Variable stars study in “Pi of the Sky” project

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ABSTRACT

The detector “Pi of the Sky”searches for optical flashes in the sky. Its main goal is to look for optical afterglows associated with gamma ray bursts (GRB), but it also has a capability to detect other phenomena like variable stars. Collected data passes through a specially designed software pipeline. At last. a collection of stars’ light curves is obtained and put into a database. At this level it is possible to study stars and analyse their variability. Example results are presented.

Keywords: variable stars, software pipeline, data reduction, photometry, astrometry, cataloguing, star database, light curve

1. INTRODUCTION

“Pi of the Sky” goal is to investigate objects of the variability timescale from seconds to years. It was optimised to look for optical counterparts of **G**amma **R**ay **B**ursts (GRB). GRB’s are short (0.01-100s) pulses emitted by extragalactic sources. They can originate from supernovae explosions followed by a colaps to a black hole, neutron stars collisions or other, even more exotic phenomena. Nowadays satellites record several GRB per month and send alerts via GRB Coordinate Network.

The “Pi of the Sky” apparatus monitors the sky continuously taking 5 images per minute. It allows us to observe many other astronomical phenomena besides GRB’s. Among them are various types of variable stars, meteors, etc.

2. “PI OF THE SKY” APPARATUS AND DATA FLOW

Two CCD cameras have been installed in Las Campanas Obserwatory (LCO) in Chile. Every night they collect about 3 000 images, about 8 MB each. That gives roughly 50 GB per night. It's impossible to store all of this data on our computer's disks for a long time. Therefore, the data have to be analysed instantly. The analysis is organised in three streams:

- online trigger
- single frame photometry
- photometry on co-added frames

The online trigger is designed to recognize fast optical transient in real time. To achieve this goal it has multilevel structure. The first level algorithms are relatively simple and their goal is to reduce quickly the data stream selecting only suspected objects. It operats on the data in a computer memory, before they are stored on a disk. Further levels can be gradualy more complicated as they have less and less data to analyse. As a result, several transient candidates are found each night and they are subject of careful human inspection.

The single frame photometry runs on a second computer, where the data are copied immediately after they aren read out from the cameras. In order to increase the range of stars to be studied and improve measurement precision, the images are added by 20 and more accurate photometry is performed. This analysis is done during the day, as soon as the data taking is ended.

At cloudless night there are roughly 20 000 stars per image from each camera. On coaded images this number increases to about 30 000 stars. In total the system makes 120 000 000 photometric measurements per night. Raw data is acessible for 5 days in a case of later comming of any external alert. After reduction, only 2 GB per night remains on disks. The disks are taken to Warsaw every 3 months for further analysis.

3. SOFTWARE PIPELINE FOR DATA ANALYSIS

The final result of the analysis is a light curve of each star, i.e. a graph of star brightness (expressed in units of *magitudo*) as a function of time. In order to achieve this, the following steps are performed.

3 .1 Reduction

Reduction goal is to reduce apparatus effects. Usually, it consists of two steps. A *dark frame substraction* allows to reduce the effect of the dark current causing parasitic charge accmulation in CCD pixels. The dark frame is obtained by taking exposure with closed shutter. *A flat-field frame division* permits to correct for optics nonuniformity and differences between pixels. The flat-field frame is usually obtained by exposing the chip to a source of homogeneous light; for example by taking the sky pictures at dawn. Unfortunately, this method is not good for large fields of view because of a brightness gradient. Instead, our flat-field images are obtained as a median of frames taken with a fixed mount. The Earth rotation causes, that the stars are in different positions in different frames. Thus, the median removes the stars and only the sky background remains.

3.2 Photometry

Photometry creates a list of stars in the frame with their pixel coordinates (x,y) and calculates their instrumental brightness. The instrumental brightness is simply the sum of pixel values in a certain predefined neighbourhood of a star, called aperture, minus the background level. In the case of “Pi of the Sky” the need for wide field observation limits the lens size, and not much light is at disposal. Therefore, in order to be able to observe objects as faint as possible, the light is concentrated on few pixels only. Hense, the aperture chosen for photometry is rather small. It consits of 13 pixels: 3×3 square plus 4 adjacent pixels of highest value among all neighbours.

3.3 Astrometry

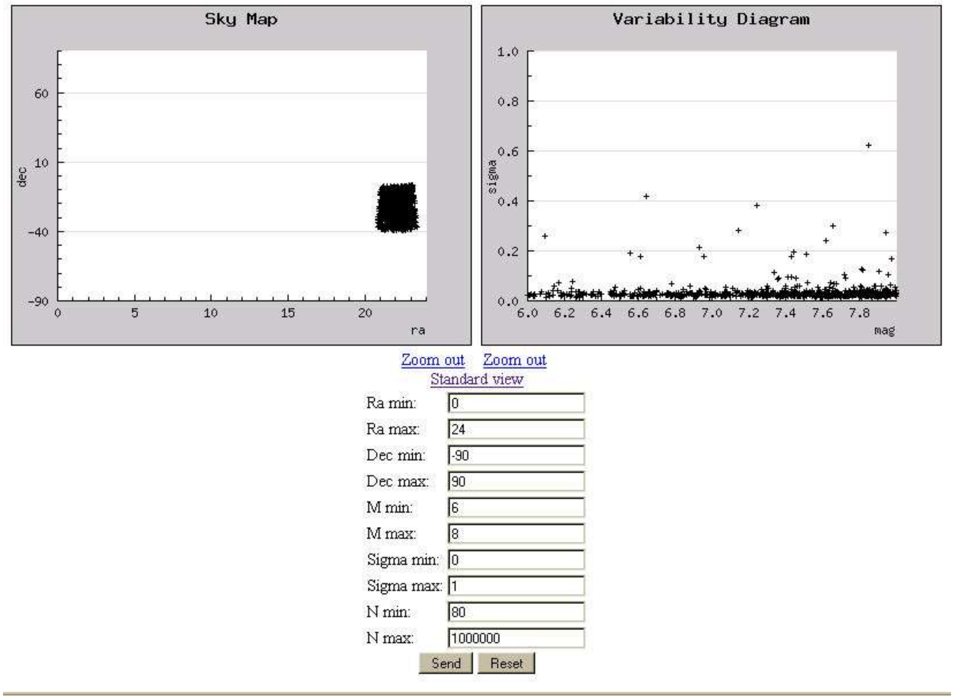
Astrometry algorithm compares the list of stars in instrumental coordinates (x,y) with a star catalogue and finds the transformation of instrumental coordinates into the physical coordinates in the sky (right ascention and declination). Then, it calculates the celestial coordinates of each star in the frame.

3.4 Cataloguing

Cataloguing procedure calibrates the instrumental brighthness by comparing results for certain number of reference stars with a catalog data, and determines the physical brightness (magnitude), of each star on the frame. After that, the data are stored in a data base (Section 4).

3.5 Visualisation

The last step of the analysis is human inspection of collected light curves. Visualisation program profits from the fact, that the data are stored in a specialy designed database. The database facilitate filtering of data according to user’s choices and enables light curve visualisation for each selected star. The database interface is presented in Fig. 1. It consists of two graphs. The left one shows the observed part of the sky. The right one is the Variability Diagram – root mean square of measurements distribution for each star versus the average brightnes of the star. This diagram is very useful for serching variable stars, as they stay away from the “main stream” of stars with the RMS determined by measurement errors.



Ra min: 0
Ra max: 24
Dec min: -90
Dec max: 90
M min: 6
M max: 8
Sigma min: 0
Sigma max: 1
N min: 80
N max: 1000000

Fig. 1. User interface to the star database.

4. DATABASE

The database consists of two main tables: stars and measurements. The star table stores the information about each star, e.g. its coordinates in the sky. The measurement table keeps the information from each measurement of a star, e.g. the measured magnitude, the measurement error and the time stamp. To speed up searching, a few statistical parameters calculated for measurements of each star are stored in the star table. Those include the mean magnitude, the RMS of magnitude, the minimum and maximum magnitude, the number of measurements. Those fields should be updated each time new measurements are added. In the prototype we are using PostgreSQL database but we plan to switch to a commercial DBMS in the future to allow distributed data storage.

In addition to the database we have created a web application which allows easy browsing of the star data and plotting light curves of selected stars. On the main page there are two plots: the sky map and the variability diagram as described above (Fig. 1). Both plots can be zoomed in by drawing a rectangle with the mouse. Both plots show only those stars which fit into the range of the axes of both plots. Apart from the ranges of RA, Dec, magnitude and RMS (“sigma”) a user can select the range of measurements for stars and the time interval when he wants to find at least one measurement.

After clicking on a star the application will show a page with the star's light curve (magnitude vs. time, as in Figs 2-8) and additional information about the star. It is also possible to get the measurement data as a text file for further processing or a ROOT package macro which draws the same plot. The light curve can be zoomed in the same way as the plots on the main page. One can also plot average values of a number of consecutive measurements. This help with analysis of faint stars because statistical fluctuations are averaged out. In addition, a light curve can be plotted modulo a given period. The application was implemented using php on the server side and java-script on the client-side. For drawing plots we used jpGraph library.

5. SYSTEMATIC ERRORS

Before claiming discovery of a variable star one has to make sure, that the variation is not caused by an instrumantal reason. There are many sources of possible errors.

5.1 Pixel-to-pixel and intra-pixel variations.

The mount movements, although rather precise, they are not perfect. If the compensation of the Earth rotation is not perfect the center of the star image may drift through the CCD. Measurements taken at different nights might have a given star recorded at different pixels. It would not be a problems if all pixels were identical and uniform. This is, however, never the case. We have observed wavy behaviour of light curves in phase with the drift of the stars through the pixels. It was significantly reduced after introducing an autoguiding with a feedback from astrometry to correct the mount speed.

5.2 Lens related effects

The lenses we use have rather large relative aperture (the “speed”) *f/d*=1.4. It is very difficult to make such lenses giving uniform illumination over the whole image. In our case the corners are twice less illuminated than the center. This effect should be to large extend corrected by the flat-field technique, but the residuals cannot be neglected. Also the shape of point spread function varies with the position on the image. Perfectly round in the center becomes more triangular towards edges. This causes that the same photometric aperture gives dirrerent result at different positions.

5.3 Vignetting by the shutter

Mechanical construction of the shutter prevents light to enter the CCD from a side. This effect may cause that some pixels near the edge of the CCD do not collect all light from a given star. This, combined with some image drift, e.g due to imperfect mount tracking, may cause a false transient effect. An example is given in Fig. 2. The ligth curve has a characteristic step, which looks like the end of an eclipse.

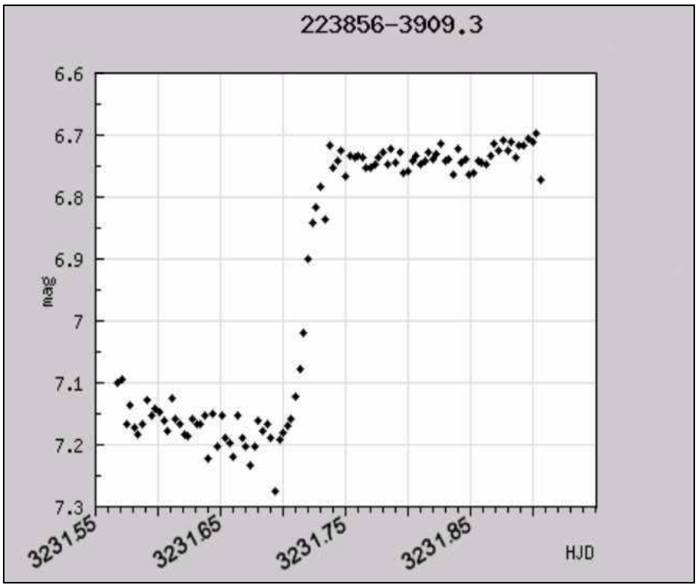


Fig. 2. A light curve with a characteristic threshold.

5.4 Clouds and the Moon

The moonlight, especially near the full Moon, causes the sky background to be much brighter. In principle, the photometry subtracts the sky background, but again, residuals might be significant. The clouds have two effects. Thin cirrus spread over the sky scatters the moonlight and increases the background brightness even higher. Denser clouds may cause "star eclipse" like the one shown in Fig. 3.

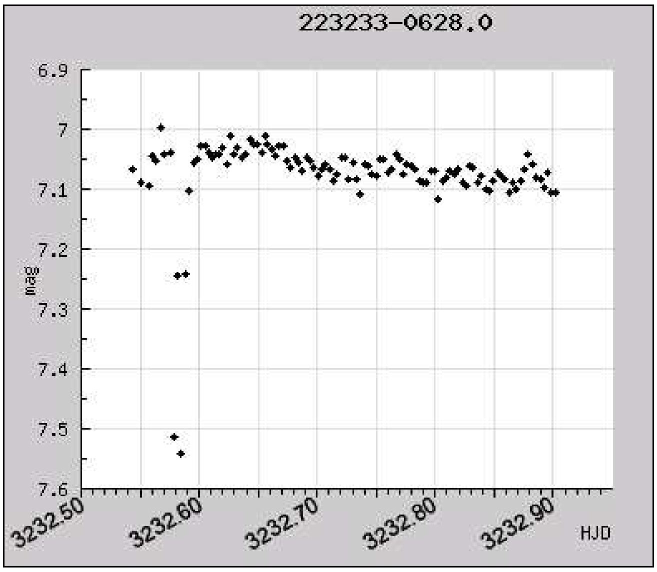


Fig. 3. An example of a light curve showing effect of a cloud covering the star for a short moment.

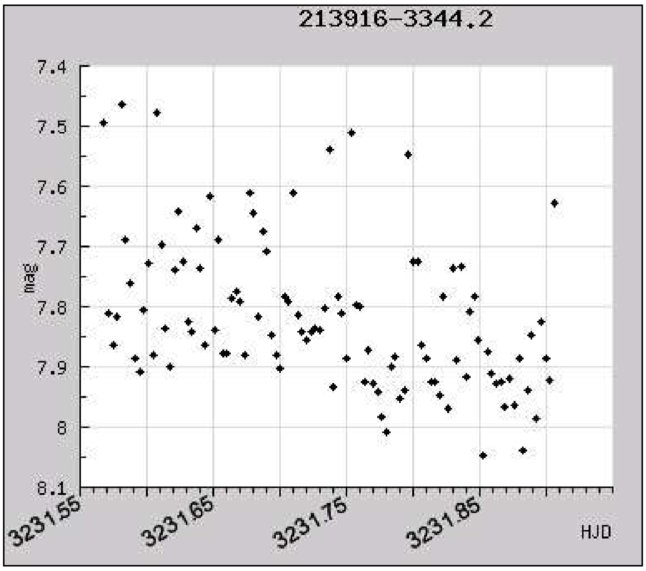


Fig. 4. An apparent variation caused by the effect of blending of nearby stars.

5.5 Blending of neighbouring stars

The pixel scale of 1 arcmin/pixel results in high density of stars, esspecialy toward the Milky Way center. Star blending causes that the photometric aperture may contain some light from another star and the background subtraction might be seriously afected. Even very small drift of the mount gives significantly different light distribution among pixels and creates an effect of an apparent variation. An example is shown in Fig. 4, where three stars (6.3m, 9.1m, and 9.3m) are within 2-3 pixels distance from each other.

6. LIGHT CURVES

After reducing the errors and eliminating light curves exhibiting apparent variation due to instrumental reasons one can begin to study real variable stars. Two examples of periodic variables are given in Figs 5 and 6. Presented observations were made during two consequtive nights. Both stars are designated as "new suspected variables" of unknown type and period. From the figures one can estimate their periods as 10h and 15h. The small values of the periods explain why the stars have been only "suspected" as variables. Observation of such fast variation is very difficult with traditional methods.

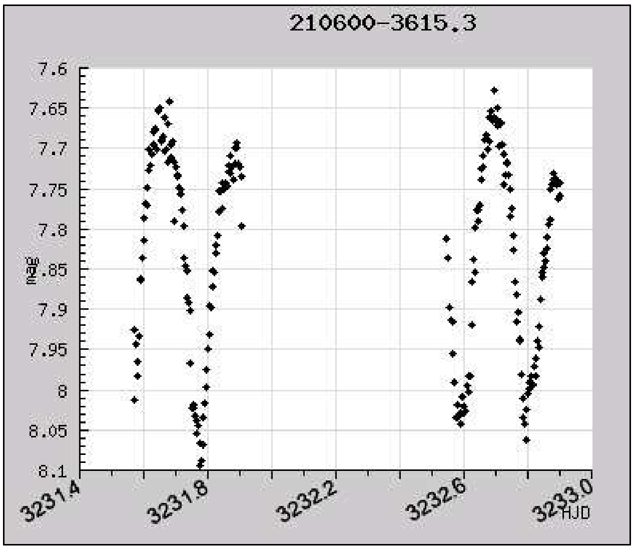


Fig. 5. Variable star HD 200670, NSV 13515.

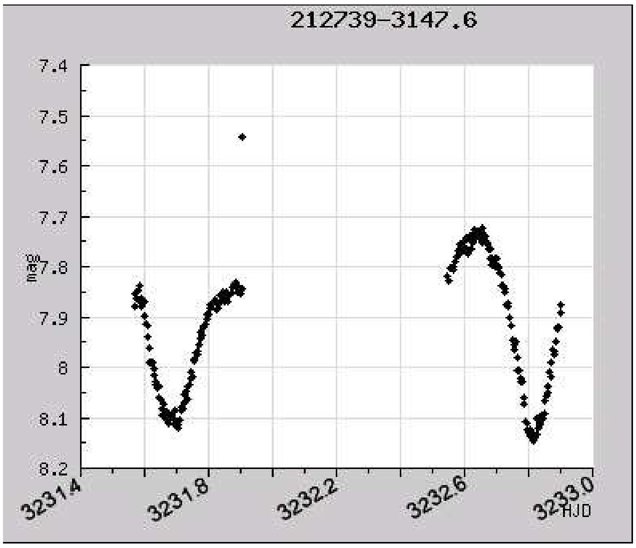


Fig. 6. Variable star HD 204179, NSV 13712.

7. CONCLUSIONS

“Pi of the Sky” apparatus, oryginally design to search for GRB optical counterparts has proven itself to be useful in studying variable stars. Thousands of measurements for each star per night enables search for short period variables with a period as short as minutes. Rapid optical transients could be observed and increase our knowlegde of cataclismic variables.

ACKNOWLEDGMENT

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