Search for Machos by the MOA Collaboration

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Presently scientists are working at Mt. John University Observatory in New Zealand using a technique known as gravitational microlensing to search for dark matter in our galaxy. This paper describes the current situation of the international collaboration known as MOA (Microlensing Observations in Astrophysics) that was formed by these scientists, together with future plans to improve the facilities.

§1. Introduction

The MOA (microlensing observations in astrophysics) collaboration was established by Japanese and New Zealand astronomers in 1995 to search for evidence of massive compact halo objects (MACHOs) in the halo of our galaxy. This was soon after the observational discovery of gravitational microlensing events by the MACHO and EROS collaborations,[1),2] following Paczyński's (1986) prediction of microlensing by the Galactic Halo.[3] Observations of the galactic rotation curve had indicated the presence of unseen masses in our galaxy — the so-called *dark matter* . Gravitational microlensing is a technique by which stars in background starfields undergo an apparent change in intensity due to the gravitational effects of intervening dark matter. This allows an estimation of the mass distribution of the dark matter to be made.

The primary goal of the group was to make observations of microlensing events and to estimate the contribution of MACHOs to the Galactic Halo. While MOA instrumentation was being constructed,[4] the MACHO collaboration observed 8 events in the direction of the Large Magellanic Cloud (LMC).[5] For this reason, MOA changed its goal slightly and now makes repeated observations of starfields in the direction of the Large and Small Magellanic Clouds (LMC and SMC) and the Galactic Bulge in the center of the Milky Way and other targets of opportunity (such as unusual microlensing events reported by other collaborations). Rapidly repeating observations enables us to search for short duration microlensing events.

Our observation location of Mount John University Observatory, New Zealand (approximately 44 degrees south latitude) is the most southern location of any microlensing search group. From this location, it is possible to see the Magellanic Clouds and the Galactic Bulge for 14 hours in the middle of the southern hemisphere winter (June and July). The MACHO collaboration at Mount Stromlo, Australia (35 degrees south) uses a telescope which cannot follow the lower transit of the Large Magellanic Cloud in the winter. The groups observing from Cerro Tololo, Chile (30 degrees south) encounter an airmass of 5.7 at the lowest transit of the LMC, making it difficult to make repeated observations. In contrast, MOA makes repeated nightly observations of the LMC between three and five times in mid-winter.

Since 1995, T. Nakamura[6] has stressed the importance of observing in different directions in order to establish whether MACHOs make up the Galactic Halo dark matter. The term MACHOs implies that the dark matter is mainly composed of baryonic matter, dim stars such as red and white dwarfs, or even neutron stars, black holes or substellar brown dwarfs. The MACHO collaboration reported[5] that half of the mass of the Galactic Halo dark matter can be accounted for by a population of half-solar mass MACHOs. Old white dwarfs are a possible explanation, but this leads to difficulties explaining why the progenitor stars have gone undetected. Their conclusion has not yet changed, as far as we are aware.[7] Another possibility is brown dwarfs. A brown dwarf is defined as an object whose mass is less than $0.08M_\odot$ (solar masses) and is thus too small to start sustained nuclear fusion. They lose potential energy until finally the brown dwarf is supported by the pressure arising from a degenerate gas of electrons.[8]

Recently, the first gravitational microlensing event in the direction of the Small Magellanic Cloud was found by the MACHO and EROS collaborations.[9),10] In 1998, another event was found in the SMC direction. By chance, the light curve of this event exhibits the shape expected from binary lensing. This allowed for the distance of the lens to be calculated from the data (something usually not possible to do directly). Unfortunately, MOA's TI camera (MOA-cam1) had a problem of vacuum leakage, and we could not participate in the observations. The event was quite dim, and almost at the observational detection limit of our 61 cm aperture telescope and CCD detector system. The PLANET collaboration managed to observe the most luminous peak corresponding to a caustic crossing using the SAAO 1 m telescope.[11] They concluded that the best interpretation of the 1998 SMC event is that the lens star is located in the SMC itself, and that it amplifies a background star also in the SMC. (This is called *self-lensing* of the SMC.) This event was apparently not caused by a dark matter gravitational lens located in the Galactic Halo between the Earth and the SMC. Two previous events also allowed distance determinations, and these also appear to be examples of self-lensing.[5),9),10)] The self-lensing mechanism was originally proposed by Sahu et al.[12)]

The LMC events first observed by the MACHO collaboration were unusual, suggesting the existence of a tidal effect between the LMC and our galaxy that distributes matter along the line of sight by chance.[13),14)] This has prompted debate on this problem and indicates that the distribution of matter in our own galaxy is still not well understood.[15)]

It is consequently necessary to collect data from more events. With such circumstances, we have observed a very interesting event in the direction of the SMC. In this paper, we report this event as an example of a variable star which could be mistaken for a microlensing event. It would be helpful to combine the data from other groups on this event to confirm the observation.

This paper is a summary of discussions held at symposia on gravitational microlensing at the Yukawa Institute for Theoretical Physics, Kyoto University, from the autumn of 1995 to 1998. About 45 scientists, mainly from Japan with a few from New Zealand, participated in the intense debates. In the remainder of this paper we briefly describe the MOA observation system (§2), and discuss the microlensing-like event in the direction of the SMC (§3). Finally, we outline our future plans and observation strategy.

§2. The MOA observation system

In this section we briefly describe the MOA[*)] observation system. The MOA collaboration uses a 61 cm aperture Boller & Chivens telescope at the Mt. John University Observatory (MJUO) in New Zealand. MJUO is located at latitude $43^\circ\,58'\,59''$ south, longitude $170^\circ\ \ 28'\ \ 1''$ east, and at an altitude of 1029 m. We record typical seeing values of $2-3$ arc seconds, and a best value of 1.1 arcseconds. The clear sky rate is about 30 to 50%, depending on the season. The midwinter and midsummer sky conditions are quite favourable for photometry.

The southern location of the observatory makes it possible to follow objects such as the LMC for 14 hours in midwinter. Observations have continued since June 1996, and MOA is granted monthly telescope time of two weeks around a new moon. Typical observation frequencies for MOA's three starfields in the LMC and two in the SMC are four times per night in winter and twice per night in summer. A typical observation time is six minutes, which consists of 300 seconds of integration time and a minute to perform CCD readout and transfer the data onto a hard disk. We selected one million target stars in the LMC and four hundred thousand stars in the SMC.

[*)] Incidentally, MOA is also the name of a very large native bird which became extinct in New Zealand around two hundred years ago.

The MOA camera is composed of 9 Texas Instruments TC-215 CCD chips arranged in a 3×3 grid with spacing equal to 0.9× [the chip width]. Four exposures are needed to expose the entire focal plane. Each chip has a usable surface of 1000×1018 pixels (∼1 million pixels per chip). The pixel size is 12 microns square and the tip is sensitive in the range 320 nm and 1050 nm, with a peak in the quantum efficiency of 50% at 630 nm. MOA uses custom filters denoted 'MOA Blue' and 'MOA Red' that transmit radiation in the ranges of 380 nm to 640 nm and 610 nm to 1100 nm, respectively. The MOA Blue filter has a 'red leak' past 1050 nm, but the CCD chip is not sensitive in this area. The details of the MOA camera system are now under preparation for publication. [16)]

Fifty minutes are required to expose the entire focal plane in the two passbands with 300 s integration time. The focal plane subtended $30' \times 30'$ for the observations from June 1996 to December 1996 when f/13.5 optics were used, and $1^\circ \times 1^\circ$ from January 1997 to August 1998 when f/6.25 optics were used. The change in the f-number of the telescope in 1997 was made in order to see a wider region per exposure. The details on this are found in Ref. 17).

The data analysis has been performed both in NZ and Japan. Images are transferred from MJUO to collaborating institutions in Japan and NZ by 8 mm Exabyte tape. Japanese data are stored on the disks of the Nagoya University STE laboratory and the KEK computation science center. The raw data are first treated using standard astronomical techniques. First, the dark current is subtracted from the raw image frames. Images of the sky background also have dark current subtracted. Science frames which are suitable for reduction are produced by combining pixels using the quantity (raw data – dark current)/(sky data – dark current). The identification of stars is made using the DoPHOT software package. [18)] An initial star catalogue (template) of the positions of all stars in the LMC and the SMC was made using images taken under the best seeing conditions. The positions of stars on other images are then compared with the template star positions, and photometry (an intensity measurement) is assigned to each star in the template. Eventually this produces a stellar intensity time series for each star in the observation regions. These intensity measurements are stored in a database on hard disk for later analysis. With this database, MOA is searching for MACHO candidates and new kinds of variable stars. Microlensing events can be detected by looking at variations in the intensity of a star over time.

For stars that are brighter than 18th magnitude, we have obtained approximately 200 data points in the observation period June 1997–August 1998. The MOA instrumental star magnitudes are transformed from MOA passbands to Johnson passbands using an approximate relation derived from the Hubble Space Telescope Guide Star Catalog GSC(HST) by the following equations:

$$M_{\rm red}({\rm GSC}) = M_{\rm red}({\rm MOA}) + 25.10^{+0.26}_{-0.36},$$
$$M_{\rm blue}({\rm GSC}) = M_{\rm blue}({\rm MOA}) + 24.82^{+0.18}_{-0.27}.$$

A further calibration program is being undertaken in New Zealand by MOA.

§3. LMC and SMC events

Within the database taken from January 1997 to January 1998, we have selected stars for data analysis which satisfy the conditions that in the LMC direction, the data set includes more than 75 data points, while that in the SMC direction, it includes more than 60 data points. The detection efficiencies for microlensing events towards the Magellanic Clouds were calculated using a Monte Carlo technique in which the actual observing conditions were simulated. The results are shown in Figs. 1 and 2 for various values of the event duration.

We have found two candidates with signatures similar to gravitational microlensing events. One is in the direction of the LMC, and the other is in the direction of the SMC. The amplification of the source star of the LMC event is $A \sim 3.5$, and the duration $\hat{t}$ was 240 days.[19] The baseline magnitude was 18.6 for the red filter and 19.5 for the blue filter (almost the limiting magnitude of our telescope). The location of the candidate (denoted here as LMC 97-1) is indicated in Fig. 3 by the mark ⊗, and the light curve is displayed in Fig. 4. The location of the source star is shown on a colour magnitude diagram (CMD) of the stars in the LMC in Fig. 5. Maximum brightness occurred on Julian Day (JD) 2450510.5 (March 2nd, 1997). Since we started the observation of this region in January 1997, we do not have the light curve of this particular star before that time. It would be useful to combine

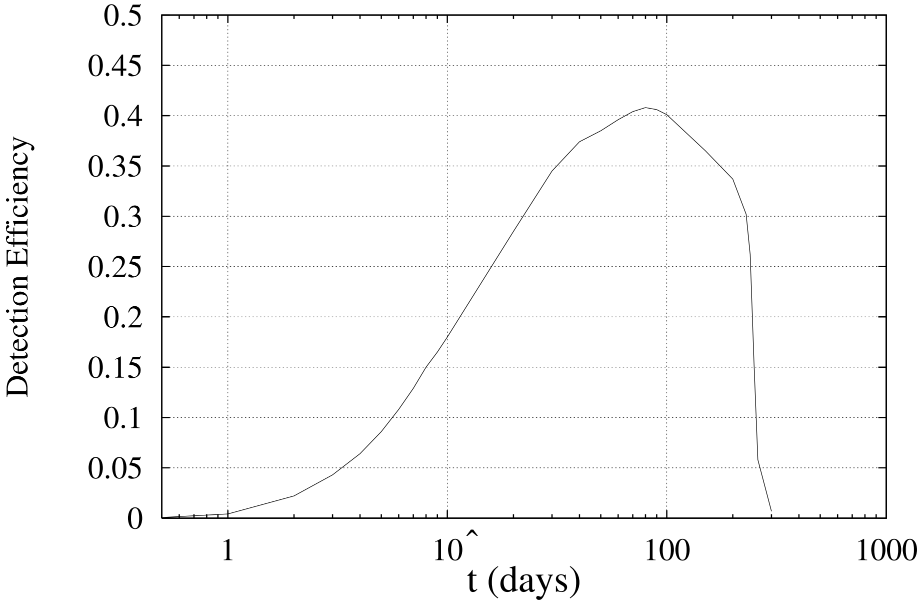

Fig. 1. The detection efficiency of gravitational microlensing events of the MOA collaboration towards the LMC direction. Actual observation conditions were used in the Monte Carlo calculations. The detection efficiency is slightly higher than that of the MACHO collaboration at ~1.5 days and 90 days.

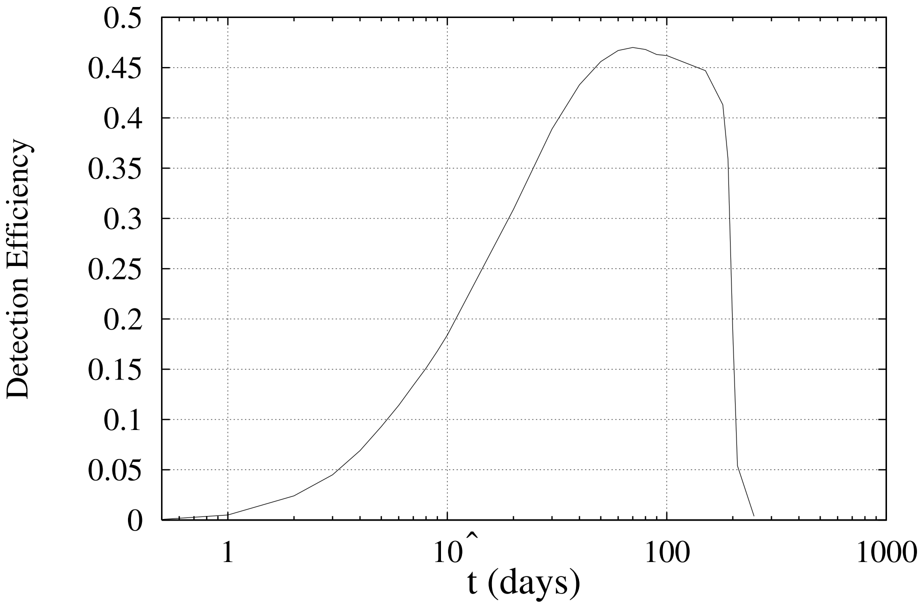

Fig. 2. The detection efficiency towards the SMC direction. The detection efficiency in the SMC direction is slightly higher than in the LMC direction, because of the better separation of stars in the SMC.

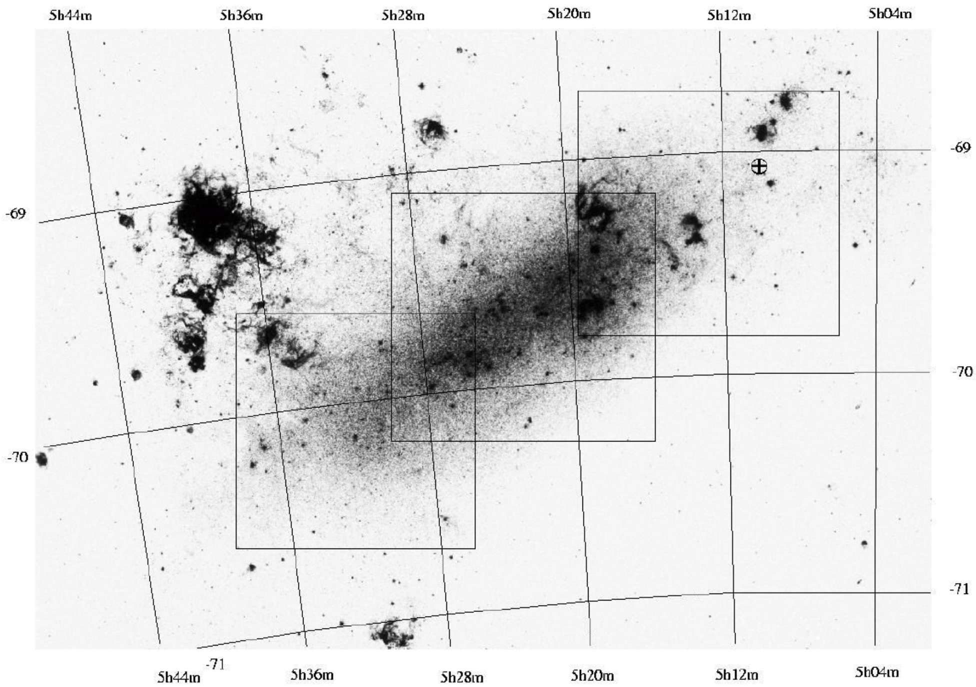

Fig. 3. The sky region currently observed by the present system is indicated by the square box superimposed on the LMC. The ⊗ mark represents the position of the MOA LMC 97-1 event.

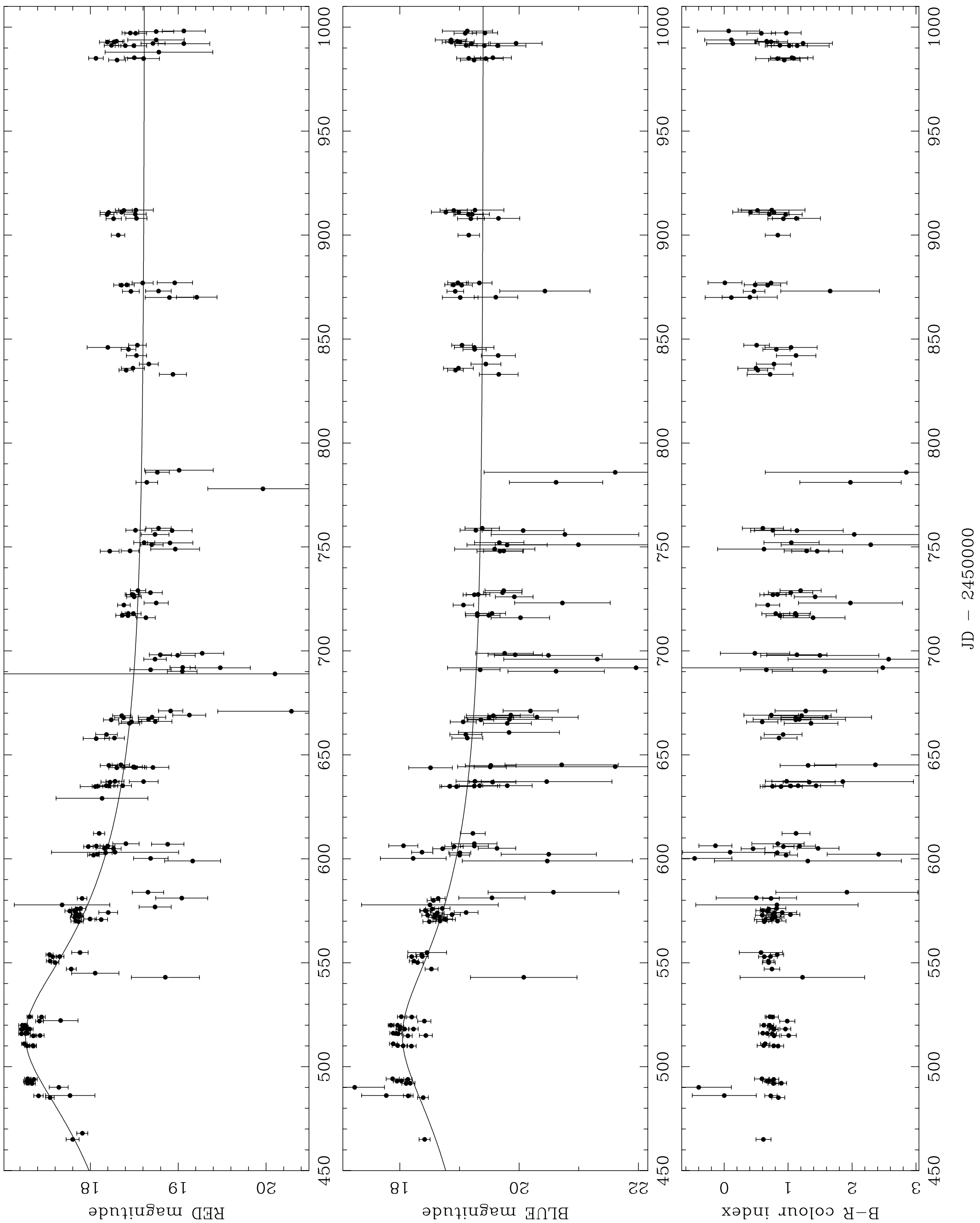

Fig. 4. The light curve of MOA LMC 97-1. The top panel shows the light curve in Johnson Red (transformed from MOA Red), the middle panel displays the Johnson Blue light curve (estimated from MOA Blue), while the bottom panel displays the colour index Blue – Red.

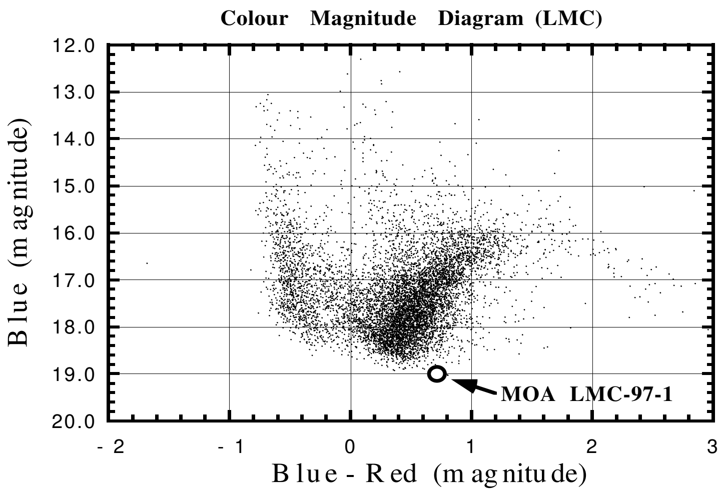

Fig. 5. The colour-magnitude diagram of LMC stars obtained by MOA. The ◯ mark corresponds to the position of the MOA LMC 97-1 source star.

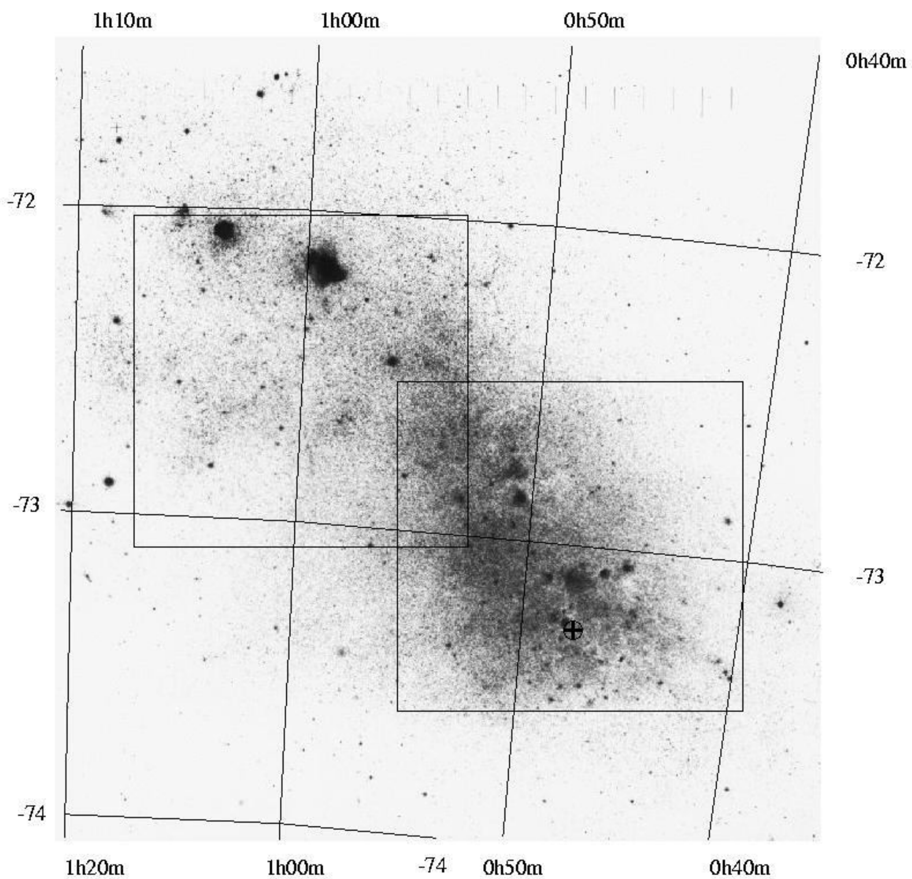

Fig. 6. The MOA sky observation region around the SMC. The ⊗ mark indicates the position of the MOA SMC 97-1 event. The square box corresponds to one square degree of sky.

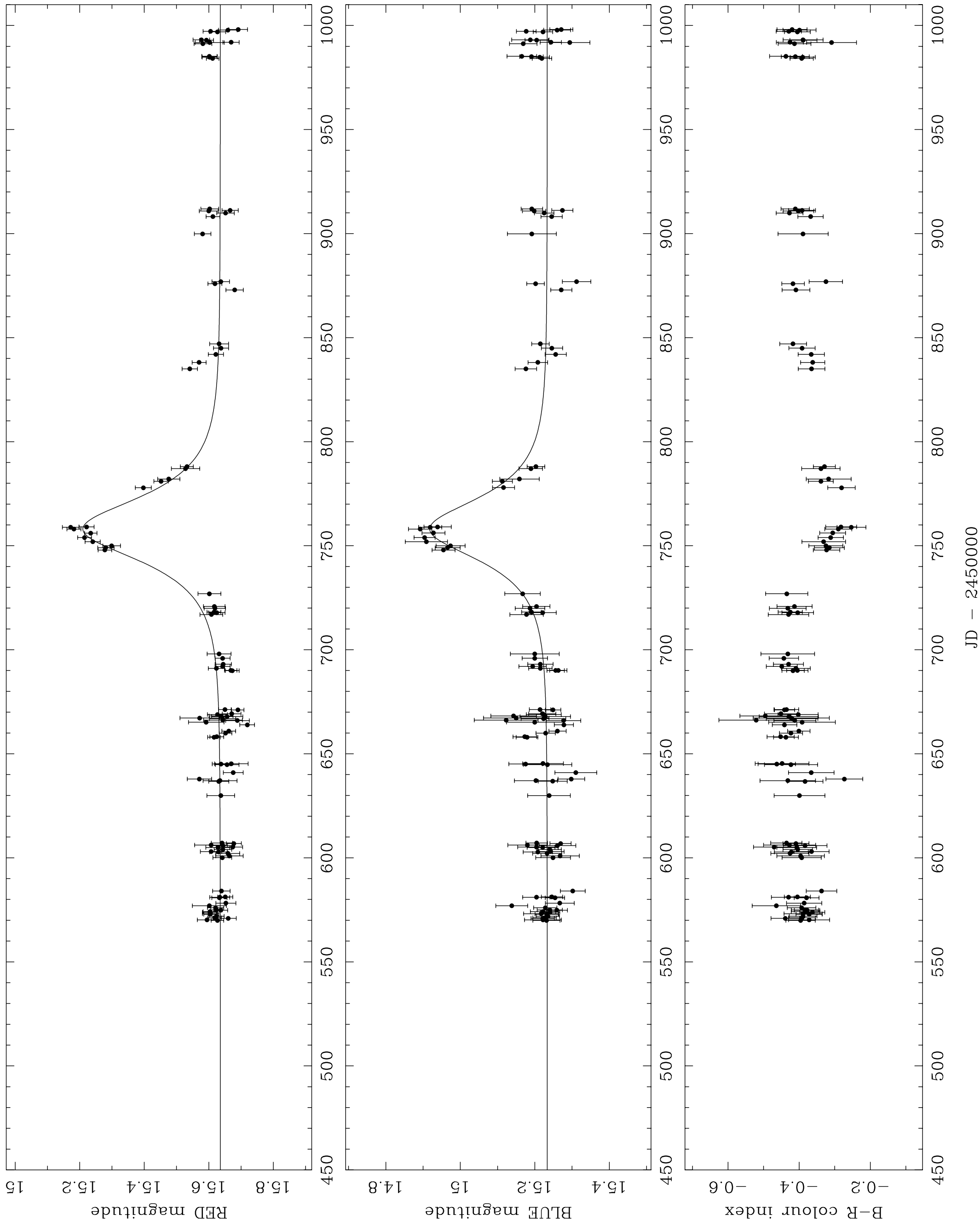

Fig. 7. The light curve of MOA SMC 97-1. The top panel displays the light curve seen through Johnson Red, while the middle panel displays the light curve in Johnson Blue. The bottom panel is the Blue – Red colour index.

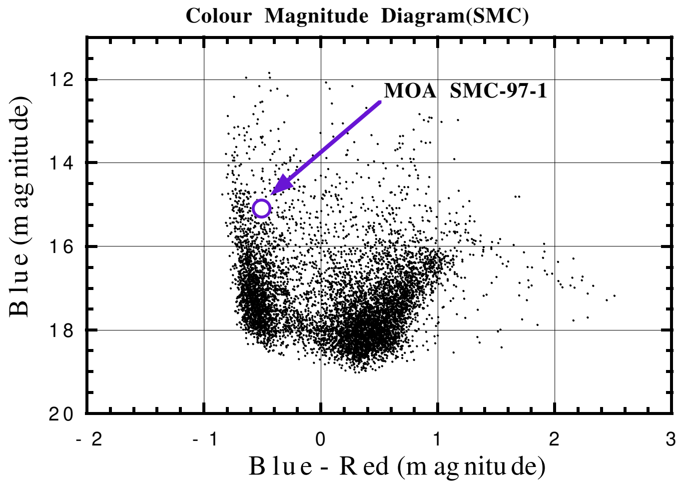

Fig. 8. The colour-magnitude diagram of SMC stars observed by MOA. The ◯ mark indicates the position of the MOA SMC 97-1 event.

our data for this event with data from other groups to confirm the observation.*)

The square boxes in Fig. 1 show the sky region where we observed. Each region is approximately one square degree. The observation regions are summarized in Table I.

Table I. The center of the target area of MOA starfields. The CCD camera captures the sky region $\pm 0.5°$ surrounding the central right ascension (α) and declination (δ). The coordinates displayed are the center of the square boxes on the starfield maps: Figs. 3 and 6.

Target	α**(2000.0)**	δ**(2000.0)**
nlmc1	$5° 14' 00''$	$-69° 25' 00''$
nlmc2	$5° 24' 00''$	$-69° 45' 00''$
nlmc3	$5° 34' 00''$	$-70° 00' 00''$
smc1	$0° 48' 20''$	$-73° 07' 00''$
smc2	$0° 59' 00''$	$-72° 31' 00''$

In the direction of the SMC, another interesting candidate was found. This is denoted by MOA SMC-97-1. The peak was observed on November 6th, 1997 (JD 2450759.4). The source star was amplified with $A \sim 1.6$, and $\hat{t}$ was 40 days. The baseline magnitude was 15.6 through the red filter and 15.2 through the blue filter. The sky position of the candidate is indicated in Fig. 6 by the mark ⊗. The square box of Fig. 6 represents the areas observed with our telescope. The light curve of this event is shown in Fig. 7, and the position in the CMD of the SMC event is shown in Fig. 8.

Note that in Fig. 7 the colour index changes in the peak region. This behaviour is not expected from simple gravitational microlensing theory. However, the direction of the colour difference is opposite to that from most variable stars. In variable stars

*) A second enhancement of the light curve was observed around 1084 days. This must be a variable star.

the colour is generally shifted in the blue direction during brightening (indicating an increase in temperature), while during such an event the colour is shifted toward the red direction near the peak. Of course, there remains the possibility that the object is a flare star or one of a recently discovered class of variable stars called "bumpers". Further observations should clarify this issue.[*)]

§4. MOA, present and future

In this section, we summarize the present status of MOA's observational programme and discuss our future plans for machos.

The MOA project stems from the significant discovery of the first gravitational microlensing event by the MACHO and the EROS collaborations. We may state here that Japanese and New Zealand scientists have 12 years history of international collaboration between them. The first Japan-NZ-Australia group (known as JANZOS) was formed upon the discovery of supernova SN1987A. JANZOS was created to confirm the arrival of ultra high energy photons from SN1987A. Japanese cosmic ray physicists went to Blenheim (New Zealand) to build a cosmic ray air shower and Cherenkov detectors. This collaboration started in September, 1987, and the lead investigator was Humitaka Sato.[20)] Even today, data analysis of photons from supernovae remnants is continuing in Vela. Eventually, part of the JANZOS group left NZ and installed a Cherenkov detector at Woomera in the Australian desert. Recently, they have found high energy TeV photons from SN1006,[21)] whose location was predicted by ASCA X-ray observations.[22)] The remaining fraction of JANZOS started the MOA collaboration in NZ, which includes astronomers from Japan and NZ, and endeavoured to discover dark matter in the Galactic Halo and Bulge. As time progressed, MOA also started investigating other time-critical astronomical phenomena.

As stated in §1, the MACHO collaboration was first to publish candidates for gravitational microlensing events, although they included observations from around the world including observations made by MOA at MJUO. We have decided to study the region where the MACHO collaboration has less sensitivity. According to the MACHO efficiency curve, in the region in which $\hat{t} < 3$ days, their detection efficiency is expected to be 2%, and even in the $\hat{t} \sim 5$ days region, the expected value is 6%. For two years we have observed the Magellanic Clouds several times per night. The number of observed stars is about 1.4 million, and our expected event rate is several per year, at most. The MACHO collaboration is monitoring almost 10 million stars in the Magellanic Clouds once nightly. We hope that MOA can increase its capabilities in the future and monitor 50 million stars per night. MOA also intends to publish the results of its search for short duration events in the master's thesis of one of the graduate students, so these results are not included here. Significant numbers of variable stars have also been observed and classified by graduate students at Nagoya University and Auckland University.

Further observations are required before any conclusion can be made regarding

[*)] A small enhancement of the light curve was seen around 1113 days.

the contribution of dark matter to the Galactic Halo. Therefore, we upgraded from a 9 million pixel to a 24 million pixel CCD camera, and we are planning to acquire a two meter class telescope with f $\sim 5-6$ and two 6k×6k–8k×8k CCD cameras. With this setup it should be possible to observe 50 million stars nightly, and to attain the projected event rate shown in Fig. 9. In fact, at the moment, we are using a 61 cm aperture telescope, which is shared with other NZ astronomy projects and is not dedicated to MOA. We need our own telescope, or we risk missing critical observation times. A dedicated telescope would also double our database making us less reliant on other collaborations.

At present it is not clear whether we can obtain the funding for a 2 m class telescope. We are consequently considering shipping a used 1 m class telescope to NZ. One possibility is a telescope located at Agematsu Kyoto University Observatory.[23] The mirrors of this telescope would need to be repolished, since they were made for infra-red work and are currently not suitable for optical observations. Also, the tracking accuracy would need to be improved from 2″ to 0.5″ by introducing a smooth tracking system. In the event of a successful funding application, we will ship this modified telescope to NZ in 2000. We already have an improved 4k×6k CCD camera, which has a characteristic quantum efficiency of 85% to extend our

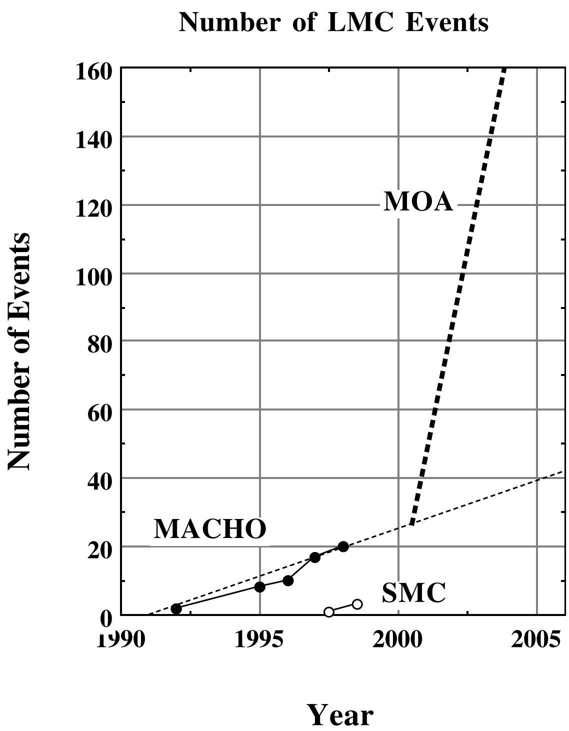

Fig. 9. The estimated event rate as a function of year. MACHO represents the number of LMC events accumulated by the MACHO collaboration, while SMC refers to the two reported events in the direction of the SMC by the PLANET, EROS and MACHO collaborations. MOA stands for accumulated events which will be detectable by the new MOA system (present proposal).

observations.

We will continue our efforts to acquire a telescope in the 1.5 m – 2.0 m range together with two CCD cameras, each with at least 6k×6k CCD pixels. It may then be possible to reach a conclusion on the nature of dark matter. We would expect to observe at least 20 events in the direction of the SMC, allowing conclusions to be drawn on the location of the lenses in this direction. Observations of globular clusters could also be made.[24] Globular clusters have only on the order of 100,000 stars, but by examining several globular clusters, the event rate may be satisfactory. This would extend the search in several directions and assist in the determination the spatial distribution of dark matter.

If observations were carried out from the Antarctic, it would be possible to observe the LMC and SMC continuously during the 24 hour long winter nights. The South Pole is a special point and normally has little wind except during icy snowfalls. Now iridium satellite telephony is possible, and the day will soon come when we can observe without being physically present in the Antarctic. Another possibility is to reorganize an international collaboration like PLANET. We do not know PLANET's future plans after 2000, but if they do not continue their nice scientific global observation, we must have a similar system. In fact, the Shuji Sato group of Nagoya University will install a 1.4 m telescope at SAAO (South Africa). With new collaboration from South American teams (EROS, OGLE, MACHO), we will continue an important global collaboration. We are expecting that the Tasmanian group from Australia will join us, and again give us a collaboration like JANZOS.

Gravitational microlensing astronomy will mature in the 21st century and we believe that this technique will become one of the leading tools in future astronomy together with gravitational wave experiments.

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