# MEASUREMENTS OF PHOTON STATISTICS WITH NANOSECOND RESOLUTION

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ABSTRACT. A photon-counting astronomical instrument for optical observations with nanosecond time resolution is being developed to observe the statistical distribution of photons in time. The purpose of this 'quantum-optical spectrometer' is to measure quantum-statistical properties of the photon gas and to study the physics of radiative deexcitation. The amount of photon bunching in time contains information on parameters such as the fraction of stimulated emission and the degree of frequency redistribution that the light has undergone.

## 1. INTRODUCTION

Quantum optics is devoted to the study of physical properties of light, and in particular those properties that can not be measured by classical optical instruments such as photometers, spectrometers, polarimeters or interferometers. The quantum theory of light generally considers light neither as an electromagnetic wave, nor as a collection of individual photons, but rather as a *photon gas* whose quantum-mechanical properties follow from the integer spin of photons, which gives them their boson nature. The first experiments outside the realm of classical optics were by Hanbury Brown and Twiss (1956), who demonstrated the existence of bunching in time of photons in chaotic (thermal) light as part of the work that led to the development of the stellar intensity interferometer. The quantum theory of optical coherence was pioneered by Glauber (1963a; 1963b) who showed that an arbitrary state of light can be specified with a series of statistical coherence functions essentially describing one-, two-, three- etc. -photon correlations. The concurrent development of the laser (which allowed different states of light to be prepared in the laboratory) led towards establishing quantum optics as an active research discipline and identified many laboratory applications of laser light scattering using photon correlation spectrometers and similar instruments (e.g. Mandel and Wolf, 1965; Cummins and Pike, 1974; 1977; Loudon, 1980).

The circumstance that light contains more information than can ever be extracted by classical optical instruments holds a potential for astro-



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physics, where the physical properties of the sources must be deduced from detailed analyses of the light received. The quantum properties of light are now becoming understood from laboratory experiments and, following recent developments in electronics, such properties now appear to be measurable also for astronomical sources. To illustrate the potential, we begin by describing general properties of light.

## 2. CLASSICAL PROPERTIES OF LIGHT

We describe light as a linearly polarized electromagnetic wave, whose electric field E contains terms of the type exp(-iωt) for angular frequencies ω. All classical optical instruments measure properties that can be deduced from the first-order correlation function of light, $G^{(1)}$, for coordinates in space $\mathbf{r}$ and time t (Glauber, 1970):

$$G^{(1)} = \langle E^*(\mathbf{r}_1,t_1)\cdot E(\mathbf{r}_2,t_2)\rangle \qquad (1)$$

where < > denotes time average and * complex conjugate. A bolometer measures $G^{(1)}$ for one coordinate in space and time: $\mathbf{r}_1 = \mathbf{r}_2$ and $t_1 = t_2$:

$$\langle E^*(0,0)\cdot E(0,0)\rangle \qquad (2)$$

which measurement yields the classical field intensity irrespective of the spectrum or geometry of the source. For the case $\mathbf{r}_1 = \mathbf{r}_2$ but $t_1 \neq t_2$, $G^{(1)}$ becomes the autocorrelation function with respect to time:

$$\langle E^*(0,0)\cdot E(0,t)\rangle \qquad (3)$$

whose Fourier transform yields the power density as function of electromagnetic frequency. That is the spectrum of light which is measured by spectrometers. For the case $\mathbf{r}_1 \neq \mathbf{r}_2$ but $t_1 = t_2$, we have the spatial autocorrelation function

$$\langle E^*(0,0)\cdot E(\mathbf{r},0)\rangle \qquad (4)$$

which is measured by interferometers and yields the angular distribution of the source power density. In the absence of absolute flux calibrations, $G^{(1)}$ is usually normalized to the first-order coherence of light, $g^{(1)}$:

$$g^{(1)} = \frac{|\langle E^*(\mathbf{r}_1,t_1)\ E(\mathbf{r}_2,t_2)\rangle|}{\{\langle|E(\mathbf{r}_1,t_1)|^2\rangle\ \langle|E(\mathbf{r}_2,t_2)|^2\rangle\}^{\frac{1}{2}}} \qquad (5)$$

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.

## 3. MULTI-PHOTON PROPERTIES OF LIGHT

The description of collective multi-photon phenomena in a photon gas in general requires a quantum-mechanical treatment since photons have integer spin (S = 1), and therefore constitute a boson fluid with properties different from a fluid of classical distinguishable particles. The first treatment of the quantum theory of coherence in a photon gas was by Glauber (1963a; 1963b), although some properties were inferred earlier from classical treatments, notably the bunching of photons in chaotic (thermal) light. Glauber introduced a series of coherence functions $g^{(1)}$, $g^{(2)}$, $g^{(3)}$, etc., essentially describing one-, two-, three-, etc. -photon correlations. A simplified classical expression for the second-order coherence $g^{(2)}$ is:

$$g^{(2)} = \frac{\langle I(\mathbf{r}_1,t_1)\cdot I(\mathbf{r}_2,t_2)\rangle}{\langle I(\mathbf{r}_1,t_1)\rangle\ \langle I(\mathbf{r}_2,t_2)\rangle} \tag{6}$$

thus describing the correlation of intensity I between two coordinates in space and time. Since a detection of a photon (measurement of I) enters twice, $g^{(2)}$ describes two-photon properties of light.

If the distribution of photons is chaotic, i.e. the photon gas is in the maximum entropy state, $g^{(2)}$ can be deduced from $g^{(1)}$ (Loudon, 1979):

$$g^{(2)} = |g^{(1)}|^2 + 1 \tag{7}$$

This property can be used to determine $|g^{(1)}|$ from measurements of $g^{(2)}$. In the intensity interferometer (Hanbury Brown, 1974) this is measured for $\mathbf{r}_1 \neq \mathbf{r}_2$ but $t_1 = t_2$:

$$\langle I(0,0)\cdot I(\mathbf{r},0)\rangle \tag{8}$$

thus deducing angular sizes of stars, reminiscent of a classical interferometer. For $\mathbf{r}_1 = \mathbf{r}_2$ but $t_1 \neq t_2$ we instead have an intensity-correlation spectrometer, which measures

$$\langle I(0,0)\cdot I(0,t)\rangle \tag{9}$$

determining the spectral width of e.g. scattered laser light (Cummins and Pike, 1974).

Now, suppose the distribution of photons does not correspond to the value $g^{(2)} = 2$ for chaotic and first-order coherent ($g^{(1)} = 1$) light. Light created by stimulated emission ideally has $g^{(2)} = 1$ (corresponding to a classical stable wave without any intensity fluctuations and to analogous states in other boson fluids, notably superfluidity in liquid helium). Chaotic light scattered against a Gaussian frequency-redistributing medium has $g^{(2)} = 4$ (Bertolotti et al., 1970). A possible observation of $g^{(2)}$ across a spectral feature then might look like Fig.1. The intensity I profiles are identical for A and B (and classically indistinguishable) but the $I^2$ profiles are not. In case B, $g^{(2)} < 2$ near line center but > 2 in the wings, suggesting an excess of stimulated emission in the line core and an excess of scattered light in the line wings.

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 the laser pumping light is increased and the emission gradually changes from spontaneous to stimulated (e.g. Chang et al., 1969). Measuring $g^{(2)}$, it is possible to deduce the atomic energy level populations, i.e. the non-LTE departure coefficients, which is an example of an astro-

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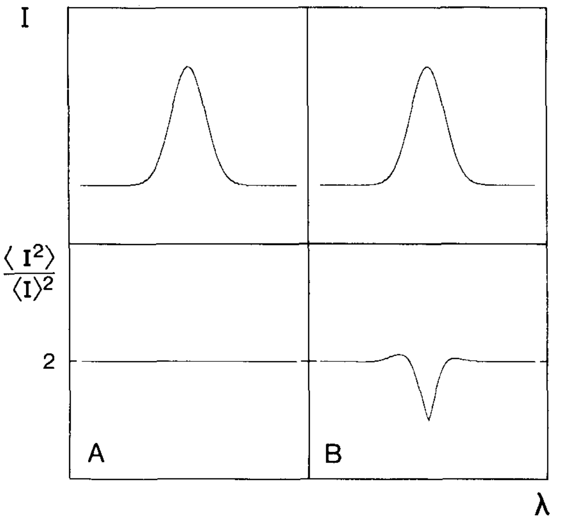


Fig.1. Hypothetical observation of two spectral features A and B that are indistinguishable by classical methods measuring intensity I vs. wavelength (top), reveal differences in photon statistics when observed with a quantum-optical spectrometer (bottom).

physically important parameter which at present only has the character of an intermediate result in theoretical calculations, and which can not be directly observed with classical instruments measuring 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 collective or statistical properties of the respective boson fluid.

Previous measurements of $g^{(2)}$ appear to have been limited to either nearly monochromatic laser light or to a (sometimes not explicit) assumption that the observed light is chaotic. If $g^{(2)} \neq 2$, neither the intensity interferometer nor the intensity-correlation spectrometer will yield correct results. E.g. a point source emitting a monochromatic stable wave (whose $g^{(2)} = 1$ everywhere and always), would appear to be spatially resolved by an intensity interferometer at any spatial baseline and spectrally resolved by an intensity-correlation spectrometer at any temporal baseline (deduced first-order coherence = 0; Eq.7) and hence give the false impression of an arbitrarily large source emitting white light.

## 4. MEASUREMENTS OF QUANTUM-OPTICAL PARAMETERS

An instrument configuration capable of measuring $g^{(2)}$ for arbitrary sources is outlined in Fig.2. Its aim is to measure $g^{(2)}$ for $\mathbf{r}_1 = \mathbf{r}_2$ and $t_1 = t_2$, i.e. the function

$$\langle I^2 \rangle / \langle I \rangle^2 \qquad (10)$$

where $I^2$ means the product $I(t) \cdot I(t + dt)$ as $dt \to 0$ ($I^2$ is not itself a physical observable). Both the spatial and temporal coherence of light are defined by the instrument, so that $g^{(1)}$ is known. The photon correlator gives $g^{(2)}$, so that the function $g^{(2)} - |g^{(1)}|^2$ can be displayed in the output, giving a measure of the density fluctuations and the

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thermodynamic state of the photon gas.

Such an instrument may be called a 'quantum-optical spectrometer' because it would be capable of measuring quantum states of optical fields, not only the ones mentioned above (which can be given classical analogies) but also e.g. photon antibunching, which with $g^{(2)} = 0$ is a purely quantum-mechanical state (e.g. Kimble et al., 1977).

If the source is spatially and temporally resolved, the signal-to--noise ratio appears to be independent of brightness, spectrum or size of the source and also of the size of the telescope. This reflects that the measured quantities are independent from the classical ones of e.g. intensity, spectrum or geometry, and is analogous to the case of the intensity interferometer (Hanbury Brown, 1974), whose signal-to-noise is ultimately limited by the radiation density in the source. An ideal telescope spatially resolving a source, creates a surface brightness and photon density in the focal plane equal to that in the source. Quantum effects become significant when the photon density is high enough for the wave functions of adjacent photons to overlap, and thus the signal-to--noise ratio is best for hot sources with dense photon gas, and is worst for cool sources whose rarefied photon gas begins to approach a classical gas of individually distinguishable particles. The intensity interferometer could not observe cool stars (not even the very brightest ones) and nor is the presently conceived instrument likely to do so. A corollary is that if the angular extent of the source is known, then its brightness temperature can be deduced by measuring the scatter in the measured $g^{(2)}$. If, however, the source is not spatially resolved by the telescope aperture, the signal-to-noise will rapidly improve with increasing telescope aperture. Since the measurement of $g^{(2)}$ is essentially the observation of $I^2$, the signal increases as the *square* of the light--collecting area and as even higher powers for higher-order coherence functions. A possible measurement of $g^{(4)}$ for a spatially unresolved source using a future 25-meter telescope would benefit by a factor $\cong$ 400,000 over a 5-meter telescope, while the gain for conventional photometry would be only a factor 25.

## 5. DESIGN OF INSTRUMENTATION

As a step towards constructing a transportable quantum-optical spectrometer to be used on solar and stellar telescopes, we have now assembled instrumentation in the laboratory. Besides a series of different calibration light sources and optical parts, there are two photomultiplier assemblies with tubes experimentally selected for low afterpulsing rates. To minimize the background count rate, the effective apertures of the S-20 cathodes are very small, 2.5 mm in diameter. The very fast amplifying and pulse discriminating circuitry is coaxially mounted very close to the tubes to assure little distortion of the output pulses. To record the full information, ideally the arrival time of each photon should be recorded for later analysis. However, the enormous data rates possible (a 10 MHz count rate would generate $10^{11}$ words in 3 hours of observation), necessitate a real-time computation of statistical functions only. The

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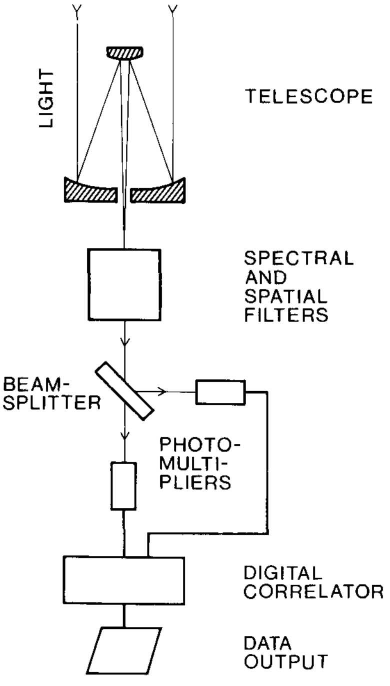


Fig.2. Possible configuration of a quantum-optical spectrometer, designed to measure intensity fluctuations in photon gas arriving from astronomical sources. The telescope collects light and selects the spatial feature to be observed, while the filter selects the desired spectral feature and defines the first-order coherence of light. Effects of correlated detector noise are minimized by the use of two photomultipliers whose output pulse trains are correlated in a digital processor.

stream of pulses is analyzed by a digital signal processor which can use the output of either one or both photomultipliers. This processor assigns each incoming pulse to a time slot whose duration is at present set to 20 nanoseconds, but which may be improved to 13 ns. Besides various monitor channels, the output consists of 64 channels of 32 bits each, which can display either the temporal autocorrelation of the output from one photomultiplier, the cross-correlation function from two photomultipliers or the statistical distribution of the occurrence of exactly 0, 1, 2, etc. up to 63 pulses per preset time interval. The functions can be modified with respect to time resolution and other parameters. The purpose of the auto- and cross-correlation modes is to study two-photon properties, i.e. $g^{(2)}$ while the statistical distribution mode can be used to measure also higher-order effects, in principle up to 63-photon properties. Data accumulation is continuous and is not interrupted by the simultaneous computations. The program of operation is under microprocessor control and is selected from a CRT console, which also displays the accumulated data in real time. Although much of the instrumentation believed to be essential is thus now available in the laboratory, we expect that a significant amount of preparatory work will have to be concluded before fruitful approaches to astrophysical problems can be made. Some of the complications are discussed in Dravins (1981a).

## 6. ASTROPHYSICAL APPLICATIONS

One may envision a series of applications of quantum-optical spectroscopy and nanosecond resolution optical observations to give insight in the physics of radiative deexcitation of astrophysical plasmas. What is the quantum nature of the light emitted from a volume with departures from thermodynamic equilibrium in the atomic energy level populations? Will a spontaneously emitted photon stimulate others, so that the path where the photon train has passed becomes temporarily deexcited and remains so for perhaps a microsecond until collisions and other effects have restored the balance? Does then light in a spectral line perhaps consist of short photon showers with one spontaneously emitted photon leading a trail of others emitted by stimulated emission? One could search for such amplified spontaneous emission ('laser action') in emission lines from extended stellar envelopes or solar active regions. In principle it may be possible to determine whether the Doppler broadening of a spectral line has been caused by motions of those atoms that emitted the photons or by those intervening atoms that have scattered the already existing photons. For such scattered light, its degree of partial redistribution in frequency might be directly measurable, with a possible impact on theories of spectral line formation.

Although the existence in principle of such effects may be clear, their practical observability is not yet known. At first sight, it might even appear that light from a star should be nearly chaotic because of the very large number of independent radiation sources in the stellar atmosphere, which would randomize the photon statistics. However, since the time constants involved in the maintenance of atomic energy level overpopulations (e.g. by collisions) may be longer than those of their depopulation by stimulated emission (speed of light), there may exist, in a given solid angle, only a limited number of radiation modes reaching the observer in a given time interval (each microsecond, say) and the resulting photon statistics might well be non-chaotic. Proposed mechanisms for pulsar emission include stimulated synchrotron and curvature radiation ('free-electron laser') with suggested timescales of nanoseconds, over which the quantum statistics would be non-chaotic. Also the photon statistics for radiation from other compact sources, such as X-ray ones or black hole candidates may well show some peculiarities. The presence of photon 'bubbles' in photohydrodynamic turbulence in very hot stars has been suggested. The bubbles would be filled with light, and the photon gas pressure inside would balance the surrounding gas pressure, but due to buoyancy the bubbles would rise through the stellar surface, giving off photon bursts. Obviously, the list of potential observing targets could be made longer.

However, before observed intensity fluctuations can be ascribed to any astronomical source, the intensity scintillations arising in the Earth's atmosphere must be adequately understood. At present the behavior at very high frequencies is not well known, and it has even been suggested that electron density fluctuations in the lower ionosphere may modulate optical light at megahertz frequencies. To clarify such properties would be of value not only for the present experiment, but also for the understanding of the more general limits and possibilities of ground-based observations. An adequate understanding of scintillation in the Earth's atmosphere might be applied to the study of the fine structure of planetary atmospheres from stellar occultations. It may even be possible to study the microstructure of the solar atmosphere by observing occultations of hot stars by the Sun at ultraviolet wavelengths. Intensity scintillations would then arise because of small-scale inhomogeneities ('seeing') in the *solar* atmosphere. With a 10 ns time resolution, structures down to the corresponding light travel distance of 3 meters could be studied.

The theoretical problem of light scattering in a turbulent medium is reasonably well studied. In particular, the equations of transfer for $I^2$ and higher-order moments of intensity have been formulated and solved (e.g. Uscinski, 1977). A result that is familiar to many people implies that stars twinkle more with increasing atmospheric turbulence. The value of I, i.e. the total number of photons transmitted may well be constant, but $I^2$ increases with increasing fluctuations in the medium. The quantum-mechanical problem of scattering of light against atoms is somewhat related, except that the timescales involved are now those of the coherence time of light.

However, theoretical treatments of astrophysical radiative transfer have so far concentrated on the first-order effects of intensity, spectrum and polarization, and not on the transfer of $I^2$ and higher-order terms. There are notable exceptions, however, like the analytical solution of the higher-order moment equation relevant for radio scintillations in the interstellar medium (Lee and Jokipii, 1975; Lerche, 1979a; 1979b) and attempts to formulate the quantum-mechanical description of the transfer of radiation, including non-Markovian effects in a photon gas (Macháček, 1978; 1979) and the transfer equation for the density matrix of phase space cell occupation number states (Sapar, 1978; Ojaste and Sapar, 1979). Still, there do not yet appear to exist any theoretical predictions for specific astronomical sources of any $I^2$-profiles analogous to those in Fig.1. Until the availability of such theoretical predictions, this work will continue to have an exploratory character.

Using our signal processor in a cross-correlation mode and placing the two detectors at different spectral or spatial locations, other types of information can be extracted. In the former case, one may search for possible correlation of intensity fluctuations in two different spectral lines, formed e.g. in the same deexcitation cascade with photons of two different wavelengths emitted nearly simultaneously. In the latter case, the instrument becomes a digital intensity interferometer. Since the detectors are to be calibrated against laboratory sources, it should be possible to perform absolute measurements of $g^{(2)}$ (and hence deduce the spatial power spectrum of a blackbody source; Eq.7) using telescopes at fixed locations and without the need for measuring relative correlations over different baselines with moving telescopes. In particular, the telescopes may be at very long baselines (10 km, say), permitting the search for fine structure, such as convection cells, on the surfaces of nearby stars (Dravins, 1981b).

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