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Iqueye at the NTT: The best light curves of the optical pulsars in the Crab, LMC B0540-69 and Vela supernova remnants

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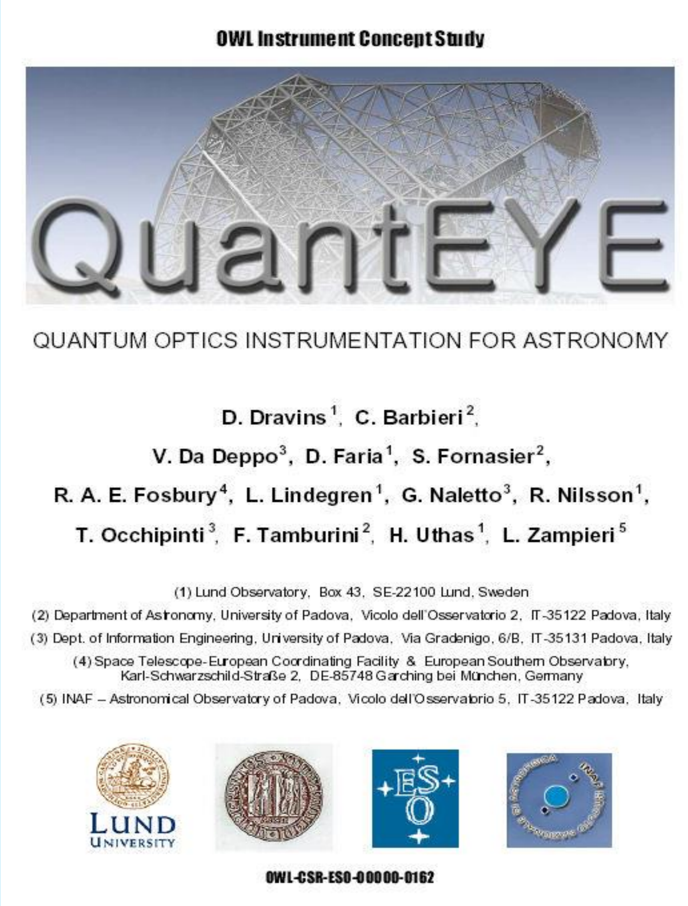
QuantEYE



OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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In 2005, we completed the study of a novel instrument for the 100 m diameter Overwhelmingly Large (OWL) telescope (QuantEYE, the ESO Quantum Eye; Dravins et al. 2005). The main objective was to demonstrate the possibility to **reach the picosecond time resolution (Heisenberg limit)** needed to bring quantum optics concepts into the astronomical domain.

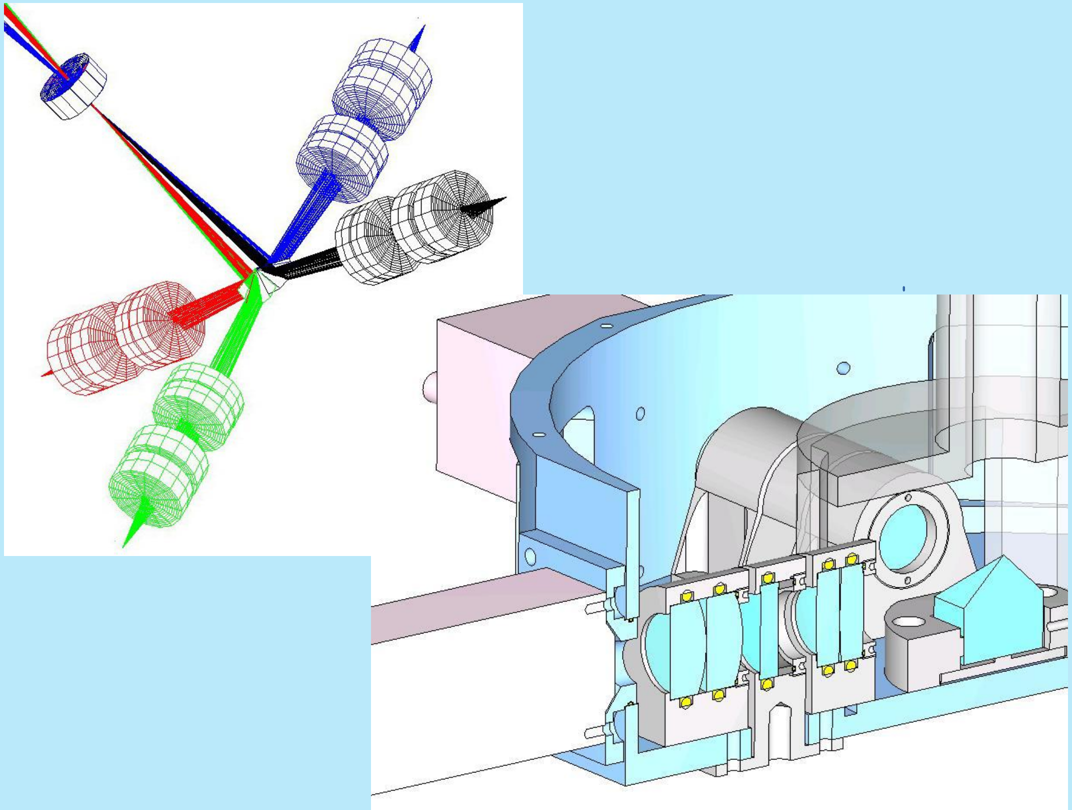
The study had two main scientific goals:

- To measure the ***entropy of light*** through the statistics of the photon arrival times.

- To perform optical ***High Time Resolution Astrophysics*** with unparalleled precision and accuracy.

Development of AQUEYE and IQUEYE

Starting from QuantEYE, we realized two similar downscaled prototypes, Aqueye and Iqueye. Both instruments adopted the concept of ***splitting the telescope entrance pupil*** in four parts, each of them focused on a Single Photon Avalanche Detector (SPAD) operated in Geiger mode.

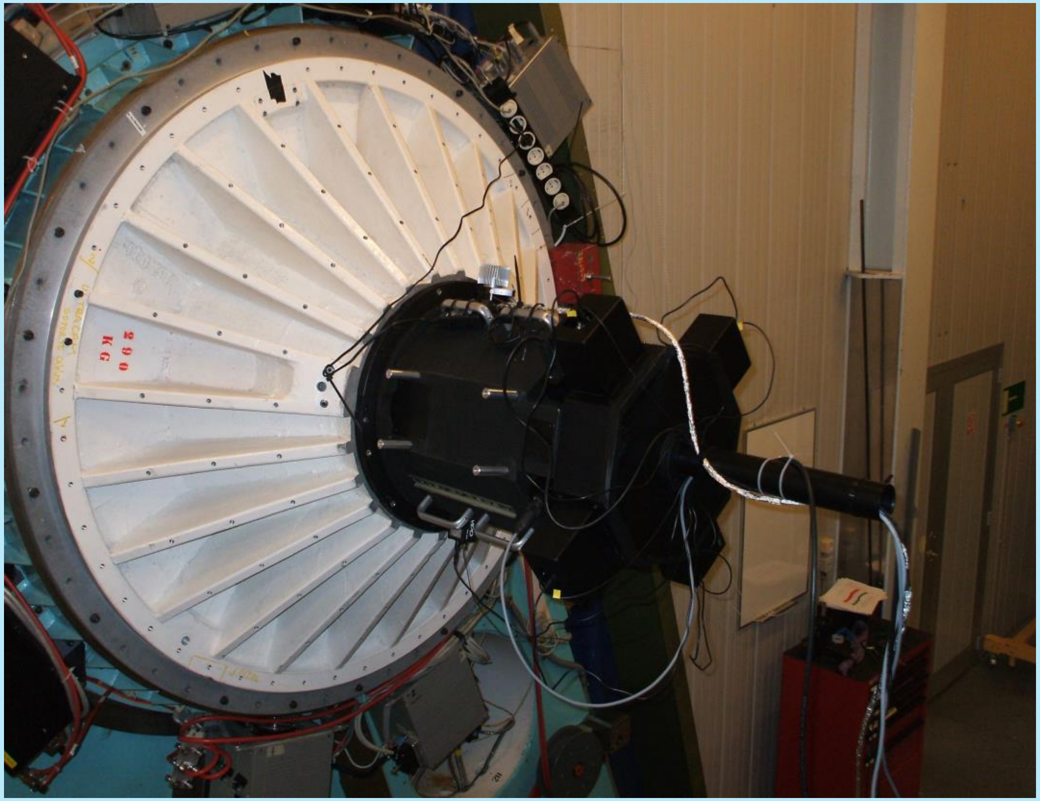


Both photometers are ***photon-counting non-imaging*** instruments, with a field of view of few arcsec, Filters can be inserted both in the primary beam before the pyramid and in each sub-beam, thus providing **multicolor simultaneous photometry**.

The two photometers

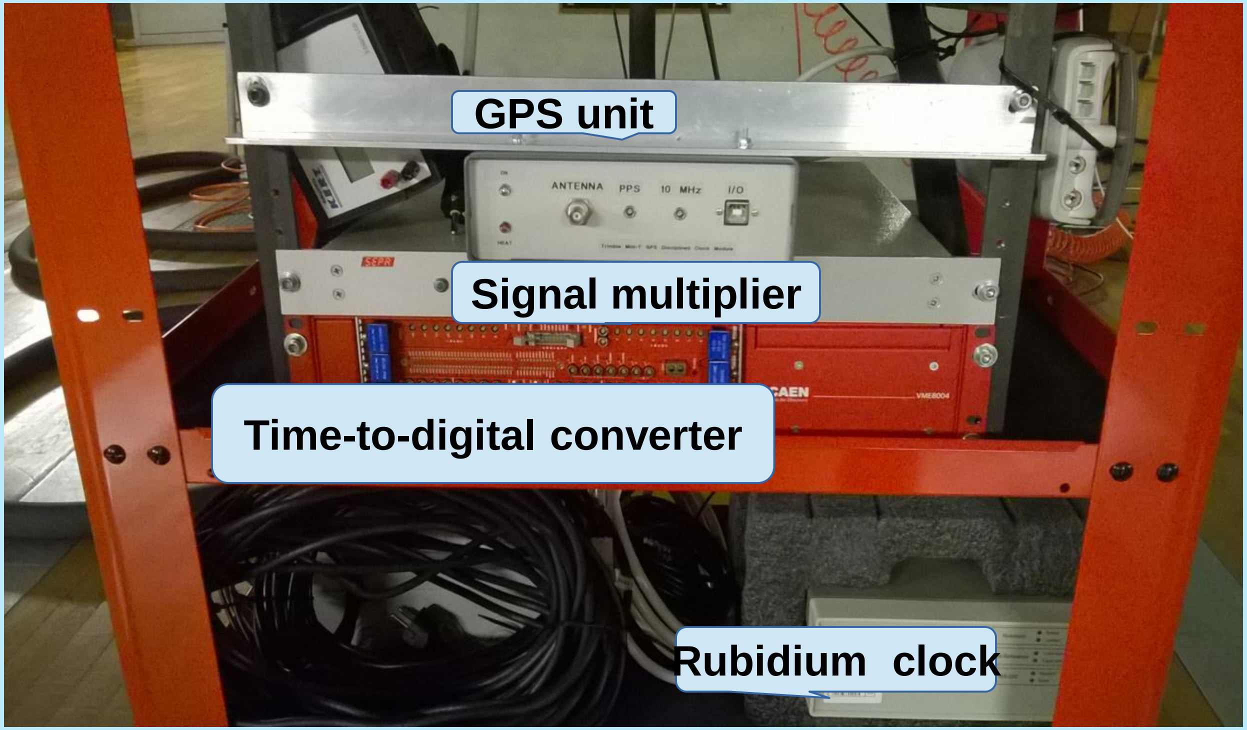
The first instrument was Aqueye (then upgraded to Aqueye+), mounted at the 1.8m Copernicus telescope in Asiago.

The second one was Iqueye. designed for 4 m class telescopes, mounted at the 3.6 m ESO NTT in La Silla in 2009 and 2010.



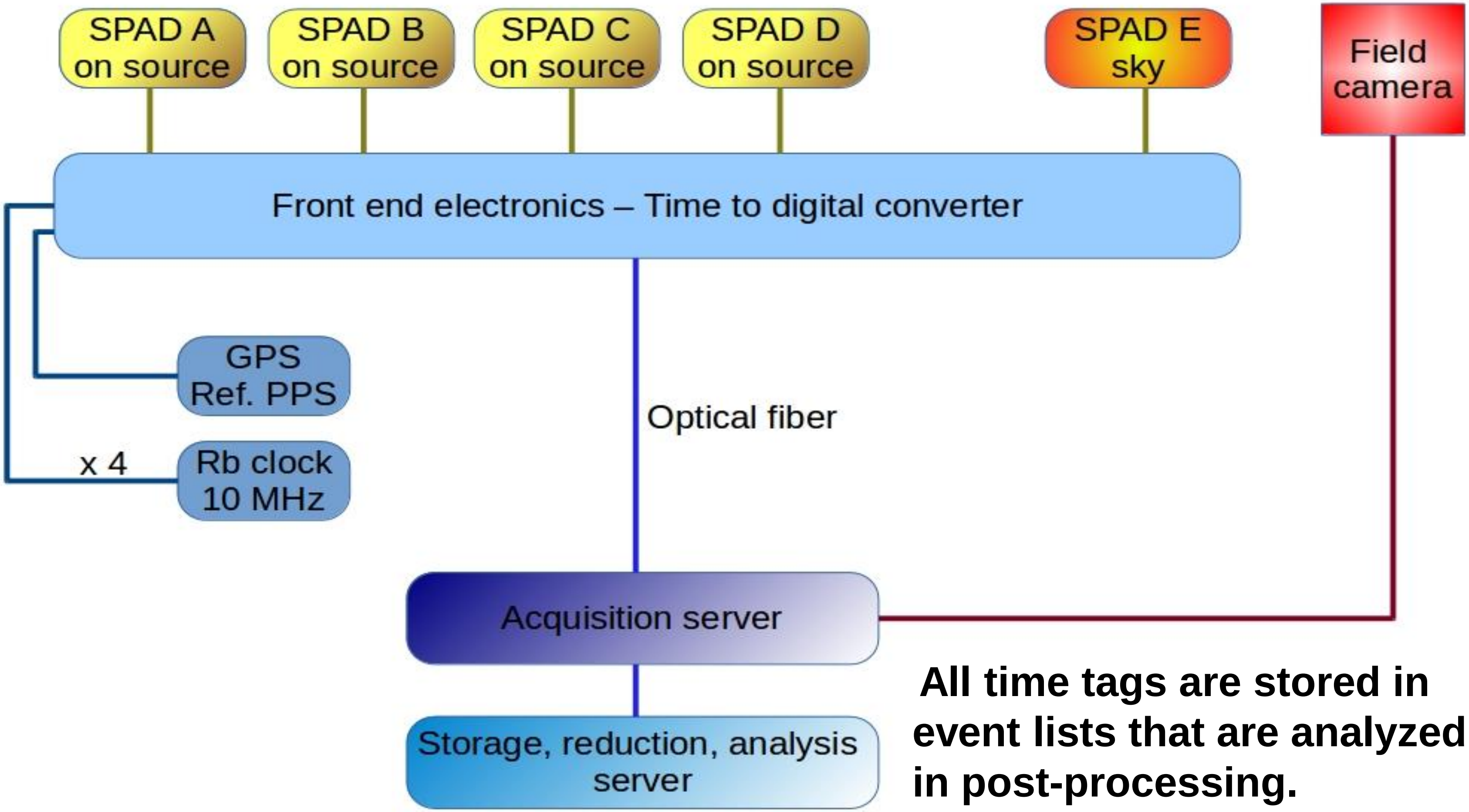
Detectors and Time Unit

Single Photon Avalanche Photodiodes *(SPADs)* with 100 μm pixel size, 35 ps time resolution, ~100 dark count rate, 6-8 MHz maximum count rate, quantum efficiency in the visible up to 60%



The Time Unit tags the photon arrival times with sub-ns accuracy on a highly accurate time scale (UTC) provided by a Rubidium clock disciplined by a GPS unit.

The overall system



SPAD A on source

SPAD B on source

SPAD C on source

SPAD D on source

SPAD E sky

Field camera

Front end electronics – Time to digital converter

GPS Ref. PPS

x 4

Rb clock 10 MHz

Optical fiber

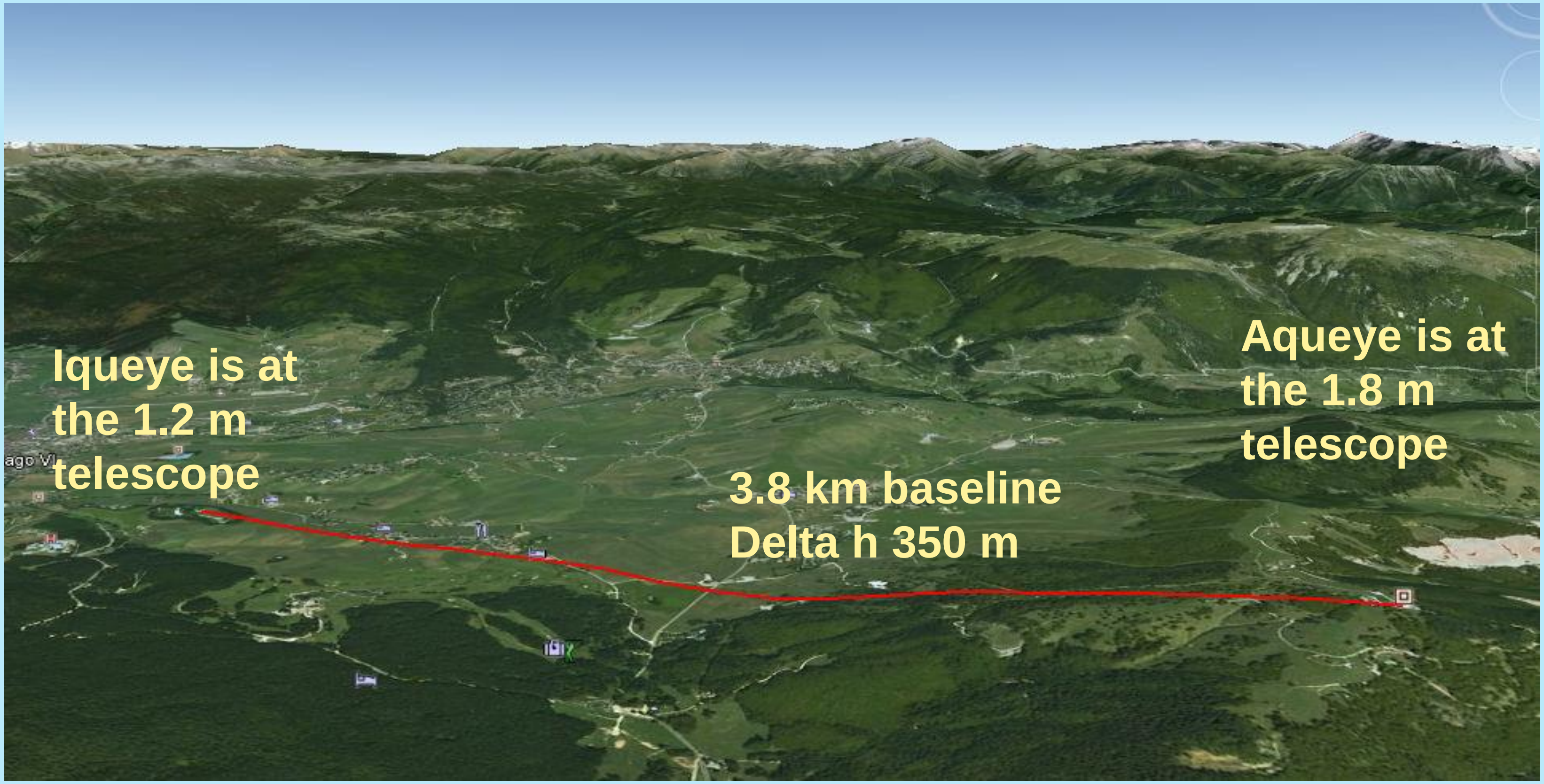
Acquisition server

Storage, reduction, analysis server

All time tags are stored in event lists that are analyzed in post-processing.

Post-processing is done with any convenient selection of time bin (from ns to minutes), thus providing a dynamic range of 6 orders of magnitude.

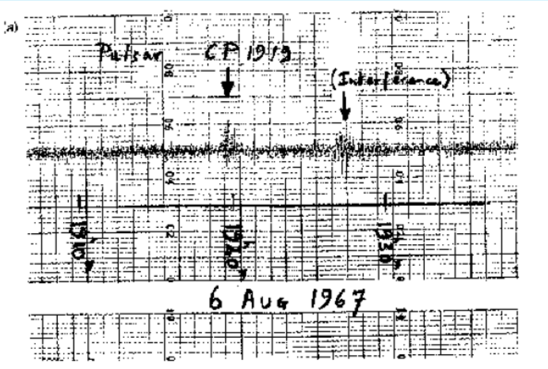
Aqueye and Iqueye are now both in Asiago



Having two identical photometers with the same accurate time frame provides another unique capability, namely the simultaneous observation of a celestial source with two distant, non optically coupled telescopes. In other words, a modern version of the Intensity Interferometry first performed by Hanbury Brown and Twiss at Narrabri more than 5o years ago. The first successful attempts have already been made.

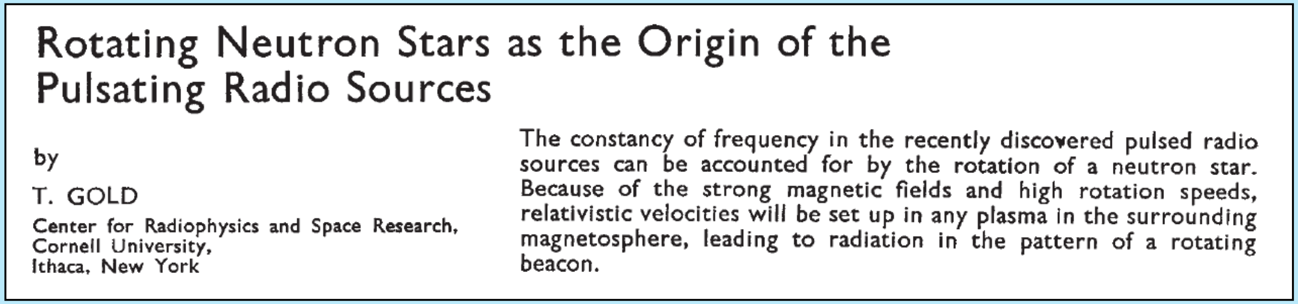
The photometers have been used for studies on *optical pulsars, lunar occultations*, *exo-planet transits* and *fast variable objects*.
Optical pulsars indeed have been a most rewarding test bed for Aqueye and Iqueye. Here, we present the results obtained at the NTT on *three optical pulsars*. Their light curves, pulse shape and phase determination appear to be the best available in the literature.

Iqueye at the NTT



Pulsars in a nut shell -1

Hewish et al. 1968, Nature, 217, 709



Rotating Neutron Stars as the Origin of the Pulsating Radio Sources

by

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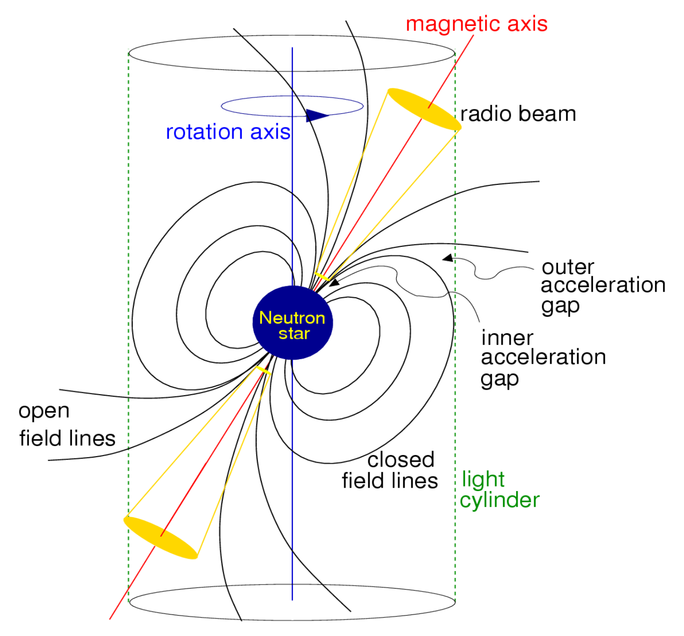
The constancy of frequency in the recently discovered pulsed radio sources can be accounted for by the rotation of a neutron star. Because of the strong magnetic fields and high rotation speeds, relativistic velocities will be set up in any plasma in the surrounding magnetosphere, leading to radiation in the pattern of a rotating beacon.

Pulsars are rapidly rotating magnetized neutron stars born from the collapse of massive stars, with rotational periods from 1 ms to 10s.

The mass of the pulsar is around 1.4 solar masses, the surface temperature is of the order of 10^5-10^6 K. The density is of the order of 10^{14} g cm^{-3}.
The inferred magnetic fields range from 10^8 to 10^{14} G.

Pulsars in a nut shell -2



Radiation is emitted in a beam that sweeps along our line of sight at every rotation. Timing means measuring the arrival time of these pulses of radiation, deriving the period and its derivatives. The characteristic age of the pulsar and strength of magnetic filed are derived from the following equations:

$$\boxed{\tau_c = \frac{1}{2}\frac{P}{\dot{P}}}$$

$$\boxed{B_{\mathrm{sd}} \approx 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}}$$

The spin frequency ν decreases with time: **dν /dt = -k ν^{n}** with a ***braking index n*** which is =3 for a perfect dipole. Our data have allowed a precise determination of ***n*** for two optical pulsars.

Pulsar in a nut shell - 3

To date, about 2500 pulsars have been identified in radio, both isolated and in binary systems.
Around 250 are detected in γ rays by Fermi (all pulsating)
Around 150 are detected in X rays (not all pulsating)
Only a score are seen pulsating in UV, optical and IR.

Different emission mechanisms correspond to different emission regions in the magnetosphere and on the star surface. Therefore, pulsars are unique laboratories for studying:

- nuclear matter equation of state
- relativistic electrodynamics
- intense gravitational fields
- particle acceleration
- interaction with their nebulae

Only multi-wavelength observations give the global picture.

Optical pulsars

There are 5 isolated radio pulsars pulsating also in optical wavelengths, and we have studied 3 of them with Iqueye at the NTT:

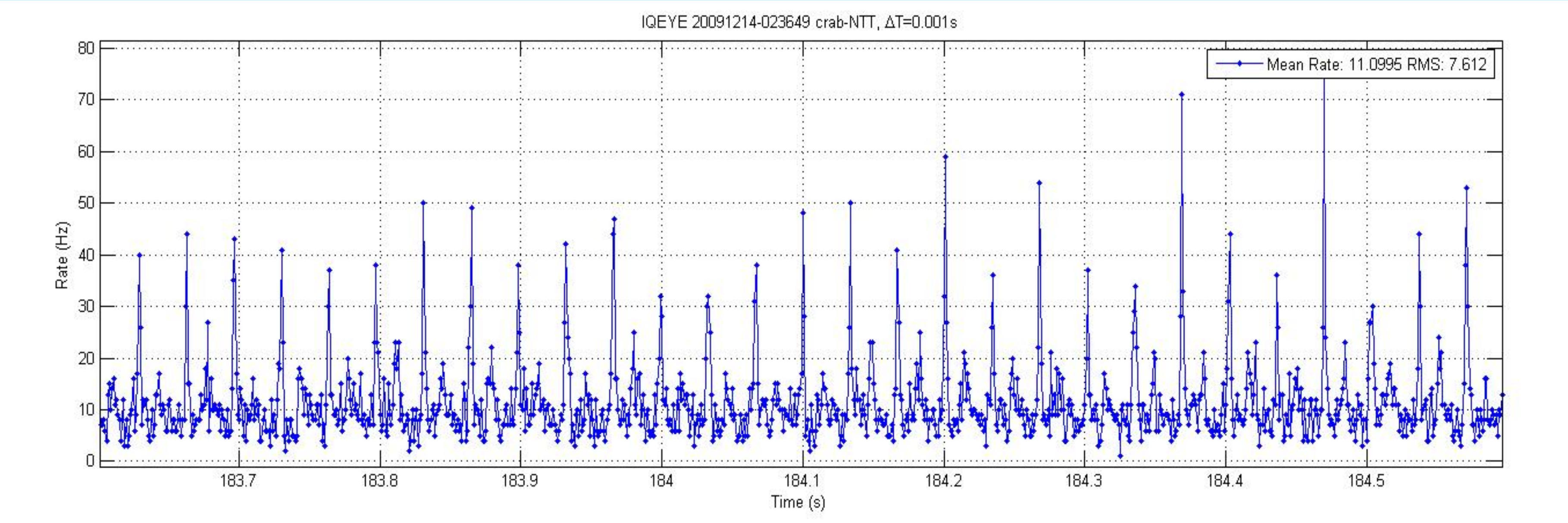
1- the V = 16.5, 33 ms Crab Nebula pulsar, in the SN remnant exploded in year 1054. Thanks to its declination it is visible both from Asiago and La Silla

2 – the V=22.5, 50 ms pulsar in the Large Magellanic Cloud (designated as B0540-69), the only extragalactic optical pulsar known today

3 – the V=23.5, 89 ms Vela pulsar

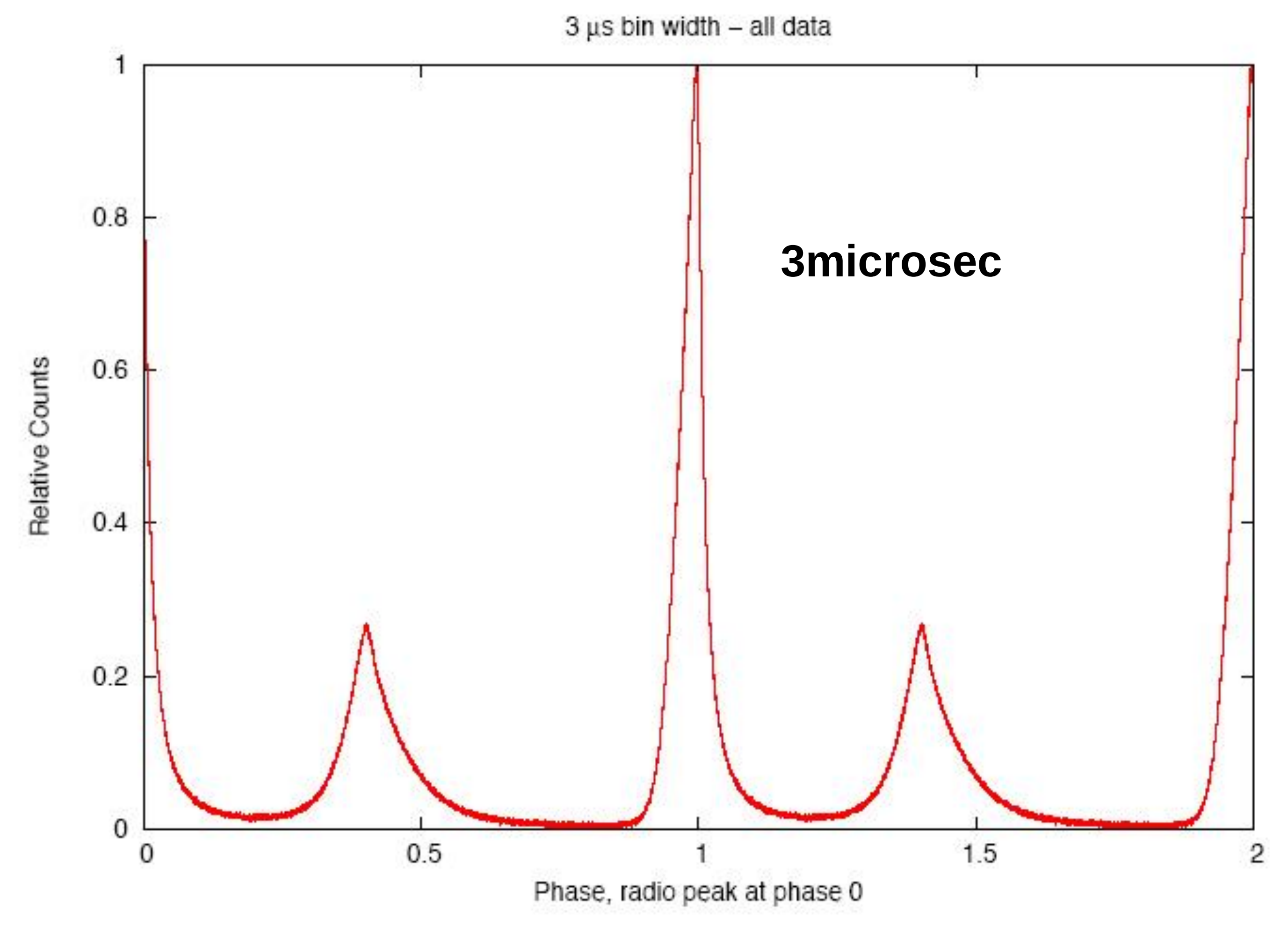
1 - The Crab pulsar

The Crab pulsar was observed at the NTT in January 2009 and again in December 2009.
In the last occasion simultaneous data were obtained with Jodrell Bank. The radio telescope detected hundreds of Giant Radio Pulses during the Iqueye observations.

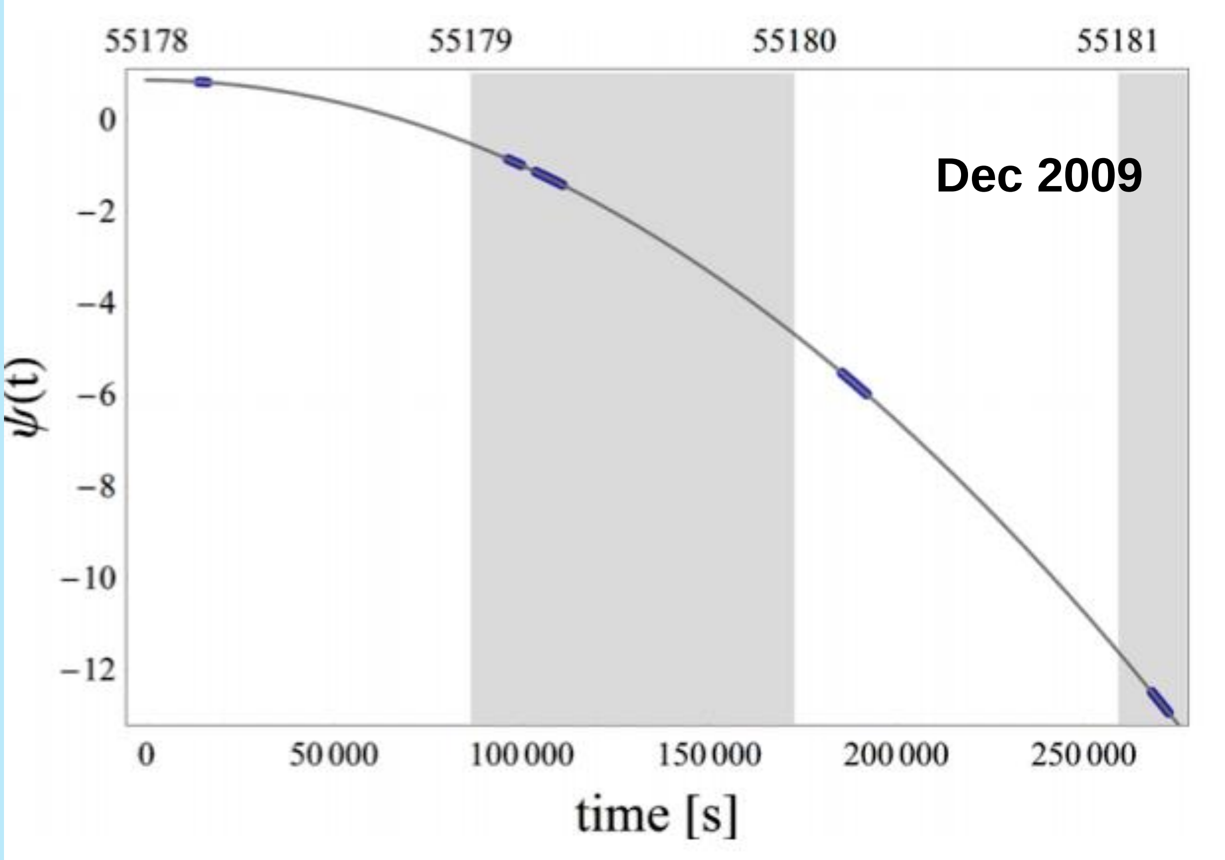


A series of individual pulses, raw data

data binned at 3 microseconds = 10^{-4} Period



Pulsar slowing down



Dec 2009

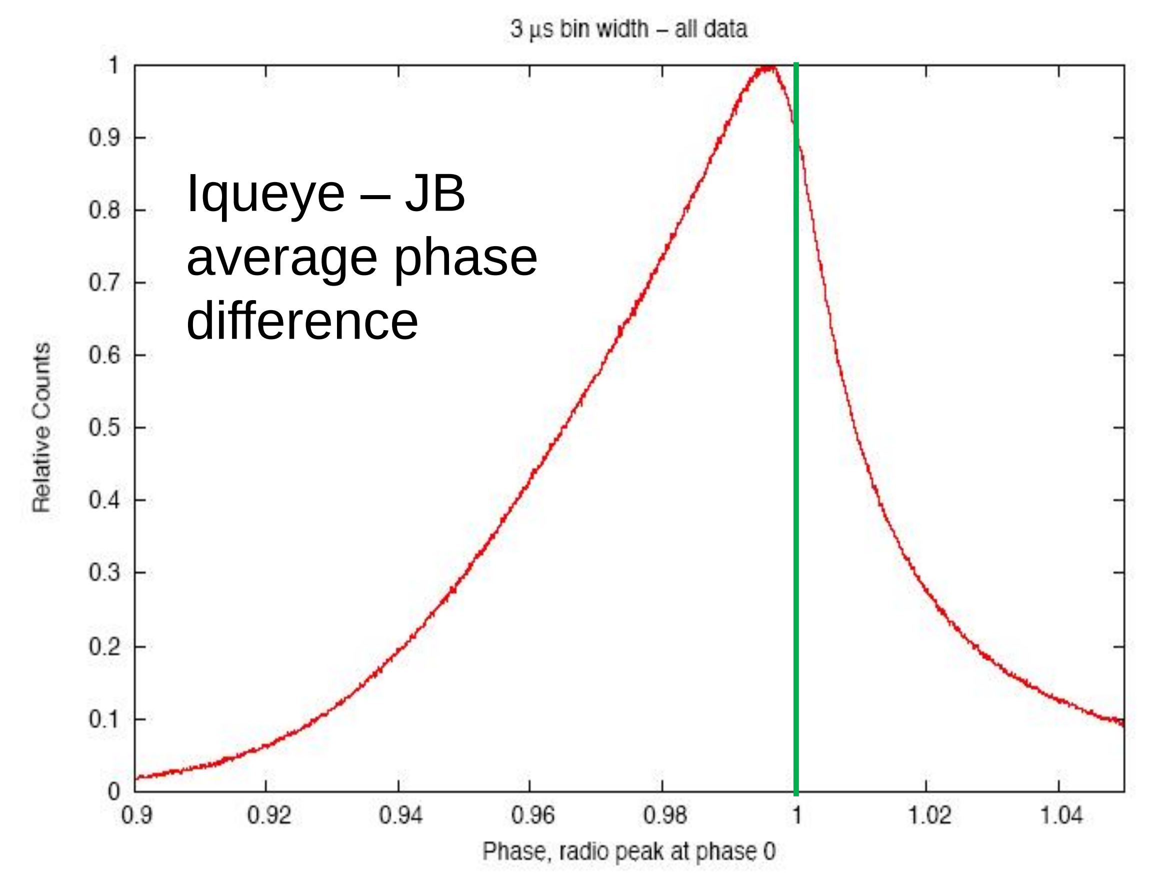
Phase of the pulses with respect to uniform rotation. Time on top axis is in MJD. Few days of Iqueye observations provide a robust estimation of the pulsar slowing down.

Combining Jan and Dec data we derive a braking index ***n*** = 2.44, similar to the radio one in the over the same period.

The age is consistent with the explosion of AD 1054

Accuracy of period and phase difference with Jodrell Bank

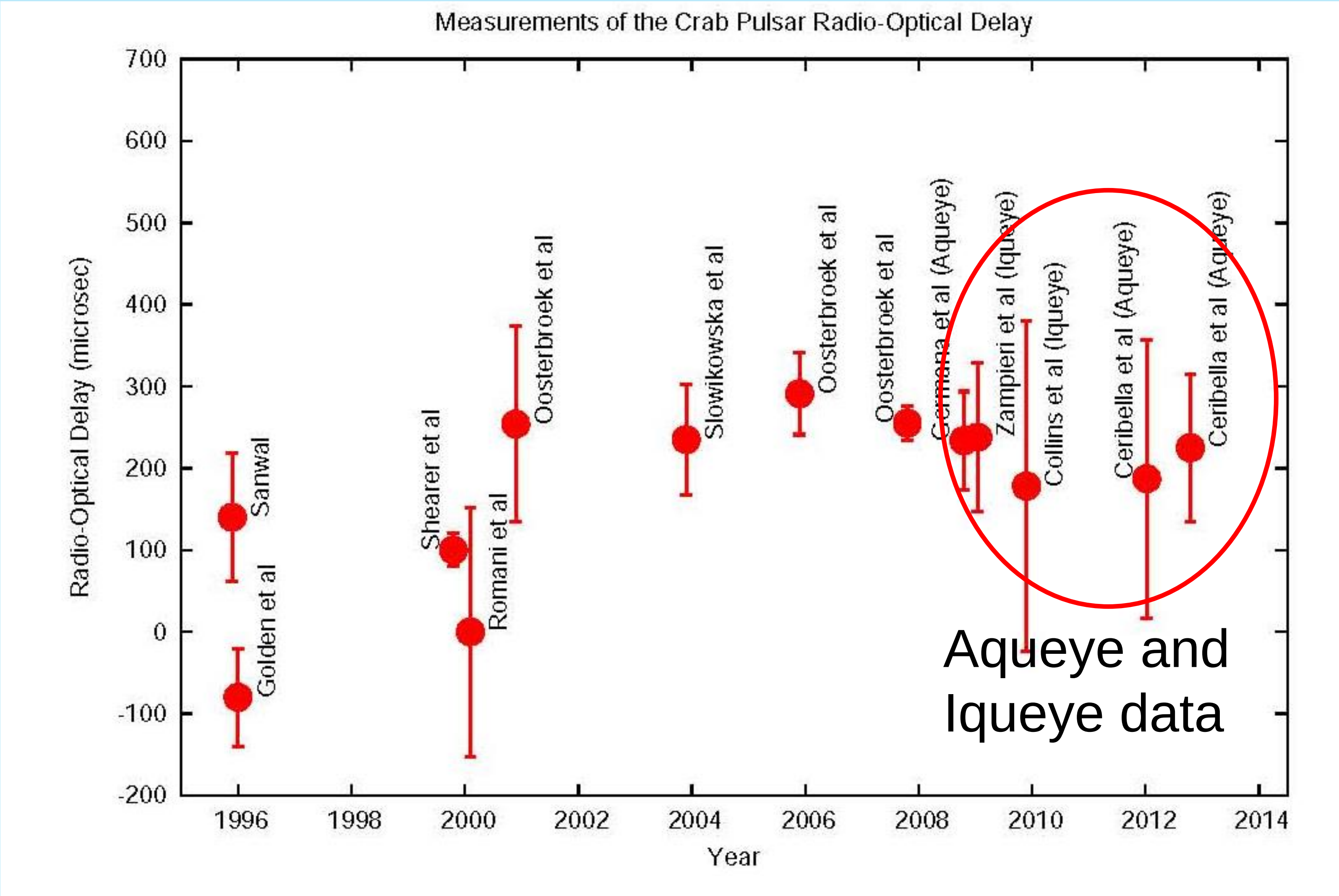
Iqueye and Jodrell Bank radio periods agree to the ***1 ps level.***



Iqueye – JB average phase difference

Iqueye data confirm the ***systematic optical-radio phase difference***, with the optical pulse preceding the radio one by about 200 microseconds.

Values of the radio – optical delay of the main peak



Aqueye and Iqueye data

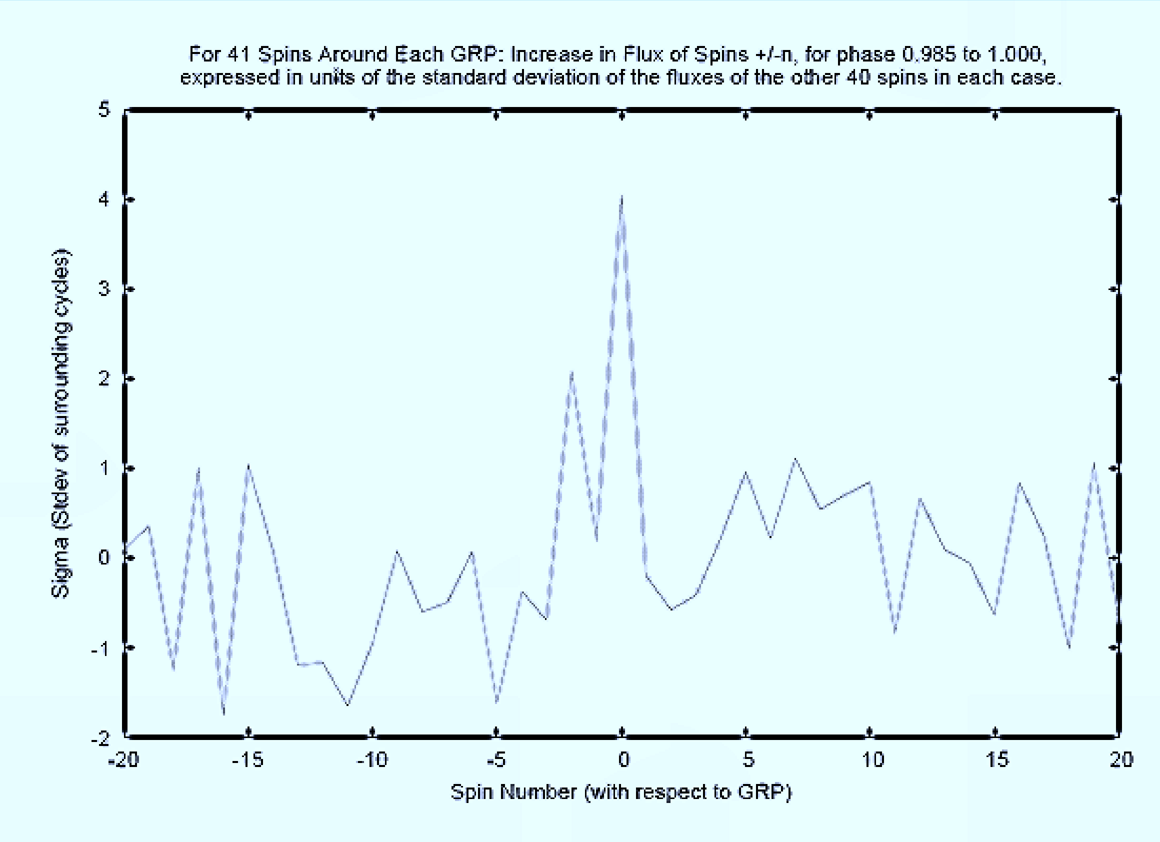
The error bars in the Aqueye and Iqueye data is **dominated by the radio errors**.

Our interpretation of the delay is that optical and radio beams are misaligned by 1.5–3 deg because at the position where electrons emit optical photons the magnetic field has a slightly different orientation.

Regular monitoring observations are carried out in Asiago do not find significan evolution of the delay.

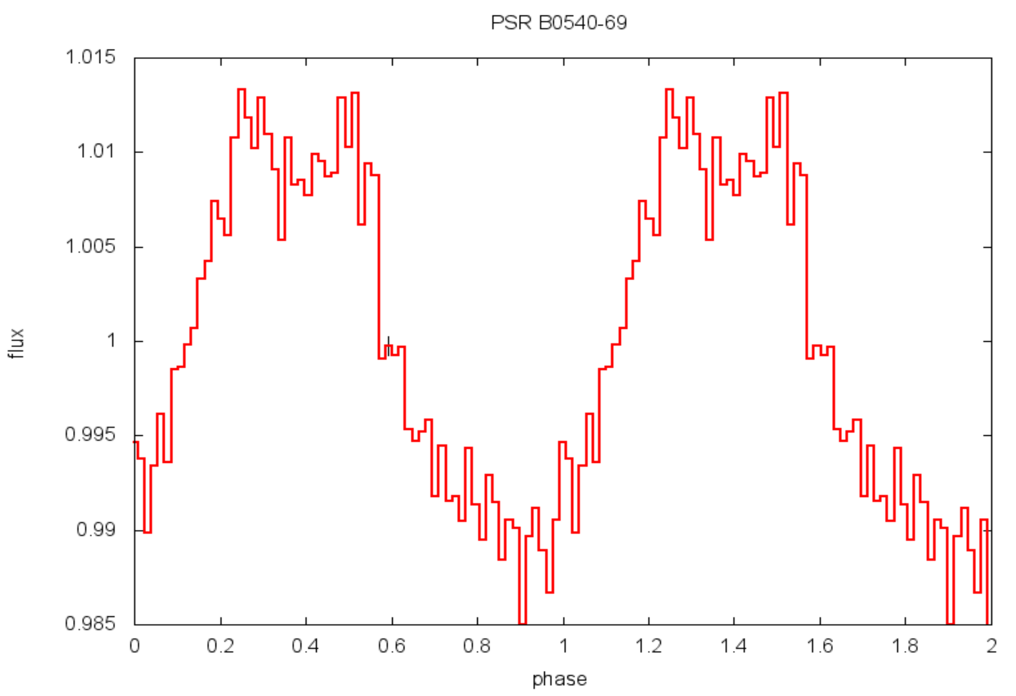
Optical signature of GRPs

The night of Dec 14, 2009 Jodrell Bank detected 737 Giant Radio Pulses (GRPs) above a 6.0-σ cutoff, of which 663 had concurrent Iqueye observations.



The Iqueye data confirm ***a noticeable increase in optical flux*** up to a 4-σ level in correspondence to the GRPs.

The second brightest pulsar: B0540-69 in the Large Magellanic Cloud

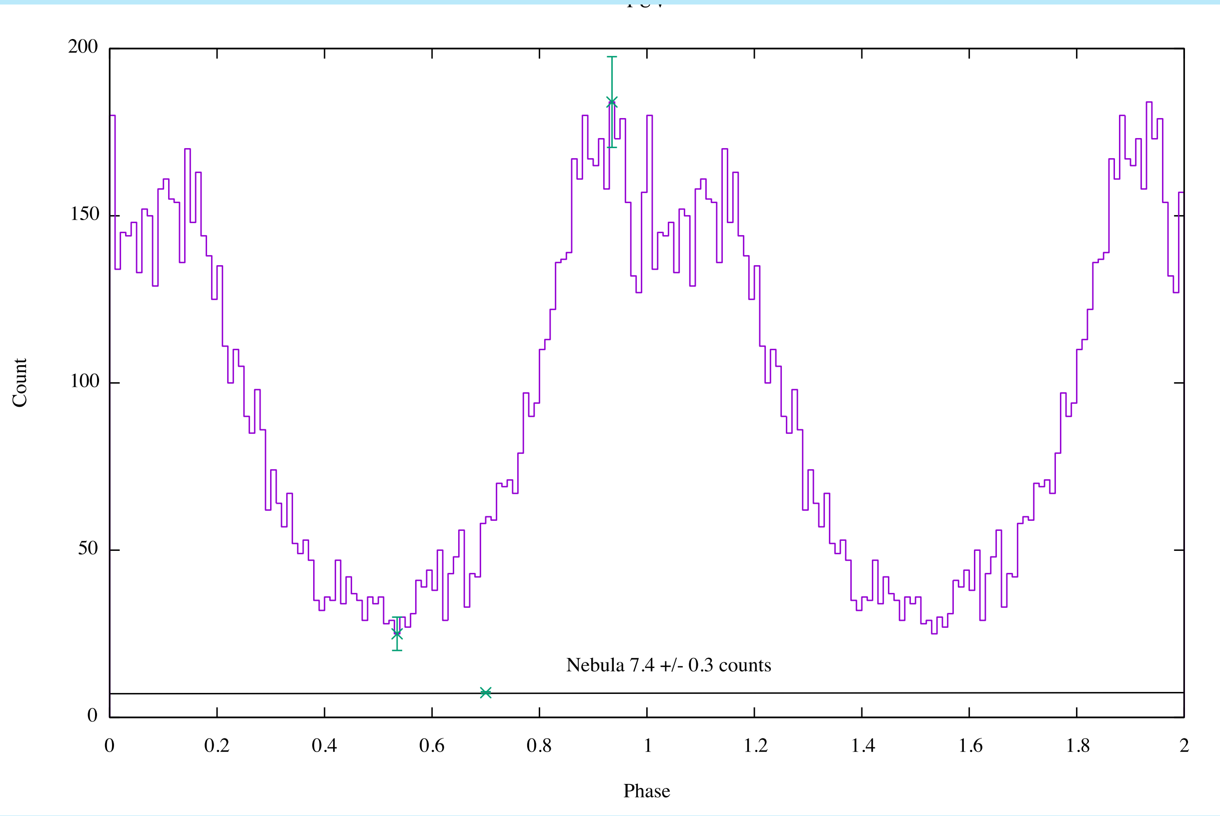


This pulsar is approximately 100 times fainter than Crab's, therefore individual pulses could not be detected.

Our observations extended by 9 years the time span over which optical data were obtained**.**

The braking index n (measurable only in optical and in X rays) over 27 years of optical observations is *n* = 2.087 +/- 0.013, decidedly lower than the magnetic dipole value.

The UV light curve



Pulsations have been seen also in the UV with the HST. B0540-69 is one of the 4 pulsars that are seen to pulsate from the radio to the gamma-rays.

2015 The Fermi LAT detection

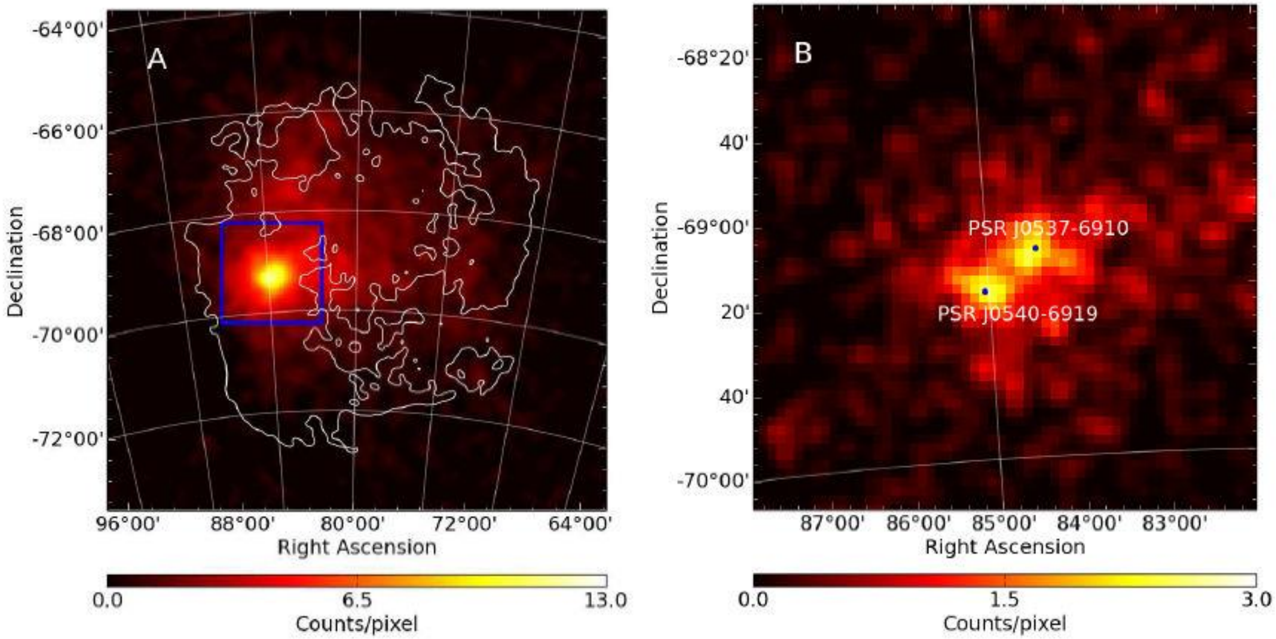
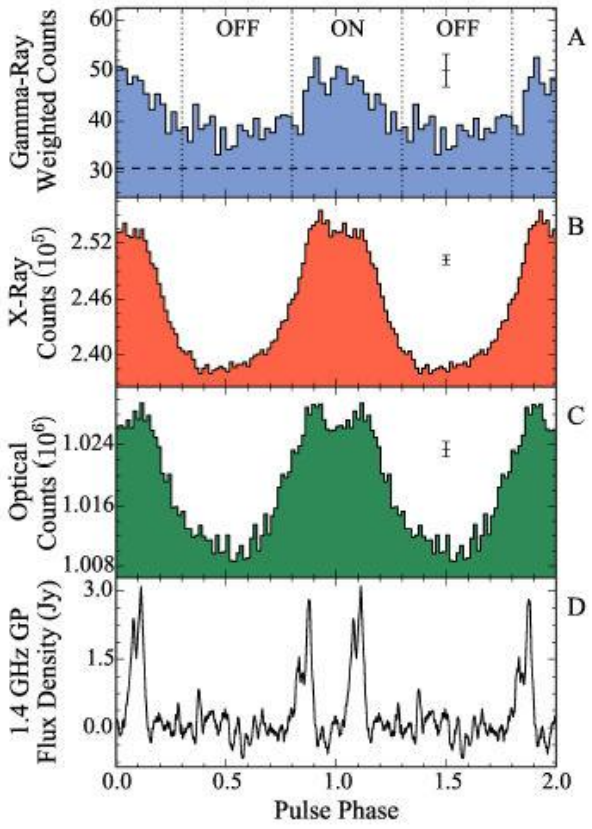


Figure 1: **Sky maps of the LMC.** (A) 0.2–200 GeV gamma-ray emission in a 10° × 10° region encompassing the LMC. The map was smoothed using a Gaussian kernel with $\sigma = 0.2°$. Emission is strongest around 30 Doradus (approximately delimited by the blue box), but also fills much of the galaxy. Contours show the atomic gas distribution. (B) 2–200 GeV gamma-ray emission in a 2° × 2° region around 30 Doradus. The map was smoothed using a Gaussian kernel with $\sigma = 0.1°$. Better angular resolution at higher energies resolves two components coincident with PSR J0540−6919 and PSR J0537−6910, whose locations are indicated as blue dots. Both maps are given in J2000 equatorial coordinates.

The Gamma to Radio light curves



Iqueye

Figure 2: **Pulse profiles for PSR J0540−6919.** (A) Probability-weighted LAT count profile. The horizontal dashed line approximates the background level. Vertical lines indicate the on- and off-pulse regions used for the LAT spectral analysis. (B) RXTE X-ray integrated count profile. (C) NTT optical count profile. (D) Parkes radio flux profile from summing 18 bright giant radio pulses at 1.4 GHz. Two complete cycles are shown. The error bars in the top three panels represent the median phase bin errors.

The faintest pulsar: Vela

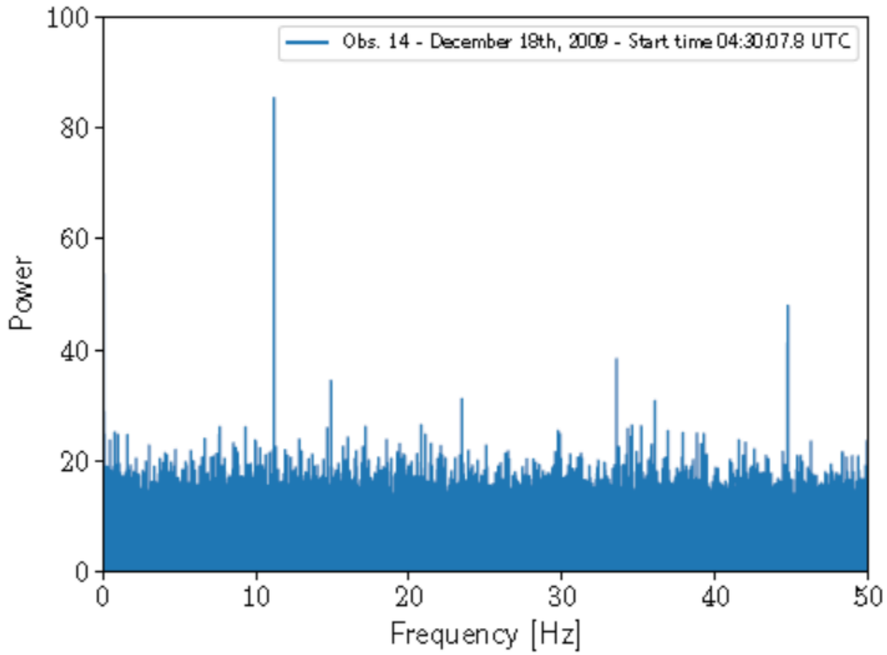
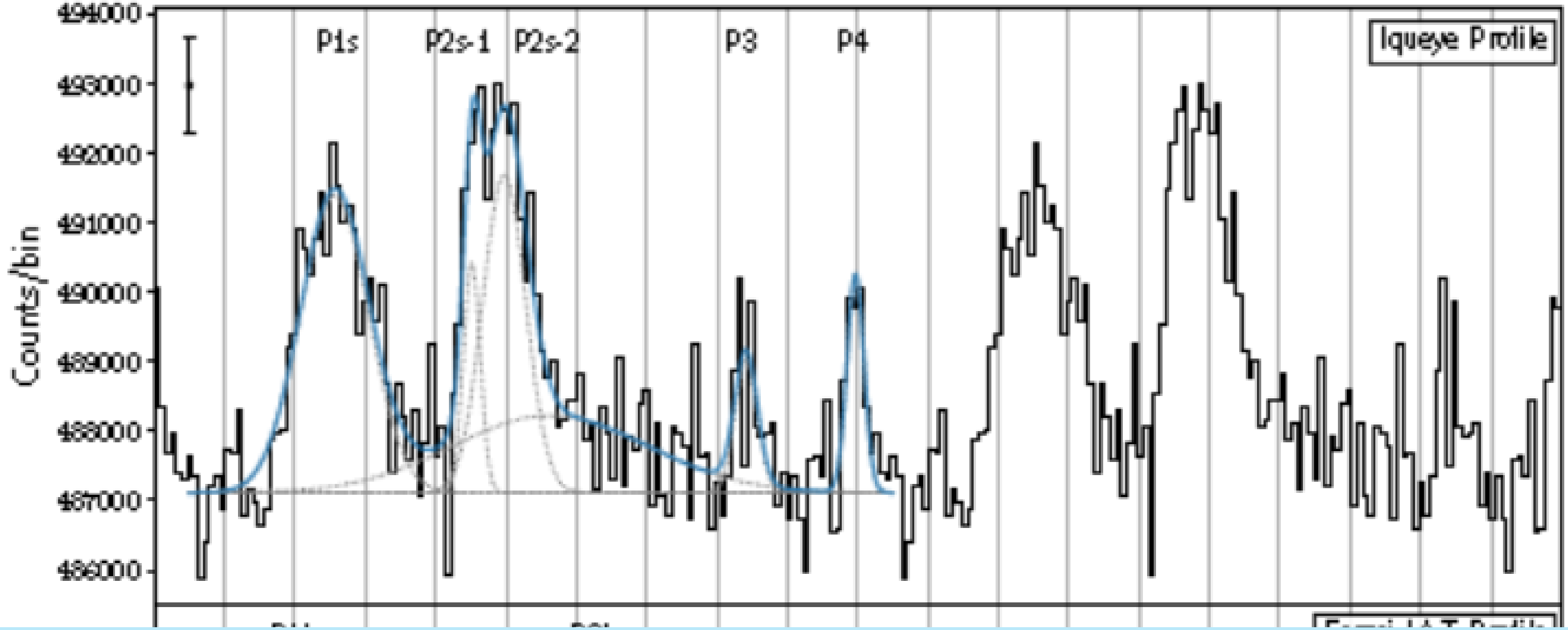


Figure A1. Leahy normalized power spectrum of Obs. 14 (see Table 1). The time bin is 0.01 s. The resolution in frequency is 10^{-4} Hz.

Vela’s pulsar is 10 times fainter than B0540-69. However, the periodic signal (period around 89 ms) is plainly evident from the Fourier transform.

The Iqueye light curve



Two cycles are shown for clarity.
The light curve is truly complex

Phase drift

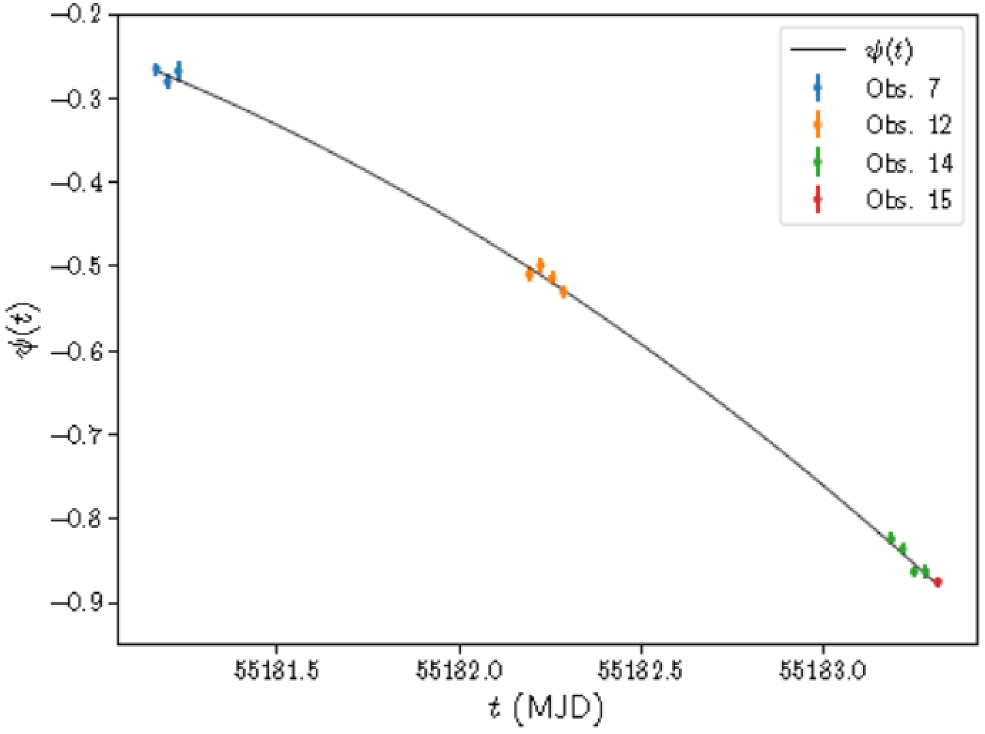
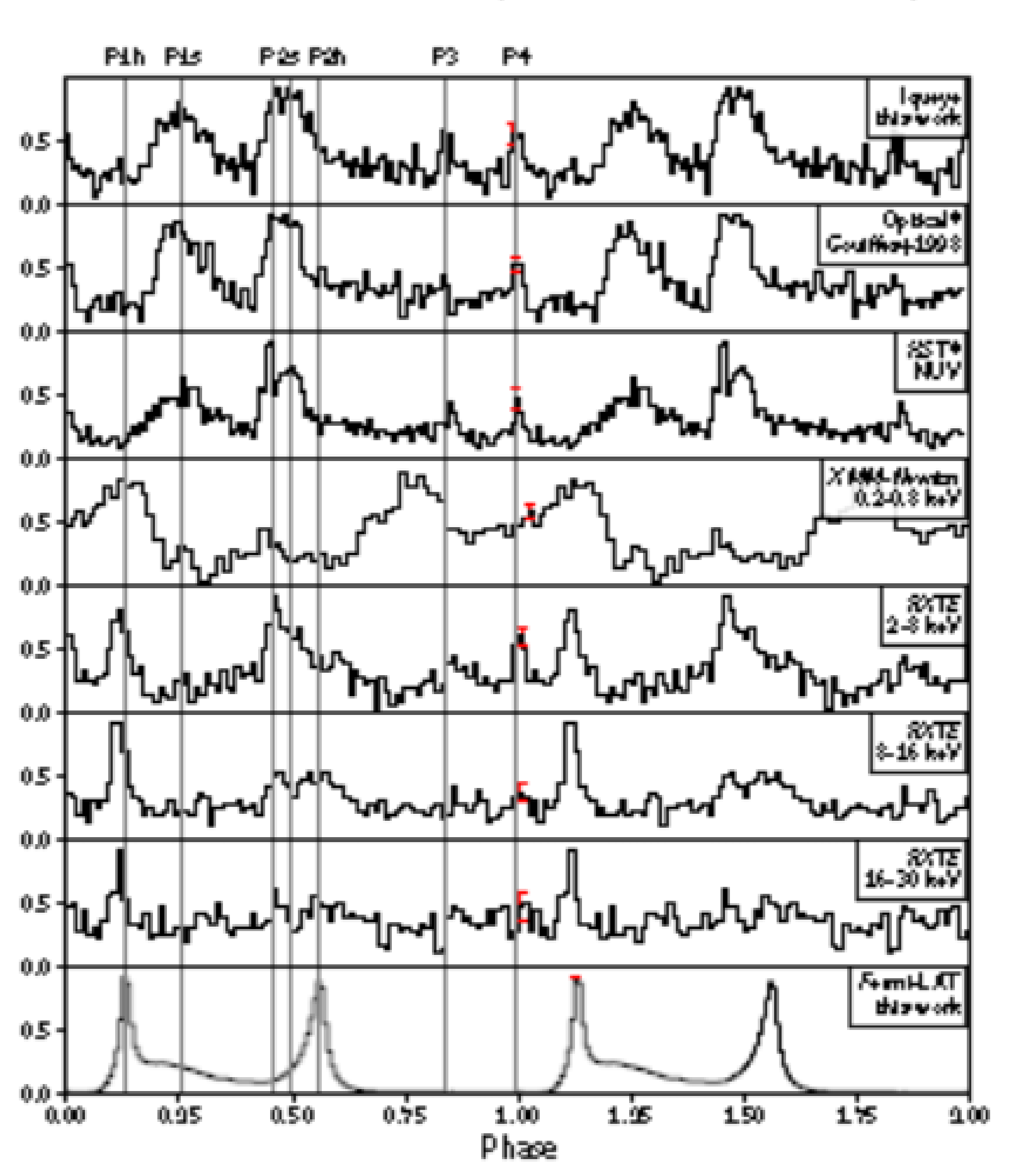


Figure 2. Phase drift of the Vela pulsar $\psi(t)$ with respect to uniform rotation. Time t expressed in MJD.

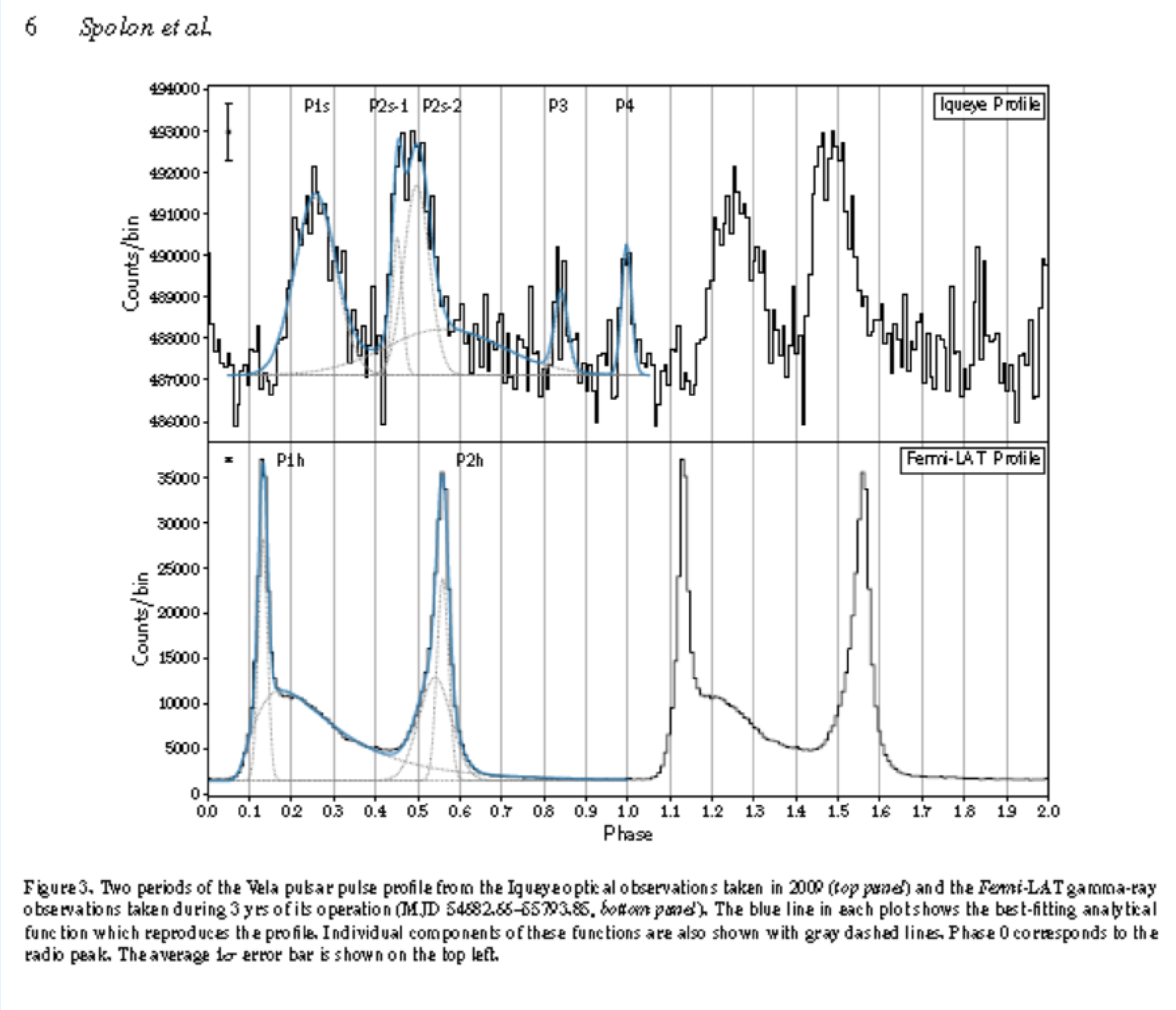
Although we could not derive ***n*** from our data alone, for the first time we determined the relative time of arrival of the radio-optical-gamma ray peaks with an accuracy of a fraction of a millisecond.

A mosaic of light curves at increasing energies.



The morphology of thelight curves changes with increasing energies, different from Crab and B0540-69

A detailed Iqueye vs Fermi-LAT



6 *Spolon et al.*

Figure 3. Two periods of the Vela pulsar pulse profile from the Iqueye optical observations taken in 2009 (*top panel*) and the *Fermi*-LAT gamma-ray observations taken during 3 yrs of its operation (MJD 54682.66–55793.85, *bottom panel*). The blue line in each plot shows the best-fitting analytical function which reproduces the profile. Individual components of these functions are also shown with gray dashed lines. Phase 0 corresponds to the radio peak. The average 1σ error bar is shown on the top left.

Conclusions

IquEYE at the NTT and Aqueye at the Copernicus in Asiago have proven the validity of our design and realization. The instruments perform very well as extremely fast photon counters and multicolor photometers, both for very bright and very faint sources. The concept is very modular, and could be adapted to any telescope.

With telescopes of modest size (< 4 m diameter) it is not possible to achieve significant results on quantum effects.

However, several astrophysical problems requiring the highest time resolution like pulsars and gamma ray bursts, can be investigated better than with other photometers, thanks to the fair quantum efficiency, superior time tagging and time keeping capability and large dynamic range selectable at will.

The examples here shown attest the validity of Iqueye and Aqueye for multi-wavelength astronomy.

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THANK YOU!