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Real time supernova neutrino burst detection with MACRO

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Abstract

The MACRO experiment has been running as a supernova neutrino detector since 1989 and is sensitive to the whole galaxy since the beginning of 1992. A galactic supernova would produce some hundreds of $\bar{\nu}_e$ events in the detector. We describe our stellar gravitational collapse online monitors and alarm system, and present the results of a search for neutrino bursts from supernovae during a period of 1.5 yr. © 1998 Elsevier Science B.V.

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1. Introduction

The main characteristics of the neutrino burst from a stellar gravitational collapse (GC) predicted by theory were successfully confirmed by the detection of $\bar{\nu}_e$s from SN1987A in the Large Magellanic Cloud by the Kamiokande-II and IMB [1,2] and probably by the Mt. Blanc and Baksan detectors [3,4].

A galactic supernova would provide more detailed information on both astrophysical models of stellar collapse and elementary particle physics. The significance of small signals from distant supernovae could be increased by exploiting the coincidence among several detectors. A coordinated network for the observation of the prompt forms of radiation from supernovae, neutrinos and gravitational waves, has been advocated in recent years [5–8].

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MACRO, a large liquid scintillator and streamer tube experiment [9] located in Hall B of the Gran Sasso laboratory (120 km east of Rome), has been operating as a galactic supernova observatory since 1989. The capabilities of the detector for stellar collapse neutrino physics and the result of a first supernova search have already been published [10]. We describe here the systems developed for the prompt recognition of neutrino bursts from stellar gravitational collapses and the results of an online supernova search during one and a half years of operation.

2. Neutrino detection in MACRO

MACRO is composed of six similar supermodules (SMs) with total dimensions $76.51 \times 2 \times 9.6$ m^3. The total liquid scintillator mass is ~ 560 t, divided into 476 individual counters. Each supermodule contains 49 horizontal counters, each with an active volume of $73.2 \times 19 \times 1120$ cm^3, organized in 3 horizontal layers (bottom, central and top). Each SM lateral face is covered with 14 vertical scintillation counters, each with an active volume of $21.6 \times 43.5 \times 1115$ cm^3. Two end faces contain only 7 vertical counters in their lower parts; their upper parts are left open for access to the electronic equipment installed over the central layer of scintillators. Detailed descriptions of the detector may be found in [9,10].

MACRO detects low energy neutrinos through their interaction with liquid scintillator. The dominant reaction induced by neutrinos from stellar collapse is:

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

Several models predict the characteristics of the neutrino burst. In the following we will refer to the model described in [10]. Reaction (1) is followed, after neutron moderation in the scintillator, by neutron capture $n + p \rightarrow \gamma + d$ with $E_\gamma = 2.2$ MeV. The average neutron moderation time is 10 μs and the average capture time is 180 μs.

Less significant, but still detectable are the neutrino elastic scattering on electrons,

$$\nu_x + e^- \rightarrow \nu_x + e^-. \tag{2}$$

and the neutral current reactions on carbon,

$$\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x, {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma(15.1\,\mathrm{MeV}) \tag{3}$$

where the photon can be observed via multiple Compton scattering. The net contribution to the signal from the above processes is about 3–6%.

The background for the detection of low-energy events is due to cosmic ray muons and natural radioactivity. Muons are observed as events with an average energy loss of 40 MeV in a single scintillation counter; their rate is 2 mHz per counter. They are vetoed when they either generate coincident scintillation counter hits or a streamer tube trigger. The residual rate of cosmic rays not eliminated by these muon vetos is 15 mHz in the whole apparatus. The background from natural radioactivity is specific to the manner by which triggers are formed in each of MACROs two GC systems described below. Typically it is 2 kHz in a single scintillator for an energy deposition $\Delta E > 1.5$ MeV and is reduced to 25–45 mHz for the whole detector with a 10 MeV threshold.

MACRO is instrumented with two independent supernova neutrino burst triggers. The Pulse Height Recorder And Synchronous Encoder (PHRASE) is a system specifically designed to detect neutrinos from gravitational collapse; the Energy Reconstruction Processor (ERP) is a system designed for the general muon trigger from individual scintillation counters with an additional dedicated event buffer able to store stellar gravitational collapse induced data. These two burst triggers reconstruct the energy deposited inside one counter by using the two counter end pulse heights and by correcting for light attenuation in the scintillator. In this way the energy threshold is uniform along the longitudinal dimension of the counter. The presence of these two systems in MACRO improves the continuity of online monitoring and reduces possible fake signals. These systems are briefly described in the following.

2.1. The PHRASE system

The PHRASE electronics generates an energy-based trigger by making an analog compensation for light attenuation in the tank. It uses a hardware primary energy threshold of ~ 7 MeV, independent of the event position along the tank. After a primary trigger, the threshold is lowered to ~ 1 MeV for 850 μs to detect the 2.2 MeV photon from n-capture on protons. The efficiency for detecting the neutron capture in the same counter was measured by means of an Am/Be source [11]; it is ≈ 25% for a secondary energy threshold of 1 MeV. After position correlation, time correlation and energy cuts are applied, the signal/background is ≃ 3.

The calibration at low energy is performed using the 2.614 MeV γ-ray line emitted by ^{208}Tl contained in the Gran Sasso rock. The average energy loss of vertical muons (≃ 40 MeV) is another calibration point at higher energy; this value is in agreement (within 10% for all counters) with the expected value when the low energy calibration point is used.

The time delay between any two events is measured with 1.6 ns precision by a fast clock and a scaler, present in each PHRASE module and driven by an external 100 MHz clock. This time resolution permits online rejection of muons hitting more than one counter, without introducing any significant dead time for events from a neutrino burst. The internal scalers are reset at run start by a synchronization pulse given to all the modules. The absolute time of each event is computed by combining the internal fast clock with the Gran Sasso Laboratory UTC. The LNGS UTC is given by a commercial (ESAT RAD100) rubidium atomic clock compared every second with the GPS UTC time; these measures, averaged every hour, are used for a smooth rephasing. The result is that the two UTC times are aligned within ~ 100 ns (FWHM) and the overall event timing has similar accuracy.

The PHRASE circuitry acts independently of all other MACRO triggers; its readout is performed by three dedicated Microvaxes. Data are taken even during maintenance or calibration of parts of the MACRO detector. The data are sent to the central VAX, where they are permanently stored, and spied by a dedicated Vaxstation where the PHRASE supernova monitor runs.

In the design of this acquisition system particular emphasis was placed on the minimization of dead time and risk of event loss. Large PHRASE Microvax memory buffers (16 Mbytes each, corresponding to about 2×10^4 events) coupled with low individual circuit dead time (4 ms per primary trigger) imply that even for 1000 events in 2 s only one event at most will be lost.

The net background (above 10 MeV) in this system from the whole detector is about 40 mHz; 15 mHz from residual muons and 25 mHz from radioactivity.

2.2. The ERP system

The ERP electronics produces an energy based trigger by incorporating flash ADCs and look up tables to calculate the energies corresponding to the PMT pulse heights measured at each end of a tank. The integrated charges and pulse arrival times for events with energy deposition greater than ~ 6–7 MeV are stored in hardware ‘GC buffers’ on each supermodule. The absolute time of each event is determined by using the ERP internal clock time (least count 8 μs) and the LNGS UTC time; the overall event time accuracy is ~ 20 microseconds.

The ERP system runs on the main MACRO acquisition system distributed on three Microvaxes. The GC buffers, each containing 818 events, are read out from each supermodule, into the main data stream as each buffer fills, typically about every 10 min. The dead time on each supermodule for each individual event stored in the GC buffer is 0.23 ms. When the GC buffer is read out an additional 30 ms dead time must be considered. These dead times imply less than one percent loss of signal in the ERP for even a supernova as close as 4–5 kpc. The data are sent to the central VAX for permanent storage and simultaneously spied by a subsidiary MACRO data acquisition computer where the ERP supernova monitor runs (see below). The residual counting rate when applying a 10 MeV online/offline software threshold is 60 mHz: 15 mHz from residual muons and 45 mHz from radioactivity induced triggers.

2.3. Sensitivity to galactic supernova

A supernova like SN1987A at the galactic centre (8.5 kpc) would yield ~ 150 $\bar{\nu}_e$ interactions in 10 s with a positron energy release $\Delta E > 10$ MeV. In a 2 s window, according to the observation of SN1987A, ~ 110 $\bar{\nu}_e$ interactions are expected in MACRO, giving a better signal/background ratio. These numbers must be compared with the Poissonian fluctuations of the residual background rates in the whole MACRO, i.e., 40 mHz for PHRASE or 60 mHz for ERP. As a consequence, the primary signature for a supernova burst would be a large, transient increase over this background rate. Events in scintillator tanks with energy deposition exceeding the 10 MeV threshold are continuously analysed online, and searches are made for sudden increases in their rate over time intervals of several seconds. The characteristic positron energy spectrum and the detection of the 2.2 MeV γ-ray due to the neutron capture in hydrogen provide an important additional check.

Fluctuations in the background rate due to radioactivity and misidentified muons may fake the signal expected for a distant supernova. With a 40 mHz background rate, the probability of having in 10 yr a single fluctuation of 20 events in 2 s (corresponding to a SN1987A signal at 20 kpc) is $< 10^{-6}$. Since 95% of the stars of our galaxy are within this distance [12], we conclude that MACRO is sensitive to stellar gravitational collapses everywhere in our galaxy. A similar conclusion may be derived considering the ≈ 60 mHz background rate.

3. Supernova monitoring online

The motivation for issuing a public bulletin derives from the hope that a notification given within one hour of a neutrino burst increases the chance of observing the onset of the optical signal. Furthermore, multiply coincident alarms emanating from more than one neutrino observatory merged into a (at this stage) hypothetical centralized computer repository offers enhanced sensitivity and directional information. SN1987A showed that the neutrino radiation precedes the optical emission by at least a few hours [1,2]. It is therefore important for a supernova neutrino detector to analyze its data in real time and, in case of a signal, rapidly distribute an 'alarm' to the astronomical community.

MACRO's redundant neutrino burst detection capability allows us to operate dual online monitors. These monitors are integrated into a single GC alarm protocol tailored to maintain the amount of mass that is insensitive, the downtime and the false alarm rate at smaller levels than would be possible with either of the two sets of electronics alone.

3.1. The online supernova monitors

The supernova monitors (SNMs) are two independent sets of fast analysis programs, running on separate computers and processing data from the PHRASE and ERP trigger systems separately. These monitors receive information from 'spy' jobs that run on a dedicated Vaxstation computer (PHRASE system) and on a subsidiary MACRO data acquisition computer (ERP system). The spy jobs run at lower priority than the main acquisition to prevent the introduction of dead time in the acquisition process. These same reconstruction and burst search algorithms are used in subsequent offline analysis [10]. Nevertheless we estimate that even for a collapse in the galactic centre less than 10% of the events might be missed by the online monitor. An online supernova signal would therefore still be seen as a large signal with respect to background fluctuations. It should be noted that no events are lost to the main acquisition, however, so that offline analysis will always be able to process all events observed in the scintillator system.

While triggering and data acquisition for the two neutrino burst systems are done differently, the basic features of the online monitoring are performed similarly. The SNMs reconstruct the energy, position and time of each PHRASE primary event (at the primary threshold) and each ERP event. The events are time ordered and classified as 'coincidences' between counters (mainly muons) or 'singles'. Coincidences are defined as primary events occurring in a small coincidence window (320 ns for the PHRASE system, 4 ms for the ERP) with other primary events or single events in coincidence (within 5 μs) with the streamer tube muon trigger. Coincidences are not used in the burst search analysis. For each 'single' event with energy $\Delta E > 10$ MeV the SNMs perform a burst search over several Δt_i time windows, where $\Delta t_i = 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64$ s for the PHRASE system and $\Delta t_i = 1, 2, 6, 8, 10, 20$ s for the ERP system. The Poisson probability of the

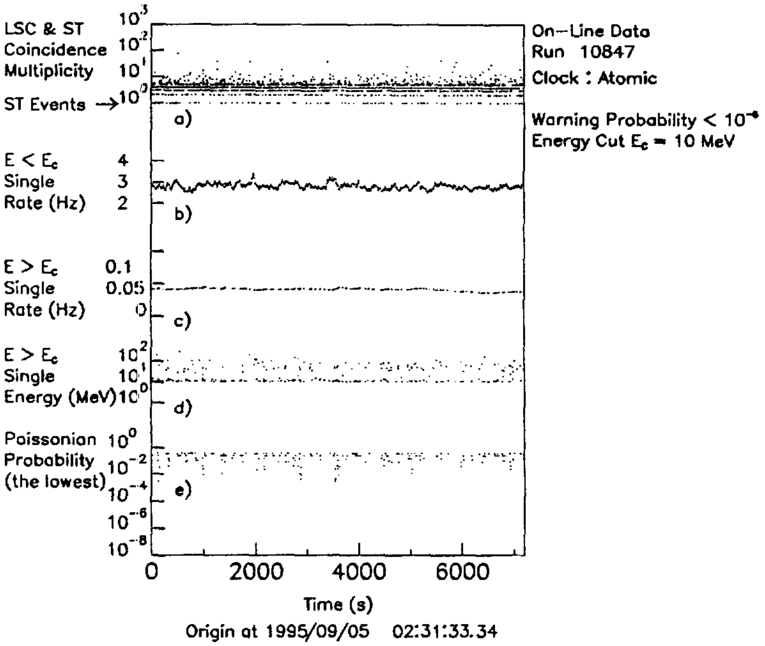

Fig. 1. The display of the PHRASE supernova monitor program. LSC means 'Liquid Scintillation Counter' and ST 'Streamer Tubes'.

multiplicity in each time interval is taken from precalculated tables based on the measured average event rate and updated periodically (every two hours for the PHRASE and once a run for the ERP). If the lowest of these probabilities is lower than a preset value (10^{-5}), the SNMs generate an alert (See Section 3.2). A warning probability of 10^{-5} corresponds, for a 40 mHz background rate, to more than 4 events in 2 s. We expect about one such signal every two months due to a background fluctuation. The SNMs also write to disk the reconstructed variables for each event of the cluster in a mini-DST file and a PAW *n*-tuple file. A plot is also produced and stored on disk for the PHRASE monitor with the information shown in Fig. 1.

One plot corresponds to 2 h of data taking. Starting from the top it contains: (a) The number of coincidences (where the streamer tube trigger, if present, is added as one coincident event); (b) and (c) The singles rates below and above the 10 MeV threshold computed using the last 150 events; (d) The energy of these last events; (e) The lowest of the multiplicity probabilities.

When an alert condition occurs, the SNMs generate e-mail, messages to cellular pagers and cellular telephone notifications to system experts on-call in the United States and in Italy [21] respectively. Each message contains a summary of the events (run, event, multiplicity, probability, supermodule information) in the candidate burst. In many cases the burst summary provides enough information to immediately reject uninteresting candidate bursts. The on-call physicist carries a portable computer and logs in as soon as possible to check the burst information in more detail. The use of a cellular phone for local alerts (i.e., in Italy) and a portable computer, both operated with batteries, enables the on-call physicist to log on the main acquisition computer at Gran Sasso from any place and without need of a network connection. The response time of both systems was measured to be less than 30 min starting from the time of the first event in the burst. The e-mail alerts contain the Poisson probability of the burst based on the current background, the background rate, the

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[21] The PHRASE SNM is also automatically started at run end on the main acquisition computer in offline mode. In this mode, if a low probability cluster is found, an e-mail message is sent to system experts.

burst window duration, burst multiplicity, and for each hit, its energy, UT time and MACRO tank identification.

The total time needed for recognizing a supernova candidate is of the order of one hour.

3.2. Generation of a supernova alarm bulletin

The issuance of a MACRO supernova alarm is predicated upon a detailed internal Protocol for External Release of Supernova Explosion Induced Data (PERSEID) which will be activated during 1997. PERSEID is based on criteria that ensure no significant signal ambiguity. Its philosophy requires, when both the PHRASE and ERP systems are active, a dual detection to confirm an event burst. The detection in each system must be independently highly unlikely to be caused by Poissonian background fluctuations, and known detector and environmental pathologies must be absent.

PERSEID contains two phases. The first defines the procedure used to verify that a GC burst signal has been detected in a particular GC trigger system. The second provides a sequence of administrative directives governing the public dissemination of essential information about the burst.

The first phase of PERSEID consists of three levels that a candidate burst must pass in each operational system before the candidate is upgraded to signal status. A fourth level gives the procedure for merging the alarms obtained by the two triggers. These levels are outlined below:

(1) Level 0. The Level 0 trigger is defined by the automatic activation of a pager or cellular phone to both the on-call physicists by either the ERP or PHRASE SNM. The thresholds of these monitors are set to correspond to a Poisson probability of 10^{-5}, which, for a 40 mHz background rate corresponds to more than 4 events in 2 s. This threshold was set to produce a minimum of 0.5–1 alarms/month when pathologies are absent. This is the rate expected from Poissonian fluctuations for a 40–65 mHz background rate. Pathologies can alter this rate in an uncontrolled way.

(2) Level 1. For every Level 0 trigger the on-call physicist checks directly on the acquisition computers the SNM data looking for the presence of specific detector-associated pathologies. The checks include verifications of: The absence of calibration pulses from lasers and LEDs; normal operation of PHRASE and ERP systems via examination of single muon trigger rates per supermodule; normal hit rates and normal high voltages of the streamer tube system; proper synchronization in the PHRASE system; the absence of a high voltage alarm on scintillation counter phototubes; the absence of voltage transients on the power mains.

(3) Level 2. For every Level 1 trigger, checks for abnormalities are performed in the data: The ERP and PHRASE 'singles' rates must have been stable during the hour preceding and 10 min after the burst. The spatial distributions of all GC events must be consistent with a uniform neutrino luminance across the detector.

(4) Level 3. When a Level 2 is established in a given system the event multiplicity over a specified time window must exceed two preset thresholds $T_{\rm low}$ and/or $T_{\rm high}$. These thresholds are associated with 'weak' and 'strong' GC alarms. The $T_{\rm low}$ multiplicity threshold corresponds to a Poisson probability of 10^{-5} for a random background fluctuation of events above 10 MeV in ten years in a specified burst search time window. For example, for a 2 s window and 40 mHz background rate, $T_{\rm low} = 8$ events above 10 MeV. The $T_{\rm high}$ threshold is set at 15 events (for a 2 s window). There is essentially no chance that background fluctuations would produce these hit multiplicities. The outcome of Level 3 for each system is classified as a 0, W(eak), S(trong) or D(ead) respectively corresponding to: Not exceeding any threshold; exceeding a $T_{\rm low}$ threshold; exceeding a $T_{\rm high}$ threshold; the system being in dead time.

(5) Level 4. The final status of a GC burst candidate is taken to be a reasonably conservative intersection of the system statuses from the Level 3 output. A 'Strong' GC alarm obtains only for the combinations 'SS', 'SW', 'WS', 'SD' and 'DS'. A 'Weak' GC alarm obtains for the combinations 'WW', 'WD' and 'DW'.

A burst that generates a 'Weak' alarm may have sufficient multiplicity to be unlikely to be a Poisson fluctuation. However one cannot exclude with certainty all conceivable spurious sources. Therefore a weak alarm bulletin is designated ultimately to be shared with other underground neutrino observatories.

Conversely, a burst that generates a 'Strong' alarm contains sufficient events to be unambiguously convincing that a neutrino burst is the likely source. In this case a MACRO bulletin would be dispatched to a hotlist of observatories via e-mail, IAU bulletins and telephone calls. The bulletin would contain: (1) The start UTC time; (2) The mean UTC time; (3) Duration of the burst; (4) The number of events > 10 MeV; (5) The mean energy; (6) Rise time (from 0.10 to 0.90 of the total number of events) (7) A measure of compatibility with a standard supernova model time distribution and energy spectrum.

4. Combined ERP and PHRASE online monitor results

The two component PHRASE/ERP MACRO supernova monitor system, albeit without the alarm generation protocol described above, has been in operation since 1992. We report below on its functioning from January 1995 and demonstrate that a continuously online, stable supernova neutrino observatory is in place.

We emphasize that the background alarm rates can be different in the PHRASE and the ERP systems because of differences in their electronics and reconstruction software. We exploit these differences to obtain confidence in candidate selection.

For the data period included here, the raw background rates (above 10 MeV) have been ~ 60 mHz and ~ 40 mHz for the ERP and PHRASE systems respectively. This difference is primarily due to the fact that the ERP electronics system is more susceptible to making event energy errors because of accidental coincidences between radioactive decays at well separated places in a single scintillator tank. These reconstruct to a larger energy than that of any of the individual events. Most but not all of these false triggers are eliminated in the ERP analysis by requiring coincidence between the event location as reconstructed from the ratio of pulse charges observed at the two ends of a scintillator and the relative signal times at two ends. The PHRASE system is much less susceptible to this mode of false triggering.

For the one and a half year period from February 1 1995 to August 1 1996, Fig. 2 shows the combined ERP and PHRASE active mass (left) and the percent up-time (right), as a function of time. The latter is computed as the fraction of time per day that at least one SM was active.

The complete readout of the 6 SMs started at the beginning of July 1995, while for the rest of the

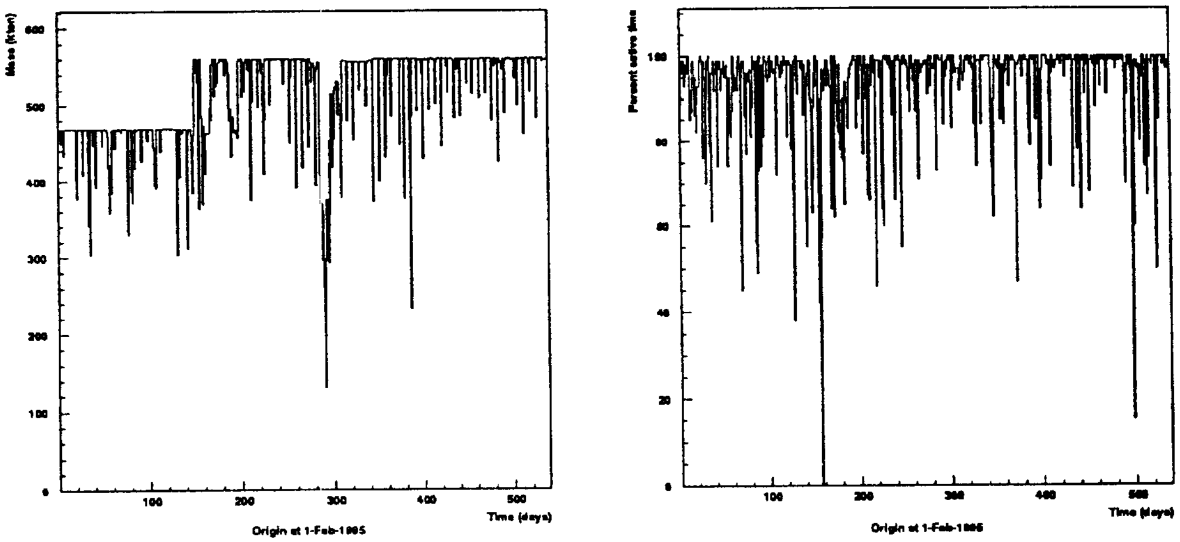

Fig. 2. Liquid scintillator active mass (left) and percentage of time in each day that the search was active (right) during the one and a half year period.

period five SMs were active. During this period the apparatus was stable, despite ongoing non-GC electronics installation and hardware repair activity. The average percent up-time was 97%. The dead time was primarily due to power supply failures and to acquisition malfunctions.

During the analysed one and a half year period the online monitors signalled in total 81 clusters of events for all time windows searched whose probabilities were lower than the fixed 10^{-5} value. These were classified as follows:

(a) underestimates of the background rate (18 events);

(b) apparatus problems (30 events);

(c) background fluctuations (33 events).

The '(a)' category is an artifact of computing the average rate over two-hour periods. During the first two hours of a run the monitor program may be using a rate computed for a previous run for which a different number of SMs was active. This problem has been solved since mid-1995 by calculating at run start the expected rate from the knowledge of the number of active Microvaxes and of the average rate per SM.

The '(b)' category clusters are caused by: (b1) The loss of synchronization between PHRASE modules, due to power glitches or missing synchronization pulses at run start, which reduces the muon rejection efficiency; (b2) Unexpected calibration pulses; (b3) The result of sparking or corona from the photomultiplier high voltage in a few malfunctioning scintillator ends. As improvements are made to the detector (e.g., replacement of bad phototubes) the rate of these 'b' category bursts can be expected to diminish. These 'b' type burst have not been observed to occur simultaneously in both systems.

The '(c)' category events contain the true Poissonian fluctuations expected from the 40–60 mHz residual BG rate. These clusters of events never exceed the W threshold.

Fig. 3 (left) shows the distribution of the 33 clusters classified as real background fluctuations (the 33 events of category '(c)') as a function of the solar time. The distribution is flat as expected, while the distribution (Fig. 3, right) of all the other 'fake' clusters (the 48 events of categories '(a)' and '(b)') as a function of solar time shows instead that they mainly occurred during working hours.

4.1. Online / offline PHRASE monitor comparison

We also compare the results of the supernova monitor on the PHRASE system with a post-run program which runs off the main acquisition without event loss. During a one year period (February 1995 to February 1996) this monitor signalled 65 alarms and the associated offline program signalled 64 warnings; 51 of the offline warnings coincided with

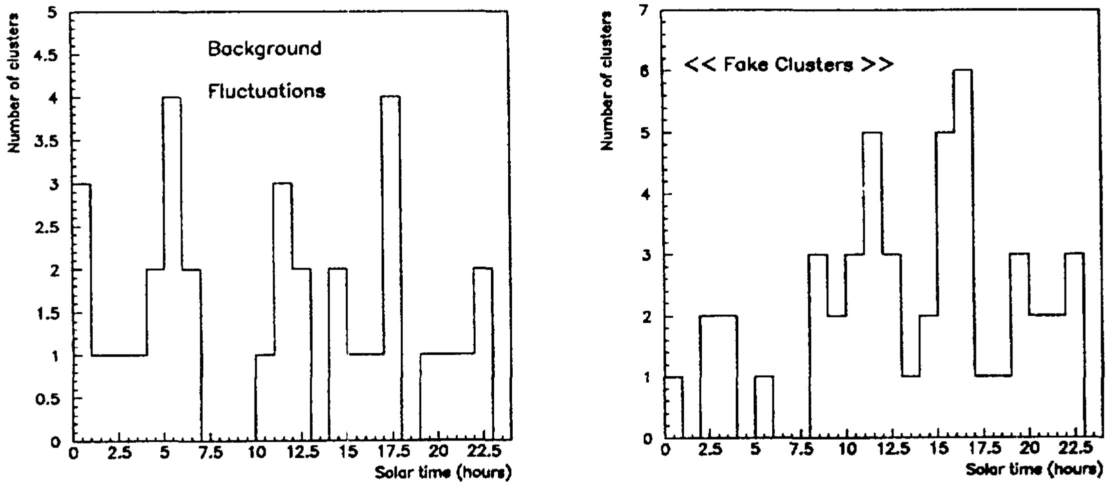

Fig. 3. Distribution of the clusters classified as (left) background fluctuations, category '(c)', and (right) 'fake clusters' categories '(a)' and '(b)', as a function of solar time.

those seen by the online program. Ten of the 14 clusters seen only by the online monitor program belong to the 'a)' category. Two other cases belonging to the '(c)' category are explained by more accurate calibration factors used for the energy reconstruction in the offline program. In the remaining two cases the general MACRO acquisition had crashed because one of the electronics modules was malfunctioning while the monitor system continued to process data. Five of the 13 warnings seen by only the offline program belong to the '(a)' category; the other 5 events were caused by low energy ($E < 10$ MeV) high rates due to LED or LASER calibrations or to one counter firing because of electronics problems. Under these conditions the online program lost some of the few events passing the threshold and causing the offline alarm. For the remaining three alarms the online program was not running for accidental reasons.

The observed offline multiplicity distributions in time intervals of two seconds (left) and eight seconds (right) for the one-year PHRASE online/offline comparison period are shown in Fig. 4. The agreement with the expectations (superimposed circles) due to background Poisson fluctuations is very good. Good agreement is also obtained for all other time intervals for which the burst search was made. These distributions represent the sums of those obtained from the offline analysis program, excluding runs with noisy counters or synchronization losses. The '(c)' category clusters signalled by the online monitor are contained in the high multiplicity tails of these distributions. The energy distribution of the '(c)' category events is not statistically distinguishable from the observed energy distribution of non-coincident radioactivity events in the scintillators. A similar analysis for the ERP system also indicates no deviation of the observed bursts from the Poisson expectations.

5. Conclusions

The MACRO experiment has been searching for neutrino bursts from stellar collapses since 1989 when the experiment started taking data in its initial configuration. This search has generally had steadily increasing sensitive mass and up-time efficiency (currently 97%), and since 1995 its full mass (560 t) has been sensitive a significant fraction of the time (Fig. 2). During this time no supernova was observed. A dual trigger supernova watch system, which we have been testing on part of the apparatus since 1992, performed well during one and a half years of operation of the complete MACRO detector. All the alerts observed were immediately attributed to hard-

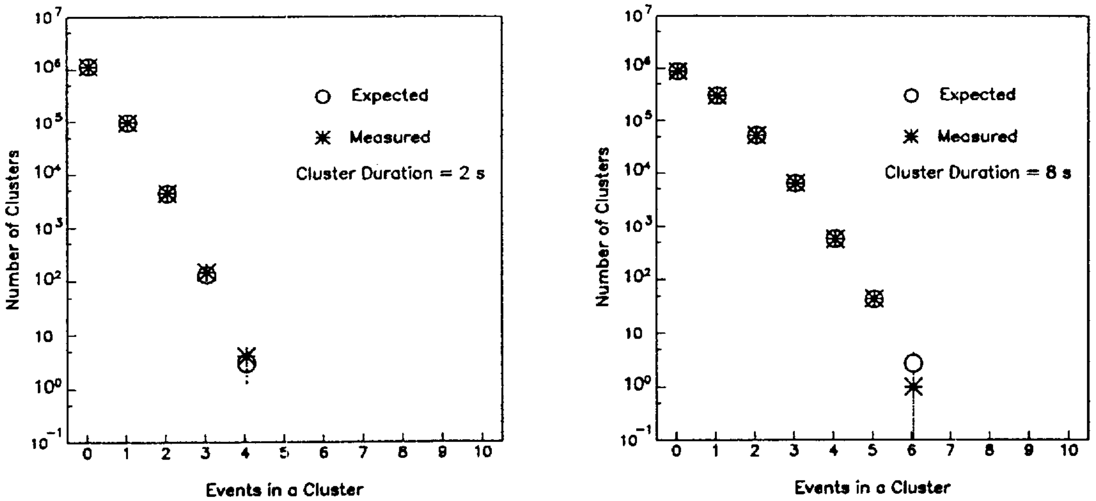

Fig. 4. Observed and predicted number of event clusters vs. cluster multiplicity for time intervals of 2 s (left) and 8 s (right) during the one-year monitoring period. A similar plot for the ERP system also indicates no deviation form the Poisson expectation.

ware failures or background fluctuations. This system allows us to recognize a supernova signal on the order of 1 h.

At present we are completing the detailed development of a fully integrated online supernova monitor with facilities to automatically reject false triggers according to fixed criteria. When this development is completed, the final criteria will be published and communications links established with other observatories.

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