Light: wave or particle?

- Wave behavior of the light. Proven in XIX century.
- Young, Fresnel, Arago, Maxwell, Hertz, Popov, Michelson,…
- Diffraction and Interference.
First-order coherence function $g^{(1)}(\tau)$

\[
E(t) = E_0(t)e^{-i\omega t} \quad I_0 = \langle E_0(t)E_0(t) \rangle
\]

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad I(\tau) = I_0 \left(1 + V \cos \omega \tau \right)
\]

\[
\omega \tau = k\Delta = kB\alpha / c
\]

\[
g^{(1)}(\tau) = \frac{\langle E_0(t)E_0^*(t + \tau) \rangle}{I_0}
\]

\[
I(\tau) = I_0 \left(1 + \text{Re} \left[ g^{(1)}(\tau)e^{i\omega \tau} \right] \right) = I_0 \left(1 + |g^{(1)}(\tau)| \cos \omega \tau \right)
\]
Interference from polychromatic source: Wiener-Khinchin theorem

- Coherence length $L_c$: optical path difference where interference vanishes
- Interference yields a clear illustration of uncertainty principle: $\Delta \omega \Delta \tau \sim 1$
- Source with broader spectrum owns shorter coherence length
- Wiener-Khinchin theorem: FT of source spectrum yields coherence function

\[
I(\omega) = \int_{-\infty}^{+\infty} I(t) e^{-i\omega t} dt = \int_{-\infty}^{+\infty} \langle E^*(t) E(t) \rangle e^{-i\omega t} dt
\]

\[
g^{(1)}(\tau) = e^{-i\omega \tau} \int_{-\infty}^{+\infty} I(\omega') e^{i\omega' \tau} d\omega' / I_0
\]
The nature of light. Light coherence.

- Michelson stellar interferometer
- Spatial coherence
- Interference of intensities
- Second-Order coherence function
- Single photon sources
Michelson stellar interferometer (1920)

- Resolution of conv. telescope is $\lambda/D < 10^{-6}$
- Interferometric measurements of star sizes
- Mount Wilson, USA, winter 1920
- Orion constellation, Betelgeuze
- Double telescope interference

100" Hooker telescope
Mount Wilson Observatory
http://www.mtwilson.edu

Orion
Resolution improvement with stellar (spatial) interferometer
Michelson stellar interferometer (1920)

- Suggested by H. Fizeau (1868)
- Increase Base → Interference vanishes
  → Resolve start size
- Angle resolution $\sim 10^{-6} - 10^{-7}$ rad
- Discovery of Red Giants
- Betelgeuze: 386 Mio. Km
- Limitations: Mechanical stability of interferometer with large Base

Light from a star

Base $\sim 6$ m

Lense (2.5 m telescope)
Fringe formation. Extended light sources.

- Finite angular size of the light source. Adding up interference fringes.
- Working example. K-band source with $2.2\mu m$ and $\Delta \lambda = 0.4\mu m$, $B = 10$ cm.
- The diameter of source is 2 arcsec
Extended light sources. Fringe formation

- Finite angular size of the light source.
- Monochromatic: Visibility is reduced due to interference adding up.
- The diameter of source is 2 arcsec + temporal coherence = fringes fade out.
- All points on surface are independent (uncorrelated).
- Let’s develop simplified theory
Spatial interferometer

\[ I(\alpha, \alpha_0') = I_0 \left( 1 + \cos k(\alpha + \alpha_0') B \right) \]

\[ I(\alpha) = \int_{-\alpha_0'/2}^{+\alpha_0'/2} I(\alpha, \alpha') d\alpha' = I_0 \left( 1 + \text{Re} \left[ g^{(1)}(\vec{B}) e^{i\vec{\alpha} \vec{B}} \right] \right) \]

Van-Cittert - Zernike Theorem

\[ g^{(1)}(\vec{B}) = \int_{-\infty}^{+\infty} I(\alpha') e^{i\alpha' \vec{B}} d\alpha' / I_0 \]
Spatial and temporal coherence

• Venus size is about 15 arcsec.
• K-band source with \(2.2\,\mu m\) and \(\Delta \lambda = 0.4\,\mu m\), variable base \(B = 1-8\) cm.
• Fringe spacing \(\lambda/B\). We observe about 11 fringes – temporal coherence
• Model Venus as disk of uniform intensity.
• Visibility follows \(\text{Besinc}(x) = 2J_1(x)/x\).
• Spatial coherence is visibility at white light fringe.
Image formation in spatial interferometer

\[ V = \left| \frac{J_1(kB\alpha/2)}{kB\alpha/2} \right| \]
Very Large Telescope Interferometer (VLTI)

• Paranal, Chile
• VLTI array
• 2 telescopes, 8 m in diameter
• Base up to ~100 m
• Resolution of ~10^{-9} rad

List of results:
http://www.eso.org/sci/facilities/paranal/telescopes/vlti/

European Southern Observatory: http://www.eso.org
Adaptive optics to correct the phase front

seeing limited

AO on 8-m telescope

spatial interferometer with 100 m baseline

0.5 arcsec seeing

50 milli arcsec resolution

4 milli arcsec resolution
Drawbacks of **amplitude** interferometer

1. **Mechanical Stability** of the construction

2. **Phase distortion** due to atmospheric fluctuations!

**Phase sensitive measurements**!
Interference of intensities!

• 1949, R. Hanbury-Brown wanted to measure angular size of Cyg-A by using Michelson interferometer
  • If the sources were small he would need to two radio telescopes on opposite sides of Atlantic ocean, provided that the phase stability is also established across that distance.
  • Technically not possible that time
  • He conceived the idea of intensity interferometry as a way of measuring the angular size of stars
Supposing, I thought, there was another man many miles away looking at another identical cathode-ray tube, would he see the same “noise-like” signal? ... The next morning I worked out the answer. ... if the radiation received at two places is mutually coherent, then the fluctuations in the intensity of the signals received at those two places is also correlated. Since the noise on a cathode-ray tube corresponds to the low-frequency fluctuations in the intensity of the signal, the pictures seen by the two observers must also be correlated. ... To my joy the mathematics showed that the correlation between their two pictures is a direct measure of mutual coherence and can therefore be used to find the angular size of the source.

R. Hanbury Brown, Boffin (1991)
Radio Astronomy

- Very long base radio interferometers
- Studying quazars, pulsars, galaxies
- Synthesized large aperture due to earth rotation and many stations

http://www.vlba.nrao.org
http://www.nrao.edu

Composite image of Whilpool galaxy M51
Hanbury-Brown and Twiss experiment

- R. Hanbury-Brown and R. Twiss in 1956, AU
- Interference with Base up to 180 m
- Phase insensitive measurements
- RF signals in band 5-45 MHz
- Measurements of Sirius star

Observing of sirius A (1954)
Intensity interferometer (1956)

- R. Hanbury-Brown and R. Twiss in 1956, AU
- Interference with Base up to 180 m
- Phase insensitive measurements
- RF signals in band 5-45 MHz
- Measurements of Correlation

\[
S(B,t) = \langle i_1(0,t) i_2(B,t) \rangle
\]

\[
S(B) \sim \langle I_1 I_2 \rangle \left(1 + \left| g^{(1)}(\tau_B) \right|^2 \right)
\]

\( \tau_B \) is the delay time due to Base

\[
\Gamma(B) \sim \langle I_1(0) I_2(B) \rangle - \langle I_1 \rangle \langle I_2 \rangle \quad \text{Signal which is measured}
\]

see R. Loudon, "Quantum Theory of light" for details of calculations
Intensity interferometer (1954)

- Small Base → signals come from one source
- Large Base → signals may differentiate
- Decrease of correlation with increase of B
- Angular resolution better than $10^{-8}$
- Angular diameter of Sirius A
- Method used in Radio Astronomy

If each individual photodetection event is a statistical quantum process, how can separated events be correlated with each other?

Fluctuations at the input results in Correlation of photocounts
Intensity interferometry on coherent sources

Beam-Splitter

435.8 nm filtered From Hg-lamp

\( \langle \Delta i_2(t + \tau) \rangle \) \( \langle \Delta i_1(t) \rangle \) \( \langle \Delta i_1(t)\Delta i_2(t + \tau) \rangle \)

PMT 1

AC-coupled amplifier

Delay generator

\( \tau \)

Multiplier

Integrator

R.Brown, R. Twiss, Nature 177, 27 (1956)
The second-order correlation function $g^{(2)}(\tau)$

- Second-order correlation function of the light:

$$g^{(2)}(\tau) = \frac{\left\langle E^*(t)E^*(t+\tau)E(t+\tau)E(t) \right\rangle}{\left\langle E^*(t)E(t) \right\rangle \left\langle E^*(t+\tau)E(t+\tau) \right\rangle} = \frac{\left\langle I(t)I(t+\tau) \right\rangle}{\left\langle I(t) \right\rangle \left\langle I(t+\tau) \right\rangle} = \frac{\left\langle I(t)I(t+\tau) \right\rangle}{\left\langle I(t) \right\rangle^2}$$

$I(t) = \left\langle I \right\rangle + \Delta I(t)$, $\left\langle \Delta I(t) \right\rangle = 0$

$$g^{(2)}(0) = \frac{\left\langle I(t)^2 \right\rangle}{\left\langle I(t) \right\rangle^2}$$

$$g^{(2)}(\tau >> \tau_c) = \frac{\left\langle I(t) \right\rangle^2}{\left\langle I(t) \right\rangle^2} = 1$$

![Graph showing Gaussian chaotic light, Lorentzian chaotic light, and Coherent light (Laser)](image)
Light is a particle: counting photons

- Human eye is sensitive to about 10 photons/sec
- Light of the star: $\sim 10^4$-$10^5$ photons/sec
- Single atom fluorescence: $\sim 10^3$ photons/sec
- Cherenkov radiation: $\sim 10$-$10^7$ photons/sec
Devices sensitive to single photons

Photo-Multiplier-Tubes (PMTs)

Single-Photon CCD

http://www.hamamatsu.com/

http://www.andor.com/

http://www.emccd.com/
Superconducting single photon counter

- Thin SC wire made of Nb or NbTi
- Photon breaks superconductivity thus creating a negative pulse in DC supercurrent
- Detection of Telecom-C photons at 1.54 μm with up to 90% efficiency
Superconducting single photon counter

See O. Kahl et al., Scientific reports, DOI: 10.1038/srep10941