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From High Speed Photometry to Quantum Astronomy?

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Abstract. In the conceptual study of a possible focal plane instrument (QuantEYE) for the future OverWhelmingly Large Telescope of the European Southern Observatory, and in general for any Extremely Large Telescope, we have shown that current technology, exploited to its limits, is capable to push the time resolution of astronomical photometers towards the limits imposed by Heisenberg's principle. In conjunction with the very large luminous flux provided by these huge apertures, the astronomer will be able to detect and measure higher order correlation functions in the photon stream, acquiring for the first time direct information on the photon production mechanism inside the astrophysical source, and/or on the scattering processes in the journey of the light to the detector. We describe in this paper some applications of such instrument to astronomy, the status of a prototype (Aqueye) being built for the 182cm telescope at Cima Ekar, and a preliminary observational program for Aqueye which includes examples of planetary sciences.

Key words. high-speed photometry, extremely-large telescopes, avalanche photodiodes, photon counting, quantum optics.

1. Introduction

Current astronomical instrumentation exploits the spatial coherence (imaging) or the temporal coherence (spectroscopy) of the incoming photon stream, in other words into the intensity of the radiation coming from a given direction, in a given spectral range and polarization state. However, intensity alone is unable to distinguish among different emission mechanisms, as exemplified in Fig.1.

Beyond this first-order coherence, and encoded in the arrival times of the individual photons, lies information about the details of emission mechanisms such as stimulated emission or scattering. We recall the classic papers by Glauber, R.J., (1963a,b,c), about second and higher order correlation functions, as exemplified in Fig. 2 (see Dravins, D., et al., (2005), Dravins, D., et al., (2006), Dravins, D., (2006), Barbieri, C., (2006) for further details). In other words, when treating radiation as a three-dimensional photon gas, other effects become significant, e.g. higher-order coherence and the temporal correlation between photons, as exemplified in Fig. 2.

The bunching of photons was first measured by Hanbury Brown, R., & Twiss, R., (1956) and explained on classical bases by Purcell, E.M., (1956) in those experiments that led to the astronomical intensity interferome-

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Fig. 1. Different light sources where the photon stream leaving the source was produced by different physical mechanisms. These sources are observed with a telescope through identical spatial, spectral and polarizing filters, adjusted so that their images and spectra are identical. Thus, the first-order spatial and spectral coherence of all sources are identical, and no classical optical instrument is able to distinguish the sources from one another. The only astronomical instrument capable of distinguishing some of them was the HBT intensity interferometer, although it would not be able to identify the causes for the differences.

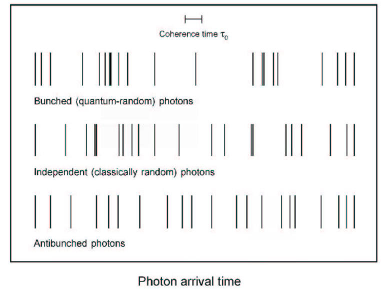

Fig. 2. Statistics of photon arrival times in light beams with different entropies. Light may carry more information than revealed by imaging and spectroscopy: Photons from a given direction with given wavelengths and polarization states provide the same astronomical images and spectra, though the statistics of photon arrival times may significantly differ. Maximum-entropy black-body radiation follows the Bose-Einstein distribution with a certain ”bunching” in time. A well stabilized laser do not show bunching but quantum photon noise. Light emitted in fluorescence resonance might show ”antibunching”, namely a purely quantum state with no classical counterpart (adapted from Loudon, 2000).

ter (in the following HBT, see Hanbury Brown, R., (1974)). Such an instrument works correctly only for sources whose emitted light is in maximum entropy, thermodynamic equilibrium state. In conclusion, different physical processes in the generation mechanisms, or in subsequent scattering processes, may cause quantum-statistical differences between light with otherwise identical spectrum, polarization, intensity, etc.

Studies of such non-classical properties of light are actively pursued in laboratory optics, but not yet in the astronomical environment, essentially for the lack of a sufficient photon flux and adequate instrumentation. To explore this new realm of information contained in the light from astrophysical sources, the diameter of the telescopes on one hand, and the time resolution and time tagging capabilities of astronomical instruments on the other, must be pushed well beyond the current values. Indeed, quantum correlation effects are fully developed over timescales equal to the inverse bandwidth of light. For example, the use of a 1 A bandpass optical filter gives a frequency bandwidth of 10^{11} Hz, and the effects are then fully developed on timescales of 10-11 seconds. Moreover, the photon flux necessary for the detection must be of the order of 1 GHz or higher; taking into account that second- and higher- order statistical functions increase with the square (and higher powers) of the intensity, the future Extremely Large Telescopes (ELTs), will provide an enormously increased sensitivity of over the existing 10 m class telescopes. Instrumentation with continuous data acquisition at such photon rates with such time resolution is not yet available, but with existing technology (albeit pushed to its limits) we are not far from that. Hopefully, it will be possible to detect the quantum effects, albeit with a decreased amplitude, also at the more manageable interval from 100 pico- to 10 nano- second on existing 10m telescopes.

Thanks to ESO, in the frame of the instrumentation for OWL, we carried out a conceptual study (QuantEYE, see Dravins, D., et al., (2005)) of the fastest time resolution photometer available to astronomy. QuantEYE can go into the domains of nanoseconds and beyond, sustaining GHz photon count-rates, thus approaching the realm of quantum optics with the capability to examine quantum statistics of photon arrival times. QuantEYE could ultimately offer a fundamentally novel information channel for astronomy.

In addition to quantum properties of light, Quanteye on ELTs will enable detailed studies of phenomena such as variability close to black holes; surface convection on white dwarfs; non-radial oscillation spectra in neutron stars; fine structure on neutron-star surfaces; photon-gas bubbles in accretion flows; possible free-electron lasers in the magnetic fields around magnetars. Photon-correlation spectroscopy will enable spectral resolutions R exceeding 107, as probably required to resolve laser-line emission around sources such as Eta Carinae. Furthermore, given two distant ELTs, QuantEYE would permit a modern realization of the Hanbury Brown - Twiss intensity interferometer (see Ofir, A. & Ribak, E.N., (2006a), Ofir, A. & Ribak, E.N., (2006b)), with much superior performances of the Narrabri realization. A more complete description of the astrophysical problems that can be tackled by QuantEYE can be found in Dravins, D., et al., (2006).

On the technical side, QuantEYE was designed (Barbieri, C., et al., (2006a), Naletto, G., et al., (2006)) taking into account the characteristics which were foreseen in 2005 for the 100 meter OverWhelmingly Large (OWL) telescope of the European Southern Observatory (ESO). Although the final OWL design will differ from these adopted characteristics, our concept maintains its full scientific appeal, and can be easily adapted to different ELTs.

The concepts developed for Quanteye can be adapted to more conventional high-speed astrophysical problems, using even small telescopes as described in the following and in the accompanying poster (Barbieri, C., et al., (2006)) about Aqueye, the prototype being built for the 182cm telescope at Asiago.

2. QuantEYE Basic Opto-Mechanical Design

The QuantEYE basic optical design was driven by two main considerations. First, the OWL telescope characteristics and performance at the date of the study, namely a 100 m aperture with an f/6 final focal ratio, and 6 mirrors. The f/6 focus was fully corrected for geometric aberrations and limited by seeing (in the absence of an adaptive optics system). On the basis of the experience with large telescopes in "normal" seeing conditions, we assumed that OWL would be able to concentrate a large fraction of the light coming from a point-like source at infinity within a 1 arcsec image over a fairly satisfactory percentage of the observing time. Owing to the 600 m telescope focal length, 1 arcsec field of view gives a 3 mm diameter focal spot.

The second factor was the limited selection of available very fast photon counting detectors. We concentrated our attention to the single photon avalanche photodiodes (SPADs, see Cova, S., et al., (2004), because of their excellent time tagging capability and good quantum efficiency. Unfortunately, CCD-type SPADs do not yet exist. The available SPAD "arrays" consist at most of active cells separated by dead zones, because of optical cross-talking problem among contiguous cells when high speed detection is required. Furthermore, each SPAD is characterized by a dead time which can be as high as 300 ns, and by a non-negligible probability of spurious pulses after a valid detection. To overcome these limitations, we decided to use a sort of distributed detector array, that is a sparse array of single SPADs. After this choice, the instrument optical design followed as a consequence, namely a collimation of the beam after the OWL focus, and a subdivision of the pupil into N×N sub-pupils, each of them focused on a single SPAD, thus giving a total of N2 SPADs (see Fig. 3 and Fig. 4). In this way, since the "distributed array" is essentially sampling the telescope pupil, a system of N2 parallel smaller telescopes is realized, each one acting as a fast photometer (i.e. with no imaging capability).

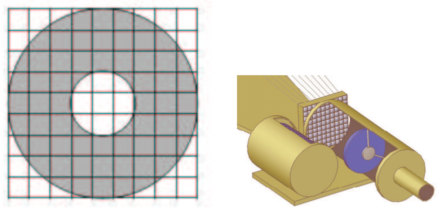

Fig. 4. Left: the 10×1l0 pupil slicing concept. The non-illuminated detectors are used for dark and spurious count statistics. Right: a 3D view of the focal reducer/collimator. Light entering the baffle cone is collimated by the telescope and is collected by the N×N lenslet array. Each lenslet is coupled to a single SPAD via optical fibers. The cylinder on the side of the telescope is the box accommodating the stack of filters and polarizers.

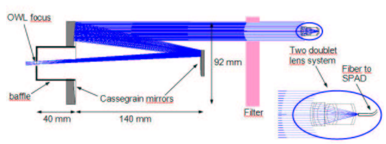

Fig. 3. The baseline optical concept for QuantEYE. (a) The collimator-lenslet system magnifies 1/60 times (collimator focal length = 600 mm, lens focal length = 10 mm), giving a nominal spot size of 50 μm for a 1-arcsec source. For sake of simplicity, only one lenslet of the whole 10×10 array is shown.

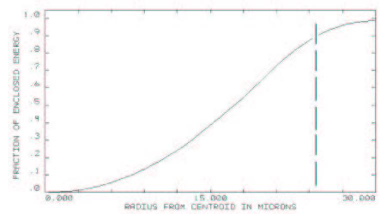

Fig. 5. Extended source encircled energy plot: percentage of energy falling within a circle of given radius for a uniformly illuminated 1arcsec extended circular source. The vertical dashed line indicates the 50μm radius of the fiber core.

The collimation is produced by an inverse Cassegrain telescope with 600 mm focal length and 100 mm diameter (f/6), placed after the focus of the telescope (see Fig. 3). After collimation, the radiation beam has an annular shape of about 100 mm radius. Here, filters and/or polarizers, stacked in a suitable location on the telescope side, can be inserted (see Fig. 4). The filtered beam is then collected by a 10 × 10 lenslet array sampling the instrument pupil. Each lenslet is an f/1 *ad-hoc* compound system of two spherical doublets with a $10 \times 10 mm^2$ section and 10 mm focal length. The 1/60 demagnification of this system reduces the 3 mm diameter (1 arcsec) focus of OWL to 50μm, corresponding to the baseline SPAD active area, either through an optical fiber link or another optical relay. Fig. 5 shows the plot of the extended source encircled energy. About 90% of the 1 arcsec source energy falls within the 50μm diameter of the fiber core. In this simulation, the extended source is assumed to have a uniform intensity: since in the real case the illumination distribution is of Gaussian type, we expect a still higher percentage of energy flux entering the fiber.

The instrument working spectral range is 400-900 nm. In this spectral region, SPADs exist with a quantum efficiency better than 40%, with very good timing accuracy (better than 100 ps), and with very low dark count rate (of the order of 50 c/s): putting together the 100 SPADs, a photon counting rate up to 1 GHz can be obtained. A second moving detector head, which can span the whole 3 arcmin scientific field of OWL, was also foreseen to observe a comparison star. The proposed solution of sampling the telescope pupil and saving in 10×10 parallel channels the photon information, greatly reduces the limiting dead time problem of the detectors: in such a way a fixed-area very high speed photometer with a tremendous dynamic range, from the 5th to the 30th stellar magnitude, a factor 10^{10} in brightness, can be obtained. In addition, it is likely that in the next few years the development of new detectors and new optical clocks can push the time resolution into the picosecond region for several hours of continuous operation. Other non-imaging optical designs (e.g. enlarging the acceptance field to 1".2, or using 3:1 tapered fibers, or entirely avoiding the optical fibers), have been studied and shown feasible. Some consideration was also given to the possibility of realizing an "imaging" detector in the absence of a CCD-type SPAD array, which seems far from being realized. Two designs we have considered, based on the availability of "granular" arrays of SPADs, namely a number of individual detectors integrated on the same Silicon wafer or on a mosaic of wafers. As a general comment, an imaging solution should consider the need of inserting the very narrow filters without degradation. We refer for details to Naletto et al., 2006.

In order to preserve its great amount of data, QuantEYE has a central storing unit with a minimum capacity of 50 Terabytes, connected to an a-posteriori analysis system with a high bandwidth transport channel. The arrival time of each photon is given as input to an asynchronous post-processor which guarantees data integrity for the following scientific investigation. This a-posteriori processing unit is a cluster of CPUs. Specific parallel algorithms will work together, optimizing the computations of the high order correlation functions between the time tagged photons. Furthermore, it was foreseen the capability to perform real time correlation functions among different detectors (on-line correlation unit), as shown in Fig. 6. The number of detectors to be analyzed in real time depends on the computational power of reprogrammable logic circuits and processors, which is connected to the technological progress of CPUs, FPGAs (Field Programmable Gate Arrays) and ASIC (Application-Specific Integrated Circuits),

A final consideration is relative to the analysis of the huge, multidimensional data base generated by QuantEYE. The necessary computational power is really large, and new algorithms have to be developed. In the near future, quantum computers with novel quantum algorithms might be available, greatly improving the computational capabilities (see Fig. 7).

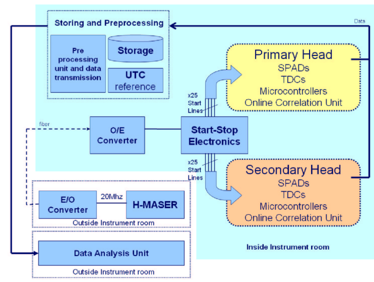

Fig. 6. The overall electronic scheme.

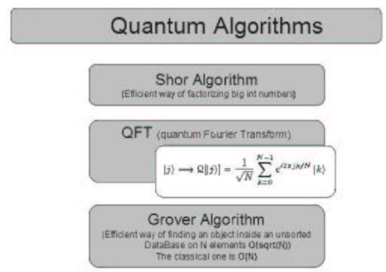

Fig. 7. Already developed quantum algorithms.

3. AquEYE for Asiago

We are currently constructing a first prototype of QuantEYE for the Asiago-Cima Ekar 182cm telescope, a prototype we call Aqueye (Asiago Quantum Eye). Details are provided in the accompanying paper by Barbieri, C., et al., (2006b). This telescope offers us a good availability of observing time, and excellent environment, from the mechanical shop to clean areas to control rooms. A further advantage of the 182 cm is the existing spectrograph AFOSC, which can be easily adapted to our goals. AFOSC is mounted on a flange which takes care of many observational needs, from pointing and guiding to field vision and rotation, etc. At the exit of AFOSC we can mount a simple pyramidal mirror which divides the pupil in 2x2 portions, each of them imaged on its own SPAD.

As detectors, we have selected the 50μm SPADs produced by the Italian firm MPD. According to the data sheet, their quantum efficiency in the visible band is better than 45%, the dead time is around 50 nanoseconds, the time tagging capability is better than 50 picoseconds, and the afterpulsing probability is less than 1%. We plan to characterize each detectors using the facilities available at Catania Observatory. An important simplification of Aqueye is the possibility to feed the SPADs without the need of the optical fibers, which were motivated in Quanteye by the difficulties to couple the very large pupil segments to the small dimensions of the detector. In this case we can feed directly the SPADs and still retain an excellent energy concentration over the 50 micron diameter, from the blue (420 nm) to the red (700nm). Furthermore, to simplify the construction of the Aqueye, we shall not build the second movable head foreseen in Quanteye. The electronic scheme is based on available commercial boards (Time to Digital Converters) used also at CERN.

We now come to the crucial question of generating and maintaining a very accurate time for minutes and even hours. First of all, the start/stop commands will be tied to the UTC by means of the GPS or Galileo Navigation Satellite Sistem (when available) signals, so that the data can be referred to a common time scale adopted by all telescopes on the ground or in space (we recall the scientific interest of correlations with X-ray and Gamma ray timing). However, we have to overcome the jitter that both for GPS and GNSS is at the level of ten nanoseconds or so. Taking into account that the available resources are fairly scanty, the 'best' clock is still under investigation, with the help of experts in INRIM Torino and INAF Cagliari. Furthermore, we shall perform experiments to tie to a common reference, to better than 100 picoseconds, the clock in Asiago with a twin clock at the telescope Vega of Lubljana Observatory. This activity is sees as a practical demonstration of time distribution to very distant observers, in view of Very Long Baseline intensity interferometry. Aqueye will fulfill two purposes. On one side, it will be a technological demonstrator (the 182 cm telescope is too small to reveal quantum properties of light). On the other side, it will permit very high time resolution on a variety of astrophysical problems. To see its capabilities, we provide in Table 1 and Table 2 an overview of the expected characteristics and performances.

Table 1. Basic instrumental data

Telescope effective area: $2.3 \times 10^5 cm^2$
effective area of each of the 4 channels: $5.3 \times 10^3 cm^2$
total transmissivity (2 mirrors +1 pyramid + 8 lenses): 0.62
detector quantum efficiency at 556 nm : 0.45
20 nm wide band filter centered at 556nm, with av. transm. 0.50

Table 2. Expected count detection in the V band

V Magnitude	Counts/s	Mean Time between 2 counts
0	1.31×10^8	7.6 ns
5	1.31×10^6	0.76 μs
10	1.31×10^4	0.76 ms
15	1.31×10^2	76 ms
20	1.31×10^0	0.76 s

The average dead time of each SPAD is 70 ns, so that the maximum count rate is 14 MHz. On the bright side, the linear regime will start around the 2nd magnitude. The dark counts are approximately 50/s, corresponding to a 16th magnitude star. Finally, the sky background as seen through a 3 arcsec diameter is equivalent to a 17th magnitude star. In conclusion, Aqueye can be used to monitor several astrophysical objects. The time resolution improvement with respect to existing photometers will provide important confirmations for previous studies and probably will bring us to the discovery of new astrophysical phenomena. In the following we give a short description of three possible programs of planetary sciences interest.

3.1. Stellar occultations by the Moon, asteroids, and Kuiper-Belt Objects

Occultations are a powerful instrument even on small and medium size telescopes not only for providing astrometric information (diameters, duplicity, etc.), but also for astrophysical considerations. See Richichi, A., (2003), Richichi, A., (2004a), Richichi, A., (2004b) for a general

Table 3. Fresnel fringes typical length, angular and time scales

Object	x(m)	Ψ (arcsec)	τ (sec)
Moon	10	0.005	0.012
Main Belt Asteroid	273	0.00019	0.018
Kuiper Belt Object	1220	0.000043	0.1776

discussion. In the visible region, the Fresnel diffraction fringes produced by occultations by the Moon, or by a Main Belt asteroid or by a Kuiper Belt Object have a typical length x, angle Ψ and duration time τ given in the following Table 3:

We concentrate our attention on Main Belt Asteroids and Kuiper Belt Objects Occultations (see e.g. Roques F. & Moncuquet, M. (2000)). Star occultations by main-belt asteroids occur frequently: about 300 asteroids occultation events by background stars up to 12th magnitude are foreseen each year, see http://sorry.vse.cz/ ludek/mp/world/mpocc1. Given their large distance, the asteroidal shadow pattern on the Earth is similar to its size (from few to hundreds km). The KBO occultations give an accurate diameter evaluation, and allow to search for possible atmospheres and for binary companions. Moreover, if an occultation is observed at different wavelengths, the profiles are different and their comparison could give information on the Fresnel scale, and then on the *distance of the occulting object*.

3.2. Exoplanets near their parent star

An important application of high temporal resolution (both relative and absolute) photometry measurements concerns the study of extrasolar planets. In particular, we propose to analyze the transit of extrasolar giant planets (few are already known, however in the next months the number of transits is foreseen to increase considerably thanks to the several space missions, such as COROT). The high temporal precision and the high photometric precision will allow us to obtain the orbital parameters of the transiting planets with high accuracy. However, the most interesting and innovative

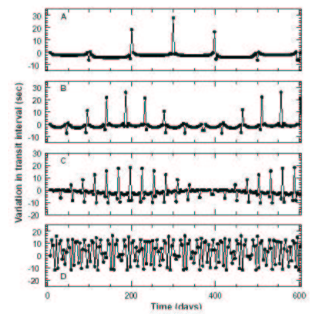

Fig. 9. Variation of the transit instants due to terrestrial size planets.

application concerns the study of transits of the same planet over the time, for several months. A comparative study of the light curves of consecutive transits will allow the detection of small variation of the orbital elements of the planets (semi-major axis and eccentricity, see Holman, M.J., & Murray, N.W., (2005)). These variations may be linked to the presence of nearby planets not detectable with the current techniques. Thanks to the high temporal and photometric precision, we think we may be able to detect planets with Earth-like masses, by studying the transit timing of much larger -Jupiter-like- planets. Although this method has a general validity, we will focus -in a preliminary stage- on the study of “hot Jupiters”, namely giant planets having very small semi-major axes (< 0.1 AU) and period of the order of some days. This is because they allow the detection of orbital perturbations on short time scales. Notice that vast resources are being invested in the discovery of Earth-like planets. Most of these researches are based on the transit technique. On the contrary, we propose to detect terrestrial planets - not necessarily transiting!- with the aid of high precision temporal measurements using a technology already available.

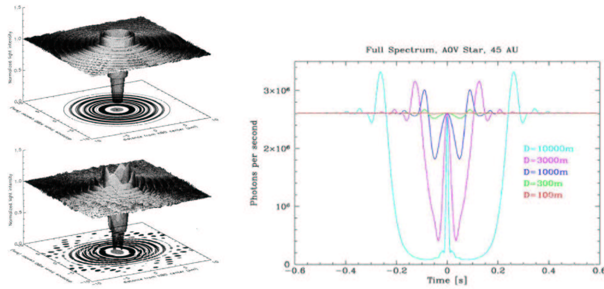

Fig. 8. Left: The shadow pattern of a 1-km radius KBO in front of a point star. The two horizontal axes are in km, and the vertical axis is the normalized stellar flux. Top: Circular KBO; Bottom: Irregular and elliptical object. The grey central spot indicates the geometrical shadow of the KBO. Right: KBO object occultation pattern as function of the KBO diameter (from 10 to 0.1 km) for an A0 V star at 45 AU.

3.3. Temporal structure of the sky background and atmospheric intensity scintillation

Another area essentially unknown is the behavior of the Earth atmosphere at frequencies above few KHz (e.g. Dravins, D., et al., (1997) and following). The night sky is not constant, and has contributions from, e.g., nanosecond-duration flashes of Cherenkov light induced by high-energy gamma rays (being studied by large light collectors); faint but numerous meteors, or fluctuations in background nightglow from aurorae. The scintillation originates as varying illumination sweeping across the entrance pupil, and is independent of how precisely that light is later focused.

These cited examples demonstrate that our instrument Aqueye may provide important results in different fields of current astrophysics.

4. Conclusions

AquEYE should be put in operation toward the end of 2006. The subsequent goal is to define an upgraded version to be brought to existing 8-10m telescopes, such as the VLT and the LBT. In particular, the two mirrors of LBT would allow to perform a modern version of the HBT Intensity Interferometer with a 100-fold improved sensitivity, thanks to the augmented quantum efficiency, the much higher electrical bandwidth, the higher collecting area, the much superior optical quality of the telescopes. Finally, consideration will be give to the possibility to mount a quantum detector in the central pixel of the Cherenkov light collector MAGIC on the Roque, as a precursor for a ELT.

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References

Barbieri, C. 2006, Verso una nuova astronomia ai limiti quantistici?, VI Seminario Annuale di tecnologia del'Informazione, Atti Accademia Galileiana Patavina

Barbieri, C., Naletto, G., Occhipinti, T., Tamburini, F., Giro, E., D'onofrio, M., Sain, E., & Zaccariotto, M. 2006, this volume

Barbieri, C., Dravins, D., Occhipinti, T., Tamburini, F., Naletto, G., Da Deppo, V., Fornasier, S., D'onofrio, M., Fosbury, R.A.E., Nilsson, R., & Uthas, H. 2006a, J. of Modern Optics, 1, 1

Barbieri, C., et al. 2006b, Galway Conference on High Time Resolution Astrophysics, NUI Galway, June 2006

Barbieri, C. et al. 2006c, this volume

Cooray, A. 2003, ApJ, 589, L97

Cova, S., Ghioni, M., Lotito, A., Rech, I., & Zappa, F. 2004, J. of Modern Optics, 51, 1267

Dravins,D., Lindegren,L., Mezey, E.,& Young, A.T. 1997, PASP, 109, 173

Dravins, D., Barbieri, C., Da Deppo, V., Faria, D., Fornasier, S., Fosbury, R.A.E., Lindegren, L., Naletto, G., Nilsson, R., Occhipinti, T., Tamburini, F., Uthas, H., & Zampieri, L. 2005, QuantEYE. Quantum Optics Instrumentation for Astronomy, OWL Instrument Concept Study, ESO document OWL-CSR-ESO-00000-0162

Dravins, D., Barbieri, C., Fosbury, R. A. E., Naletto, G., Nilsson, R., Occhipinti, T., Tamburini, F., Uthas, H., & Zampieri L. 2006, Astronomical Quantum Optics with Extremely Large Telescopes, in P.Whitelock, B.Leibundgut, M.Dennefeld, eds. ”The Scientific Requirements for Extremely Large Telescopes”, IAU Symposium 232, Cambridge University Press, pp.502-505.

Dravins, D. 2006, Galway Conference on High Time Resolution Astrophysics, NUI Galway, June 2006

Glauber, R.J. 1963a, Phys. Rev. Letters, 10, 84

Glauber, R.J. 1963b, Phys. Rev., 130, 2529

Glauber, R.J. 1963c, Phys.Rev., 131, 2766

Hanbury Brown, R., & Twiss, R. 1956, Nature, 177, 27

Hanbury Brown, R., The intensity interferometer. Its applications to astronomy, Taylor & Francis, London, 1974

Holman, M.J., & Murray, N.W. 2005, Science, 307, 1288

Naletto, G., Barbieri, C., Dravins, D., Occhipinti, T., Tamburini, F., Da Deppo, V., Fornasier, S., D'Onofrio, M., Fosbury, R.A.E., Nilsson. R., Uthas, H., & Zampieri, L. 2006, QuantEYE: A Quantum Optics Instrument for Extremely Large Telescopes, In: Ground-Based and Airborne Instrumentation For Astronomy, SPIE Proc. Vol. 6269. In press

Ofir, A., & Ribak, E.N. 2006a, MNRAS, 368 (4),1646

Ofir, A., & Ribak, E.N. 2006b, MNRAS, 368 (4),1652

Purcell, E.M. 1956, Nature, 178, 1449

Richichi, A. 2003, A&A, 397, 1123

Richichi,A. 2004a, Combining Optical Interferometry with Lunar Occultations, in: Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, Proc. of the Workshop held 20-24 October 2003 in Dubrovnik, Croatia. Edited by R. W. Hidlitch, H. Hensberge and K. Pavlovski. ASP Conference Series, Vol. 318. San Francisco: Astronomical Society of the Pacific, 2004, p. 148-156

Richichi,A. 2004b, Interferometry and Lunar Occultations: Status and Prospects of Ground-based Milliarcsecond Resolution Observations, in: The Environment and Evolution of Double and Multiple Stars, Proceedings of IAU Colloquium 191, held 3-7 February, 2002 in Merida, Yucatan, Mexico. Edited by Christine Allen & Colin Scarfe. Revista Mexicana de Astronoma y Astrofsica (Serie de Conferencias) Vol. 21, pp. 247-250

Roques, F., & Moncuquet, M. 2000, Icarus, 147, 530