Study of rapidly varying astrophysical objects with the “Pi of the Sky” apparatus

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ABSTRACT

"Pi of the Sky" is a detector designed for search for optical flashes of the cosmic origin in the sky. Its primary goal is to look for optical afterglows associated with the gamma ray bursts (GRB), but it is also good to tool to study any kind of short timescale astrophysical phenomena.

The apparatus consists of two arrays of 16 cameras each, which allow for simultaneous observation of big fraction of the sky. Due to on-line data analysis in the real time, it has self-triggering capability and can react to external triggers with negative time delay. The prototype with two cameras has been installed at Las Campanas (Chile) and was operational in period since June 2004 till August 2005 and upgraded in June 2006.

Database for storing large amount of astronomical measurements was developed. The general idea of experiment, apparatus and data analysis in the experiment will be presented.

Keywords : Gamma Ray Bursts (GRB), afterglows, optical flashes, detectors, robotic telescopes, short timescale phenomena, optical observations of large sky areas, mass photometry

1. INTRODUCTION

Perhaps the most powerful cosmic processes ever observed are gamma ray bursts (GRB) [1]. They stand for one of the most difficult and most interesting puzzles of today’s astrophysics. Those are

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0.1-100 s short pulses emitted by extragalactic sources. Energy of typical burst is estimated to be of the order of 10^{51} erg. Intensity of the burst is often higher than the total background from all other sources in the sky in gamma rays.

Generally there are to classes of GRBs , long bursts lasting longer then 1 sec and short bursts shorter then 1 sec. According to current knowledge long bursts are caused by death of massive star in the so called hypernova scenario. It is similar to much better understood process of supernova explosion, but it ends in a black hole rather then a neutron star. The hypernova hypothesis seems to be a satisfying theory for long bursts. However there are still many details which require better understanding. The situation is even worse in case of short bursts. Thanks to observations performed by the HETE [2] and Swift [3,4] satellites some progress was recently achieved. Most promising hypothesis is the coalescence of two compact objects in binary system. Such objects can be neutron star or black hole. The merger scenario is strongly favored by recent measurements by HETE [5] and SWIFT. In three cases SWIFT observed optical signal from short bursts and determined the distance and host galaxy [6]. Certainly, in such kind of processes extremely high energy density states are created. Study of those processes may bring new information about fundamental interactions involved in processes responsible for bursts and give new direction to particle physics.

In order to proceed with understanding the physics of GRB more data is required, one needs to observe them in wavelengths different than gamma rays. It is natural to expect that GRB should be accompanied by optical flashes [7,8]. Systematic study of optical flashes accompanying GRB can impose important limits for theories explaining bursts mechanism and their energy engines. Perhaps not every GRB is accompanied by a bright optical flash. If GRB originates from a very distant region of the Universe, its light might be strongly red-shifted and/or absorbed by an interstellar gas. Thus, studying cosmic flashes influence our knowledge of fundamental interactions and the early Universe – the very dramatic experiment which follows the basic laws of physics.

Observations of optical flashes related to GRB is quite a difficult task as it is impossible to know where and when the next GRB will occur. After discovery of afterglows by Beppo-SAX satellite in 1997 a lot of fast robotic telescopes have been build to perform follow-up observation of GRB after receiving position from the GCN network.
Development of GCN network [9,10] was important step in investigating GRB events. Thanks to it an information about observed GRB could be passed from satellites and used to guide an optical Earth-based telescope. In early years of GCN, low accuracy of measured GRB position required a long scanning of a large piece of the sky. Big inertia of typical telescopes caused that in the best case the object in question was found after many hours as a faint afterglow.

Till the launch of SWIFT the outcome of early optical observations has been rather limited and only about 60 GRB (out of several thousand detected by satellites) were identified with optical sources. Most of them were observed by large telescopes, many hours after the GRB. On this time scale the observed afterglow of the order of 20^m faints at the rate of 1^m per several hours. Only in two cases a bright optical flash was observed within first minute after GRB trigger. One was caught by ROTSE

group [11] equipped with a small robotic telescope. A flash was observed as bright as 8.6^m. The other observation was done by RAPTOR experiment [12].
At present about two dozens of devices search for GRB related flashes all over the world. These are small telescopes of relatively short focal lengths (135-500mm) with robotic mounts. They are guided by satellite signals towards a given position in the sky. Unfortunately, also in this case the delay of the signal received from the satellite and the inertia of the device itself make the chance for the flash observation within a minute to be rather small. Continues observations of big area of the sky is needed to systematically study this kind of unpredictable processes.
The SWIFT satellite has an on board optical/ultraviolet (UVOT) camera which allows fast observations of the source. The time delay is mainly due to slew of the spacecraft to the burst position and it is on average 30 sec. Fast observations performed by Swift's UVOT telescope gave limits for 6 afterglows (first half of 2005) in first 2 minutes after the gamma emission detection [13]. It is very important for understanding the dynamics of the central engine to observe prompt emission in optics, but it is still very difficult to catch the GRB in optical band when it is going on. Probably this task can only be realized by a set of wide field camera which covers big fraction of the sky and any bursts will be already in its **F**ield **O**f **V**iew (FOV) without necessity of moving the telescope. The GRB models predict also that there should be a large number of so called “orphaned afterglows” which are afterglows of the GRBs which due to geometry cannot be detected in gammas and only optical counterpart is visible from the Earth, it would be very important to observe and analyze these events.

Another motivation for wide field optical observations is the possibility of correlating position and/or time of the optical signal with signal in other bands like ultrahigh energy cosmic rays or gravitational waves, which can be detected in near future and will require confirmation. Such observations can be scientifically meaningful only if permanently recorded.

The strongest motivation to search for cosmic flashes is a desire to investigate the universe of short time scale phenomena in visual light, which has not been systematically explored yet. The history of science shows that every time a new “window on the Universe” was open, always something unexpected was discovered. We hope that the short time optical window will bring similar surprises.

Systematic search for such phenomena with typical astronomical equipment is rather difficult. Professional telescopes with long focal length are designed to observe faint objects and they have extremely narrow field of view (typically 30×30 arcsec^2). Short flashes, if exist, are too rare to have any chance to happen just in the current field of view of some large telescope. New ideas are needed and below we describe a possible one.

2. GENERAL IDEA

In order to overcome the two major problems of classical robotic telescopes we propose a different approach, based on authors' experience from particle physics experiments. The trigger propagation time can be eliminated if the device has self-triggering capability. The inertia of the system does not matter if the object in question is already inside FOV before the investigated phenomenon (e.g. GRB) takes place. The apparatus described in this paper exhibits those two features.

We propose to build a system consisting of a number of CCD cameras covering as wide field of view as possible. The cameras continuously monitor the sky by taking relatively short (5-10s) exposures. The data are analyzed on-line, in search for optical transients. The idea is simple: it is enough to check for a presence of a star-like object in a given frame, which was not present in preceding frames. The practical realization is, however difficult, because of large data stream involved. It is impossible to invent a single algorithm, which is fast enough and has high efficiency and low rate of false triggers. The problem could be solved by implementing a multi-level trigger system. The first level algorithms are very simple and have high efficiency for interesting events, but they produce a lot of background.
The rate of background events at this stage can be several orders of magnitude higher than the expected rate of real events. The only purpose of the first level algorithms is to reduce the data stream to be analysed by higher levels. Thus, the second level algorithm can be somewhat more complicated and perform a better background rejection. The highest levels deal only with a very low rate of suspected events and can employ sophisticated algorithms to clean up the final sample. More detailed description of flash recognition algorithms developed for this experiment can be found in [14,15]. Selected events can be submitted to larger telescopes to follow and can be checked against GRB triggers from other sources, even if they come much later. The raw data cannot be stored for a long time, because of limited disk space, but can be temporarily kept in a buffer, to examine any late arriving external alerts. However raw data can be reduced by about factor of ~10 without loosing important information and can be kept permanently in the database.

3. APPARATUS DESIGN

The design assumes that the large part of the sky is observed continuously. This is achieved by two sets of 16 CCD cameras, with each camera covering $20^\circ \times 20^\circ$ Field Of View (FOV). The total FOV of the system is thus 2 x 2 steradians which will cover FOV of Swift BAT detector [4] which is currently most efficient satellite detecting GRBs. It also matches the FOV of the GLAST LAT detector [16]. The original plan was to cover 2π steradians, justifying the name of the project.

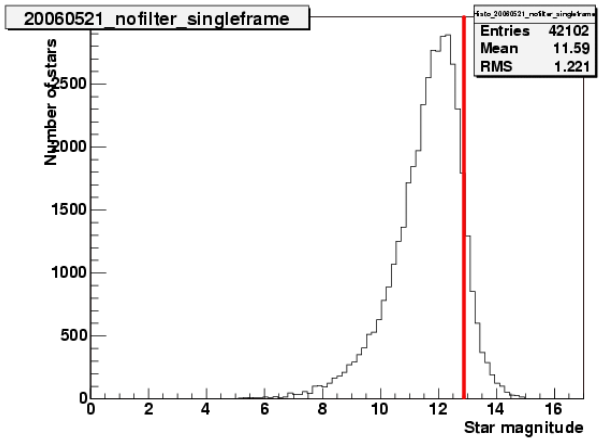

Fig 1. Distribution of stars brightness on single 10 sec image

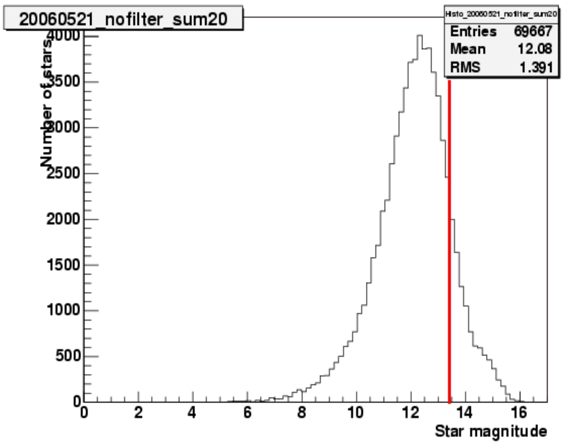

Fig 2. Distribution of star brightness on sum of 20 images

Each set of 16 cameras will be organized in such a way that 4 cameras will be installed on single mount and each site will have 4 mounts [17,18]. Cameras in separate sites will be paired and each pair will observe same field of the sky, coincidence of cosmic events in both cameras will be required. Sites will be separated by distance of ~100km which will allow to reject near Earth objects up to 30000km orbit thanks to parallax. Each camera has a CCD of 2000 x 2000 pixels of 15 x 15 μm^2. Cameras are equipped with CANON EF f=85mm, f/d=1.2 photo lenses. This gives the pixel scale of 0.6 arcmin/pixel.

Cameras read out and control is done through gigabit ethernet interface [19]. An alternative USB2.0 interface is also provided. The expected limiting magnitude for 10s exposures is 12-13m (see Fig. 1) and for 20 exposures added together it is 13-14m (see Fig. 2). Optical afterglows light curves were extrapolated to early times after the gamma emission and indicate that it will be possible to observe significant fraction of GRBs which have optical counterpart visible from Earth [20]. The apparatus is currently under construction and is planed to start collecting data in the end of 2006.

4. PROTOTYPE

A prototype consisting of two cameras has been build and installed at Las Campanas Observatory (LCO) in Chile. Regular operation started in July 2004 and was finished in August 2005, in June 2006 the prototype has been upgraded and it is currently working. The system consists of two custom designed CCD cameras installed on robotic mount.

Fig 3. Prototype in LCO after upgrade in June 2006 with CANON EF objectives f=85mm

The cameras are based on the CCD442A sensor by Fairchild Imaging. The CCD has 2032 x 2032 sensitive pixels, 15 x 15 μm^2 each. It is read out with a frequency 2 MHz/pixel, so the entire matrix is read out in 2s. After amplification, the signal is digitized by a 16-bit ADC and stored in the memory. The camera is read out and controlled by a PC through the fast USB 2.0 interface. Data transfer takes less than one second and can be done while the next exposure is already being taken. The readout speed, amplifier gain and other parameters are programmable via the USB. The sensor is cooled with a stack of two Peltier modules about 35 degrees below the ambient temperature. Design of cameras electronics is described elsewhere [21] A special heavy-duty mechanical shutter was designed to sustain over 10^7 opening cycles. The prototype has been tested at high frequency in the lab. The first signs of degradation have appeared after 1.2 x 10^7 cycles. In 2004 and 2005 the prototype operated with objectives CarlZeiss f=50mm, f/d=1.4. In 2006 objectives CANON EF f=85 mm, f/d=1.2 were installed in order to test optics which will be used in the final version of the detector.

4.1 System Automation and Observing Strategy

The apparatus is controlled by a PC located inside the dome. Two other PCs, located in a nearby Control Room are used for off-line data analysis. The system is fully autonomous, but also fully controllable via Internet. During the normal operation the system runs autonomously according to the preprogrammed schedule. Dedicated script language has been developed to make the schedule programming easy and flexible [22]. Every evening script is automatically generated according to satellite pointing information available on WWW. For most of the time the cameras follow the field of view of the SWIFT [4], INTEGRAL [23] or HETE satellite [2]. When it is not possible to observe any of the satellites, another location in the sky is programmed. The system is also listening to GCN alerts. Should an alert located outside the current FOV arrive, the mount automatically moves towards the target and exposures are being taken. Twice a night an all sky scanning is performed, which lasts 2 x 50 min.

5. DATA ANALYSIS

5.1 Data analysis requirements

The two main goals of the data analysis in “Pi of the Sky” experiment are to find interesting astrophysical processes and to reduce the raw data to the amount which can be stored permanently on the disks. Finding interesting astrophysical objects requires efficient background rejection algorithm which will remain satisfying efficiency of signal detection. Amount of data coming from the prototype is quite big and when scaled to the full design of the experiment it becomes huge so the tasks of reducing it to the required amount is not trivial, table below gives rough estimates of the amount of data produced.

STAGE	RAW DATA [2]/ NIGHT	RAW DATA / HOUR	REDUCED AND COMPRESSED/ NIGHT
PROTOTYPE	48 GB	5 GB	SINGLE FRAMES ~ 2.5 GB SUM20 ~ 1.5 GB ON-LINE RESULTS ~ 0.1 GB SCAN ~ 0.5 GB TOTAL ~ 5 GB
FULL VERSION	768 GB	80 GB	SINGLE FRAMES ~ 40 GB SUM20 ~ 24 GB ON-LINE RESULTS ~ 1.6 GB TOTAL ~ 66 GB

Table 1: Data stream in pi experiment for prototype and full version estimates

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[2] Raw data means without any compression

The amount of data in the full design is quite substantial and probably it will be necessary to reduce it more in order to keep it permanently.

5.2 On-line data analysis

The main purpose of on-line data analysis is to find short time scale optical flashes and possibly distribute alerts to astronomical community so that bigger telescopes can make follow-up observations. On-line algorithm must be simple and fast It acts on pixels, comparing image with the average of several previous images and finds objects which appeared on new one and were not present on previous images. More details on on-line flash recognition algorithm can be found in [14,15] . Currently there are three versions of algorithm running on-line, which allows to detect flashes in different time scales :

- coincidence on single 10 sec exposures, this algorithm requires coincidence of optical flash on both cameras in same position and time
- confirmation on next frames, this algorithm acts on frames from single camera and requires confirmation of object on 2 consecutive images
- coincidence of optical flash on both cameras but on sum of 8 consecutive images, this allows to look for flashes of times scale of about 1.5 minutes

Since the start of the prototype about 100 of optical flashes were detected with the on-line algorithm. The most interesting one was the outburst of the flare star CN Leo [24] . On-line events are immediately placed on WWW server and are analysed by person on duty, in case interesting astrophysical phenomena event is found it can be send to other astronomers.

5.3 Off-line data analysis

Off-line data analysis is based on a database. In order to store the results of measurements a repository using PostgreSQL database has been developed. Star catalogue database structure can be found in [25].

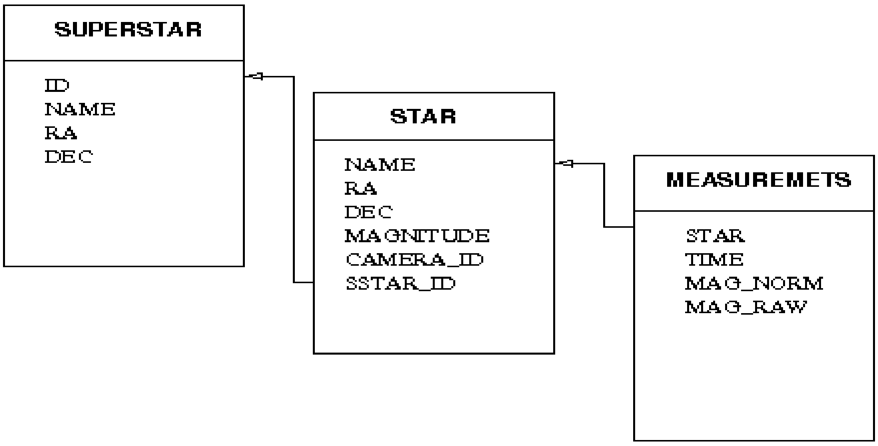

Fig 4. Pi star catalog database structure

For every star observed by the telescope a record in table Star is created and subsequent brightness measurements are inserted into table Measurements and linked to Star table record. Database tables have much more fields, however only these most important are show on the Fig. 4. A lot of effort was done in order to optimize writing large amounts of data and fast read of data from the database. This includes creating of indexes and clustering data so that all measurements of given star are stored in same place on the disk allowing fast readout. For more details see [25]. Conversion of raw data to final structure in the database requires several steps of processing. Raw data from cameras is saved to files in FITS format [26], each FITS corresponds to a single image of the sky. Generally files consist of text header and binary data. The header contains useful information about instrument, coordinates, weather conditions etc, in simple form KEYWORD=VALUE. In the binary section the data from the CCD chip is placed, containing values of all pixels on CCD chip as continues sequence of bytes. The main parts of the reduction process are the following :

- **photometry** – acts on `fits` files, finds all stars on each image, calculates their magnitudes by summing values in pixels surrounding the star within defined aperture, determines (x,y) coordinates of each star on CCD chip. Result of this step is saved to so called `mag` file, which is basically list of stars with instrumental magnitudes and chip coordinates.
- **astrometry** – acts on `mag` files, finds transformation from chip coordinates (X,Y) to celestial coordinates (RA,DEC), calculates (RA,DEC) for all stars in `mag` file and saves it to star list file `ast`, so the difference between `mag` and `ast` file is that `ast` contains (RA,DEC) coordinates.
- **normalization** – acts on `ast` files, uses external star catalogue. Up to this moment calculated magnitudes are instrumental magnitudes and require normalization in order to become absolute magnitude. This is done in such a way that stars in `ast` file are found in star catalogue (currently Tycho catalogue is used) and correction of magnitude which must be added is calculated, according to formula :

$$\Delta mag = mag_{CAT} - mag_{\pi}$$

After calculating this correction for all stars which exist in `ast` and also have corresponding star in catalogue correction image which is a map of correction values for every pixel on CCD chip is created. For every pixel on the CCD the correction value is calculated according to interpolation of several nearby pixels with catalogue stars. For all stars in `ast` file magnitude correction $\Delta mag(x,y)$ is applied. Results of this stage are passed to the next step, as both normalization and cataloguing are realized by single program and do not require saving of temporary results

- **cataloguing** – this is last step and acts on results of normalization phase, it saves data to the database. This stage contains several main steps, executed for every `ast` file, these are :

    1. Data quality check – checks if the data is good enough to be stored in the database. This includes : cloudy data rejection, bad astrometry rejection, etc ...
    2. In case `ast` file from new sky position (field) is detected, stars from this position are selected from the database
    3. Stars in `ast` file are matched to stars selected from database
    4. In case a star in `ast` file does not have counterpart in database new record Star is created
    5. For each star in `ast` file new record Measurements, containing normalized and raw magnitude and time, is created and linked to the Star record
    6. In table Star multiple instances of same celestial object can exists multiple times as seen by different cameras. Final instance of astrophysical object is stored in table SuperStar. Every Star record should finally be linked to a single SuperStar record. In this step each record in table Stars is examined and in case SuperStar record is missing it is created and Star record is linked to it.

- Database optimalization and recalulation of statistics for all stars for fast access to star information like : mean magnitude, dispersion of magnitude etc ...

After the last step of the pipeline the data is catalogued in the database and optimized for fast access. This processing pipeline is already working in Las Campanas, so the data collected each night is stored in database allowing fast and easy access to star brightness observations.

5.4 Off-line data analysis algorithms.

Database gives an opportunity to perform many kinds of analysis. This can be manual analysis of selected objects using specially developed WWW interface [25], java client using Tomcat server [27] or more sophisticated automatic analysis in form of program/script accessing database and finding interesting objects. There are several off-line algorithms already working or in very advanced phase of development :

- *nova recognition algorithm* , analysis scan data and looks for new star like objects appearing on the sky. Scan of all sky is performed twice a night so it can generally find new objects with one day resolution, this is described in more details here [28]
- *fast-nova recognition algorithm,* is a version of *nova recognition algorithm* but instead of acting only on scan data it acts on normal night data, which allows to find new objects appearing on the sky with the seconds to hours resolution.
- *flare recognition algorithm* - is a algorithm for finding sudden brightness increase of stars already present in database, some stars called “flare stars” have sudden explosions due to magnetic field reconfiguration effects and can increase their brightness by several magnitudes. This algorithm is a tool for finding such kind of variations in our data. More details on this type of algorithm will be given in the next subsection.
- *variable star identification* – the purpose of this algorithm is to identify variable stars in “Pi of the Sky” data and classify them to proper class of variability. In final version it will be possible to run this algorithm on any kind of data to find all types of variable stars with long and short periods [25]

This database based algorithms are recently developed and are now being incorporated into the system after the upgrade. Some of them were already tested off-line on data collected in data run June 2004 – August 2005 and gave promising results which can be found in [28] .

5.5 Flare recognition algorithms

This algorithm was developed to find outbursts of stars which are already in “Pi of the Sky” catalogue, but manifest sudden increase of brightness. The analysing script find_flare.pl was written in perl, and most important steps for this analysis are the following :

- selection of stars with number of measurements >= limit (= 20), next steps are performed for each selected star
- find magnitudo range in which 50% of measurements reside, the border values are named as final_min_mag and final_max_mag, brightness limit for potential flare is chosen as value final_min_mag and named as mag_max_allowed

- longest serious of measurements with mag < final_min_mag with monotonic behaviour is found and is assumed to be a flare. Flare magnitude in maximum brightness and number of flare points is determined and checked against given thresholds
- (X,Y) coordinates are checked, to ensure that flare occurred during long observation on single field and it is not any kind of effect due to position change and measurement instability
- coincidence of flare on both cameras in the same time is required

In case all criteria which were briefly summarized above are satisfied the star is written to the database table FlareEvents and its light curve can be further inspected by human to check if it can really be an interesting flare event.

The figure below shows a nice example of flare star EQ Peg which was inspected as known flare star by human and also nice example of flare candidate found be algorithm.

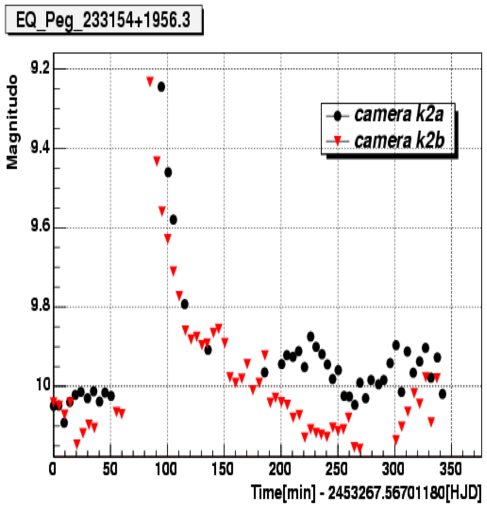

Fig 5. Light curve of outburst of flare star EQ Peg

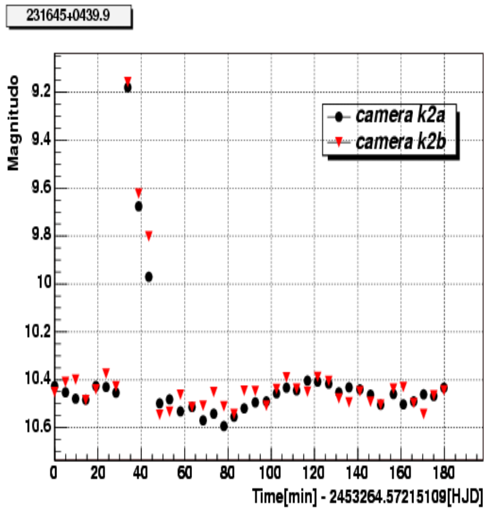

Fig 6. Flare candidate found by the algorithm

6.CONCLUSIONS

The “Pi of the Sky” experiment is in an advanced phase of development. Dedicated hardware and software solutions were developed and are continuously tested on the prototype in Las Campanas. Data analysis software was developed and is giving promising results, showing that final version of the detector with large sky coverage will be a good tool for investigation of the short timescale optical processes in the Universe. Final version of the detector is planed to start collecting data in the end of 2006.

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