Hindawi Publishing Corporation
Advances in Astronomy
Volume 2010, Article ID 194946, 9 pages
doi:10.1155/2010/194946

Research Article

"Pi of the Sky" Detector

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Received 29 June 2009; Accepted 27 October 2009

Academic Editor: Taro Kotani

"Pi of the Sky" experiment has been designed for continuous observations of a large part of the sky, in search for astrophysical phenomena characterized by short timescales, especially for prompt optical counterparts of Gamma Ray Bursts (GRBs). Other scientific goals include searching for novae and supernovae stars and monitoring of blasars and AGNs activity. "Pi of the Sky" is a fully autonomous, robotic detector, which can operate for long periods of time without a human supervision. A crucial element of the detector is an advanced software for real-time data analysis and identification of short optical transients. The most important result so far has been an independent detection and observation of the prompt optical emission of the "naked-eye" GRB080319B.

1. Introduction

"Pi of the Sky" is a robotic telescope designed to perform observations in autonomous mode, without any human supervision. The detector has been designed mainly to search for the optical prompt emission of the Gamma Ray Bursts (GRBs) which can possibly occur during or even before gamma emission. The standard approach to look for optical afterglow associated with GRBs is to wait for satellite alerts distributed by the GCN network (The Gamma Ray Burst Coordinates Network) [1] and move the telescope to start observations of the target as fast as possible [2]. However, this approach causes an unavoidable delay of the optical observations with respect to the GRB event and it does not allow for catching the optical emission from the source exactly at the moment or before the GRB explosion. The "Pi of the Sky" apparatus design and operation strategy is based on a different philosophy: it assumes a continuous observation of a large fraction of the sky, which increases the chances that a GRB will occur in the observed area.

The full "Pi of the Sky" system will consist of 2 sites separated by a distance of ~100 km. Each site will consist of 16 highly sustainable, custom-designed survey CCD cameras. Pairs of cameras work in coincidence and observe the same field of view. The whole system is capable of continuous observation of about 2 steradians of the sky, which roughly corresponds to the field of view of the Swift BAT instrument [3].

Before construction of the full system, the necessary hardware and software tests were performed using a prototype. It has been located in the Las Campanas Observatory in Chile since June 2004. It consists of two specially designed

CCD cameras observing the same $20^0 \times 20^0$ field of view with a time resolution of 10 seconds. During the past 4 years, the control software and analysis algorithms have been regularly developed, to improve the overall system performance and the sustainability, as well as flash and nova-like stars recognition algorithms. In 2008, the prototype indeed automatically recognized and observed the prompt optical emission from the famous “naked-eye” GRB080319B. This detection and subsequent observations have confirmed that the idea of the “Pi of the Sky” detector allows for the efficient search for prompt optical counterparts of GRBs.

2. Inspiration

It is commonly acknowledged that Bogdan Paczyński was one of the greatest minds of the contemporary astrophysics. One of the least discussed aspects of his remarkable personality is his ability to motivate and inspire other people to pursue research in the directions which he himself considered interesting. Professor Paczyński strongly supported the application of small robotic telescopes to study astrophysical phenomena, with ASAS [4] and HAT [5] being perhaps the best examples of how right he was.

In the beginning of 2000s, Paczyński was visiting Warsaw from time to time. His seminars attracted attention not only of astrophysicists but also of people from other branches of physics. This is how a small group of particle physicists came across Paczyski’s idea that small robotic telescopes may play an important role in solving perhaps the most intriguing astrophysical mystery of that time, namely, the nature of Gamma Ray Bursts. It did not take long before, after some discussions, we realized that indeed, apart from different sources of input signals—stars instead of particles—the general architecture of a wide-field, all-sky fast optical transients detector would resemble very much what we are accustomed to in particle physics experiments. Moreover, as self-triggering would give such a detector precious independence on satellite information, it was taken into account from the very beginning in the design. Here the proper strategy for searching of a GRB optical emission, like for a needle in a hay stack, could be based on a multilevel trigger scheme well-known from particle physics experiments searching for rare events, which could be, for example, footprints of creation of a new particle.

We started R&D work armed with modest grants from Professor Paczyński and the Polish Ministry of Science. Soon it becomes obvious that with money we had we could only dream about buying detector components from a shelf; so we decided to build the detector from the scratch on our own. As it has been demonstrated by the future development, this decision was right and has proved to be the key to success of the whole project. We did not only build, for example, CCD cameras for less money but also could design these cameras with features which later turned out to be crucial. Like a submarine crew which takes part in the final construction of their boat in order to know every piece of its mechanism, we know every element of our detector and in case of some failure, which is unavoidable during a long operation period, we can come with an effective work-around strategy. There is also no way to overestimate gains stemming from detailed knowledge of software, including drivers for all devices, which were home-written as well.

What started as a small project soon became a larger enterprize because the news spread out and more students came, interested in taking part in a new project. Although key elements have been built by full-time professionals, a lot of, for example, software has been written by students coming to us for master thesis, and so forth Participation in our project became a challenge for the best young people studying around, and that development turned out to be quite an asset as well.

In the meantime, other groups, motivated by GRB observations, develop their own robotic systems. BOOTES [6], RAPTOR [7], REM [8], ROTSE [9], MASTER [10, 11], TORTORA [12], WIDGET [13], WFOC [14], and so forth presented unique, technologically advanced designs. Robotic follow-up telescopes and wide-field survey systems have become part of the mainstream astronomy.

Gamma Ray Bursts were discovered more than 40 years ago. Studies of these unusual phenomena are based on data collected by gamma detectors located on satellites as well as by optical and IR ground telescopes. It is widely accepted that GRBs are associated with extremely energetic explosions in distant galaxies. It is almost certain that bursts are due to collapsing massive stars or merging of two neutron stars [15]. The most interesting piece of GRB’s puzzle is the nature of the central engine, that is, the place where gravitational energy is converted into burst energy in timescales of milliseconds. The detailed mechanism of the central engine is still unknown. It is certain that multiwavelength observation of prompt emission can reveal hints which eventually will allow us to construct a robust theory of the central engine mechanism or mechanisms. It is hard to imagine other types of detectors which can serve this mission, but robotic, wide field, all-sky like “Pi of the Sky” telescope.

3. “Pi of the Sky” Final System

The most important ingredient of our strategy for independent search for optical counterparts of GRBs and other fast optical transients is the self-triggering capability. This strategy has been tested and developed using the prototype telescope located in the Las Campanas Observatory. Tests of the real-time flash recognition algorithms revealed that the most common background sources are flashes due to cosmic rays hitting the CCD and near-Earth flashes from the Sun light reflections from satellites. For efficient search for prompt optical counterparts of GRBs we have designed a system consisting of two mirror sites. In order to reduce the background flashes, mirror sites should be located at a distance ~100 km and their cameras should observe pairwise the same field of view. The reflections from satellites could then be identified and removed by their parallax, and cosmic rays can be eliminated by analyzing the coincidence on both cameras. A schematic view of the final system is shown on Figure 1. Here one site consists of 16 CCD cameras installed on four parallactic mounts [2].

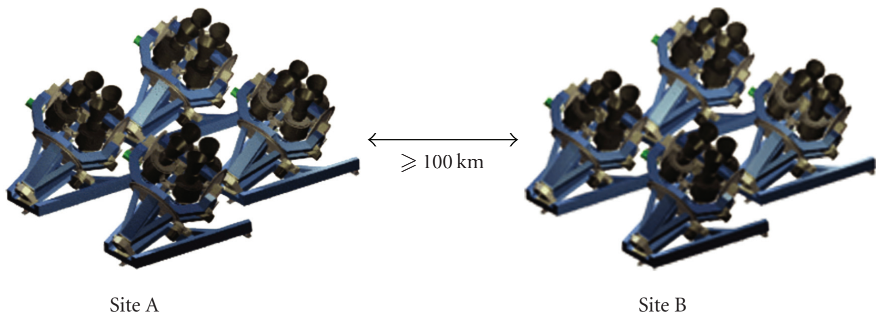


Figure 1: Schematic view of the final “Pi of the Sky” detector.

In order to ensure full control over the detector design and construction, we have decided to build custom-design CCD cameras. $STA0820$ 2 k × 2 k CCD chips with 2 dual-stage outputs have been selected because of their relatively low price and satisfactory price/performance ratio. The pixel size is $15 \times 15\,\mu\text{m}^2$. The readout frequency, gain, CCD temperature, mechanical shutter, and other parameters are remotely controlled via Ethernet or USB2.0 interface. The CCD is cooled with a two-stage Peltier module up to 40 degrees below the ambient temperature. EF CANON lenses with the focal length $f = 85$ mm and $f/d = 1.2$ have been chosen as the optical system. With this setup, one camera covers a field of view of approximately $20^0 \times 20^0$, with pixel size corresponding to 36 arcsec on the sky. The final system will cover ~2 steradians that correspond approximately to the field of view of the BAT instrument on board the Swift satellite [3].

Following the FoV of the Swift detector, “Pi of the Sky” can detect optical counterparts of GRBs at the very beginning and during the gamma emission, or even before it. No time is needed for repointing the telescope to the coordinates from GCN. The dead time which arises from the decision process and signal propagation from the satellite to the GCN and from the GCN to a ground instruments is eliminated as well. Small, fast follow-up telescopes can minimize the delay arising from inertia, but the problem of the delay time due to the signal propagation cannot be solved in this way. Even a very fast reaction to a GCN alert cannot guarantee the detection of the prompt emission. Hence our primary strategy is to continuously follow, if possible, the FoV of Swift. Moreover, this strategy allows us to observe or determine the upper limit for a precursor in the optical band.

The system is in the final construction phase now. Most of parallactic mounts and cameras have already been completed and hardware as well as software is being assembled and tested now. We plan to begin the installation of the final system by the end of 2009.

4. Prototype

The prototype was installed in Las Campanas Observatory (LCO) in Chile. Regular observations started in June 2004. The place was selected because of very good and stable weather conditions (Figures 2 and 3).

Design of the prototype detector follows the assumption that it should be a scalable version of the final detector. It consists of 2 CCD cameras on a common parallactic mount. It is just a small version of the final instrument and apart from performing regular observations, it serves for testing both hardware and software solutions. From the very beginning, the prototype as well as the final instrument has been designed to operate in autonomous mode, with minimum human supervision, although remote control via Internet is possible as well. It is clear that a robotic system must be very reliable. This goal has been accomplished with the help of the special diagnostic software, which monitors continuously the system performance in the autonomous operation mode, detects problems, if any, and reacts to them. Every software module which controls a piece of hardware writes status file every 60 seconds. This file contains all important information about the current state of the module and also contains information if any problem was self-detected by this particular module. Another script is checking all status files every 5 minutes and is able to automatically identify the problem in a single status file or combine information from several files. In case such problem is detected, certain repairing action is undertaken to fix the problem. In addition, the appropriate information is sent to the mobile phone of a person in charge. Interestingly enough, the diagnostic software is practically 100% effective in solving encountered problems, a performance which was never achieved before by humans. System sustainability has been also increased by hardware redundancy and careful, flexible system configuration avoiding choke points.

Cameras monitor the sky taking 10 seconds exposures with 2-second readout time at the readout speed of 2 Mpixel/second. The limiting magnitude for a single frame is 12^m and rises to approximately 13.5^m for a frame stacked from 20 exposures. This rather short magnitude range is a price paid for wide field observations. With the 10 second time resolution and 2 second readout time, one camera collects from 2 to 3 thousand frames per night, depending on the time of the year. With such a large number of opening cycles, a really heavy-duty shutter is a must. We have designed a special, mechanically durable shutter, which can sustain about 10^7 opening cycles. It corresponds to a few years of continuous operation. The shutter is based on voice-coil principle used, that is, to control read-write

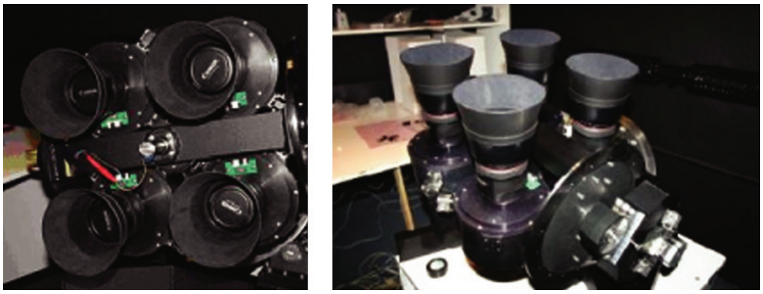


Figure 2: "Pi of the Sky" mount with 4 cameras.

Figure 3: "Pi of the Sky" prototype located in the ASAS dome, Las Campanas Observatory, Chile.

heads in hard disks. Such construction results in lack of friction between diaphragm and its support as a key factor in shutter's durability. In addition, before the shutter hits the bumper while opening or closing, the voice-coil is actuated by precisely adjusted pulse with negative sign. Such electronic brake slows down speed of the shutter and reduces the stresses to the mechanism. Since May 2009 one of the CCD cameras has been equipped with the R-band filter in order to facilitate absolute calibration of measurements.

Because of the field of view which is smaller than for the final telescope, the prototype cameras follow, for most of the time, the center of the Swift's BAT FoV. When the Swift FoV is not visible from LCO, an alternative target like the INTEGRAL FoV or some other interesting object from the special target list is chosen automatically. The system also reacts automatically to GCN alerts. When the target from the received GCN alert is located outside the current FoV, the system moves telescope towards the alert position and starts taking exposures. The software takes decision about repointing automatically. It also sends an information to the person in charge every time when detector reacts to a GCN alert and moves to the GRB's position.

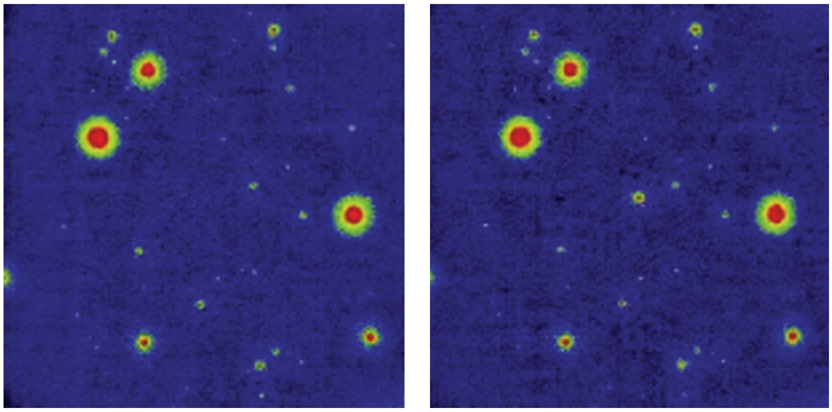
In the normal observing mode images are analyzed on-line in order to find optical transients, possibly optical counterparts of GRBs. An algorithm searching for short optical flashes by comparing a new image with the stack of recently taken frames has been developed. The algorithm design resembles multilevel triggering system known from high-energy physics experiments.

Twice a night, at the beginning and at the end, a systematic all-sky scans are performed in order to search for transients with a longer timescale. During one scan the system collects three 10 second images for each of about 30 predefined fields, which are observed each time. Systematic observations of the whole visible sky are important for investigation of objects with variability timescale from hours to days and longer. Hence, an off-line algorithm searching the scan observations for novae, supernovae, and other optical transients not associated with GRBs has been developed and tested as well [16].

5. Results

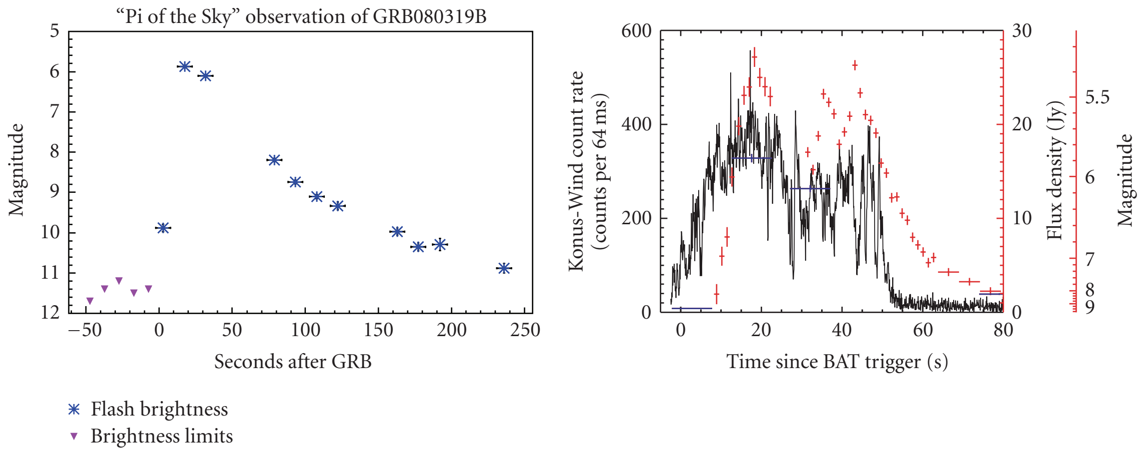
5.1. Optical Counterparts of GRBs

5.1.1. Prompt Optical Observation of GRB 080319B. On March 19, 2008 the "Pi of the Sky" prototype observed the prompt optical emission from long-duration gamma ray burst GRB080319B [17]. It was later measured that the burst occurred at the redshift $z = 0.937$ [18]. Luckily, this was the second burst that night. At 5:45 UT the Swift satellite detected an intense pulse of gamma rays (GRB 080319A). The determined position was sent via GCN and ground experiments moved to follow-up optical observations of this burst. The "Pi of the Sky" prototype also started observing that object. Less than 30 minute later, at 6:12:49 UT, the BAT detector was triggered by gamma emission from another GRB. This moment is marked $T = 0$ for GRB 080319B. The position of the burst was distributed over GCN and the "Pi of the Sky" system received it at 6:13:06 UT. Fortunately, the angular distance between GRB 080319A and GRB 080319B was only about $\sim 11.8^0$ and so it was just small enough for the second burst to occur in the FoV of the "Pi of the Sky" detector. The "Pi of the Sky" telescope had continuously



(a) (b)

Figure 4: Optical counterpart of GRB 080319B taken by "Pi of the Sky" prototype detector. The prompt optical emission is clearly visible on the right image, taken during the gamma emission at 06:14:03 UT. The prompt emission is no more detectable on the left image, taken 10 minutes after the burst.



(a) (b)

Figure 5: Light curve of GRB 080319B prompt emission. (a) shows "Pi of the Sky" measurements alone. (b) (taken from Racusin et al. [18]) shows the "Pi of the Sky" (blue), "TORTORA" (red), and Wind-Konus (black) data.

observed this area for more than 23 minutes before the burst, pointing to the first GRB position. 2 seconds before BAT was triggered by the second burst, at 6:12:47 UT, the detector started a new 10 second exposure. The burst recognition algorithm automatically detected a new object [17]. The prompt optical emission from GRB 080319B was bright enough to be observed by the "Pi of the Sky" prototype for more than 4 minutes (Figures 4 and 5). As it is well known now, the optical flash was so strong that for about 40 seconds it could even be seen with a naked eye, without any instruments. For this reason the GRB 080319B burst is generally known as the "naked-eye burst."

Early optical observations during the very first tens of seconds from the beginning of the gamma emission, together with later data that cover wavelengths from radio to gamma rays, are shown on Figure 6. These observations challenged many existing models of GRB emission and demonstrated usefulness of wide-field detectors, capable of continuous monitoring of large parts of the sky. In practice such systems are probably the only choice to observe the prompt optical emission from the gamma ray bursts in a systematic way.

The most unexpected result coming from the analysis of the prompt emission of GRB 080319B was the flux density difference between optical and gamma-ray spectrum (Wind-Konus data [19]) appointed during the first three 10 second intervals centred at T_0+3 s, T_0+17 s, and T_0+32 s. As is turned out, the optical flux from the flash detected by "Pi of the Sky" prototype was ~10000 larger than the extrapolation of the flux density of the gamma emission (Konus-Wind data, Figure 7). The Konus-Wind data have been extrapolated to the optical domain using the best-fit Band function [9]. Such a bright optical component suggests that optical photons are emitted in a different mechanism than γ ray emission. An interpretation has been proposed that optical emission arises from synchrotron emission and the high-energy gamma emission comes from a synchrotron self-Compton process.

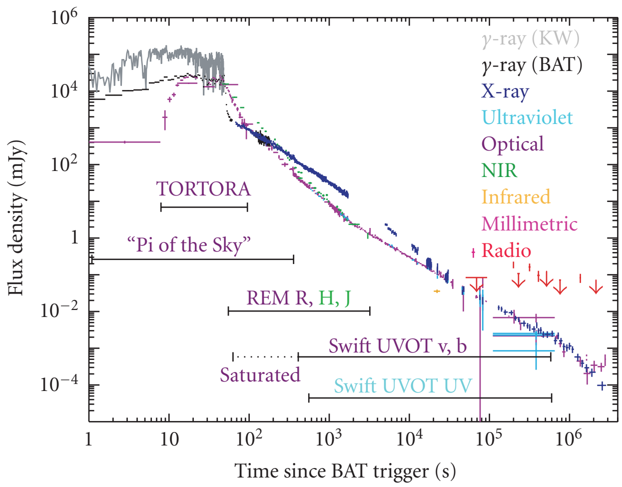


FIGURE 6: Light curves of GRB 080319B, including radio, milimetric, infrared, NIR, optical, ultraviolet, X-ray, and gamma ray flux densites. The original light curve was taken from Racusin et al. [18]. Bars with names of different instruments show timescales of different observations.

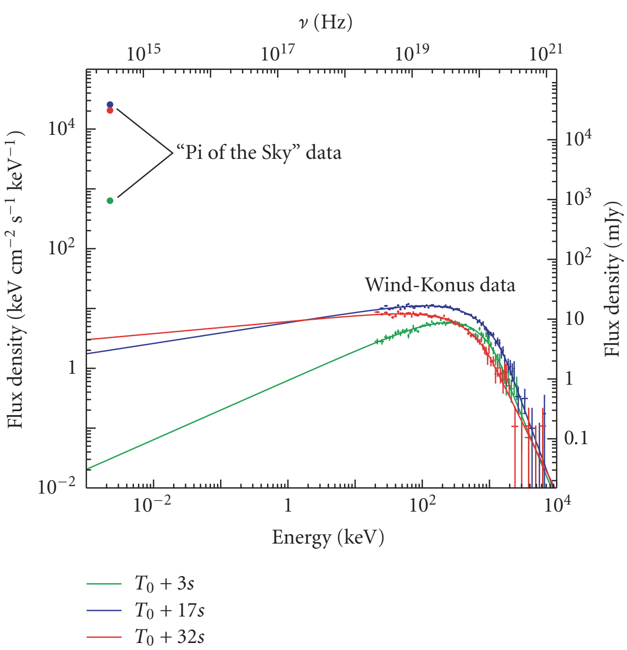


FIGURE 7: Spectral Energy Distribution of the prompt emission of GRB 080319B [18].

This interpretation implies the existence of a third, harder, spectral part, GeV component. Unfortunately, this third component remained undetected in case of GRB080319B. However, more than one year later the ground experiment TUPI [20] detected the first GeV emission from GRB 090315.

Based on GRB080319B measurements, new models of a GRB have been considered [18, 21–25]. Observations of this unique GRB continued for weeks afterwards, following fading afterglow, and provided important clues to understanding of a mechanism of the GRB emission.

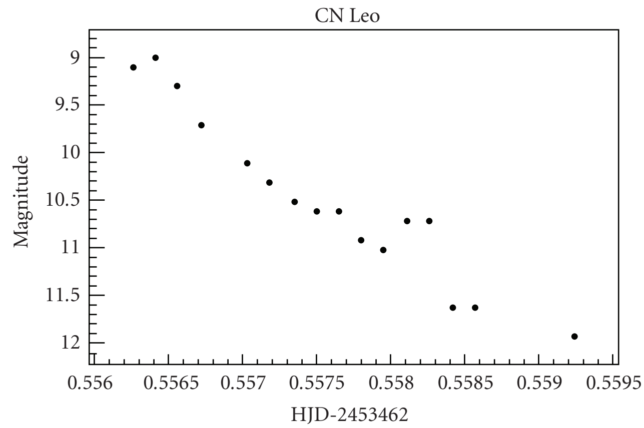


FIGURE 8: Outburst of CN Leo star (02.04.2005). On the image taken before the outburst, the star was not visible. During a few seconds its brightness raised by a factor of 100 and then faded away during several minutes.

5.1.2. Other Observations of GRBs. The "Pi of the Sky" prototype has been active from 2004.07.01 to 2005.08.07 and from 2006.06.01 till now, with 10-month break due to maintenance of CCD cameras. As of 2008.06.05 different gamma-ray satellites observatories detected a total of 404 gamma ray burst with known positions. The "Pi of the Sky" detector could observe only 81 of them, that is, only those which occurred during local nighttime, on the southern hemisphere, with sufficiently high altitude above the horizon and during good weather conditions. Table 1 summarizes statistics of the "Pi of the Sky" observations of these events.

In 77 cases, when GRBs occurred outside "Pi of the Sky"'s FoV, the system repointed to the burst position after receiving an alert from the GCN. Four GRBs occurred inside the FoV of the prototype but only in the case of GRB 080319B an optical transient was detected. In addition, upper limits of magnitude for 14 optical counterparts for GRBs set by "Pi of the Sky" have been published as GCN Notes.

5.2. Optical Flashes. Since June 2004 the basic software of the "Pi of the Sky" telescope has been regularly developed and tested in order to improve both on-line and off-line transient-detection algorithms. During this period the prototype detected more than 200 short optical flashes in a single frame and 7 flashes visible in two frames. It is very likely that most of flashes visible in a single frame are sunlight reflexes from satellites, which have not been recognized by our algorithms. Optical flashes visible for more than 1 frame are unlikely to be satellite images, because staying for more than 10 second in a single pixel would require very high orbit, which contradicts their high brightness. However, no coincidence with any satellite GRB trigger was detected. Two of them were recognized as flashes of astrophysical origin. The first one was identified as the outburst of CN Leo flare star ($\alpha = 10:56:29$, $\delta = +07:00:53$) on 2005.04.02 (Figure 8), and the second one as the optical counterpart of GRB 080319B.

Table 1: Statistic of "Pi of the Sky" observations.

Apparatus off	North hemisphere	Daytime	Below horizon	Clouds	Outside FOV	Inside FOV
19	35	196	57	16	77	4

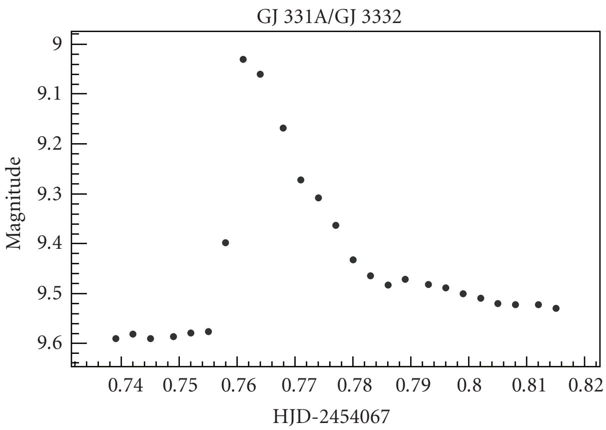
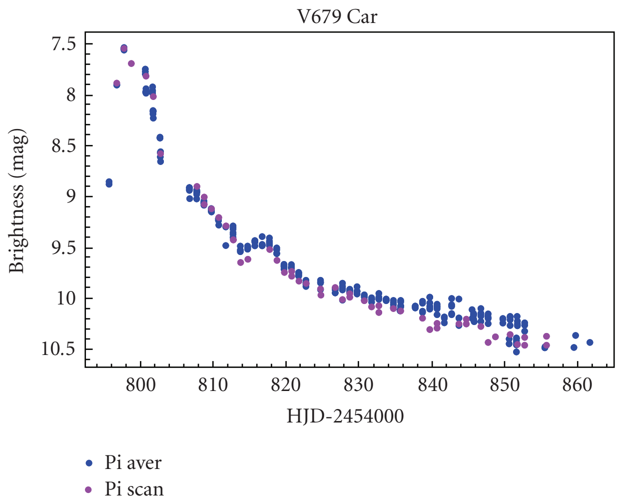


Figure 9: During the night 27/28.11.2006 the "Pi of the Sky" automatically detected outburst of a flare star GJ3331A/GJ3332 ($\alpha = 05:06:50$, $\delta = -21:35:06$). Each point on the light curve corresponds to a sum of 20 images, 10 second exposure each.



(a)

(b)

Figure 10: (a) shows a light curve of V679 Car. Data are taken from the "Pi of the Sky" database. Blue points denote measurements taken during all-sky scans and violet points from regular observations. (b) shows an optical image of the V679 Car (indicated by an arrow) taken by Alain Maury, Steve Barnes, Caisey Harlingten, and Stephane Guisard on December 1, 2008.

5.3. Optical Flares. A separate off-line algorithm has been developed in order to search for outbursts of flare stars. The algorithm gets light curves of stars from the database and looks for significant increase of brightness (Figure 9). The algorithm is still being developed and tested. As for 05.06.2009, the "Pi of the Sky" apparatus has detected seven optical flares.

5.4. Novae Stars. Identification algorithm for novae uses the data collected during all-sky scans as an input. The algorithm does not try to determine the parameters of novae but simply looks for a new object in the data. The algorithm requires that the new object is visible on two or more single 10 second images taken one by one. All selected events must be detected on images taken by both cameras. The next condition is that the new object is not present in the TYCHO2 database [16]. The final analysis is taking into account a few more technical conditions, introduced to increase background rejection efficiency of the algorithm. All the selected events are sent to Warsaw for examination of their light curves and visual inspection of sequences of images taken before and during the new object detection. Such algorithm gives good results as far as search for novae and other variable stars and planetoids is concerned. The most impressive results were discoveries of two dwarf novae and one classical nova and the identification of V5115 Sgr in our database. The first dwarf nova 1RXS J023238.8-371812, most likely a WZ Sge type dwarf nova, was discovered in mid-September 2007 [26]. Two months later "Pi of the Sky" algorithm identified another WZ Sge type dwarf nova: WZ Sge type in Hydra constellation (VSX J111217.4-353828) [27]. In November 2008 classical nova Nova in Carina (V679 Car) [28] was automatically detected as well. A light curve of V679 Car is shown on Figure 10.

5.5. Catalog of Variable Stars. A catalog of variable stars with periods from 0.1 to 10 days identified in the "Pi of the Sky" data was published in [29]. Light curves of 925 201 stars observed during the period 2004-2005 were analyzed by a variability search algorithm to find variable stars. The AoV method [30] was used to determine periods and reject stars with false variability. Classification based on the shape of light curves was performed by a visual inspection. The catalog consists of 725 variable stars. Most of them are eclipsing binaries of W UMa type.

Analysis of data collected during 2006-2007 has been performed as well [31]. We have selected about 3000 stars for further analysis. We are currently working on visual inspection of light curves and types of variability determination for these stars.

5.6. Public Databases. Data acquired during the “Pi of the Sky” observations are reduced and only light curves of stars are stored in the database. Two public databases containing star’s measurements from 2004-2005 and 2006-2007 have been created so far, with observations from 2007-2008 being analyzed just now. These databases contain all measurements taken by the “Pi of the Sky” detector. The first database covers VII.2004-VI.2005 and contains about 790 mln measurements for about 4.5 mln objects. The second database covers period V.2006-XI.2007 and includes about 1002 mln measurements for about 10.8 mln objects. A dedicated web interface has been developed to facilitate public access to databases of the “Pi of the Sky” project. The interface allows to search for stars by magnitude, coordinates, and other parameters and to view a light curve of a selected star [32]. Public databases are available on the “Pi of the Sky” web page http://grb.fuw.edu.pl/pi/.

5.7. Minima of Binary Stars. Several binaries observed by the “Pi of the Sky” were analyzed in order to determine times of their minima using the method of Kwee and van Woerden [33]. The web access to the database with individual times of minima is available at http://www.as.ap.krakow.pl/miniauto/.

6. Conclusions

We have described the design, philosophy, construction and the prototype performance of the “Pi of the Sky” robotic wild-field telescope. The “Pi of the Sky” has indeed been operating in the fully autonomous mode, practically without any human supervision for about a year, 3 years after the prototype installation in the Las Campanas Observatory in Chile. The key element behind this achievement has been development of special diagnostic software which supervises the system and reacts to problems which appear during system operation.

High sustainability of the “Pi of the Sky” instrument has allowed us to concentrate on gathering and analysis of data. The dedicated software performs an on-line search for optical transients. The successful detection of a prompt GRB emission during the night of March 19, 2008 has shown that the software is indeed capable of identifying an optical counterpart of a GRB prior to the satellite alert distributed by the GCN. In addition, we have presented results of searches for flare stars, novae, and other optical transients, which are performed off-line.

The full “Pi of the Sky” system, currently in the completion and testing phase, will consist of 2 mirror sites with 12 or 16 CCD cameras each. We plan to begin installation of the final system by the end of 2009.

Acknowledgments

The authors are very grateful to G. Pojmański for access to the ASAS dome and sharing his experience with them. They would like to thank the staff of the Las Campanas for their help during the installation of the apparatus. This work was financed by the Polish Ministry of Science in 2005–2009 as a research project. They are grateful to A. Pollo for careful reading of the manuscript.

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