Quantum
Astronomy
and ELTs

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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LUND

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Main topics of the talk

1. The shortest time domain
2. Quantum properties of (non-thermal) light
3. Intensity interferometry
4. New detectors
5. Precursors to Quanteye
6. Precursors to ELTs
The shortest time domain

Astronomy expands by pushing parameter envelopes, e.g.
  . in wavelength
  . in spatial resolution

Future:

Very High-Time Resolution Astrophysics to Reach Non-thermal processes and ‘Quantum’ properties of light, and perform VLB Optical Intensity Interferometry?
The giant pulses observed from 0.4 to 8.8 GHz with nanosecond resolution are the brightest pulses in the Universe. The source must be smaller than 1 meter in size!


From milliseconds

- Pulsars
- Quasi-periodic oscillations
- Lunar and stellar Occultations
- Milli-, micro- and femto-lensing
- Accretion instabilities
- Photon-gas effects
- Neutron-star oscillations
- Photon emission mechanisms
- Coherent radiation bursts
- Photon quantum statistics
- Etc.

To nanoseconds

04 May 2006
Quantum optics in astronomy - 1

Photons are more complex than is generally appreciated! Light may carry more information than that revealed by imaging and spectroscopy!

• Classical astrophysics merges all radiation of a certain wavelength into the quantity "intensity". When instead treating radiation as a three-dimensional photon gas, other effects also become significant, e.g. higher-order coherence and the temporal correlation between photons.

• Glauber (1963a, 1963b) showed that an arbitrary state of light can be specified with a series of coherence functions essentially describing one-, two-, three-, etc. -photon-correlations with respect to position $r$ and time $t$. 
Quantum optics in astronomy - 2

• These quantum correlation effects are fully developed over timescales equal to the inverse bandwidth of light. For example, the use of a 1 Å bandpass optical filter gives a frequency bandwidth of $10^{11}$ Hz, and the effects are then fully developed on timescales of $10^{-11}$ seconds. Instrumentation with such continuous resolutions is not yet available, but it is possible to detect the effects, albeit with a decreased amplitude, also at the more manageable 100 picosecond timescales.

• The largest possible flux of photons is then necessary: Extremely Large Telescopes are absolutely needed to bring non-linear optics to astronomy.
## Advantages of very large telescopes

<table>
<thead>
<tr>
<th>Telescope diameter</th>
<th>Intensity (\langle I \rangle)</th>
<th>Second-order correlation (\langle I^2 \rangle)</th>
<th>Fourth-order photon statistics (\langle I^4 \rangle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 m</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8.2 m</td>
<td>5</td>
<td>27</td>
<td>720</td>
</tr>
<tr>
<td>4 x 8.2 m</td>
<td>21</td>
<td>430</td>
<td>185,000</td>
</tr>
<tr>
<td>50 m</td>
<td>193</td>
<td>37,000</td>
<td>1,385,000,000</td>
</tr>
<tr>
<td>100 m</td>
<td>770</td>
<td>595,000</td>
<td>355,000,000,000</td>
</tr>
</tbody>
</table>

With ELTs, Quantum Astronomy could thus be a fundamentally new information channel to the Universe.

04 May 2006
First order correlation function - 1

Suppose we have a light source oscillating at frequency $\nu$. The temporal coherence of light is quantified by the first order correlation function:

$$g^{(1)}(\tau) = \frac{\langle \alpha^*(t)\alpha(t+\tau) \rangle}{\alpha_0^2}$$

whose modulus is also equal to the fringe visibility:

$$|g^{(1)}(\tau)| = V(\tau) = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

In the ideal case of a perfectly sinusoidal wave of constant amplitude, the visibility function is always $= 1$, and the first order correlation function is totally independent of $\tau$ (infinite coherence time). More realistically, the signal will have some (even small) spread $\Delta \nu$ in frequency around the central frequency $\nu$, which we can approximate with a Gaussian function in the frequency domain, giving:

$$g^{(1)}(\tau) = e^{-\pi \Delta \nu^2 \tau^2 / 2}$$

In other words, the first order correlation function is a Gaussian function of $\tau$ whose width is inversely proportional to the frequency spread: for a broad spectrum the correlation time becomes very short.

Any realization of a photometer, spectrometer and Michelson type interferometer measures some properties of this first order correlation function (see next slides).
First order correlation function - 2

D. Dravins, ESO Messenger 78, 9 (1994)

Thus, classical measurements do not distinguish light sources with identical $g^{(1)}$. All such measurements can be ascribed to quantities of type $E^*E$, corresponding to intensity $I$, which in the quantum limit means observations of individual photons or of statistical one-photon properties. Thus possible multi-photon phenomena in the photon stream reaching the observer are not identified, not even in principle.

All classical optical instruments measure properties of light that can be deduced from the first-order correlation function of light, $g^{(1)}$, for two coordinates in space $r$ and time $t$. The different classes are collected in this Figure, where $E$ is the amplitude of the field, $<>$ denotes time average, and * complex conjugate.
Therefore, conventional optical instruments, like photometers, spectrometers, polarimeters or interferometers, are capable of measuring properties of light such as its intensity, spectrum, polarization or coherence. However, such properties are generally insufficient to determine the physical conditions under which light has been created.

Thus it is not possible, not even in principle, to distinguish between e.g. spontaneously emitted light reaching the observer directly from the source; similar light that has undergone scattering on its way to the observer; or light predominantly created through stimulated emission, provided these types of light have the same intensity, polarization and coherence as function of wavelength. The deduction of the processes of light emission is therefore made indirectly via theoretical models.

Yet, such types of light may have quantum-statistical differences regarding collective multi-photon properties in the photon gas. Such properties are known for light from laboratory sources and, might ultimately become experimentally measurable also for astronomical sources.
Second order correlation function - 1

The description of collective multi-photon phenomena in a photon gas requires a quantum-mechanical treatment since photons have integer spin, and therefore constitute a boson fluid with properties different from a fluid of classical distinguishable particles. A simplified expression for the second-order correlation function is given in the next figure. It describes the correlation of intensity between two coordinates in space and time.

With respect to time, the second order correlation function is defined by:

\[ g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle^2} = g^{(2)}(-\tau) \]

Notice also that the second order correlation function is not bounded between 0 and 1. At \( \tau = 0 \) it is easy to show that:

\[ g^{(2)}(0) = \frac{\langle I(t)I(t) \rangle}{\langle I(t) \rangle^2} = \frac{\Delta^2}{\langle I \rangle^2} + 1 \geq 1 \]

\[ \frac{\langle I(t)I(t+\tau) \rangle^2}{\langle I(t)^2 \rangle \langle I(t+\tau)^2 \rangle} \leq 1 \]
Second order correlation function - 2

For ergodic or time stationary systems the two terms at the denominator are equal, consequently we must have:

\[ g^{(2)}(\tau) \leq g^{(2)}(0) \]

for all time delays. For a perfectly stable wave, the sign = applies, so that:

\[ g^{(2)}(\tau) = g^{(2)}(0) = 1 \]

For any classical wave the degree of coherence should also be less than \( g^{(2)}(0) \). This result is contradicted for quantum states of light. If the distribution of photons is chaotic, i.e. the photon gas is in a maximum entropy state, the second-order coherence \( g^{(2)} \) can be deduced as \( g^{(2)} = [g^{(1)}]^2 + 1 \). This property can be used to determine \( |g^{(1)}| \) from measurements of \( g^{(2)} \).
In thermodynamic equilibrium, the chaotic distribution of photons corresponds to the value $g^{(2)} = 2$ for first-order coherent [$g^{(1)} = 1$] light. Such photons follow a Bose-Einstein distribution, analogous to a Maxwellian one for classical particles. However, away from equilibrium, photons may deviate from Bose-Einstein distributions (just as classical particles can be non-Maxwellian). For example, light created by stimulated emission in the limiting case of a stable wave without any intensity fluctuations has $g^{(2)} = 1$, corresponding to analogous states in other boson fluids, e.g. superfluidity in liquid helium. Chaotic light scattered against a Gaussian frequency-redistributing medium has $g^{(2)} = 4$. In the laboratory, one can observe how the physical nature of the photon gas gradually changes from chaotic ($g^{(2)} = 2$) to ordered ($g^{(2)} = 1$) when a laser is "turned on" and the emission gradually changes from spontaneous to stimulated. Measuring $g^{(2)}$ and knowing the laser parameters involved, it is possible to deduce the atomic energy level populations, which is an example of an astrophysically important parameter (non-LTE departure coefficient) which cannot be directly observed with classical measurements of one-photon properties. Just as it is not possible to determine whether one individual helium atom is superfluid or not, it is not possible to determine whether one individual photon is due to spontaneous or stimulated emission: both cases require studies of statistical properties of the respective boson fluid.
Fundamental quantities measured in two-photon experiments. All such measurements can be ascribed to quantities of type $I^*I$, i.e. intensity multiplied by itself, which in the quantum limit means observations of pairs of photons or of statistical two-photon properties.

In the intensity interferometer (HBT) this is measured for $r_1 \neq r_2$ but $t_1 = t_2$: $<I(0,0) I(r,0)>$, thus deducing angular sizes of stars, reminiscent of a classical interferometer.

For $r_1 = r_2$ but $t_1 \neq t_2$ we instead have an intensity-correlation spectrometer, which measures $<I(0,0) I(0,t)>$, determining the spectral width of e.g. scattered laser light.
Many different quantum states of optical fields exist, not only those mentioned above which can be given classical analogs, but also e.g. photon antibunching which with $g^{(2)} = 0$ is a purely quantum-mechanical state. This implies that neighboring photons "avoid" one another in space and time. While such properties are normal for fermions (e.g. electrons), which obey the Pauli exclusion principle, ensembles of bosons (e.g. photons) show such properties only in special situations. An antibunching tendency implies that the detection of a photon at a given time is followed by a decreased probability to detect another immediately afterward.
Photons from given directions with given wavelengths give the same astronomical images and spectra, though the light may differ in statistics of photon arrival times. These can be "random", as in maximum-entropy black-body radiation (Bose-Einstein distribution with a certain "bunching" in time), or may be quite different if the radiation deviates from thermodynamic equilibrium.
Photon statistics and antibunching

PHOTON STATISTICS IN GAUSSIAN AND LASER SOURCES


H. Kimble, M. Dagenais, L. Mandel

Photon Antibunching in Resonance Fluorescence


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Quantum-Optical Spectroscopy

Classically identical spectral lines may differ in photon statistics.
Some examples

The different statistical properties of thermal and laser laboratory sources

Right: the very different autocorrelation function of a normal star and of the continuum of the Crab star, down to microsec resolution
Data taken at Skinakas Observatory 1.3 m telescope, Oct. 2004; OPTIMA (MPE) + QVANTOS Mark II (Lund)

04 May 2006
Cosmic Lasers in Action

- The invention of the laser can be dated to 1958 with the publication of the scientific paper, Infrared and Optical Masers, by Arthur L. Schawlow, then a Bell Labs researcher, and Charles H. Townes, a consultant to Bell Labs. The first successfully optical laser was (probably) constructed by Maiman (1960).

- The first astrophysical maser was discovered in 1965-68 in Orion (the OH 18 cm)

- A (too) early paper on optical astronomical laser:

Abstract: The radiative transfer equation is written in microscopic form, and from some simplifications on the ratio of occupation numbers for upper and lower level, a laser action is suggested.
**Cosmic laser/maser sources**

Two review papers:


  **Abstract:** A brief account is given of the discovery of the astronomical maser and laser effects in OH radicals and in molecules of water (H2O), carbon monoxide and dioxide (CO and CO2), ammonia (NH3), methyl alcohol (CH3OH), formaldehyde (CH2O), and silicon oxide (SiO). A detailed table is given of all the currently known molecular stimulated-emission lines.

**Natural CO2 IR-lasers in Mars and Venus atmospheres (1983)**


Nonthermal emission occurs in the cores of the 9.4- and 10.4-μm CO2 bands on Mars, and has been recently identified as a natural atmospheric laser. The emission is believed to be excited by absorption of solar flux in the near-IR CO2 bands, followed by collisional transfer to the 00°1 state of CO2.

Caption to lower Figure: the blue profile is the total emergent intensity in the absence of laser emission. Red profile is gaussian fit to laser emission line. Radiation is from a 1.7 arc second beam (half-power width) centered on the subsolar point.

*The construction of large-volume radiation-pumped lasers, which utilize CO2 planetary mesospheres as a gain medium, is theoretically possible (SETI?).*

Abstract: I draw attention to a maser which occurs within the ground term of Fe (10+). In many photoionized environments, infrared fine-structure lines and the forbidden O I 6300 Å line become optically thick but maser amplification of ionic fine-structure lines is unusual. During the course of development of a code designed to simulate gas under radiative-collisional equilibrium, the radiative transfer of roughly 500 ionic/atomic emission lines was treated using escape probabilities. Nearly all forbidden lines can become optically thick under extreme conditions, but the $3P_j = 1, 0$ forbidden Fe XI 6.08 micron transition is the only line which routinely mases and can reach optical depths smaller than -5.

Maser effects can alter the intensity ratio of the infrared line relative to $3P_j = 2, 1$ 7892 Å by 1/2 order of magnitude under certain conditions. A model of the coronal line region of Nova Cyg 1975 is presented, which illustrates the effects of this maser.
Observations with HST have identified a gas cloud that acts as a natural ultraviolet laser, near the huge, unstable Eta Carinae - one of most massive and energetic stars in our Milky Way. The interstellar laser may result from Eta Carinae's violently chaotic eruptions, in which it blasts parts of itself out into space, like an interstellar geyser. (analysis by S. Johansson, a specialist in atomic spectroscopy at the University of Lund in Sweden, of HST observations made with the Goddard High-Resolution Spectrograph).
Laser Emission in Eta Carinae - 2

See the Paper: astro-ph/0501246, 13 Jan 2005:
S. Johansson, V.S. Letokhov: *Possibility of Measuring the Width of Narrow Fe II Astrophysical Laser Lines in the Vicinity of Eta Carinae by means of Brown-Twiss-Townes Heterodyne Correlation Interferometry*

A high-resolution image of Weigelt's blob in Eta Car, obtained with the VLT NACO in the L’ band (≈ 3.8µm), from Chesneau et al., 2005)
Other possible lasing mechanisms in cosmic sources: Random-laser and free electron laser emission


A free-electron laser consists of an electron beam propagating through a periodic magnetic field (CRAB Nebula?). The situation is not much different from what occurs in synchrotron radiators, however a lasing effect can be generated when the magnetic field and the radiation combine to produce a beat wave (called a ponderomotive wave) that travels slower than the speed of light and can be in synchronism with the electrons.

The lased light can be of any wavelength from the IR to the UV to the X-rays.
3 - The Intensity Interferometer

The correlation or *intensity* stellar interferometer was invented in about 1954 by R. Hanbury Brown and R. Q. Twiss. A large interferometer was completed in 1965 at Narrabri, Australia, and by the end of the decade had measured the angular diameters of more than 20 stars, including main sequence stars. Each 'mirror' is a mosaic of 252 small hexagonal mirrors, 38 cm (made by Officine Galileo in Florence). The focal lengths were selected to make the large mirrors approximate paraboloids. Great optical accuracy was not sought, since it was only required that the starlight be directed onto the photocathodes.

The light-gathering power of the 6.5 m diameter mirrors, the detectors, electronics etc. allowed the Narrabri interferometer to operate down to magnitude $+2.0$ (30 or so stars).
The correlator

The two 'mirrors' directed the starlight to two photomultipliers (RCA Type 8575, photocathode 42 mm diameter, stellar image about 25 mm). The starlight was filtered through a narrow-band interference filter. The most-used filter was 443 nm ± 5 nm.

The photocurrent is a measure of the total intensity, required for normalizing the correlation coefficient. The photocurrent is sent to a wide-band amplifier, then through a phase-reversing switch, and then through a wide-band filter that passes 10-110 MHz. The signals from the two photomultipliers then are multiplied in the correlator in that frequency range.

This bandwidth excludes seeing frequencies, thus eliminating their effects.
Signal processing

The electrical bandwidth of 100 MHz implies that the signal paths from the photomultipliers to the correlator must be equal to about 1 ns to avoid loss of correlation due to temporal coherence. This seems like a very tight requirement at first view, but it is much easier to equalize electrical transmission lines that optical paths. The 1 ns corresponds to about 30 cm in length, which is easy to reach (in the case of the Michelson stellar interferometer, the paths must be equal to a wavelength or so).

Small lamps in the photomultiplier housings, turned on when the shutters were closed, gave uncorrelated light, so any correlation that is recorded when they are on is false.

Another contribution to the correlation was anticipated, that of the Cherenkov radiation from cosmic rays. This is a faint blue streak of light (that both mirrors would see simultaneously, and would thus correlate) that is produced when the cosmic ray is moving at greater than the speed of light (c/n) in the atmosphere. This proved to be unobservable. Meteors would have the same effect, but they are very rare.
**Results of HBT**

The filtered starlight is a quasi-monochromatic signal, in which the closely-spaced frequency components can be considered to beat against one another to create fluctuations in intensity, $<\Delta A^* \Delta A^*>$. There are also accompanying fluctuations in phase, but these are lost (but…).

The correlation measured in the intensity interferometer is proportional to $<\Delta I_1 \Delta I_2>$, where $\Delta I = I - I_{av}$ is the fluctuation in $I$. If expressions for the quantities are inserted in terms of the amplitudes, it is found that the normalized correlation is proportional to $|\gamma_{12}|^2$, the square of the fringe visibility in the Michelson case. The phase information is gone (but…), but the magnitude of the degree of coherence is still there, and that is enough for the measurement of diameters (and possibly of limb-darkening).

Measurements were finally made on 30 or so stars of **spectral types B0 to F5**. Measurements **could not be made on Betelgeuse**, since the mirrors could not be brought closer than 10 m apart, and besides the 6.5 m mirrors would themselves resolve the star, reducing the correlation to zero.

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**CHANGE OF CORRELATION WITH BASELINE** (a) Beta Cru (B0 IV); (b) Alpha Eri (B5 IV); (c) Alpha Car (F0 II)
The S/R of the HBT interferometer increases very rapidly *with the temperature of the star* (see figure), essentially because at any given magnitude the cooler stars will be more resolved than the hotter ones.
Expected improvements with modern HBTI

\[
\frac{S}{N} = K_{instr} \times QE \times Area_{Telescope} \times \sqrt{Count_{Bandwidth}} \times \sqrt{T}
\]
Future of HBTI?

The advantages of the Brown and Twiss interferometer which still survive in the post-VLTI era include:

1- ease of adjusting the time delays of the channels to equality within few centimeters (electronic instead of optical compensation);
2 - immunity to seeing: *adaptive optics is not required*
4 - blue sensitivity, with the possibility to utilize the large body of data from Michelson-type interferometers and to supplement their data with observations in this spectral region.
The most exciting development of the HBT interferometer is the an Intensity Interferometry with two distant telescopes, therefore an optical (intensity) VLBI! No optical link is indeed needed, only time tagging to better than say 100 ps and proper account of atmospheric refraction and delays. The concept could be tested immediately with two or all telescopes e.g. with the two apertures of the LBT, which would provide essential (almost) zero-delay information.
4 - DETECTORS

for High-Time-Resolution Astrophysics & Quantum Optics

1 - PMTs
2 - Streak Cameras
3 - Hybrid Photo Detectors,
Etc...,

only two are shown in the following
Single Photon Silicon Avalanche Photo-Diodes (SPADS)

SPADs (Geiger mode detectors) find an increasingly important role in many applications, in particular for lidars, laser ranging, adaptive optics.
- Perkin-Elmer
- Technical University of Prague
**MPD SPADs**

**PDM Series**

*Photon Counting Detector Module*

**Applications**
- Fluorescence detection
- Single molecule detection
- Adaptive Optics
- Quantum Cryptography
- LIDAR
- Educational detector for photon counting application

**Features**
- Robust and low cost
- TE cooling not required (optional)
- Detection efficiency 47% @ 532nm
- Timing resolution 50ps FWHM
- Low power consumption
- Easy to use
Counting stellar photons in the visible with SPADs

Counting photons from bright stars (here Vega) was one of the first operations attempted by Barbieri et al. in Matera, in order to calibrate the sensitivity of the apparatus, to see the influence of the atmospheric turbulence and to discover peculiarities in the system. We used a P-E Spad with a tagging capability better than 1 ns (atomic clock controlled), a dead time of 300 ns and a 3A wide filter centered at 532 nm. Although the statistics of the arrival times seems consistent with a Poisson distribution, we also notice some peculiar structures that deserve more consideration (a detector effect?).

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**Photon counting in the near-IR**

- There is a tremendous effort to achieve high QE photon counting in the ‘eye-safe’ region around 1.5 – 1.8 micrometer region, for communication purposes.

- At moment QE around 15% are quite possible.

- Big advances are to be expected soon.

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Time-correlated photon counting data illustrating the germanium SPAD timing resolution, horizontal scale: channel number, 18 ps/channel, vertical scale: number of counts in the range 0–1000 counts/channel, 100 μm diameter diode, 77 K, 3.5 V above breakdown voltage. FWHM = 67 ps.
Il disegno di Quanteye - 1

L'ottica ‘pupil-slicing’
Il disegno di Quanteeye - 2
Il disegno di Quanteye - 3

MASER clock

CPU Cluster

STORAGE

CRATE 1

CRATE 2

2 QuantEYE Heads + Calibration unit

Inside Instrument room
Gli algoritmi di Quanteeye

Quantum Algorithms

Shor Algorithm
( Efficient way of factorizing big int number)

QFT (quantum Fourier Transform)

\[ |j \rangle \rightarrow \Omega[|j\rangle] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} e^{i2\pi jk/N} |k\rangle \]

Grover Algorithm
( Efficient way of finding an object inside an unsorted Database on N elements \( O(\text{sort}(N)) \)
The classical one is \( O(N) \)
Precursors to Quanteye

Aqueye: The Asiago Quantum Eye
Aqueye

Pupil sliced in 4 sub-apertures. No fibers. Low cost commercial solution.

Collaboration also with Andrej Cadez (Lubjana).
Time Distribution among two distant telescopes

• The existing GPS and probably also the future Galileo fall short of the needed precision (say 100 ps or better).

• The problem of distributing a very precise and extremely well synchronized time among distant observers is bound to become easier and easier in the next few years.

• VLBI indeed is not the only science requiring this accurate time: terrestrial and interplanetary communications will act as a most powerful driver.
Some examples of very accurate time distribution

A proposed ESA system:
Only one master clock is needed on the ground

(courtesy of Carlo Gavazzi Space)
In a first long distance Bell experiment the entangled photons are sent from a LEO based entanglement source to two ground stations, more than 1000 km apart. Depending on the actual orbit there could be two of the three possible stations in view (Graphic courtesy of Contraves, CH).
Domanda al PRIN 2006
1 - Padova (Università, INAF, INFN)+ Roma Monte Porzio (INAF)
2 - Cagliari (INAF)
3 - Catania (INAF)

Se finanziato, sarà lo sviluppo di Aqueye per TNG, LBT, VLT? Vedremo....
MAGIC (the Cerenkov light collector) provides a central 'empty' pixel which could be adapted to our purposes. The second telescope (MAGIC II) now under consideration would give interferometric HBTI possibilities.

Furthermore, MAGIC is few hundred meters below the TNG. The possibility of collaborating with Quantum Astronomy projects is currently under examination.
The southern Pierre Auger Observatory is presently under construction in Malargue, Mendoza, Argentina. It combines two complementary air shower observation techniques; the detection of particles at ground and the observation of associated fluorescence light generated in the atmosphere above the ground. Experimentally, this is being realised by employing an array of 1600 water Cherenkov detectors, distributed over an area of 3000 km², and operating 24 wide-angle Schmidt telescopes, positioned at four sites at the border of the ground array. The Observatory will reach its full size in 2006.
The Auger Schmidt telescopes

The main elements of the aperture system are the 2.2 m diaphragm including a corrector ring (not installed at each telescope, yet) and an UV transmission filter made of MUG-6 glass. The light is reflected by segmented 13m² spherical mirrors.
The focal plane of the mirror is instrumented with a camera arranged in 20x22 pixels. Thus, each of the 440 PMTs (XP 3062 of Photonis) of a camera views approximately $1.5 \times 1.5$ of the sky. The PMT signals are continuously digitised at 10 MHz sampling rate with a dynamic range of 15 bit in total. An FPGA based multi-level trigger system records traces out of a random background of 100 Hz per pixel.
The Auger Atmospheric Monitoring and Calibration

To realize the full advantage of the calorimetric fluorescence measurement, absolute calibration and careful atmospheric measurements are necessary.

– Atmospheric Monitoring
  • Lidar for atmospheric profiling and “shooting the showers” (atmospheric measurement along the shower path).
  • Fixed vertical and steerable lasers at array center for atmospheric monitoring, timing and calibration checks.
  • Continuous horizontal attenuation monitors.
  • Balloon borne atmospheric measurements.

– Absolute Calibration
  • End to end absolute calibration

Drum for uniform illumination of each fluorescence camera – part of end to end calibration.

Lidar at each Fluorescence Central Laser Facility (laser optically linked to adjacent surface detector tank)

Year around balloon borne atmospheric measurements.

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Auger and astronomy

From the previous slides it is clear the tremendous benefit of the Pierre Auger experiment to Quantum Astronomy, because of the high time resolution, high collection area of blue photons, Very Long Baseline characteristics and of the careful atmospheric monitoring at distant locations. Therefore a collaboration is strongly encouraged!
Photon Entanglement in Astrophysics?

- Together with superposition, entanglement is a peculiar property of Quantum Optics, with no classical counterpart and with counterintuitive consequences. However, it is a well established property, with a wealth of novel applications (lithography, medical diagnostics, communications, etc.).

- Non linear crystals are used in the lab to generate entangled photons, and quite possibly natural phenomena occur too (pion decay?), but a deeper investigation is needed in the astrophysical context.
An extreme case of
Quantum superposition over cosmic distances: Wheeler’s Delayed Choice Experiment

How to do it:
- you must not know which path the photons went through (Dirac), so you must impose in the shorter branch the exact delay before the beamsplitter to synchronize the two paths.
- or you count the photon arrival times and check for the coincidences (polarization aided).

Extension of fundamental quantum properties to cosmological scales
Detection of entangled photons from the QSO?
Better limits to space-time geometry?
**Light curves of cosmological Gravitational Lenses**

The **light curve of the two images** can display:

- **Correlated variations** due to flaring of the QSO, they would allow detection of different light times (already done)

- **Uncorrelated variations** due to millilensing (galaxies) and/or microlensing (stars) and/or femtolensing (neutron stars and black holes). **This program is another exciting possibility with OWL.**
An example of gravitational lens

HE 0512-3329, z = 1.95, z\text{gal} + 0.98

http://cfa-www.harvard.edu/castles/

RA(arcsec)  0  -0.168±0.000  0.033±0.024
Dec(arcsec)  0  -0.619±0.000  0.010±0.007
F555W  18.23±0.01  18.40±0.09  20.46±2.08
F814W  17.75±0.14  17.40±0.12  17.60±0.58

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Photon Orbital Angular Momentum (OAM)

Photon Orbital Angular Momentum (OAM)

Photons have spin angular momentum $\pm \hbar$ along their direction of propagation. Beams of photons carrying the same spin are circularly polarized. However, Laguerre-Gaussian and Bessel laser modes also carry OAM because the Poynting vector and the linear momentum density of these beams have an azimuthal component $l$. Beams having as much as $l = 300 \hbar$ OAM have been realized in the lab.
For any given $l$, the beam has $l$ intertwined helical phase fronts. For helically phased beams, the phase singularity on the axis dictates zero intensity there. The cross-sectional intensity pattern of all such beams has an annular character that persists no matter how tightly the beam is focused.

Can POAM be used for nulling the light on axis (as a coronagraph), and then help the discovery of faint objects close to a bright source (e.g. extrasolar planets)?

Can we try it on existing (small) telescopes? Experiments are carried out in Padova-Asiago
POAM In Cosmic Sources??


1 - masers as probes of large density inhomogeneities in the ISM. Very small scale discontinuities (edges of shocked domains) might induce POAM on a maser beam.

2 - the same could happen to intense beams from very pointlike sources as pulsars, quasars, Kerr blackholes

3 - SETI. A very clever population could artificially generate photons with PAOM (and also entanglement).

Considerable theoretical effort is needed to elucidate these possibilities.
A most ambitious quantum instrument for OWL

- 4-Dimensional detector system
  (2D spatial + 1D spectral & polarization + 1D temporal)
- 1024 x 1024 imaging elements
- Each imaging element with 100 spectral & polarization channels

POTENTIAL DATA RATES:

* 1024 x 1024 imaging elements
  @ 100 spectral & polarization channels
* Each channel photon-counting
  @ 10 MHz with 1 ns time resolution
  Data rate = 10^{14} photon time-tags per second
  = 1 PB/s (*Petabyte*, $10^{15}$ B)
  = some EB/h (*Exabyte* = $10^{18}$ B)
  = several ZB/y (*Zettabyte* = $10^{21}$ B)