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Salt Lake City, January 29th, 2009

Quantum of Quasars

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Quick summary

g^{(1)} \rightarrow g^{(2)}
The first-order correlation function $g^{(1)}$

\[ g^{(1)} = \frac{\langle E^*(r_1, t_1) E(r_2, t_2) \rangle}{\langle E(r, t) \rangle^2} \]

Complex!

$g^{(1)}$ is a measurement of the spatial and/or temporal coherence of the wavetrain.
Particular case 1: $t_1 = t_2$

Theorem of van Cittert-Zernike:

$g^{(1)}$ is equal to the Fourier Transform (FT) of the light distribution on sky, along the projected baseline.
The visibility is precisely $g^{(1)}$!

$$E_{\text{detector}}(t_1 = t_2) \propto \frac{1}{\sqrt{2}} (E^*(r_1) \pm E(r_2))$$

$$I = I_0 \left[ 1 \pm \text{Re} \left( g^{(1)} \right) \right]$$

$$V \equiv \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = |g^{(1)}|$$
Particular case 2: $r_1 = r_2$

**Theorem of Wiener-Khintchine:** $g^{(1)}$ is equal to the FT of the spectral density distribution of the source.

Classical spectrometer: the grating perform the FT.

FT spectrometer: interferences are recorded.
(Very) particular case 3: $r_1=r_2$, $t_1=t_2$ (Bolometer)

Introduction to light statistics

\[ I(t) = \langle I \rangle + \Delta I(t) \]
\[ \langle \Delta I(t) \rangle = 0 \]
\[ \langle \Delta I(t)^2 \rangle > 0 \]
Transition

\[ \tau \rightarrow \sigma \]

coherence  variance
For a laser, its poissonian

A section of 30 cm of a laser lightbeam at 6330Å with a power of 1 nW contains 3 photons in average.

The distribution of the photon number of a monochromatic laser, within an interval $\Delta t$, is poissonian

$$\sigma^2(n) = \bar{n}$$
Fundamental reason: the uncertainty principle

\[ \Delta n \Delta \varphi \geq \hbar \]

- Number of photons
- Phase of the wave
Classification of light according to statistics

- **Poissonian**
  \[ \sigma^2(n) = \bar{n} \]
  random (Laser)

- **Super-Poissonian**
  \[ \sigma^2(n) > \bar{n} \]
  bunching (Thermal)

- **Sub-Poissonian**
  \[ \sigma^2(n) < \bar{n} \]
  anti-bunching (Fluorescence)
(Photodetection: losses)

- Optics efficiency (only a fraction of the incident light is collected)
- Losses through absorption, diffusion, reflections on various surfaces.
- Efficiency of the detection process itself (quantum efficiency)

Every process of collection/detection tends to make the statistics more poissonian.
The quantum efficiency $\eta$ express the fidelity of the measurement of the statistics.

$$\sigma^2(N) = \eta^2 \sigma^2(n) + \eta(1 - \eta)\bar{n}$$
The second-order correlation function $g^{(2)}$

$$g^{(2)} = \frac{\langle I(r_1, t_1) I(r_2, t_2) \rangle}{\langle I(r, t) \rangle^2}$$

Real!

$g^{(2)}$ is a measurement of correlation degree, spatially and/or temporally, between photons.
The second-order correlation function $g^{(2)}$

$$g^{(2)} = \frac{\langle I(r_1, t_1)I(r_2, t_2) \rangle}{\langle I(r, t) \rangle^2}$$
$g^{(2)}$ in photon counting.

$g^{(2)} < 1$ reveal the quantum nature of light.
The intensity interferometer

Photograph courtesy of Prof. John Davis

They have received the Eddington medal of the RAS en 1968.
Why it worked at measuring stellar radii?

For chaotic light (black body):

\[
\left| g^{(1)}(\tau) \right| = \exp \left[ -\frac{\pi}{2} \left( \frac{\tau}{\tau_c} \right) \right] \quad g^{(2)} = 1 + \exp \left[ -\pi \left( \frac{\tau}{\tau_c} \right)^2 \right]
\]

\[
\left| g^{(1)} \right|^2 = g^{(2)} - 1
\]

*Et voilà!*

Valid for chaotic light only (Glauber, 2007, p115)
Observations at Narrabri: Only hot(ter) stars.

\[
\begin{align*}
\text{Poisson} & \quad \sigma^2(n) = \bar{n} \\
\text{Bose-Einstein} & \quad \sigma^2(n) = \bar{n} + \bar{n}^2
\end{align*}
\]

"Signal"

\[
\left( \frac{S}{N} \right) = V^2 \sqrt{\frac{T_{\text{exp}}}{\tau}} \frac{1}{\exp(h\nu/kT) - 1}
\]
Have you seen my big telescope?...

\[ g^{(1)} \rightarrow g^{(2)} \]

Let’s talk about detectors....
New Avalanche Photodiodes from CEA/LETI

(see J. Rothman et al. 2008, J.Elec.Mat., 37, 1303)

$\eta \sim 100\%$

$\Delta t \lesssim 80$ picoseconds

$15\mu m < \lambda < 3000\text{Å}$ (→?X)

Possibility to build matrices (at least arrays)

(APDs not in silicium, but in HgCdTe)
The quantum limit in the optical

\[ \Delta E \Delta t \gtrsim \hbar \]

\[ R = 40\ 000 \]

\[ \Delta t \sim 80 \text{ picoseconds} \]

\[ \lambda \sim 60\ 000 \text{ Å} \]
Signal-to-Noise, in practice.

\[
\left( \frac{S}{N} \right)_{RMS} = A \eta R^n V^2 \sqrt{\frac{T}{2\tau}}
\]

- telescope’s mirror area
- overall reflectivity
- visibility
- exposure time
- detector’s quantum efficiency
- detector’s bandwidth

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Comparison with LeBohec & Holder (2005):

\[ \eta = 0.4, \tau = 10^{-9} \text{s} \quad \leftrightarrow \quad \eta = 0.95, \tau = 8 \times 10^{-11} \text{s} \]
$g^{(2)}$ so what?
Science is an essentially anarchistic enterprise: theoretical anarchism is more humanitarian and more likely to encourage progress than its law-and-order alternatives.
New techniques, new ideas. Yes we can!

\[
\left| g^{(1)} \right|^2 = g^{(2)} - 1
\]

New application of the correlation of fluctuations? Where are accessible cosmic sources with non-thermal light?
Topology of the Universe through II of the CMB?

### WMAP First-Year Results: Parameters

#### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (68% Confidence Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude of galaxy fluctuations, $\sigma_8$</td>
<td>$0.9 \pm 0.1$</td>
</tr>
<tr>
<td>Characteristic amplitude of velocity fluctuations, $\sigma_0 \Omega^{0.6}$</td>
<td>$0.44 \pm 0.10$</td>
</tr>
<tr>
<td>Baryon density/critical density, $\Omega_b$</td>
<td>$0.047 \pm 0.006$</td>
</tr>
<tr>
<td>Matter density/critical density, $\Omega_m$</td>
<td>$0.29 \pm 0.07$</td>
</tr>
<tr>
<td>Age of the universe, $t_0$</td>
<td>$13.4 \pm 0.3$ Gyr</td>
</tr>
<tr>
<td>Redshift of reionization, $z_r$</td>
<td>$17 \pm 5$</td>
</tr>
<tr>
<td>Redshift at decoupling, $z_{\text{dec}}$</td>
<td>$1088 \pm 1$</td>
</tr>
<tr>
<td>Age of the universe at decoupling, $t_{\text{dec}}$</td>
<td>$372 \pm 14$ kyr</td>
</tr>
<tr>
<td>Thickness of surface of last scatter, $\Delta z_{\text{dec}}$</td>
<td>$194 \pm 2$</td>
</tr>
<tr>
<td>Thickness of surface of last scatter, $\Delta t_{\text{dec}}$</td>
<td>$115 \pm 5$ kyr</td>
</tr>
<tr>
<td>Redshift at matter/radiation equality, $z_{eq}$</td>
<td>$3454^{+31}_{-35}$</td>
</tr>
<tr>
<td>Sound horizon at decoupling, $r_h$</td>
<td>$144 \pm 4$ Mpc</td>
</tr>
<tr>
<td>Angular diameter distance to the decoupling surface, $d_A$</td>
<td>$13.7 \pm 0.5$ Gpc</td>
</tr>
<tr>
<td>Acoustic angular scale, $\theta_A$</td>
<td>$299 \pm 2$</td>
</tr>
<tr>
<td>Current density of baryons, $n_b$</td>
<td>$(2.7 \pm 0.1) \times 10^{-7}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Baryon/photon ratio, $\eta$</td>
<td>$(6.5^{+4}_{-3}) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Note: Fit to the WMAP data only.

a Assumes ionization fraction, $x_e = 1$.

$4 \theta_A = \pi d_A / r_h$.
Topology? Multi-connected universe?

Luminet et al. 2003
Topology of the Universe through II of the CMB?
Microquasars:
Sources of “extravagant” radiation in our Galaxy

Jet ↔ black-hole spin?

Synchrotron emission from jet originate from non-thermal particles (power-law spectrum)

Microquasars:
Sources of “extravagant” radiation in our Galaxy

Energy flux ($\nu F_\nu$)

Photon rate

Microquasar with $M_{\text{bh}}=10M_\odot$, $\dot{M} = 10^{-2} M_{\text{Edd}}$, $d=10\text{kpc}$, “hot”
In the immense zoo of quantum phenomena

Unruh effect expected to produce entangled photons!

Schützhold et al. 2006, Phys. Rev. Let. 97 (12), 1302

Hawking radiation “black-hole evaporation”
Conclusions

\[ \left| g^{(1)} \right|^2 = g^{(2)} - 1 \]

Beyond intensity interferometry: black-hole physics!
Please note:

On the intensity interferometry and the second order correlation function \( g^{(2)} \) in astrophysics

C. Foellmi, A&A submitted

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We are organizing a 2-days workshop on quantum/photonic astrophysics with physicists, astronomers, ingeneers

Grenoble, May/June 2009

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