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# Resolving Accretion Disks with Quantum Optics

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Accretion disks around compact objects have been known for about 60 years however their study has been limited because they are unresolved sources in the optical/ultraviolet and X-rays, where they emit. Hanbury Brown & Twiss discovered intensity interferometry in the 1950s, and explained as a quantum effect in the early 60s. We review the capabilities of intensity interferometry in the optical which are becoming available with the advent of very large area telescopes and very fast single photon detectors and their potential to measure accretion disks parameters. Correlating the arrival times of photons detected by Telescopes with mirror areas reaching 1000m$^2$ allows to reach resolutions of nano degree in the optical and to reconstruct images of accretion disks and jets in galactic and extragalactic sources, the potential sources of UHECR.

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## 1. Introduction

Although accretion flows around compact objects are somewhat ubiquitous and similar over scales reaching billions in mass and size, their study has been limited because they remain unresolved point like sources in the optical/ultraviolet and X-rays, where they emit. In the optical, the apparent size of accretion disks is of the order of 1-40$\mu$arcsec in nearby quasars, Seyfert galaxies and galactic cataclysmic variables. For low mass X-ray binaries in our Galaxy, powered by stellar mass black-hole and neutron stars, the optically emitting disks have angular sizes of only 0.1-1$\mu$arcsec. The accretion disks of blazars are faint but they accelerate bright jets with optical scale of tens of $\mu$arcsec.

Radio and infrared interferometry allowed to image several components of accreting sources, such as radio jet (with a resolution reaching 20$R_G$ in the nearest sources), large scale outflows and inflows (narrow-line region and dusty torii of Active Galactic Nuclei) imaged in the infrared with a resolutions of $10^4 R_G$ or hot electrons in the very inner region ($< 10R_G$) of the accretion disk of M87 [1]. Milli- to $\mu$arcsec resolutions are not currently achievable in the optical/ultraviolet, where accretion disks emit, because atmospheric turbulence on long baselines decorrelates the phase information. Cophasing systems of multiple appertures have been proposed for baselines reaching up to 100m [2], too small to resolve accretion disks.

Hanbury Brown & Twiss [3, 4] invented intensity interferometry and measured the size of some bright stars with two optical telescopes. The physics has been explained as a quantum effect in the early 60s [5] and was foundational in the development of quantum optics, as nicely introduced in R. Glauber's Nobel lecture [6]. Intensity interferometry relies on the fact that wave functions of multiple quanta could interfere [7]. In an incoherent (e.g. thermal) source, the wave functions of the photons have different phases and the combined probability function features beat frequencies, creating a deviation from the photon arrival time Poisson distribution, i.e. bunching. As a result, the probability to detect two photons simultaneously in a coherence time is increased. The quantum nature of the effect has been verified correlating bosons and fermions, with bunching observed for the former and anti-bunching for the latter [8]. When the separation between the two detectors $|\vec{x}_1 - \vec{x}_2|$ is increased, bunching dilutes because of the different light paths and the decrease of the coincidence probability provides a measure of the source projected angular size as $\approx \lambda/|\vec{x}_1 - \vec{x}_2|$.

Intensity interferometry uses arrival times of photons recorded in different telescopes with very high time resolution (up to $>$ 30ps). Compared to amplitude interferometry which require constant phase tracking, intensity interferometry has the advantage of being practically insensitive to atmospheric turbulence or optical imperfections. The detection signal-to-noise depends on the telescope size, the detector time resolution, and the number of independent spectral channels observed simultaneously. Extremely large telescopes and ultrafast Single Photon Avalanche Diode detectors [9], with a timing accuracy better than the atmospheric noise, bring the key improvements to build a perfect intensity interferometer on ground, reach in the optical angular resolutions better than these achieved in the radio by the Event Horizon Telescope and obtain the first images of accretion disks around galactic and extragalactic compact objects.

Correlating the arrival times of photons detected by e.g. the ELT in construction and the four VLT separated by 20km in the Acatama desert, will allow to constrain the parameters of accretion flows in quasars in a new way, e.g. determining accretion disk inclination, mapping the radial variations of disk temperature, or measuring the mass of super-massive black-holes. Using smaller telescopes separated by few km and available now will allow to resolve bright accretion disks collapsing on white dwarfs in cataclysmic variables. Using fast detectors and large mirror areas spread over kilometers will improve the sensitivity and the spatial resolution of intensity interferometers by factors of $10^3$, a very high gain in observing capabilities, and will open new fields of investigation in astronomy in general. For instance, images could also be obtained of the surface of Solar like stars and binary systems at a distance of 1kpc, of the surface of core-collapse Supernova at 100kpc, or of the inner optical jets of blazars at 100Mpc. Using 30-40m class telescopes separated by several hundreds km could even resolve accretion disks in low mass X-ray binaries.

## 2. Instrument Concept

The unique feature of intensity interferometry, at a timing resolution of $\Delta t$, is that the optical-path tolerance is $< c\Delta t \sim 1$ cm for the fastest modern detectors. As a result reaching nano-degree resolution (10 km baseline) is possible with existing technology. Observing with two telescope (with parameters and locations $\vec{x}$ identified by the subscripts 1 & 2), in $N_{\text{chan}}$ independent waveband channels, the exposure time required to reach a given cross-correlation signal-to-noise ratio *SNR* is

$$t_{\text{exp}} = \frac{(1 + B_1/\Phi)(1 + B_2/\Phi)\sqrt{\Delta t_1 \Delta t_2}}{A_{\text{eff},1}\ A_{\text{eff},2}\ N_{\text{chan}}\ \Phi^2\ |V(\vec{x}_1 - \vec{x}_2)|^4}\ SNR^2.$$

where $A_{\text{eff}}$ is the geometric mean of the telescope effective areas multiplied by the optical and detector efficiencies, $\Phi \approx 10^{-4-\text{m}_\lambda/2.5} \times \lambda/(1\,\mu\text{m})$ is the spectral photon density of the source and $B$ the Night Sky Background (NSB) integrated in the telescope point spread function (PSF) both in unit of photons $\text{m}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1}$. V is the interferometric Fourier visibility normalised to $V(0) = 1$ that can be defined for a range of baselines by exploiting the Earth's rotation just as in radio interferometry.

The challenges are to get high timing resolutions, large number of independent spectral channels and large effective areas. These factors were what limited the historical Narrabri instrument to 32 bright stars [10]. Intensity interferometry has been shown to work using small standard telescopes or the larger areas, but poor optical quality, offered by Cherenkov telescopes. The instrument design discussed here combines several technical novelties to optimise resolution and sensitivity.

The angular resolution of an interferometer is inversely proportional to the baseline between the telescopes. Optical resolutions of 50, 5 and 0.1$\mu$arcsec, needed to probe accretion disks in cataclysmic variables, active galactic nuclei and galactic LMXB, could be achieved with baselines of 2, 20 and 700km available e.g. at the ORM in La Palma, between the Very Large Telescopes and Extremely Large Telescope or between the ELT and the Giant Magellan Telescope.

The purpose of the detector is to time tag the arrival of every photon with high accuracy. An ideal detector should reach a time resolution of the order of the atmospheric natural jitter of 10-30 ps, which also corresponds to the relative stability of a White Rabbit [11] timing network over the correlation measurement period (typically 15 minutes). Absolute timing is not required as only the strength of the correlation is measured, not the delay.

To increase the signal-to-noise ratio, many wavelength channels need to be measured simultaneously and independently. Current SPAD array technology (cells of $\approx 50\mu$m) allows to build narrow arrays with high spatial detector coverage allowing to measure of the order of a thousand independent wavelength channels. The optical system should disperse the light on a length of some cm covering a wavelength range up to 400-650 nm corresponding to the peak of the detector efficiency. Such SPAD arrays could replace the usual CCD detectors of low resolution spectrographs providing a dispersion of 2-20nm/mm for a PSF $\approx 50\mu$. The efficiency is about 0.65 (telescope transmission) $\times$ 0.95 (optical system transmission) $\times$ 0.95 (gaps between detector pixels) $\times$ 0.4 (quantum efficiency) i.e. $\sim$ 0.2. If the pixels are small one may need to cope with optical- and detector- cross talks by combining list of photon time tags from adjacent pixels before being correlated. The photon rate per channel will typically be $10^4$ times smaller than the detector timing resolution and dead time.

The mirror area should be as large as possible, however it is not useful to get a photon rate per sampled waveband channel larger than the inverse of the detector dead time. The detected photon rate is $10^{10.5-\mathrm{m}_\lambda/2.5} A_{\mathrm{eff}} \frac{\Delta\lambda}{\lambda}$. For a wave band of width $\Delta\lambda/\lambda \sim$ 0.05% (typically 0.25 nm), a source of 8 or 14 magnitude leads to photon counting rates of 0.1 MHz or 0.5 kHz for a VLT class telescope and of 2 MHz or 9 kHz for the ELT. Such photon rates are much smaller than the inverse of the detector dead time and of the the night sky background within the point spread function and the seeing. The analog signal of the photon counting detectors will be digitized at each telescope and photon arrival time tags will be either stored for later processing or sent in real-time to a central correlator. The photon time tags from the various telescope pairs will be correlated independently for each wavelength channel. As different emission components (accretion disk, emitting line regions, galactic emission) will contribute to the spectrum, a wavelength dependent model of these components will be needed to analyse the data, providing in addition the possibility to probe the geometry of various structures simultaneously. Note that a polariser could also be added before the disperser.

Single-photon avalanche diode (SPAD) can detect single photons and generate a sizable voltage or current signal in correspondence of that detection. In state-of-the-art SPADs, the timing uncertainty of photon detection is typically better than 100ps, with a record 12.1ps FWHM [9]. Thanks to the CMOS-compatibility of some SPADs, one can also integrate on the same chip time-to-digital converters (TDC, removing the correlation between rise time and signal strength) including delay elements to increase the sampling rate, phase lock loop (PLL) for time tagging and dead time reduction electronics achieving dead time as low as a few ns [9]. Integrated time discrimination has single-shot uncertainties of the order of 10ps, while the integral and differential non-linearity is usually $\pm(0.1-1)$ of the least significant bit.

The photon detection probability (PDP) of a SPAD varies in wavelength, typically, from NUV to NIR from a minimum of 1-3% to a maximum of 50-60% at 480-550 nm. The dark noise (measured as dark count rate DCR) varies as a function of temperature and excess bias voltage, or the voltage of the bias in excess to the breakdown voltage. Figure 14 in [9] shows the normalized DCR as a function of timing jitter. Afterpulsing and cross-talk are forms of correlated noise that falsify photon detection in SPADs, therefore overestimating the PDP. Afterpulsing is due to parasitic avalanches following photon-triggered avalanches, while cross-talk relates to false avalanches due to optical and electrical interaction with other SPADs. Both effects occur with a probability that is generally lower than 1%. Current SPADs can be designed to be round or square and their separation can range from 2.2 µm [12] to millimeters.

For our purpose, the best SPADs would have a size of the order of 50$\mu$m (to be optimized for effective area and noise). They would reach simultaneously a jitter time of $\sim$ 10ps, peak PDP of 50%, deadtime <10ns, dark count rate below 1Hz for a temperature below -30°C and an after-pulsing probability <0.1% [9]. An array of $(256 - 512) \times 2 - 12$ of such pixels could be built in a single chip, including the number of TDCs capable to cope with the highest event rate foreseen, the PLLs and the connection pads providing the list of time tags and pixel identifiers through a serial interface. Trenches between SPADS reduce the optical cross-talk. Two to four chips could be mounted, with gaps as low as 100$\mu$m, providing 1024-2048 pixels on a physical size of several cm. Each SPAD would then have a wavelength width of $\sim 0.1 - 0.2$nm with an average detector efficiency of the order of 40%.

The width of the correlation peak, and therefore the sensitivity of the instrument, is determined by the time jitter impacting the measurements. The time jitter induced by the inter telescope time distribution can be maintained to < 10ps up to $\sim$ 10km [11]. Systematic delays between telescopes are irrelevant as long as they don't drift out of the correlation delay calculation window. The time jitters add in quadrature and if two telescopes have the same jitter the correlation peak will be wider by a factor $\sqrt{2}$. As a summary, as long as the single photon rate over the selected bandwidth is less then 10MHz, the arrival of every photon can be stamped to an absolute time accuracy of 30-50ps.

Assuming that the streams of strictly increasing timestamps from the detectors is encoded using variable-length coding and that timestamps are quantized in 20ps time-bins, the throughput is approximately 10Gbps for two VLTs and 100Gbps when the ELT is included. At Mag. 14 the throughput drops down to less than 1Gbps for all configurations. Correlating timestamps rather than waveforms requires to subtract timestamps, from two different telescopes, up to an offset equal to the duration of the correlation window. Such algorithms can be implemented in real-time either on GPUs or FPGAs, as long as the computing and data transfer capabilities are fulfilled. For a source of Mag 8, with time bins of 20ps and for an output correlation window of 100ns, the most demanding correlation requires 20TFLOPS of compute power. A small number of high performance compute units are required to implement the central correlation facility.

An intensity interferometer measures the absolute amplitude of the Fourier transform of the source image. These amplitudes can be used directly to fit model parameters (e.g. disk inclination, size, temperature profile) but the Fourier image cannot be inverted to give a 2D sky image. Indeed the correlation measures the square of the electric field and is not preserving the photon phase information. An intensity interferometer with numerous baselines gives however an extensive coverage of the u-v plane.

## 3. Science Case

In most super-massive black holes at the centre of galaxies the accretion rate is low and a low density, low collision rate, optically thin, radiatively inefficient, two temperature plasma forms. The Event Horizon Telescope has recently resolved such flows in M87 and Sgr A* [1, 13] and confirmed several aspects of the model. Particles accelerated close to the horizon of Sgr A* were detected a likely signature of the Blandford-Znajek [14] process.

When the accretion rate is higher, momentum can be dissipated by viscosity and the flow probably proceeds via geometrically thin disk-shaped structures, emitting in the optical and ultraviolet. Our main purpose is to resolve these disks to progress as the EHT did for low accretion rate systems. High resolution data could probe how concentrated is the optical emission, its size and orientation, if that emission is more concentrated than the broad line emission (in AGNs), how the temperature varies with radius, if and how the disk geometry varies.

Two cases are presented here, illustrating science goals which could be reached immediately and when ELT-class telescopes will become available.

### 3.1 Immediate goal: SS Cygni

Cataclysmic variables are made of a white dwarf accreting material from a low mass companion. The inner regions of the accretion disk are unstable, get ionised and collapse quickly (typically in weeks) on the compact object and become much brighter than the companion star. The disk then refills over several months and the process repeats few times per year. SS Cygni is a prototype system located at 114 pc and oscillating between visual magnitude of 12 and 8 a few times per year. During outburst, the bright inner disk radius probably shrinks from 10 to 1 $\mu$arcsecond, although the exact physics involved is still incomplete [15]. At its maximum brightness, the correlation peak can be detected with a signal-to-noise of 5 within minutes. Figure 1 shows the evolution of the accretion disk model of SS Cyg during an outburst (in visible light), the reconstructed interference pattern on ground, and MCMC parameter reconstruction. A baseline of few km allows to measure the disk geometry (size, inclination, temperature distribution) at the beginning of the outburst even using Cherenkov Telescopes.

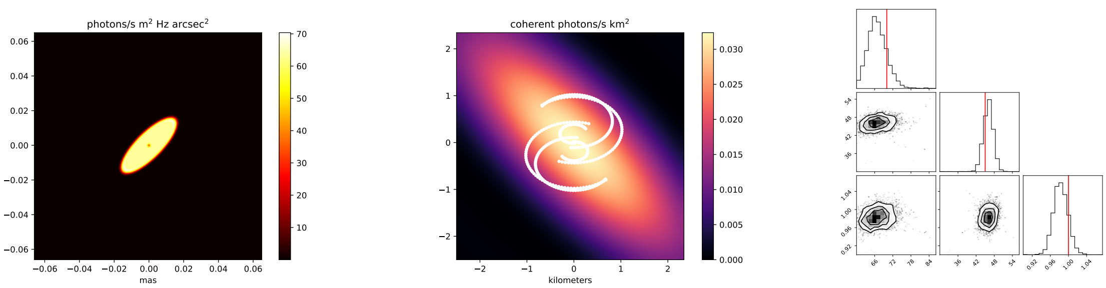


**Figure 1:** Sky image (left) and ground correlation amplitude image (middle, together with the GTC/TNG/WHT u-v plane tracks for one night, multiplied by the wavelength) of the accretion disk of SS Cygni. Right: MCMC parameter reconstruction for one night of observation assuming 1000 spectral channels (red lines are the input model parameters).

The aim of these interferometric observations is to confirm that disks-like structures indeed exist in CVs (which is already well established by tomographic/eclipse measurements) and in particular to check and constrain the predictions of the thermal-viscous instability theory on the inner disk, in term of instability radius, temperature distribution and gas dynamics, all linked to the disk viscosity and vertical structure. Interferometric and tomographic observations could be combined to provide 3D geometrical constraints.

### 3.2 Longer time goal: accretion discs of Active Galactic Nuclei

Seyfert galaxies harbour super-massive black holes surrounded by accretion disks. The brightest of them are located within 200Mpc and have apparent V magnitudes reaching 10 to 14. Even if the standard model of active galactic nuclei invokes accretion disks, little is really understood. Disks could be flows where the momentum is not advected by viscosity. Galactic dynamics and interactions as well as tidal disruption events could generate gas flows of variable momentum axis and unrelated to the central black-hole spin. Furthermore, the inner disks are dynamic structures surrounded by a complex environment made of corona, magnetic fields, winds, jets and their physics is weakly constrained by the observations. Simple quantities such as the disk size and inclination could be hard to define and various observations produce estimates varying by a factor of 10.

For instance, accretion disk sizes have been probed observationally by the study of lags between various spectral bands and by disk micro-lensing. [16] indicated that for black-hole masses above $10^7$ $M_\odot$, disk sizes are about three times larger than predicted by the thin disk theory with a lamppost geometry ($R \sim M^{2/3}$), possibly scaling as $R \sim M^{1/3}$. Contributions from other reprocessing regions, temperature fluctuations, contribution from the broad emission line region, effects of winds or more complex disk coronal model have been suggested to explain the discrepancy. Obtaining independent measurements of the size, orientation and thermal structure of accretion disks is needed to better constrain the models and our understanding of how accretion proceeds.

An observation of one night with the ELT and VLTs allows to reconstruct the disk parameters of bright Seyfert galaxies with an accuracy of 5% showing that the $\alpha$ and $\beta$ models can be easily distinguished. A few nights of observation of the quasdar 3C 273 with the same telescopes allows to measure the disk size and therefore decide if the black-hole mass is either $6.5 \times 10^9$ $M_\odot$ as evaluated from reverberation mapping or $2.6 \times 10^8$ $M_\odot$ as evaluated by from the rotation curve of the broad line region. Intensity interferometry can reconstruct parameters of AGN accretion disks and provides new constraints. Even if the results are model dependent, such observations can test the model validity, and evaluate their parameters such as black-hole masses, accretion rate, temperature gradient, orientation. Variability and obscuration could also be probed in relation to X-rays observations. Many open questions on the nature of accretion disks could be tackled in an independent way. Line emitting regions could also be imaged independently thanks to the spectroscopic capabilities of the proposed instruments. For faint galactic nuclei, the galaxy contribution should be taken into account as a background photon source and the exposure increased by the ratio of the galactic to AGN fluxes.

## 4. Discussion

A new region of parameter space could be probed with optical spectro-imaging observations approaching resolutions of milli- to $\mu$arcsecond scales. To achieve this goal the instrument concept presented here uses several technical novelties:

- multiple large scale telescopes separated by kilometers to reach a spatial resolution of $\mu$- to nano- arcsec, to resolve in the optical accretion discs around galactic and extra-galactic compact objects and black-holes.

- arrays of sensitive SPAD detectors placed behind a disperser to increase the number of independent simultaneous measurements by a large factor and to enable spectroscopic studies.
- state-of-the-art SPAD detectors, with time discriminator and deadtime optimizer electronics embedded in the detector silicon to obtain detector time resolution of the order of the natural time jitter of the atmosphere (30ps) and detector dead time much lower than the inverse of the photon counting rate.
- photon time tags produced at the telescope and made available for correlation, instead of the full wave forms, reducing the data volume by thousands.

Such instruments can be built with technologies available and ready to be used. No single telescope on Earth has the sharpness to create an optical image of a black hole or of any other compact object and of their surroundings. The Event Horizon Telescope collaboration innovated in the radio. Reaching the same spatial resolution in the optical with intensity interferometry requires a baseline of only 4km and optical telescopes around the world could reach a resolution thousand times sharper. Improving our observing capacity by orders of magnitude in any parameter is a significant step. There is simply no other credible option than intensity interferometry for realizing optical imaging at such angular resolution.

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