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ORIGINAL ARTICLE

An avalanche photodiode photon counting camera for high-resolution astronomy

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Abstract A system is described which makes best use of the high quantum efficiency and high count rate capability of avalanche photodiodes for high time resolution observations of optical pulsars. The use of three APDs allows simultaneous photometry of the target and a reference star, and the monitoring of the sky background. By minimising the optical components in the light path the optical efficiency of the system is maximised. The TRIFFID (Shearer, A., Stappers, B., O'Connor, P., Golden, A., Strom, R., Redfern, M., Ryan, O.: Science **301**, 493–495 (2003)) and OPTIMA (Straubmeier, C., Kanbach, G., Schrey, F.: Exp. Astron. **11**, 157–170 (2001)) have shown that fibre-fed APD arrays can produce excellent results. This, new, system was used on the 6m BTA in November 2003 – results on the Crab pulsar are presented.

Keywords Detectors · Avalanche photodiode · Fibre optic · Optical pulsars · Photon counting

1. System description

Figure 1 has a schematic representation of the system, described by Ryan [7]. The principle is to use a mirror (item 4 in the figure, a first surface mirror with quarter wave surface quality and an enhanced aluminium coating) at 45° to the input plane to reflect the telescope image plane (7) onto a CCD (9) for viewing. The fibre needle head (containing three fibres) is slotted through a hole cut at 45° in the centre of the mirror. Two achromat lenses refocus the telescope image plane onto the fibre head and mirror. An appropriate choice of lenses allows the matching of the input optics of the system to the telescope beam f-number and plate

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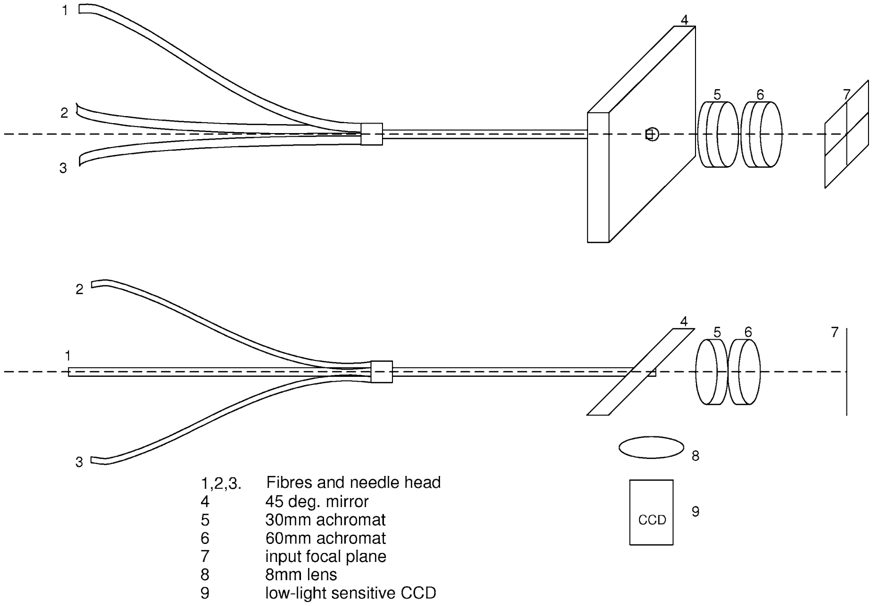


Fig. 1 A schematic representation of the 45° mirror and short fibres scheme, with a partial side view above and a plan layout below

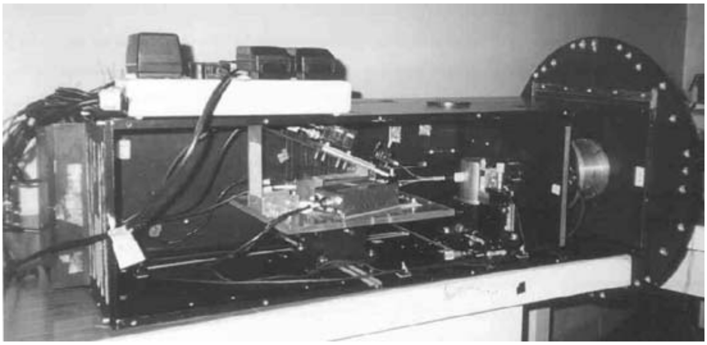


Fig. 2 A photograph of the system in preparation for mounting on the SAO 6m telescope

scale. Using a 2:1 lens ratio with the 6 m BTA SAO gave an image plane at the mirror with plate scale of 17.2 arcsec per mm and f-number of 2 (the SAO has a pixel scale of 8.6 arcsec per mm and an f-number of 4). Figure 2 has a photograph of the system in preparation for mounting at the prime focus.

The three APD modules used in the photometer system are from PerkinElmer [6] and are all active quench single photon counting modules with extremely low dark counts (two with dark counts typically 150–250 counts per second, the third with typically 250–500 counts per second). They exhibit a very wide spectral response with high efficiency especially in the red band, and a peak of $\sim$70% at 700 nm, as shown in Figure 3. Each has an active area of 180 μm. While the theoretical maximum count rate for an APD module is 15 Mcps [6], they are highly non-linear at this stage due to diode overheating and a practical limit for $\sim$1%

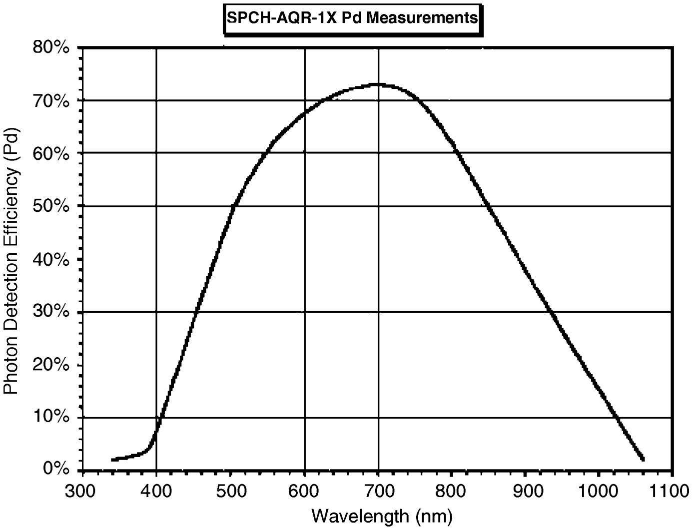


Fig. 3 The spectral response of the APDs from the manufacturer's datasheet [6]

photometric accuracy is ~200 kcps. As large modules with a single pixel detection area the issue of positioning more than one in an image plane is resolved through the use of fibre optics which allows multiple APDs to be used simultaneously.

The fibres are 20 cm long, have a 200 μm core diameter and are in an equilateral triangular arrangement in the needle head with a centre-centre separation on each side of 240–245 μm, manufactured to specification [5]. This gave a field of view on the sky of 3.44 arcsec per fibre with centre-centre separation of 4.13 arcsec at the SAO prime focus with the above mentioned 2:1 lens design. This would allow the positioning of the Crab pulsar in one fibre, a reference star in another (Trimble28) and the sampling of the background in the third.

Initially designed for use on the WHT Cassegrain focus (plate scale of 4.51 arcsec per mm and an f-number of 10.94), there was no initial need for the two achromat lenses. The mirror with fibre head can be placed directly in the WHT focal plane thus removing the throughput losses of the lenses, and increasing the overall system efficiency further. But this would have given a fibre field of view of 0.9 arcsec on the Crab pulsar making the observation even more dependent on (very good) seeing conditions.

The shortness of the fibres and the wish to keep them as straight as possible (to avoid transmission losses over their lengths and at bends) restricted the space available for positioning the three APDs beside each other. This was solved by tiering the APDs, one above the other two. One APD sits on a pedestal inclined at 25° above the two others, which are angled towards each other at the base of the pedestal with approximately 40° between them (Figures 1 and 2).

The CCD uses a TV signal 1/3 inch EXview Sony HAD (hole accumulation diode) CCD sensor [9] that increases its efficiency by extending its sensitivity out to the near-infrared region. An interface to a framegrabber was created with MATLAB and its image acquisition toolbox [4] to provide a realtime video signal from the CCD, as well as allow realtime binning, filtering and processing of individual frames.

The CCD used an 8 mm f/2 lens which provided a very limited and vignetted field of view, but due to time constraints before the run could not be replaced. An image from the CCD

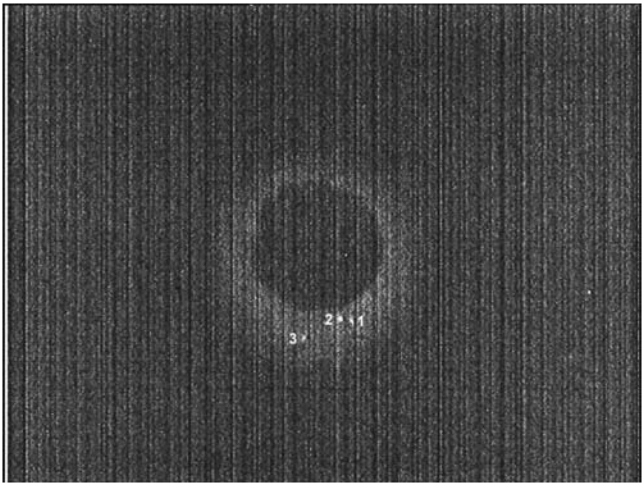
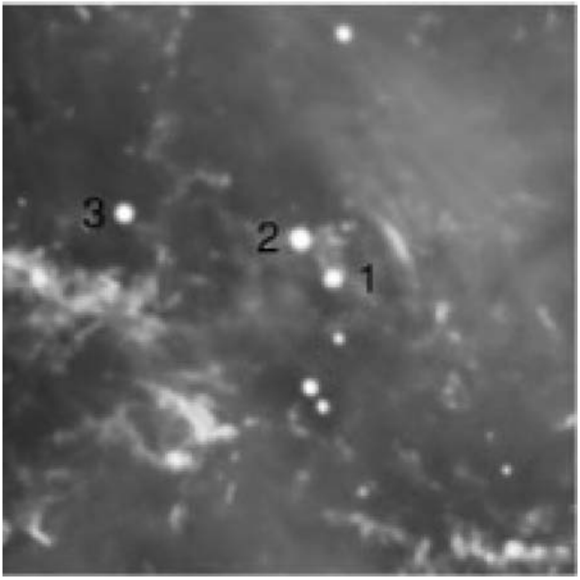


Fig. 4 An image of the Crab pulsar, marked ‘1’, taken from the CCD viewer. The image is composed of 250 CCD frames, a noise frame subtracted from each individually, and a Gaussian noise subtraction filter applied to the end summation. Above the marked stars is the 45° hole through the mirror. The same numbering scheme is used in Figure 5

Fig. 5 A high resolution image of the Crab nebula, from [2], with the pulsar marked ‘1’. The same numbering scheme is used in Figure 4



when viewing the Crab pulsar is given in Figure 4 and a comparison high resolution field image from ESO [2] is given in Figure 5. Despite the small field of view the position of the Crab pulsar was confirmed in two ways — first from the positions of the two reference stars, and second by taking a sample of data from the target and checking for the characteristic pulses. The pixel scale on the CCD images is 2.63 pixels per arcsec = 1 pixel per 0.38 arcsec, measured knowing the separation of identified stars on the sky. With this scale the diameter of the mirror hole on the sky was 59.3 arcsec (154 pixels).

Table 1 32 bit wide APD data format, as saved to file. Refer to the text for an explanation

APD2	APD 3	24 bit counter					
32 bit UTC stamp							
APD 1	APD 1	APD 1	APD 1	APD 1	APD 1	APD 1	APD 1
4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits
4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
APD2	APD 3	24 bit counter					
32 bit UTC stamp							
APD 1	APD 1	APD 1	APD 1	APD 1	APD 1	APD 1	APD 1
4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits	4 bits
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

1.1. APD and CCD data collection

A system based on TTL IC logic devices was created to collect data from the three APDs [1]. The modular nature of the design electronics allows the addition and removal of the three detectors without limiting the performance of other elements within the system. The data path is designed so that archiving integrity is maintained while the data path is simultaneously used for realtime analysis and display. The dedicated electronics for the APD detectors were designed to incorporate timing information and buffer the incoming data.

The APD used to collect target data, APD1, can have a timing resolution of 1 μs, 2 μs, 4 μs or 8 μs, while the counts of the remaining two APDs used for sky and standard star references, APD2 and APD3, are binned per millisecond. Normally used at the maximum setting, the absolute time of arrival of each detected photon from APD1 is then known to one microsecond. This is achieved by using an oven-stabilised 10 MHz oscillator and the GPS receiver system that provides UTC time and a 1 pulse per second (1 PPS) signal that is accurate to better than 0.1 μs. By connecting a 24-bit counter to the oscillator output, microsecond timing accuracy can be assured. Every second the UTC time from the GPS receiver is inserted into the data stream to ensure absolute timing accuracy. All APD data is stored to a binary file, the format of which is given in Table 1.

Referring to Table 1, the two lines containing APD2 and APD3, the 24-bit counter and the UTC stamp occur every ten thousand cycles of the 10 MHz oscillator (10000 cycles $\sim$1 ms with the 10 MHz clock giving 10,000,062.15 ticks per second). The 24-bit counter holds a count of the number of clock cycles up to that point since the last GPS 1 PPS. APD2 and APD3 each are assigned 4 bits and hold the counts from both APDs over the last 10000 cycles. Each subsequent 4 bit segment (until the next time stamp) holds the APD1 counts collected over 1 μs, 2 μs, 4 μs, or 8 μs, according to the resolution setting. The 24-bit counter is reset every GPS 1 PPS. The APD2 and APD3 counters are reset every 10000 cycles. The APD1 segments will be mostly zeros - when a count is found (typically 1 or 2) in processing the data, the time of arrival is calculated knowing the UTC, 24 bit counter count (converted to seconds), and the position of the segment in the data flow from the last timestamp, converted to seconds (each segment step equals one time resolution unit).

The data from the data acquisition electronics is simultaneously archived to disk as well as transmitted over Ethernet as a multicast stream. This allows realtime display and analysis programs to be located anywhere on the local network without disturbing the integrity of the archiving process.

The low-light sensitive CCD outputs a TV signal at 25 frames per second. A framegrabber was used to collect these frames, and an interface program written in MATLAB [4] to control the framegrabber as well as to display, manipulate and save the images. Images are archived with a UTC timestamp.

2. APD sample pulsar data

Of three nights from November 24th–26th 2003 at the 6m BTA SAO telescope approximately 114 minutes of APD data on the Crab pulsar was recorded, the end of which was severely hampered by the coming of dawn. Electrical difficulties between the observatory's UPS ground plane and our equipment prevented proper data collection the first night, and part of the second night. The Crab pulsar data was taken on this second night approaching dawn. The third night was clouded over and gave no chance of an observation. Despite this, the restricted amount of time on the Crab was enough to validate the design of the fibres for the APDs.

The 150–250 cps dark count rate of the APD gives a limiting magnitude of $\sim$22 mag (m_v) on the SAO (m_v(Crab) $= 16.8$ mag). An example of the raw data collected is given in

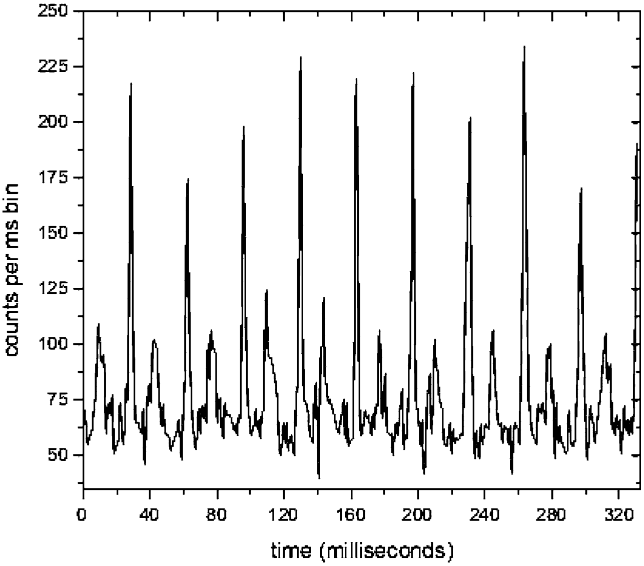


Fig. 6 A series of raw *individual* Crab pulses uncorrected for background counts taken at the 6 m SAO telescope. Plotted are counts per millisecond against time in milliseconds

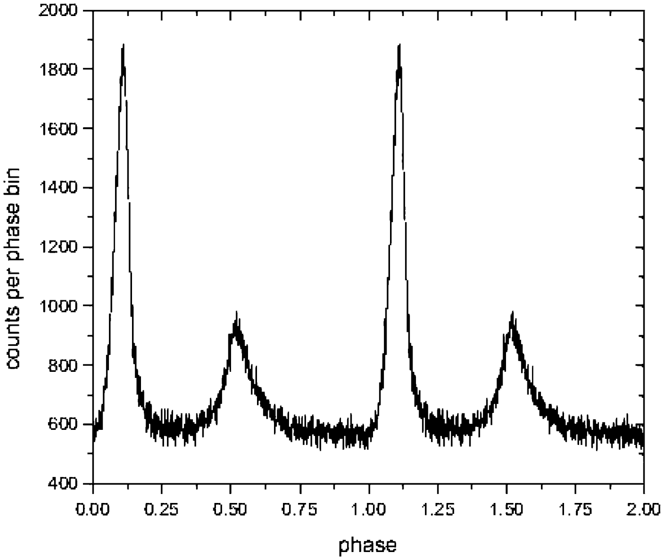


Fig. 7 Two cycles of the phase folded lightcurve of the Crab pulsar compiled from 9.62 s worth of raw data taken by the APD on the 6m SAO. The data has been barycentred to the solar system centre of mass using the Jodrell Bank Crab pulsar ephemeris [3], but has not been background corrected. The zero phase point was arbitrarily chosen. There are 1000 bins per full phase rotation

Figure 6. This figure displays the first 330 ms of data taken on the Crab pulsar – the data is given in its raw state and has not been background corrected, nor barycentred. The pulse counts have been summed into millisecond wide bins and are graphed as such.

Approximately ten seconds worth of the data in Figure 6 was taken aside and used to create the integrated pulse profile of Figure 7. The data was not background corrected but it has been barycentred using the Jodrell Bank Crab pulsar ephemeris [3]. Two full phases of rotation are displayed with the zero phase point arbitrarily chosen. This data was used to estimate the APD system efficiency as ∼39% (combined efficiencies of the two achromat lenses, short fibre, and APD), and from this a quite respectable fibre throughput of ∼69%. It should be noted that with an f/2 beam input at the SAO (the f/4 SAO beam refocussed with our 2:1 lens ratio), the f/2.27 fibres are actually somewhat overfilled. Clearly the corresponding light loss has been offset by the fibres' excellent intrinsic efficiency.

3. Conclusion

The use of short fibres proves to be highly beneficial in increasing light throughput to the single photon counting modules, maximising the use of their high photon counting sensitivities. With an improved viewer the system shall provide good continuous data of the Crab pulsar, amongst other targets, collecting larger photon rates at the high time resolution of 1 μs.

The advantages of single photon counting modules with avalanche photodiodes are such that they are highly desirable in astronomical photometry. Their modular nature allows them to be interchangeable and easily incorporated into an existing photometer system. They have a broad spectral responses and high quantum efficiencies. They allow for high count rates (greater than 1 Mcps) with short deadtimes (40 ns), and with low dark count rates (less than 250 cps generally).

The modules have been used to great effect in the TRIFFID [8] and OPTIMA [10] systems.

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