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DETECTION OF UNIVERSALITY OF DARK MATTER PROFILE FROM SUBARU WEAK LENSING MEASUREMENTS OF 50 MASSIVE CLUSTERS

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ABSTRACT

TBD

1. INTRODUCTION

2. PROPERTIES OF SECURE CANDIDATES

2.1. *Properties of secure candidates*

In this section we discuss properties of secure candidates whose light curve has a typical transient feature (flash, contiguous variation, etc.), as shown in the left panel of Fig. **??**. Our classification of different types of time-variable stars is based on our eye-ball checks of their light curves. We found 11,462 secure candidates.

To study color of each secure candidate we used the g-band data of M31 that was taken in the engineering run on June 16, 2013, in addition to our r-band data. The g-band data have a seeing size of about $0.6''$, consist of 10 exposures, and have 750 seconds in total ($120 \times 5 + 30 \times 5$). We made the coadd images of the g-band data. We used Kurucz (1993) to model the stellar color taking into account the HSC filter responses we used.

In the following, we summarize properties of each type of time-variable candidates. The typical light curve for each type is shown in Fig. **??**, and the light curves for individual promising candidates are given in Appendix 2.3.

- Eclipsing binary
  This type of candidates display a light curve with eclipse dip, during a given duration, and then such a transient feature repeats with a given period. We classify these kinds of candidates as an eclipse binary of stars, where two stars are rotating around each other and either of the two stars causes an eclipse on another star, leading a dip in the light curve of their total flux. The depth of ellipse, time duration and period are different from candidate to candidate. All the candidates seem to be M-type stars based on their *g-r* colors. The candidates are described in Fig. **??**.

- Binary stars
  For candidates that have pulsating light curves, we classify those as candidates of binary stars. If the two amplitudes of light curve within one period are similar, the stars have almost same mass and size stars. Their *g-r* colors indicate that almost all binary systems are M-type stars. About 10 systems have a period shorter than our observation duration (about 7 hours), and the shortest period is about 1.2 hours. These short period binary systems would be a contact binary system, where the two stars share the common envelope. These binary systems we found are shown in Fig. **??**.

- Cepheid variable stars
  For candidates whose light curves display a rising or declining curve over 7 hours with about 0.1-1 magnitude change, we classify those as Cepheid variable star candidates. Most Cepheid candidates are found along the disk region of M31, and the distribution seems to match the distribution of classical δ Cep variable stars found by PAndromeda project (Kodric et al. 2013). Due to the limited time observation, we can't measure an entire period of the light curve, so can't determine the period of each candidate. Their g-r colors indicate that most candidates are A- or F-type stars. Fig. **??** show the Cepheid candidates.

- Stellar flare
  For the candidates whose light curve shows a sudden magnification in brightness, followed by an almost exponential decay, we classify the candidates as a stellar flare. The magnification is typically 1 mag, but one candidate shows almost more than 2 magnitude magnification. Their g-r colors indicate that most candidates are M-type stars. Hence, these flare stars are likely to be in the MW halo region. Prominent star flare is a well-known phenomena for a M-type star, and originates from a reconnection of the magnetic field in the atmosphere as observed in the Sun. We didn't find a flare candidate for G-type star. This is consistent with the previous work, which shows that M-stars have more frequent flare events because energetics in the atmosphere is more affected by their magnetic field compared to G-type stars (Moffett 1974; Lacy et al. 1976; Henry & Newsom 1996).

- Moving objects: asteroids in the Solar system
  These candidates are main confusion to microlensing search. These candidates display a Gaussian-shape curve at the fixed WCS position. However, after more careful look of these candidates, we found that these candidates are moving objects: point-source images in the time-sequential difference images display a clear trail in the postage-stamp image region. Hence, we consider these candidates as asteroids or comets in the Solar system. We have so far found two promising candidates of asteroids.

- Fake candidates near to the edge of CCD chip
  We sometime found fake candidates that are around pixels within a few pixels from CCD chip edge. These are electrostatic effects near the edge of CCDs (a few pixels for our Hamamatsu CCDs) which means that the photometry is incorrect. This magnification feature

is unique property for shot-period sampling: from the same test as discussed in § 2.1, we found that candidates from longer sampling selection are not sensitive to this incorrect photometry. One example is displayed in Appendix 2.2.

- Artificial candidates due to imperfect photometry correlated with seeing size
These are fake candidates whose light curve is as shown in Fig. **??**. Even if we identify a candidate from a PSF-like source in the difference image and then make the photometry to measure the light curve from the time-sequential difference images, the resulting light curves has a similar shape or correlation with seeing size. Hence, we conclude that this is due to an imperfect subtraction of the reference image from the target image due to the imperfect PSF measurement. Hence, we think that the light curve has a correlation with the seeing size. In particular, the exposures around ~ 3500 and $\sim 14,000$ sec have a bad seeing ($\sim 1.0''$), and the light curve shows a feature (e.g. bump or dip) around the particular epochs. When a CCD pixel has a defect, it sometimes causes an artificial image in the difference image. Furthermore, we sometime found artificial candidates in the vicinity of a bright star due to the imperfect image subtraction. After checking these images by visual inspection, we identify these fake objects. Some examples are shown in Appendix 2.2.

- Candidates whose light curve peaks at the best-seeing epochs
1,000 candidates have a similar light curve which peaks at the best-seeing epochs. The exposures of best-seeing conditions are deepest, and the PSF photometry at the candidate position has least contamination from the surrounding stars. Most candidates have a peak magnitude of $r \sim 24.5$ - 25, and the distribution of these candidates is across the halo region of M31. If these candidates are RR-Lyrae variable stars, which have an absolute magnitude of $r \sim 1$mag, the apparent magnitude is consistent with the hypothesis that the RR-Lyrae stars are in 750 kpc distance, which is the distance to M31. However, selection from color criteria of the Solar spectral models suggests that many of them are M-type or K-type stars, which is inconstant with empirical law that RR-Lyrae variables tend to be A-type or F-type stars. Still there are more than 100 candidates of A-type or F-type candidates. Note that currently we cannot distinguish these candidates from fake candidates (see the detail in § 2.1).

Following the above study we also get some indication of event properties as follows:

(1) Frequency of time variables for each type of variable stars
Our observation has unique property that many light curves has a peak ~ 11000sec, around the best seeing period as displayed in Fig. **??**. To see if these peaks are real, we imposed another detection conditions as following § **??**: first separate all images into even-odd groups using serial numbers. For each group we conducted the same detection tests as mentioned before; imposing selection conditions to the each stacked images that are composed of five time-sequential images. The final time-variable candidates are constructed from those which passed the conditions more than twice. Therefore we construct two sets of candidates which can imply for the variable stars with timescale longer than 20 minutes.

We compared the two results of even-odd tests with the candidates of 10 minutes cadence, derived from § **??**. The candidates are be classified into three groups by the detection frequency and property: the first group including those detected in both even-odd cases, the second corresponding to those detected either in even-odd criteria, and the third constructed by those detected in only in previous analysis. The first group includes candidates that are feasible, most of which contain smooth curve or bumps; characteristics often seen in Cepheid stars or binary stars. Also the candidates categorized in the third group are likely to be fakes because many of them have noisy behavior or log-flux peaks. The unique event with peaks around the best seeing are contained in all three group sets, with almost the distribution for three cases. The same is true for events with sub-peaks correlated with the variation of seeing. Although we cannot get clear implications for the seeing-correlated events, this sampling rate test can work as a way to remove fake candidates.

(2) Color and magnitude property
Color and magnitude are important rulers to measure the stellar property. In this study we classify the time-variable candidates with these properties. Fig. **??** shows the results. Color selection suggest that many variable candidates have colors corresponding to low temperature stars, with similar distribution as suggested by faint star distribution. Also, most of stars in M31 disk have similar color or magnitude properties with g-$r \sim 0$.

2.2. *Effects from non-celestial moving bodies*

Short-cadence transient survey can be suffered from non-celestial causes from telescope or CCD properties. In this section we summarize the possible properties suggested from our results.

- Defraction spikes
There are around 80 events with some sharp peaks in the light curves, which are not correlated with the time-variation of seeing. For these events many spiky patterns show up as in Fig. **??**, especially around nearby bright stars. These spikes are artificial noise of telescope, caused by the change of the targeting direction in the sky. The patterns turn clockwise around a star as the observation goes on, and magnify the surrounding stars when the spikes pass by.

- CCD edge
In this HSC-M31 study we fixed the observational field of view by automatic tracking system of the telescope so as to reduce the coordinate uncertainty in image difference technique. However, there exists small movement due to the uncertainty of the tracking system as displayed in the lower left panel of Fig. **??**. Therefore electrostatic effects near the edge of CCDs (a few pixels for our Hamamatsu CCDs) cause incorrect photometry, which induces magnification of flux for nearby objects as in the upper left panel. Around a few hundred stars

close to CCD edges are detected as candidates in our observation.

- CCD defect
  There also exist around 30 cases where small defected parts of CCD are detected as transient candidates. As CCD defects cannot give correct flux measurement, they sometimes produces small bright region in difference images, which are detected as time-variant candidates.

2.3. *Characteristics of unique events*

In this section we describe some detailed properties of unique candidates.

2.3.1. *Eclipsing binary stars: white - brown dwarf system*

Among the eclipsing binaries we found a unique candidate; as shown in Fig, **??**, one dark star totally hide the other star so that the flux becomes totally dark. This system is considered to be composed by a white dwarf and a brown dwarf.

2.3.2. *A star before nova*

A red nova was found on February 2015, about three months after our observation. Therefore the candidate might be at the stage of merging of two stars. Fig. **??** shows the light curve and image of the target star, at 00h 42m 07.99s +40d 55m 01.1s in radec coordinate which is close to M31 bulge. This object is not detected with our selection criteria probably due to small change of flux. The magnification is only 0.02 mag during our observation, which is so small that we cannot say clearly if this is true.

2.3.3. *Appearing star or disappearing star*

There are around 10 stars which suddenly appear or disappear during observation without the effect from CCD edge. We could not find out the reason so far, but many of them reside close to the bulge region.

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