

Review of the ultrafast time resolution photopolarimeters based on SPADs

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Abstract. We review photopolarimeters that are based on the Single Photon Avalanche Diodes (SPADs) and were designed, built, developed, and extensively used for high time resolution studies of astrophysical sources. Examples of such detectors are OPTIMA, GASP, AquEYE, and IquEYE which can measure the time of arrival of single optical photons with an accuracy of down to 50 picoseconds. We describe the most exciting results obtained with the SPADs detectors starting from the best existing optical polarimetric measurements of the Crab pulsar, the discovery of the first optical magnetar and its quasi-periodic oscillations, as well as a verification of exoplanets around eclipsing cataclysmic variables. Additionally, we discuss possible applications of such detectors for asteroseismology.

Keywords. photometers, polarization, pulsars, magnetars, cataclysmic variables, exoplanets

1. Single Photon Avalanche Diodes (SPAD) instruments

OPTIMA – Optical Pulsar Timing Analyzer (Straubmeier 2001, Kanbach *et al.* 2003 and 2008, Stefanescu 2011) is a very high time resolution, single-photon sensitive optical photometer and polarimeter. It uses optical fibres to gather light from fixed apertures in the focal plane to SPADs, while the field surrounding the apertures is imaged using a standard CCD detector. Single photons are recorded with absolute UTC time-scale tagging accuracy of ~ 5 ns. The quantum efficiency of the SPADs reaches a maximum of 60% at 750 nm and lies above 20% in the range 450–950 nm. The system was designed from scratch as a guest instrument, easily adapted to different telescopes. It can be reconfigured for photometric or polarimetric use within one observing run.

GASP – Galway Astronomical Stokes Polarimeter is a fast, full Stokes, astronomical imaging polarimeter. Its construction allows to measure all four elements of the Stokes vector (I, Q, U, V) simultaneously over a broad wavelength range (400–800 nm). Measuring linear and circular polarization with a time resolution of the order of microseconds makes GASP a unique astronomical instrument (Kyne *et al.* 2010).

IquEYE and AquEYE – ultra-high-speed photometers capable of tagging the arrival time of each photon with a resolution and accuracy of 50 picoseconds, for hours of continuous acquisition, and with a dynamic range of more than 6 orders of magnitude (Barbieri *et al.* 2009, 2012, Naletto *et al.* 2009).

All these detectors are portable and were used successfully at several observatories.

2. Example results

Crab pulsar and its nebula. The linear polarization of the Crab pulsar and its close environment was derived with a time resolution as short as 11 μ s, which corresponds to a phase interval of 1/3000 of the pulsar rotation (33 ms). High sampling allows

to derive polarization details never achieved before (Słowikowska *et al.* 2009). These results were recently confirmed by Moran *et al.* (2013). On the other hand, AquEYE allowed the first sub-microsecond optical timing of the Crab (Germanà *et al.* 2012).

First optical magnetar. We observed extremely bright and rapid optical flaring in the Galactic transient SWIFT J195509.6+261406 (Stefanescu *et al.* 2008). Its optical light curves are phenomenologically similar to high-energy light curves of soft γ -ray repeaters and anomalous X-ray pulsars, which are thought to be neutron stars with extremely high magnetic fields – magnetars.

HU Aqr – a Jovian companion? The eclipsing binary HU Aqr is a polar (mWD + M4 V) with an orbital period of 125 minutes. This binary exhibits periodic variations of the observed-minus-calculated (O–C) curve. We performed a detailed study of archival and new OPTIMA observations, in terms of a new Light Travel Time (LTT) ephemeris model, formulated with respect to the Jacobi coordinates with the origin in the mass center of the binary. We found that the observations are best explained by one periodic signal, which can be interpreted by the presence of a ~ 7 Jupiter-mass planet, in a ~ 10 yr quasi-circular orbit (Goździewski *et al.* 2012, Słowikowska *et al.* 2013).

3. Conclusions

High time resolution instruments based on SPADs allow to time tag single optical photons with accuracy even down to 50 picoseconds. They have been successfully used to study rapidly changing sources such as optical pulsars, cataclysmic variables, including polars and intermediate polars (Nasiroglu *et al.* 2012), as well as very fast flares from optical magnetars. SPAD instruments can be successfully used also in case of pulsating stars to study different oscillation modes, especially at high frequencies. Such oscillations penetrate to different depths inside the stars and provide information about their otherwise unobservable interiors.

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