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Search for GRB related prompt optical emission and other fast varying objects with "Pi of the Sky" detector

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Abstract Experiment "Pi of the Sky" is designed to search for prompt optical emission from GRB sources. 32 CCD cameras covering 2 steradians will monitor the sky continuously. The data will be analysed on-line in search for optical flashes. The prototype with 2 cameras oparated at Las Campanas (Chile) since 2004 has recognised several outbursts of flaring stars and has given limits for a few GRB.

1 Observing strategies to search for new objects or transients

The most violent processes in the Universe often manifest themselves by sudden bursts at various wavelengths. Interesting examples are Gamma Ray Bursts (GRB) and outbursts from Active Galactic Nuclei (AGN). In this paper we refer to an apparatus especially designed to search for such phenomena, called "π *of the Sky*" .

The system will consists of 32 CCD cameras covering 2 steradians of the sky. It will monitor the sky continuously with 10 s exposures. Fast optical transients will be detected automatically in real time.

At present, the only systems monitoring a large part of the sky continuously are fish eye cameras having very restricted limiting magnitude. Therefore, for the sky monitoring one usually uses one of the three methods:

1. A telescope observes selected object for a long period. This method is often used in AGN observing campains. For continuous monitoring one would, however, need as many telelscopes as objects to be observed.

2. A telescope performes sky scanning, imaging the sky field by field. The method is usually used to search for asteroids or comets. The drawback of this strategy is a long dead time between two observations of the same field.

3. A telescope turnes towards an object after receiving an external alert. This is the common method to search for GRB optical counterparts. The weak point of such strategy is that one has to rely on an external alert and cannot discover any new object.

The "π *of the Sky*" system avoids all those drawbacks and can be used for all applications described above. The priced to be paid for the large field of view is restricted limiting magnitudo. The range is limited by the sky background. It is equal to 12-13^m without a filter in the case of single exposures and 13-14^m for 10 exposures superimposed. This would mean that one could observe an object which has V magnitudo roughly equal to about 14 and 15 respectively (depending on the object spectrum). An important question is, if such range is enough to observe interesting phenomena.

2 "π *of the Sky*" design

The design assumes that the large part of the sky is observed continuously. This is achieved by two sets of 16 CCD cameras, each camera having $20° \times 20°$ field of view (FoV). The total FoV of the system is thus 2×2 steradians. This is larger than FoV of Swift BAT gamma ray detector and close to the FoV of BATSE LAT detecor. The original plan was to cover 2π steradians, giving the name to the project.

Each camera has a CCD of 2000×2000 pixels of $15 \times 15\,\mu\text{m}^2$. The CCD has two outputs and with the speed of 2 Mpixels/s can be readout in 1 s. Ethernet intrface enables remote control of the camera. Cameras are equipped with CANON EF $f = 85$ mm, $f/d = 1.2$ photo lenses. This gives the pixel scale of 0.6 arcmin/pixel.

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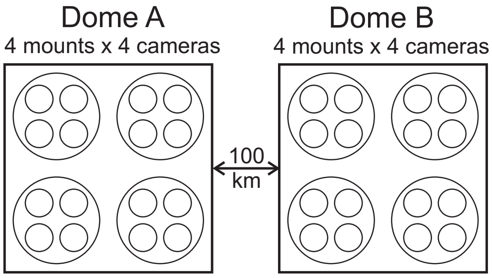

Fig. 1 Layout of the "π *of the Sky*" system.

Single parallactic mount holds 4 cameras. They can work in two modes:

– *side by side*: cameras cover adjacent fields;
– *common target*: all cameras observe the same field.

Four mounts (i.e. 16 cameras) will be placed in a common dome. Two domes will be installed at sites ~100 km from each other to enable rejection of near Earth objects by parallax. The apparatus is currently under construction.

3 "π *of the Sky*" prototype

3.1 The apparatus

A prototype consisting of two cameras has been built and installed at Las Campanas Observatory (Chile) in June 2004. Each camera has a CCD of 2000 × 2000 pixels of $15 \times 15\,\mu\text{m}^2$. Cameras have been equipped with Carl Zeiss Planar T* photo lenses of $f = 50$ mm, $f/d = 1.4$, giving $33° \times 33°$ field of view and the scale of 1 arcmin/pixel. The limiting magnitude for 10 s exposures is $10^m - 11^m$ and for 20 exposures added together it is $12^m - 13^m$ depending on environmental conditions. In May 2006 the lenses have been exchanged for the final choice of CANON EF $f = 85$ mm.

The cameras are installed on a robotic mount controlled by a computer via RS232 interface. The same PC controlls the cameras and acquire the data performing real time analysis in search for rapid transients. The data are instantly copied to the second PC, located in a nearby Control Room for off-line analysis.

3.2 Observing schedule

The system is fully controllable via Internet, but during the normal operation it runs autonomously according to a preprogrammed schedule. Dedicated script language has been developed to make the schedule programming easy and flexible. The script for a given night is generated automatically to perform the following tasks:

– Initialize modules - make mount calibration, start cameras cooling immediately after the system startup.
– Start dark frames collection - 15 minutes before the Sun sets 10° below horizon.
– Perform evening and morning scan of the sky when the Sun is 15° below horizon.
– Observe field of view of a satellite that search for GRBs - Swift, HETE or Integral.
– Shutdown the system - 5 minutes after the Sun rises 10° below horizon.

System observes only fields from a predefined list of $30° \times 30°$ fields overlapping by 15°. Scan scripts are generated according to odd fields from the list on one day and according to even fields on next day.

The algorithm to chose the field to be observed works as follows.

– Satellites on the list (currently Swift, Integral and HETE) are checked if altitude of their FoV is at least $h_{min} = 30°$ above the horizon and in such case the position is chosen.
– Otherwise, the satellite with biggest part of FoV above horizon is chosen, but it is preferable that satellite FoV is rising rather than setting.
– In case it is not possible to find any field according to the above rules the generator can choose an alternative object (e.g. Large Magellanic Cloud) or choose position above horizon in place where soon one of the satellites will come after rising above horizon.
– Chosen field is checked against calculated position of the Moon and in case it is closer then minimal distance allowed (depends on the Moon phase, for full Moon it is equal to 30°) it is rejected and other object and position must be determined.
– The program calculates the time when last followed field is lower then 30° and a new position must be determined for this moment.

During the night the script is being executed. A number of parameters (like CCD temperature, number of stars in each frame, disk space, etc.) is monitored by the system manager program. In case of any problem an e-mail and SMS is sent to a human operator.

The system listens to the GRB Coordinate Network GCN [1]. If an alert is received the script execution is interrupted and the mount turns immediately towards the target.

3.3 Data flow

The 10 s exposures are being taken continuously. The images are immediately analyzed while in the computer RAM in search for flashes with a rise time of the order of seconds. Then, they are temporarily stored on a disc and can be reexamined in case of late arrival of an external alert. If a flash candidate is found the 100 × 100 pixel samples of ±7 frames are stored permanently for the record. In the meantime, the images are copied to the second PC, which superposes the images and searches for optical transients with a rise time of minutes.

During the day, two analyses are performed in parallel on the temporarily stored data. The first PC runs fast photometry on individual frames, which can be used later to study rapidly varying objects. The second PC performs precise photometry on images superposed by 20. The results are stored permanently on a hard disk. Out of almost 30 GB of data taken every night, about 2 GB of results is stored permanently. After 2-3 months a 200 GB removable disk with the results is replaced and taken to Warsaw for further analysis.

3.4 First results

During the first year of operation of the prototype each camera collected about one million exposures. Each night several optical flashes were detected. Most of them were attributed to sunlight reflected by a satellite by comparing coordinates with those calculated from a satellite database. Several flashes have been identified as flaring star outbursts. Examples are shown in Figures 2 and 3.

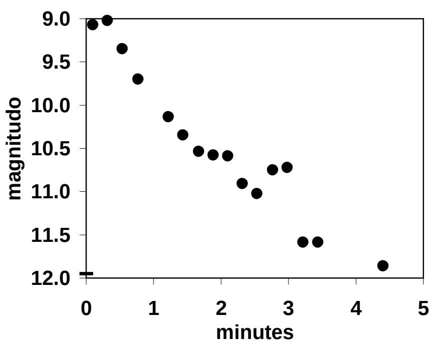

Fig. 2 Outburst of CN *Leo* flare star automaticaly detected 2005.04.02 1:13:42 UT = 3462.55620 HJD

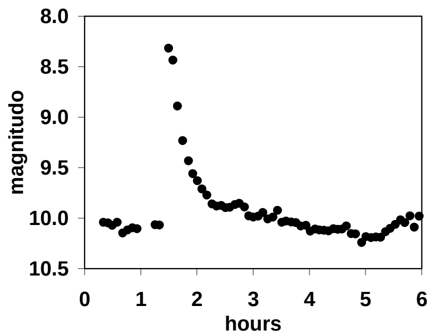

Fig. 3 Outburst of EQ *Peg* flare star 2004.09.19. Time in hours after 2453267.56 HJD. Peak at 2453267.6224

No GRB optical counterpart has been found, but a number of limits have been given. They are indicated by triangles in Fig. 4.

4 GRB optical observations and "π *of the Sky*" limits

Optical observations of Gamma Ray Bursts at the very begining of the phenomenon are crucial to understand the mechanisms of energy release and transport [2]-[6]. Enormous progress in this domain has been achieved thanks to the GRB Coordinate Network GCN [1] distributing burst alerts from satellites.

Robotic Earth based telescopes can turn towards the target and search for an optical counterpart in about one minute. This method, however, does not give a possibility to observe the object during the first minute and certainly not before the γ-ray emission. This is illustrated in Figures 4 and 5. During the first 100 s only 27 observations have been made and within the first 50 s — as few as 9. So far, there is no observation during the first 20 s, not counting GRB 041219a and GRB 050820a triggered by precursors preceeding by a few minutes the proper burst.

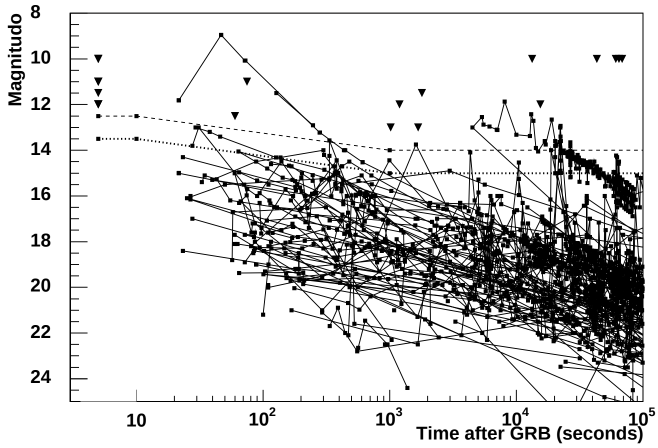

Fig. 4 Optical observations of GRB's. Measurements are taken from [7]. Triangles indicate "π *of the Sky*" limits. Dashed and dotted lines correspond to "π *of the Sky*" limiting magnitude estimated for white and V filters respectively.

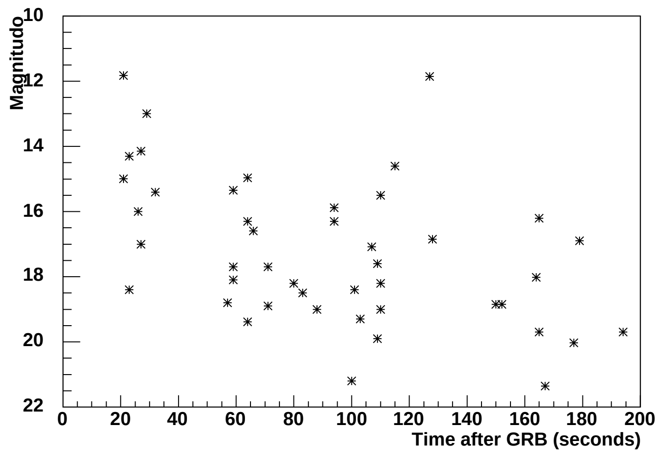

Fig. 5 Optical observations for $\leq$200 s after a GRB [7].

Distribution of GRB brightness (usually measured with an R or V filter) measured during the first 100 s is shown in Fig. 6. One can see that only 3-8 bursts are within "π *of the Sky*" reach. However, the lack of observations during the first 100 s does not necessarily mean, that the object was not bright enough to be seen. Usually, it means simply that no one was fast enough to turn his telescope.

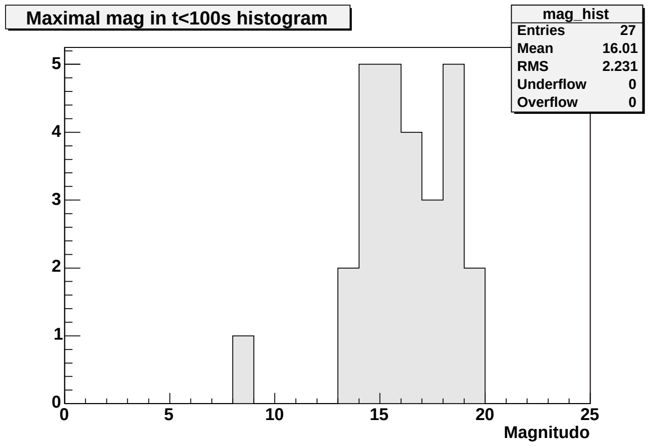

Fig. 6 Maximal optical brightness of GRB during the first 100 s [7].

An attempt to estimate a real distribution of GRB optical brightness at $t_0 + 30$ s is illustrated in Fig. 7. The figure shows the result of extrapolation of light curves including those, which have no measurements during the first 30 s. Only measurements with $t \leq t_0 + 5000$ s have been used to avoid problems with the knee caused by the jet break. Details are given in [8].

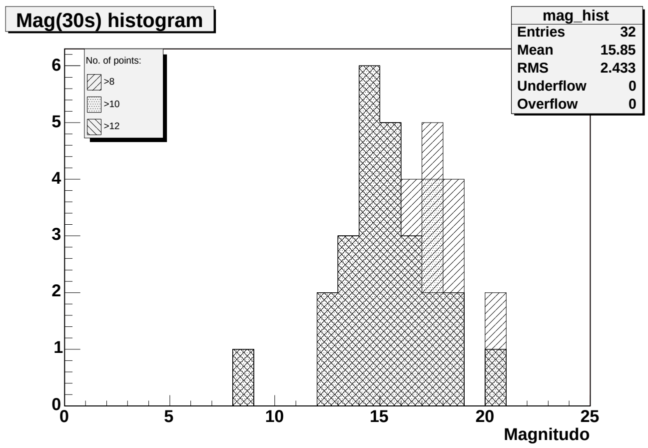

Fig. 7 GRB optical brigtness extrapolated to $t_0 + 30$ s from curves with ≥ 8, 10 and 12 points.

One can see from Fig. 7 that the most probable GRB optical brightness is about 14-15 magnitudo. From the distribution one can estimate that the "π *of the Sky*" system shoud be able to see about 1/4 of the bursts detected by satellites, of course only among those which happened during the night above the horizon.

5 Observing campains for AGN

The outburst of the blazar 3C454.3 at the beginning of 2005 [9] is a spectacular example showing the need for continuous all sky monitoring. This giant burst has been noticed at its falling egde only. The chance to observe the developement of the phenomena has been lost. Multiwavelength observations of the outburst have not been undertaken until very late.

The maximal brightness of the blazar 3C454.3 was R=12. It is well within the range of "π *of the Sky*" apparatus. In fact, the blazar has been recorded by the prototype cameras, however, it happened only at the falling edge of the burst because earlier the object has not been seen at the Southern hemisphere. Anyway, it confirms that "π *of the Sky*" apparatus can be used to study objects as remote as 3C454.3, i.e. z=0.9. After commissioning the full size apparatus we are going to join AGN observing campains like GTN (Global Telescope Network) [10] or WEBT (Whole Earth Blazar Telescope) [11].

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