Upper bound on the collapse rate of massive stars in the Milky Way given by neutrino observations with the Baksan underground telescope

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We describe an experimental search for neutrino bursts from collapsing stars with the Baksan underground scintillation telescope, and we present the results of 12 years' observations of the Milky Way. No Galactic neutrino bursts have been detected, yielding an upper limit $f(90\%\ \text{conf.}) < 0.21\ \text{yr}^{-1}$ on the mean frequency of stellar collapse in the Galaxy.

1. INTRODUCTION

More than 25 years ago, Zel'dovich and Guseĭnov proposed[1] that the gravitational collapse of the core of a massive star in the final stage of evolution would be accompanied by a brief but powerful pulse of high-energy neutrinos; discussion immediately turned to the possibility of detecting those neutrinos.[2] In the ensuing 10 to 15 years, more and more massive underground detectors capable of responding to the neutrinos emitted in stellar collapse were constructed at various sites around the world (the largest of these are still in operation).[3–9] Another two large-scale Čerenkov detectors had been built by the end of the 1980s.[10,11]

The detection of a neutrino signal on 23 February 1987 from the type II supernova SN 1987A,[12–15] which erupted in a neighboring galaxy—the Large Magellanic Cloud—provided the first experimental confirmation of certain fundamental features of the general theoretical picture of gravitational collapse, such as the amount of energy liberated, the mean neutrino energy, and the duration of the neutrino pulse.

On account of the remoteness of the exploding star ($R=50$ kpc), however, the small number of neutrinos recorded (11, 8, and 5 events at the KAMIOKANDE II, IBM, and Baksan telescopes, respectively) precludes a test of the detailed progress of the collapse. For instance, we cannot distinguish the gravitational collapse *per se* from the cooling of a newly-formed neutron star, nor can we deduce a standard spectrum for the neutrino emission.

The most important lesson to be learned from the experience with SN 1987A is that installations capable of detecting the collapse neutrinos must be maintained in a perpetual high state of readiness.

Every one of the three installations that recorded the neutrino signal at 7:35 UT on 23 February 1987 was in the midst of some sort of malfunction (partial shutdown of the high-voltage power supply of the IBM detector, clock errors at both the KAMIOKANDE II detector and the Baksan telescope).

As a result, the uncertainties in the absolute arrival times—± 1 min at KAMIOKANDE II and $(-54 - +2)$ sec at the Baksan telescope—when combined with the accurate clock readings at the IBM detector (± 50 msec), rule out an accurate reconstruction of the temporal profile of the neutrino pulse. Nevertheless, most investigators have adopted the arrival of the first event in each signal as the zero-point in time, and stacked the profiles accordingly, although there is little basis for doing so, given the disparate clock calibration errors and different energy detection thresholds. The thresholds of the various devices (defined as the energy required for 50% detection efficiency) are 8.5 MeV for KAMIOKANDE II, 10 MeV for the Baksan telescope, and 35 MeV for IBM.[12,14,16]

Since experimental detection of the neutrino pulse obviously lasted no more than approximately 15 sec overall (~ 13 sec for KAMIOKANDE II, ~ 9 sec for the Baksan telescope, and ~ 6 sec for IBM), the differences in arrival time among the initial events at the three detectors could amount to several seconds.

With all this in mind, we can construct a temporal profile for the original neutrino signal by piecing together the data from the different observatories in various ways. The result appears in Fig. 1.[17]

It is clear from Fig. 1a that the temporal profiles of the events at KAMIOKANDE II and the Baksan telescope mimic one another, but the IBM events do not conform to the same pattern if the first event is taken to signal $t=0.0$ as in the other two detectors; this is shown in Fig. 1b. Other possibilities for piecing the signals together (Figs. 1c, 1d) may well be considered to yield alternative structures for the original neutrino pulse. Contemporary collapse models have not progressed far enough to enable one to choose between Figs. 1c and 1d.

Other questions relating to the experimental data also remain to be resolved, having to do, for instance, with the angular distribution of IBM neutrino events,[16] as well as a possible concomitant correlation among events of various kinds observed several hours prior to the arrival of the neutrino signal.[18]

The detection of such an event in our own Galaxy, yielding signals expected to be at least an order of magnitude stronger, would be of particular import.

Predictions of the mean rate of occurrence of type II

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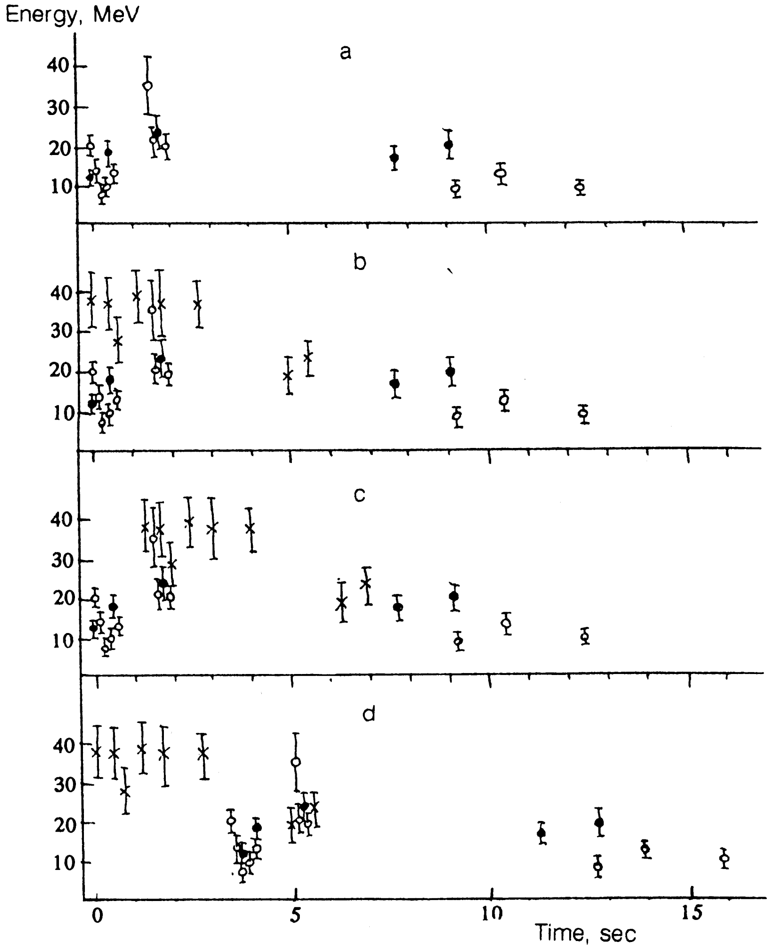

FIG. 1. a) Temporal profiles of events detected by KAMIOKANDE II and the Baksan telescope; b) events detected by all three detectors (KAMIOKANDE II, Baksan, and IBM). Arrival of the first event is taken as $t=0$ for each installation. Panels (c) and (d) show alternative ways of superposing the neutrino signals. Notation: KAMIOKANDE II—○, Baksan—●, IBM—×.

supernovae in the Milky Way differ widely—clearly a result of the many assumptions and approximations employed. The latter include the luminosity of the Galaxy,[19] its morphological type,[20] the zero-age mass function,[21] the fraction of all pulsars that are detectable,[22] and many others.[23–26]

Pulling these multifarious estimates together, we find that the predicted rate ranges somewhere between one event about every 10 years[27–29] and one event every 100 years[20] or more.

The theory of stellar evolution predicts that the gravitational collapse of the core of a massive star ($M > 8$–$10M_{\odot}$) and subsequent cooling of the newly formed neutron star will produce a powerful burst of neutrinos with total energy greater than approximately 10^{53} erg. This phenomenon is commonly assumed to be accompanied by the explosion of a type II (or possibly type Ib) supernova (see Refs. 30–33 and references therein).

It is to be hoped that the detailed detection of a burst of collapse neutrinos generated somewhere in our own Galaxy will not only address some of the questions raised by SN 1987A about the structure and properties of the neutrino signal, but will also furnish us with important information about the properties of the neutrino itself, such as its mass.

Continuous monitoring of the Galaxy to search for bursts of collapse neutrinos began at the Baksan underground scintillation telescope (operated by the Nuclear Research Institute of the Russian Academy of Sciences) on 30 June 1980. In the present paper we review the observational results and derive an upper limit on the collapse rate in the Galaxy.

2. THE BAKSAN SCINTILLATION TELESCOPE

The Baksan underground scintillation telescope[6,34] (Fig. 2) is located in a tunnel at a depth of 850 mwe (meters water-equivalent) in the mountains of the North Caucasus. The eight planes comprising the telescope (four vertical and four horizontal, of which the bottommost three are known as the interior planes) form a closed structure that is fully covered with standard scintillation counters.

Each counter ($70\times70\times30$ cm^3) is filled with an organic white-liquor based scintillator (C_nH_{2n+2}, $n\sim9$) containing special additives to shift the wavelength of the emitted light to the peak sensitivity range of the FÉU-49 photomultiplier (photocathode diameter 15 cm) that monitors it. All photomultipliers are magnetically shielded by a metal housing.

There are 3150 standard counters in all, and they have been matched for physical characteristics (gain, detection energy threshold, etc.), which are held constant to 5–10%.

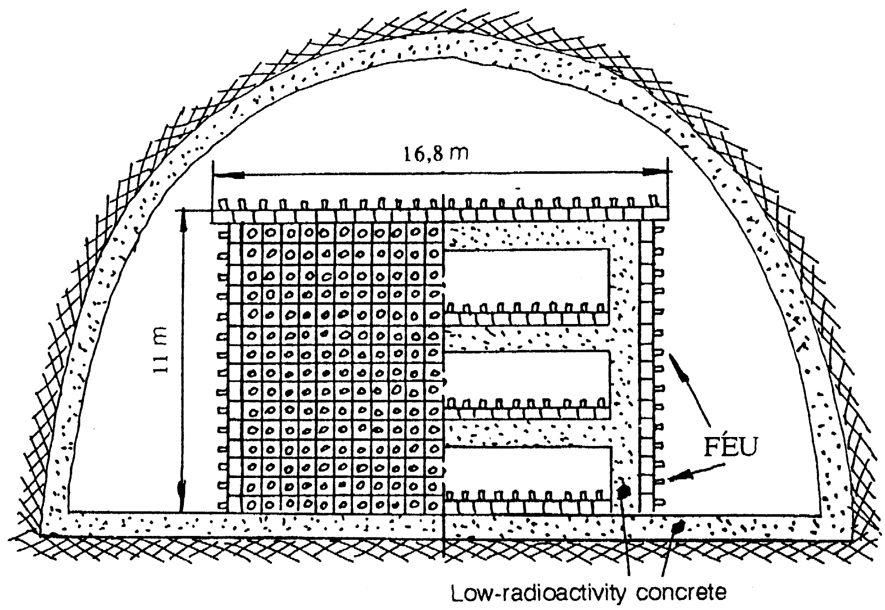

FIG. 2. Diagram of the Baksan underground scintillation telescope.

Detector operation is continuously controlled on the basis of information received during data-taking. The energy spectrum is calibrated using the energy peak of cosmicray muons that pass through the detector layer. The energy spectrum in a horizontally oriented detector is shown in Fig. 3a.

The smooth curve in Fig. 3a is the result of a calculation that incorporates the detector characteristic and the angular distribution of muons. The maximum comes at ~ 50 MeV, liberating ~ 2000 photoelectrons from the photomultiplier cathode.

When the telescope went into operation, the energy threshold was 12.5 MeV; an effort was launched in 1985 to lower it to 10 MeV. The latter threshold was maintained until December 1991, when it was again lowered. Since 1992, the detection energy threshold has been 8 MeV in horizontal-layer detectors and 10 MeV in vertical-layer detectors.

Figure 3b shows the electron detection efficiency as a function of the energy liberated in a single detector, for threshold energies 10 MeV and 8 MeV. The maximum efficiency is clearly $\sim 90\%$, a result of edge effects in the detector (the particle trajectory lies partially outside the detector).

At the telescope, the neutrino signal from a supernova explosion will show up for as long as the neutrino burst lasts as a series of signals from the individual detectors that have been triggered, since the time of flight of the interaction products of ~ 10–12 MeV $\bar{\nu}_e$—positrons—within the scintillator essentially completely constrains them to remain within the confines of a single detector, and the predicted total duration of a $\bar{\nu}_e$ burst (~ 10–20 sec) is much greater than the instrument's dead time (~ 4 msec).

To reduce the background produced by its major contributor—cosmic-ray muons that leave behind a trajectory of triggered counters when they traverse the telescope—the collapse neutrino observing program records only those events in which exactly one detector out of the 3150 has been triggered. The database fields for that program thus contain information about isolated trigger events. This approach to event sampling has made it possible to reduce the count rate of individual counters in the interior planes by more than a factor of 1000.

The frequency of isolated detector trigger events, however, depends on detector location within the telescope. In Fig. 4, we show the total count rate for isolated background pulses as a function of the number of detectors (target mass) under consideration. To do so, we sorted the counters in order of ascending frequency of isolated counts; the curve in Fig. 4 represents the cumulative sum of that series.

There are two knees in the curve: the first at a target mass of 130 tons and a background count rate of ~ 0.012 $\sec^{-1}$, and the second at a target mass of ~ 200 tons and a count rate of ~ 0.034 $\sec^{-1}$. The entire linear segment of the curve in Fig. 4 is due to detectors belonging to the three interior planes of the telescope (Fig. 2), which contain a total scintillator mass of 130 tons. The slope of the curve changes as soon as detectors belonging to the exterior planes are taken into consideration, since those detectors are more poorly shielded from cosmic-ray muons, and therefore contribute a higher rate of isolated trigger events. The count rate is quite different for counters in the upper and lower series of vertical planes, since a baffle one detector wide at the uppermost horizontal layer does a good job of shielding the upper half of the vertical layers from muons.

The second change in the slope of the curve in Fig. 4, at a mass of 200 tons, thus indicates that after the counts from the three interior horizontal planes and the upper seven sets of vertical planes have been considered, the subsequent inclusion of detector outputs from the lower sets of vertical planes leads to a rapid rise in the background.

The instrument's electronics record the onset time of an event, its amplitude, and the coordinates of any telescope detector that may have been triggered. The temporal

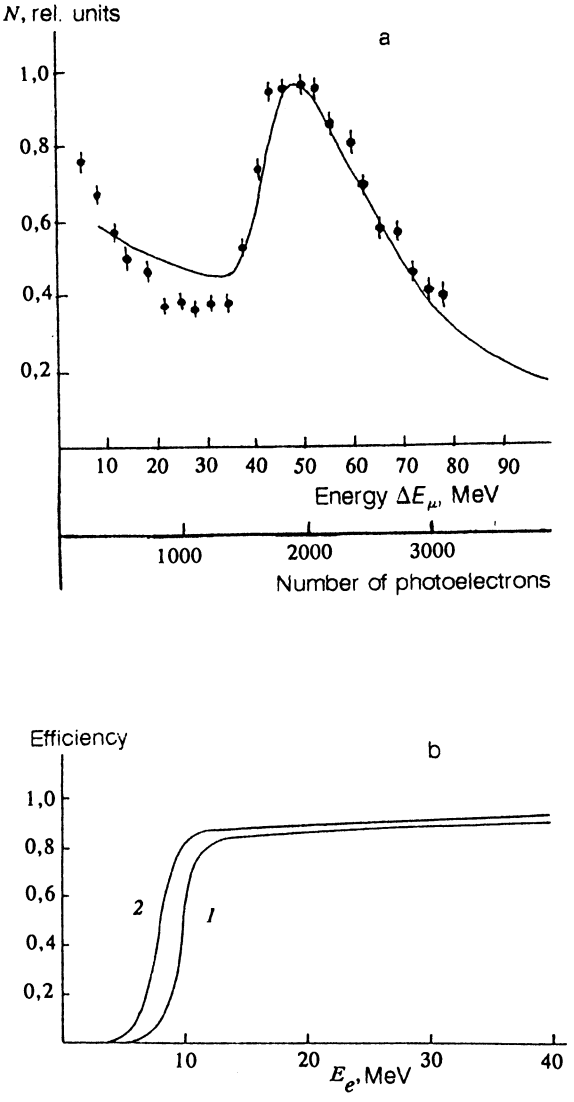

FIG. 3. a) Spectrum of cosmic-ray muon energy deposition in a horizontal detector of the telescope. Smooth curve: calculated result. b) Detection efficiency as a function of energy in an individual detector for threshold values 10 MeV (curve *1*) and 8 MeV (curve *2*).

resolution is ∼4 msec, a relatively long time that reflects the large amount of data to be processed and the somewhat limited capabilities of the instrument's online minicomputer.

A preliminary analysis is carried out daily on incoming data for the detectors in the three interior planes (the "trigger" mass), which show the lowest background. As necessary, however, that analysis can also take into account data from the entire telescope (with a target mass 330 tons).

In this experiment, the major contributors to the background, as noted above, have been penetrating cosmic-ray muons and photomultiplier noise. The contribution of the latter has been significantly reduced in recent years, as is evident from Fig. 5, where we have plotted the mean annual frequency of isolated counts in the interior detectors.

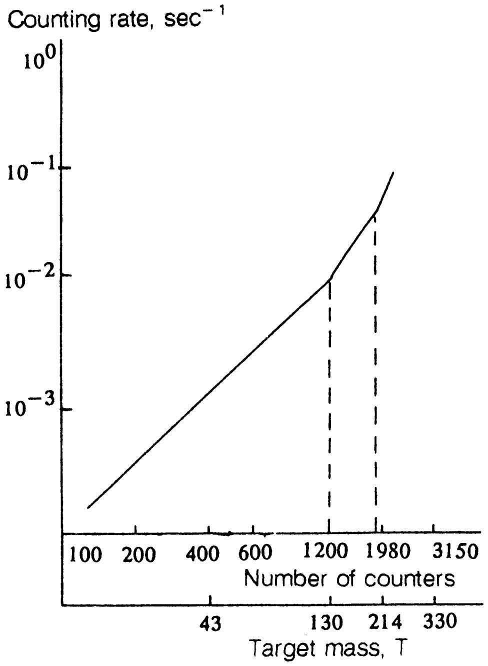

FIG. 4. Total rate of detection of isolated background events as a function of the number of counters (target mass). Detection threshold 10 MeV.

Clearly, between 1985 and the end of 1991, the telescope background was essentially constant.

If some sort of interesting signal shows up in the 130-ton trigger mass, or if a message is relayed from another neutrino detector, as happened in the case of the neutrino signal from SN 1987A,[14] then all available information can be used in the data analysis.

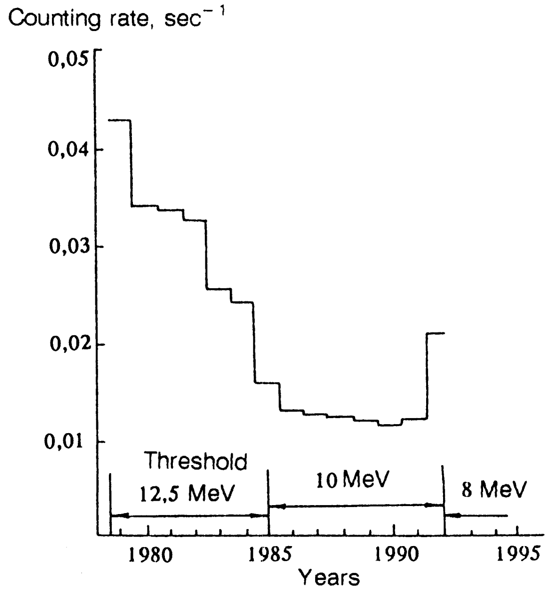

FIG. 5. Mean annual trigger count rate for individual detectors in the three interior planes of the telescope (target mass 130 tons mwe).

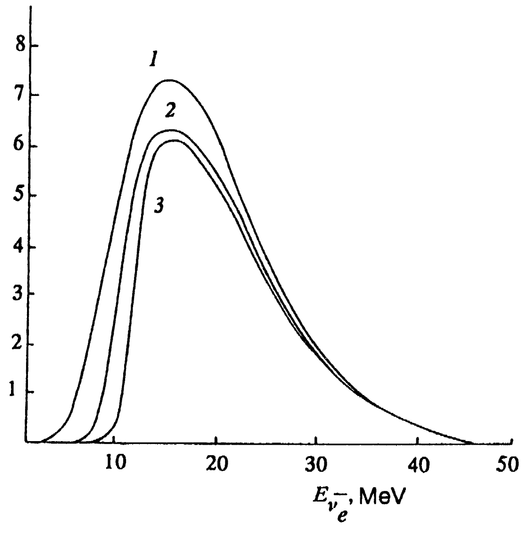

FIG. 6. Energy spectra of $\bar{\nu}_e$ events detected at the telescope. *1*) Initial spectrum with zero detection threshold; *2*) 8 MeV threshold; *3*) 10 MeV threshold. For these spectra, $k_B T_{\bar{\nu}_e} = 3.5$ MeV, $\sigma_{\bar{\nu}_e p}(E)$ is the reaction cross section for $\bar{\nu}_e + p \to n + e^+$, and $\eta(E)$ is the charged particle (electron) detection efficiency.

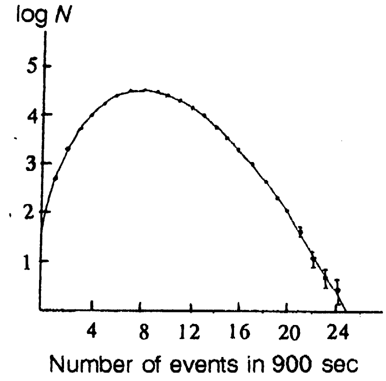

FIG. 7. Distribution of observed background events among 900-sec time intervals. Data from 1985–1991. Smooth curve: Poisson statistics.

The telescope's absolute timing accuracy is of paramount importance. The relative time of arrival of any event can be measured to ~ 1 msec, but up through 1987 absolute time determinations were found to be unreliable, owing to the lack of an independent local time standard. This situation was corrected following the dramatic events surrounding the detection of the neutrino signal from SN 1987A, and since February 1988 the telescope's absolute timing accuracy has been several milliseconds.

3. DATA PROCESSING

Although the explosion of a type II supernova is expected to generate a powerful neutrino pulse lasting $\sim$10–20 sec, in which all types of neutrinos except the ν_e (in other words, the $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$) carry off approximately equal shares of the total energy liberated in the gravitational collapse [$\sim (2\text{–}3) \cdot 10^{53}$ erg; see Refs. 30–33], the overwhelming majority of events detected by the Baksan telescope will be due to the absorption of an electron antineutrino by a free proton in the scintillator, in the reaction $\bar{\nu}_e + p \to n + e^+$.

Figure 6 illustrates how a finite detector threshold affects the shape of the original energy spectrum of detected $\bar{\nu}_e$ events (curve *1*): curve *2* shows the result for an 8 MeV threshold, and curve *3* for a 10 MeV threshold. In calculating $F(E_{\bar{\nu}_e})$, the $\bar{\nu}_e$ were assumed to have a Fermi–Dirac spectrum with a neutrino "temperature" $k_B T = 3.5$ MeV. Thus, with a 10 MeV threshold, $\sim 70\%$ of the original $\bar{\nu}_e$ will be detected; at a threshold of 8 MeV, $\sim 80\%$ will be detected. An even larger fraction will be detected if the neutrino temperature is higher.

If a star were to collapse near the center of the Galaxy (i.e., at a distance of ~ 8 kpc), the standard model[30–33] would predict $\sim$40–60 events due to $\bar{\nu}_e$ interactions in the 130 ton mass of the scintillator, or $\sim$100–150 events in the telescope as a whole.

Furthermore, other types of neutrinos can interact with the carbon in the telescope target, via the reactions

$$\nu_i(\bar{\nu}_i) + {}^{12}\mathrm{C} \to \nu_i(\bar{\nu}_i) + {}^{12}\mathrm{C}^*$$
$$\downarrow$$
$${}^{12}\mathrm{C} + \gamma, \quad E_\gamma = 15.1 \text{ MeV}; \quad i = e, \mu, \tau,$$

$$\nu_e(\bar{\nu}_e) + {}^{12}\mathrm{C} \to e^-(e^+) + {}^{12}\mathrm{N}({}^{12}\mathrm{B}),$$

$$E \gtrsim 16.827(13.880) \text{ MeV}.$$

These reactions, however, will contribute at most $\sim$5–10% of the total signal,[35] as compared with the $\bar{\nu}_e$ absorbed by protons; the energy dependence of charged-particle detection efficiency (Fig. 3b) must be borne in mind here.

Given that stellar collapse is a rare event, the long-term stability of the instrument and a proper understanding of the background become important issues. In Fig. 7, we have plotted the distribution of the number of events occurring in 900-second bins over the course of approximately seven years' operation of the three interior planes of the telescope, with a detection threshold of 10 MeV. It is clear that a Poisson distribution provides a good fit to the telescope background, and that there are no outliers in the tail.

The most important processing to take place as part of this experiment, besides the test and utility programs used

TABLE I. Rate of arrival of background event clusters for signals selected by the sliding window method (window width 20 sec, frequency of isolated background events 0.012 sec^{-1}).

Number of events in signal	Signal frequency
3	$\sim$27 day^{-1}
4	$\sim$2 day^{-1}
5	$\sim$1 week^{-1}
6	$\sim$2 yr^{-1}
7	1 in 12 years
8	1 in 360 years

TABLE II. Basic characteristics of the Baksan telescope.

	Period		
Parameter	6/30/80–12/31/85	1/1/86–12/11/91	12/12/91–12/31/92
Observing time, yr	4.60	5.45	0.96
Energy threshold, MeV	12.5	10	8 (130 T) 10 (200 T)
Dead time, %	5.6	7.6	7.5
Mean frequency of isolated background events in 130-ton target, sec^{-1}	0.0265	0.0121	0.0206

for the telescope as a whole, as already mentioned, involves the daily analysis of data from the three interior planes. Those data are reduced with a sliding window 20 sec long, a duration chosen to be approximately equal to the predicted length of a neutrino pulse. The time window slides from one event to another in succession, and the number of events reaching the interior is calculated.

In Table I we show the predicted frequency of various clusters of events selected by this method for a background rate of $\sim 0.012 \ sec^{-1}$.

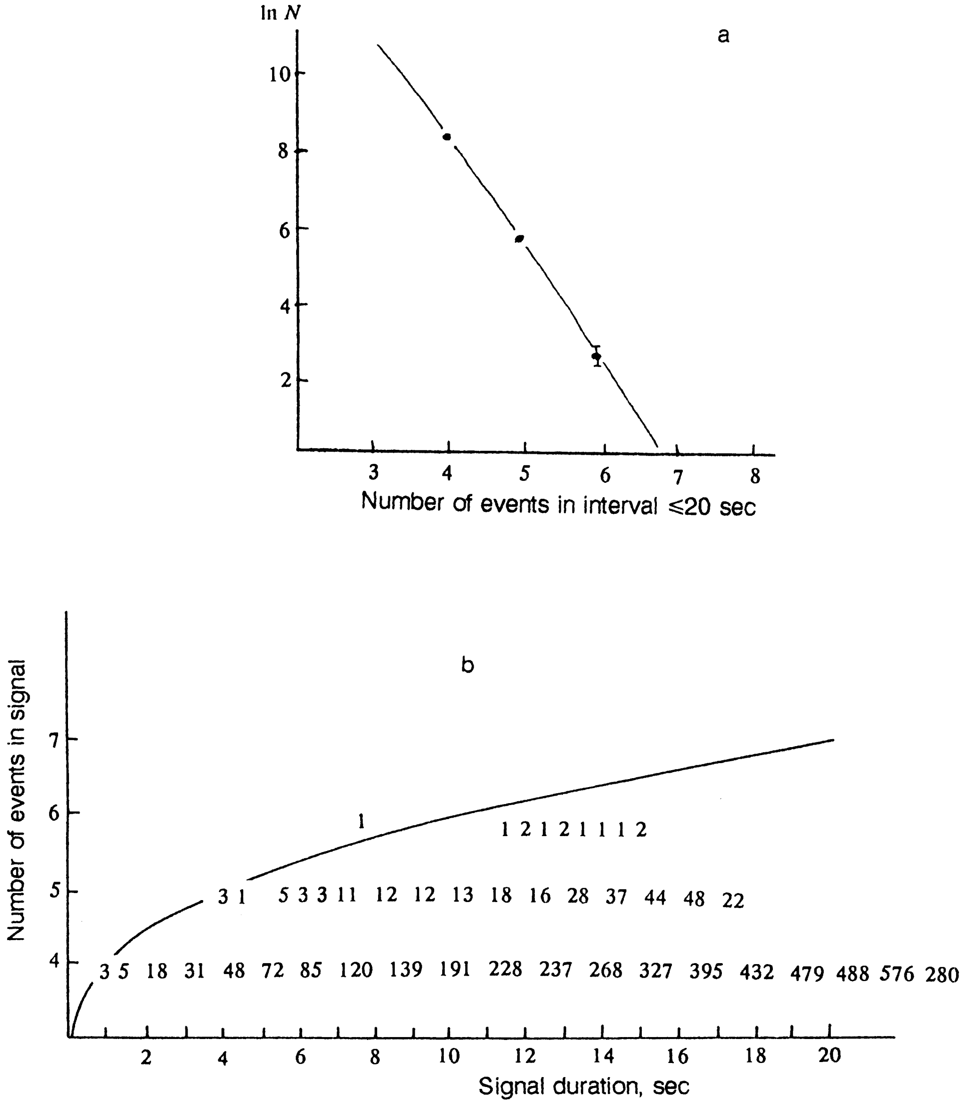

FIG. 8. a) Distribution of signals selected by the sliding window method, based on the number of events in each. Smooth curve: theoretical prediction (see text) at a background rate of 0.012 sec^{-1}. b) Distribution of the number of events in signals as a function of their duration for the data shown in Fig. 8a. Smooth curve: theoretical prediction for signals that appear once per six years. The number of signals of a given duration containing a given number of events is indicated.

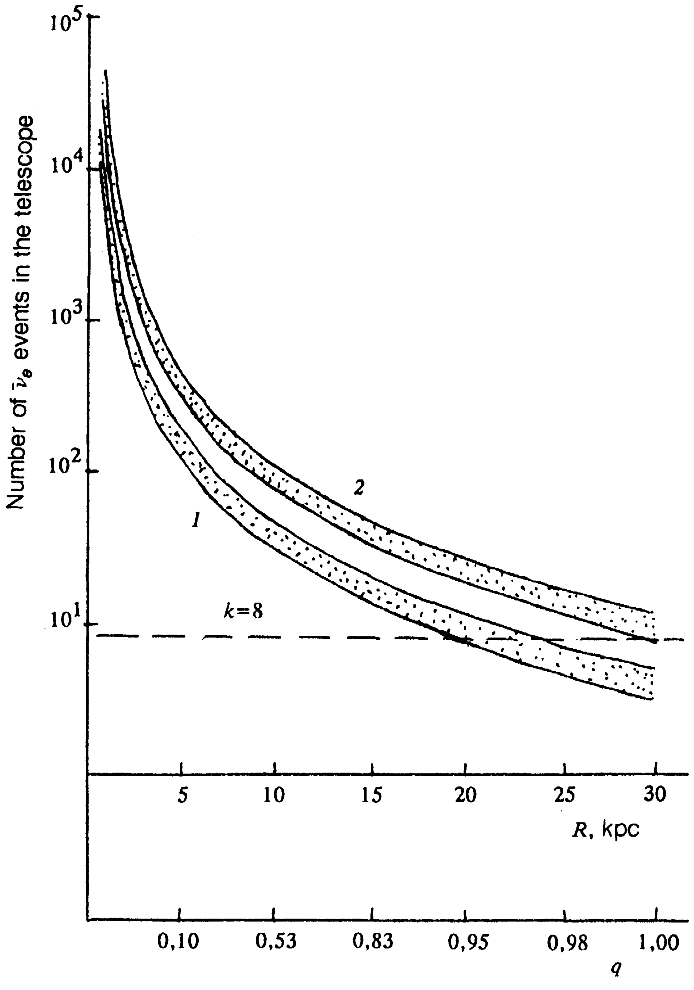

FIG. 9. Sensitivity curve for the Baksan telescope: the predicted number of $\bar{\nu}_e$ events in the 130-ton target (curve *1*) and the whole telescope (curve *2*) as a function of distance R from a collapsing star. Here q is the fraction of the Galactic disk within distance R of the sun.

We selected signals corresponding to at least four events for subsequent analysis; when these appeared at a steady rate, we also effectively had a simultaneous equipment check. We examined the distribution of both signal duration and number of events, and the overall temporal sequencing.

Furthermore, we searched for and analyzed signals of various lengths, ranging from several milliseconds to hundreds of seconds, that had a low probability of occurrence. Modeling has shown that in addition to neutrino bursts lasting some tens of seconds, which can result from the collapse of a supernova and the subsequent formation of a neutron star, it may also be possible to observe the much briefer neutrino signals (lasting several seconds) that result from gravitational collapse to a black hole,[36] although for an earth-based observer, the redshift stretches the apparent duration.[37]

4. RESULTS

As mentioned above, the Baksan underground scintillation telescope has been continuously monitoring the Galaxy in a search program for collapse neutrino bursts since 30 June 1980. Telescope operation in the intervening years can be divided into three periods that correspond to modifications in such characteristics as the energy detection threshold and the magnitude of the background. Basic telescope parameters for those three periods are summarized in Table II.

The rise in dead time to $\sim 7.5\%$ following 1985 is due to the fact that more physical problems are being addressed by the telescope. A second data access line is currently being installed, which will vastly improve present data-handling capabilities.

Ever since monitoring of the Galaxy began with the Baksan telescope, not a single signal in the 0–20 sec range has been detected. A chance signal of that duration would be highly unlikely, and could be interpreted to be a neutrino burst.

As an example, Fig. 8 shows the distribution of signals detected in the 130-ton target during 1986–1991, in terms of the number of events (Fig. 8a) and the ratio of number of events in the signal to signal duration (Fig. 8b).

Poisson statistics do not apply to the probability distribution of signals containing different numbers of events that are selected by the sliding window method, since a given event can show up in several different signals. To estimate the number of distinct signals, we therefore chose an expression that provides a faithful representation of the experimental distribution:

$$N(\kappa)_{slid.wind.}=N_0 e^{-m\tau}\left[\frac{(m\tau)^{k-1}}{(k-1)!}+2\,\frac{(m\tau)^k}{k!}+3\,\frac{(m\tau)^{k+1}}{(k+1)!}+\dots\right], \quad (1)$$

where $N_0=Tm$ is the total number of events taking place in time T, m is the mean count rate for isolated background events, τ is the width of the sliding window, and k numbers the events in the signal, including the first event, which starts off the timing interval.

The smooth curve in Fig. 8a shows the calculated numbers of different background signals predicted for the indicated period, and the smooth curve in Fig. 8b shows that distribution when signals appear once every six years. These two figures make it clear that we have detected no low-probability events. We obtain similar results when we analyze data from the other periods noted in Table II.

The results in Table I, obtained by calculating the rate at which different clusters of events appear, were also used in Eq. (1).

Figure 9 shows the "sensitivity curves" for the Baksan telescope, i.e., the way in which the predicted number of $\bar{\nu}_e$ events in the 130-ton target (curve *1*) and in the whole telescope (330 tons, curve *2*) depends on the distance to a collapsing star. The parameters used for the calculation were: total energy liberated in the collapse, $E_{\rm tot}=3\cdot10^{53}$ erg; energy carried off by electrons antineutrinos, $E_{\bar{\nu}_e}=(5\pm1)^{-1}\cdot E_{\rm tot}$; Fermi-Dirac spectrum of $\bar{\nu}_e$ with "temperature" $k_B T_{\bar{\nu}_e}=3.5$ MeV; mean neutrino energy, 11 MeV. The finite width of the curves is a result of the spread in the fraction of energy carried off from the star by antineutrinos ($\bar{\nu}_e$).

Figure 9 also contains a straight line that corresponds to a signal containing eight $\bar{\nu}_e$ events. The rarity of such a chance signal in the background might indicate a collapse, if such a signal were indeed found, but a final decision would have to await the detection of similar signals at other installations.

The horizontal axis of Figure 9 also shows the fraction of stars in the Galactic disk within a distance R of the sun.[27] We see here that the "radius of sensitivity" of the Baksan telescope is $\sim$20 kpc; i.e., this telescope can essentially peer through our entire Galaxy.

Thus, apart from the neutrino signal from SN 1987A in the Large Magellanic Cloud, we have detected no events at all with this telescope, throughout its entire observing lifetime, that can be interpreted with any assurance as Galactic $\bar{\nu}_e$ bursts.

5. CONCLUSIONS

Since by 31 December 1992, the accumulated observing time with the Baksan telescope was 11 years, and in that time no signals from Galactic neutrino bursts were detected, we can derive an upper limit on the mean rate of gravitational collapse in the Galaxy. Denoting that rate by f_0, and assuming that it obeys Poisson statistics and that the probability of no signal occurring is less than 10%, we obtain for a total observing time $T=11$ yr

$$e^{-f_0 T}<0.1; \quad (2)$$

solving for f_0 yields

$$f_0(90\%\ \text{confidence})<0.21\ \text{yr}^{-1}. \quad (3)$$

We also find from Eq. (2) that to obtain an estimate of f_0 at the same confidence level consistent with the theoretically predicted lower limit, $\sim0.1\ \text{yr}^{-1}$,[27-29] the Baksan telescope must effectively remain in operation another 10 years (the "live" time for data-taking is $\gtrsim85\%$ of wall-clock time).

If the theoretical prediction is correct, then, we may expect to detect neutrinos from the gravitational collapse of the core of a massive star in the Milky Way some time in the near future.

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