PROCEEDINGS OF SCIENCE

"Pi of the Sky" - an innovative approach to astrophysical optical transients detection

K. Malek*, **L. Mankiewicz**
Center for Theoretical Studies PAS, Al. Lotnikow 32/46, 00-668 Warsaw, Poland
E-mail: malek@cft.edu.pl

J. Uzycki, M. Zaremba
Faculty of Physics, Warsaw University of Technology, Pl. Politechniki 1, 00-661 Warsaw, Poland

G. Kasprowicz
Institute of Electronic Systems, Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warsaw, Poland

M. Cwiok, H. Czyrkowski, R. Dabrowski, W. Dominik, L.W. Piotrowski, A.F. Zarnecki
Institute of Experimental Physics, Warsaw Univeristy, Hoza 69, 00-681 Warsaw, Poland

M. Biskup
Institute of Informatics, Warsaw University, Banacha 2, 02-097 Warsaw, Poland

A. Majcher, A. Majczyna, K. Nawrocki, M. Sokolowski, G. Wrochna
Soltan Institute for Nuclear Studies, Hoza 69, 00-681 Warsaw, Poland

M. Denis, J. Juchniewicz, R. Pietrzak, R. Wawrzaszek
Space Research Center, Polish Academy of Science, Bartycka 18 A, Warsaw, Poland

The "Pi of the Sky" experiment is designed for continuous observation of a large part of the sky in search for optical flashes associated with gamma ray bursts (GRBs) and other short optical transients. It is also a sophisticated instrument looking for novae and supernovae stars. The apparatus consists of two arrays, 16 CCD cameras each, working in coincidence mode. The whole system continuously observes 2 steradians of the sky with a time resolution of 10 seconds. The whole system is currently in an advanced stage of construction. Required hardware and software tests were performed with a prototype. It is located in Las Campanas Observatory in Chile and consists of two cameras working in coincidence. The detector allows us to search for optical counterparts of GRBs and study other kinds of short timescale astrophysical phenomena. The "Pi of the Sky" analysis system is a very efficient tool. The automatic trigger detected bright flares (for example CN Leo, GJ 3331A / GJ 3332), cataclysmic variables (for example dwarf nova 1RXS J023238.8-371812), some spectacular meteor explosions and others interesting events.

Supernovae: lights in the darkness (XXIII Trobades Científiques de la Mediterrània)
October 3-5 2007
Mao, Menorca, Spain

*Speaker.

PoS(SUPERNOVA)020

1. Introduction

The aim of the "Pi of the Sky" project is to investigate objects with variability time scales ranging from seconds to years, but the primary goal is to search for optical transients related to Gamma Ray Bursts (GRBs). These fascinating phenomena were discovered in 1967 but the first information was published four years later [1]. For the first 28 years of study the only method to observe the GRBs was the detection performed by satellites equipped with gamma and X-ray detectors. The situation changed in 1997 when the Italian-Dutch X-ray satellite BeppoSAX determined precise coordinates, with estimated error radius 50" [2] only 8 hours after the burst GRB970228. The coordinates were send to several instruments on the ground. Telescopes started to observe this part of the sky a dozen hours later and faint optical and radio afterglows were detected [3]. It was the step forward in the GRB studies because of possibility to perform spectral analysis and measure the distance. These measurements confirmed that the bursts occur at cosmological distances. This first observation using satellite and ground instruments proved that this type of follow-up cooperation is necessary to study these intriguing phenomena. This also shows that in order to understand the nature and mechanism of GRB, observations in all wavelengths are required. Unfortunately, less than 280 GRBs were detected in the optical range because of the large dimensions of telescopes, which require some time to move to the desired position of the sky.
The motivation of the "Pi of the Sky" project is to search for GRB bright optical flashes within, during or even before GRB triggers. This time region is yet unexplored and could reveal new, significant information about the physical processes in their sources.
Unique design of the "Pi of the Sky" detector and special observation mode also gives opportunity to automatically identify other interesting processes on the sky. Each night, the whole sky is scaned twice, the first time at the beginning and the second time at the end of the night. This systematic scan is very important for investigation of objects with variability timescales of days and more [4].

2. The inspiration

We propose a system that can continuously monitor a large part of the sky in the visible searching for the GRBs optical counterparts and other short timescale phenomena. The idea is to take short exposures of the sky and compare the present frame with preceding one looking for new star-like objects. Because of the large data stream involved, we decide to make use of the experience from particle physics experiments. A special multi-level trigger system was implemented, which rejects background step-by-step. Selected candidates are compared with other cameras and objects that are found only on one camera, in catalogues of satellites or constant stars are removed. A set of sophisticated steps yields only a small number of potentially interesting events per night [5]. These events are subject to human inspection and interpretation.

3. "Pi of the Sky" full detector

The "Pi of the Sky" system is designed to continuously observe as large part of the sky as possible. We suggest a system consisting of two sets of 16 CCD cameras installed on robotic,

PoS(SUPERNOVA)020

parallactic mounts with declination and right ascension drives [6]. For budget reasons it is not possible to place each camera on it is own mount. Finally, we decided to install 4 cameras on one mount, but with two observing modes. In the first mode cameras observe neighbour fields of the sky. In the second mode all 4 cameras observe the same field. The total Field of View (FOV) of the system will be 2 steradians which covers the FOV of Swift satellite [7]. The Swift satellite was chosen because it is currently the most efficient GRB detecting instrument.

This aim is achieved in practice by two sets of 16 CCD cameras. Each camera covers 20^o x 20^o FOV. One mount with four cameras permits to cover 40^o x 40^o FOV. One set with 4 robotic mounts and 16 cameras is able to cover planned 2 steradians. The second set consisting of 16 cameras observes the same part of the sky, but from a distant location (about 100 km). This kind of design allows to reject sunlight reflexes from satellites and other near-Earth sources by parallax. Another common background source for our detector are the cosmic rays. The simplest method for eliminating cosmic rays is taking coincidence with camera from the second set observing the same field of the sky.

Each camera is based on a CCD matrix with 2048 x 2048 pixels. The sensor is cooled with a Peltier module about 30 degrees below the ambient temperature. CANON EF with focal length f=85 mm and f/d=1.4 photo lenses were used. The pixel resolution is 15 μm which corresponds to 36 arcsec on the sky. The cameras continuously monitor the sky and take 10 seconds exposures. The expected limiting magnitude for 1 frame is 12^m and for 20 frames added together is 14^m. Cameras are equipped with custom designed, special heavy-duty mechanical shutter which can sustain over 10^7 opening cycles [8]. The readout frequency, gain, CCD temperature, mechanical shutter and lens position are remotely controlled. Sensors for on-line monitoring of atmospheric condition were also added. This option permits measurement of the temperature and humidity inside and outside the camera device.

The full system is under construction now. The design and plan phases has been already completed and the first parallactic mount and the cameras are tested now.

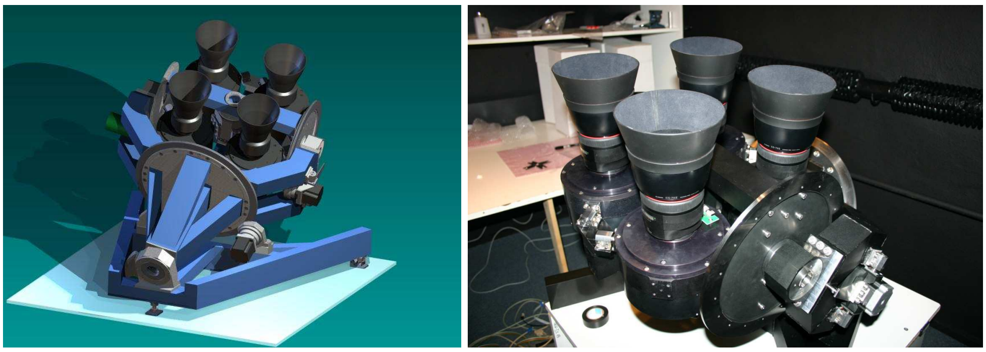

Figure 1: Robotic mount - scheme and the final construction.

PoS(SUPERNOVA)020

4. Prototype

4.1 The apparatus design

A prototype was installed in Las Campanas Observatory in Chile. This site was chosen because of very good weather conditions for observation. Regular observations started in June 2004. The instrument consists of 2 CCD cameras designed for automated surveys, mounted on a common parallactic mount. Prototype CCD cameras were equipped with Fairchild Semiconductors CCD sensors of 2000 x 2000 pixels with 15 μm pixel size and photo lenses of f=85 mm, f/d=1.2, giving 20^o x 20^o FOV. One pixel is equivalent to 36 arcsec on a sky. The sensor is cooled about 40 degrees below the ambient temperature by a Peltier module. Every night the system collects about 2000 images from one camera only. Because of the limited FOV, the prototype detector cannot observe the whole sky at once.

Figure 2: "Pi of the Sky" prototype, Las Campanas, Chile.

4.2 Observing schedule

Every evening the special script for the instrument is automatical generated. A dedicated script language has been developed to simplify the communication between the detector and the controlling computer. This schedule is used to initialize the modules, dark frame collection, observing FOV of Swift and shutdown the system. The cameras follow the FOV of the Swift satellite for most of the observation time, but twice a night, at the beginning and at the end of the night all sky scan is performed. During the scans, the cameras visit nearly 30 pre-defined fields and collect three 10s images of each field. This series of images of the whole celestial sphere taken every night is important for the investigation of objects of the variability timescale from hours to days and more. The scan mode is responsible for searching and monitoring cataclysmic stars.
During the night the system manager program monitors parameters like CCD temperature, number of stars on images etc. The system is reliable, fully automatic and remotely controllable via the Internet. In case of any problems, an email or sms is sent to the human operator.

4.3 Results

The prototype worked without a permanent human supervision from July 2004. During this time, basic software was regularly developed to improve flash and nova-like star recognition algorithms. Throughout 3.5 years the system detected about 150 optical flashes of unknown origin visible on a single frame and 2 cameras. It is possible that they are caused by flashing satellites, which are not present in available databases. The algorithms also found 8 events visible on 2 images which corresponds to >12s duration time. One of them was identified as bright outburst of CN Leo flare star (RA = $10^h56^m29^s$, Dec = $+7^o01'$). On images before the outburst, the star was not visible and during a few seconds, its brightness raised by factor 100 and then it gradually faded away during several minutes. An example of this automatic on-line detection confirms that "Pi of the Sky" is capable to discover optical flashes of astrophysical origin.

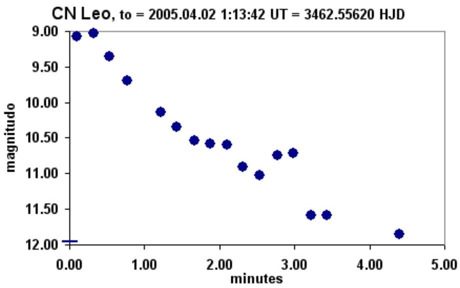

Figure 3: Outburst of CN Leo star automaticaly detected by flash recognition algorithm.

The final instrument is still under construction and all observations are carried out with the prototype. From 2004.07.01 to 2008.01.08 satellites observed 245 GRBs with known positions. Only 39 were accessible from our cameras (because of the night time, south hemisphere, altitude above the horizon, weather conditions etc.) and 3 of them occurred inside the FOV of the prototype. In case of the remaining 36 GRBs the system moved to the desired position after receiving the alert from the Gamma ray bursts Coordinates Network (GCN), but no optical sources have been found. Limits for optical counterparts for them set by 'Pi of the Sky' were published as GCN Notices.
Identification algorithms for novae are performed on data collected during the all sky scans. The nova-searching on-line algorithm does not concentrate on the determination of nova parameters, but rather on the fact of observing new object. Another one, novae searching retroactive algoritms is based on nova characteristic function of brightness. Both of them are efficient tools for searching for novae and other variable stars as well as planetoids. The most impressive results of both algorithms were: the identification of Nova V5115 Sgr in our database and the discovery of two dwarf novae stars. The first dwarf nova was 1RXS J023238.8-371812, a large-amplitude cataclysmic binary, most likely a WZ Sge system [9]. The "Pi of the Sky" algorithm identified this star in the middle of September 2007. Two months later, at the end of December 2007, the same algorithm discovered the second cataclysmic star: a WZ Sge variable in Hya (RA = $11^h12^m17.4^s$, Dec = $-35^o38^m29^s$) [10]. The American Association of Variable Star Observers (AAVSO) has published a special notice related to these two objects and the astronomers still observe and analyse their characteristic. The "Pi of the Sky" detector, designed to search of GRB optical counterparts, has proven to be useful in discovering new cataclysmic objects on the sky.

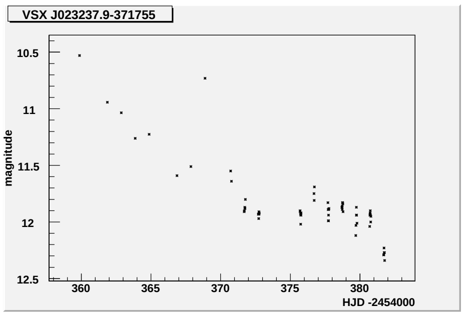

Figure 4: Outburst of 1RXS J023238.8-371812 automatically detected 2007.09.16 08:53:44 UT = 2454359.874 HJD. All measurements coming from the "Pi of the Sky" database.

We analyzed also all our measurements from years 2004-2005 to find variable stars and determine their variability periods. We published a catalog of 725 variable stars [11]. The catalogue contains stars with periods ranging between 0.1 and 10 days. The types of variability were determined through a visual inspection. Most of the variable stars in our catalog are eclipsing binaries of W UMa type. We also determined accurate periods for 15 stars from the GCVS catalog for which periods were unknown [11]. The catalogue and algorithms results are available on the "Pi of the Sky" webpage http://grb.fuw.edu.pl.

References

[1] R. Klebesadel, I. Strong, R. Olson, *Observation of gamma ray burst of cosmic origin*, The Astronomical Jurnal, 182:L85, 1973

[2] E. Costa et all., E. IAU Circ. No. 6572 (1997)

[3] C. Akerlof, *Observation of contemporaneous optical radiation from a big gamma-ray burst*, Nature 398, pp. 400-402,1999

[4] K. Malek, L. Mankiewicz, L.W. Piotrowski, M. Sokolowski, *All sky scan analysis for "Pi of the Sky" project*, Proc. SPIE Vol. 634, 2006

[5] L.W. Piotrowski, M. Sokolowski, *Simulation of point-like optical flashes in the sky*, Proc. SPIE Vol. 5484, pp. 290-299, 2004

[6] M. Cwiok et all.,*"Pi of the Sky" robotic telescope*, Proc. SPIE Vol. 6159, pp. 154-159, 2005

[7] N. Gehrels et all., *The Swift Gamma-Ray Burst Mission*, astro-ph/0405233,2005

[8] A. Burd et all., *Pi of the Sky - all-sky, real-time search for fast optical transients*, astro-ph/0411456, 2004

[9] AAVSO Special Notice 72, *1RXS J023238.8-371812 rapid fading*, October 12, 2007

[10] AAVSO Special Notice 87, *New WZ Sge variable in Hya*, January 5, 2008

[11] A. Majczyna et all., *The catalog of short periods stars from the "Pi of the Sky" data*, New Astronomy, 2008, in print