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Fast photon-counting optical astronomy

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Abstract. Fast sub-second optical variability exists in some important classes of astrophysical sources, in particular pulsars and X-ray binaries. We regularly perform ultra-fast optical photometric campaigns on some of the most interesting targets and transient events. At the same time, we are tackling new campaigns searching for fast optical variability in other types of sources (Fast Radio Bursts, magnetars). To this end we use and develop dedicated fast photon counting instrumentation in the visible band, an area in which our team is the leader. Observations are carried out within the framework of multiwavelength campaigns and in synergy with facilities operating at other wavelengths. Here we report on some of the most recent observing campaigns and technological developments, and on the outcome of a km-baseline experiment of stellar intensity interferometry carried out in photon counting mode.

Key words: Astronomical instrumentation, methods and techniques – Instrumentation: photometers – Techniques: interferometric – stars: magnetars – pulsars: general – pulsars: individual: PSR J1023+0038 – pulsars: individual: SGR J1935+2154 – radio continuum: transients – fast radio bursts – FRB 20180916B

1. Introduction

The project of Fast Photon Counting Optical Astronomy (FPC-OA) in Padova is focused on the study of sub-second optical variability in various types of astrophysical sources, and on experimental applications of Quantum Optics concepts to astronomical observations. We also design and develop optical fast photon counting instrumentation for these observations and applications.

The two main instruments that we realized and operate are AQuEye+ (Asiago Quantum Eye+; Barbieri et al. 2009; Naletto et al. 2013; Zampieri et al.

2015, 2019b), mounted at the Copernicus telescope in Asiago, and IQuEye (Italian Quantum Eye; Naletto et al. 2009), that was mounted at several telescopes around the world and is now attached at the Galileo telescope in Asiago. Other technological activities involve the low-impact fiber-feeding of FPC-OA instrumentation to telescopes (Iqueye Fiber Interface, IFI; Zampieri et al. 2019b). With the goal of carrying out further technological activities within the framework of this project, we recently realized a dedicated laboratory at Cima Ekar, in Asiago, where the Copernicus telescope is located. This ASTRI-AQUEYE laboratory serves jointly for the assembly, test, and verification activities of the FPC-OA project and for those of the ASTRI Mini-Array Stellar Intensity Interferometry Instrument (Zampieri et al., 2022a).

Several observing FPC-OA programs are currently undertaken, such as the simultaneous multicolor observations of optical pulsars, the timing of optical transients and X-ray binaries, the searches for optical flashes from Fast Radio Bursts (FRBs) and magnetars, the monitoring of the intra-night variability of Blazars, Lunar and asteroidal occultations, and Stellar Intensity Interferometry experiments. Time at the telescopes is granted through two approved proposals for visitor instruments, for a total of 28 nights/year at the Copernicus telescope (cycles 22-24) and 2-3 nights/month at the 1.2-m Galileo telescope.[1] Observations are often carried out within the framework of simultaneous or coordinated multiwavelength (MWL) campaigns with other facilities from the radio to the gamma-ray bands (e.g. SRT, NC, GMRT, TNG, NICER, HXMT, MAGIC).

This paper reports a summary of the results and activities in FPC-OA that we carried out in the last few years.

2. Aqueye+ and Iqueye

Aqueye+ and Iqueye[2] are non-imaging instruments with a field of view of a few arcseconds tailored to performing very fast photon counting observations in the optical band (Barbieri et al. 2009; Naletto et al. 2009, 2013; Zampieri et al. 2015, 2019b). Their distinctive features are: an optical design with an entrance pupil split, four on-source Single Photon Avalanche Detectors (SPADs), one on-sky SPAD detector (offset by 10 arcmin), an acquisition system capable of sub-nanosecond time tagging accuracy with respect to UTC.

Both instruments adopt the same concept of splitting the telescope entrance pupil proposed for QuantEYE (Dravins et al., 2005). The pupil is divided into four parts, each of them focused on a single SPAD detector. SPADs have < 50 ps time resolution, $\sim$100 cts/s dark count rate, $\sim$8 MHz maximum count rate, and $\sim$50% photon detection efficiency. The acquisition electronics time tags and stores the arrival time of each detected photon with < 100 ps relative time accuracy and < 500 ps absolute time accuracy with respect to UTC. All times

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[2] http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html

are stored in event lists that can be analyzed in post-processing. The maximum data rate in the linear regime is a few MHz.

Aqueye+ is regularly mounted at the 1.8-m Copernicus telescope in Asiago, while Iqueye was mounted at the New Technology Telescope at La Silla, the William Hershel Telescope in La Palma, and the Telescopio Nazionale Galileo in La Palma. Since 2015, it is fiber-fed at the 1.2-m Galileo telescope in Asiago through a dedicated instrument (the Iqueye Fiber Interface, IFI).

3. PSR J1023+0038: The first ms optical and UV pulsar

Since the beginning, one of the main goals of the project was to study optical pulsars at the highest time resolution and to search for new optical pulsators. In 2017, millisecond optical pulsations were indeed discovered in PSR J1023+0038 by Ambrosino et al. (2017). Soon after, we succeeded in detecting them with Aqueye+@Copernicus, for the first time with a 2-m class telescope (Zampieri et al., 2019a). Other detections both in the optical (Karpov et al., 2019) and UV bands (Jaodand et al., 2021) were also reported since then.

PSR J1023+0038 is a pulsar in a binary system (Papitto & Martino, 2022). The neutron star is rotating with an amazingly small spin period of 1.69 milliseconds, and is weakly magnetized ($10^8 - 10^9$ G), while the companion is a low mass ($< 1 M_\odot$) star. Old millisecond radio pulsars in binary systems are 'recycled' and spun up by deposition of angular momentum from the companion in an accreting Low Mass X-ray Binary phase (Wijnands & van der Klis, 1998). PSR J1023+0038 was discovered as a radio pulsar in 2009 (Archibald et al., 2009) and later observed to switch from a rotation-powered ms pulsar to an accretion (subluminous) X-ray binary phase. It is probably crossing an unstable evolutionary phase, swinging between the two states and, for this reason, it is called a transitional Millisecond Pulsar (tMP). Besides PSR J1023+0038, two similar systems are known at present: XSS J1227-4853 (de Martino et al., 2010) and IGR J1824-2452 (Papitto et al., 2013). They are clearly instrumental to understanding the formation of ms pulsars and the accretion physics in low magnetic field neutron stars.

3.1. Optical versus X-ray pulse

From 2017 through 2023 we have extensively monitored PSR J1023+0038 with Aqueye+. Nearly simultaneous observations were carried out in the optical band with the fast photometer SiFAP2 at Telescopio Nazionale Galileo, and in the X band with the satellites *XMM-Newton* and *NICER*.

We found that the optical pulse lags that in the X-rays by $\sim 150 \mu$s (Figure 1; Illiano et al. 2023), with Aqueye+ and NICER providing the best absolute temporal uncertainty with respect to UTC. We note, in passing, that measurements are performed after correcting for the orbital motion, with the parameters (in particular the time of passage at the ascending node) estimated

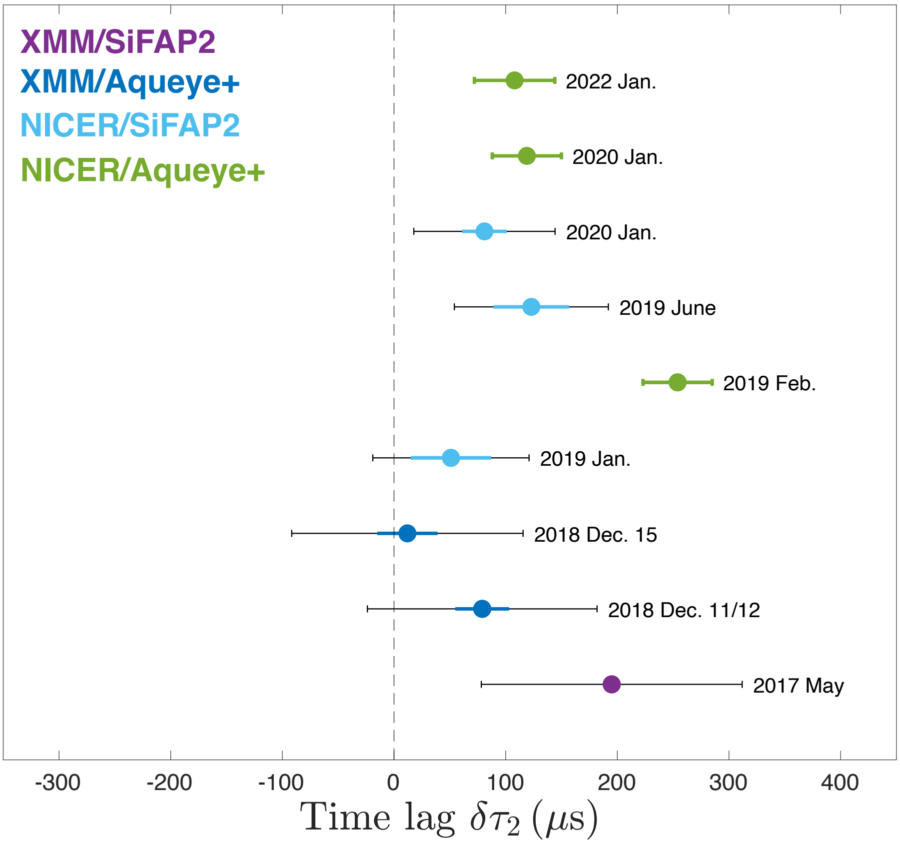

Figure 1. Optical - X-ray delay of the second harmonic component of the pulse profile of PSR J1023+0038. The dashed line indicates a zero time lag. Measurements indicate that the optical pulse lags that in the X-rays by $\sim 150\mu$s. Colored error bars represent 1σ statistical uncertainties, while the black error bars indicate the total error (including systematics). The best timing accuracy is provided by the Aqueye+ and *NICER* measurements (from Illiano et al. 2023).

as described in Illiano et al. (2023). In principle, if the optical observations are not exactly simultaneous with those of the satellite in orbit, the timing of the orbital ephemeris could affect the lags. For this reason, in the future, we plan to repeat this measurement using only strictly simultaneous observations.

This result indicates that both the optical and X-ray pulsations come from the same region, confirming a common emission mechanism. Both pulsations could originate from synchrotron emission in the shocked region that forms within a few light cylinder radii away (~ 100 km) from the pulsar, where its striped wind encounters the accretion disc inflow (Papitto et al., 2019).

This result is also consistent with the spin-down rate measured from Aqueye+ data, which is only ∼5% faster than that measured in the radio band during the radio pulsar phase (Burtovoi et al., 2020), suggesting that the pulsar engine is still active during the subluminous X-ray binary phase.

4. Fast Radio Bursts and magnetars

In the last three years we started a new observing program aiming at searching for prompt/delayed optical emission from Fast Radio Bursts (FRB 20180916B; Pilia et al. 2020; Trudu et al. 2023) and magnetars during outburst/flaring activity phases (SGR J1935+2154; Zampieri et al. 2022b).

Fast Radio Bursts (FRBs) are transient radio pulses lasting from a millisecond to a few seconds. They have luminosity between 10^{38} erg s^{-1} and 10^{46} erg s^{-1}, large dispersion measure and isotropic sky distribution. FRBs are detected in the range 150 MHz-8 GHz and their radio emission is likely to be coherent emission from relativistic particles. The first FRB was discovered by Lorimer & Narkevic in 2007, looking through archival pulsar survey data (Lorimer et al., 2007). Many FRBs have since been recorded (> 500), including several that have been detected to repeat ($\sim 4\%$; e.g. Petroff et al. 2022).

The origin of FRBs is still not understood, but several of them are associated to normal galaxies (at $z < 0.5$). A number of models predict the existence of multiwavelength (MWL) counterparts of FRBs in the form of an afterglow or an impulsive event (e.g. Nicastro et al. 2021). A MWL and/or optical detection would provide critical information on the nature of the progenitor and would greatly enhance our understanding of the FRB phenomenon.

4.1. Searching for prompt/delayed optical flashes in FRB 20180916B

FRB 20180916B shows repeating burst activity (CHIME/FRB Collaboration et al., 2019), detected from 150 MHz (Pastor-Marazuela et al. 2021; Pleunis et al. 2021) up to 6 GHz (Bethapudi et al., 2023). It is localized with high accuracy and associated to a star-forming region in a nearby (redshift $z = 0.0337 \pm 0.0002$) massive spiral galaxy (Marcote et al., 2020). A 16.33 days periodicity in the arrival times of the radio bursts (with an activity window of ±2.6 days) has been reported (Chime/Frb Collaboration et al. 2020; Pleunis et al. 2021). Clearly, such a periodicity allows for dedicated searches for bursts at other wavelengths during time intervals of possible radio activity.

Between 2020 and 2021 we carried out simultaneous multi-instrument/MWL campaigns on FRB 20180916B (Pilia et al. 2020; Trudu et al. 2023). Within the framework of this collaboration, we performed a fast photometric campaign in the optical band with our instruments in Asiago. In the observations carried out between Oct 2020 and Aug 2021, the net on-target observing time was 122 ks for Aqueye+@Copernicus and 62 ks for IFI+Iqueye@Galileo. The count rate, averaged over all acquisitions, was ~3000 c/s for Aqueye+ and ~1300 c/s for IFI+Iqueye (Trudu et al., 2023).

A total of 14 radio bursts were detected during optical observing windows, 9 of which in Nov 2020 with the Sardinia Radio Telescope (SRT) and another 5 between Feb and Aug 2021 with the Giant Metrewave Radio Telescope (GMRT) (Trudu et al., 2023). No prompt emission has been detected in any of the observations. For Aqueye+, the upper limit in an interval of ±100 ms around the detection of the radio bursts with a sampling time 1 ms is $V_{min} = 14.25 - 14.64$ mag per ms, corresponding to a fluence $F_{max} = 4.6 \times 10^{-15}$ erg cm^{-2} (fluence density 0.005 Jy ms) and a luminosity $L_{max} = 1.2 \times 10^{43}$ erg s^{-1} at 150 Mpc.

In fact, a 1 ms-long Fast Optical Burst (FOB) was detected (at the 90% confidence level) 13.971 s before the arrival time of the second SRT radio burst (barycentric time of arrival at infinity frequency MJD 59162.8343320911; see Figure 2). The FOB has $V = 14.4$ mag per ms, corresponding to a fluence $F_{max} = 6.4 \times 10^{-15}$ erg cm^{-2} (0.007 Jy ms) and a luminosity $L_{max} = 1.6 \times 10^{43}$ erg s^{-1} at 150 Mpc. We calculate a detection threshold n_t corresponding to a chance probability of $0.0027/N_{trials}$ to exceed a Poissonian distribution at the average rate in any of the bins, where N_{trials} is the total number of bins in the time interval considered. The peak is statistically above the threshold ($n_t = 15$ counts/bin) for a window of ±15 s centered around the time of arrival of the radio burst, but it is below the threshold obtained considering the bins of the entire observation ($n_t = 19$ counts/bin). We then can not robustly tag it as the optical counterpart of the radio burst.

The nature of this event is under investigation. It could be a faint foreground event produced by a field meteor. The rate of this type of events at this magnitude level (14.5) is completely unknown. Extrapolations from measurements made with fast photomultipliers in the '80s (Cook et al., 1980) could be roughly consistent with our observations. However, this conclusion is highly uncertain and needs further investigation in the future.

5. Stellar Intensity Interferometry: The pilot Asiago km-baseline experiment on Vega

One of the most innovative activities that we have undertaken within the framework of the FPC-OA project is certainly the photon counting, the km-baseline experiment of Stellar Intensity Interferometry (SII) in Asiago (Zampieri et al., 2021). It consists in a measurement of the (2nd order) spatial correlation of the intensity of the light from a star with two Asiago telescopes (Copernicus and Galileo), equipped with Aqueye+ and IFI+Iqueye. A pioneering astronomical experiment devoted to measuring stellar radii with SII was performed by Hanbury Brown and Twiss from 1964 through 1972 (see, e.g., Hanbury Brown 1974).

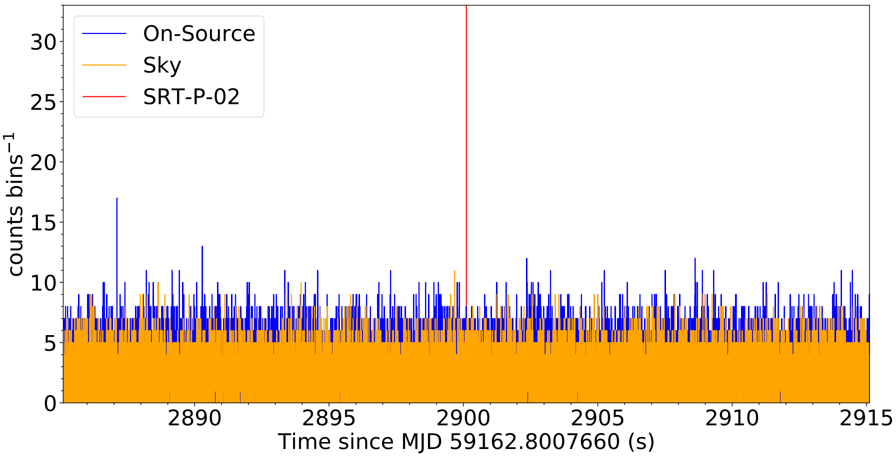

Figure 2. Light curves (binned at 1 ms) of the on-source (blue) and sky (orange) detectors of the Aqueye+ observation corresponding to the detection of an SRT radio burst (Obs ID 20201109-200635, on 2020/11/09; the Aqueye+ starting time has been barycentred). An interval of ±15 s around the time of arrival of the burst (red vertical line) is shown (from Trudu et al. 2023).

This pilot Asiago experiment turned out to be successful. We performed for the first time measurements of the correlation of the star Vega counting photon coincidences with sub-nanosecond time resolution in post-processing by means of a single photon software correlator and exploiting entirely the quantum properties of the light emitted from the star. We successfully detected the temporal correlation of Vega at zero baseline (discrete degree of coherence $< g^{(2)} >= 1.0034 \pm 0.0008$) and also performed a measurement of the correlation on a projected baseline of ~2 km.

Measurements are consistent with the expected degree of coherence for a source with the 3.3 mas diameter of Vega. We can also place a constraint on the size of any potential bright feature on the star surface, that has to be > 30 μas (3×10^9 cm) to be consistent with the absence of correlation on ~2 km.

This experiment represented a crucial for addressing the feasibility of potential future implementations of SII in photon counting mode on arrays of Cherenkov telescopes (like the INAF ASTRI Mini-Array; Zampieri et al. 2022a).

6. Technological Developments

6.1. Iqueye Fiber Interface+ (IFI+)

The Iqueye Fiber Interface (IFI) is the instrument that allows to fiber-feed Iqueye at the 1.2-m Galileo telescope. It was designed and realized during 2014-

2016 to perform the Asiago SII experiment. It consists of a focal reducer with a demagnification 1:2, that injects light in an optical fiber, and a field camera for pointing and guiding, fed by an 8-92% beam splitter (Zampieri et al., 2019b). The specifications of the optical fiber are carefully chosen so as to match the telescope Point Spread Function (PSF) and minimize the beam aperture. The overall efficiency of IFI tested in the laboratory is ∼80%.

At the beginning of 2023, IFI was completely re-aligned with the telescope optical axis and refurbished. New more robust supports for the lenses and the field camera have been installed. Two optical fiber patches with core diameters 365 μm and 200 μm (that can work alternately) were included to couple IFI directly with the Extended Fiber Interface (see below). An additional optical fiber with a core diameter of 365 μm can be positioned directly on the telescope focal plane with a movable arm. We refer to this upgraded version of the instrument as IFI+ (see Figure 3).

6.2. Fiber-fed Aqueye+

During the last few years, a parallel technological activity for the implementation of an optical fiber interface for Aqueye+@Copernicus was also performed, with the main purpose to trigger a prompt use of Aqueye+ in Target of Opportunity mode for observing transients. The main requirement is coupling the large field of view (400 μm) at the focal plane with the small instrument detector area (100 μm). To this end, we positioned a dedicated tapered optical fiber with a low numerical aperture directly off-axis at the Cassegrain focus (exploiting the mechanical support provided by the spectrograph AFOSC). The taper has inner and outer diameters of 400μm and 200μm, respectively, and a numerical aperture 0.12. For pointing and guiding we use the telescope field camera. Light from the optical fiber is then injected into Aqueye+ through a separate module positioned in front of Aqueye+. The system is still in the testing phase and can reach at present an overall efficiency of $\sim 20\%$ (compared to Aqueye+ directly mounted).

6.3. Extended Fiber Interface (EFI)

To improve the optical efficiency in fiber-fed mode at the Copernicus telescope, we decided to realize an additional module (Extended Fiber Interface, EFI; see Figure 4) with an on-board SPAD detector fed directly through the optical taper positioned at the Cassegrain focus. EFI consists essentially of a focal reducer with a demagnification 1:2.5. The incoming beam is collimated through an achromatic lens doublet and then focused on the SPAD detector with a second achromatic doublet. The focal lengths of the two doublets are 75 mm and 30 mm, respectively. The second doublet is centered and focussed on the detector through a xyz translation stage. Filters can be inserted in the collimated portion of the beam. At the polychromatic autofocus, the spot radius is 31 μm, while

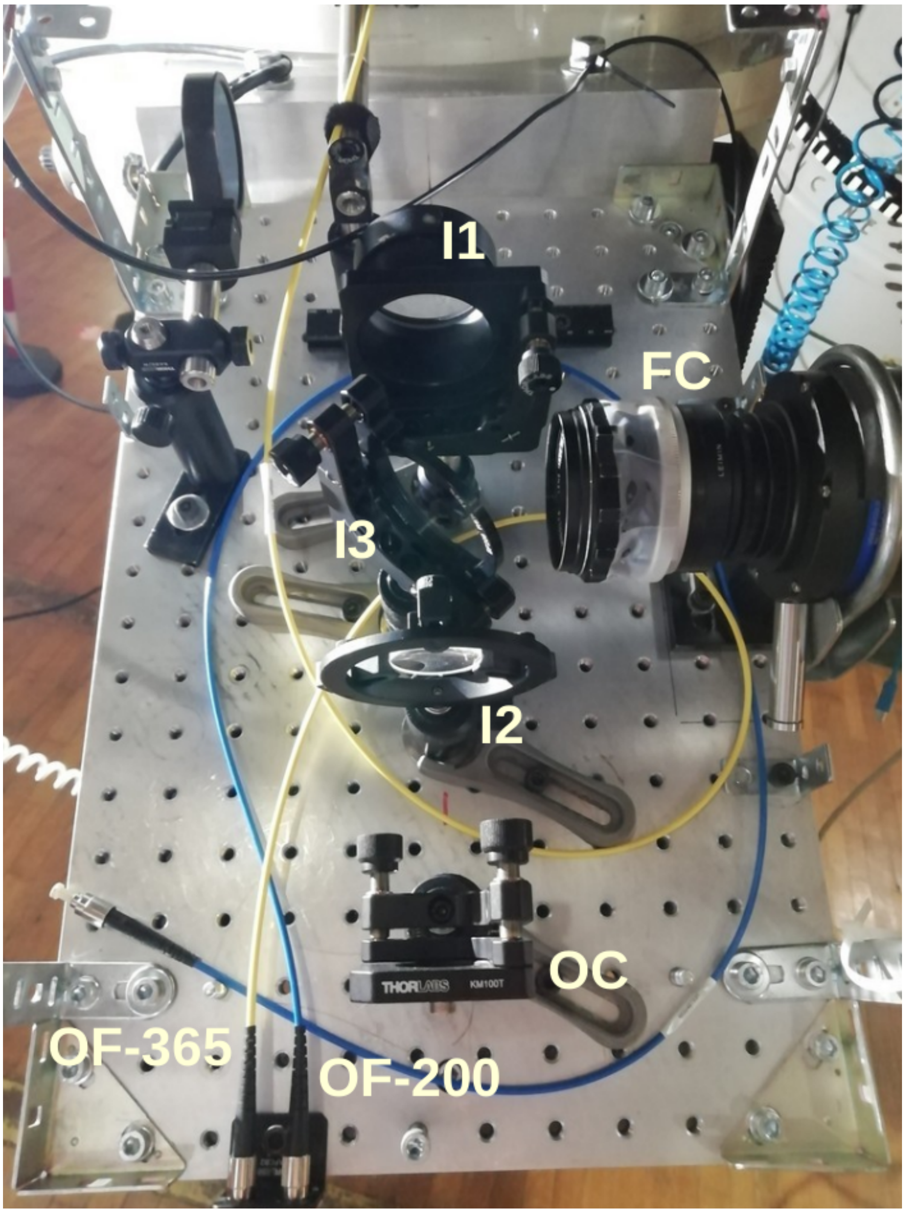

Figure 3. Iqueye Fiber Interface+ (IFI+) mounted at the Nasmyth focus of the 1.2-m Galileo telescope in Asiago. The optical components indicated on the image are: Achromatic lens doublet with focal length 200 mm (I1), achromatic lens doublet with focal length 100 mm (I2), 8-92% reflecting mirror (I3), field camera (FC), optical fiber with 365 μm core (OF-365), optical fiber with 200 μm core (OF-200), optical fiber connector (OC).

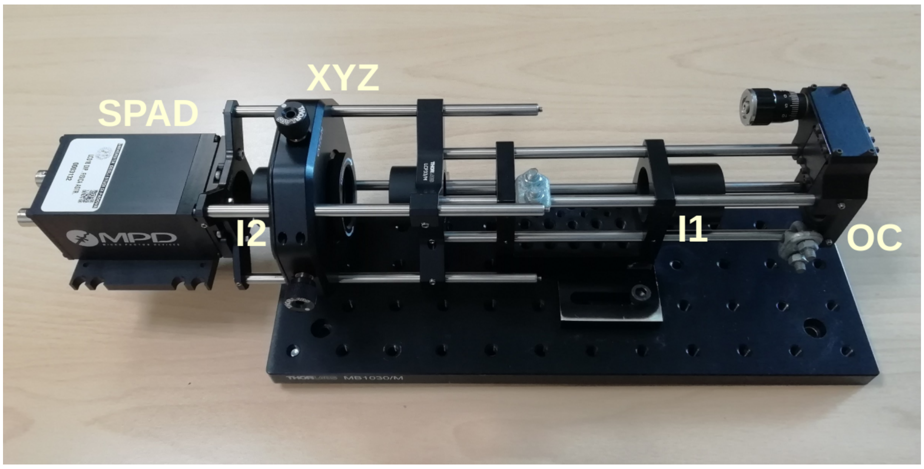

Figure 4. Extended Fiber Interface (EFI). The components indicated on the image are: Achromatic lens doublet with focal length 75 mm (I1), achromatic lens doublet with focal length 30 mm (I2), xyz translation stage (XYZ), SPAD detector (SPAD), optical fiber connector (OC).

the ensquared energy distributions is 98%. The overall transmission efficiency of the focal reducer in the V band, measured in the laboratory, is 80%.

The module can host a second SPAD detector fed with an additional optical fiber also positioned at the telescope focus for monitoring the sky. Both SPADs are connected to the Aqueye+ acquisition electronics so that the entire system can work as a stand-alone instrument. EFI can, in fact, also work together with IFI+ and be fed through it at the Galileo telescope. The entire system is still under test and development.

7. Conclusions

From 2017 through 2023 we have extensively monitored the optical ms pulsar PSR J1023+0038 with Aqueye+. Nearly simultaneous observations were carried out in the optical and X-ray bands. We found that the optical pulse lags in the X-rays by $\sim 150\,\mu$s, with Aqueye+ and NICER providing the best absolute temporal uncertainty with respect to UTC. This result indicates that both the optical and X-ray pulsations come from the same region, confirming a common emission mechanism and supporting the model of a mini pulsar wind nebula fueled by the shock between the pulsar wind and the accretion disk.

We also perform regular observations and participate to multiwavelength campaigns of repeating Fast Radio Bursts and magnetars in outbursts. The main goal is searching for prompt/delayed optical flashes in these sources. We presented the results of the most recent campaign carried out on FRB 20180916B, which, together with a similar campaign on the magnetar SGR J1935+2154, provide the deepest upper limits for optical emission coincident with bursts for these sources to date. A 1 ms-long Fast Optical Burst was detected (at the 90% confidence level) 13.971 s before the arrival time of a radio burst in FRB 20180916B, but we can not robustly tag it as the optical counterpart of the radio burst.

One of the most innovative activities that we have undertaken within the framework of the FPC-OA project is certainly the photon counting, km-baseline experiment of Stellar Intensity Interferometry in Asiago. We successfully detected the temporal correlation of the star Vega at zero baseline and also performed a measurement of the correlation on a projected baseline of ∼2 km. This experiment represented a crucial step for addressing the feasibility of potential future implementations of SII in photon counting mode on arrays of Cherenkov telescopes (like the INAF ASTRI Mini-Array).

Finally, we reported on new technological developments in our work on efficient fiber coupling and our photon counting instrumentation on meter-class telescopes. In particular, we presented the new design and prototype realization of the Extended Fiber Interface.

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References

Ambrosino, F., Papitto, A., Stella, L., et al., Optical pulsations from a transitional millisecond pulsar. 2017, *Nature Astronomy*, **1**, 854, DOI: 10.1038/s41550-017-0266-2

Archibald, A. M., Stairs, I. H., Ransom, S. M., et al., A Radio Pulsar/X-ray Binary Link. 2009, *Science*, **324**, 1411, DOI: 10.1126/science.1172740

Barbieri, C., Naletto, G., Occhipinti, T., et al., AquEYE, a single photon counting photometer for astronomy. 2009, *Journal of Modern Optics*, **56**, 261, DOI: 10.1080/09500340802450565

Bethapudi, S., Spitler, L. G., Main, R. A., Li, D. Z., & Wharton, R. S., High frequency study of FRB 20180916B using the 100-m Effelsberg radio telescope. 2023, *Monthly Notices of the RAS*, **524**, 3303, DOI: 10.1093/mnras/stad2009

Burtovoi, A., Zampieri, L., Fiori, M., et al., Spin-down rate of the transitional millisecond pulsar PSR J1023+0038 in the optical band with Aqueye+. 2020, *Monthly Notices of the RAS*, **498**, L98, DOI: 10.1093/mnrasl/slaa133

Chime/Frb Collaboration, Amiri, M., Andersen, B. C., et al., Periodic activity from a fast radio burst source. 2020, *Nature*, **582**, 351, DOI: 10.1038/s41586-020-2398-2

CHIME/FRB Collaboration, Andersen, B. C., Bandura, K., et al., CHIME/FRB Discovery of Eight New Repeating Fast Radio Burst Sources. 2019, *Astrophysical Journal, Letters*, **885**, L24, DOI: 10.3847/2041-8213/ab4a80

Cook, A. F., Weekes, T. C., Williams, J. T., & Omongain, E., Flux of optical meteors down to $M_{PG} = +12$. 1980, *Monthly Notices of the RAS*, **193**, 645, DOI: 10.1093/mnras/193.3.645

de Martino, D., Falanga, M., Bonnet-Bidaud, J. M., et al., The intriguing nature of the high-energy gamma ray source XSS J12270-4859. 2010, *Astronomy and Astrophysics*, **515**, A25, DOI: 10.1051/0004-6361/200913802

Dravins, D., Barbieri, C., Fosbury, R. A. E., et al., QuantEYE: The Quantum Optics Instrument for OWL. 2005, *arXiv e-prints*, astro, DOI: 10.48550/arXiv.astro-ph/0511027

Hanbury Brown, R. 1974, *The intensity interferometer. Its applications to astronomy*

Illiano, G., Papitto, A., Ambrosino, F., et al., Investigating the origin of optical and X-ray pulsations of the transitional millisecond pulsar PSR J1023+0038. 2023, *Astronomy and Astrophysics*, **669**, A26, DOI: 10.1051/0004-6361/202244637

Jaodand, A. D., Hernández Santisteban, J. V., Archibald, A. M., et al., Discovery of UV millisecond pulsations and moding in the low mass X-ray binary state of transitional millisecond pulsar J1023+0038. 2021, *arXiv e-prints*, arXiv:2102.13145, DOI: 10.48550/arXiv.2102.13145

Karpov, S., Beskin, G., Plokhotnichenko, V., Shibanov, Y., & Zyuzin, D., The study of coherent optical pulsations of the millisecond pulsar PSR J1023+0038 on Russian 6m telescope. 2019, *Astronomische Nachrichten*, **340**, 607, DOI: 10.1002/asna.201913663

Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F., A Bright Millisecond Radio Burst of Extragalactic Origin. 2007, *Science*, **318**, 777, DOI: 10.1126/science.1147532

Marcote, B., Nimmo, K., Hessels, J. W. T., et al., A repeating fast radio burst source localized to a nearby spiral galaxy. 2020, *Nature*, **577**, 190, DOI: 10.1038/s41586-019-1866-z

Naletto, G., Barbieri, C., Occhipinti, T., et al., Iqueye, a single photon-counting photometer applied to the ESO new technology telescope. 2009, *Astronomy and Astrophysics*, **508**, 531, DOI: 10.1051/0004-6361/200912862

Naletto, G., Barbieri, C., Verroi, E., et al., Aqueye Plus: a very fast single photon counter for astronomical photometry to quantum limits equipped with an Optical Vortex coronagraph. 2013, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **8875**, *Quantum Communications and Quantum Imaging XI*, ed. R. E. Meyers, Y. Shih, & K. S. Deacon, 88750D

Nicastro, L., Guidorzi, C., Palazzi, E., et al., Multiwavelength Observations of Fast Radio Bursts. 2021, *Universe*, **7**, 76, DOI: 10.3390/universe7030076

Papitto, A., Ambrosino, F., Stella, L., et al., Pulsating in Unison at Optical and X-Ray Energies: Simultaneous High Time Resolution Observations of the Transitional

Millisecond Pulsar PSR J1023+0038. 2019, *Astrophysical Journal*, **882**, 104, DOI: 10.3847/1538-4357/ab2fdf

Papitto, A., Ferrigno, C., Bozzo, E., et al., Swings between rotation and accretion power in a binary millisecond pulsar. 2013, *Nature*, **501**, 517, DOI: 10.1038/nature12470

Papitto, A. & Martino, D. d. 2022, *Transitional Millisecond Pulsars*, ed. S. Bhattacharyya, A. Papitto, & D. Bhattacharya (Cham: Springer International Publishing), 157–200

Pastor-Marazuela, I., Connor, L., van Leeuwen, J., et al., Chromatic periodic activity down to 120 megahertz in a fast radio burst. 2021, *Nature*, **596**, 505, DOI: 10.1038/s41586-021-03724-8

Petroff, E., Hessels, J. W. T., & Lorimer, D. R., Fast radio bursts at the dawn of the 2020s. 2022, *Astronomy and Astrophysics Reviews*, **30**, 2, DOI: 10.1007/s00159-022-00139-w

Pilia, M., Burgay, M., Possenti, A., et al., The Lowest-frequency Fast Radio Bursts: Sardinia Radio Telescope Detection of the Periodic FRB 180916 at 328 MHz. 2020, *Astrophysical Journal, Letters*, **896**, L40, DOI: 10.3847/2041-8213/ab96c0

Pleunis, Z., Michilli, D., Bassa, C. G., et al., LOFAR Detection of 110-188 MHz Emission and Frequency-dependent Activity from FRB 20180916B. 2021, *Astrophysical Journal, Letters*, **911**, L3, DOI: 10.3847/2041-8213/abec72

Trudu, M., Pilia, M., Nicastro, L., et al., Simultaneous and panchromatic observations of the fast radio burst FRB 20180916B. 2023, *Astronomy and Astrophysics*, **676**, A17, DOI: 10.1051/0004-6361/202245303

Wijnands, R. & van der Klis, M., A millisecond pulsar in an X-ray binary system. 1998, *Nature*, **394**, 344, DOI: 10.1038/28557

Zampieri, L., Bonanno, G., Bruno, P., et al., A stellar intensity interferometry instrument for the ASTRI Mini-Array telescopes. 2022a, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **12183**, *Optical and Infrared Interferometry and Imaging VIII*, ed. A. Mérand, S. Sallum, & J. Sanchez-Bermudez, 121830F

Zampieri, L., Burtovoi, A., Fiori, M., et al., Precise optical timing of PSR J1023+0038, the first millisecond pulsar detected with Aqueye+ in Asiago. 2019a, *Monthly Notices of the RAS*, **485**, L109, DOI: 10.1093/mnrasl/slz043

Zampieri, L., Mereghetti, S., Turolla, R., et al., Deep Upper Limit on the Optical Emission during a Hard X-Ray Burst from the Magnetar SGR J1935+2154. 2022b, *Astrophysical Journal, Letters*, **925**, L16, DOI: 10.3847/2041-8213/ac4b60

Zampieri, L., Naletto, G., Barbieri, C., et al., (Very) Fast astronomical photometry for meter-class telescopes. 2019b, *Contributions of the Astronomical Observatory Skalnate Pleso*, **49**, 85, DOI: 10.48550/arXiv.1908.03396

Zampieri, L., Naletto, G., Barbieri, C., et al., Aqueye+: a new ultrafast single photon counter for optical high time resolution astrophysics. 2015, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. **9504**, *Pho-*

ton Counting Applications 2015, ed. I. Prochazka, R. Sobolewski, & R. B. James, 95040C

Zampieri, L., Naletto, G., Burtovoi, A., Fiori, M., & Barbieri, C., Stellar intensity interferometry of Vega in photon counting mode. 2021, *Monthly Notices of the RAS*, **506**, 1585, DOI: 10.1093/mnras/stab1387