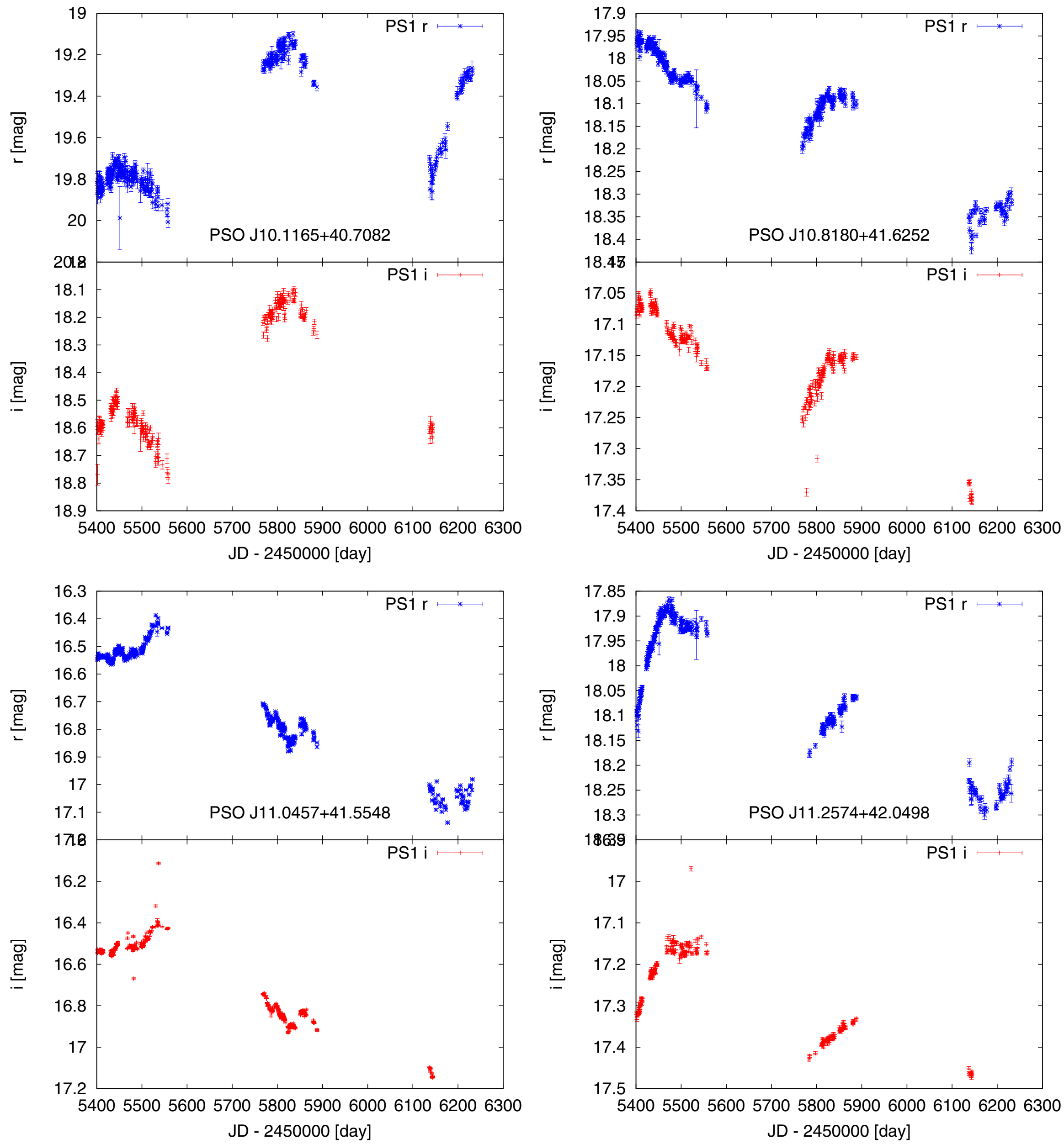

Figure 5. Light curves of our LBV candidates. From left to right top to bottom: PSOJ10.1165+40.7082, PSOJ10.8180+41.6252, PSOJ11.0457+41.5548, and PSOJ11.2574+42.0498. The light curves are obtained from the PS1 PAndromeda survey. The blue and red points indicate the r_{P1} and i_{P1} observations, respectively.
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(Gössl & Riffeser 2002) based on the idea of image differencing analysis advocated by Alard & Lupton (1998). This includes the creation of deep reference images from the best seeing data, stacking of observations within one visit to have a better signal-to-noise ratio (hereafter "visit stacks"), subtraction of visit stacks from the reference images to search for variabilities, and creating light curves from the subtracted images.

We have shown in Kodric et al. (2013) how to obtain light curves for resolved sources from the PAndromeda data. The major difference of the data used in this work is that our present data set contains 3 yr of PAndromeda data instead of 1 yr and a few days from the second year of data used in Kodric et al. (2013). The sky tessellation is also different, because the central region of M31 is in the center of a skycell (skycell 045), instead of at the corner of adjacent skycells (skycell numbers 065, 066, 077, and 078) as in Kodric et al. (2013); the skycells are larger and overlap in the new tessellation. The new tessellation is drawn in Figure 1 of Lee et al. (2013). We have extended the analysis to 47 skycells, twice as many as the number of skycells used in Kodric et al. (2013). The skycells we used are 012–017, 022–028, 032–038, 042–048, 052–058, 062–068, and 072–077, which cover a 7 $\deg^2$ area of M31. The search of variability is conducted in both r_{P1} and i_{P1}, where we start from the resolved sources in the r_{P1} reference images and check for variability in both r_{P1} and i_{P1} filters.

In addition, we also use the deep photometric catalog from the LGGS (Massey et al. 2006). The LGGS utilized the 4 m KPNO telescope to observe the M31 galaxy. Their Mosaic CCD camera has a resolution of $0\farcs261$ pixel^{-1} at the center which decreases to $0\farcs245$ pixel^{-1} toward the corner. The field-of-view of the camera is roughly $36' \times 36'$. M31 was observed between 2000 and 2002 in Johnson *UBVRI* filters with seeing values from

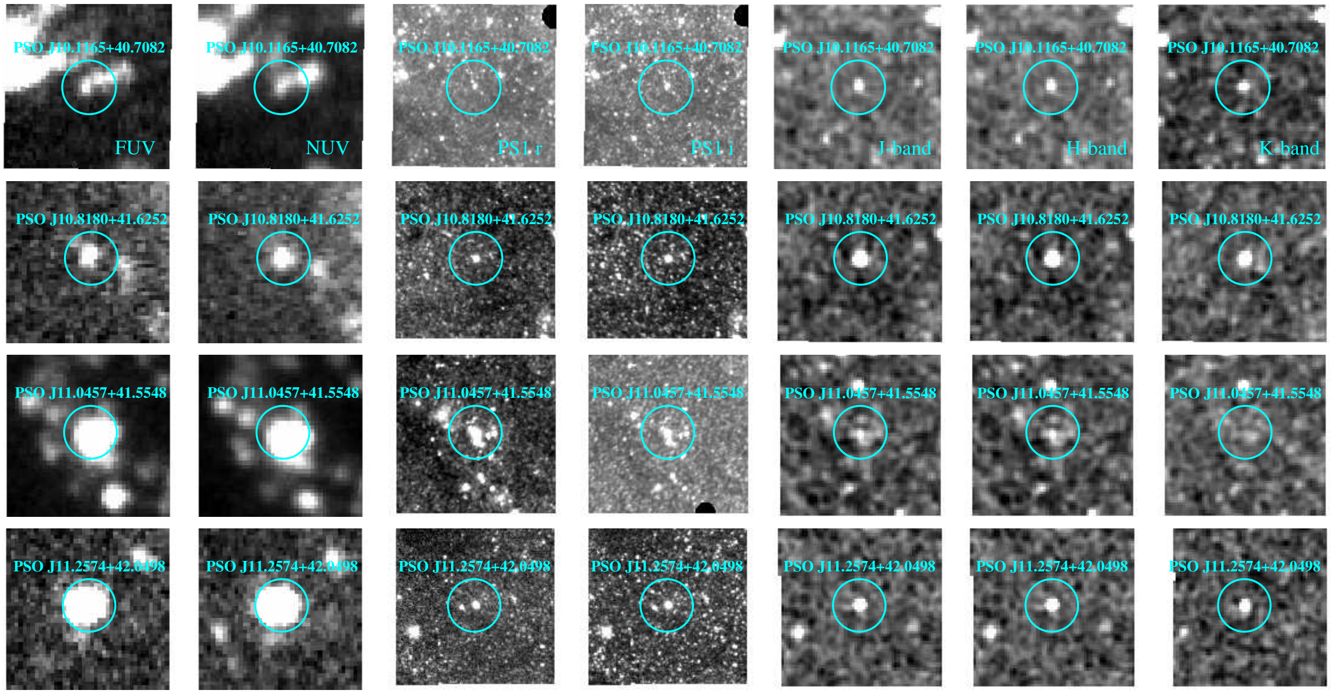

Figure 6. NUV (1516 Å, first column), FUV (2267 Å, second column), r_{P1} (third column), i_{P1} (forth column), and 2MASS JHK_s (fifth to seventh columns) postage stamps of our LBV candidates. The circles have a radius of 10″. North is to the top and east is to the left. NUV and FUV images are taken from *GALEX* Nearby Galaxy Atlas (Gil de Paz et al. 2007).

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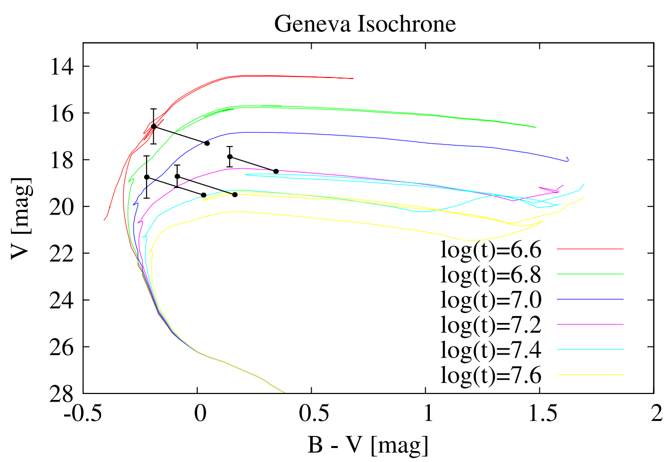

Figure 7. Location of our LBV candidates in the $B-V$ vs. V CMD, overplotted with the Geneva massive star isochrones. We adopt the distance modulus of 24.4 mag from Freedman & Madore (1990). We apply a correction for the extinction effect on $B-V$ color using the extinction map by Montalto et al. (2009). By assuming $A_V/E(B-V)=3.1$, we also correct the extinction effect on the V-band magnitude. The positions on the CMD before and after extinction correction are linked with black lines. The extinction corrected value are marked with error bars. The four candidates are indicated in black. Evolutionary tracks of metallicity $Z=0.014$ with different ages, $\log(t)=6.6, 6.8, 7.0, \ldots, 7.6$ are shown with different colors from top to bottom. The errors on the magnitude are not photometric errors, but are taken from the variability seen during the time span of PAndromeda, as shown in Table 2.

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0″.8 to 1″.4. The observations cover 10 fields, corresponding to 2.2 deg^2 along the major axis of M31 (see Figure 1 of Massey et al. 2006).

The astrometric solution for each frame was derived by matching with the USNO-B1.0 catalog (Monet et al. 2003). The point-spread function (PSF) photometry in each filter was obtained with the IRAF DAOPHOT routine, and calibrated against the Lowell 1.1 m data with zero points and color terms. The final LGGS catalog contains 371,781 stars in M31, with 1%–2% statistic error at 21 mag and 10% at 23 mag. When matching the LGGS catalog to the PAndromeda catalog, we found a median astrometric difference of 0″.36.

2.2. Infrared Data

In this work, we utilize the catalog and images delivered by the 2MASS (Skrutskie et al. 2006). 2MASS employed two 1.3 m telescopes located at Mt. Hopkins, Arizona and Cerro Tololo, Chile to simultaneously survey the full sky in 3 yr infrared passbands J(1.25 μm), H(1.65 μm), and K_s(2.16 μm). The pixel scale of the 2MASS CCDs is 2″ pixel^{-1}. 2MASS observed every patch of the sky with six times 1.3 s integration time. The raw images were dark subtracted, flat-fielded, sky subtracted, resampled to a 1″ pixel^{-1} coordinate grid in a flux-conserving manner, and coadded to generate an Atlas Image.

The source detection was performed on the Atlas Images with PSF profile-fitting, yielding a sensitivity of 15.8, 15.1, and 14.3 mag at 10σ level in J, H, and K_s bands, respectively. The astrometry was calibrated against the *Tycho*-2 Reference Catalog (Høg et al. 2000) and yielded an order of 100 mas accuracy for bright sources.

We selected a 3 × 3 deg^2 area from the 2MASS point-source catalog centered at M31 via the NASA/IPAC Infrared Science Archive, and retrieved 43,723 sources in this region. In addition, we also retrieved postage stamp images from IRSA to examine the sources.

3. SELECTION METHOD

We designed our selection algorithm based on the optical and infrared properties of known LBVs.

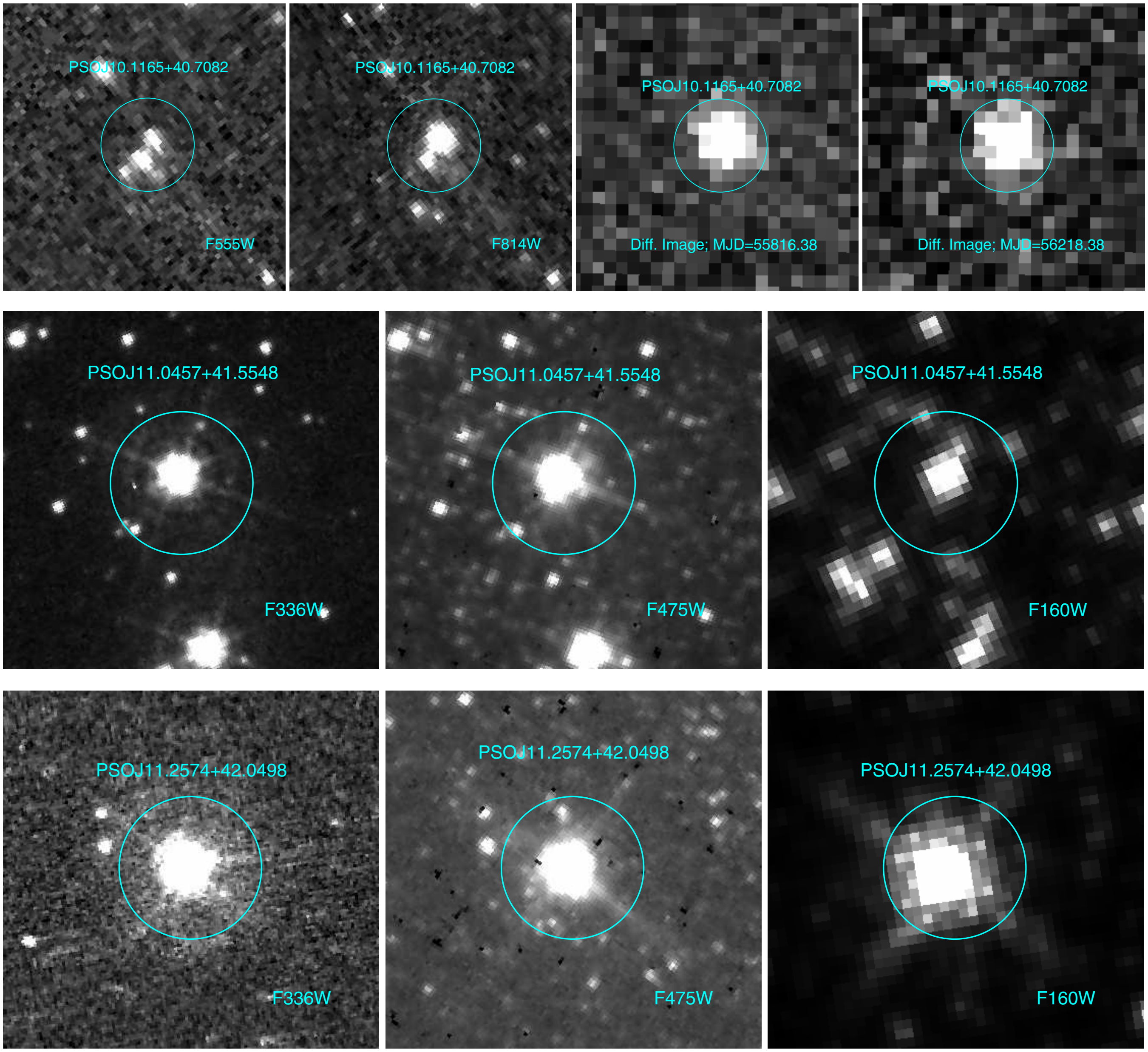

Figure 8. Postage stamps from the *HST* archive. Upper panel: *HST* images of PSOJ10.1165+40.7082 from the "Treasury Imaging of Star Forming Regions in the Local Group" program (Bianchi et al. 2012). Middle and lower panels: *HST* images of PSOJ11.0457+41.5548 and PSOJ11.2574+42.0498 from the "Panchromatic Hubble Andromeda Treasury" program (Dalcanton et al. 2012). The LBV candidates are indicated by the cyan circles, which have a radius of 1″. The observed passbands (F160W, F336W, F475W, F555W, and F814W) are also indicated in the lower corner of each stamp. All *HST* images are astrometrically aligned to the PAndromeda image using our own pipeline (M. Kodric et al. in preparation). The median positional difference between the LGGS catalog and the PAndromeda catalog is 0.″36.

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

The first criterion is the optical color. As can be seen in Figure 2, the known LBVs and LBV candidates presented by Massey et al. (2007) are rather blue in the $B-V$ versus V color–magnitude diagram (CMD). We thus set the criterion that $B-V < 0.5$ mag and V brighter than 20 mag to select for optically blue and luminous objects. This enables us to filter out possible contaminations from foreground stars and unresolved background galaxies.

The next criterion utilizes the optical variability from PAndromeda data. Since OB stars also show aperiodic variation at the <0.1 mag level, the so-called α Cyg variables (van Leeuwen et al. 1998), and since Clark et al. (2012) have accounted for a variation of $\leqslant 0.4$ in magnitude in their M33 LBV candidates by similar mechanism, we require light curve variations of >0.4 mag from $r_{\rm P1}$ to secure mid-term LBV variability. Relaxing this criterion might allow us to find more candidates. We will come to this point in Section 4.4. Occasionally there are a few data points that have large error bars that deviate from other observations. Such outlier measurements could render a light curve with $\Delta\,$mag > 0.4 and leads to false detection. To reduce the number of false detections, we thus require that at least 25 data points vary at the 10σ level with respect to the mean value from all the measurements in a single light curve.

The last criterion is set by the infrared color. Kraus et al. (2014) have indicated that B[e] supergiants (B[e]SGs) also show variabilities similar to LBVs, and pointed out that LBVs and B[e]SGs can be distinguished from the infrared colors as shown in a recent study by Oksala et al. (2013) using samples from

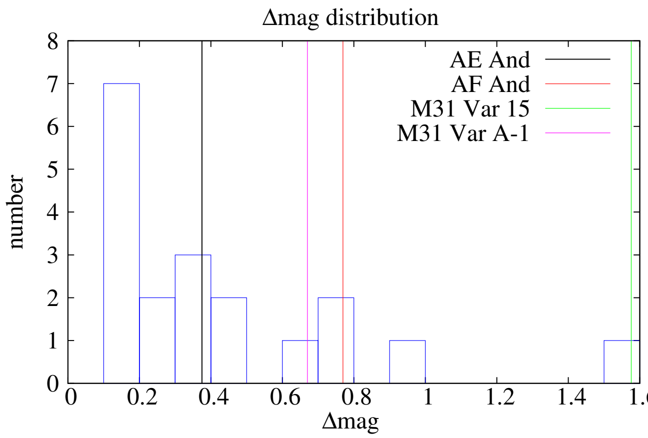

Figure 9. $\Delta\,\mathrm{mag}_{r_{P1}}$ distribution of variable sources passing our optical and infrared color criteria: we show the number of light curves that fulfill both the $H - K < 0.5$, $V < 20$, and $B - V < 0.5$ criteria. Seven light curves pass these criteria, and four of them are previously unknown. The rest of them are known LBVs. The vertical lines indicate the variability of known LBVs from Massey et al. (2006).

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

the Milky Way and Magellanic Clouds. We plot the sample of Oksala et al. (2013) in Figure 3, as well as the four known LBVs in M31. The M31 LBVs follow the distribution of Galactic LBVs; most of them have $H - K < 0.5$. We thus set an upper $H - K$ limit of 0.5 to select candidate LBVs.

There are seven sources that pass the aforementioned criteria. We inspect their light curves individually and select four as candidate LBVs. The remaining three sources are all known LBVs (AE And, M31 Var 15, and M31 Var A-1). The only known LBV that does not pass our selection criteria is AF And, due to its variability smaller than the 0.4 mag criterion (0.375) during the time span of PS1.

The number of stars that passed each criterion is listed in Table 1. There are in total four previously unknown sources that pass all of our criteria. Their optical and infrared photometry, as well as their spatial distribution and light curves, are shown in Table 2 and Figures 4 and 5, respectively.

We discuss these sources in the following section.

4. DISCUSSION

In this section, we examine the properties of our LBV candidates, investigate whether they are UV emitters, derive their ages from the massive star evolutionary model, and examine their *HST* images (if available).

4.1. Galaxy Evolution Explorer UV Detection

It has been suggested that LBVs can be revealed in the UV channel (Massey et al. 1996). We have plotted the positions of our candidates on the *GALEX* near-UV images (*GALEX* nearby galaxy atlas; Gil de Paz et al. 2007). As shown in Figure 6, all LBV candidates are aligned with bright UV sources, and they are located in the spiral arms of M31 (see Figure 4). For comparison, we also show close-up views of the known LBV and LBV candidates listed in Massey et al. (2007) in the Appendix.

4.2. Comparison with Isochrones

In order to see whether our candidates are consistent with the evolutionary model of massive stars, we compare the $B - V$ color and the V band magnitude of these four candidates with the latest Geneva evolutionary tracks (Ekström et al. 2012). As shown in Figure 7, our candidates are in good agreement with the Geneva models. In addition, from the evolutionary tracks, we are able to estimate their ages. As indicated by the models, their ages are of the order of 10^7 yr.

In Figure 7, we also indicate the possible variabilities of LBVs by drawing the photometric variations $\Delta\,\mathrm{mag}_{r_{P1}}$ seen from PAndromeda as an error bar. LBVs can also suffer from dust extinction from their circumstellar material. To take this into account, we apply a correction for the extinction effect on $B - V$ color using the extinction map by Montalto et al. (2009). By assuming $A_V/E(B-V) = 3.1$, we also correct the extinction effect on the V-band magnitude. Taking the extinction effect into consideration, the true $B - V$ value of our LBV candidates would be smaller. In this case, our LBV candidates would be blueward on the color–magnitude plot in Figure 7, which is still consistent with the evolutionary model of an age on the order of 10 Myr.

4.3. Hubble Space Telescope Observations

To confirm that our LBV candidates are stellar objects, we thus request M31 *HST* images from the Panchromatic Hubble Andromeda Treasury project (PHAT; Dalcanton et al. 2012). Since the PHAT survey only covers the northern disk of M31, we only find images for two of our LBV candidates, PSO J11.0457+41.5548 and PSOJ11.2574+42.0498. We show the *HST* Advanced Camera for Surveys images of them in Figure 8. With the exquisite spatial resolution of *HST*, we can see that the shape of PSO J11.0457+41.5548 and PSOJ11.2574+42.0498 traces the typical PSF in the field.

In addition to the PHAT archived images, we also found PSO J10.1165+40.7082 covered by the "Treasury Imaging of Star Forming Regions in the Local Group" program (Bianchi et al. 2012). The *HST* images of this candidate, astrometrically aligned to the PAndromeda data using our own pipeline (M. Kodric et al. in preparation), is shown in Figure 8 as well. *HST* resolved two sources within 1 arcsec of PSO J10.1165+40.7082. To distinguish the varying source, we examine the difference image from PAndromeda during maximum flux (at MJD = 55816.38 and 56218.38) and found that the brighter source in the F814W band is the varying source.

4.4. A Further Look at the Variability Criterion

In Figure 9, we plot the number of sources that pass our optical and infrared photometric criteria against the photometric variability from PS1 r_{P1}-band light curves. In total, there are seven sources showing $\Delta\,\mathrm{mag}_{r_{P1}} > 0.4$ mag, four of which we selected as possible LBV candidates. The remaining three are all known LBVs (AF And, M31 Var 15, and M31 Var A-1). In Figure 9, there are three additional sources that vary at the 0.3 mag level, which are AE And with $\Delta\,\mathrm{mag}_{r_{P1}} = 0.375$ and other variables with $\Delta\,\mathrm{mag}_{r_{P1}} = 0.339$ and 0.307. Even if we lowered the $\Delta\,\mathrm{mag}_{r_{P1}}$ criterion to the lowest value of known LBVs (0.375), we would only select AE And, but no additional new LBV candidates.

For comparison, we also show the r_{P1} light curves of the four known LBVs listed in Massey et al. (2007) in the Appendix.

5. SUMMARY AND OUTLOOK

We study the photometry of known M31 LBVs from Massey et al. (2007) and present a new approach to search for LBVs

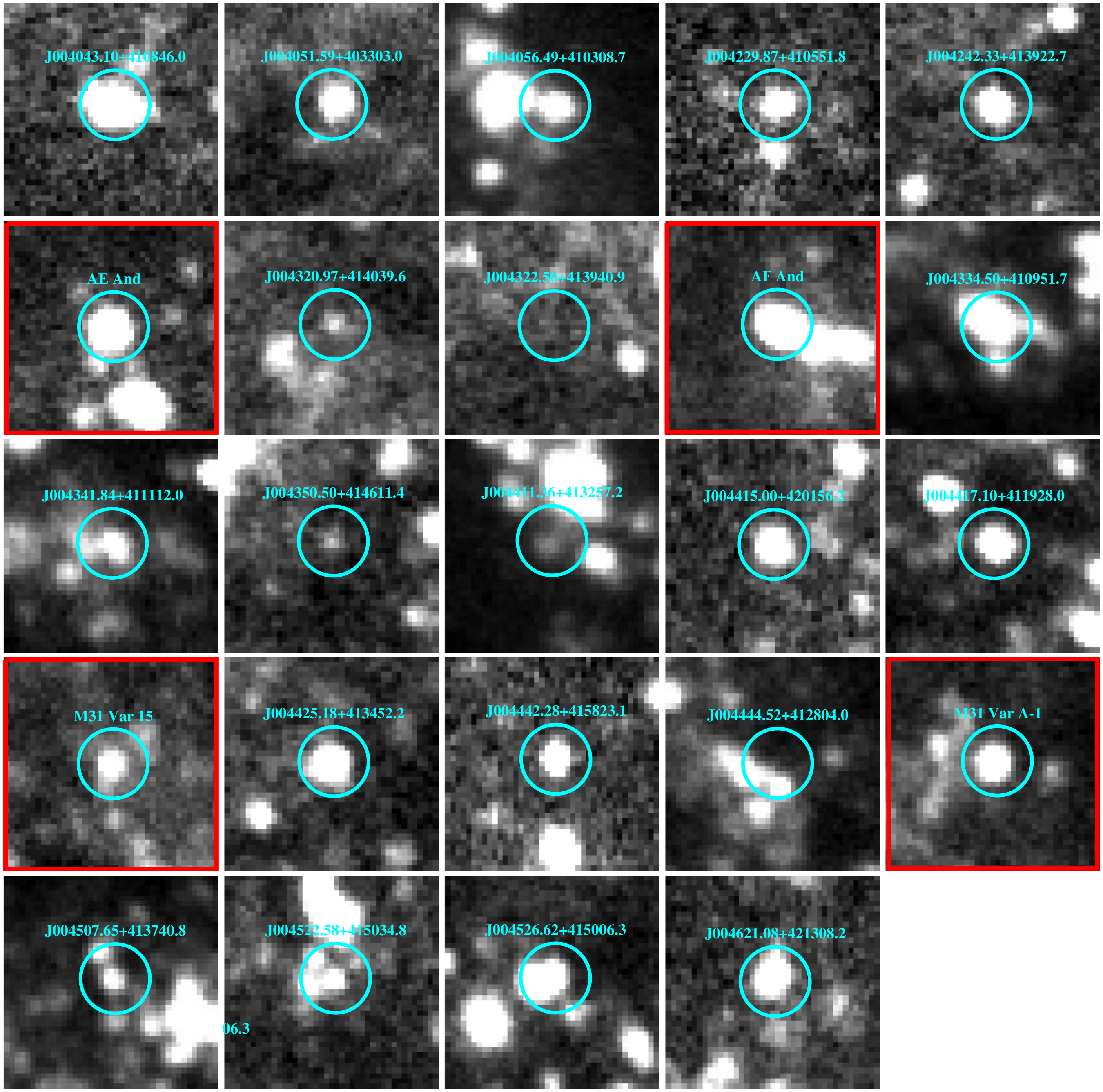

Figure 10. NUV postage stamps of the LBV and candidate LBV sample from Massey et al. (2007). The red squares outline the four known M31 LBVs. The images are taken from the *GALEX* Nearby Galaxy Atlas.

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

using optical and infrared information. We have selected four candidate LBVs sharing the same properties of known LBVs in terms of optical and infrared colors; they are also observed in the *GALEX* UV data and all of them are located within M31 spiral arms. Our sample exhibits photometric variation >0.4 mag as seen from the PAndromeda survey. These sources are in agreement with the stellar evolution model of the Geneva group, which gives an age between 10 and 100 Myr. This implies that while low mass stars are still in the early stage of evolution in the spiral arms, massive stars have already evolved into the LBV stage. Though the true nature of our sample awaits a spectroscopic confirmation, the bright UV emission, optical and infrared colors, photometric variability, and the *HST* image altogether indicate that our candidates are very likely LBVs.

We will request spectroscopic observation to confirm that our candidates are true LBVs, and classify them according to the taxonomy scheme outlined by Massey et al. (2007). In addition, it has been shown that LBVs can be surrounded by nebula with dust (Vamvatira-Nakou et al. 2013). Spectra in the mid-infrared will help us to probe dusts with colder temperatures; Waters et al. (1997) have used the short wavelength spectrometer on board *Infrared Space Observatory* to obtain mid-infrared spectra of several known LBVs and led to the discovery of cold circumstellar dust with a temperature about ∼50 K. Future space observatories such as the *SPICA* telescope (Nakagawa &

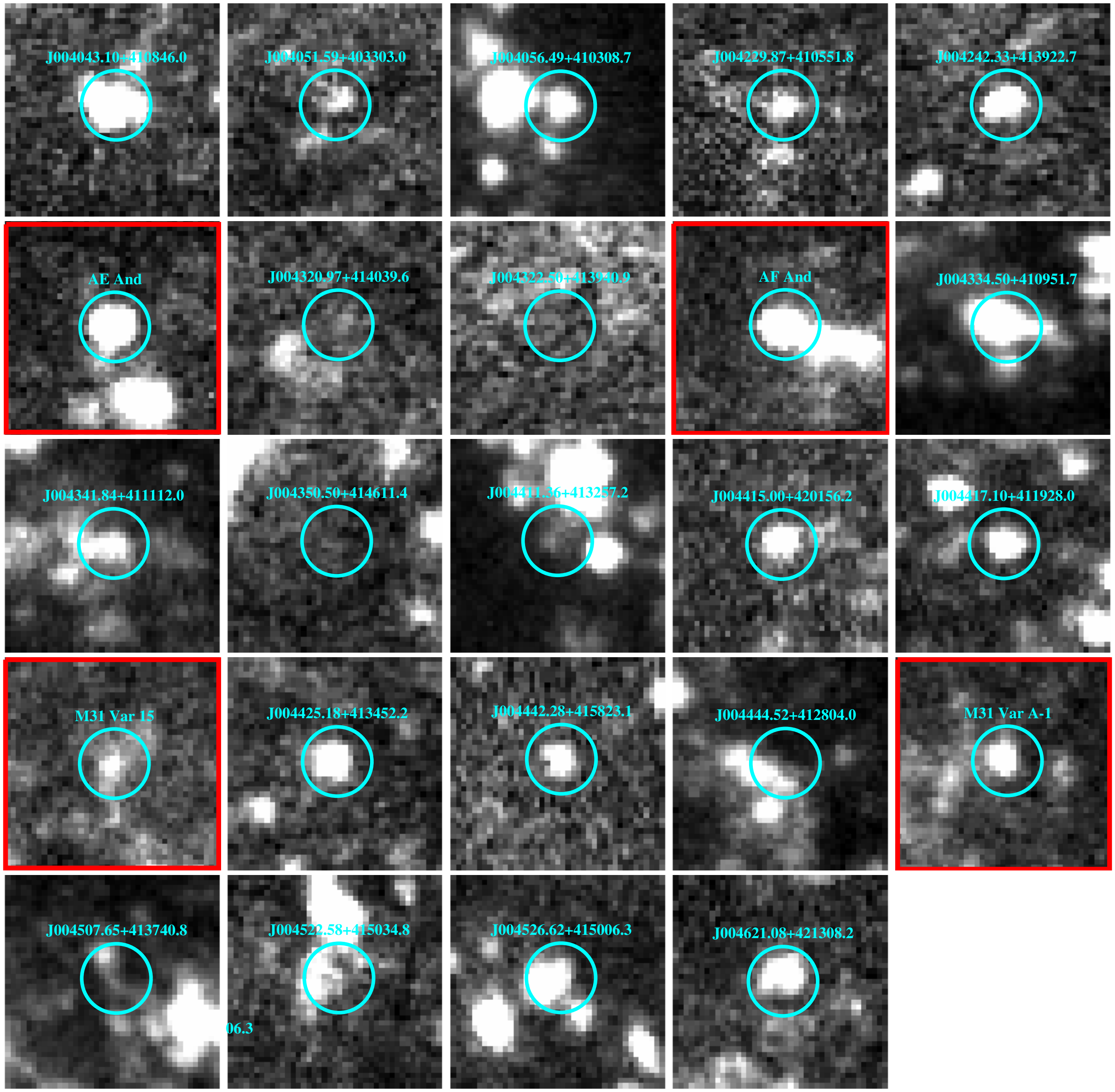

Figure 11. FUV postage stamps of the LBV and candidate LBV sample from Massey et al. (2007). The red squares outline the four known M31 LBVs. The images are taken from the *GALEX* Nearby Galaxy Atlas.

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SPICA Working Group 2001) will also provide spectra in the wavelength of mid-infrared.

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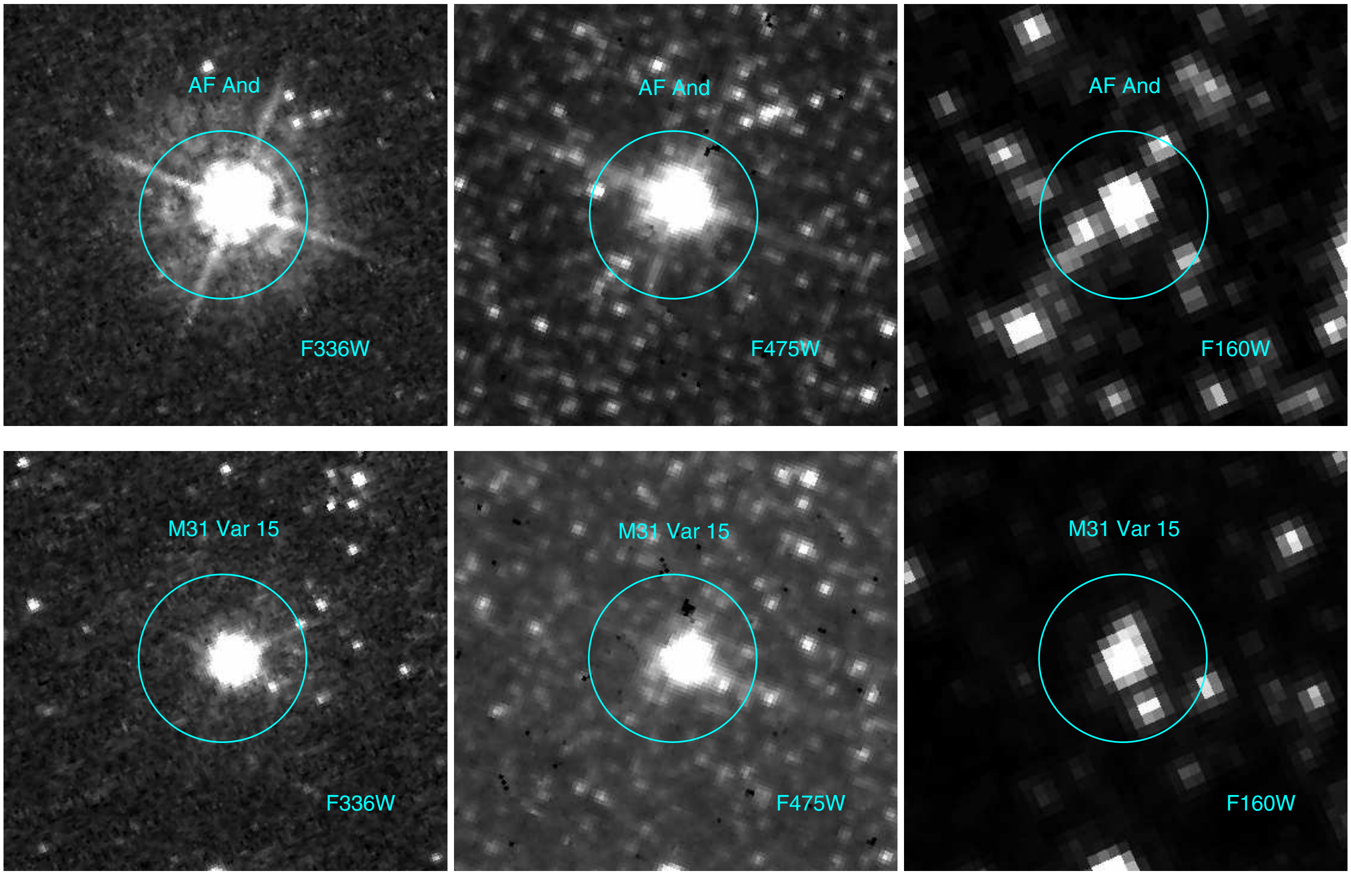

Figure 12. Postage stamps of the *HST* observations from Dalcanton et al. (2012). The upper and lower panels show the *HST* images of AF And and M31 Var 15, respectively. The LBVs are indicated by the cyan circles, which have a radius of 1″. The observed passbands (F160W, F336W, and F475W) are also indicated in the lower corner of each stamp.

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

Table 3
Properties of Known LBVs

Name	LGGS Nomenclature	V	$B-V$	Δm in r_{P1} (mag)
AE And	J004302.52+414912.4	17.426 ± 0.005	-0.153 ± 0.005	0.375055
AF And	J004333.09+411210.4	17.325 ± 0.004	0.013 ± 0.004	0.769598
M31 Var 15	J004419.43+412247.0	18.450 ± 0.004	-0.007 ± 0.004	1.575990
M31 Var A-1	J004450.54+413037.7	17.143 ± 0.004	0.211 ± 0.005	0.669998

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This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

APPENDIX

In this section, we present information of LBV and LBV candidates from Massey et al. (2006), as supporting material to show that our LBV candidates have similar properties to known LBVs.

In Table 3, we collect the V-band magnitude, the $B-V$ color, and the photometric variability in the r_{P1} light curve of four known LBVs in the Massey et al. (2007) sample.

A.1. *Galaxy Evolution Explorer UV Detection*

We collect UV images of known LBV and LBV candidates listed in Massey et al. (2007) and present in Figures 10 and 11. The images are taken at near- and far-UV (NUV and FUV) by *GALEX*. Most of the LBV and LBV candidates in Massey et al. (2007) are bright sources in the NUV, but some of them show faint or no FUV emission.

A.2. *Hubble Space Telescope Observations*

We search for *HST* archive images of the known LBVs listed in Massey et al. (2007) in the "Panchromatic Hubble Andromeda Treasury" program (Dalcanton et al. 2012), and found that two of

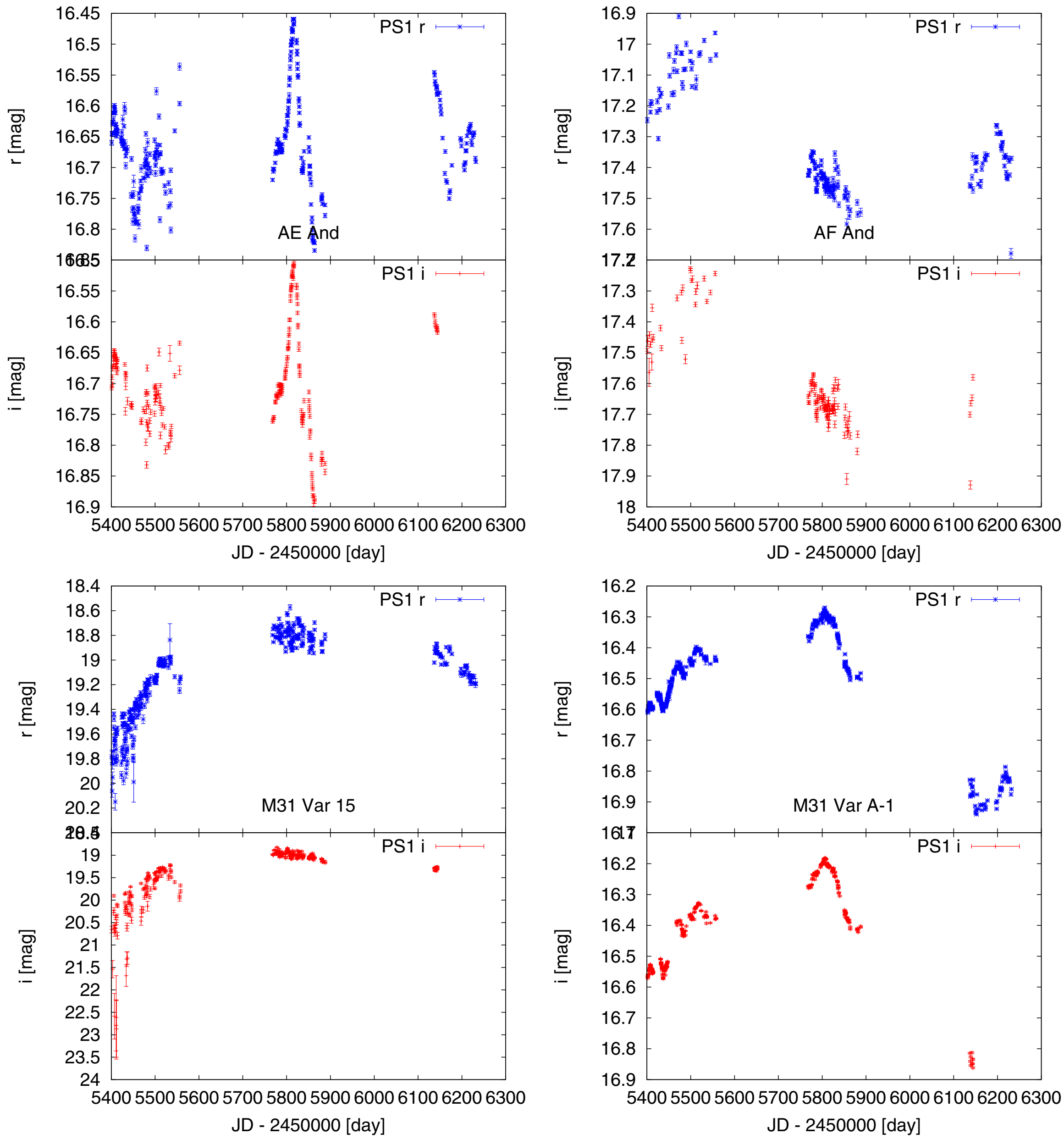

Figure 13. PS1 light curves of known LBVs from Massey et al. (2007).
(A color version of this figure is available in the online journal.)

the known LBVs (AF And and M31 Var 15) have been observed by this program. Their images are shown in Figure 12.

A.3. Light Curves from PS1 Data

We show the light curves of four known LBVs from Massey et al. (2007) in Figure 13. The light curves are from our PS1 3 yr data. The photometric variation during the 3 yr time span are listed in Table 3.

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