THE ANGSTROM PROJECT ALERT SYSTEM: REAL-TIME DETECTION OF EXTRAGALACTIC MICROLENSING

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ABSTRACT

The Angstrom Project is undertaking an optical survey of stellar microlensing events across the bulge region of the Andromeda galaxy (M31) using a distributed network of 2 m class telescopes. The Angstrom Project Alert System (APAS) has been developed to identify candidate microlensing and transient events in real time, using data from the Liverpool and Faulkes North robotic telescopes. This is the first time that real-time microlensing discovery has been attempted outside of the Milky Way and its satellite galaxies. The APAS is designed to enable follow-up studies of M31 microlensing systems, including searches for gas giant planets in M31. Here we describe the APAS, and we present a few example light curves obtained during its commissioning phase that clearly demonstrate its real-time capability to identify microlensing candidates as well as other transient sources.

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1. INTRODUCTION

Gravitational microlensing has proved itself to be a powerful tool for planetary, stellar, and Galactic studies (Paczynski 1996; Beaulieu et al. 2006; Gould et al. 2006). It has also been used to look for dark matter in the Andromeda galaxy (M31), where the stellar crowding is much more severe (Calchi Novati et al. 2003; Riffeser et al. 2003; de Jong et al. 2004). Many of the exciting discoveries made by microlensing within our own Galaxy are possible only because microlensing is alerted in real time by survey teams such as OGLE (Sumi et al. 2006) and MOA (Sumi et al. 2003), allowing follow-up networks such as MicroFUN (Gould et al. 2006) and PLANET/RoboNet (Beaulieu et al. 2006) to target candidate events with high time resolution. The requirement of both rapid and robust data processing has until now prevented the development of an alert system for M31 microlensing.

The Andromeda Galaxy Stellar Robotic Microlensing (Angstrom) Project aims to use microlensing to probe the geometry and stellar mass function of the M31 bulge (Kerins et al. 2006). Since many of these events are expected to have durations of just a few days, the survey employs a distributed network of telescopes to enable round-the-clock monitoring of the M31 bulge. Two of the telescopes within the network are fully robotic, allowing data to be collected and processed rapidly. The Angstrom Project is taking advantage of this to develop a real-time data processing pipeline as part of a microlensing and transients alert system. The Angstrom Project Alert System (APAS) is designed to enable follow-up studies of candidate events in M31 in a similar vein to those conducted within our own Galaxy. Chung et al. (2006) has highlighted how such an alert system could enable microlensing discovery of gas giant planets in M31 itself. Other benefits of such a system would be a greater ability to identify and characterize binary microlensing events (Kim et al. 2007), which are estimated to comprise around 15% of all M31 events (Baltz & Gondolo 2001), and the possibility of measuring finite source effects, which can be used to constrain lens and source parameters.

In this Letter we describe the design and implementation of the APAS, and we show some early results from its commissioning phase during the 2006/2007 Angstrom observing season. The results illustrate the potential of the system for real-time microlensing and transient discovery.

2. ANGSTROM PROJECT OBSERVATIONS

The Angstrom Project\textsuperscript{8} employs a network of 2 m class telescopes. These include the robotic 2 m Liverpool Telescope (LT) on La Palma (Steele et al. 2004), the robotic 2 m Faulkes Telescope North (FTN) in Hawaii, the 1.8 m telescope at Bohyunsan Observatory in Korea, the 2.4 m telescope at MDM in Arizona and, recently, the 1.5 m at Maidanak Observatory in Uzbekistan. The telescope network provides excellent round-the-clock coverage of the M31 bulge during the observing season, which lasts from August through to February. Angstrom aims to obtain upward of three observations per 24 hr period in order to be able to detect and characterize short-lived microlensing events typically induced by low-mass M dwarf stars in the M31 bulge (Kerins et al. 2006).

The APAS primarily utilizes incoming data from the two robotic telescopes, the LT and FTN. These telescopes operate autonomously, executing programs that are queued by an intelligent scheduler program (Fraser 2006). Images obtained by these telescopes are automatically preprocessed and made available via the web typically within 15 minutes of observation. Both telescopes employ identical optical cameras with a 4.6' field of view and 2k × 2k CCD arrays. Angstrom observations are conducted primarily in the Sloan-like $i$ band on both telescopes, typically with a sequence of exposures totalling around 30 minutes. Each exposure within the sequence is short (no more than 200 s) in order to avoid saturating the core of the M31 bulge. The individual

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exposures are then stacked to form a single 30 minute exposure image for each epoch. More details can be found in M. J. Darnley et al. (2007, in preparation; hereafter D07), which describes the main processing pipeline for the whole telescope network.

In addition to LT and FTN data, the APAS uses archive data from the POINT-AGAPE dark matter microlensing survey of M31 (Calchi Novati et al. 2003). POINT-AGAPE used the wide-field camera of the 2.5 m Isaac Newton Telescope on La Palma to survey a 0.6 deg$^2$ area of the M31 disk and bulge. Around 65% of the LT/FTN reference field overlaps with the POINT-AGAPE data. For the APAS we have reprocessed all Sloan $i$-band data from the POINT-AGAPE survey obtained between 1999 and 2001. We use it to provide an extended data baseline for the subset of light curves lying in both Angstrom and POINT-AGAPE survey regions.

3. THE ANGSTROM PROJECT ALERT SYSTEM (APAS)

M31 presents a challenging target for real-time microlensing discovery. At a distance of 780 kpc it is 2 orders of magnitude more distant than typical microlensing sources toward the Galactic bulge where the majority of Galactic microlensing alerts occur. This means that larger telescopes and longer exposures are required to obtain sufficiently sensitive photometry. It also means that we have to deal with stellar fields that are far more crowded and where the typical microlensing source is completely unresolved at baseline (see Fig. 1). This is the so-called pixel-lensing regime.

The challenge of developing an alert system for an M31 pixel-lensing survey differs in some key respects from that of a Galactic microlensing alert system. One downside is that toward the core of the M31 bulge we reach the variable star crowding limit. Reliable photometry for individual variable objects becomes difficult even when using difference imaging (Alard & Lupton 1998). This means that very often more than one variable source contributes to the light curve at a given position, as illustrated in the variable source map shown in Figure 1c. However, variable signals in the M31 bulge must necessarily involve a significant source flux change in order to be detectable above the very bright M31 bulge surface brightness. Therefore, there are fewer classes of variable stars that are sufficiently bright and variable to provide potential false positive signals.

With these potential difficulties in mind, we have adopted a pragmatic approach in developing the APAS. We do not require it to autonomously and robustly flag up high-quality microlensing alerts. Rather, the APAS presents a modest list of light curves that exhibit transient or microlensing-like behavior. The list is then reviewed by a human observer who makes the final decision on whether to issue an alert for any of the signals. The role of the APAS is to present to the observer via a web-based interface a compact list (typically no more than a few dozen light curves) of the currently most interesting transient signals from a continuously updated database of around 20,000 light curves. The observer is then in a position to quickly review ongoing signals of potential interest. The APAS also records the positions of all variable signals in the immediate neighborhood of each light curve in the list so that the observer can check and quantify any light-curve contamination.

The APAS comprises two stages: a robust real-time data reduction pipeline and an event classification scheme. We now describe both of these stages in more detail.

3.1. Real-Time Data Reduction

The Angstrom Data Analysis Pipeline (ADAP) is responsible for reducing all Angstrom data from both robotic and nonrobotic telescopes and is described in detail in D07. The nominal mode of operation of the ADAP is to process the full data set offline at the end of each observing season. However, we also employ the ADAP to process a 1k $\times$ 1k rebinned copy of the 2k $\times$ 2k robotic telescope images that can be processed in real time. The pixel size of the rebinned data is still only 0.26" and so adequately samples the typical seeing disk (1"–1.5"). The ADAP offline processing is described fully in D07, whereas here we concentrate on the real-time processing of the rebinned data that forms part of the APAS. Many of these stages are similar or identical to the ADAP offline processing, so we keep our description brief and refer the reader to D07 for further details.

First, an initial quality control score is made of each frame based on the shape and size of the point-spread function (PSF). Images that fail this check are dropped from the subsequent analysis as their inclusion would result in unacceptable difference image quality. For the surviving images the APAS performs defect masking, cosmic-ray rejection, and image alignment. Then the APAS defringes each frame using an iterative method described in D07. Images taken within the same run (i.e., sequentially at one epoch) are then PSF-matched and stacked using the AngstromISIS difference image engine, which is a modified version of a subset of routines from the ISIS image subtraction package (Alard & Lupton 1998). AngstromISIS is described in detail in D07. The image stack selected to be the reference is then convolved and subtracted from the other image stacks to create a sequence of difference images. These are then used to produce one likelihood map of variable sources for each epoch, using an indicator of statistical significance similar to that of Cash (1979). Sources from within each likelihood map are then identified and matched, and an updated master list of variable sources is compiled. PSF-fitting
TABLE 1

| Object Status | Number of Objects | Percentage of Total |
|---------------|-------------------|---------------------|
| Void          | 6311              | 34.0                |
| Invalid       | 54                | 0.3                 |
| Flat          | 9931              | 53.6                |
| Variable      | 2197              | 11.8                |
| Follow        | 12                | 0.1                 |
| Old           | 0                 | 0.0                 |
| Alert         | 38                | 0.2                 |

photometry is performed on the difference images, and the resulting photometry is stored within a MySQL database. The time between observation and adding new photometric points to the database is about 2 hr.

This pipeline is applied both in real time to the LT and FTN data and offline on regions of legacy POINT-AGAPE data that overlap with the Angstrom field. The LT and FTN are essentially identical telescopes, and the observations were taken using matched filter systems, so a simple linear scaling is sufficient to deduce relative light-curve scalings and offsets for these telescopes. The POINT-AGAPE i-band data are matched to LT/FTN i-band photometry by fitting a sample of periodic variables present in both the Angstrom and POINT-AGAPE fields.

3.2. Candidate Classification

APAS event classification is initiated each time a new robotic observation is added to the light-curve database. The APAS employs a number of selection criteria to classify each light curve into one of seven different categories.

Each object’s light curve is separated by telescope (LT, FTN, or POINT-AGAPE), with each telescope being initially processed separately. The APAS deems an object to be valid if it contains at least seven LT light-curve points from the first (2004/2005) and second (2005/2006) Angstrom observing seasons. It must also contain at least seven FTN light-curve points from the second Angstrom season. If an object does not meet these criteria, it is classified as “void” and will never be processed again by the APAS. If a light curve does not contain at least seven points in the current (2006/2007) observing season, then the object is marked as “invalid.” Such objects are reviewed again when new observations are added to the database.

For remaining objects a baseline is estimated for each telescope by determining the median light-curve flux. The APAS then looks for indications of transient behavior. Any point that is at least 5σ above the baseline is considered “significant.” For each object the APAS then investigates any clusterings of significant points (“peaks”) for each telescope. A peak is defined as a clustering of at least five significant points, all lying within the same observing season. Within the peak some leeway is permitted—up to three consecutive nonsignificant points are admitted within the peak provided that they are followed by a significant point within the same season and that their presence coincides with worsening seeing.

Objects containing no peaks are classified as “flat.” These objects will be reanalyzed and possibly reclassified when new observations are added to the database. If an object contains no peaks in the current season but contains at least one peak within a previous season, then it is classified as “variable,” undergoing reanalysis when additional observations are obtained. Objects containing peaks in the current season are checked for the presence of peaks in previous seasons. The APAS must allow for the fact that the crowding of variables may superpose variability on the baseline of transient and microlensing events (e.g., candidate PA-99-N1; Paulin-Henriksson et al. 2003). Accordingly, it does not necessarily classify objects as variable if they show variability on previous seasons as well as in the current one. Instead, if peaks are seen in previous seasons, then the object is classified as variable unless a peak in the current season is at least 150 reference image counts and is at least 50% greater than the highest amplitude peak in any previous season. Other than these, the only remaining objects are those that show only peaks during the current season.

The APAS now considers all surviving objects to be transients and flags them as “followed.” The FTN and POINT-AGAPE (where available) light curves for these objects are now scaled to the reference image of the LT data, and a reduced Paczynski profile is then fitted with a flux $F(t) = B + \Delta F[1 + 12(t - t_0)/H_{\text{FWHM}}]^{1/2}$, where $t$ and $t_0$ are the epochs of observation and maximum brightness, $B$ is the baseline flux, $\Delta F = F(t_0) - B$ is the maximum flux deviation, and $H_{\text{FWHM}}$ is the duration of the full width at half-maximum. The values of $B$ and $\Delta F$ are telescope- and bandpass-dependent. We require that the best fit $t_0$ does not occur before the first observation of the current season and that it does not occur after the anticipated start of the next season. The FWHM of the event must be in the range of 1 day $\leq t_{\text{FWHM}} \leq 365$ days. Finally, we require that the amplitude of the event be positive. Objects passing these criteria are classed as “alerts.” Objects that fail any of these criteria remain classed as “followed,” unless they were previously classified as an alert in which case they are reclassified as “old.”

The APAS utilizes a web-based interface to report results. While allowing a user to examine the light curves of all alerted and followed objects, it also displays light curves of all objects within a 3° vicinity of each alert. This is helpful in deciding whether an object is a true alert but may have a baseline contaminated by a nearby variable source.

3.3. Results from the Commissioning Phase

The Angstrom Project is currently in its third observing season, and this is the first season in which we have implemented the APAS. Table 1 contains a snapshot summary of statistics from a recent run of the APAS. Around 12% of the light-curve catalog is classified as variable or transient. The bulk of the rest of the light curves are either “flat” because they do not show significant light-curve variation or “void” because they do not comprise enough data points in previous observing seasons. Reassuringly, the number of variables flagged up by the APAS is in line with the variable number density derived from an analysis of three years of data from the wide area POINT-AGAPE survey (An et al. 2004). This indicates that, while probably not optimal, the APAS nonetheless competes in terms of sensitivity with previous non–real-time pipelines. We can expect that the offline ADAP analysis of the unbinned data will be more sensitive still. APAS also succeeds in presenting an easily manageable number of alerted and followed light curves for a human observer to review.

Three light curves from the subset of 38 listed alerts are shown in Figure 2. Clearly, these examples represent credible microlensing (Figs. 2a, 2b) and nova candidates (Fig. 2c). The APAS therefore demonstrates the capability to provide a rapid, robust, and credible extragalactic alert system. The first candidate in particular appears to be a very short high signal-to-noise ratio microlensing event with a measured $t_{\text{FWHM}} = 1$ day. Such events tend to be sensitive to finite source effects, and this event is currently the subject of a separate study (J. P. Duke et al. 2007, in preparation). The
detected CN (Fig. 2c) has a measured decline time of $t_* \leq 10$ days, which classifies it as a “very fast” nova. This light curve represents one of the best-sampled extragalactic very fast novae, with the nova being followed for over 120 days postoutburst.

4. DISCUSSION

We have successfully implemented the Angstrom Project Alert System (APAS), which performs real-time reduction and identification of extragalactic transient sources and microlensing events. This is the first system of its type to process extragalactic observations. The APAS has been commissioned during the third season of Angstrom observations and is already displaying the capability to identify credible microlensing and nova candidates. During the first few weeks of the commissioning process the APAS detected the shortest timescale microlensing event seen outside the Galaxy (and satellites) and obtained one of the best-sampled light curves of an extragalactic nova to date. The very nature of these events demonstrates the power of the Angstrom survey to detect events with timescales shorter than those seen by previous monitoring surveys of M31. This performance during the commissioning stage bodes well for the outcome of further observing seasons which will be further enhanced by targeted follow-up observations of alerted events. During the remainder of the current 2006/2007 observing season and in the following observing seasons, we aim to use the APAS to flag up candidate sources for higher cadence follow-up in order to obtain detailed light curves of novae outbursts, and to identify exotic microlensing systems.

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