OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** engineering

Ultrafast, Low-Resolution Spectroscopy with Fiber-Coupled Single Photon Detectors

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CoI(s): Philip Mauskopf (Arizona State University), Edward Schroeder⋆ (Arizona State University), Genady Pilyavsky⋆ (Arizona State University)

Abstract of Scientific Justification

Single photon detectors are now achieving high quantum efficiency, low dark count rates, and fast time resolution, opening up new possibilities for high-speed astronomy. Silicon avalanche photodiodes have maximum count rates of several MHz and time resolution of 100s of picoseconds while superconducting single photon detectors can have even higher count rates and time resolution of 10s of picoseconds. Some applications for these new detector technologies include spectral monitoring of rapidly varying sources and intensity interferometry. We propose to demonstrate a single detector module fiber-coupled to the Cassegrain focus of the Kitt Peak 90“ telescope and observe known calibration sources. In the future, additional units could be installed at multiple telescopes on Kitt Peak and nearby observatories to enable intensity interferometry with uniquely long baselines.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	90”	f/9	PI	*		5	bright	Nov-Dec	Oct-Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	Crab Pulsar	05:34:31.97	+22:00:52.1	V= 16.5, optical pulsar
2	PSRB1937+21	19:39:38.56	+21:34:59.14	millisecond pulsar
3	GD71	05:52:27.5	+15:53:17	V= 13.032, white dwarf calibration source
4	GD191	05:05:20.6	+52:49:54	V= 11.781, white dwarf calibration source
5	F11	01:04:22	+04:13:37	V= 12.065, calibration star
6	F24	02:35:08	+03:43:57	V= 12.411, calibration star
7	9596	03:52:54	+00:00:19	V= 10.010, calibration star

Approval for Instrument Use from PI: See attached e-mail from Nathan Smith

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Nathan Smith	Philip Mauskopf		no	yes

Scientific Justification

In 1956, R. Hanbury Brown and R. Q. Twiss performed an experiment that demonstrated an ability to correlate the intensity fluctuations of starlight as detected by two photomultipliers. Using the second-order correlation function to perform intensity interferometry, Hanbury Brown and Twiss were able to determine the diameter of Sirius (Hanbury Brown & Twiss, 1956). Limited at that time as they were by detector speeds and data storage capabilities, only bright sources of light with large angular diameters relative to the detectors could be measured. Recent advances in single-photon detection, however, have once again inspired scientists and engineers to open the book on intensity interferometry for astronomical applications, which could enable the direct measurement of stellar diameters that are far smaller than any other astronomical measurements have proven capable of making through a statistical analysis of photon arrival times in detectors pointed at the same target (see Trippe, 2014).

To perform conventional phase interferometry, light from separated telescopes must be first physically combined and then detected. Due to practical limitations, these baselines cannot be larger than hundreds of meters. In addition, traditional Michelson interferometry requires dividing the input light from each telescope to combine it with other telescopes and therefore the signal to noise ratio does not increase quickly as the number of telescopes increases. On the other hand, in intensity interferometry, as illustrated in Figure 1, the incoming signals are first detected and then combined. In this case, the data from two detectors containing the arrival times of photons can be stored digitally and the correlations performed in post-processing, theoretically allowing for arbitrarily large baselines. In addition, the signal to noise increases rapidly with the number of telescopes as each baseline contributes independently and there is no division of the signal from individual telescopes.

Already, the AQUEYE and IquEYE 4-SPAD arrays are measuring the light curves from pulsars with high signal-to-noise ratios, and the scientists operating those arrays have future plans to continue to improve their instrumentation (Barbeiri, 2009). However, there has so far been no demonstration of intensity interferometry with either SPADs or superconducting single photon detectors.

We propose to use the 90" telescope on Kitt Peak to quantify our ability to efficiently couple starlight through both multimode and single-mode fiber optic cables to our single-photon detection modules (SPAD and SSPD) as a precursor to exploiting several of the mountain's telescopes for intensity interferometry with potential baseline coverage shown in Figure 2 and discussed in the Experimental Procedure section. Additionally, by splitting the signal in the fiber optic cable, a reference measurement of photon correlations from several targets can be obtained. If this is successful, unique measurements of stellar diameters can be made at a future date using two or more Kitt Peak telescopes.

A narrow-bandwidth filter is required to both achieve appropriate photon statistics and limit the amount of light coming in so as to not overload the detectors, an extension of this initial experiment can be executed where several filters are used to both perform spectroscopic measurements and decrease the integration time of the detectors. By taking unfiltered light from a fiber-optic cable and splitting it into several wavelength channels with, e.g. a prism or grating, each to their own fast single photon detector, each multiple baselines can be measured simultaneously with each pair of telescopes and used to estimate the size of an object in different bands. This method effectively serves as a way to increase the effective occupation number of the target in the optical system to decrease integration time by a factor N = the number of independent wavelength channels.

In addition to these steps to employ intensity interferometry for astronomical measurements, the proposed observations are also useful for high-speed astronomy. By pointing our detectors at optically variable sources, we can both establish the proper calibration of our system and measure ultrafast, spectral intensity changes at extremely small time scales. By using silicon avalanche photodiode detectors, this time scale is on the order of 100s of picoseconds. Our research group is also planning on using super-conducting nanowire detectors that can operate at 10 ps, further pushing the boundary of high-speed astronomy.

The silicon avalanche photodiode is a type of single-photon avalanche photodiodes (SPADs, shown in Figure 3). When a photon creates an electron hole pair in the multiplication region of a SPAD, the strong E-field formed at the p-n junction motivates impact ionization, resulting in an avalanche pulse that coincides with a

photon arrival with hundreds of picoseconds of time jitter. This is good, but the detection of single photons is greatly improved with superconducting detectors. In order to count greater numbers of photons with higher accuracy, we can implement superconducting nano-wire single photon detectors (SNSPDs). The SNSPDs that we will consider use a thin (3.5 nm) and narrow (100 nm) niobium nitride (NbN) meandering nano-wire to detect incident photons. The device must be cooled to 4 K to become superconducting and it must be biased with a current close to the current at which superconductivity is destroyed in the circuit, the critical current (Hortensius, 2012). The bias current is what allows a single photon to generate a readable voltage pulse signal.

The advantages to astronomical studies afforded by the use of fast detectors at large, scientific telescopes are great. By using the instruments available at Kitt Peak together with the instruments being developed at Arizona State University in this field, precise insights into the size and composition of stars and other bright objects can be gained and used to develop theories regarding stellar and planetary evolution.

References

Barbieri, C., et al. (2009). Very fast photon counting photometers for astronomical applications: IquEYE for the ESO 3.5 m new technology telescope. SPIE, 7355.

Brown, R. Hanbury, & Twiss, R. Q. (1956). A test of a new type of stellar interferometer on sirius. Nature, 178, 1046-1048.

Hortensius, H.L., et al. (2012). Critical-Current Reduction in Thin Superconducting Wires Due to Current Crowding. Applied Physics Letters, vol. 100.

Trippe, Sascha, et al. (2014). Optical Multi-Channel Intensity Interferometry - Or: How to Resolve O-Stars in the Magellanic Clouds. Journal of the Korean Astronomical Society, 00, 1-19.

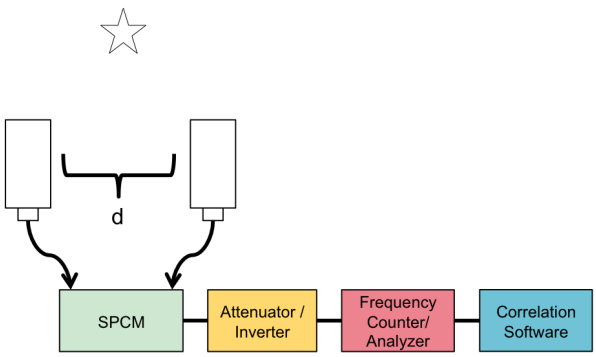

Figure 1: A simplified overview of an intensity interferometer where two telescopes are each coupled to fiber optics that couple to a single-photon counting module. Then, through GPS link, these digitized time streams are electronically analyzed to determine the degree of coherence between the two original signals.

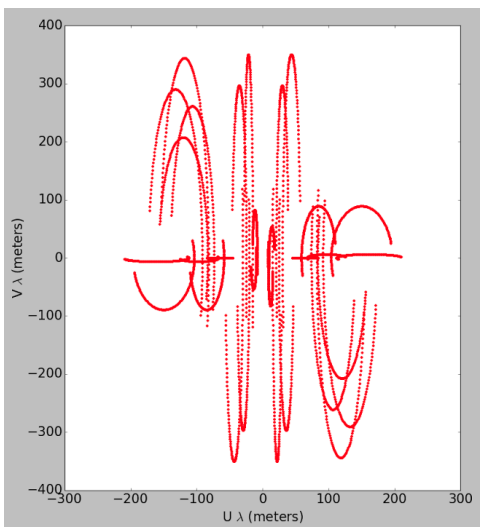

Figure 2: An example of the baseline coverage available at Kitt Peak for one of our targets, the Crab Pulsar, in an example simulation.

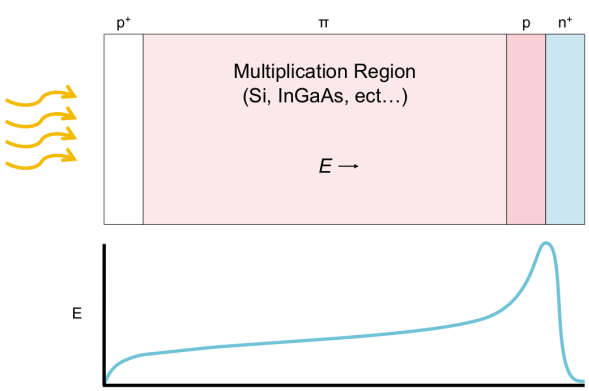

Figure 3: The interior of a SPAD showing how the electric field across the length of the multiplication region induces the avalanche effect.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

The purpose of engaging on an initial observation run using the 90" telescope on Kitt Peak is to quantify the coupling efficiency from starlight through the telescope aperture to our single-photon detector via both multimode and single-mode fiber optic cables. There are two reasons that a telescope of this class is required for this experiment: precise tracking stability and large collecting area.

The single photon detectors have a maximum count rate that limits the brightest stars that we can observe. Similarly the faintest stars we can detect are limited by the sky background. The effective range of magnitudes accessible to our system using a 10-nm filter at 656.3 nm is 12.45 - 19, and, for a 2-nm filter at the same wavelength, the effective magnitude range is 10.70-19 assuming system efficiency of 50 percent. The list of targets all consist of stars for which a photon correlation signal between two detectors coupled to the same signal from the 90" telescope can be detected by analyzing photon statistics at the following count rates (assuming a 2-nm filter):

1. Target 1: 9.6 kHz
2. Target 3: 234 kHz
3. Target 4: 740 kHz
4. Target 5: 570 kHz
5. Target 6: 414 kHz
6. Target 7: 378 kHz

Our time at the observatory for this first round of experiments will be spent first on mounting and aligning the optical systems required to couple fiber-optic cable to the Cassegrain focus of the telescope. Designing around the schematics for the mounting plate of the 90" telescope, a beam splitter will be affixed near the focal point allowing our group to observe the exact position of the focal point relative to the 200-um aperture of a multimode fiber for the SPADs and the 10-um aperture for the SNSPDs using a small, high-resolution camera placed at the end of one path of the beam splitter. Several filters will be used during the course of observations, and alignment will need to take place after each one.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is an initial proposal for UAO and therefore we have not been awarded any prior UAO nights.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

There has been no prior use of Steward Observatory facilities within the past 2 years.