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PRINCIPLES AND APPLICATIONS OF THE SYNCHRONOUS NETWORK OF REMOTE TELESCOPES

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Abstract. A new approach for the search of microvariability and high-speed phenomena in variable stars is presented. It gives a new technology of observation and analysis of the data. Statistical photometry stands on the three pillars: the digital filtering technique, the photon counting statistics based on the Mandel equation, and the integral transforms of the light curves. This technique permits to investigate low-amplitude and rapid variability of stars.

Key words: techniques: photometric – methods: statistical – stars: variable

1. INTRODUCTION

The Synchronous Network of Remote Telescopes (SNT) represents a novel approach in astrophysics. The SNT involves telescopes at four observatories in Ukraine, Russia, Greece and Bulgaria equipped with GPS receivers to control local photometer timing systems relative to UTC. To integrate some apertures in a uniform network, we need to synchronize all remote telescopes to UTC within the sampling time. Synchronous operation of several remote telescopes enables us to obtain data sets with the same true signal and independent uncorrelated noise. This makes it possible to increase the S/N ratio. The SNT network involves an innovative observational technique and dedicated data processing software. It incorporates state-of-the-art experiments, providing information of unprecedented quality on small-scale variability.

Modern observations of microvariability may be analyzed in the context of statistical photometry. Analytical solutions for two important special cases can be obtained: (1) in the case when stochastic variability on the shortest time scale can be detected and evaluated using the Mandel equation and (2) by using a probability integral transformation of the single-site light curves with subsequent conversion them to the cumulative probability functions. In both cases a considerable gain can be achieved with the SNT approach. These techniques make possible the detection of photometric events comparable to the limit of the counting statistics. The study of superfast varying sources when characteristic time scale is much less than the mean time between two photons can be put into practice with the SNT, too.

2. A STATISTICAL APPROACH TO STELLAR PHOTOMETRY

Light curves are of little use if we operate on a short time scale or observe faint stars. The situation looks hopeless when some unknown signal is dissolved in noise and is invisible by the naked eye. Fortunately, this is not the case. Any signal carries some energy and may be detected and estimated even in the conditions of *a priori* uncertainties.

Quantum physics treats radiation as microscopic *photon gas* with non-classical properties. One of the best known non-classical properties of light are the quantum fluctuations. All sources with a constant intensity I exhibit apparent fluctuations in photon counts that are random in their nature. These counts follow the Poisson distribution

$$p\,(n,\tau) = \frac{n_0^n}{n!} \cdot e^{-n_0}. \tag{1}$$

Here n is the number of photons detected for the sampling time τ, $n_0 = qI\tau$ is its time average, where $I = const$ is the constant intensity, q is the quantum efficiency. In the case of the variable intensity $I \neq const$ we have in reality an integrated intensity

$$U(t) = \int_t^{t+\tau} I(t')dt'. \tag{2}$$

Generally, the quantity U follows some unknown distribution $p\,(U)$. In this case a distribution of counts is described by the fundamental *Mandel equation*:

$$p\,(n,\tau) = \int_0^{\infty} \frac{U^n}{n!} \cdot e^{-U} p\,(U) dU. \tag{3}$$

It should be noted that $p\,(U)$ is the unknown function, so we have a Fredholm integral equation of the first kind. There are several methods to solve it, such as the Fourier transformation or expansion of $p\,(U)$ in orthogonal Laguerre functions, etc. The simplest way to solve it consists in applying the method known as the method of moments. The distribution function $p\,(U)$ can be defined through its moments

$$< U^k >, \ k = 1, 2, 3, ... \infty,$$

where $< ... >$ denotes a time average. One can show that the moments of U have a form

$$< U^k > = < \frac{n!}{(n-k)!} > = < n(n-1)...(n-k+1) > = n_{[k]}, \qquad (4)$$

where $n_{[k]}$ are the so-called factorial moments. It is convenient to use the normalized factorial moments

$$h_{[k]} = \frac{n_{[k]}}{< n >^k} \ .$$

In the case of Poisson statistics it may be shown that all the moments $h_{[k]} \equiv 1$ identically for any k. Hence if any $h_{[k]}$ differs from one, we may affirm that variability is detected.

2.1. Application to stochastic variability

To detect activity of the flare star EV Lac on the shortest timescales, the above mentioned Mandel relation was applied. The expression

$$\varepsilon = \frac{\sigma^2 - < n >}{< n >^2} = h_{[2]} - 1$$

specifies the relative power of fluctuations ε in the frequency domain $\Delta f = (\frac{1}{2\Delta t} - \frac{1}{N \Delta t})$, where Δt is the sampling time, N is the length of the data segment. Choosing an appropriate value of N, one can calculate the power spectrum of fluctuations by averaging of ε over time. The actual value of ε caused by atmospheric scintillation can be determined from the measurements of a reference star. The difference in ε between the observed relative power of the star and that of the atmospheric scintillation, which is derived from the observation of the control star, is taken to be the intrinsic ε – spectrum of the star.

Figure 1 shows the stochastic variability of EV Lac in a quiet state. The relative power of the brightness variations is about 2.5% in the frequency interval 0.05–3.5 Hz. It is higher than those of the control

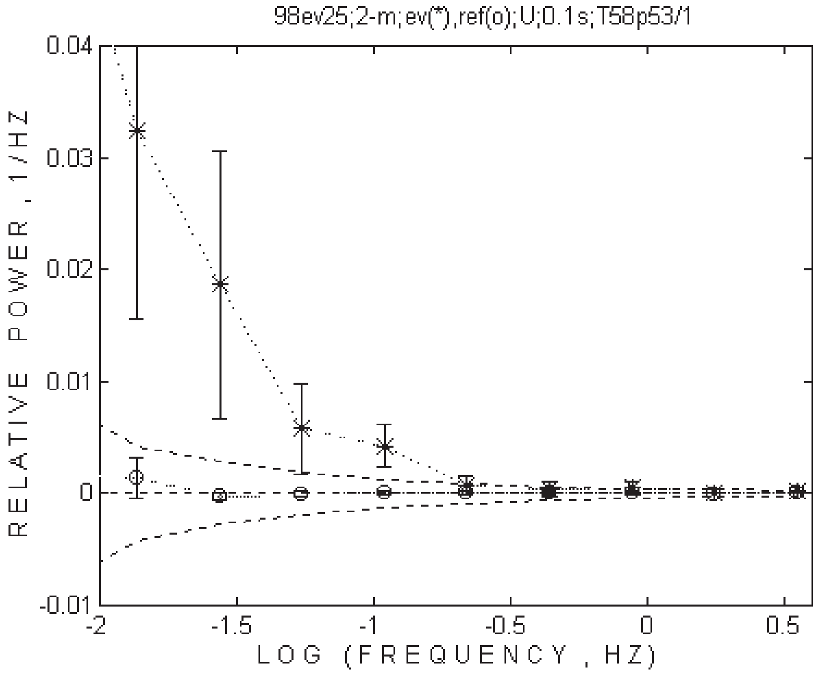

Fig. 1. The relative power spectrum of EV Lac (stars) and that of the control star (circles). Peak Terskol, 2 m telescope, U passband.

star by a factor of 30. So far the time-averaged flare power of EV Lac was evaluated on time scale extending to some hours only. It may amount to about 2% of the total luminosity in the U passband. Our new approach enables us to evaluate the micro-flare power in the frequency range up to several Hz.

3. INTEGRAL TRANSFORMS OF THE LIGHT CURVES

This section concerns the detection of the fine-scale variability with several synchronously operated telescopes. We shall consider the problem for a Poisson density function (1) with mean and current intensities n_0 and n. Let us convert the light curve using the cumulative Poisson distribution

$$P(n, n_0) = \sum_{k=0}^{n} \frac{n_0^k}{k!} \cdot e^{-n_0}, \tag{5}$$

which is equal to the probability to get the reading value of n. For large intensity ($n_0 \geq 30$) it is desirable to have an asymptotic

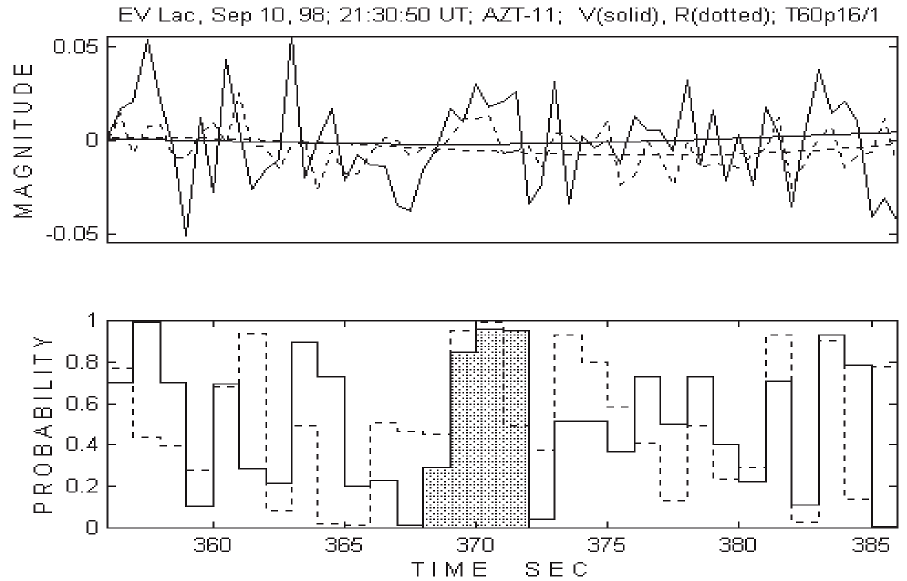

Fig. 2. The V (solid) and R (dotted) light curves (upper panel) of EV Lac and their cumulative probability functions (lower panel). The filled area corresponds to a small flare event with $\Delta V = 0.03$ mag. The Crimean AZT-11 telescope, 11 September 1998, 21:30 UT.

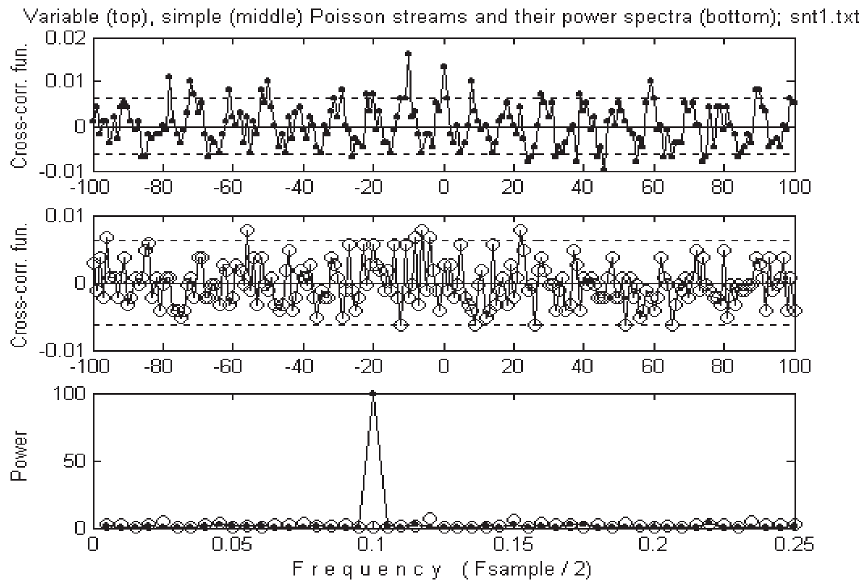

Fig. 3. Computer-generated noise plus sinusoidal wave signal, showing sharp distinction from the noise data (see text).

approximation

$$P(n, n_0) \approx 1 - \Phi[2(n+1)^{\frac{1}{2}} - 2n_0^{\frac{1}{2}}] \ ,$$

where $\Phi(n, n_0)$ is the standard normal cumulative. Then

$$SL = 1 - P(n, n_0) \simeq 1 - \Phi[n, n_0]$$

is the significance level to obtain the reading value of n in the light curve. Large values of the statistic P may correspond to the true photometric events in the light curve. In particular, it can be applied to the detection of photometric events at selected critical value of probability. Since the SL statistics can take on values anywhere between 0 and 1 equiprobably, the quantity $-2\ln(SL)$ follows the chi-square distribution with two degrees of freedom.

To calculate the joint probability for m synchronously operating telescopes, we may write

$$SL_m = -2\sum_{i=1}^{m} \ln(SL_i). \tag{6}$$

It is clear that the statistic SL_m follows the χ^2_{2m} distribution with $2m$ degrees of freedom. If some flare event is registered with a single telescope at the 2σ confidence level (the probability is 97.5%), such an event cannot be certified as very significant. However, if such an event has been registered with two or three instruments simultaneously, its significance level increases up to $SL = 0.005$ and 0.001, respectively. Its confidence probability amounts to about 99.5 and 99.9% ! Figure 2 shows that the SNT plus cumulative probability approach may lead to substantial possibilities in detecting of extreme small-scale stellar variability.

4. APPLICATION OF THE SNT FOR THE DETECTION OF THE ULTRAHIGH-FREQUENCY VARIABILITY

For sparse quantum fluxes light curves are of little use. However, according to the Fourier theorem, there are not any restrictions on the absolute values of the mean intensity, frequency of sampling, etc. The minimum detectable amplitude of a signal depends on the total number of photons, which have arrived.

The data network synchronization of the SNT is based on GPS receiver ACUTIME 2000 to discipline local photometer timing systems relative to UTC. At present we can set the sampling time $\simeq 20\ \mu$s as a typical value. Different telescopes can be synchronized to UTC within better than $\simeq 1\ \mu$s. Thus, the shortest detectable temporal variations are of 25 kHz. Figure 3 shows the cross-correlation functions (CCF) and the cross-spectrum for two runs of generated noise as well as the sum of noise and sinusoidal wave with an amplitude equal to the noise standard deviation.

The noise is Poisson-distributed random integers. The computer simulation conditions are such that the mean interval between photons is a hundred times greater than the sampling time. The total number of measurements and photons that have arrived are of 10^5 and $\sim 10^3$, respectively. The photoefficiency was chosen to be equal to 10%.

To summarize, the results obtained give some evidence that there is a completely reliable opportunity to study ultrahigh-frequency variability with the Synchronous Network of Remote Telescopes.

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