METHODS AND RESULTS OF AN OPTICAL SEARCH FOR EXTRATERRESTRIAL CIVILIZATIONS

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Abstract. The prospects for searches for optical signals arriving from extraterrestrial civilizations are discussed. Two criteria for an artificial origin for optical emission are analyzed – intensity variations with a a semiotic time structure and the presence of narrow laser lines. We propose to attempt to detect and study these signals by investigating "suspicious" astronomical objects with extremely high time resolution, $10^{-7}s$. We will use the special hardware/software photometric complex MANIA (Multichannel Analysis of Nanosecond Intensity Alterations), which consists of a photometer, a "time - code" converter that is the recording system, a PC/AT 486 computer, and a tape recorder. Special statistical methods and programs for the search and analysis of any type of brightness variability of astronomical objects on time scales from $10^{-7} - 10^{2}s$ are described. The criteria for choosing objects to be included in the search for extraterrestrial civilizations signals are discussed. We propose to search for Type I civilizations by investigating 161 stars of spectral types F9V–G5V within 25 pc of the Sun. As possible beacons (transmitters) of Type II extraterrestrial civilizations, we propose to consider objects that have unusual characteristics, in particular, lineless optical spectra. The results of observations of 60 objects and the limits for the power of possible signals are reported.

Key words: SETI, Search for signals, Pecular objects, Sun-like stars, High speed photometry

1 Introduction

In reality, we cannot know what means of communication would be chosen by civilizations considerably more developed than ours (Types II and III, defined by Kardashev) – we can only guess. Let us suppose that electromagnetic waves in the optical band are the most suitable. Indeed, according to the theorem of Shannon, the information content of transmissions at these wavelengths can be $10^5 - 10^6$ times greater than at radio wavelengths. This is equivalent to the difference between the information content in an ABC book and in all existing encyclopedias (10^6 and 10^{11} bits, respectively). The possibilities of extraterrestrial communications in the optical band have been noted by Shvartz and Townes (1961) and discussed in detail by Shvartsman (1977).

Two kinds of ETI signal coding are possible: spectral and temporal. Consider the use of laser signals with extremely narrow line widths ($\Delta\lambda/\lambda \simeq 10^{-9}$) located at an unusual frequency ν_0 (Shvartz and Townes, 1961) (Fig. 1a). This type of spectral signal coding causes short-term photon correlations (i.e., intensity fluctuations) on time scales $\tau_c \sim 1/\Delta\nu = (\lambda/\Delta\lambda)\cdot 1/\nu \sim 10^{-6}s$ (this excludes the pure coherent radiation of a single-mode laser, when $\tau_c \sim 1/\Delta\nu \sim 10^{-15}s$). One possibility for time signal coding was analysed by Shvartsman (1977). In particular, he considered the pulse modulation of laser radiation: its duration τ_ν, filling factor β,

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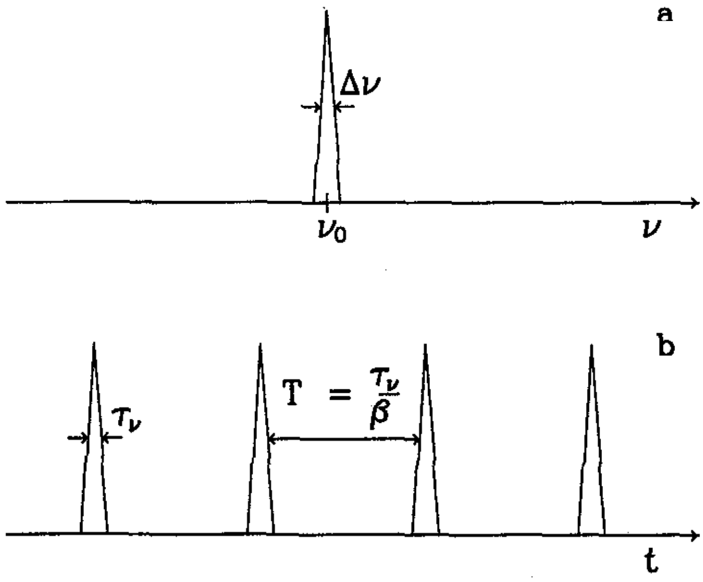

Fig. 1. Two types of signal coding: a - spectral, b - temporal

and time-dependent shape k are elements of the code (Fig. 1b). In both cases of the signal coding, the criterion for detection of a variable signal is that the photon statistics deviate from Poisson statistics, which characterize ordinary astronomical objects.

The search for optical variability in peculiar objects was started at the Special Astrophysical observatory of the Russian Academy of Sciences in 1972. Since 1978, the observations have been carried out with the 6-m SAO telescope. This is the so-called MANIA (Multichannel Analysis of Nanosecond Intensity Alterations) experiment (Shvartsman, 1977; Beskin et al., 1982; Zhuravkov et al., 1994). The main aim of this experiment is to study super-rapid variability of various objects using extremely high time resolution of about 10^{-7} s.

2 Methods: Hardware and Software

The MANIA hardware consists of a detector, a "time–code" converter acting as the recording system, a PC/AT 486 computer, and a tape recorder. The detector can be any device that provides output such that for every detected photon there is a corresponding standard impulse together with additional i information about the photon, i.e., spatial coordinates, frequency, polarization, etc.. Currently, a photometer with a set of diaphragms ($4''$ - $20''$) and filters (U, B, V, R) is used as the detector. Its dead time is 10^{-7}s, and its quantum efficiency is a few percent.

A special "Quantochron" time–code converter registers the photon arrival times with an accuracy of $\pm$ 20 nanoseconds and stores their 16-bit codes and 16-bit codes for the additional information in the computer. We briefly describe the operation of the "Quantochron" below (Zhuravkov et al., 1994). There are three impulse counters:

- a 36-bit counter for the impulses coming from the time standard service at the "precise" frequency 100 kHz (the frame counter);
- a 16-bit counter for the high frequency impulses (50 MHz) coming from the internal generator;
- a 4-bit counter for the photons arriving between the time service impulses (the frame life time).

In addition, there are two identical sets of registers. They consist of fifteen 16-bit registers for storing the nonius counter values and fifteen 16-bit registers for holding the additional information about the detected photons.

The measurements of the photon arrival moments and registration of their channel numbers are performed in successive frames. The nonius counter and the photon counter are set to 0 when the next time service impulse comes (the beginning of the frame). At the time when the next high-frequency impulse comes, the nonius counter is increased by 1, the photon counter is increased by 1, having detected the next photon, and the nonius counter values and coordinate information are stored in the buffer registers. The coordinate code is set on the "Quantochron" input by the detector that has registered the photon.

The main characteristics of the "Quantochron" are:

- the data acquisition rate without distortion with a PC/AT 286–486 is up to 370,000 photons/s (in the single-channel mode, up to 750,000 photons/s);
- 16–bit registers are used to register the arrival times of photons in 2^{16} channels simultaneously (coordinates, wavelengths, etc);
- the accuracy of the time measurements is ± 20 ns, which is equal to the dead time.

The observational method of the MANIA experiment is based on measuring the arrival times of detected photons and analyzing the statistical properties of the resulting time sequence. The photon statistics for artificial signals will deviate from the Poisson statistics that characterize usual, nonvariable astronomical objects. As noted above, from the point of view of mathematics, the problem of finding a signal coded both "spectrally" and "temporally" reduces to analysis of the detected photon statistics. Thus, our task in searching for signals from extraterrestrial civilazations is to search for variability in the emission of peculiar objects over a wide range of time scales $10^{-7} - 10^2 s$.

When studying variability on time scales smaller than the mean interval between photon counts, the classical methods for light curve analysis are not effective due to the very small fluxes involved and, therefore, the huge amount of data. A special, so-called y_2 function method (Shvartsman, 1977) was developed for these purposes. The y_2 function method is based on statistical analysis of the time intervals between photons. The y_2 function is defined to be

$$y_2(\tau_i) = \frac{P_o(\tau_i) - P_s(\tau_i)}{P_s(\tau_i)}, \tag{1}$$

where $P_o(\tau_i)$ is the fraction of intervals of duration from τ_i to $\tau_{i+1} = 2\tau_i$ in the flux from the object; $P_s(\tau_i)$ is the same for the standard flux. The d_2 function method is used on times larger that the mean interval between photons, and is an analog of the variance method. The d_2 function is defined to be

$$d_2(\tau_i) = \frac{D_o(n_o(\tau_i)) - D_s(n_s(\tau_i))}{[M(n_o(\tau_i))]^2}, \tag{2}$$

where $D_o(n_o(\tau_i))$ and $D_s(n_s(\tau_i))$ are the sample dispersions of the number of photon counts $n_o(\tau_i)$ and $n_s(\tau_i)$ in a window of duration τ_i for the object and standard fluxes, respectively, and $M(n_o(\tau_i))$ is the expected value of $n_o(\tau_i)$.

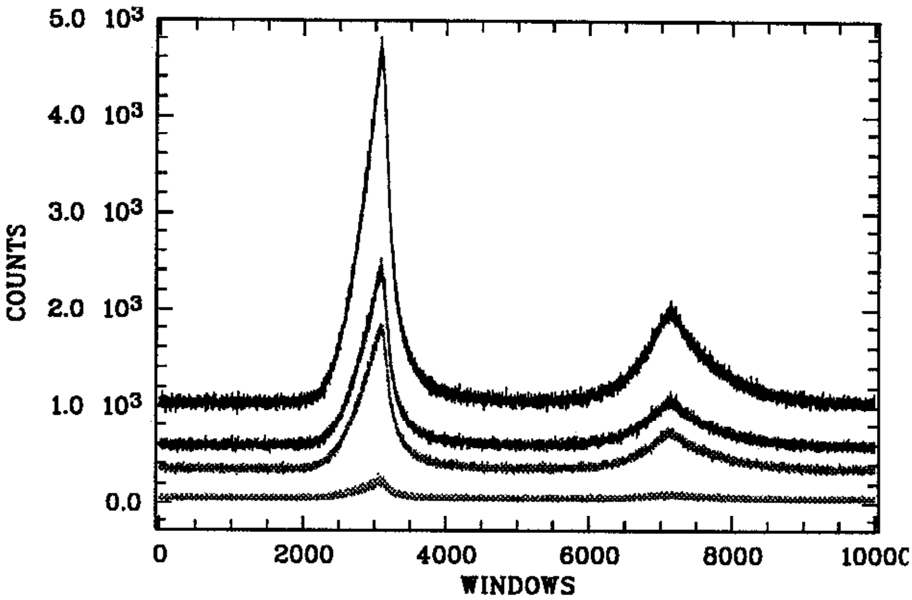

Fig. 2. Light curves of the pulsar PSR 0532+21 with time resolution 3.3μs in the U+B+V+R, B, R, and U band (top to bottom).

As a standard flux, we can use either the flux of a comparison star or a constant Poisson flux. It can be shown that there is a relation between variability parameters (mean amplitude, filling factor, mean time, etc.) and deviations of the y_2 and

d_2 functions from 0, which provides possibilities to estimate the parameters. In the presence of variability, the y_2 and d_2 functions show an increase on times less than the characteristic variability time (Shvartsman, 1977; Plokhotnichenko, 1983; Plokhotnichenko, 1992). To investigate slow brightness variations, a "classical" light curve is constructed and "classical" analysis methods are used.

3 Targets and Results

The MANIA hardware and software allow us to detect and investigate brightness variations of astrophysical objects on time scales from 10^{-7} to $10^3 s$, corresponding to narrow emission lines with widths of 10^{-3} - $10^{-7} Hz$. The list of MANIA objects includes candidates for single black holes, X-ray binaries, pulsars, flare stars, Sun-like stars, etc.. We obtained light curves of the Crab pulsar with a temporal resolution of $3.3 \mu s$ in the UBVR colour bands simultaneously (Fig. 2), and found the colours as functions of phase. We did not find any fine structure, with the exception of statistical "noise" (Shvartsman et al., 1988b).

When studying the low-mass X-ray binaries A0620-00, MXB 1735-44, and GRO0422+33, we detected supershort bursts (with duration τ_ν from 1 ms to 10s). Such fine structure testifies to the nonthermal origin of these flares and leads us to suspect a nonthermal mechanism for the accretion in these systems (Shvartsman et al., 1989a; Beskin et al., 1994; Bartolini et al., 1994). The search for temporal fine structure in bursts in UV Ceti-type M-dwarfs (Shvartsman et al., 1988b) showed that they are thermal.

During the 18 years over which we have run the experiment at the 6-m telescope, we have investigated more than 200 objects along with the objects that are interesting for SETI. These are DC white dwarfs, stars with measured proper motion and continuous spectra (Shvartsman et al., 1989a), ROCOSes, radio objects with continuous optical spectra (Shvartsman et al., 1989c), and Sun-like stars. Objects with continuous optical spectra are of fundamental interest, since they are very rare among usual astrophysical objects, and we can only guess the nature of many of them. We consider several hypothetical explanations.

It is possible that we observe haloes of accreted interstellar gas around isolated solar-mass black holes. Shvartsman 1971 showed that their optical spectra should be featureless and their brightness should vary on time scales of $10^{-4} - 10^{-5} s$. It could also be that the absence of lines indicates that the radiation has an artificial origin. As continuous spectra rarely occur in nature, high-level civilizations could use such spectra to draw our attention to their laser transmitters.

We compiled a list of DC dwarfs containing more than 110 objects, and have observed about 20. Our selection criteria were that lines be absent with high confidence, that the colors be non-thermal, and that the object vary on a time scale of a month to years. The search for variability was carried out in the time range from 500 ns to 40 s. The statistical analysis showed no brightness variations at the 99% confidence level. We estimated upper limits for the relative power of flashes with a duration of 1 microsecond and frequency 1 Hz (laser pulses) to be $S \sim 7 \cdot 10^{-4}$ of the object luminosity. Thus, we can set an upper limit on the power of hypothetical lasers that could transmit flashes towards the Sun from the vicinity of DC dwarfs $p = S(\alpha^2/4\pi)L_{DC}$, where $\alpha \sim 1a.u./D, D \sim 10pc, L_{DC}$ is the luminosity. This is about 10^7 W, approximately one millionth of the Earth's energy production.

The search for variations of brightness in 21 ROCOSes (the full list includes 80 objects) was carried out in the same time range with the same result. Typical upper limits for the relative power of rapid variable components on time scales from $10^{-6}s$ to $10^{-2}s$ range between 20% and 5% for flashes with a filling factor of 0.2. For rare flashes with a filling factor 10^{-3} the limits are 10 times better. Thus, there are probably neither single black holes with a few solar masses nor transmitters of extraterrestrial civilizations among ROCOSes.

While studying ROCOSes and DC dwarfs, we hoped to detect signals of high-level Type II and III civilizations from specially built transmitters situated far from their creators. Observing Sun-like stars of spectral types F9V–G5V, we expected to detect transmissions from Type I civilizations from their habitable areas. We completed a list of these objects up to 161 stars, paying more attention to those that have planetary systems. We observed about 20 Sun-like stars with extremely high time resolution on the 6-m and 1-m telescopes. We searched for brightness variations in the time range from 100 nsec to 100 sec. No brightness variations have been detected for any of these objects at the 99% confidence level. Our estimates of upper limits on the relative power for rare flashes (one per second) with durations of 1 microsecond are about $2 \cdot 10^{-2} - 6 \cdot 10^{-2}\%$. We derived an upper limit of approximatly 10^9 W for the power of the hypothetical lasers from extraterrestrial civilizations. It is important to note that if Earth-type civilizations transmitted their messages from DC dwarfs or Sun-like stars, we could detect these signals. Limits on the laser power are 10^6 and 10^9 for DC dwarfs and Sun-like stars, respectively, which corresponds to the Earth's technological potential (recall the American SDI program).

4 Conclusions

We have observed about 60 peculiar objects and Sun-like stars with extremely high time resolution, and failed to find any signals from ETI. However, we have not given up. We intend to improve our equipment and methods and extend the list of objects to be studied, and the search will be continued.

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