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THE M33 SYNOPTIC STELLAR SURVEY. II. MIRA VARIABLES

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ABSTRACT

We have applied the newly developed semi-parametric periodogrom (Citation Coming Soon) on M33 optical observation to search for Miras. We developed M33 data specific models to calculate the probabilities of being Mira for all possible targets. The training data set was constructed by simulating the M33 Mira light curves with known periods and non-Mira light curves in order to train our models. We found XXX Mira candiates, with a XX% discovery rate and XX% purity, which are estimated from the training data set. We tentatively classified the Oxygen-rich and Carbon-rich Miras and give their Period-Luminosity relations.

1. INTRODUCTION

Mira variable stars (Miras) belong to one type of long period variables which is commonly, and empirically, defined as periodic variables with V-band varition greater than 2.5 mag. The pulsating periods of Miras typically range from 100 days to 700 days, but extreme cases can reach beyond 1500 days. They are involved medium or low mass stars at the asymptotic giant branch (Feast 2009).

Thousands of Miras have been identified in the directions of the Milky Way bulge and Magellanic Clouds by the Optical Gravitational Lensing Experiment [Udalski et al. (1992); hereafter OGLE] and MACHO project (Alcock et al. 1993). The Mira light curves obtained by these projects are usually charactered by long time span, full phase coverage, and hundreds of epochs. The Mira light curves are not strictly periodic, but show long-term variations in the mean magnitude and cycle-to-cycle variations. The curve shape for different Miras also varies. Some examples of the light curve variation were described in Huemmerich & Bernhard (2012).

The Mira Period-Luminosity relation (P-L relation) was initially suggested by Gerasimovic (1928). Recent sudies (Glass & Evans 2003) have shown this relation exhibits small scatter at K ($\sigma\sim0.13$ mag), which can be used as distance indicator. The near-infrared Mira P-L relations in Large Magellanic Cloud (LMC), Small Magellanic Cloud, and the Galactic bulge have been explored by Soszyński et al. (2009), Soszyński et al. (2011), and Soszyński et al. (2013) respectively. However, extragalactic Mira P-L relations have not yet been calibrated. Bloom (2013) have proposed a dedicated Mira search in megamaser galaxy NGC 4258 to obtain the infrared Mira P-L relations. In the near future, the LSST project will cover dozens of nearby galaxies where Mira P-L relations can be obtained (LSST Science Collaboration et al. 2009).

In this paper, we conducted a Mira search in M33 using the DIRECT and its follow-up observations [Kaluzny et al. (1998); Pellerin & Macri (2011); hereafter M33 observations]. Although the observational baseline is up to nine years, the number of observations and data quality are significantly lower than those of the OGLE and MACHO projects. At low cadence, the non-periodic variation components of the Mira light curves obstruct period detection. To address this problem, we adopted a semi-parameteric periodogram (Citation Coming Soon) to search for Miras and their periods. This periodogram, which is designed for low-cadence Mira observations, has a Gaussian process component to account for the deviations from exact periodicity, and gives better performances than Lomb-Scargle (Lomb 1976; Scargle 1982) periodogram for M33 observations.

To help identify Miras among other type of stars, we carried out a comprehensive simulation and built classification models using machine learning methods. We extracted XXX features from simulated light curves and their frequency spectra to train the models, then applied the models on the M33 observations to classify Miras. We obtained XXX Mira candidates in M33 with a XX% misclassification rate.

This paper is organized as follows. Section 2 introduces the observations of M33. In Section 3 we report the methods of simulating M33 observations with prior knowledge of light curve classes and periods if they are Miras. Section 4 describes the models which were used to identify Miras and estimate their periods. Section 5 gives the results on real M33 observations.

2. OBSERVATIONS AND PHOTOMETRY OF M33

The detailed descriptions of observations and photometry procedures can be found in the first paper of the series (Pellerin & Macri 2011). Here we briefly summarize them.

Almost the entire disk of M33, which spans approximately half square degree in the sky (Roberts 1895), was observed by the DIRECT project and follow-up observations. The original DIRECT project used the Fred L. Whipple Observatory 1.2m telescope and the Michigan-Darmouth-MIT 1.3m telescope to observe M33 during 1996 September to 1999 Novemeber. Addtional observations was obtained at the Wisconsin-Indiana-Yale-NOAO Observatory 3.5m telescope between 2002 August to 2006 August. In this paper we refer them collectively as M33 observations. We only used the I-band data to search for Miras. The number of I-band observations for individual objects is shown in Figure 1. It is common that there is more than one observations in one night, and as a result the median number of nights with observations

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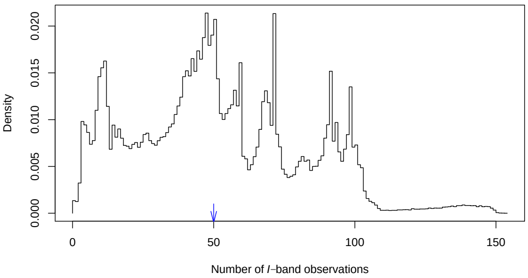

FIG. 1.— The distribution of number of I-band observations for the objects in M33. Objects without detection in certain frames do not count as observations. The blue arrow indicates the median number of observations.

is around 30. The observations consists of 29 fields, and different fields have different distributions of number of observations.

We used the photometry products from Pellerin & Macri (2011). They performed PSF photometry using the DAOPHOT, ALLSTAR, and ALLFRAME (Stetson 1987, 1994), and carried out photometric calibration based on Massey et al. (2006). We used the I-band light curves with Stetson's variability index $J > 0.75$ (Stetson 1996).

3. SIMULATION OF M33 OBSERVATIONS

1. lmc mira to M33
2. constant + gaussian noise from sigma-mag relation
3. constant + under-estimated gaussian noise
4. constant + gaussian noise from sigma-mag relation + few obnormal

points (bad pixels, cosmic rays, blending, numeric failure, mismatch, image boundary)

5. eclipsing, nova, SRV, irregular variable

4. MODELS

$1 - 5 lightcurves - - > Stetson's J > 0.75 - - > Simulateddataset$

Apply GP on simulated data set

4.1. *model 1*

Regression (ridge, lasso ?)

4.2. *model 2*

Beyes, cart, svm?

4.3. *model 3*

Deep learning?

5. RESULTS

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