光子統計を用いた天体観測手法の提案

Photon Statistics as a tool for Astronomical Observation

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Abstract

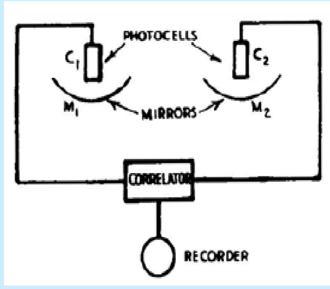
Photon number statistics tells us not only the total flux of radiation, but also their brightness temperature, intensity correlation and, possibly, phase information under appropriate condition.

One application is a photon counting terahertz interferometry (PCTI), which is an improved version of the intensity interferometry demonstrated by Hanbury Brown and Twiss in 1956. Exo-planet imaging can be made with PCTI, since we can apply the interferometry for very long baseline interferometry. Observation of far-infrared atomic lines from Antarctic plateau can be an interesting test case for PCTI.

Another, and more simple, application of photon statistics is to measure the physical temperature of astronomical sources, such as Cosmic Microwave Background Radiation with an accuracy of $\Delta T/T \sim 10^{-6}$. Inflation universe might be probed in large angular scale.

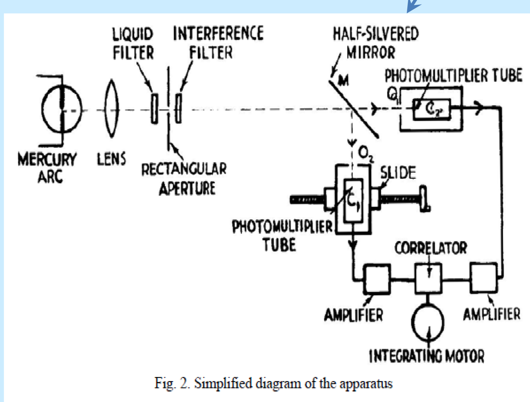
Development of photon counting terahertz detectors are proposed using superconducting tunnel junction detectors.

Hanbury Brown and Twiss Experiment
The first demonstration of intensity interferometry (HBT 1956)



Schematics

Setup

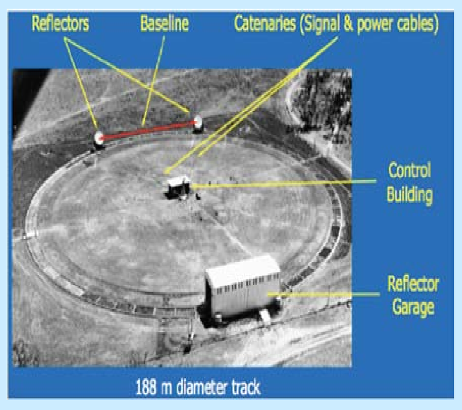


Results

Table 1. COMPARISON BETWEEN THE THEORETICAL AND EXPERIMENTAL VALUES OF THE CORRELATION

	Cathodes superimposed ($d = 0$)		Cathodes separated ($d = 2\alpha = 1.8$cm)	
	Experimental ratio of correlation to r.m.s. deviation $S_e(0)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(0)/N$	Experimental ratio of correlation to r.m.s. deviation $S_e(d)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(d)/N$
1	+ 7.4	+8.4	−0.4	~ 0
2	+ 6.6	+8.0	+0.5	~ 0
3	+ 7.6	+8.4	+1.7	~ 0
4	+ 4.2	+5.2	−0.3	~ 0

Narrabri
Stellar Interferometer



Limitation of intensity interferometry in optical wavelengths

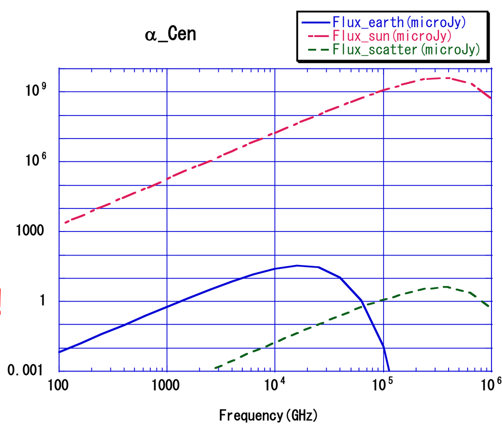
- High brightness temperature is required.
  $T_B > 10^5$ K for high coherency.
- Phase information is missing.

Merits of Photon Counting Terahertz Interferometry (PCTI)

- Lower brightness sources are coherent.
  $T_B > 100$ K at 2 THz
- Phase information can be obtained.
  Bunched photon can be used to measure time delay of photon arrival.

Possible application of Photon Counting Terahertz Interferometry

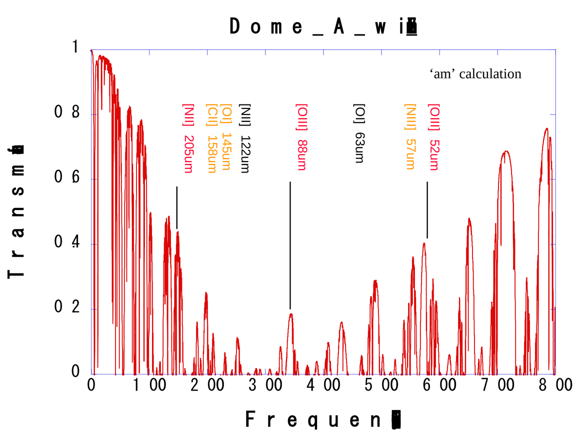
- Search for exo-planets
  Earth-like planets (300K, R=6000 km) can be observed by PCTI.
  Using 6 m telescopes in space, flux from earth like planet at 1.3 pc is:
  2 μJy or 2×10^{-20} W/m² when ν=2THz, B=1THz
  5×10^{-19} W
  Photon rates:
  Planet 500 Hz
  Background 150 kHz
  Primary star 150 MHz

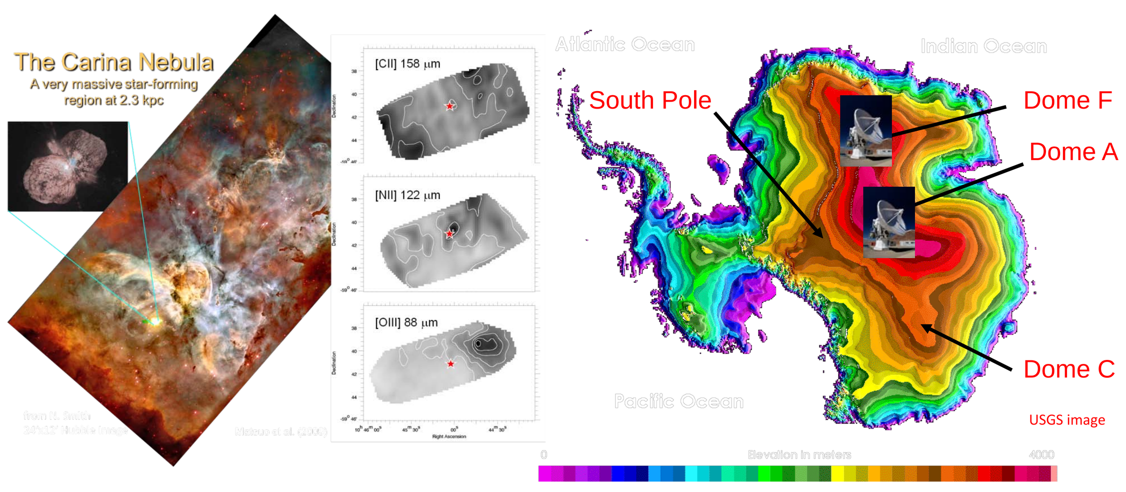


High dynamic range is required !
Suppression of primary star is useful, but not necessary.

- Observation from Antarctic Plateau

FIR atomic line from massive star-forming region can be observed.
Photon rate of 50 MHz is expected from [OIII] 88 μm line from Carina Nabula.



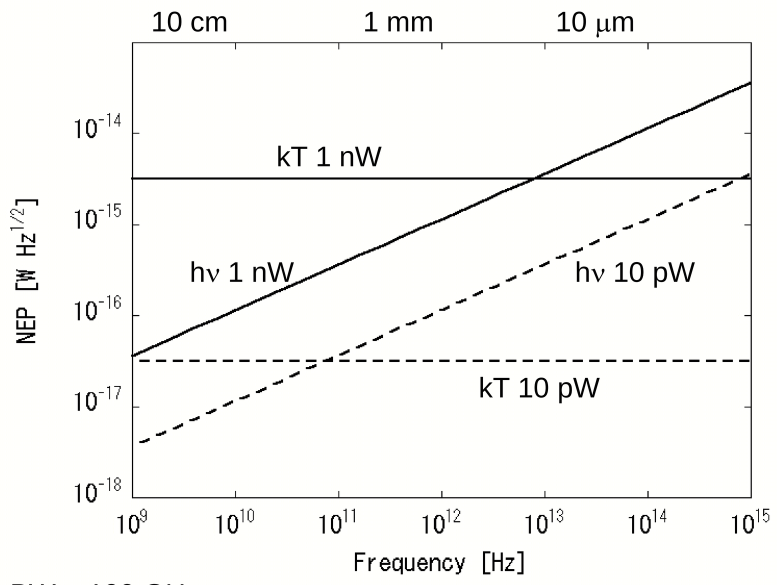


Fluctuation of thermal radiation

$$\Delta n = \sqrt{n + n^2}\ ,\quad \text{where}\quad n = \frac{1}{e^{h\nu/kT} - 1}$$

$$\text{NEP} = \sqrt{2P\cdot(h\nu + kT_B)}\,[\text{W}/\sqrt{\text{Hz}}]$$

Poisson fluctuation and coherent fluctuation is plotted separately for brightness temperature of 2.5K and 250K.



The use of photon bunching ?

- Brightness temperature measurements
  Photon statistics changes by the brightness temperature of sources. -> Application to CMB measurements
- Application to Terahertz Interferometry
  Photon bunches have wave information, so the delay of photon arrival or phase can be measured.
- Application to high energy phenomena ?
  Measurements of electron distribution.

Is Phase Measurement Possible ?

- When photon rate is 100 MHz, measurement time of 100 sec, number of photon reaches 10^{10}.
- If variation of photon arrival is 1/100MHz = 10^{-8} sec, then relative timing accuracy can be as small as 10^{-8} / sqrt(10^{10}) = 10^{-13} sec
- This accuracy is enough to measure phase in terahertz frequencies.

Photon Counting VLBI ?

- Yes, PCTI is a photon counting VLBI technology, Sensitive to low brightness temperature sources, Such as exo-planets.
- Application of precise timing used in VLBI technology enables Δt < 10^{-14} sec.

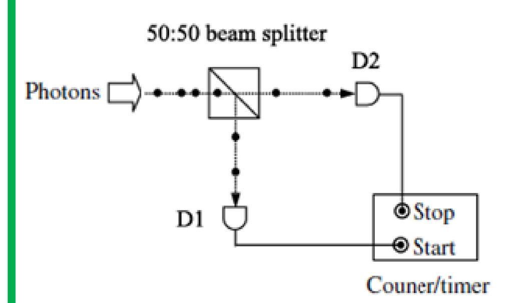
First order correlation function

$$g^{(1)}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}(t+\tau)\rangle}{\langle |\mathcal{E}(t)|^2\rangle}.$$

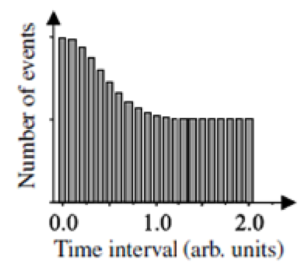
Second order correlation function

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

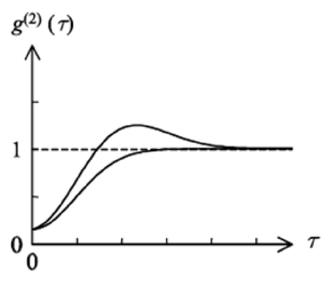
HBT and 2nd order correlation



setup for $g^{(2)}$ measurements

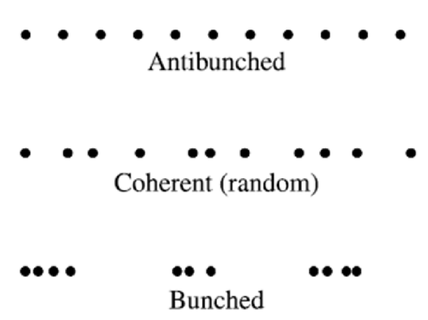


bunched



anti-bunched (two cases)

Photon Bunching, Anti-bunching



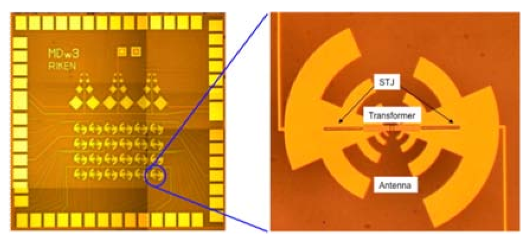
- bunched light: $g^{(2)}(0) > 1$,
- coherent light: $g^{(2)}(0) = 1$,
- antibunched light: $g^{(2)}(0) < 1$.

From 'Quantum Optics' by Mark Fox (2006)

Requirements on detectors

- High count rate: 1-100 MHz
- Wavelength range: 30-300 μm
- High quantum efficiency is required.

STJ detectors photon counting possible ?



Ariyoshi et al. LTD-14 presentation

An example of THz photon detectors. Low leakage device is required for photon counting in THz.

Roadmap to the Future

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