The OPTIMA Detector System for High-Time Resolution Astrophysics

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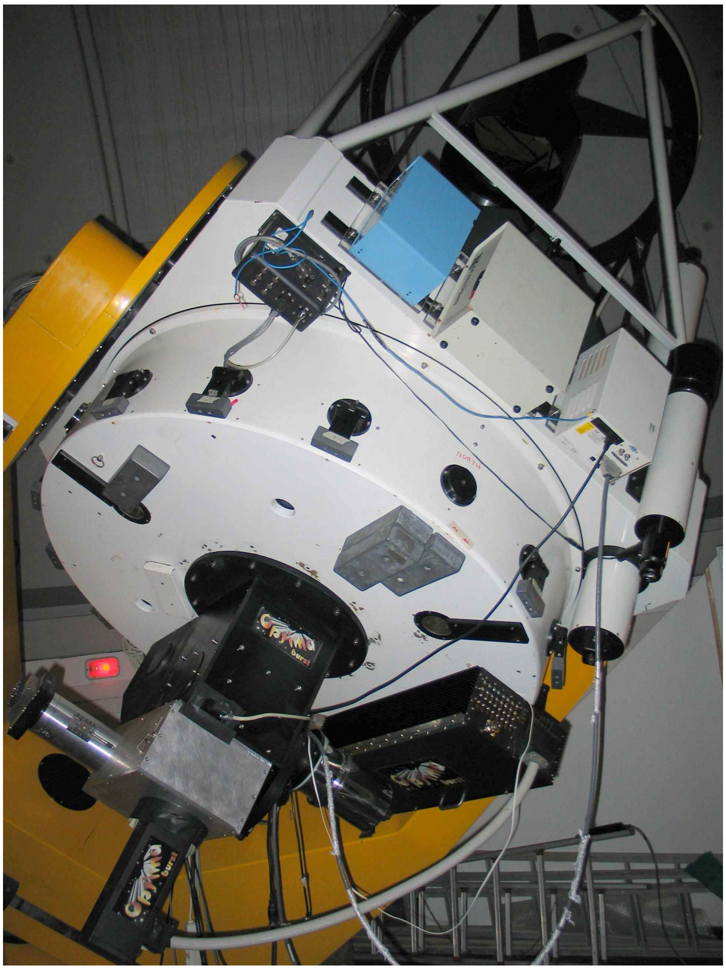


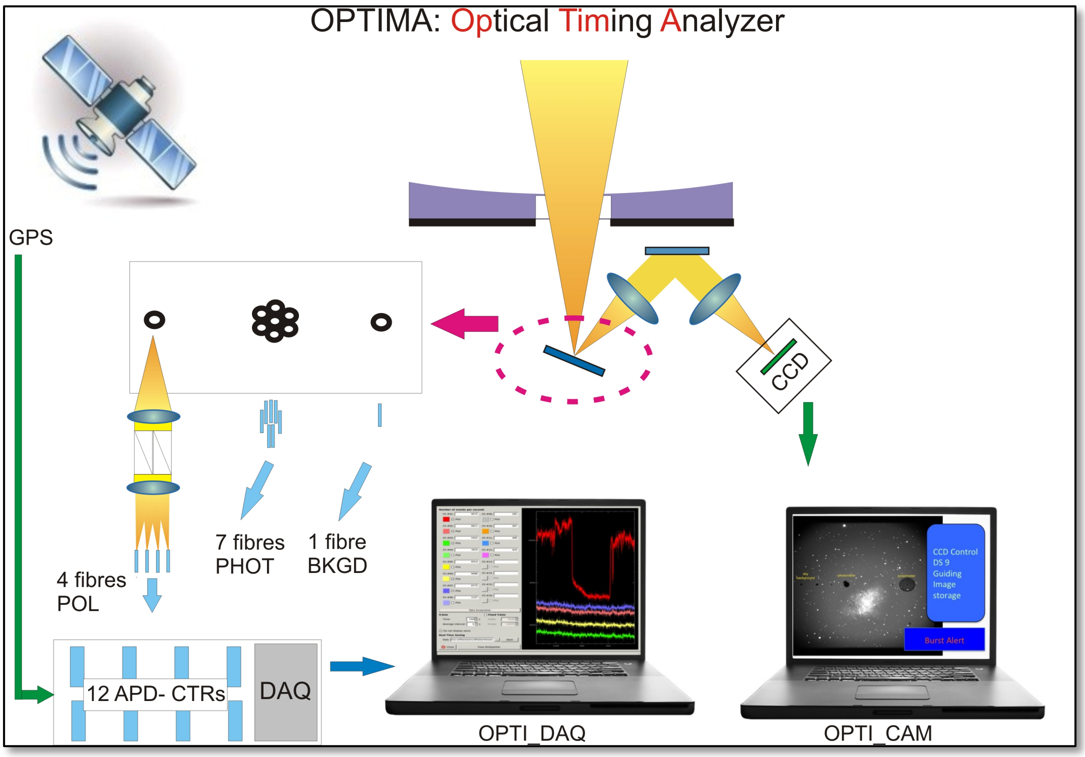
GENERAL OVERVIEW

OPTIMA, short for OPtical TIMing Analyzer, is a sensitive, portable, stand-alone high-speed photo-polarimeter, designed for observations of highly time variable sources like pulsars, magnetars, cataclysmic variables, X-ray binaries, and flare stars. It is a light-weight and easy-adaptable system which has already been operated successfully at a number of telescopes around the Globe.

In order to study fast optical variablity, OPTIMA records the arrival times of individual optical photons passing either through hexagonal fibre unit for photometry or through a Twin Wollaston prims for polarimetry. The main charateristics of the system are:

Detector wavelength range:	**450-900 nm (Q.E. >35%, max ~73% at 680 nm)**
Single photon timing:	**5 ns relative time tagging to GPS UTC**
Sensitivity (1s integration):	**mag$_V$ ~ 20 (at 2.4m TNO telescope)**

The general outline of the OPTIMA operation is as follows and schematically shown in the figure below: After passing through the telescope, the focal plane image of a star field including the scientific target is reflected from a slanted mirror ('field view mirror') and recorded on a CCD camera which provides guidance and control of targets and stars in the field. The corresponding computer (OPTI_CAM) displays and records the images and derives slewing and offset commands (manual or directly via data interface) to the telescope control system. During a scientific exposure the CCD camera is set to take sequential short exposures (typical 10 sec), which are used to monitor and control telescope guidance, seeing, and atmospheric transparency. An independent, telescope supplied, guider is however highly desirable for smooth OPTIMA observations.



OPTIMA provides two principal modes of measurement, which can be selected by positioning a target on specific apertures embedded in the slanted mirror:

- **Photometry** ('PHOT') records photons from targets positioned on a hexagonal integral field unit of fibre pick-ups. Usually the central fibre contains the target, and the ring of six fibres monitors the nearby sky (or nebular) background. In addition, a single aperture ('BKGD') records the celestial background at a distance of typically an arcminute from the photometer.
- **Polarimetry** ('POL') can be selected by positioning the target on a diaphragm with 300mm opening. The collimated beam is then split in two parts and illuminates two Wollaston prisms. After re-focussing the beam to 4 polarized images, with polarization angles of 0°, 45°, 90°, and 135°, the photons are recorded on 4 fibre pick-ups. From the relative intensities the state of linear polarization of the incoming light can be deduced.

The system currently contains 12 photon counters (single-photon sensitive avalanche photo diodes, APD) and time tagging electronics (FPGA, GPS). Photon data are transmitted to the data acquisition computer (OPTI_DAQ) via optical LAN and stored in FITS format files. Online displays of the measured rates provide immediate control of the observation.

The OPTIMA data analysis is based on the recorded photon FITS files and the supplementary series of images taken with the field-viewing camera. From the photon files target and background data are evaluated separately. Corrections due to variations in seeing or atmospheric transparency are applied at this stage. The reduced data for the target intensity rates (with optional binning), polarimetry measurements, pulsar or CV lightcurves, etc., are stored in graphical and numerical formats for subsequent analysis and interpretation.

OPTIMA has been adapted to and was used successfully at several observatories:
1.3m Skinakas (Greek); 1.9m SAAO (Australia); 2.2m ESO La Silla (Chile); 2.56m NOT, La Palma; and 3.5m Calar Alto (Spain)

MECHANICAL AND OPTICAL CONFIGURATION

OPTIMA consists of three components:

1) a **focal plane assembly (FPA)** containing the fibre pick-ups and apertures for the photometric and polarimetric channels as well as the field-viewing optics and camera. A schematic drawing is shown in Fig. 2a and the optics are shown in Fig. 2b. The internal focal distance from the attachment flange is about 200 mm. The central box measures 300x400x200 mm, the entrance window has a diameter of 100 mm. The box is attached to the telescope with M8 screws located on a circle of radius 135 mm concentric with the entrance window. The fibre pick-up and polarimeter box extends 350 mm from the central box and the field camera extends about 270 mm. The total weight of the assembled FPA is about 30 kg. Field Camera control and data transmission is via an USB cable to a camera control laptop.

2) an **APD counter box** with an attached front-end data acquisition electronics unit and a remotely mounted GPS antenna. The APD box is mounted at a distance of less than 1.5m from the FPA somewhere on the co-moving focal plane platform. Dimensions for the APD box are: 850 x 350 x 200 mm and it weighs about 33 kg. The optical fibres from the focal plane pick-ups are about 2m long. They are protected in a sturdy but flexible conduit, and feed the astronomical photons to 12 single photon avalanche detectors (SPADs) in the box. Cables for power supply, the GPS antenna, the field viewing camera, and the Ethernet connection are dragged from the APD box to the telescope floor and connect the instrument to the remote control room. A typical set-up of OPTIMA at the Cassegrain focus of the 1.3m telescope on Mt. Skinakas, Crete, Greece is shown in Fig. 3 (left).

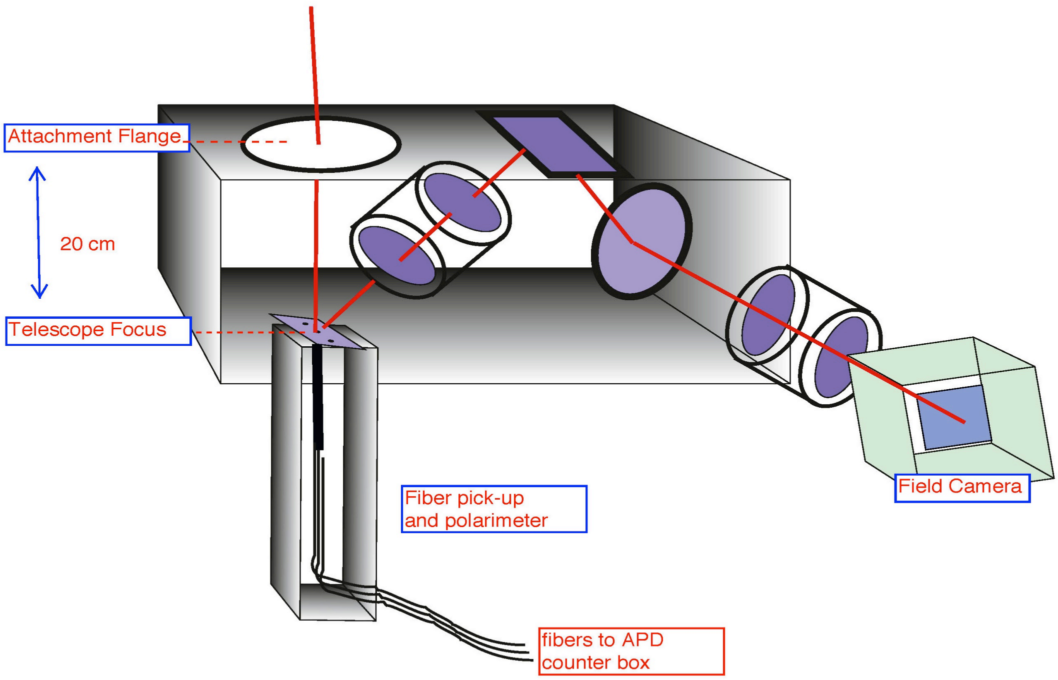


Fig 2a: Schematic of OPTIMA focal plane assembly (FPA)

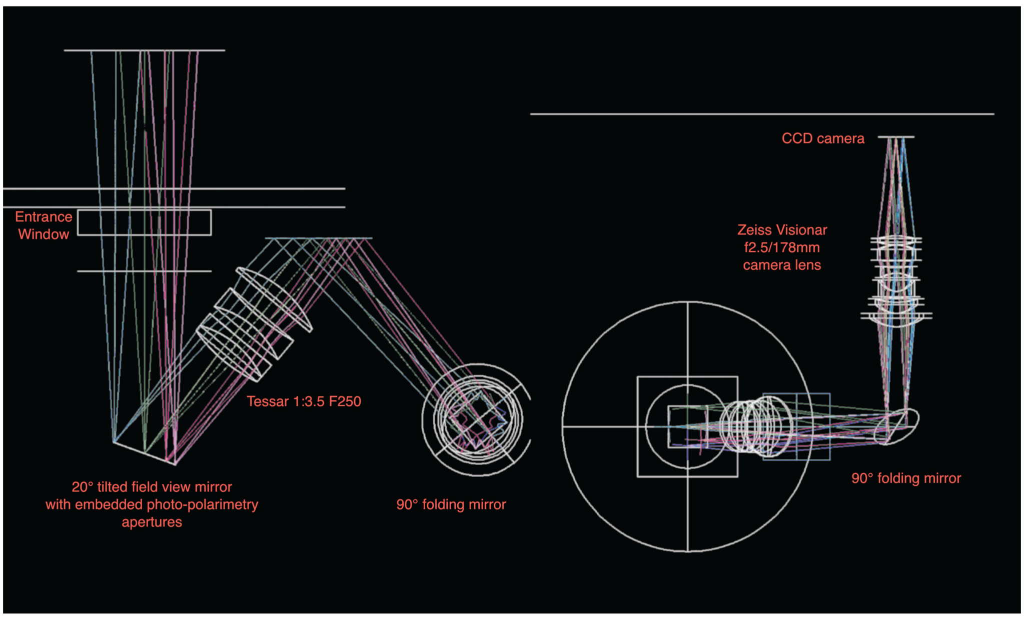


Fig. 2b: Field viewing optics (ZEMAX ray tracing) to provide an image of the environment around the photon counting apertures in the slanted mirror.

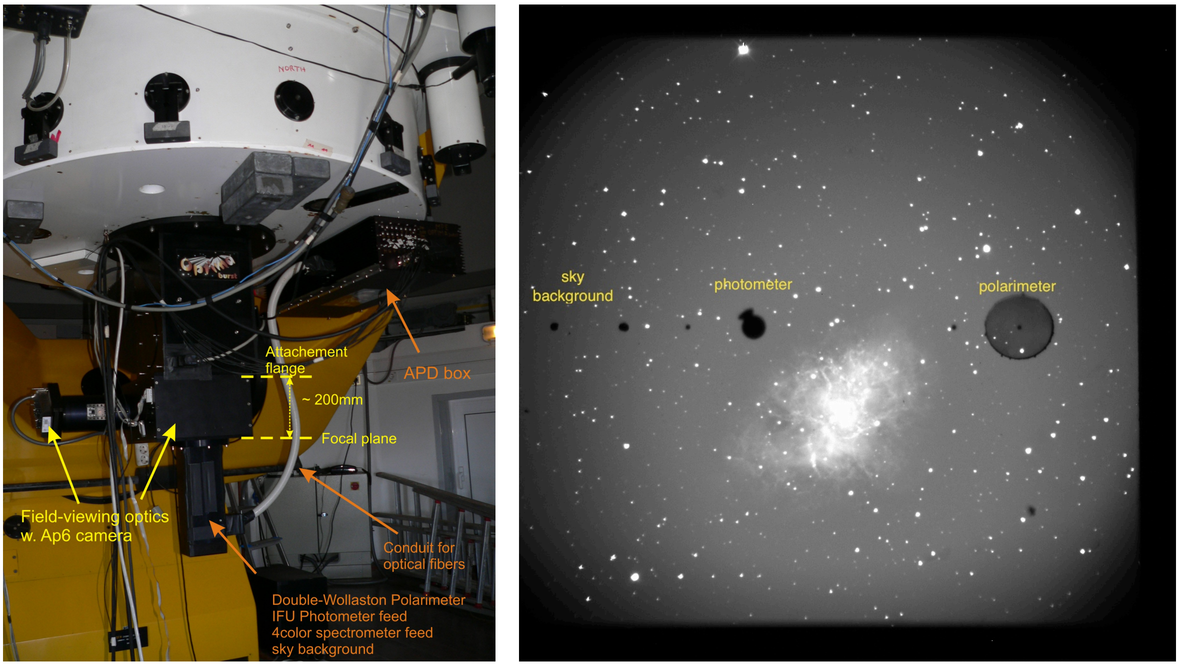


Fig. 3: (left) OPTIMA mounted on the Cassegrain focus of the 1.3m telescope on Mt. Skinakas, Crete (Greece). (right) Image of the Crab nebula in the field-viewing camera (SKO 1.3m, 2012). Apertures (fibre pick-ups) for the photon-counting modes are indicated.

3) **Data Acquisition and Control**: two laptop computers situated in the control room manage the field viewing camera and the photon counters. A typical image from the field-viewing camera is shown in Fig. 3 (right): the Crab nebula with the apertures for photometry, polarimetry, sky (in this case nebular) background, and fiducial markers are visible on the slanted mirror with a typical field of view of 10 arcmin.

To position and hold the desired target in the photon-counting apertures, we determine moves, offsets, and guiding of the telescope with the field-viewing system. The data can then be transmitted to the telescope control system either manually or via a data interface.
The field-viewing system can also be set up to accept external position triggers, e.g. via an internet socket connection from the gamma-ray burst coordinates network (GCN). After acceptance by the operator, the telescope will move to the triggered source.
The data acquisition computer formats the incoming data stream of photon time tags from 12 separate counters into FITS files and stores the data. At the same time a real time display of rates is displayed and allows the operator to quickly assess the quality of the observations. Fig. 4 shows such a display for the eclipsing CV HU Aqr from 2012 observations at Skinakas observatory.

4) **Auxiliary equipment, installation, and operation:** 2 power supplies (220V on the telescope floor) , the GPS antenna (outside the building), small interface boxes to control the shutter, fiducial lights and camera (control room). We need about one day to assemble and calibrate the OPTIMA equipment on a laboratory table (about 2m size), technical help to mount and balance the equipment on the telescope, and some storage space to hold 3 aluminum shipping boxes. Two people are normally needed to operate OPTIMA.

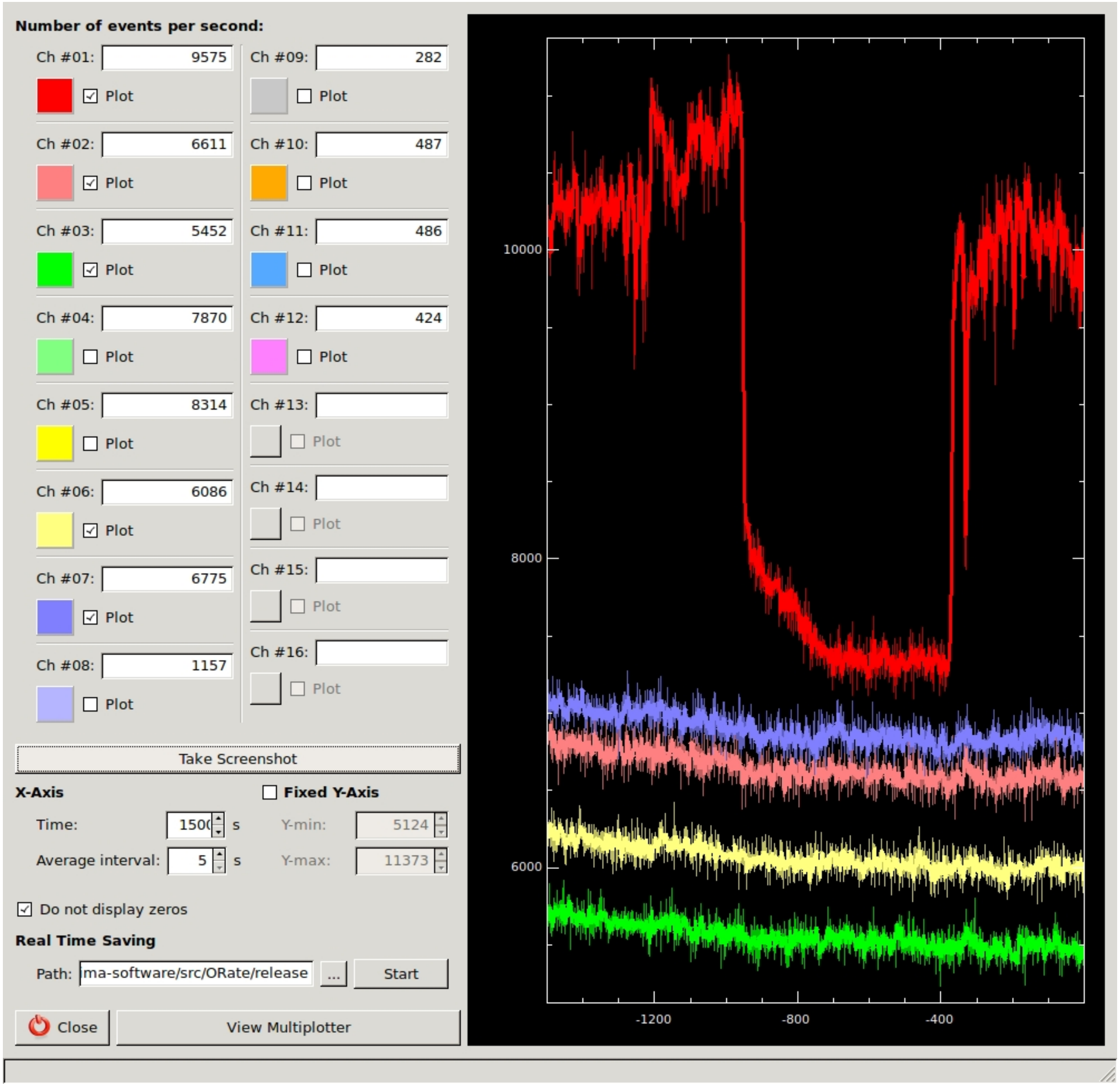


Fig. 4: Realtime display of rates for an eclipse of HU Aqr with 1 second resolution. Four channels of sky background intensity are also displayd (data taken at Skinakas observatory 2012)

MAJOR SCIENTIFIC RESULTS FROM OPTIMA

OPTIMA observations, carried out at various observatories since the year 2000, have led to four PhD theses, four Master and Diploma theses, and many publications in journals (among them 2 in Nature, 3 in MNRAS, 6 in A&A, and in many conference proceedings; for a complete bibliography see http://www.mpe.mpg.de/270787/publications).

Here we highlight some of the major discoveries:

Correlated fast X-ray and optical variability in the black-hole candidate XTE J1118+480 (Kanbach et al., Nature 414, 180, 2001):

Using simultaneous high-time-resolution X-ray (RXTE) and optical (OPTIMA) observations of the transient source XTE J1118+480 (a.k.a. KV UMa), we discovered strong and puzzling correlations between the emissions in these two bands. The optical emission rises suddenly, within 30 ms, following an increase in the X-ray output. We also observe a dip in the optical intensity about 2 seconds in advance of the X-rays. This result is not easy to understand within the simplest model where the optical emission is generated by reprocessed X-rays from an accretion disk. The data are more consistent with an earlier suggestion that the optical light is cyclo-synchrotron emission that originates in a region about 20,000 km from the black hole. We therefore proposed that the observed X-ray vs. optical time dependence is evidence for a relatively slow (0.1c), magnetically controlled outflow, where shocks from the central engine (X-rays) lead to optical emissions with the observed time delays.

Very fast optical flaring from a possible new Galactic magnetar (Stefanescu et al., Nature 455, 503, 2008):

Highly luminous rapid flares are characteristic of processes around compact objects like white dwarfs, neutron stars and black holes. In the high-energy regime of X-rays and gamma-rays, outbursts with variabilities on timescales of seconds or less are routinely observed, for example in gamma-ray bursts or soft gamma-ray repeaters. At optical wavelengths, flaring activity on such timescales has not been observed, other than from the prompt phase of one exceptional gamma-ray burst. This is mostly due to the fact that outbursts with strong, fast flaring are usually discovered in the high-energy regime; most optical follow-up observations of such transients use instruments with integration times exceeding tens of seconds, which are therefore unable to resolve fast variability. With OPTIMA we discovered extremely bright and rapid optical flaring in the Galactic transient SWIFT J195509.6+261406. Our optical light curves are phenomenologically similar to high-energy light curves of soft gamma-ray repeaters and anomalous X-ray pulsars, which are thought to be neutron stars with extremely high magnetic fields (magnetars). This suggests that similar processes are in operation, but with strong emission in the optical, unlike in the case of other known magnetars.

Optical polarisation of the Crab pulsar: precision measurements and comparison to the radio emission (Slowikowska et al., M.N.R.A.S. 397, 103, 2009):

The linear polarization of the Crab pulsar and its close environment was derived from OPTIMA observations at the 2.56-m Nordic Optical Telescope on La Palma. Time resolution as short as 11 μs, which corresponds to a phase interval of 1/3000 of the pulsar rotation, and high statistics allow the derivation of polarization details never achieved before. The degree of optical polarization and the position angle correlate in surprising details with the light curves at optical wavelengths and at radio frequencies of 610 and 1400 MHz. Our observations also show that there exists a subtle connection between presumed non-coherent (optical) and coherent (radio) emissions: in the Crab main pulse the minimum of optical polarization occurs at the phase of maximum radio emission and a strongly polarized optical component is observed at the phase of the low frequency radio precursor. This findings support previously detected correlations between the optical peak intensity and the occurrence of giant radio pulses in the Crab. Interpretation of our observations requires more elaborate theoretical models than those currently available in the literature.

On the HU Aquarii planetary system hypothesis (Gozdziewski et al., M.N.R.A.S. 425, 930, 2012):

Eclipse timing of the polar binary HU Aquarii has been observed for almost two decades and OPTIMA contributed about 90 high precision eclipse egress times spanning the years 1999 to 2012. The eclipse times can not be described with a simple ephemeris but show rather large (O-C) periodic deviations with amplitudes of about 15 seconds. Early interpretations of the data suggested that two massive jovian companions orbit the close binary system. We improved the Keplerian, kinematic model of the Light Travel Time (LTT) effect and re-analysed the whole currently available data set. Using the consitent set of high resolution, precision OPTIMA light curves, we find that the (O-C) deviations are best explained by the presence of a single circumbinary companion of about 7 Jupiter masses, orbiting in a nearly circular orbit at a distance of about 4.5 AU, with a period of about 10 years. This object could be the next circumbinary planet detected from the ground, similar to the announced companions around close binaries HW Vir, NN Ser, UZ For, DP Leo or SZ Her, and planets of this type around Kepler-16, Kepler-34 and Kepler-35. Observations of the HU Aqr system with precision eclipse timing are needed in the coming years to firmly establish this planetary hypothesis.