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Integration of the Super Nova Early Warning System with the NOvA Trigger

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Abstract. The NOvA experiment, with a baseline of 810 km, samples Fermilab's upgraded NuMI beam with a Near Detector on-site and a Far Detector (FD) at Ash River, MN, to observe oscillations of muon neutrinos. The 344,064 liquid scintillator-filled cells of the 14 kton FD provide high granularity of a large detector mass and enable us to also study non-accelerator based neutrinos with our Data Driven Trigger framework. This paper will focus on the real time integration of the SNEWS with the NOvA Trigger where we have set up an XML-RPC based messaging system to inject the SNEWS signal directly into our trigger. This presents a departure from the E-Mail based notification mechanism used by SNEWS in the past and allows NOvA more control over propagation and transmission timing.

1. Supernova Neutrinos

When large stars run out of nuclear fuel, their massive cores can no longer support themselves against gravity and collapse into a neutron star. This collapse produces an initial burst of electron neutrinos as most of the protons in the core turn into neutrons via electron capture. The resulting neutron star is so hot that a wide range of particles are produced via pair production from the available thermodynamic energy. However, neutrinos with their small cross section are the only particles to escape the dense core: all others immediately interact again. While neutrino pair production is mediated by the weak force and is comparatively rare compared to the production of more strongly interacting particles, the proto-neutron star quickly ($\sim$ms) becomes transparent to neutrinos. These escaping neutrinos are thus the dominant cooling mechanism, and carry away 99% of the $\mathcal{O}(10^{53}\,\text{ergs})$ of the available gravitational binding energy released by the change in size of several solar masses of stellar core collapsing to a few kilometers of neutron star. About one percent of the resulting neutrinos comes from that initial neutronization burst in the first second, with the bulk of the luminosity spread over tens of seconds of cooling time. All flavors of neutrinos are produced, with average neutrino energies of about 12 MeV for ν_e, 15 MeV for $\bar{\nu}_e$, and 18 MeV for all other flavors. While neutrinos escape the star promptly after core collapse, other forms of radiation do not: the surface of the star, visible in electromagnetic radiation, remains undisturbed until the shock wave starting in the core reaches that surface and blows it apart. Thus, the neutrino signal leads the electromagnetic signal by the transit time of the shock wave over a stellar radius: $\sim$hours, depending on the size of the progenitor star.

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Table 1. Summary of neutrino detectors currently contributing supernova alarms to SNEWS. Neutrino event estimates are approximate.

Detector	Type	Mass (kton)	Location	Events at 8.5 kpc	Live period
Super-K	H_2O	32	Japan	8000	1996-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.4/PMT	South Pole	N/A	2007-present
Daya Bay	C_nH_{2n}	0.16	China	80	2012-present

This scenario was confirmed by observations of SN1987A in the proton decay detectors operating at the time [1–3]. Examples of calculations of the resulting neutrino flux can be seen in [4–6]. Details of the spectrum and time profile would provide valuable insight into the supernova process itself [7], as well as the properties of the neutrinos: a supernova is perhaps the only place in the universe with a high enough neutrino density for neutrino-neutrino interactions to cause noticeable perturbations of the overall signal [8,9]. A comprehensive summary of modern supernova neutrino detection can be found in Ref. [10].

2. SNEWS: The Supernova Early Warning System

While electromagnetic telescopes can catch the $\sim 0.1\%$ of the energy released in photons from a supernova across the observable universe (and in fact do so about once per day), neutrinos have such a low cross section that the current generation of neutrino detectors are sensitive to only those in the Milky Way and its immediate environs. Estimates of the supernova rate in a galaxy like ours suggest several per century [11] could be seen in neutrinos. To ensure the best use of such a rare occurrence, a network of neutrino experiments (Tab. 1) is collaborating in a coincidence network called SNEWS: The Supernova Early Warning System [12, 13]. The network's motivation is to provide a coincidence trigger for the issuing of an automated alert that a galactic supernova has just happened. While any individual experiment is sensitive to a supernova, many things can happen in a detector which look like a burst of low energy neutrinos: for example, electronic noise or energetic cosmic rays causing a string of spallation induced radioactive decays. Any individual experiment will thus carefully review its data to filter out noise-induced supernova triggers before telling the world. Experience shows that this human intervention takes about an hour: unfortunately the same order as the "early warning" provided by the neutrinos in advance of the electromagnetic explosion. However, the likelihood that such noise happens in two difference experiments at the same time is small. Requiring a coincidence between experiments filters out such false alarms. This coincidence trigger between experiments allows a rapid, automated alarm to be sent to the community, providing advance warning that the galactic event of the century is about to happen. If each experiment has an individual false alarm rate of less than once per week, a 10 s coincidence window yields a Poisson probability of a false coincidence of around once per century: less than the rate of real supernovae.

This coincidence trigger is implemented by running a central coincidence server, located at Brookhaven National Lab with a backup server located at INFN Bologna. These run in parallel to provide redundancy in case of network or server troubles with the primary server. The server program is implemented in C and watches standard Unix TCP sockets for SSL signed datagrams sent by the participating experiments (see Tab. 1). Each experiment is wholly responsible for the details of what they call a potential supernova, and sends a datagram to the SNEWS server containing at least time information. Optionally, other information

such as significance, possible problems, or estimated locations can be included. If at least two such triggers are coincident within 10 s, SNEWS sends emails first to the participating experiments' experts, then a GNU Mailman mailing list. This mail list is open to anyone who wishes to sign up: as of this writing, 2,974 individual addresses are subscribed, via the SNEWS website (`http://snews.bnl.gov/`). Some of those are multiple addresses per person (in particular, email-to-SMS gateways are popular), others are mailing lists that pass along the notice to their subscribers. Most notably *Sky & Telescope* in collaboration with the AAVSO (American Association of Variable Star Observers) maintains an "AstroAlert" list (`http://www.skyandtelescope.com/resources/proamcollab/AstroAlert.html`). Both organizations are experienced at coordinating expert amateur observations.

In addition to the 4π coverage from many expert amateur eyes (recall that SN1987A was discovered fortuitously simply by someone looking up and saying "hey that star's not supposed to be there!"), operators of X- and gamma-ray transient observing satellites will also learn that the next flash they see will be particularly interesting. Astronomers across the spectrum will thus have some time to get ready to start observing the new supernova from as close to the start of the electromagnetic fireworks as possible. This will be especially useful for such a nearby supernova: most supernovae are discovered days or weeks after the fact by robotic surveys of distant galaxies, rendering observations more difficult both by late starting time and large distances.

3. The NOvA Experiment

The NOvA (NuMI Off-axis ν_{e} Appearance) experiment [14] is a long baseline neutrino experiment observing Fermilab's NuMI neutrino beam 14 mrad off-axis both near its source and 810 km away in Ash River Falls, Minnesota. Its primary goal is to measure the neutrino oscillation amplitude θ_{13} via electron neutrino appearance in the primarily muon neutrino beam. By comparing three years of neutrino data with three years of anti-neutrino data, it will be sensitive to a range of values of the CP-violating δ_{CP} and the neutrino mass hierarchy. Systematic errors are minimized by comparing the signal from a 300 kt "near detector" at the beam's source and a 14 kt "far detector". Both detectors are constructed of PVC cells filled with liquid scintillator, with the light piped out via wavelength shifting fiber to avalanche photo diodes (APDs). While designed to get high resolution on the electromagnetic showers produced by $\sim$GeV scale electron neutrinos, 10 MeV electron antineutrinos reacting in the detector via inverse beta decay will produce positrons that will traverse several cells. A core collapse supernova in our galaxy will cause several thousand such interactions over tens of seconds.

While comparable in mass and signal to the detectors currently contributing to SNEWS (Tab. 1), the NOvA far detector is on the surface, with minimal overburden. This results in a cosmic ray rate in the tens of kilohertz. While cosmic ray muon tracks can be easily distinguished from low energy positrons, Michel electrons and low energy neutrons originating from those muons which stop are harder to filter. While a real-time analysis of the data is being developed to sort out the SN signals part of NOvA's "Data Driven Trigger" system [15], this aspect of the experiment is not yet ready for prime time. However, should a supernova occur, the data need to be preserved for later offline analysis.

4. NOvA/SNEWS Integration

NOvA's data acquisition system [16] buffers the 900 MB/s of raw data streaming from the APDs using a commodity server farm. Triggers are issued by a "Global Trigger" (GT) program, and events built out of the time window specified in the trigger. The rest of the buffered data is lost. The trigger central to the experiment's main goal of long baseline neutrino oscillation is generated by timestamping the NuMI beam spill: that time stamp is propagated from the accelerator complex at Fermilab to both NOvA detectors via a XML-RPC message passing

system. Other triggers are simple minimum bias periodic pulsers, or data driven triggers looking for interesting event topologies such as data resembling magnetic monopoles.

Since NOvA's own real-time supernova recognition code isn't ready yet, we have replicated the machinery used by the beam spill trigger to let the SNEWS coincidence server at Brookhaven trigger both NOvA detectors in event of a supernova alert. The SNEWS server sends the alert time to a NOVA DAQ machine at Fermilab, which forwards the XML-RPC to both detectors' GT processes and forces the buffered data to be dumped to disk starting at the alert time. Currently 2 s of data is dumped. Continuous readout of such high volumes of data exposed bugs in NOvA's event building and data logging code; tests have shown the ability to log the tens of seconds needed to fully record a supernova neutrino signal and fixes are currently being deployed. Additionally, the SNEWS server sends regular short (100 μs) triggers to ensure the triggering infrastructure is functioning, once per minute. It also sends a full length SN trigger once per day. This data turns out to be useful to other NOvA analyses as regularly recorded minimum bias data for efficiency calculation and monitoring purposes.

5. Conclusions

Today's neutrino experiments are sensitive to the next core-collapse supernova in our galaxy. While experiments individually might be slow at telling the world about their signal, a coincidence between different experiments allows a rapid automated alarm. The SNEWS system provides this for astronomers: and it now also provides this to the NOvA long baseline experiment. Using an XML-RPC message, a supernova coincidence triggers the NOvA detectors to save a long period of buffered data, to prevent this large but noisy (at the 10 MeV level) experiment from missing "once in a career" style data.

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