Astrophysics on Its Shortest Timescales

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The VLT will permit enormously more sensitive searches for high-speed phenomena in astrophysics, such as those expected from instabilities in accretion onto compact objects, or in the fine structure of photon emission. On [sub]millisecond timescales, light curves are of little use, and measurements have to be of power spectra or other statistical functions, which increase with the light collected to a power of 2 or more, making the gains very much greater than for ordinary photometry or spectroscopy.

High-Speed Astrophysics

The frontiers of astrophysics have expanded through observational breakthroughs. The Universe has turned out to be more enigmatic than even the creative fantasy of astronomers had been able to predict. It is worth recalling that many of today's 'ordinary' topics such as quasars or stellar coronae are results of discoveries enabled by improvements in technology. This mode of advance is different from the situation in e.g. particle physics, where it is often possible to make predictions of novel phenomena, and then to construct experimental apparatus to verify some specific theory. In astronomy, the discovery of quasi-periodic oscillations in accretion disks or of millisecond pulsars was not the result of theoretical predictions, but rather the inescapable revelation once the sensitivity in the relevant parameter space had been sufficiently enhanced. In the past, one major thrust in expanding the parameter envelope of astrophysics was the addition of new wavelength regions, in particular through space missions. Now, that most regions are accessible, the thrusts are moving toward other domains, such as higher spatial and temporal resolution. This article is concerned with the latter of these.

High-speed astrophysics, entering the previously unexplored domains of milli-, micro-, and nanosecond variability, has the goal to discover and explore the possible very rapid variability in astronomical objects. One aim will be to examine radiation from accretion systems around compact objects in the Galaxy where, in some cases, variability is already known to exist on timescales down to milliseconds. Highly energetic events occur in such gas flows onto white dwarfs, neutron stars or presumed black holes. The environments of such objects are promising laboratories to search for very rapid phenomena: the geometrical extent can be very small, the energy density very high, the magnetic fields enormous, and a series of phenomena, ranging from magneto-hydrodynamic turbulence to stimulated synchrotron radiation might well occur. Some processes may occur over scales of only kilometers or less, and there is no immediate hope for their spatial imaging. Insights can instead be gained through studies of their small-scale instabilities, such as hydrodynamic oscillations or magneto-hydrodynamic flares. Phenomena which might be encountered on timescales of seconds, milli-, or even microseconds, include:

- Plasma instabilities and fine structure in accretion flows onto white dwarfs and neutron stars
- Small-scale [magneto-]hydrodynamic instabilities in accretion disks around compact objects
- Radial oscillations in white dwarfs ($\simeq$ 100–1000 ms), and non-radial ones in neutron stars ($\lesssim$ 100 μs)
- Optical emission from millisecond pulsars ($\lesssim$ 10 ms)
- Fine structure in the emission ('photon showers') from pulsars and other compact objects
- Photo-hydrodynamic turbulence ('photon bubbles') in extremely luminous stars
- Stimulated emission from magnetic objects ('cosmic free-electron laser')
- Non-equilibrium photon statistics (non-Bose-Einstein distributions) in sources far from thermodynamic equilibrium.

Parameter Domains of Astrophysics

The whole science of astronomy can be subdivided into parameter domains with respect to electromagnetic wavelength, and the timescale of study. Classical astronomy, for example, was largely confined to wavelengths accessible from the ground, and timescales between perhaps 0.1 seconds and 10 years.

Advantages of observing in the optical

Rapid astrophysical events are generally expected in accretion processes near compact objects such as white dwarfs, neutron stars or presumed black holes. A number of such sources have previously been studied in the subsecond and millisecond ranges, both in X-rays and in the optical (e.g. Motch *et al.* 1982; Beskin *et al.* 1994).

There are quasi-periodic oscillations, flashes, pulsars, and other phenomena. For best detection and visibility, X-rays could appear to be most attractive, since they often originate in high-temperature regions quite close to the compact object.

Nevertheless, the optical region may in practice be the best for the detailed study of the most rapid phenomena. The reason is that the number of photons that can be detected per second (and especially per millisecond!) is often much greater from the optical parts of the sources (as observed with large telescopes), than that from their X-ray parts, observed with current space instruments. Foreseeable satellites will not be able to collect more than typically a thousand X-ray photons per second, even from quite bright objects (Bradt *et al.* 1990). While this will be adequate to explore many exciting phenomena, it is probably not adequate in searches for *very* rapid fluctuations.

In contrast, optical light curves of some accretion sources showing periodicity on the scale of seconds can be quite prominent already when recorded with telescopes in the 1.5-m class (Larsson 1985; Imamura *et al.* 1990). Using an 8-metre telescope, and an instrumental efficiency improved by a factor 3, implies some 100 times more photons collected. Detailed light curves could then be seen if their periodicity was merely tens of milliseconds (with count rates on the order of a million photons per second).

Another advantage of the optical is the feasibility to ultimately detect quantum

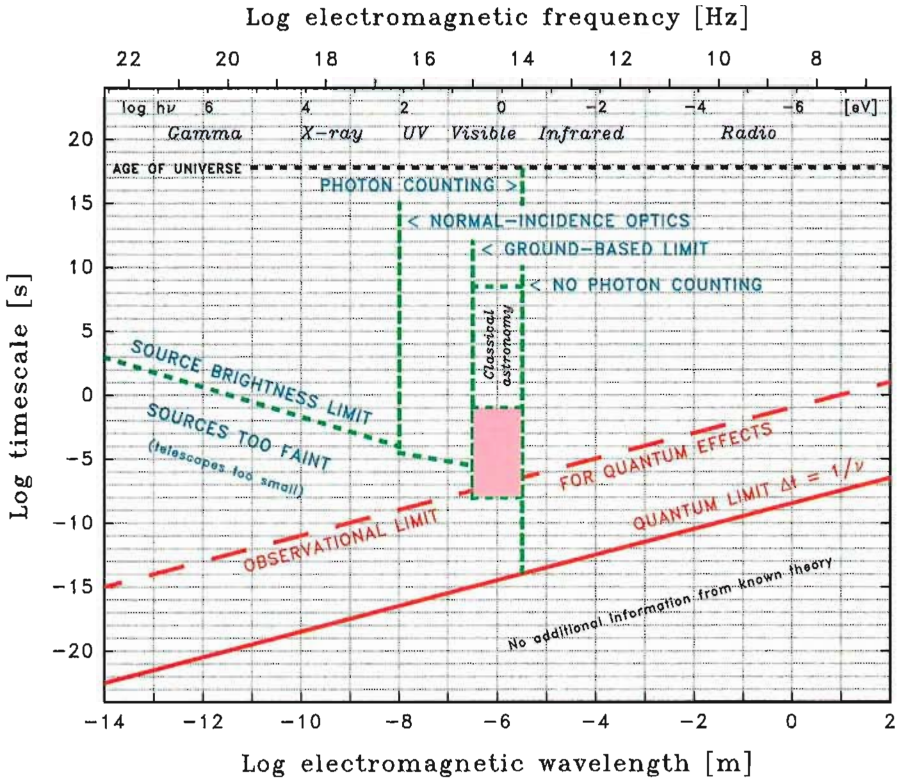

Figure 1: *Parameter domains of astrophysics, subdividing electromagnetic radiation with respect to timescale of study, and the wavelength. This diagram (covering some 500 square decades in parameter space) encompasses all of astrophysics, save neutrino, gravitational, cosmic-ray, and in-situ studies. All regions are not yet accessible to observation, in particular due to insufficient observable photon fluxes for high-energy radiation. The optical high-speed domain is marked in pink.*

phenomena. At present, these seem unreachable for X-rays, due to their much higher electromagnetic frequencies (Figure 1). Some quantum effects are easier to observe in radio (e.g. the bunching of photons appears as 'wave noise'), but a limit is set by the difficulties of photon counting at wavelengths beyond the infrared. While this does not hinder studies of rapid variability as such, it does preclude full studies of quantum effects in radiation.

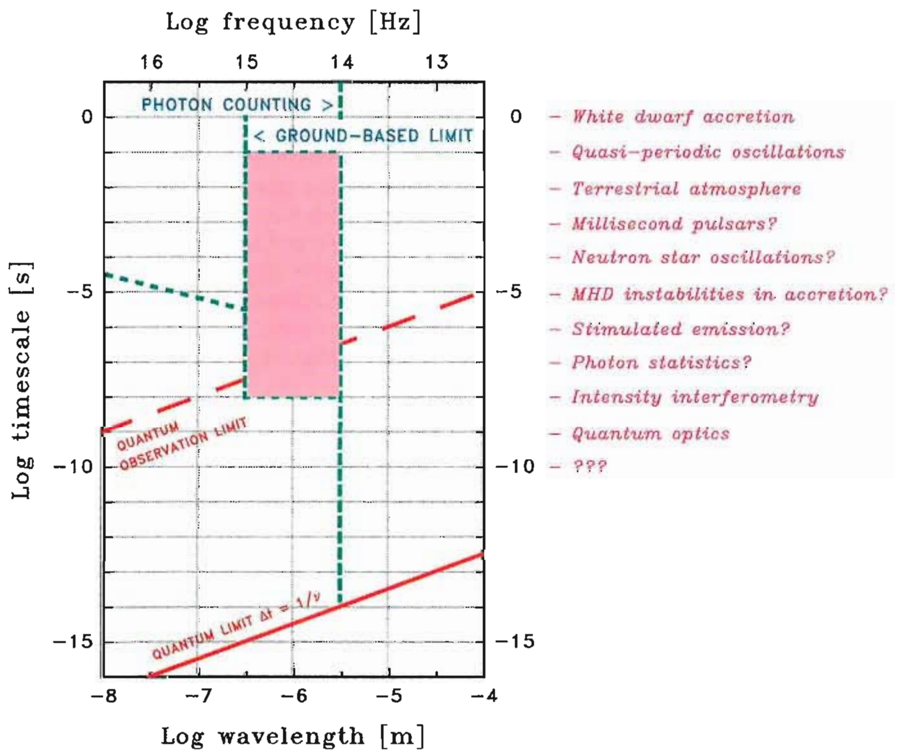

Figure 2: *A subset of Figure 1, showing a region around the optical, with expected timescales for various astrophysical processes marked.*

Accretion Physics for High-Speed Studies

What novel phenomena can we expect to detect in accretion processes? An artist's vision, combining established knowledge with predicted phenomena unfolds in the painting of Figure 3. In a close binary system, matter is escaping from the dynamic and unstable outer atmosphere of an evolved red giant and impinging into an accretion disk surrounding a black hole. (For a general review of phenomena in such systems, see e.g. Livio, 1994.) Here, the accretion flow is neither smooth, nor regular. It is turbulent, and eddies can be seen on many different scales (Meglicki *et al.* 1993). The disk is asymmetric (perhaps reflecting the time history of matter flows from the giant star; Kaitchuck *et al.* 1994; Lanzafame *et al.* 1993; Marsh *et al.* 1994; Whitehurst 1994); the accretion flow is spiral shocked (Heemskerk 1994) and warped perpendicular to its main plane (perhaps due to tidal torques or differential precession; Iping & Petterson 1990). A well-collimated jet is ejected from the central portions, but after some distance it becomes unstable (due to its internal helical magnetic field?) and disintegrates after suffering a supersonic collision with the surrounding circumstellar medium. At certain distances from the centre, hydrodynamic instabilities appear as various types of waves (Chen & Taam 1992; Honma *et al.* 1992; Wallinder 1991), possibly seen by a distant observer as quasi-periodic oscillations. The angular momentum of some of the inflowing matter conspires with moving hydrodynamic shocks to form a three-dimensional structure above and around the disk (Hawley & Smarr 1986). Some of these 'walls' are very thin, their thickness perhaps reflecting electric current sheets. Differential gas motions inside and around the accretion disk feed a dynamo which generates a chaotic magnetic field on many different spatial scales (Stone & Norman 1994; Torkelsson & Brandenburg 1994), whose energy is released in short and energetic flares of magnetic reconnection, accompanied by local mass ejections and high-energy radiation. Some magnetic areas are cooler than their local surroundings ('spots'; Bao 1992;), while others dissipate with magnetic heating and appear hotter (Horne & Saar 1991). Such magnetic processes also contribute to sustaining a hot chromosphere and corona surrounding the disk (Mineshige & Wood 1990). At the very centre, a glimpse of

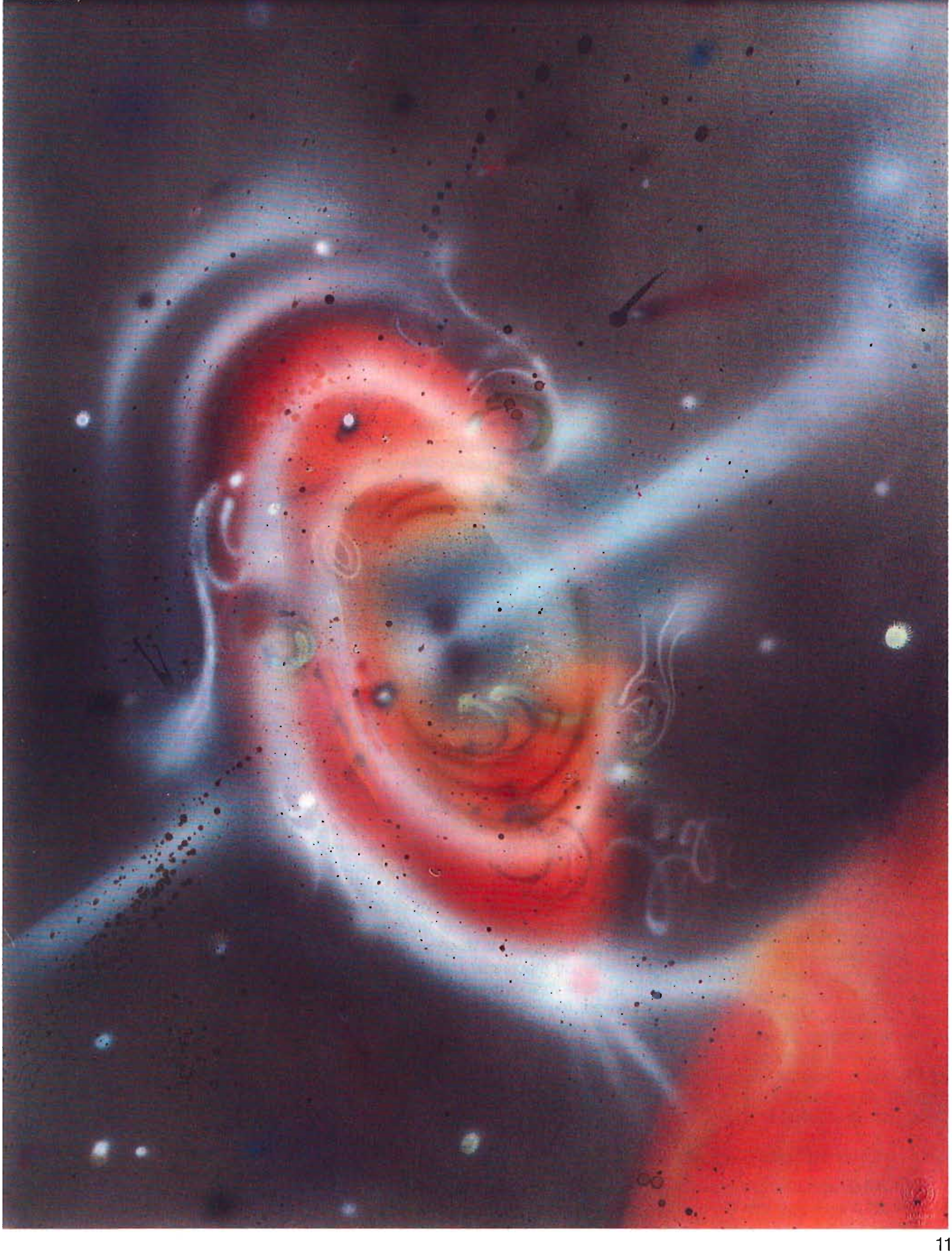

Figure 3: *Artist's vision of accretion processes in a close binary system, where matter is escaping from an evolved red giant star onto an accretion disk surrounding a black hole. This illustrates the very great complexity that may be expected in accretion flows around compact objects: numerous hydrodynamic instabilities interfere with the dynamo generation of chaotic magnetic fields, with relativistic effects visible near the centre. While there is no hope to obtain any detailed images of these phenomena in the near future, such small-scale physics of accretion processes can nevertheless be studied from analyses of rapid temporal fluctuations in their radiation. (Artwork by Catrina Liljegren, Bild & Form, Lund; copyright by the author.)*

processes very near the black hole can be seen: the appearance is asymmetric because the flux (and wavelength) of light is altered by both the gravitational field and by the Doppler effect in the rotating gas (the side approaching the observer is brighter; Fukue & Yokoyama 1988). Further, relativistic ray-bending permits us to view also the 'back' side of the central region. All this is accompanied by infalling planetisimals and crashing comets, possibly remnants of a former planetary system (Pineault & Landry 1994), local hydromagnetic instabilities seen as vortices in the gas streams ('tornados'; Abramowicz *et al.* 1992), gas ejections collimated by local magnetic fields, and many other small-scale instability phenomena (Mineshige & Kusunose 1993). On larger scales, the whole disk is undergoing acoustic oscillations (Nowak & Wagoner 1992).

How much could be reality and what is fantasy? Of course, nobody *knows* exactly what an accretion disk looks like (and, arguably, none has ever been *directly* observed). However, all the phenomena depicted in Figure 3 were inspired by predictions in the literature. Some of the processes hinted at occur over very small dimensions, and it will not be possible to image them with any presently foreseen interferometer (although some features could be made visible through Doppler imaging or similar techniques). In order to learn more, we are driven toward high time resolution. Even if there is no [immediate] hope for the spatial imaging, signatures of many events may be observable in the time domain, on timescales of seconds, milli-, or even microseconds. A resolution of 1 μs translates to a light travel distance (and thus 'resolution' along the line of sight) of 300 metres, irrespective of distance to the source.

How Rapid A Variability Can Be Detected?

Increasing the temporal resolution to microseconds, one should encounter successively more rapid events, on timescales such as those expected for magnetic instabilities in accretion systems, or for non-radial oscillations in neutron stars. However, there do not yet appear to exist any predicted *macroscopic* processes in the nanosecond domain. Such resolutions, however, lead into the *microscopic* realm of quantum optics, and the quantum-mechanical statistics of photon counts. To understand what information they carry, we have to examine the physical properties of light.

Nanoseconds and quantum optics

Classical physics 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. The best known non-classical property of light is the *bunching of photons*, first measured by Hanbury Brown and Twiss in those experiments that led to the astronomical intensity interferometer, used to measure stellar sizes (Hanbury Brown 1974). Different physical processes in the generation of light may cause quantum-statistical differences (different amounts of photon bunching in time) between light with otherwise identical spectrum, polarization, intensity, etc., and studies of such non-classical properties of light are actively pursued in laboratory optics.

Such quantum correlation effects are fully developed over timescales equal to the inverse bandwidth of light. For example, the use of a 1 nm bandpass optical filter gives a frequency bandwidth of $\simeq 10^{12}$ Hz, and the effects are then fully developed on timescales of $\simeq 10^{-12}$ seconds. Instrumentation with continuous data processing facilities of such resolutions is not yet available, but it is possible to detect these effects, albeit with a decreased amplitude, also over more manageable nanosecond intervals.

Beyond Imaging, Photometry and Spectroscopy

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 could have physical 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 ones.

To understand the 'parameter domains' in 'knowledge space' that are accessed by e.g. photometers or spectrometers, we need to understand their working principles on a very fundamental level, i.e. not superficial specifications such as field-of-view or spectral resolution, but rather their workings concerning the physical observables accessed.

One-photon experiments

We describe light as an electromagnetic wave of one linear polarization component whose electric field E contains terms of the type exp($-i\omega t$) for angular frequencies ω. 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 (Glauber, 1970). The different classes are collected in Figure 4, where $< >$ denotes time average, and * complex conjugate. For example, a bolometer measures $<E^*(0,0)\ E(0,0)>$, yielding the classical field intensity irrespective of the spectrum or geometry of the source (we define the coordinates with the observer initially at the origin). 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, $<E^*(0,0)\ E(0,t)>$, whose Fourier transform yields the power density as function of electromagnetic frequency. That is the spectrum of light which is measured by spectrometers. The function is explicitly sampled by Fourier transform spectrometers while e.g. gratings 'perform' the transform to the spectrum through diffractive interference. For the case $\mathbf{r}_1 \neq \mathbf{r}_2$ but $t_1 = t_2$ we instead have the spatial autocorrelation function $<E^*(0,0)\ E(\mathbf{r},0)>$, which is measured by imaging telescopes and [phase] interferometers, yielding the angular distribution of the source power density. The need for accurate timekeeping at both sites $\mathbf{r}_1$ and $\mathbf{r}_2$ originates from the requirement $t_1 = t_2$. In the absence of absolute flux calibrations, $G^{(1)}$ is usually normalized to the first-order coherence $g^{(1)}$.

Two- and multi-photon properties of light

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. Possible multi-photon phenomena in the photon stream reaching the observer are not identified.

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 quan-

ONE–PHOTON EXPERIMENTS

1:st order correlation function:

$$G^{(1)}[r_1,t_1;\ r_2,t_2] = \langle E^*(r_1,t_1)\ E(r_2,t_2) \rangle$$

Special case: $r_1 = r_2,\ t_1 = t_2$

$\langle E^*(0,0)\ E(0,0) \rangle$ – BOLOMETER

Special case: $r_1 \neq r_2,\ t_1 = t_2$

$\langle E^*(0,0)\ E(r,0) \rangle$ – [PHASE] INTERFEROMETER

Special case: $r_1 = r_2,\ t_1 \neq t_2$

$\langle E^*(0,0)\ E(0,t) \rangle$ – SPECTROMETER

Figure 4: *Fundamental quantities measured in one-photon experiments. 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. To this category belong all direct and interferometric imagers, spectrometers, and photometers, i.e. all ordinary instruments used in astronomy. Time average is denoted by < > while * marks complex conjugate.*

TWO–PHOTON EXPERIMENTS

2:nd order correlation function:

$$G^{(2)}[r_1,t_1;\ r_2,t_2] = \langle I(r_1,t_1)\ I(r_2,t_2) \rangle$$

Special case: $r_1 = r_2,\ t_1 = t_2$

$\langle I(0,0)\ I(0,0) \rangle$ – "QUANTUM SPECTROMETER"

Special case: $r_1 \neq r_2,\ t_1 = t_2$

$\langle I(0,0)\ I(r,0) \rangle$ – INTENSITY INTERFEROMETER

Special case: $r_1 = r_2,\ t_1 \neq t_2$

$\langle I(0,0)\ I(0,t) \rangle$ – CORRELATION SPECTROMETER

Figure 5: *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. The intensity interferometer was the first astronomical instrument in this category.*

MULTI–PHOTON PROPERTIES

Chaotic light:

$$\langle I^n \rangle = n!\ \langle I \rangle^n$$

Stable wave:

$$\langle I^n \rangle = \langle I \rangle^n$$

Chaotic light scattered by Gaussian medium:

$$\langle I^n \rangle = (n!)^2\ \langle I \rangle^n$$

Anti–bunched light:

$$\langle I^n \rangle = 0 \quad [n > 1]$$

Figure 6: *Properties of light, measurable in multi-photon experiments. Such measurements can be ascribed to quantities of type I^n, i.e. intensity multiplied n times by itself, which in the quantum limit means observations of groups of n photons or of statistical n-photon properties. The information contained in such higher-order photon correlations may include thermodynamic information of how the light was created or how it has been redistributed (scattered) since its creation. Although such problems are studied in theoretical astrophysics, they are not yet accessible to direct observational tests.*

tum 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, first observed by Hanbury Brown and Twiss. An arbitrary state of light can be specified with a series of coherence functions essentially describing one-, two-, three-, etc. -photon-correlations. A simplified expression for the second-order correlation function is given in Figure 5. It describes the correlation of intensity 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.

$G^{(2)}$ is often normalized to the second-order coherence, $g^{(2)}$. Although its strict definition involves quantum-mechanical operators, a simplified expression can be given in terms of intensities: $g^{(2)} = \langle I(\mathbf{r}_1,t_1)\ I(\mathbf{r}_2,t_2)\rangle / \langle I(\mathbf{r}_1,t_1)\rangle\langle I(\mathbf{r}_2,t_2)\rangle$. If the distribution of photons is chaotic, i.e. the photon gas is in a maximum entropy state, the second-order coherence can be deduced as $g^{(2)} = [g^{(1)}]^2 + 1$ (e.g. Loudon 1983). This property can be used to determine $|g^{(1)}|$ from measurements of $g^{(2)}$. In the intensity interferometer this is made for $\mathbf{r}_1 \neq \mathbf{r}_2$ but $t_1 = t_2$: $\langle I(0,0)\ I(\mathbf{r},0)\rangle$, 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 $\langle I(0,0)\ I(0,t)\rangle$, determining the spectral width of e.g. scattered laser light.

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 tell 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.

For a first-order coherent source with $g^{(2)} \neq 2$, neither an intensity interferometer nor an intensity-correlation spectrometer will yield correct results. E.G. a point source emitting a monochromatic stable wave whose $g^{(2)} = 1$ everywhere, would appear to be spatially resolved by an intensity interferometer at any spatial baseline and spectrally resolved by an intensity-correlation spectrometer at any timelag, and hence give the false impression of an arbitrarily large source emitting white light. This example demonstrates that additional measurements are required to fully extract the information content of 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 neighbouring 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. Experimentally, this is seen through sub-Poissonian statistics, i.e. narrower distributions of recorded photon counts than would be expected in a 'random' situation. Since the intensity of light is now a function whose average square ($\langle I^2 \rangle$) is smaller than the square of its average ($\langle I \rangle^2$), it cannot be represented through classical mathematics: this requires a quantum description.

For an introduction to the theory of such quantum optical phenomena, see e.g. Loudon (1980; 1983), Meystre & Sargent (1990), or Walls & Milburn (1994). Experimental procedures for studying photon statistics are described by Saleh (1978).

Astronomical Quantum Optics

One can envision applications of nanosecond resolution optical observations to give insight in the physical processes of radiative deexcitation of astrophysical plasmas, fields of study which presently are the almost exclusive realm of theoreticians.

Physics of emission processes

What is the physical nature of light emitted from a plasma with departures from thermodynamic equilibrium of 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? Such [partial] 'laser action' has been predicted in mass-losing high-temperature stars, where the rapidly recombining plasma in the stellar envelope can act as an amplifying medium (Lavrinovich & Letokhov 1974; Varshni & Lam 1976; Varshni & Nasser 1986). Analogous effects could exist in accretion disks (Fang 1981). In the infrared, there are several cases where laser action is predicted for specific atomic lines (Ferland 1993; Greenhouse *et al.* 1993; Peng & Pradhan 1994).

Somewhat analogous situations (corresponding to a laser below threshold) have been studied in the laboratory. The radiation structure from 'free' clouds (i.e. outside any laser resonance cavity) of excited gas with population inversion can be analysed. One natural mode of radiative deexcitation indeed appears to be the emission of 'photon showers' triggered by spontaneously emitted ones which are stimulating others along their flight vectors out from the volume.

In principle, quantum statistics of photons might permit to determine whether e.g. 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. Thus, for such scattered light, its degree of partial redistribution in frequency might be directly measurable.

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 of light would be non-trivial. In general, photon statistics for the radiation from any kind of non-thermal source could convey something about the processes where the radiation was liberated. For example, 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 but due to buoyancy, the bubbles would rise through the stellar surface, giving off photon bursts (Prendergast & Spiegel 1973; Spiegel 1976). Obviously, the list of potential astrophysical targets could be made longer.

Interpreting observed photon statistics

The theoretical problem of light scattering in a [macroscopic] 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 [moderately] increasing atmospheric turbulence. The value of I, i.e. the total number of photons transmitted may well be constant, but I^2 increases with greater fluctuations in the medium. The quantum problem of scattering of light against atoms is somewhat related, except that the timescales involved are now those of the coherence times of light.

However, theoretical treatments of astrophysical radiative transfer have so far almost exclusively concentrated on the first-order quantities of intensity, spectrum and polarization, and not on the transfer of I^2 and higher-order terms. There are some exceptions, however, like the analytical solution of the higher-order moment equation relevant for radio scintillations in the interstellar medium (Lee & Jokipii 1975; Lerche 1979a; 1979b) and attempts to formulate the quantum mechanical description of the transfer of radiation, including non-Markovian effects (i.e. such referring to more than one photon at a time) in a photon gas (Macháček 1978; 1979), the transfer equation for the density matrix of phase space cell occupation number states (Sapar 1978; Ojaste & Sapar 1979), or the introduction of concepts from non-linear optics (Wu 1993).

Still, there do not yet appear to exist any theoretical predictions for specific astronomical sources of any spectral line profiles of higher-order than one (i.e. ordinary intensity versus wavelength). Until the availability of such theoretical predictions (of e.g. the second-order coherence versus wavelength), this work will continue to have an exploratory character.

Do we understand what we are doing?

When entering new domains of physical measurement, not only the optics and electronics of the experiment, but also the fundamental physics of the quantum-mechanical interaction between the measuring instrument and the photon gas to be studied, must be adequately understood. One example will illustrate the problem. Although in common speech the opposite is often uttered, there actually does *not* appear to exist any known method of *directly* detecting photons. All 'photon-detectors' instead give some electrical signal of photo-electrons as the output to the observer. It is a sobering thought that quantum statistical properties to be measured, e.g. the bunching of several photons in the same quantum state, is a property that can *not even in principle* be possessed by these electrons. Since these have quantum spin = $\frac{1}{2}$, they are fermions and obey the Pauli exclusion principle, which prohibits two or more particles to occupy the same quantum state.

Even the optics inside an instrument may fundamentally affect the signal to be measured. For example, the reader might want to ponder what are the effects of a common beamsplitter, which makes a 50-50% split of the intensity of light. What will become of the statistical distributions of photons after the photon gas has been cleaved by this beamsplitter? (For an introduction to the theory and experiment on such issues, see e.g. Aspect & Grangier 1991.)

Instrumentation for High-Speed Astrophysics

A number of criteria can be defined for optimizing an observing instrument in high-speed astrophysics, and there have been efforts by different groups toward this end.

We have designed one such unit at Lund Observatory, named *QVANTOS* for '*Quantum-Optical Spectrometer*'. Its first version was used on La Palma to test instrumentation and observation methods, and to explore what challenges in understanding the terrestrial atmosphere that must be met before astrophysical variability on short timescales can be convincingly demonstrated to exist. The main design criteria for the *QVANTOS* instrument and a description of its performance are in Dravins *et al.* (1994), while examples of data recorded with it appear below. Basically, its key components are rapid photon-counting detectors and very fast digital signal processors for real-time computation of various statistical functions of the photon arrival times. The design issues included:

- Handling huge amounts of data: The highest time resolutions lead to data rates of perhaps megabytes per second. To make the analysis manageable, there is a need for *real-time data reduction* to statistical functions only.
- For faint sources, one wants to study variability also on timescales shorter than typical intervals between successive photons. While not possible with conventional light-curves, it is enabled through a *statistical analysis of photon arrival times*, testing for deviations from randomness.
- The terrestrial atmosphere causes rapid fluctuations of the source intensity, and a segregation of astrophysical fluctuations requires a correspondingly accurate measurement and correction for atmospheric effects.

Previous work by other groups illustrates that meeting all such (and other) requirements is non-trivial. The pioneering *MANIA* experiment at the Northern Caucasus 6-metre telescope (recently used also in Argentina; Shvartsman 1977; Beskin *et al.* 1982; 1994), has limitations in the maximum photon count rates that can be processed. Networks of telescopes used in searches for stellar oscillations, have been limited by atmospheric intensity scintillation. Instruments in space avoid the terrestrial atmosphere: the *High Speed Photometer* on the *Hubble Space Telescope* was a major effort (Bless 1982), but only limited quantities of data could be stored onboard.

The post-CCD era of optical detectors

CCD's and similar silicon-based imaging detectors now dominate optical astronomy, thanks to their high quantum efficiency and ease of use. However, such detectors are not really optimal for measuring rapid variability, due to their relatively long read-out times. Although devices and methods for more rapid CCD-frame readout (milliseconds) are being developed, there seem to be fundamental trade-offs between speed and noise. For timing individual photons on submillisecond scales, one has hitherto been limited to photocathode detectors such as photomultipliers or microchannel plates.

Such photocathode detectors, however, have a limit in their achievable quantum efficiency, and in its extension toward the infrared. As stressed further below, the signal-to-noise ratio in measured statistics of intensity fluctuations increases rapidly not only with telescope size but equally with increased detector efficiency. Since future observational needs will include relatively faint accretion sources in the Galaxy, some of which may be reddened by circumstellar material, we are facing the need for a high quantum efficiency extending into the [infra]red. Such challenges are now stimulating the gradual emergence of a new post-CCD generation of detectors for optical astronomy: combining imaging at high quantum efficiency, photon counting with nanosecond resolution into the infrared, and even intrinsic spectroscopic resolution.

Photon-counting avalanche diodes

The quantum efficiency for a silicon detector, compared to photocathode ones, can be several times greater, and may extend into the far red to about 1 μm.

During recent years, the development of *silicon avalanche photodiodes* has reached a point, where they can now be used for photon counting (Brown *et al.* 1990; Dautet *et al.* 1993; Nightingale 1991; Sun & Davidson 1992; Szécésnyi-Nagy 1993). Absolute quantum efficiencies in single-photon detection up to 76% (at λ 700 nm) have been experimentally demonstrated (Kwiat *et al.* 1994). Some astronomical groups (including ourselves) have now acquired such detectors, at least for the purpose of laboratory evaluation. Besides photon counting at impressive efficiencies, avalanche diodes however also bring a number of new and undesired (and partly unknown) properties. One phenomenon not seen in photocathode detectors is that the electronic avalanche during the photon detection temporarily disturbs the semiconductor and causes light to be *emitted* from the detector surface. The dark count can be *bistable* in the sense of sudden jumps between discrete levels, apparently due to phenomena at impurity sites inside the diode. Awkward problems are caused by their very small physical dimensions. While the light-sensitive area in photomultipliers typically extends over several mm, the usable area of present photon-counting diodes is typically no more than some 1% that of a normal photomultiplier. For use on a large telescope, this circumstance makes the optical and mechanical designs quite challenging.

Developments of larger-area avalanche diodes are being pursued in industry, and prototypes of significantly larger size have been tested (e.g. Woodard *et al.* 1994). Some other problems related to the active quenching of the avalanches (giving shorter dead-times and thus permitting higher count rates) have apparently been solved, but there still remain some non-uniformities in sensitivity across the detector area, and the dark signal increases for larger detectors. Solutions to these and other problems are actively being sought in the industry. Also, photon-counting with *germanium* avalanche diodes has

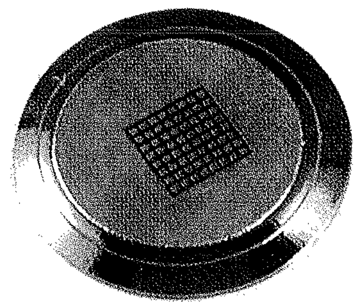

Figure 7: *An avalanche photodiode array, example of an optical detector for the post-CCD era. This class of detectors has the potential for quantum efficiency approaching unity (and extending into the infrared), while counting individual photons at nanosecond resolution (Madden 1993).*

been demonstrated, extending sensitivities further into the infrared (Lacaita *et al.* 1994; Owens *et al.* 1994).

In another development with silicon devices, *avalanche photodiode arrays* have recently been developed (Fig. 7), stimulated by non-astronomy needs such as detectors for ladar (laser radar), recording laser-pulse illuminated scenes, where the distance to objects imaged in the field is determined by timing photon arrivals within nanoseconds. Although such devices do not yet appear to be available in photon-counting mode, a conceivable future photon-counting 4096 $\times$ 4096 photodiode array with, say, a 1 MHz photon count rate per pixel could generate more than 10^7 Mb (= 10 Terabytes) per second, or 10^{12} Mb (= 1 Exabyte) during a 3-night observing run. The data handling issues will become interesting, but only with such detectors could one begin to really exploit the potential of the VLT for high-speed applications. Even so, they would be far from ultimate, since there is still no intrinsic energy nor polarization resolution, and in order to separate different wavelengths, spectrometers or filters would still have to be used, with all their known inefficiencies in light transmission.

Spectrally resolving detectors

Astrophysical variability may be different in different wavelength regions (where different opacities enable one to see differently deep into accretion flows); inside and outside a spectral line (where the radiative non-equilibrium and deexcitation may be different from that in the continuum); or even in different polarizations (where the emission may come from different magnetic regions). Thus, to extract all information, photon arrival times and positions should be recorded with a high spectroscopic and polarimetric resolution. Especially for extended astronomical sources, such studies are hampered by the two-dimensional nature of common photon detectors. Even if spectrometers were efficient, most light would be lost because the instrument must scan in the spatial or spectral domain. Here, energy-resolving detectors are needed, which in addition to spatial and temporal data also measure the photon wavelength. Such detectors are widely used in X-ray astronomy, and developments are in progress to apply related techniques also in the optical and infrared.

One line of development concerns photon counting using superconducting tunnel junctions (Perryman *et al.* 1992; 1993; 1994). The principle is that a photon impinging on the detector generates charge carriers within it, and these are collected by nearby elements in a junction array. The energy required to create a charge carrier within a superconductor is some three orders of magnitude less than in a semiconductor such as silicon. It is of order milli-eV, and thus an optical photon (of a few eV energy) creates a 'cloud' with perhaps 100–1000 of charge carriers. Even if not all are detected, the impact of the optical photon is recorded with an efficiency approaching unity (analogous to X-ray detectors, where an energetic photon liberates many electrons). The timing of the arrival of this 'cloud' to the nearest elements of the junction array permits both positional encoding and time resolution. Pulse counting gives the number of liberated charge carriers, and thus the energy of the absorbed photon, i.e. its wavelength. This concept promises large-area detectors of very high sensitivity, photon-counting at high time resolution, combined with a moderate wavelength resolution ($\lambda/\Delta\lambda \simeq 30$).

Another line of development, permitting extremely high spectral resolution in the detector ($\lambda/\Delta\lambda \geq 500{,}000$), exploits certain organic molecules, cryogenically cooled. The method involves a persistent spectral hole-burning in a dye-doped polymer film, a technique otherwise being developed for optical data storage; Keller *et al.* (1994a; 1994b).

An organic molecule such as chlorin is used in a film cooled by liquid helium. The natural line width of chlorin at this temperature is about 0.2 pm ($\lambda/\Delta\lambda \simeq 3\ 10^6$). A superposition of such very narrow but overlapping absorption lines forms a broad and smooth absorption band, some 10 nm wide. This wavelength spread of the individual absorption lines is due to wavelength shifts enabled by local electrical potentials. When a molecule absorbs a photon, it undergoes a photo-reaction which makes the molecule insensitive to light in that particular wavelength band, analogous to the functioning of dyes in a color film. The spectral information is retrieved using a scanning dye laser: tests on the solar spectrum confirm a performance comparable to the highest resolution spectrometers used in astronomy. Time resolution, however, is as yet lacking in this concept.

These examples of detector developments for the post-CCD era in optical astronomy illustrate both the new possibilities that may come, and the many challenges that yet remain. Future detector gains will add to the telescope ones, making a VLT with future detectors enormously more powerful than with its first-generation instruments.

The Role of the VLT

At very high time resolution, data rates are very high, and classical light curves are of little use. Measurements thus have to be of autocorrelations, power spectra, or other statistical properties of the arriving photon stream. All such statistical functions depend on a power of the average intensity that is higher than one. For example, an autocorrelation (which is obtained by multiplying the intensity signal by itself, shifted by a time lag) is proportional to the *square* of the intensity. Due to this dependence, very large telescopes are much more sensitive for the detection of rapid variability than ordinary-sized ones.

A search for e.g. magneto-hydrodynamic instabilities in accretion disks around supposed black holes, using autocorrelation techniques, will benefit a factor $(8.2/3.6)^4 \simeq 27$ if using one 8.2-metre telescope instead of a 3.6-m one, rather than the ratio $(8.2/3.6)^2 \simeq 5$ that is valid for the intensity. For other measures, e.g. those of the fourth-order moments of the photon distribution, the signal will increase as the fourth power of the intensity, making a full Very Large Telescope with four 8-metre units some 185,000 times more sensitive than a 3.6 m one (implying that one night of observing on the full VLT gives the same signal as 500 years of integration with a 3.6-m! (Fig. 8).

These large numbers may appear unusual when compared to the more modest gains expected for classical instruments, and initially perhaps even difficult to believe. Such numbers are, however, well understood among workers in non-linear optics. The measured $\langle I^4 \rangle$ is proportional to the conditional probability that four photons are recorded within a certain time interval. $\langle I^4 \rangle$ itself is,

	Telescope diameter	Intensity $< I >$	Second-order intensity correlation $< I^2 >$	Fourth-order photon statistics $< I^4 >$
	3.6 m	1	1	1
	8.2 m	5	27	720
	4 * 8.2 m	21	430	185,000

Figure 8: *Comparisons between the observed signal of source intensity (I), its square and fourth powers, for telescopes of different size. The signal for classical quantities increases with the intensity I; the signal in power spectra and similar functions suitable for variability searches, as I^2; and that of four-photon correlations as I^4, as relevant for quantum statistics studies. The advent of very large telescopes greatly increases the potential for high-speed astrophysics.*

strictly speaking, not a physical observable: either one detects a photon in a time interval, or one does not. $<I^4>$ therefore has the meaning of a rapid succession of intensity measurements: $<I(t)\, I(t+\Delta t)\, I(t+2\Delta t)\, I(t+3\Delta t)>$. In an experiment where one is studying the multi-step ionization of some atomic species, where four successive photons have to be absorbed in rapid succession, one notes how a doubling of the light intensity causes a 16-fold increase in the ionization efficiency. Or indeed, for light of identical intensity, how the efficiency may increase if the illuminating light source is changed to another of the same intensity but with different statistical properties, i.e. a different value of $<I^4>$. But it does not stop here. The prospect of improved detectors will further increase the efficiency in a multiplicative manner. An increased quantum efficiency in the visual of a factor 3, say, or in the near infrared a factor 10, will mean factors of 10 and 100 in second-order quantities, while the signal in fourth-order functions will improve by factors 100 and 10,000, respectively. These factors should thus be *multiplied* with those already large numbers in Figure 8, to give the likely gains for the VLT equipped with future detectors, as compared to present ones.

Due to analogous steep dependences on intensity, the research field of non-linear optics was opened up for study by the advent of high-power laboratory lasers. In a similar vein, the advent of very large telescopes could well open up the field of high-speed astrophysical variability and bring astronomical quantum optics above a detection threshold.

Signal-to-noise at the quantum limit

In the limit of the highest time resolution, the statistical nature of light has to be understood, including those properties that may appear non-intuitive, if approached from classical optics. The higher-order optical coherence functions are independent from the first-order ones (which define e.g. the brightness or the spectrum of the source). It then follows that also the signal-to-noise ratios must be independent from the latter. This somewhat non-intuitive situation was encountered already in the intensity interferometer which could not measure cool (red) stars, not even the brightest ones (Hanbury Brown 1974). The practical observability limit for quantum phenomena is set not by the apparent brightness of the source (measured as photons arriving per unit time), but more by the number of photons per [spatial and temporal] coherence volume.

An ideal telescope may re-create, in its focal volume, the same photon density as in the source (but no more, due to the laws of thermodynamics). Thus a solar telescope may achieve a photon density corresponding to a $\simeq$ 5800 K blackbody: the solar surface temperature, but no hotter. An ideal telescope observing *Sirius*, however, could reach its surface temperature of 10,000 K. *Sirius'* angular size is some 6 milliarcseconds; the diffraction limit for one 8-m telescope is about twice that, i.e. the diffraction-limit volume is $\simeq 2^3 = 8$ times that image volume where T_{eff} would be 10,000 K. Compared to the Sun, the *Sirius* surface flux density is $(10{,}000/5{,}800)^4 \simeq 9$ times greater, and thus one 8-m telescope, if operated at its diffraction limit, will measure about the same photon density in its focal volume if it is pointed at *Sirius* or at the Sun!

Atmospheric Intensity Scintillation

However, before observed intensity fluctuations can be ascribed to any as-

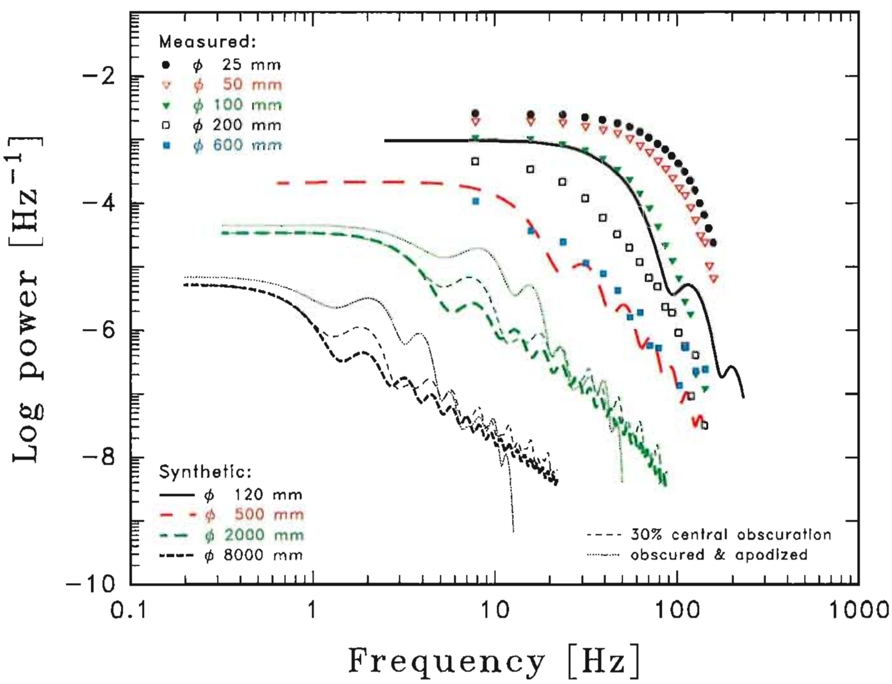

Figure 9: Atmospheric intensity scintillation around λ 500 nm for telescopes of different aperture sizes. The symbols are values measured on La Palma during good summer conditions for small telescope apertures. This sequence was fitted to synthetic power spectra for up to 8 metre diameter, thus predicting the scintillation in a VLT unit telescope. The bold curves are for fully open apertures. The inclusion of a central obscuration, corresponding to the secondary mirror (here taken as 30% of the primary diameter), increases the scintillation power, while apodization of this aperture (i.e. introducing a smooth intensity fall-off near its edges), decreases it for high temporal frequencies (Dravins et al. 1995).

tronomical source, the intensity scintillations caused by the Earth's turbulent atmosphere must be adequately understood, measured, and calibrated for. An understanding of atmospheric scintillation is needed both for the optimal design of instrumentation and the observing strategies, and in the analysis of the data, segregating astrophysical variability from terrestrial effects.

For this purpose, extensive observations of stellar intensity scintillation on short and very short time scales (100 ms–100 ns) were made during several weeks of observing with the *Mark I* version of our *QVANTOS* instrument, used on the Swedish 60-cm telescope on La Palma (Dravins et al. 1995). Atmospheric scintillation was measured as function of telescope aperture size and shape; degree of apodization; for single and double apertures; for single and binary stars; in different optical colours; using different optical passbands; at different zenith distances; at different times of night; and different seasons of year. Data were recorded as temporal auto- and cross-correlation functions, and intensity probability distributions, sometimes supplemented by simultaneous video recordings of the stellar speckle images, as well as seeing disk measurements in an adjacent telescope.

Several scintillation properties can be understood in terms of the illumination pattern caused by diffraction in inhomogeneities of high atmospheric layers. These structures are carried by winds, resulting in 'flying shadows' on the ground (Codona 1986). The dependence on aperture diameter $\oslash$ was studied, using rapidly changeable mechanical masks in front of the telescope. This aperture dependence disappears for $\oslash \leq 5$ cm. On such spatial scales, the structures in the 'flying shadows' on the ground appear resolved (both the autocorrelation half-widths and the amplitudes then become independent of aperture size). On these scales, also differences in scintillation between different colours become apparent.

Measured autocorrelations were transformed to power spectra. The power decreases for larger apertures (especially at high frequencies), reflecting the spatial averaging of small-scale turbulence elements. At frequencies $f \geq 100$ Hz, the power decreases approximately as f^{-5}. The observed statistics of intensity variations can be adequately described by log-normal distributions, varying with time.

Scintillation in the VLT: what will change?

Very large telescopes integrate the 'flying shadow' pattern over a correspondingly larger area, averaging out primarily the smaller-scale (and thus more rapidly varying) components. This is seen in Figure 9, which shows the scintillation power spectrum predicted for the 8-metre VLT unit telescopes. These curves were obtained from theoretical models for apertures of different size (computed by A.T.Young), where the normalization to actual scintillation amplitude and atmospheric windspeed was obtained by fitting the models to representative observations.

What will not change?

By no means will effects of scintillation disappear in very large telescopes. While some quantities (e.g. the power in Fig. 9) will decrease, others are independent of telescope size. An example of the latter is the temporal correlation between scintillation in different colours. Near zenith, the intensity fluctuations are simultaneous, but with increasing zenith angle (and increasing wavelength difference), a time delay may develop (Fig. 10). This is visible as a shift of the cross correlation maximum away from the origin. The 'flying shadows' on the ground become chromatic, a projection onto the ground of the starlight which has been spectrally dispersed by the atmosphere. The 'blue' part in the 'flying shadows' on the ground is displaced from its 'red' part, but the structure of the 'shadows' is similar. As these race past the telescope, a time difference is visible. In the violet, the dispersion of air changes rapidly with wavelength, which explains the significant differences between the nearby wavelenghts of λ 365 and λ 400 nm. These effects, however, appear only if looking along a wind direction, i.e. the direction of motion of the 'flying shadows'. At right angles from this, there is no effect.

An understanding of such phenomena is obviously required when searching for astrophysical phase shifts between variations in different colours, such as between oscillations in different layers inside accretion columns (visible at different wavelengths due to different opacities), or in searching for time delays between fluctuations in different spectral lines, perhaps formed in the same deexcitation cascade with photons of different wavelengths emitted more or less simultaneously.

A deeper understanding of scintillation in the Earth's atmosphere might be ap-

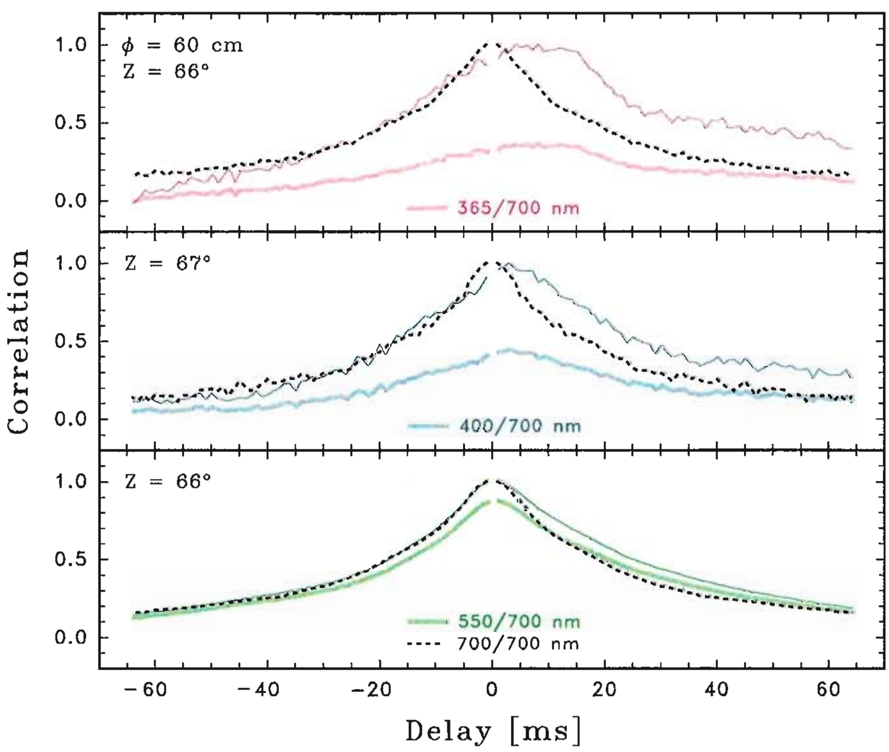

Figure 10: *Cross correlation between atmospheric intensity scintillation in different colours. Near zenith such fluctuations are simultaneous, but with increasing zenith angle a time delay develops. In this sequence from La Palma, scintillation at λ 700 nm was auto-correlated, as well as cross-correlated with that simultaneously measured at λ 550, 400, and 365 nm. With increasing wavelength difference, (a) the 'agreement' (i.e. degree of correlation) between scintillation in different colours decreases (thick curves), and (b) a time delay develops, visible as a shift of the correlation maximum (normalized thin curves). This effect is due to atmospheric dispersion, which causes chromatic displacements of the 'flying shadows' on the ground, an effect due to the atmosphere and independent of the size of the telescope (Dravins et al. 1995).*

plied also to the study of the fine structure of planetary atmospheres from stellar occultations, another application of high-speed measurements.

Conclusions and Outlook

Various approaches have been outlined for attempts to reach into the new parameter domains of milli-, micro- and nanosecond astrophysical variability. Such studies must of course be made in close contact with those in other wavelength bands (in particular X-rays), and in parallel with theoretical modelling. What makes the prospects especially exciting at the present time, is the new generation of very large optical telescopes. Since the signal of statistical variability increases dramatically with light collecting power, large telescopes become *enormously more sensitive* than ordinary-sized ones; new detector developments further enhance the potential. This quantum jump in sensitivity might well open up the field of high-speed astrophysical variability and bring astronomical quantum optics above a detection threshold.

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