AQUEYE+ and IQUEYE: From the timing of optical pulsars to the Asiago Hanbury Brown and Twiss experiment

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http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html
Outline

Start and development of the AQUEYE+IQUEYE project

Instrument(s) design and capabilities

Scientific goals, experiments and observing programmes

Timing of optical pulsars

Lunar and trans-Neptunian objects occultations

The challenge: The Asiago stellar intensity interferometry experiment
Start and development of the AQUERE+IQUERE project

In Sept. 2005 we completed a study in the framework of the design studies of new instrumentation for the Overwhelmingly Large telescope (Dravins et al. 2015)

Goals:

Demonstrating the possibility to reach picosecond time resolution needed to bring quantum optics concepts into the astronomical domain

Performing optical High Time Resolution Astrophysics with ms or sub-ms time resolution
Start and development of the AQEUYE+IQUEUEYE project

The QUANTEYE concept was tested with AQEUYE, the Asiago Quantum Eye, mounted on the AFOSC Instrument at the Copernico telescope in Asiago (Barbieri et al. 2009)

The second step was IQUEUEYE, the Italian Quantum Eye, designed for applications to 4m class telescopes: Mounted on the ESO 3.5m NTT in La Silla, and the TNG and WHT in La Palma (Naletto et al. 2009)
Start and development of the AQYEYE+IQUEYE project

Aqueye+: a new ultrafast single photon counter for optical high time resolution astrophysics (Naletto et al. 2013, Zampieri et al. 2015)

From Aqueye to Aqueye+:

- An independent instrument remotely controlled, easily mountable at the Copernicus telescope, and with improved photometric performances
- New technological features (high sensitivity CMOS field camera)
- New software tools (acquisition software and data analysis pipeline)
In 2015 IQUEYE was mounted at the 1.2 m Galileo telescope in Asiago to perform intensity interferometry experiments. We adopted a soft-mount solution, installing a dedicated interface (IQUEYE Fiber Interface, IFI) at the Nasmyth focus and connecting IQUEYE to it through an optical fiber (Zampieri et al. 2016).

A parallel work on the implementation of an optical fiber interface is also being done for AQUEYE+ (AQUEYE+ Fiber Interface, AFI). AFI is attached at the spectrograph AFOSC. AQUEYE+ is in a dedicated, thermally controlled room, permanently available.
Instrument(s) design and capabilities

**Optical design:** 4-split pupil concept

- To better couple the SPADs effective area to the telescope pupil
- To increase the sustainable count rate and partly recover dead time effects in each SPAD
- To perform simultaneous multicolour acquisitions and/or and cross-correlate among different sub-pupils
Instrument(s) design and capabilities

Acquisition and timing system

- Time tags and stores arrival time of each individual photon with < 100 ps relative time resolution (< 500 ps absolute time accuracy wrt UTC)

- Stores all acquisitions producing event lists that can be analyzed in post-processing

SPADs have <50 ps time resolution, 10-100 dark counts/s, 6-8 MHz maximum count rate, visible quantum efficiency up to 60%
Scientific goals, experiments and observing programmes

*Achieve picosecond time resolution, needed to bring quantum optics concepts into the astronomical domain – We are pursuing it in exploratory experiments:*

- Experiment astronomical applications of the second order correlations of light and a **modern version of the Hanbury Brown Twiss Intensity Interferometry** → to reach extreme spatial resolution and resolve stellar environments on sub-milli-arcsec angular scales

*Performing optical High Time Resolution Astrophysics with ms or sub-ms time resolution – We are pursuing it in a number of regular observing programs:*

- **Optical pulsars** (in synergy with facilities operating at other wavelengths) to study with unprecedented accuracy their timing behaviour and pulse shape

- **Lunar occultations** to measure stellar radii with milli-arcsec angular resolution and determine their binary nature and separation

- **Transits/occultations of Trans-Neptunian Objects** to determine their orbit and physical properties

- **Timing of optical transients and counterparts of binary systems** with compact objects to search for rapid optical variability (e.g. PSRJ 1023+0038; see A. Papitto's and P. Casella’s talks tomorrow)
Recent collaboration with the University of Vienna and Austrian Academy of Sciences

Anton Zeilinger, Thomas Scheidl, Johannes Handsteiner

Preparatory experiments for a Cosmic Bell Test with quasars

- The goal of the measurement campaign is to statistically significant violate Bells inequality within a Bell-Test with measurement settings generated by quasars
Timing of optical pulsars

Crab pulsar monitoring – Regularly monitored with AQUEYE+@Copernico (Germanà et al. 2012; Ceribella et al. 2017): The only regular optical monitoring program (that I am aware of), analogous to the Jodrell Bank radio monitoring program

Observations taken also with IQUEYE@NTT in two runs in 2009 (Jan, Dec) (Zampieri et al. 2014)

Timing (phase coherent) analysis

- The phase of the main peak is measured folding the light curves in few-seconds time intervals and is tracked for several consecutive nights
- The peak shifts because the pulsar is slowing down
- A timing solution is derived fitting the measurements
- From the fit, the statistical uncertainties on the phase of the main pulse and the rotational period are $\approx 1 \, \mu s$ and $\sim 0.5 \, \text{ps}$
Timing of optical pulsars

Crab pulsar timing - This timing accuracy allowed us to compute the optical phase coherent timing solution of the Crab pulsar over the entire year 2009.

Spin-down of the pulsar very accurately described by a 3rd order polynomial or a braking-index model.

In agreement with radio timing solution. Since optical data do not depend on dispersion measure variations, they provide a robust and independent confirmation of the radio timing solution.

Regular monitoring shows that daily and monthly residuals (timing noise) are present (glitches or modulations), nonetheless a braking law can reproduce well the average long term phase evolution.

But for how long? We investigated this issue performing a detailed joint radio/optical analysis of the pulsar phase noise (Cadez et al. 2016)
Timing of optical pulsars

**Crab pulsar optical-radio delay** - The pulse in the optical leads that in the radio by 150–250 μs

*Optical and radio beams are probably misaligned (1.5–3 deg) because at the position where electrons emit optical photons the magnetic field has a slightly different orientation*

**Crab pulsar optical-GRPs correlation** (Collins et al. 2011)
Timing of optical pulsars

**PSR J0540-6919 and Vela pulsar pulse profiles** – Both were observed with IQUEYE@NTT in 2009 (Gradari et al. 2011, Ackermann et al. 2015, Spolon et al. 2017)

Folding and summing in phase the data of 5 observations, we obtained the most accurate optical pulse profile of the Vela pulsar available to date

- A distinct narrow component is detected on the top of one of the two main optical peaks, which was not resolved in previous observations
- For the first time we find marginal evidence of the detection of an optical peak aligned in phase with one of the two main X-ray/gamma-ray peaks

Complex structure of the multiwavelength pulse profile (see A. Burtovoi’s talk)
Lunar and Trans-Neptunian Objects occultations

**Lunar occultations** – A regular Moon occultation program started in 2016

Observing the diffraction fringes that the Moon produces when occulting a field star (see A. Richichi’s talk)

Spatial information (star radius, binary separation) are embedded in the fringes (Richichi et al. 2017)
The challenge: The Asiago stellar intensity interferometry experiment

In its essence, stellar Intensity Interferometry (SII) consists in a measurement of the spatial correlation of the intensity of the light from a star with telescopes at two different positions A and B separated by a distance $d$ (2nd order spatial correlation; Mandel 1963, Dravins et al. 2013, Naletto et al. 2016):

$$\langle I_A I_B \rangle = \langle I_A \rangle \langle I_B \rangle (1 + 0.5|\gamma|^2)$$

(1)

where $\gamma$ is the degree of coherence of light (its absolute value is the visibility of the fringes for a classical phase/amplitude interferometer).

$\gamma$ is defined in terms of the mutual coherence function $\Gamma$ [$\gamma = \Gamma/\langle \langle I_A \rangle \langle I_B \rangle \rangle^{1/2}$], that is calculated from the van Cittert–Zernike theorem:

$$\Gamma(u,v) = \iint_{\text{source}} I_{\text{source}}(l,m) e^{-2\pi i (ul + vm)} \, dl \, dm$$

Far from a source, $\Gamma$ is the Fourier transform of its surface intensity $I_{\text{source}}$.

For a uniform brightness monochromatic circular source of wavelength $\lambda$ and angular diameter $\theta$, it is (e.g. Tango & Davies 2002):

$$|\gamma| = 2 J_1(\pi \theta d/\lambda)/(\pi \theta d/\lambda)$$

Airy disc profile

Using the quantum description of light, one can measure $|\gamma|^2$ using photon counts. This is usually done introducing the (discrete) degree of coherence:

$$g^{(2)} = \frac{N_{AB}}{N_A N_B}$$

$N_A, N_B$ = number of photons detected at telescopes A and B in time T
$N_{AB}$ = number of “simultaneous” detections in small time bins $dt$ in T
$N$ = number of intervals $(T/dt)$

Expressing $N_A, N_B$ and $N_{AB}$ in probabilistic form in terms of the average intensities $<I_A>, <I_B>, <I_A I_B>$, integrating over time $T$ and using eq. (1):

$$N_{AB} = \frac{1}{T} N_A N_B (dt + 0.5 \int |\gamma|^2 d\tau)$$

$$g^{(2)} = 1 + 0.5/dt \int |\gamma|^2 d\tau = 1 + 0.5 |\gamma(0)|^2 (\tau_c/dt) \quad (2)$$

where $\tau_c = 1/\Delta v = (\lambda/c)(\lambda/\Delta\lambda)$ is the coherence time, i.e. the interval over which a signal in a wavelength interval $\Delta\lambda$ may be considered coherent in time (i.e. its phase does not jump randomly).

For optical light in a wavelength range $\Delta\lambda = 1$ nm, $\tau_c \sim 1$ ps.

The major contribution to $N_{AB}$ comes from random uncorrelated coincidences.

The 'signal' is a tiny excess of coincidences related to the quantum nature of light (bosons giving a joint detection probability greater than that for two independent events).
The challenge

**Long term goal: Resolving stellar systems and their environments with sub milliarcsec angular resolution**

Bright ($V<6-7$) and hot stellar systems not only provide a significant photon flux (needed to have a significant S/N), but also are compact enough to have a large coherence area and produce significant visibility over 100-1000 m baselines.

Some 2600 stars are hotter than 9000 K and brighter than $V=7$

Among them, targets of primary scientific interest are:

- Rapidly rotating stars: Vega (alpha Lyr, Aufdenberg et al. 2006, Peterson et al. 2006, Monnier et al. 2012), Achernar (alpha Eri)
- Evolved stars with mass loss (Paladini et al. 2017)
- Stars with circumstellar discs/shells: l Pup, eps Aur (A9Ia, Kloppenborg et al. 2010), T Lep (Le Bouquin et al. 2009), zeta Tau (Carciofi et al. 2009)
- Wolf-Rayet stars and their environments: g2 Vel, WR 140
- Luminous blue variables: P Cyg
- Interacting binaries: Spica (alpha Vir), HD 193322
- Cepheids and their envelopes: Y Oph, α Per (Merand et al. 2007)
- Exoplanetary host stars: 70 Vir, 94 Cet, HD 60532
The challenge: The Asiago stellar intensity interferometry experiment

A successful realization of a SII experiment using the particle nature of light, modern fast single-photon counters, and a long baseline has still to be convincingly performed (Capraro et al. 2010; Horch et al. 2013)

Present technology is sufficiently mature to allow to achieve an unprecedented resolution of tens of microarcseconds using a baseline of a few km (main advantage of intensity over phase interferometry)

A SII photon counting preparatory experiment on a km baseline Asiago, Italy (Zampieri+ 2016, Naletto+ 2016)

- BASELINE ~ 3885 m, with a significant E-W component ~ 2000 m for a source at small elevation at E or W
  Interferometer has a variable baseline because its projected component perpendicular to the wavefront changes in time

- Telescopes equipped with our two very fast photon counters: Aqueye+ and Iqueye

We observed a few stars including Deneb (α Cyg, A2Ia, V=1.25 mag, 2 mas

Very narrow band filters are inserted in the collimated beam to increase the coherence time
The future

- AQUEYE+@Copernico permanently available in ToO mode

- A new optical HTRA instrument, fiber-fed, with comparable timing accuracy but simpler optical design for 4 m call telescopes, to complement instrument with high time resolution available at other wavelengths

- Further experiments for implementation of an intensity interferometer on the MAGIC telescopes and eventually on the ASTRI Mini-array and CTA

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L. Zampieri – AQUEYE+ and IQEYE