Atmospheric Intensity Scintillation of Stars on Milli- and Microsecond Time Scales

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Abstract

Stellar intensity scintillation on short and very short time scales ($\approx$100 ms – 100 ns) was studied using an optical telescope on La Palma (Canary Islands). Photon counting detectors and real-time signal processing equipment were used to study atmospheric scintillation as function of telescope aperture size, degree of apodization, for single and double apertures, in different optical colors, at different zenith distances, times of night, and seasons of year. The statistics of temporal intensity variations can be adequately described by log-normal distributions, varying with time. The scintillation timescale ($\approx$10 ms) decreases for smaller telescope apertures until $\approx$5 cm, where the atmospheric 'shadow bands' apparently are resolved. Some astrophysical sources may undergo very rapid intrinsic fluctuations. To detect such phenomena through the turbulent atmosphere requires optimized observing strategies.

1. The challenge of high-speed astrophysics

The present study is part of a broader program in high-speed astrophysics, an exploratory project entering the domains of milli-, micro-, and nanosecond variability. Possible future studies include:

- Plasma instabilities in accretion flows onto white dwarfs and neutron stars
- Magneto-hydrodynamic instabilities in accretion disks around compact objects
- Radial oscillations in white dwarfs, and in neutron stars
- Optical emission from millisecond pulsars
- Emission fine structure ('photon showers') from pulsars and other objects
- Photo-hydrodynamic turbulence ('photon bubbles') in extremely luminous stars
- Stimulated emission from magnetic white dwarfs ('cosmic free-electron laser')
- Non-thermodynamic-equilibrium photon statistics from exotic sources

To study such rapid phenomena is not possible everywhere in the spectrum. For high photon energies (e.g. X-rays), a limit is set by the observable photon count rates with current spacecraft, and for low energies (e.g. radio), counting of individual photons is not yet feasible, precluding studies of certain quantum effects. The most promising domain therefore seems to be the ground-based optical, the region for which we have constructed a dedicated instrument, '*QVANTOS*' ('Quantum-Optical Spectrometer'). Its design considerations included, in particular, the following points:

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Data glut: 1 ms resolution means 3.6 million points an hour, and 100 Mb in three nights. However, 1 μs gives 100 Gb, and a mere plot of the light curve (at laser printer resolution) would subtend $\simeq$100 meters per second. Thus, there is a need for real-time data analysis, and a reduction of the data to manageable statistical functions only.

Faint sources: Many interesting sources are faint. To study variability on time-scales *shorter* than typical intervals between successive photons, a statistical analysis of their arrival times is required to test for deviations from randomness.

Time resolution: The highest time resolution that is meaningful, is set by quantum-optical properties of light, e.g. the bunching of photons in time. Such properties are fully developed on times equal to the inverse frequency bandwidth of light ($\simeq 10^{-14}$ s), but may be detectable also on much longer (nanosecond) timescales.

The terrestrial atmosphere causes rapid fluctuations of the source intensity. Accurate determinations of astrophysical fluctuations require a correspondingly accurate measurement, calibration, understanding, and correction for atmospheric effects.

The first version of our instrument (*QVANTOS Mark I*) has been extensively used to study atmospheric scintillation using the Swedish 60-cm telescope, located at 2400 m altitude at the observatory on Roque de los Muchachos (La Palma, Canary Islands). In this paper, we describe some of the results from these observations.

2. Observations, instrumentation, and data reduction

Systematic observations of stellar intensity scintillation on timescales between $\simeq$100 ms and $\simeq$100 ns were made. About 25 full nights were used to study the dependence on telescope aperture size, degree of apodization, for single and double apertures, for single and binary stars, in different colors, using different passbands, at different zenith distances, at different times of night, and different seasons of year. Scintillation properties were recorded as temporal auto- or cross covariance 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.

The photometer optics and detectors (very fast photon-counting photomultipliers) were placed at the Cassegrain focus, with cables leading to digital signal processors and real-time data displays on the observing floor. Computations are made of the temporal autocovariance (ACO), cross covariance (CCO) and photon count distribution (probability density, PDE). The time resolution (sample time) is selected in software to between 20 ns and 1 s. With 64 registers for data storage, the covariance measurements are made with 64 different time delays simultaneously. In PDE mode, the number of occasions when $0, 1, \ldots, 63$ photons are recorded during one sample interval, is measured.

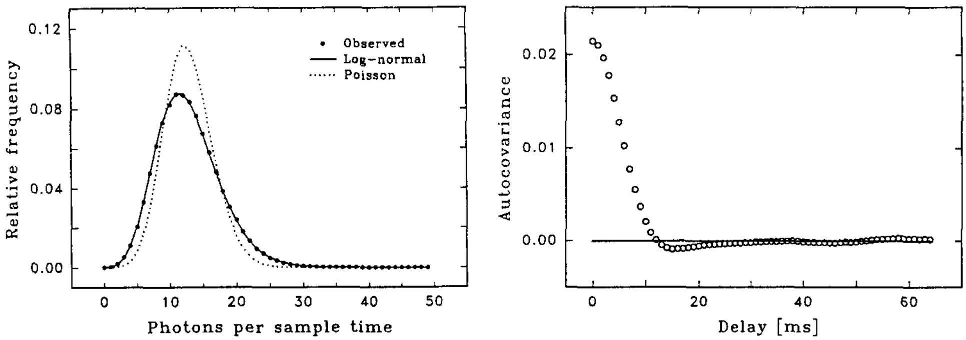

Figure 1. To the left a typical observed photon-count distribution is shown. A log-normal distribution is fitted to the data. The Poisson distribution corresponding to zero atmospheric intensity fluctuation is also shown. To the right is a typical autocovariance function of the starlight intensity, measured at time delays 1, 2, 3, etc. milliseconds, here integrated for 100 s.

The function ACO(τ) measures the strength of the intensity fluctuations for different delays τ. It satisfies ACO$(0) = \sigma_I^2$ and ACO$(\infty) = 0$, where σ_I is the root-mean-square value of $(I - \langle I \rangle)/\langle I \rangle$. The Fourier transform of ACO(τ) yields the scintillation power spectrum. The autocorrelation is the normalized function ACO(τ) / ACO(0).

The PDE is a measure of the statistics of the intensity fluctuations. The observed distribution is a convolution of the atmospheric fluctuations with the Poisson distribution (inherent in the detection process) of the photon counts. We have fitted log-normal distributions to all our data (several hundred measurements under different conditions), and found it to be an adequate distribution for $\sigma_I^2 < 0.4$.

Elementary theory predicts a functional dependence of σ_I^2 on aperture diameter D, wavelength λ, and zenith distance z, with the limits for large and small apertures:

$$\sigma_I^2 = \begin{cases} \text{const} \cdot D^{-7/3} (\sec z)^3 \int_0^\infty h^2 \, C_N^2(h) \, dh, & D >> r_0 \quad \text{(1a)} \\ \text{const} \cdot \lambda^{-7/6} (\sec z)^{11/6} \int_0^\infty h^{5/6} \, C_N^2(h) \, dh, & D < r_0 \quad \text{(1b)} \end{cases}$$

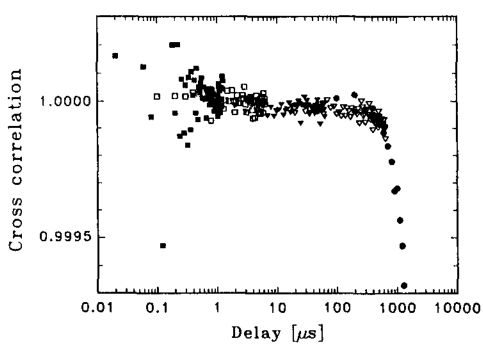

Figure 2. Stellar scintillation on very short time-scales. This plot shows the small deviations from unity close to the origin. This particular measurement (λ 550 nm, 60 cm aperture) was made as a cross correlation between the signals from two detectors, each measuring the same star through a beamsplitter. This arrangement minimizes effects of photomultiplier after-pulsing. Photon noise causes a spread of data points for the shortest delays.

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(e.g. Roddier 1981), where r_0 is Fried's parameter and $C_N^2(h)$ the refractive index structure coefficient as function of height h above the telescope.

Several properties can be understood in terms of the illumination pattern caused by diffraction in inhomogeneities in high atmospheric layers. These structures are carried by winds, resulting in 'flying shadows' on the ground (e.g. Codona 1986).

3. Scintillation on extremely short timescales

Figure 2 shows an example of the autocorrelation for very short time delays. On longer timescales, the curve is smoothly decreasing (cf. Fig. 1b), but at shorter delays there is largely a lack of structure. In this domain one may expect to find signatures of the *inner scale* of atmospheric turbulence, i.e. the smallest eddies with temperatures, etc. distinctly different from their surroundings. From other studies, that scale is expected to be $\simeq$3 mm. With the 'flying shadow' patterns carried across the telescope by windspeeds of $\simeq$10 m/s, a linear size of 3 mm corresponds to characteristic times of $\simeq$300 μs.

4. Aperture dependence

Rapidly changeable mechanical masks in front of the telescope were used to study the dependence on different types of aperture. Figure 3 shows how the fluctuations change with aperture size until $D \lesssim 5$ cm, where the structures in the 'flying shadows' on the ground appear to be resolved. The spatial properties were also studied with *apodized* (i.e. 'unsharp') telescope apertures, achieved by placing suitably airbrush-painted thin mylar films in front of the telescope. Such apodized apertures are expected to generate

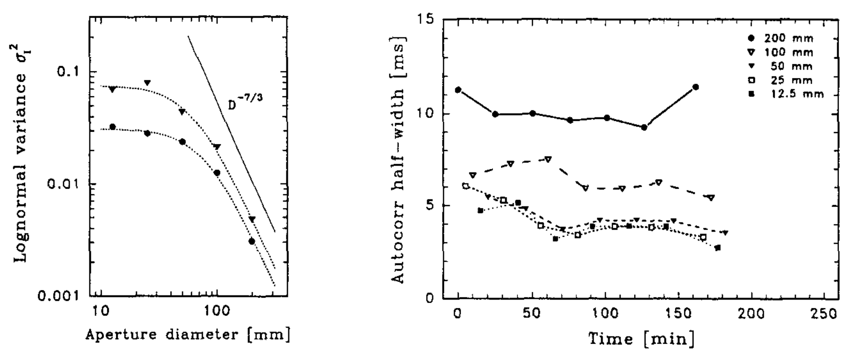

Figure 3. Aperture dependence of the scintillation variance $\sigma_I{}^2$ (obtained by fitting a log-normal distribution to the observations; left), measured at two different times. The slope $-^7/_3$ corresponds to Eq. (1a), the expected behavior for large apertures. At right is the aperture dependence of autocorrelation timescale [width at half-maximum of ACO(τ)], as well as typical changes over a few hours. Both the half-widths and the amplitudes become essentially independent of aperture size for $D < 5$ cm, where the structures in the 'flying shadows' on the ground appear to be resolved.

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less scintillation power at high temporal frequencies, since the bright and dark bands in the 'flying shadows' are then subject to a more gradual intensity cutoff at the edge of the telescope aperture (Young 1967).

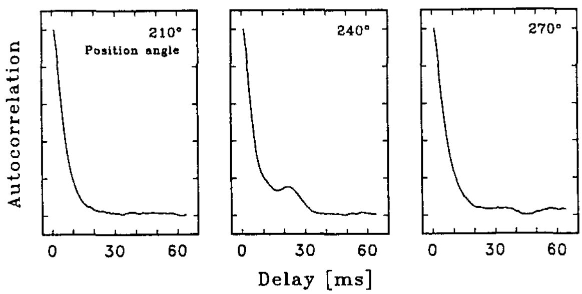

Figure 4. Intensity autocorrelation, measured through a mask with *two* holes. If the same 'flying shadows' pass both holes, a secondary peak appears. From the spacing (here 30 cm), and position angle of the holes, the speed and direction of the 'flying shadows' can be determined. Typical delays indicate a speed of $\simeq 15$ m/s, apparently the wind-speed in the upper atmosphere.

5. Wavelength dependence

This was studied with different broadband filters and different aperture sizes. For apertures smaller than $\simeq 10$ cm there is a measurable difference for different colors. For small apertures, our data agree well with the theoretical slope $-7/6$ in Eq. (1b), but the wavelength dependence rapidly diminishes for larger apertures. At shorter optical wavelengths, the fluctuations are thus more rapid, and show a greater variance.

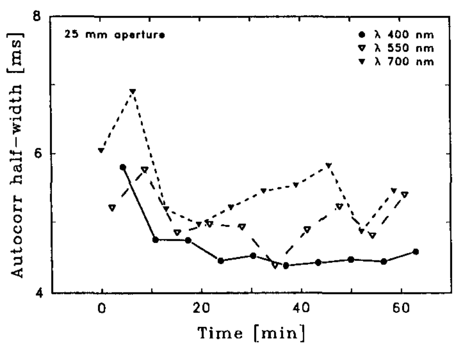

Figure 5. Wavelength dependence of the scintillation timescale, measured with a 25 mm aperture, also showing typical atmospheric changes during one hour.

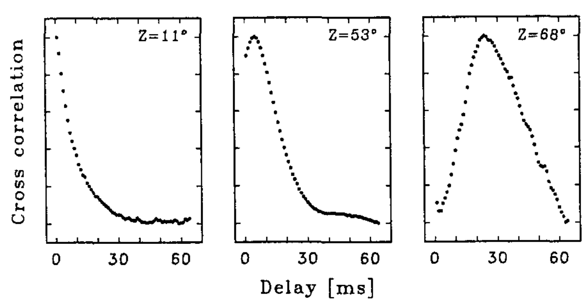

Figure 6. *Cross correlation* between fluctuations at λ 400 and 700 nm, and its zenith-angle dependence. Near zenith the fluctuations are simultaneous, but with increasing zenith angle a time delay develops. This is due to atmospheric dispersion, which causes chromatic displacements of the 'flying shadows'.

6. The search for rapid astrophysical phenomena

The analysis of these and other data is in progress with an aim of better understanding the properties and physical origins of stellar scintillation (e.g. Jakeman et al. 1978; Stecklum 1985), and for comparing the La Palma conditions to those at other observatories, such as Mauna Kea on Hawaii (Dainty et al. 1982).

The final aim, however, is to utilize this understanding in order to detect rapid fluctuations in astronomical objects. From laboratory experiments, Figure 7 shows an example of how microsecond scale fluctuations in light intensity can be detected. For astronomical sources, such fluctuations will be superposed on the most rapid atmospheric scintillations (cf. Fig. 2), and a careful segregation of atmospheric effects must precede any astrophysical conclusions. It appears that simultaneous observations of a calibration star will be required, whereupon variability in the target may be identified from differences of the intensity statistics between it and the calibration star.

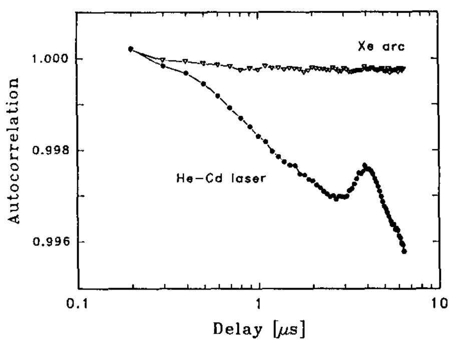

Figure 7. Rapid fluctuations in laboratory light sources. Autocorrelation functions are shown for a largely stable xenon arc lamp, and a more unstable He-Cd laser. The gradual falloff of the latter curve indicates a slower variability, while the peak around $4\mu s$ is a signature of plasma oscillations at ≈ 250 kHz in this low-pressure source. Fluctuations this rapid have not yet been detected in any astronomical object.

Acknowledgements

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Discussion

R.M. Genet: *Would a very close comparison star or fast, on-line computation of some sort, allow more accurate differential photometry? This is of interest to us as scintillation is the main limit to the precision of our measurements.*

Dravins: Yes, real-time monitoring of a close enough comparison star should indeed permit more accurate photometry. Ideally, one could think of a grid of close comparison stars, surrounding the target object. Note, however, that the comparisons should be observed in the same colour as the target, since scintillation is colour-dependent.

A. T. Young: *The area of sky over which scintillations of stars are correlated is the angular size of the telescope pupil as seen from the upper troposphere where scintillation comes from, (about 10 Km). For an 8-metre telescope, this angular scale is* $8 \cdot 10^{-4}$ *radians, or about 2 arc minutes. So stars separated by less than 1 or 2 arc minutes will have partly correlated scintillations.*

The Deputy Lord Mayor of Dublin, Councillor Brendan Brady with Denis Sullivan, Whetu Tirikatene-Sullivan and Patrick Wayman at the Civic Reception in the Mansion House

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