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Search for Microlensing Events Towards M31 Galaxy

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Abstract. M31, the prominent galaxy of the Local Group, is located at a distance of about 700 kpc. Due to its convenient orientation, it is an alluring target for gravitational microlensing to search for massive astrophysical compact halo objects (MACHOs), in both the Galactic halo and its own halo. We have carried out the observations of the suburb of M31 galaxy using the 104-cm Sampurnanand Telescope of the State Observatory, Naini Tal, India. The observations have been accumulated for about hundred nights spanning over 800 days during 1998-2001. After the initial tests and preliminary analysis of the first two years data we have detected some possible M31 Cepheid variables of period between 10 to 85 days. Also using pixel method we have got an irregular variable and further analysis is in progress to detect the lensing events in the observed region.

Keywords : Galaxy: halo – cosmology: gravitational microlensing – galaxies: M31 – pixel technique: variable star

1. Introduction

Identification of dark matter in the Universe is one of the important problems in Physics as well as Cosmology, towards which a considerable amount of effort has been directed in recent years. A number of candidates, both baryonic (light mass ($10^{-7} M_\odot$) objects like brown dwarfs to massive ($\sim 10^6 M_\odot$) black holes) and non-baryonic ($\sim eV$ neutrinos to Weakly Interacting Massive Particles) have been proposed as candidates for dark matter. Paczynski (1986) proposed the implications of gravitational lensing in the search for dark matter, in which the flux of a star temporarily enhances in a characteristic way when a foreground compact object like brown dwarf passes close to its line of sight. To detect such a lensing event, a large number of stars have to be observed for a long time as the probability of the event is usually low of the order of 10^{-6}. Such observations therefore could not be carried out till a decade ago. Development of high speed, large area charged-coupled devices (CCDs) as an astronomical detector in recent years has provided a boost to this area of research as it could cover several tens of arcmin^2 of the sky with an advantage of observing stars much fainter than photomultiplier or photographic plates with a given size of telescope. In fact small and moderate size optical telescopes coupled with the CCDs have started playing major role in gravitational microlens monitoring projects (cf. Sagar 2000). As the size of the CCD detector has grown up by a multiplicative factor ($8K \times 8K$), it is possible to cover millions of stars at a time which clearly enhances detection capability of lensing events in the other galaxies apart from our own Milky Way. A pioneering result is already accomplished towards Magellanic Clouds by MACHO (Alcock et al. 1993) and EROS (Aubourg et al. 1993), towards the Galactic bulge by MACHO, OGLE (Udalski et al. 1993) and DUO (Alard et al. 1995). More than 500 lensing events having duration between 10 days to 100 days have been detected to date by various observing groups (MACHO $\sim$ 325, OGLE $\sim$ 175, EROS $\sim$ 10, DUO $\sim$ 13), mostly towards the bulge of our galaxy.

However, in other galaxies like Andromeda where not many stars can be resolved and monitored, the conventional observations cannot be used to recognize a lensing event. Different techniques have been developed and are being used by some groups to alleviate the problem. We have also initiated the search for the lensing event in M31 galaxy at State Observatory Naini Tal, India, where we have used the pixel technique initially proposed by Andromeda Gravitational Amplification Experiment (AGAPE) group (Bailon et al. 1993). We hope to implement the project in the following steps, with the observations and data analysis strategy depending on one another.

i) To verify that phase is maintained between variations of first and subsequent years. We test this using the bright variable stars.

ii) To test the accuracy of the photometric calibrations and confirmation that pixel variations can be dependably extracted from our observations. We shall try to extract both pixel microlensing events and pixel variable stars at this stage of the project.

iii) To prepare a catalogue of pixel variable stars and use the data to estimate the efficiency of our detections at various period ranges, amplitudes and absolute magnitudes. At this stage we will be in a position to compute the optical depth and other parameters of the microlensing events towards M31.

The present paper is a preliminary report of our efforts on gravitational lens monitor during the 1998 and 1999 seasons. Here we show that indeed phase of variable stars is maintained between the years. We also demonstrate the expected variations in the amplitude due to errors in photometric calibrations. In the next section, we summarize the importance of Andromeda galaxy as a target for gravitational lensing. Present observations and its global relevance along with the variability of the resolved stars present in our field are described in the remaining sections of the paper.

2. M31: A Unique Venue for Gravitational Lensing

To search the lensing events beyond the directions of the Galactic bulge and Magellanic clouds, M31 provides a unique laboratory for many reasons. The direction of M31 is complementary to the Magellanic clouds and Galactic bulge observed so far, which gives an opportunity to detect MACHOs in other part of the Galactic halo. It provides thousand times more sources than available towards the LMC, SMC and the Galactic bulge which increases probability of lensing events. Due to the position of M31 in the sky, it is possible to probe its halo at various lines of sights. M31 is also roughly 15 times far away than the Magellanic clouds, so due to smaller angular size of stars in M31, such a search is sensitive to much lower mass limit for MACHOs in galactic halo (Crotts 1992). The 77° inclination of the M31 galaxy along the line of sight provides near-far asymmetry and hence more MACHOs pass in front of its far-off disk as we probe a larger area of the M31 halo in that direction. Therefore the probability of lensing events due to MACHOs in M31 halo in the direction of far-off disk will be higher. Though the number of possible lensing events is certainly enhanced by large number of sources in the field of view against M31, only highly magnified lensing events or those with very bright sources are actually detectable against such a bright background, thus reducing the number of events that are picked up.

When the observations are carried out towards the M31, events may be produced by MACHOs of both in Galactic halo as well as in the M31. Galactic and M31 halo events have almost similar parameters like same masses and similar transverse speeds. Also the equivalence between observer-lens distance for Galactic halo with lens-source distance for M31 halo and vice versa, the two population events have similar time scales and Einstein ring radius. Various methods have been proposed to separate Galactic halo/M31 halo events. Parallax method (Gould 1994b) and proper motion of MACHOs (Gould 1994a, Han & Gould 1996) can be used to separate the Galactic halo events from the M31 halo events. Han & Gould (1996) proposed that $\sim 10-15\%$ of the total events in the direction of M31 bulge are caused by Galactic halo MACHO assuming an all MACHO halo.

3. Initiatives to Detect MACHOs in M31 at Naini Tal

Since number of lensing events have already been discovered towards Galactic bulge and Magellanic clouds, there are only a few lensing events which are detected towards the Andromeda galaxy because of poor sampling of resolved stars in M31 galaxy. Therefore pixel lensing technique was adopted to detect lensing towards the M31 galaxy. In recent times various collaborative programs particularly Columbia-VATT collaboration (Tomaney & Crotts 1996) on MDM 1.3-m and Vatican Advanced Technology 1.8-m telescope, AGAPE (Bailon et al. 1993, Ansari et al. 1997) on 2-m Bernard Lyot Telescope of the Pic du Midi Observatory, POINT-AGAPE (Kerins 2000, Kerins et al. 2001) employing the Isaac Newton 2.5-m Telescope and Microlensing Exploration of the Galaxy and Andromeda (MEGA), a successor of Columbia-VATT collaboration at MDM observatory (Crotts et al. 2000) have started pixel lensing surveys towards M31. A numbers of candidate lensing events were reported by these groups but only a few of them have been confirmed so far as a longer time baseline of observations need to ascertain their confirmity.

The detection of MACHOs in M31 galaxy requires observations of the M31 for a short time each night but over a long period of time. Considering its importance, we started CCD observations of a target field ($\alpha_{2000} = 0^h43^m24^s$ and $\delta_{2000} = 41°11'.4$) located at a radial distance of $\sim$ 11 arcmin from the center of M31 galaxy in October 1998 at the f/13 Cassegrain focus of 104-cm Sampurnanand telescope. The target field is shown in Fig. 1 with MDM field overlapping on the figure of M31 galaxy. We monitor the target field from October to January each year and have secured observations for about sixty nights during first two years (see Table 1). Observations were only performed when M31 was higher than 35^0 above the horizon to reduce air-mass effect.

Table 1. Summary of CCD observations taken in unbinned mode. Exposure time for all the frames is 20 minute.

Observing season	size of CCD	Field arc min^2	Filter	No. of frames per night	Total nights in the season
1998-1999	$1K \times 1K$	$\sim 6 \times 6$	R	3	28
			I	3	26
1999-2000	$2K \times 2K$	$\sim 13 \times 13$	R	2	34
			I	3	21

During the observing run 1998-1999, the observations were carried out using a Tektronics chip containing 1024×1024 pixels^2. Each pixel corresponds to 0.37×0.37 arcsec^2 and entire CCD system covers a field of view $\sim 6 \times 6$ arcmin^2. The gain of the camera was 2.96 e^{-1}/ADU and read out noise of 4.1 e^{-1}. During 1999-2000, the observations were carried out with another larger size CCD chip having 2048×2048 pixels^2. Each pixel of this CCD also corresponds to 0.37×0.37 arcsec^2 but covers a larger field of view of $\sim 13 \times 13$ arcmin^2. The gain and read out noise of the new CCD are 10 e^{-1}/ADU and 5.3 e^{-1} respectively.

As most of the possible lensing sources in the direction of observation are luminous red stars i.e. giant and supergiants, we have taken observations in the Cousins R and I filters which are sensitive to these type of stars. Observations in two different colours would help us to discriminate the lensing events from the variable stars. To reduce the cosmic rays, short exposure images were taken and these were averaged to get high signal

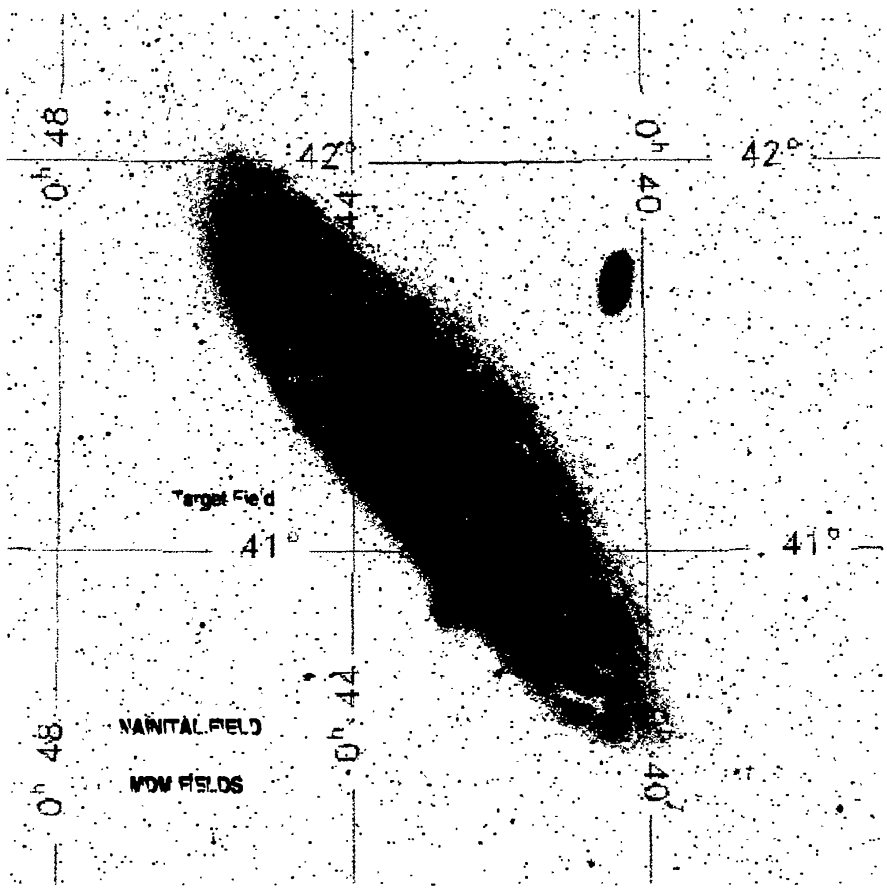

Figure 1. Field of observation juxtaposed over M31 Galaxy. The field denoted by smaller rectangular box is $\sim 6 \times 6$ arcmin^2 NTL field and is well outside the $\sim 17 \times 17$ arcmin^2 MDM field.

to noise ratio. The log of the observations is given in Table 1. The twilight flat field and bias frames were also taken frequently.

3.1 Data Reduction: Pixel Method

The essential idea of pixel lensing is as follows: We image a specified region of the target galaxy onto same pixels of the CCD camera during the observations. After taking into account the fluctuations due to variable night sky background and effects due to seeing fluctuations, the photon counts in any pixel will show variation either due to intrinsic variability of stars in the target galaxy or transient events like lensing. Consequently, comparision of the normalised pixels in two wavebands can be used to detect possible microlens event, even though the lensed star cannot be resolved under normal circumstances.

Standard technique have been used for pre-processing the CCD data at the State Observatory, Naini Tal using MIDAS software package. Since most of the stars of M31 are not resolved, we have to use the pixel technique to search for any variability in our target field. Various steps involved in this technique are discussed below.

3.1.1 *Geometric Alignment*

A particular pixel of the CCD does not cover the same part of the sky in different nights therefore we have to correct the images of all the nights with respect to a reference image. This correction is called geometric alignment. For this purpose, we selected an image of good observing night as a reference and based on a few resolved faint stars, calculated linear transformation in two dimensions for all other images with respect to the reference image using MIDAS and corrected the images for any translational and rotational changes between the i_{th} and reference image.

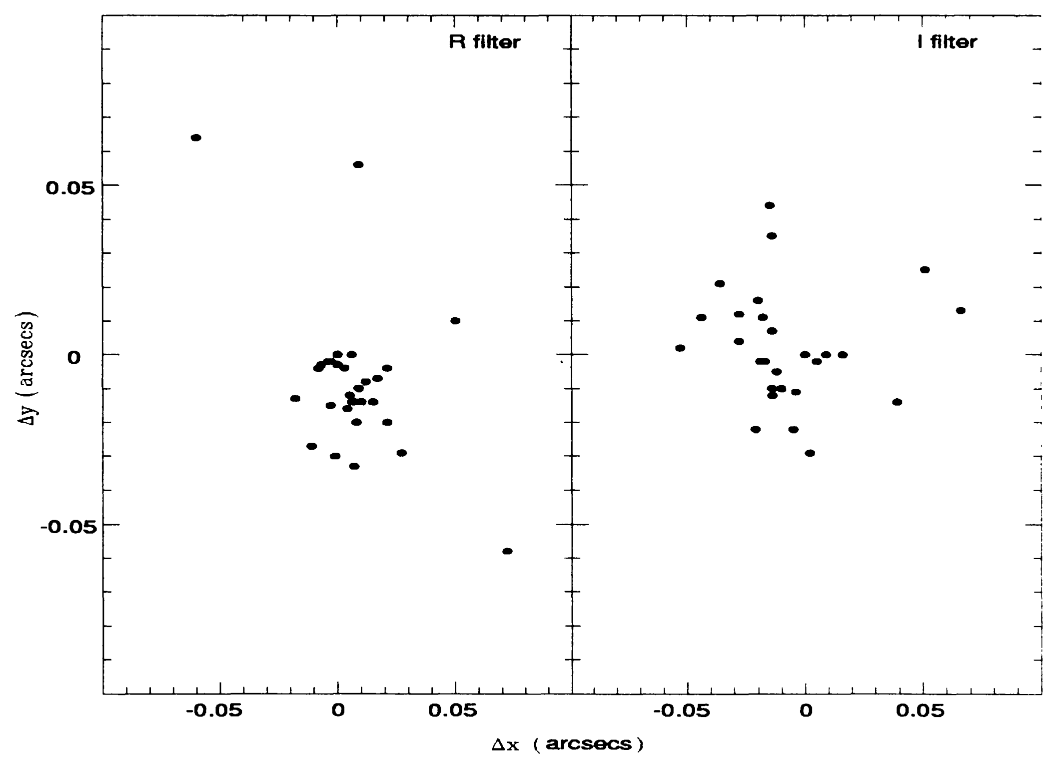

Figure 2. Dispersion of a pixel after geometric alignment. Δ x and Δ y are change in x and y coordinate respectively.

Fig. 2 shows the dispersion of the positions of the star (322,124) after the geometric alignment which clearly indicates that a high degree of precision (better than ±0.1 arcsec) has been achieved on the geometric alignment. After geometric alignment, we selected an area from $2K \times 2K$ CCD observations corresponding to the area covered by the $1K \times 1K$ image of the 1998-99 observing run. Further analysis was carried out only for this $\sim 6 \times 6$ arcmin^2 area.

The photometric conditions, namely atmospheric absorption, sky background light and seeing are never the same for different nights. We therefore further corrected the images of each night for these variations. The process in detail will be described in forthcoming paper.

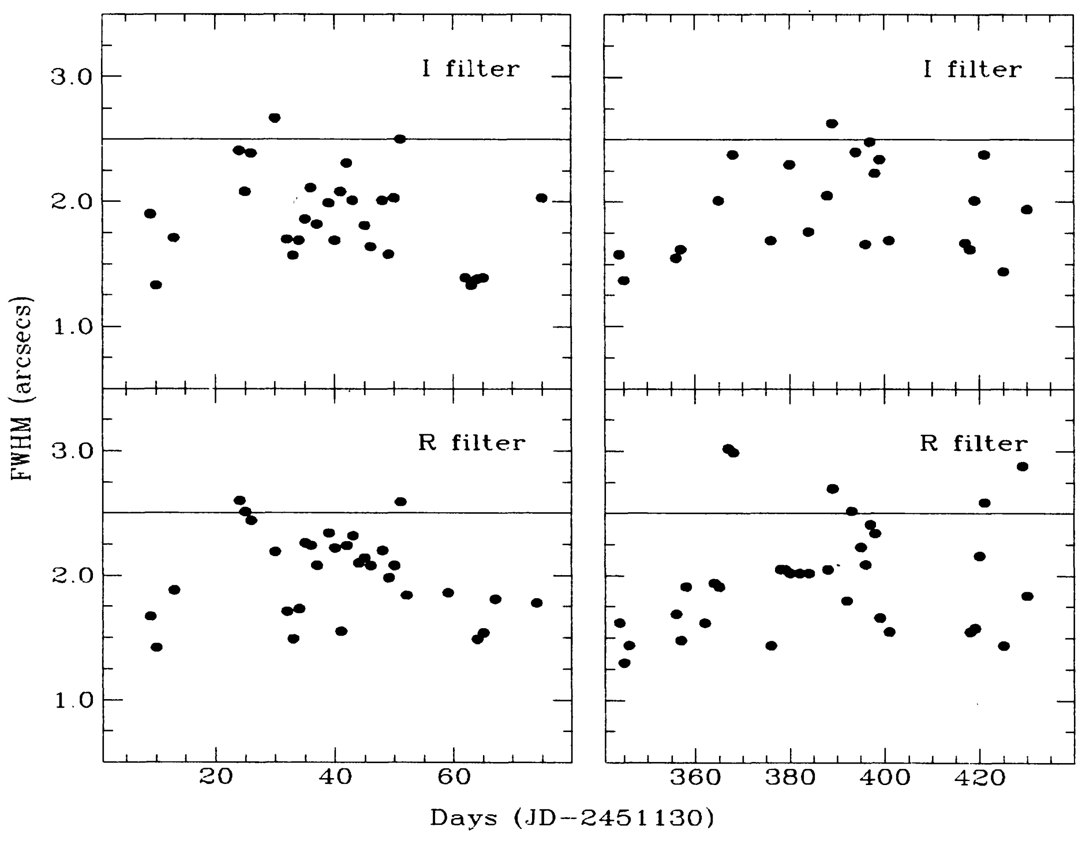

Figure 3. Evolution of FWHM during the two year long observations in both I and R bands. Dotted line indicates the cut-off barrier above which we have rejected the data.

3.1.2 *Seeing fluctuation and Superpixeling*

The seeing size of stellar objects on different nights was estimated from the FWHM of the resolved stellar images using the IRAF package. If an object shows a FWHM significantly higher than the average value, it was not considered in estimating the average value of FWHM. We finally used 20 well isolated stars to estimate the seeing.

Since FWHM is not steady from night to night as seen from Fig. 3 and varies from 1.3 to 3.1 arcsec, the elementary pixel undergoes a strong fluctuation due to such seeing variations which can hamper detection of lensing event. To overcome the problem we rejected all those data points in which FWHM exceeds 2.5 arcsec to achieve a good pixel stability. The variations due to FWHM are minimized by constructing a super pixels of 6×6 pixel^2 for the study of the pixel light curve. Each superpixel corresponds to ~ 2.2 arcsec whereas the average FWHM of the two observing runs is $\sim 2.0 \pm 0.4$ arcsec.

3.2 Pixel light curves

To detect the variability of the pixels, we proceed in the following manner:

i) Pixels around bright stars were not considered in the analysis as they show a quite large variation on different nights. This criteria left with about 75% pixels in the observed field.

ii) Average intensity and standard deviation of each pixel for an observing run was calculated. If any pixel showed a variation greater than 0.5σ in both R and I bands for more than 50% of the observing nights of a particular run and simultaneous variation is in the same direction for $\sim$ 80% of the observations, it was considered for the further analysis.

iii) In the next step superpixel of 6×6 pixel^2 was made around the pixels showing variability.

iv) To get the pixel light curve in an observing season, differential intensity of a pixel have been calculated by subtracting the intensity of that pixel on the first night.

$$\Delta F_{pixel}(JD) = F_{pixel}(JD) - F_{pixel}(JD_0)$$

where JD_0 is the Julian date for the first observing night of that season and ΔF_{pixel} is the differential counts of the pixel. Differential counts of the pixel were plotted with respect to the observing days (JD) for each observing season independently. A careful inspection of two years data yields some superpixels showing significant variation in their light curves.

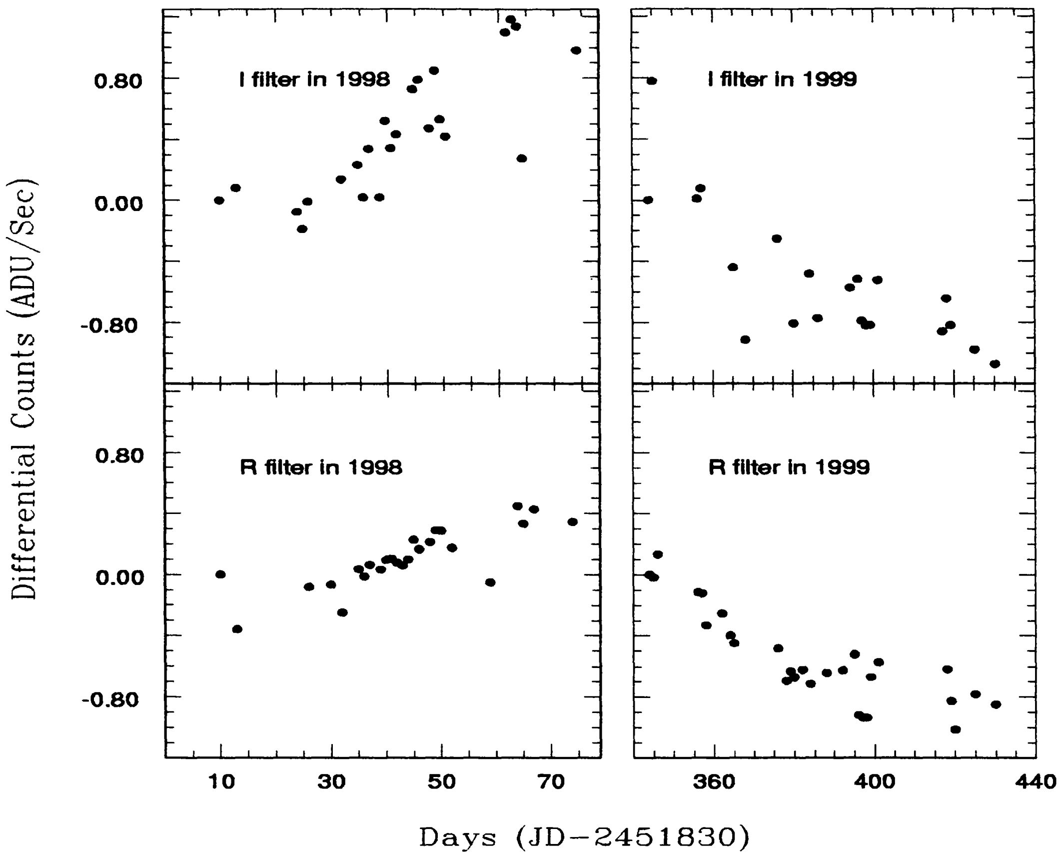

Figure 4. The light curve of superpixel (337,29) in both I and R passbands.

3.3 A Pixel Variable

The light curve of superpixel around pixel (337,29) ≡ (α_{2000} = 0^h43^m25s, δ_{2000} = 41°08.9′) shows an irregular nature of the variability. In the first year observations the intensity is in increasing phase whereas next year observations shows a decreasing trend. The flux change in the two filters is slightly out of phase and has different amplitude which indicates it as a variable star. Further observations are needed to ascertain its nature of variability. Fig. 4 shows the light curve of the pixel in a time span of around 440 days.

4. Star extraction and variable stars

The variable stars have been searched by extracting the stars from the frame in both the filters and carrying out the stellar photometry for the resolved stars in the field using

DAOPHOT photometry package (Stetson 1987). PSF was obtained for each frame using several uncontaminated stars. One star of the field was taken as comparison star and differential magnitude and colour of each star were obtained. The differential magnitudes were then standardized after the aperture correction. The transformation equations used for the CCD system are:

$$\Delta(R-I) = (0.955 \pm 0.008) \times \Delta(r-i)$$
$$\Delta(R-r) = (0.03 \pm 0.03) \times \Delta(R-I)$$

where R and I are the Landolt (1992) standard magnitudes while r and i are the corresponding aperture instrumental magnitude. The probable errors in zero points are of the order of 0.017 mag in R and 0.007 mag in (R-I).

To check variations in the stars we have rejected all those data points which were showing an error of more than 0.1 magnitude. The light curves of 8 stars for the two observing runs indicate statistically significant variability of 0.6 magnitude or larger (see Table 2). Though we have got many more variables of higher period, but insufficient data prevents us to make any conclusion about the nature of their variability.

Table 2. Period and magnitude variation of variable stars. Coordinates $\Delta\alpha$ and $\Delta\delta$ are relative to $\alpha_{2000} = 0^h43^m$ and $\delta_{2000} = 41°$. ΔR and ΔI are the variation from the mean magnitude of the star for the R and I filters respectively. Nomenclature is as per SIMBAD data archive.

Star No.	$\Delta\alpha$ (sec)	$\Delta\delta$ (arcmin:arcsec)	R $\pm\Delta R$ (mag)	I $\pm\Delta I$ (mag)	Period (days)	Nomenclature
1	29.6	14:13	20.36 ± 0.55	20.19 ± 0.34	10.48	[TC96]16
2	26.2	12:02	20.05 ± 0.48	19.39 ± 0.50	13.75	[TC96]20
3	38.7	14:23	20.92 ± 0.53	20.09 ± 0.42	15.26	[TC96]196
4	37.2	14:31	19.85 ± 0.32	19.75 ± 0.43	15.94	[TC96]194
5	37.6	11:13	20.02 ± 0.46	19.51 ± 0.50	16.50	[BHG88]40 4614
6	37.4	14:17	19.66 ± 0.50	18.84 ± 0.55	28.74	[TC96]30
7	40.4	11:09	19.26 ± 0.32	18.69 ± 0.31	56.50	DIRECT V164
8	12.4	11:19	20.12 ± 0.55	19.54 ± 0.33	87.54	[BHG88]40 4426

The period of these 8 stars were calculated using the method to search for periods in unequally spaced data based as described by Press & Rybici (1989). The data were initially phased for all periods between 5 and 400 days in steps of 0.4 days, and later refined the search for period in increments of 0.1 days. The light curves were inspected visually with the period. The phase light curves are plotted in Fig. 5 for both R and I filters.

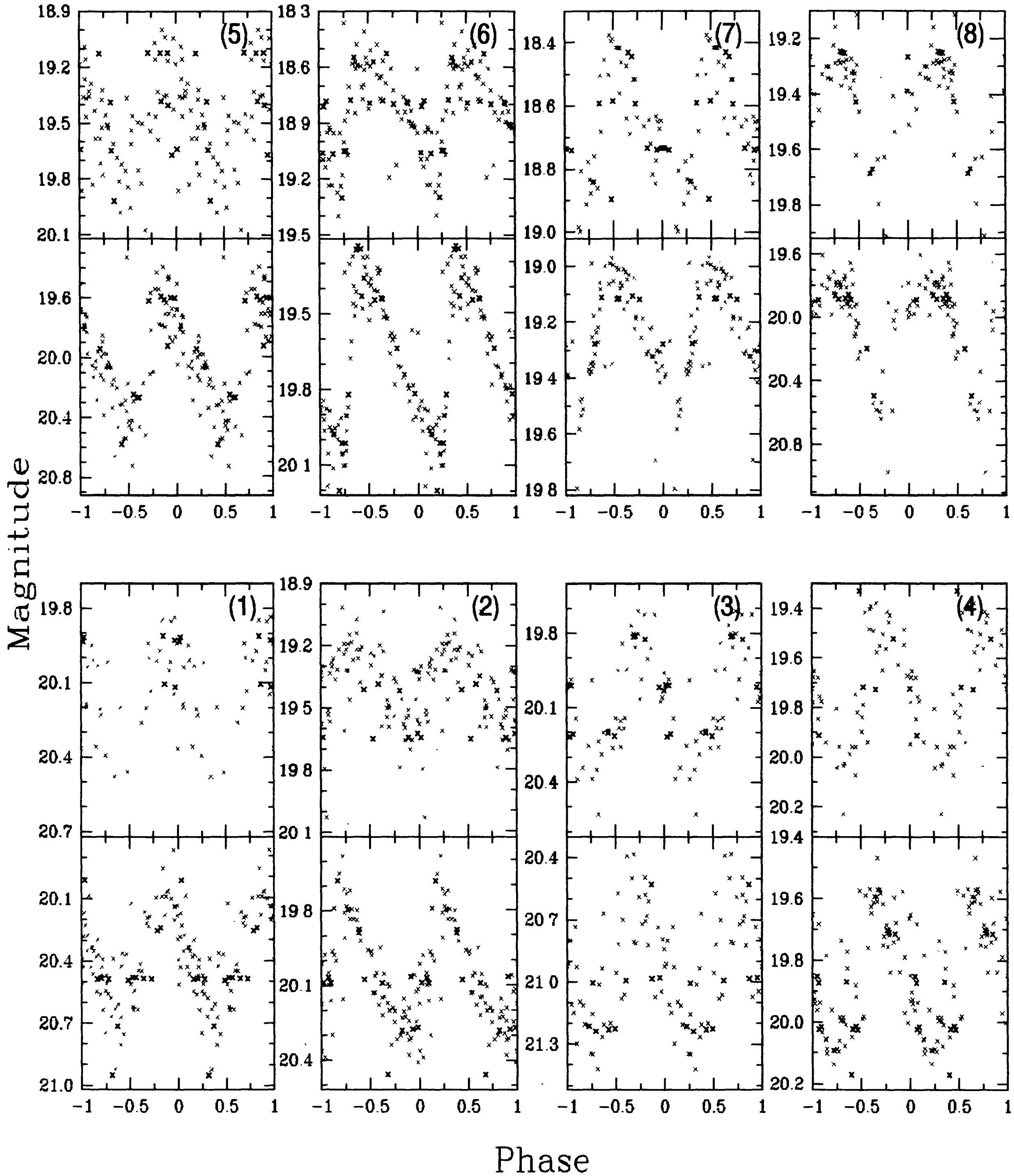

Figure 5. the phase magnitude diagrams of the 8 variable stars observed in the target field. Upper panel is for I filter and lower one is for R filter. For each star phase have been plotted twice and magnitude scale is adjusted for each variable.

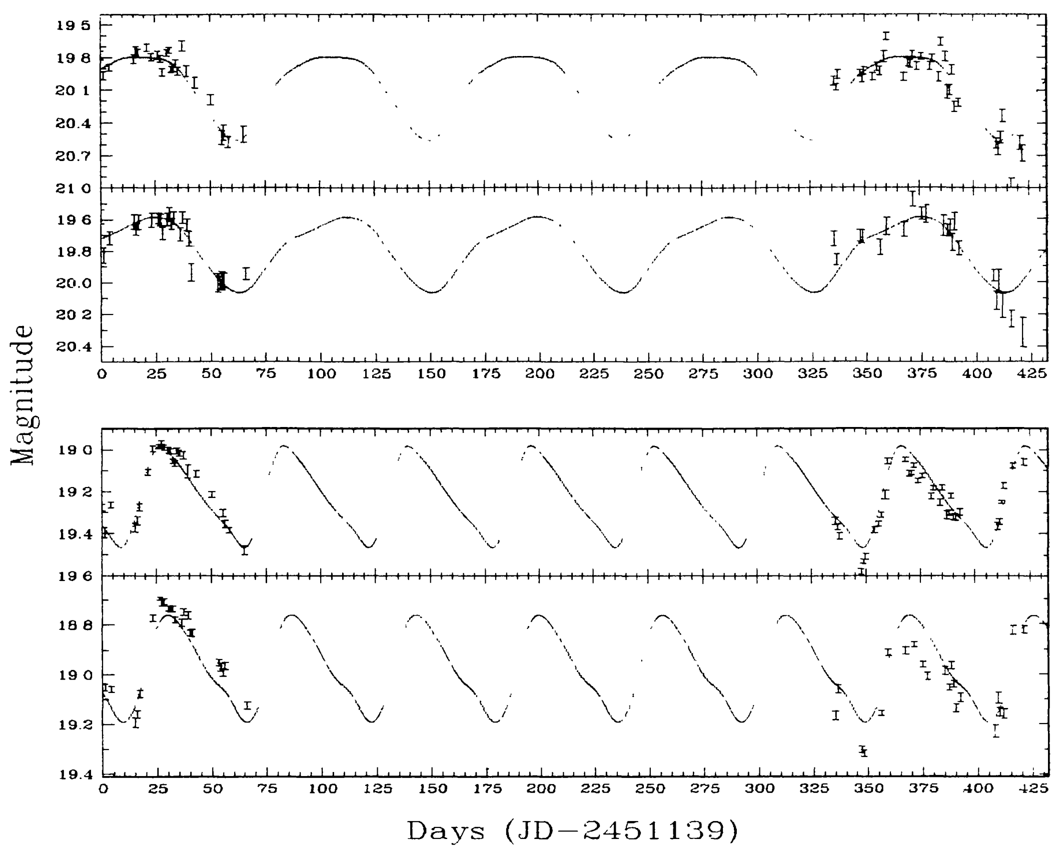

Figure 6. The light curves of the 2 variable stars. For each variable, upper one is for I and lower one for R filter. Star at the lower end is likely a M31 Cepheid of period 56.5 days while star at the upper end might be a possible Mira variable with period 87.54 days.

As phase coverage of the light curve is not uniform, the mean magnitude for each variable has been calculated by the equation given for phase weighted magnitude (Saha & Hoessel 1990)

$$m = -2.5\log_{10}\sum_{i=1}^{n} 0.5(\phi_{i+1} - \phi_{i-1})10^{-0.4\times m_i}$$

where m_i and ϕ_i are the magnitude and phase respectively of the i_{th} observation and n is the total number of observations.

For these 8 variable stars, coordinates for epochs 2000, phase weighted mean magnitude in filters R and I and periods are listed in Table 2. Out of 8, 7 variable stars appear to be classical Cepheids of period ranging from ~ 10 to ~ 56 days while one of them may be a possible Mira variable of period 87.54 days and all of them belonging to M31 galaxy. For all the stars, the light curve for both years we have analysed is in good agreement with our calculated period in the R as well as I band. All stars except [BHG88]40 4614 and [BHG88]40 4426 have already been reported in SIMBAD catalogue and only one star DIRECT V164 is reported as Cepheid. The variable nature of the two stars [BHG88]40 4614 and [BHG88]40 4426 is being reported for the first time. The agreement in the phase over the two seasons is encouraging for our efforts to monitor microlensing events. In Fig. 6, we have shown the full time magnitude diagram for one of the Cepheid and the possible Mira variable.

5. Future Perspective of NTL Project

We have demonstrated the feasibility of detecting pixel variable stars as well as transient events like pixel microlenses through our monitor program. The pixel map of one season can be mapped over those obtained during the previous year. However, detection of a microlensing which is a chance event, the higher signal to noise ratio is needed in comparision to variable star of same magnitude because there is no periodic signal. Consequently, we are in the process of testing possible lens-like signals. We are hopeful that there could be one such event, though confirmation through the analysis of subsequent year's data and exact photometric alignment would be needed before we can provide the light curve. After combining our data with the observations from 1.3-m McGraw-Hill Telescope at the MDM observatory and 2.5-m Isaac Newton Telescope (INT), we would be able to test the lensing nature of our candidate event.

The number of events one expects depends on the detailed process of analysis and on the event selection, which are not yet settled at this stage. However crude estimate following Han (1996) and Gould (1996) indicates at least one event per year in 6×6 arcmin^2 field considering whole dark matter consists of MACHOs. If we do not observe expected number of lensing event in the direction of our observation it would allow us to put a constraint on the amount of dark matter present in the M31 halo. Because of the frequency and duration of our observations, short duration (< 10 days) events may not be detected. However supplementing our data with MDM and INT data, we may be able to detect them. We are thus confident that the present project will contribute significantly to our knowledge about the nature of dark matter.

6. Conclusion

A CCD R and I photometric observations carried out for two years towards the M31 galaxy has yielded superpixel variability as well as well tested 8 pulsating variables from the resolved stars in the field with periods ranging from ~ 10 to ~ 85 days in which seven appear to be likely Cepheids and one may be a possible Mira variable.

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