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Design and First Results of the Fast Photon Counting Photometer OPTIMA

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Abstract. The high-speed photometer OPTIMA has been designed as a sensitive, portable detector to observe optical pulsars and other highly variable sources. The detector contains eight fiber fed avalanche photodiode photon counters, a GPS timing receiver, a CCD camera for target acquisition and a computerized control unit. The central fibers are configured as a hexagonal bundle around the target fiber, while one fiber is located at a distance of $\sim 1'$ as a monitor for the night sky background. During the commissioning phase since January 1999 OPTIMA proved its scientific potential by measuring a detailed lightcurve of the Crab Pulsar as well as by observing Geminga, cataclysmic variables and X-ray transients.

1. Introduction

OPTIMA (an acronym for Optical Pulsar Timing Analyzer) is a small, highly versatile photometer with single photon sensitivity based on fibre-fed avalanche photo diode (APD) detectors and GPS timing. The primary science goal for OPTIMA is to detect and measure the optical lightcurves of young high-energy pulsars known to emit X- and γ-ray photons. Up to now the search for modulated optical emissions from these pulsars has only succeeded in five significant or at least suspected detections, namely the Crab ($V_{avg} \sim 16.5$), Vela (~ 23.6), PSR B0540-69 (~ 22.4), PSR B0656+14 (~ 25), and PSR B0630+17 (Geminga, ~ 25.5) (Cocke et al. 1969; Wallace et al. 1977; Middleditch & Pennypacker 1985; Shearer et al. 1997; Shearer et al. 1998). The Crab pulsar is by far the brightest object in this list and often serves as the verification standard for new instrumentation. The lightcurves from the fainter optical pulsars need to be measured with better statistics in order to make meaningful comparisons across their complete emission spectra. Several other optical pulsar candidates have been listed from counterpart searches performed with HST, VLT and other observatories in the visual range or ROSAT and Chandra at X-ray energies. Only the detection of regular periodicities can confirm the identification of such counterparts. A secondary, but no less important, goal for any fast photometer is the observation of radiation from the environment of compact objects in binary systems (white dwarves, neutron stars, black hole candidates).

From the requirements to detect the faintest periodic sources as well as transient aperiodic processes and to observe these sources from various telescopes around the world the design for OPTIMA had to provide for the following:

- the best available sensitivity in the optical band by using detectors of high quantum efficiency and wide spectral response

- isolate and select the target photons through a suitable diaphragm (fibre diameter) to improve the signal to noise ratio; measure the sky background around the target

- record the absolute time for each photon to enable coherent folding at the pulsar rotational frequency over long observing times. This also enables periodicity searches, the derivation of irregular time profiles with various binnings, and the correlation with data from other observatories in off-line data analysis.

- OPTIMA should be a compact, portable instrument that can be fitted to various telescopes; target/data acquisition and operations of OPTIMA are completely stand alone.

Since January 1999 the OPTIMA detector system, in various stages of completion, has been commissioned at several telescopes to fine-tune operations and to acquire first scientific data. We observed amongst others the Crab pulsar to demonstrate the very high time resolution of a few microseconds and the long-term timing stability over several consecutive days (Straubmeier 2001).

2. Detector Design

2.1. General Layout

Figure 1 displays a schematic layout of OPTIMA. The light from the telescope is incident on a slant mirror with an embedded bundle of optical fibres. Optionally one can insert filters or a rotating linear polarizer into the incoming beam. The field around the fibres, visible in the mirror (typical size $2' \times 3'$), is imaged with a target acquisition camera (SBIG ST-7). The optical fibres are arranged in a centre-filled hexagonal array for the target and its close environment (7 channels) and a single fibre about $1'$ distant from the target for sky background monitoring. We have mostly used 'tapered' fibres with $300\mu m$ diameter at the pickup (equivalent to $\sim 2''$ resolution at the 3.5m telescope on Calar Alto) and an exit diameter at the detector of $100\mu m$. Since the fibres are easily exchanged, different sizes can be installed to adapt to the focal scale or the seeing conditions. The timing of individual photons is controlled by the signals from the Global Positioning System (GPS) to an absolute accuracy of $\sim 2\mu s$. The OPTIMA detector is operated with two PCs and is autonomous except for the need to have a good telescope guiding system.

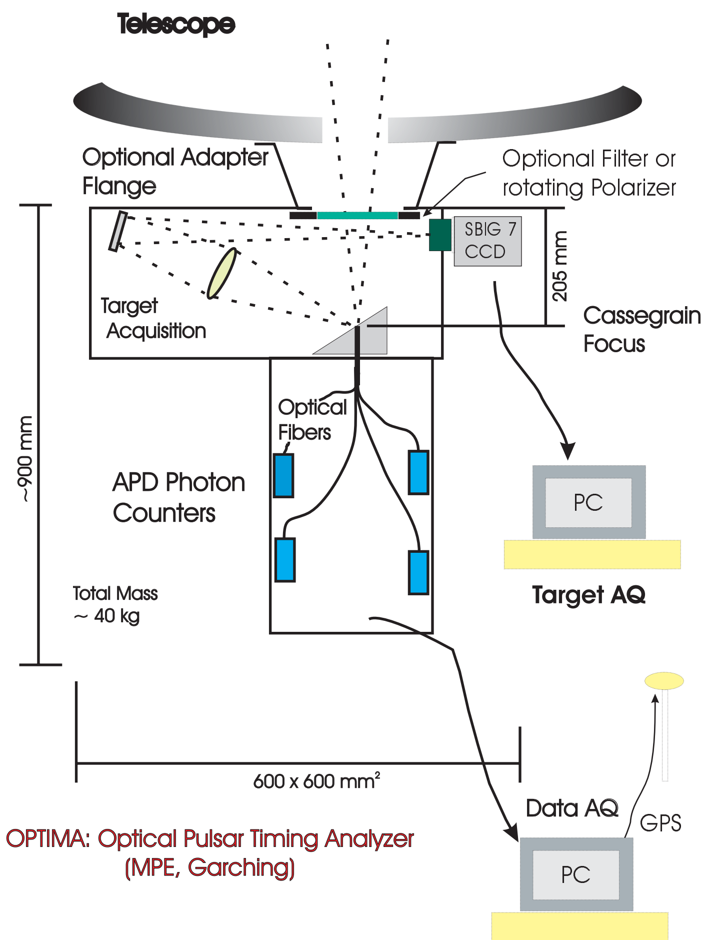

Figure 1. Schematic layout of OPTIMA

2.2. The Photometer

For the observation of faint sources it is very important to convert the highest possible fraction of incoming photons into countable signals, i.e. to have detectors with high quantum efficiency over a wide spectral band. Most previous systems for recording single optical photons with time resolutions of a few microseconds used photomultiplier tubes or detectors based on a similar technology. Their photo cathodes have a peak quantum efficieny of about 20% and a narrow wavelength range of sensitivity. Much better quantum efficiencies can be reached with solid state detectors. OPTIMA uses therefore state-of-the-art Avalanche Photodiodes (APDs). These new silicon semiconductor devices offer ideally peak quantum efficiencies of up to 80% and a wide band of sensitivity ranging from 250 to 1100 nm. We use commercially available APD based Single Photon Counting Modules of Perkin Elmer Inc. These highly integrated devices operate in a Geiger counter mode where a photon initiated avalanche pulse is quenched by the instantaneous reduction of the bias voltage. The diodes are of 0.2 mm diameter and are electrically cooled. The selected units offer low dark count rates of typically less than 50 Hz, are insensitive to electromagnetic interference and are very reliable in operation. They can record photons up to rates of several 100 kHz before noticeable dead-time losses occur. The achieved quantum efficiency of these detectors is shown in figure 2. Although it falls short of the above ideal values it is still above 20% for a spectral range from 450 to 950 nm, which results in about a factor of 6 improvement in sensitivity compared to a PMT based system.

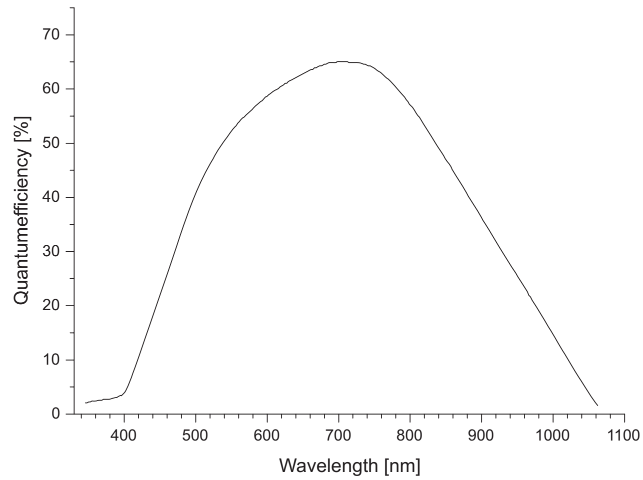

Figure 2. Quantum efficiency of the APD single photon counting modules from Perkin Elmer Inc.

2.3. Timing and Data Acquisition

An absolute time base easily available anywhere is provided by the global GPS satellite system. We use a special receiver which can process the clock pulses of up to six satellites simultaneously and reaches an absolute time accuracy of the one pulse per second GPS clock of better than two microseconds. This PPS signal disciplines a local high frequency oscillator with the same precision. For OPTIMA we use a GPS based time and frequency processor of Datum Inc., which provides a continuous UTC time signal with a self adjusting absolute accuracy of better than $2\mu s$ to the system bus of the PC used for data acquisition (DAQ). The task of the DAQ unit is thus to correlate the electronic signals of the APD detector modules with the high resolution time base and thus assign UTC arrival times to each detected photon. This association is done on hardware level to ensure a reliable operation even on a non realtime operating system and under high system load. The timing of the conversion cycles of the DAQ card is controlled by the GPS based high frequency oscillator, so that the transfer of the APD detector signals is running at a fixed rate. The absolute starting time of each software triggered acquisition sequence is precisely known. The controlling software counts the number of conversion cycles since the start of the sequence and stores this sequential number together with an identifier of the respective detector channel for each detected photon. Based on the cycle number, the acquisition frequency and the absolute time of the start of the sequence the UTC arrival time of every recorded photon can be restored during data analysis.

Typical count rates from the night sky in dark conditions are $\sim 1-2$ kHz per fibre resulting in several GBytes of data for one night of observing. Data are first staged to RAM and periodically ($\sim$ every 10 mins.) stored on HDD. Off-line data analysis includes the options to correct the topocentric photon arrival times to the solar system barycentre arrival times. Pulsar phases and light curves can be calculated if the pulsar ephemeris is known. If unknown periodicities or irregular variations are investigated FFT analysis and rate plots are available.

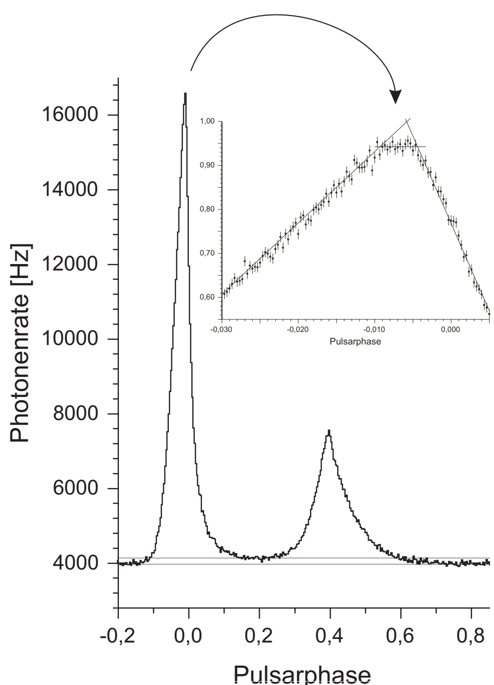

Figure 3. Lightcurve of the Crab pulsar. The full lightcurve (phase binning $112\mu s$) is based on 10 min of data obtained at the 3.5m Calar Alto telescope; the detail of peak 1, with $11.2\mu s$ binning, was derived from the sum of four exposures in the nights Dec 30, 1999 to Jan 2, 2000 totalling about 100 minutes.

3. Recent Results

In late December 1999 / January 2000, when OPTIMA was only equipped with two detector channels, we observed the bright Crab Pulsar and the Geminga pulsar at the 3.5m telecope of the German-Spanish observatory on Calar Alto, Spain. Considering the technical limitations due to the small number of available detector channels and due to a not yet optimized set of optical fibers, the results of these short observations are nevertheless quite striking. More recent observations in July 2000 were performed with five detector channels using the 1.3m telescope on Mt. Skinakas in Crete. Since then the set of detectors has been completed and the number of operational APD detectors modules has reached the proposed number of 8 channels. Now the measured flux at the position of a target can be corrected for the contributions of the atmospheric background and other nearby astronomical objects.

3.1. Crab Pulsar

In figure 3 the lightcurve of the Crab pulsar as measured with OPTIMA in December 1999 is shown. The plotted count-rates are the summed intensities of atmospheric background, Crab nebula and pulsar, whose rotational ephemeris was given by radio observations published monthly by the Jodrell Bank Radio Observatory (Lyne et al. 1992). A comparison of the basic characteristics of our lightcurve to that published by Percival et al. (1993) using data from the high-speed photometer aboard the Hubble Space Telescope, shows that the OPTIMA detector contributes no detectable timing noise or other non-linear intensity responses to the optical signal of the pulsar. The stability of the OPTIMA timing system is further demonstrated by the details in the peak regions of the pulses. The inset in figure 3 shows the maximum of the first peak with a binning of $11.2\mu s$. One recognises a flattening of the peak over a duration of about $165\mu s$, which corresponds to a rotational angle of 1.8 degrees. A similar flattening at the top of the first peak, although slightly rounded or inclined, has been measured by Smith et al. (1978) and Percival et al. (1993) with resolutions of $20\mu s$ and $22.8\mu s$ respectively. This flattening could be due to either the spatial and angular extent of the optical emission region or to self-absorption in the compact radiation source.

3.2. Geminga

The Geminga pulsar PSR B0630+17 is one of the brightest high energy gamma-ray sources in the sky. Its optical counterpart is very faint ($m_v = 25.5^m$) and was identified as a moving object by Bignami et al. 1987. A possible pulsed emission in the B band was found by Shearer et al. (1998) with a level of $m_B \sim 26^m$. During the 1999/2000 OPTIMA campaign at the 3.5m telescope on Calar Alto we took data from Geminga for about 24 hours. It should be noted that some of these measurements were adversely affected by seeing and a pick-up fibre of reduced transmission ($\sim 40\%$). A straightforward folding of these data with the rotational ephemeris known from gamma-ray observations with EGRET (Mattox, private comm.) resulted in the lightcurve shown in figure 4. No detectable modulation can be discerned. Before we can state a discrepancy with the previous result in the B band we should keep in mind that the OPTIMA spectral range extended far into the red and therefore the sky background influences the signal to noise level considerably. Simulations performed by Straubmeier (2001) concluded from the measurement that for a sharp 'Crab-like' lightcurve the limit on the pulsed component is less than 30% of the expected source intensity while for a wider sine shaped modulation the detection limit is about 70% . This result is still marginally compatible with Shearer et al. (1998). Future OPTIMA measurements will use filters ($\lambda < 750$ nm) to improve the S/N ratio. The full array of detectors will then also allow to detect a DC level of unpulsed emission from Geminga by determining the exact sky brightness in the vicinity of the source.

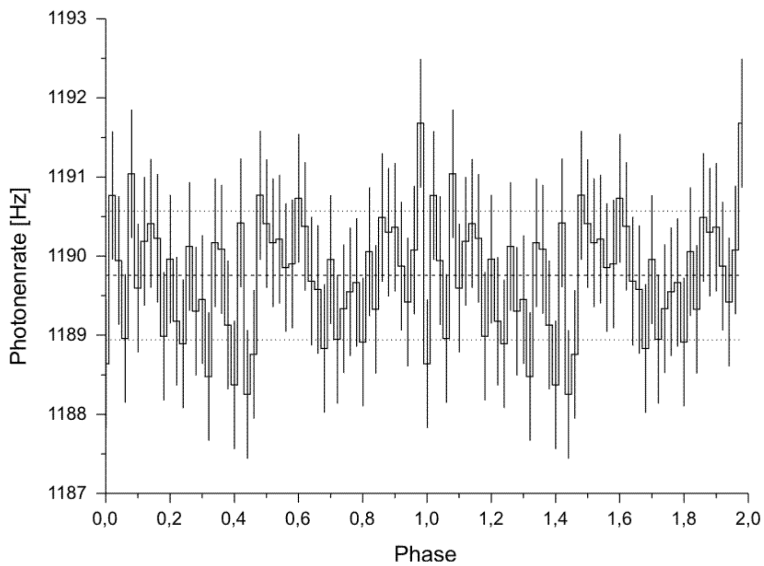

Figure 4. Lightcurve of Geminga from data taken during four nights from Dec 30, 1999 to Jan 2, 2000 with a total exposure of about 24 hours. The dashed lines indicate single phase bin deviations at the 1σ level.

3.3. A Cataclysmic Variable: HU Aquarii

The AM Her type cataclysmic variable HU Aqr (RE 2107-05) is a close eclipsing binary system containing a highly magnetic white dwarf and a secondary star of type M4V. The orbital period is $\sim$ 125 minutes. With a range of observed magnitudes from $\sim$ 15 to 18 it is one of the brightest sources of this type (Schwope, Thomas, & Beuermann 1993). Since very short timing signatures were expected in this object, in particular at the eclipse entry and exit of the dwarf star, we used OPTIMA in July 2000 at the 1.3m telescope on Mt. Skinakas, Crete to monitor this source over several orbits. Figure 5 shows a lightcurve with 1 sec resolution measured on July 5, 2000. Two eclipses of the white dwarf are the dominant features of this lightcurve. Since the sky background in the vicinity of the source has been subtracted using data from three fibres around the target fibre the low countrate level in the eclipse is due to the secondary star. Glenn et al., 1994 determined the mid-eclipse V-magnitude of the secondary M4 star to 19.1^m. The major features of the lightcurve starting from the eclipse are the following:

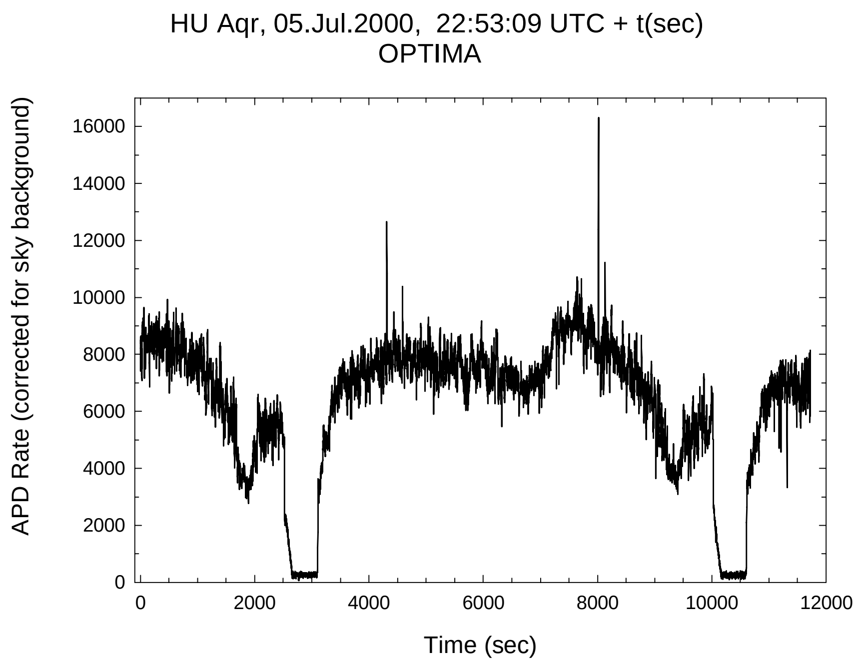

Figure 5. Lightcurve with 1 sec resolution of the eclipsing cataclysmic variable HU Aqr. The observation was taken from Skinakas observatory on Crete, Greece.

1. the egress of the accretion spot with a duration of about 7 seconds. Using the orbital velocity of the white dwarf of $\sim$ 200 km/s this duration corresponds to a spot size of about 1400 km. The same duration is observed at the ingress of the hot-spot into eclipse.
2. a light curve with two humps. This is interpreted as the beaming pattern of cyclotron emission produced in the polar regions of the accretion column above the white dwarf.
3. sharp spikes of optical emission with clearly resolved time scales of 1-2 seconds and a brightness increase of up to a factor of 2. These features, observed for the first time, could be due to strong inhomogeneities in the mass accretion flow. A final interpretation of this new phenomenon is still outstanding.
4. before the eclipse a dip of the intensity is observed. This is explained as an absorption effect when the accretion stream moves in front of the hot-spot

on the white dwarf. The depth and orbital phase of this absorption dip indicate that in this observation of HU Aqr the mass accretion rate was unusually high.

5. after the precipitous entry of the hot-spot into eclipse, a gradually fading component can be detected. This is interpreted as the entry of the larger accretion stream into the eclipse behind the secondary star

4. Conclusion and Outlook

With these observations of high time resolution and sensitivity, OPTIMA demonstrates the scientific potential for this frontier of astronomy, in particular for the investigation of radiation processes in the vicinity of compact objects, like black holes, neutron stars and white dwarves. At optical wavelengths the development of fast multi-colour photometers and polarimeters promises further insights into the physics of these sources. We plan to develop OPTIMA in these directions. The current version has already an optional rotating polarisation filter above the fibre pick-up. First measurements were performed in 2001 but are not yet analysed. The development of a multi-colour resolution is still a project for the next year.

Another important aspect of the absolute timing accuracy of the GPS based OPTIMA detector is the potential for correlated observations at different wavelengths. Such a simultaneous campaign was already performed with OPTIMA and the RXTE satellite on the X-ray transient source RXTE J1118+48 in July 2000. A total of 2.5 hours of coincident optical and X-ray observations were obtained on this black hole candidate at high galactic latitudes. The exciting correlations between optical and X-ray emissions are described in Kanbach et al. 2001. Accurate timing on scales of milliseconds is essential for these investigations.

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