7-1997

SONTRAC-a low background, large area solar neutron spectrometer

C B. Wunderer
University of New Hampshire - Main Campus

D Holslin
Science Applications International Corporation

John R. Macri
University of New Hampshire - Main Campus, John.Macri@unh.edu

Mark L. McConnell
University of New Hampshire - Main Campus, mark.mcconnell@unh.edu

James M. Ryan
University of New Hampshire, James.Ryan@unh.edu

Recommended Citation

Wunderer, C.B.; Holslin, D.; Macri, J.R.; McConnell, M.; Ryan, J.M., "SONTRAC-a low background, large area solar neutron spectrometer," High Energy Radiation Background in Space, 1997 Conference on the , vol., no., pp.73,76, 22-23 Jul 1997 doi: 10.1109/CHERBS.1997.660251

SONTRAC – A Low Background, Large Area Solar Neutron Spectrometer

Cornelia B. Wunderer[1], Daniel Holslin[2], John R. Macri[1], Mark McConnell[1], and James M. Ryan[1]
[1]Space Science Center, University of New Hampshire, Durham, NH 03824-3525, USA
[2]Science Applications International Corporation, San Diego, CA 92121, USA

Abstract – SONTRAC will measure 20 - 250 MeV neutrons from solar flares using scintillator fibers viewed by CCD cameras to track neutron-proton scatters. SONTRAC can also be used to track gamma rays above 20 MeV. Veto shields are used to reject all charged particles. Gamma-ray and neutron events have very different track densities, allowing discrimination between the two. Double neutron-proton scatters allow unambiguous determination of the incident neutron energy and direction. Therefore, SONTRAC is capable of rejecting almost all background except neutrons from the solar direction. SONTRAC would have detected the June 15, 1991 flare with 42σ for 20-100 MeV neutrons, having an effective area of 17 cm² in that energy range. We present SONTRAC prototype performance results both for neutrons at threshold energy and for cosmic-ray muons.

I. INTRODUCTION

Understanding the acceleration of particles to high energies is a key step in solving the solar flare problem. High-resolution measurements of each particle's energy, direction, and production time would be ideal. Charged high-energy particles from solar flares cannot easily be observed at earth because they - unlike neutrons and photons - are influenced by the interplanetary magnetic fields. Solar flare protons of around 20 MeV at the Sun can be sampled by nuclear gamma ray peaks. Above 250 MeV they can be sampled by gamma-rays from pion production and decay. Solar flare protons in the interesting intermediate energy range of 20 to 250 MeV at the Sun, however, are poorly sampled by gamma rays, but they interact with the denser layers of the sun to produce high energy neutrons of comparable energies. Fig. 1 shows a schematic of solar neutron and gamma-ray production for a power-law proton spectrum. Measuring high-energy neutrons from solar flares with good spectral and temporal resolution will allow us to construct an accurate spectrum of solar flare protons between 20 and 250 MeV.

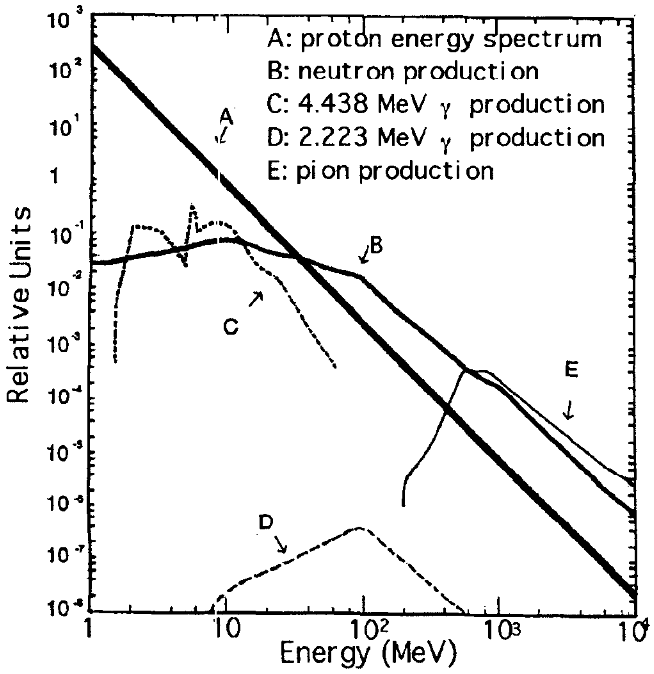

Fig.1: Schematic representation of solar neutron and gamma-ray production [1]

Measuring solar flare neutrons presents a unique challenge. High-energy neutrons from every direction are present in a spacecraft environment. They are products of cosmic-ray particles incident on either the earth's atmosphere or the spacecraft itself. By using a neutron telescope as a spectrometer, we are able to reject most of the background due to geometrical considerations, thereby greatly enhancing our signal-to-noise ratio. Directional neutron telescopes/ spectrometers based on double scatters have been used for many years [2], [3], [4], [5].

We present here the predicted capabilities of SONTRAC (Solar Neutron Tracking Telescope). SONTRAC combines the method of double scatters with current fiberoptic scintillator, image intensifier and CCD technology to perform the much needed neutron measurements described above. SONTRAC can also act as a high energy gamma ray telescope above 20 MeV. It is the basis of a NASA SMEX mission proposal for the upcoming solar maximum.

II. STATEMENT OF PROBLEM

The radiation background encountered by an instrument in near-earth orbit consists of charged particles, gamma rays and neutrons. Primary cosmic rays consist mostly of protons and, to a lesser degree, electrons. The secondary component has many more constituents.

The neutron background originates from the earth's atmosphere and the spacecraft. The omnidirectional neutron background encountered by a spacecraft at about 400 km altitude was measured by Morris et al. [6] using one of the D1-modules of COMPTEL on the Compton Gamma Ray Observatory (CGRO). They measured omnidirectional neutron fluxes of $3.28 \cdot 10^{-3}$n MeV^{-1}cm^{-2}s^{-1} at 20 MeV, $1.77 \cdot 10^{-3}$n MeV^{-1}cm^{-2}s^{-1} at 60 MeV, and $1.63 \cdot 10^{-4}$n MeV^{-1}cm^{-2}s^{-1} at 200 MeV. This must be compared to the neutron flux from solar flares.

This work is supported under NASA's Space Physics Supporting Research and Technology Program (NAGW - 5076).

The neutron emission (at the Sun) measured for some larger solar flares is shown in Table 1.

TABLE 1: MEASURED SOLAR NEUTRON FLUX FOR SEVERAL LARGER FLARES

Flare	Energy range	Neutron flux	Instrument
24 May 1990	>100 MeV	$3.5{\cdot}10^{30}sr^{-1}$	GRANAT, [7]
3 June 1982	>100 MeV	$8{\cdot}10^{28}sr^{-1}$	SMM, [8]
11 June 1991	9-100 MeV	$2.1{\cdot}10^{28}sr^{-1}$	CGRO, [9], [10]
15 June 1991	9-100 MeV	$8.8{\cdot}10^{27}sr^{-1}$	CGRO, [9], [10]

III. THE SONTRAC INSTRUMENT CONCEPT

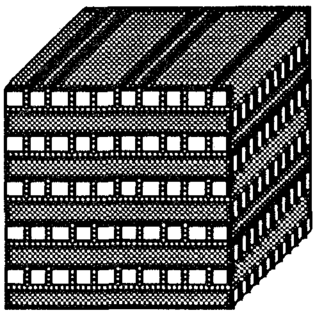

Fig.2: $(3mm)^3$ segment of the $(22cm)^3$ scintillating fiber block of the SONTRAC flight instrument.

The proposed SONTRAC tracker consists of a 22×22×22cm block of square, 300μm pitch, densely packed organic plastic scintillator fibers. The fibers are arranged in stacked planes with the fibers in each plane orthogonal to those in the planes above and below. Scintillation light is collected at both ends of each fiber in the bundle. One end is viewed by PMTs, the other by a chain of image intensifiers and CCD cameras. The concept of using a scintillating fiber block for tracking recoil protons in this context was originally suggested by Frye et al. [11].

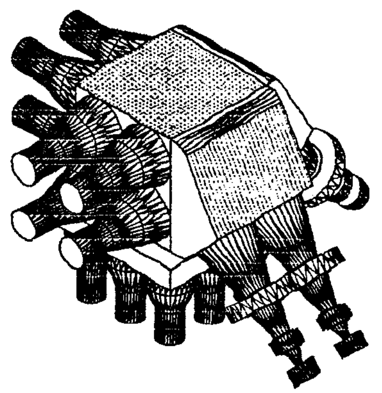

Fig.3: Isometric drawing of the SONTRAC tracker with its PMTs (left), imaging components with CCDs (right) and BGO calorimeter with PMTs (bottom).

A sketch of a small section of the fiber block is shown in Fig. 2, and an isometric drawing of the telescope in its flight configuration is shown in Fig. 3. A 1 mm Ta sheet rests on top of the fiber scintillator block and a BGO-Calorimeter is mounted below. The Ta sheet is necessary for the gamma-ray "mode" of the instrument. The whole instrument – tracker and BGO – will be surrounded by a 4π veto dome. Made of plastic scintillator and viewed by PMTs, it will allow us to recognize incoming charged particles and to reject any events generated by them. A conceptual sketch of the whole instrument configuration is shown in Fig. 4.

A neutron incident on the detector scatters off a proton (H) in the plastic scintillator. The proton leaves a visible track in the scintillator. The CCD cameras take a stereoscopic image of the proton track, showing its length - corresponding to energy - and its direction. Two proton scatters of one incident neutron allow unambiguous determination of the incident neutron energy and direction. A schematic of such a double neutron scatter is shown in Fig. 5.

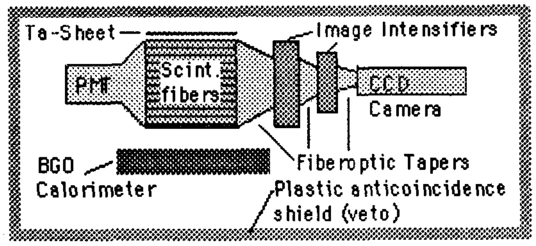

Fig.4: Schematic SONTRAC Instrument Concept.

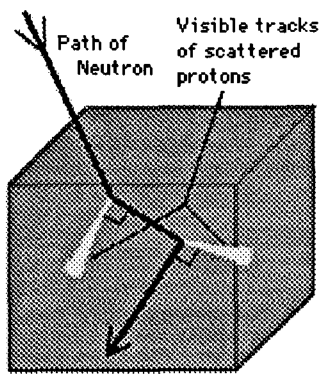

Fig.5: Schematic of double neutron scatter

The BGO calorimeter beneath the scintillating fiber block aids in determining the proton energies when proton tracks leave the scintillator. This extends the neutron energy range of the instrument.

If a solar origin for the incident neutrons can be assumed (this is the case if other parameters have established a flare event), single proton scatters or carbon scatters that result in a forward oriented cascade of particles can also be used. For these other reactions, the BGO calorimeter is necessary to measure the full energy, especially for the case of the carbon inelastic scatters.

Similar to the neutron imaging process, a high energy photon incident on the tracker undergoes pair conversion in the Ta converter or the scintillator block itself. The resulting electron-positron-pair leaves visible tracks in the scintillator that are recorded by the CCD-cameras. The stereoscopic images of the tracks allow unambiguous determination of the incident photon direction, and the combined energies of electron and positron deposited in the scintillator block and/or the BGO calorimeter allow determination of the photon energy.

Tracks of protons (from neutrons) and relativistic electrons (from gammas) can be differentiated from one another by their density. While the electron tracks are minimum ionizing, proton tracks are heavily ionizing – more so with decreasing energies.

SONTRAC is a self-triggering device. A (cumulative) PMT signal above a certain threshold gates the image intensifiers and CCD cameras. Along with the image, the PMT pulseheight as well as a time tag are stored. Knowledge of the energy (in the case of a neutron) and the arrival time are necessary to assign a production or release time for the high energy particle at the sun.

Using interaction probabilities calculated by Frye et al. [11], we predict an effective area of 17 cm^2 for 20-100 MeV and an average effective area of about 10 cm^2 for SONTRAC's whole energy range of 20-250 MeV.

IV. SONTRAC'S ABILITY TO REJECT BACKGROUND

SONTRAC will be able to reject almost all background. Any charged particles can be eliminated by requiring no coincident signal from the 4π veto shield for valid events.

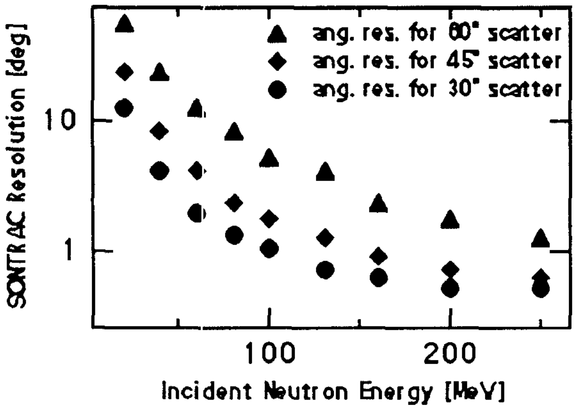

Fig.6: SONTRAC's estimated HWHM angular resolution for different scatter geometries.

The estimated HWHM angular resolution of SONTRAC for different scatter geometries is illustrated in Fig.6. The following calculations have been done assuming 45° scatters. We have used only the spatial resolution of the endpoints of the tracks to estimate the instrument's angular resolution. Additional energy and kinematic information could be used to improve the angular resolution for individual neutron events. When detecting and measuring solar neutrons, the angular resolution will allow us to reject 95.7% of the background at 20 MeV by restricting the field of view around the sun. Even more background can be rejected at higher energies (99.85% at 60 MeV). Based upon the omnidirectional flux reported by Morris et al. [6], this leaves us with a background event rate of 0.15 cts $min^{-1}MeV^{-1}$ at 20 MeV and 0.00027 cts $min^{-1}MeV^{-1}$ at 60 MeV or about 1.06 cts min^{-1} from the solar direction between 20 and 250 MeV. For these calculations, we assumed an isotropic distribution of background neutrons. Since most of the background neutrons are secondary neutrons from either the spacecraft or the earth's atmosphere (and both of those are behind or to the side of SONTRAC when it is pointed at the sun), our estimates are conservative.

Accidental coincident tracks will also contribute to the background. Two neutrons can enter the detector at the same time, leaving proton tracks that, by chance, fulfill the geometry requirements for a double scatter (correct angle between tracks, correct track direction). Pulse shape analysis on the PMTs will allow us to identify and reject any two proton signals generated more than about 1 µs apart. The image retention time of the phosphors in the image intensifiers is on the order of 1 ms and unrelated tracks may be present in the image. The frequency of two background neutrons entering the detector within 1 µs is about 0.03 mHz, the probability of those two generating a "plausible" track image is less than 0.4%. This results in a neutron background rate from accidentals of less than $7 \cdot 10^{-6}$ cts/min.

The estimated total neutron background rate for SONTRAC is 1.06 cts/min, the total background rate for 20-100 MeV is 1.053 cts/min. This would have allowed SONTRAC to measure the neutron spectrum between 20 and 100 MeV of the June 15 1991 flare (neutron rate 6.8 cts/min [9], [10]) with a significance of 42σ over the 40-minute flare duration. The 5σ level over SONTRAC's full energy range would have been easily reached for a flare 1/10 its size.

V. PROTOTYPE DESCRIPTION AND RESULTS

A small prototype of the SONTRAC detector was built at SAIC and is operational at UNH. Its core is a 12×12×100 mm organic scintillator plastic fiber bundle. The fibers are all parallel to each other, and only 2-D imaging is possible.

Each individual fiber has a 300 µm square cross section, consisting of a 230×230 μm^2 active polystyrene scintillator core, covered with two layers of fiberoptic cladding (10 µm total) and black extramural absorber (25 µm) to minimize crosstalk.

The fiber bundle is viewed by a PMT on one end. The other end of the bundle is viewed by a chain of two image intensifiers followed by a fiberoptic minifying taper and a CCD camera. The first image intensifier is always gated on. Its phosphor (P43) holds an image for about 1 ms, long enough for the PMT electronics to determine if the PMT signal exceeds threshold. If so, a trigger signal is generated. This signal gates open the second image intensifier and opens the electronic shutter of the CCD camera. An image of the track is then recorded. A schematic of the SONTRAC prototype is shown in Fig. 7. A more detailed description of the prototype can be found in Ryan et al. [12].

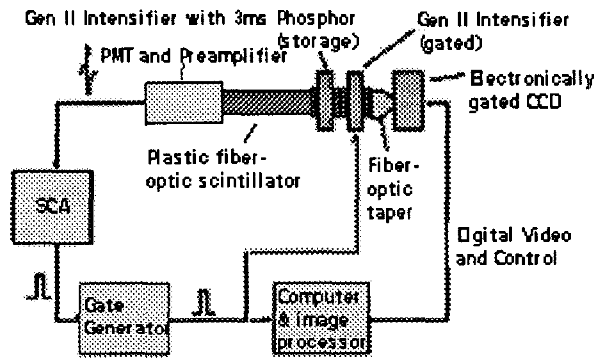

Fig.7: Schematic of SONTRAC prototype.

The scintillating fiber bundle was manufactured by Bicron. We use two image intensifiers from DEP (2nd stage gateable, with gate unit HiLight 2522), a fiberoptic taper from Schott (minification 2.8:1), and a Pulnix TM - 9701 CCD camera. The CCD camera is operated in digital mode with a Matrox Pulsar board on a Pentium PC. We use imaging software from Matrox (MIL 32). A PMT from EMI (9125B, selected for low noise properties) views the bundle from the other end. Standard NIM modules process the trigger logic.

We performed two tests of the track imaging ability of the prototype by exposing it to (1) cosmic ray muons, whose (minimum ionizing) tracks are of the same density as those of relativistic electrons and positrons, and (2) 14 MeV neutrons, which result in ~ 10 MeV proton tracks.

An image of a cosmic-ray muon track perpendicular to the fiber axis is shown in Fig. 8. The track traverses the full 12.7 mm width of the fiber bundle. This image was obtained by overlaying the CCD image with a calibrated mask of fiber locations. Note that the "dark" parts of the track coincide with the areas where the muon track traverses cladding and EMA (extramural absorber), both of which are non-scintillating materials. We expect about 4 photoelectrons per fiber at the first intensifier's photocathode. The density of scintillation light observed agrees within statistics with this estimate.

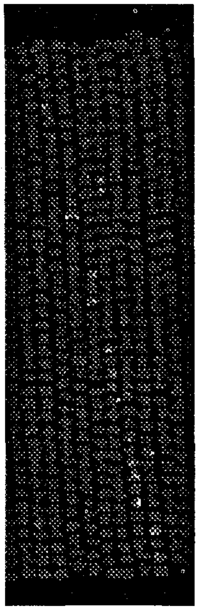

Fig.8: Cosmic-ray muon track. The black areas represent cladding and extramural absorber.

We exposed the prototype to 14 MeV neutrons at the San Diego State University's neutron generator facility. Figures 9 and 10 show images of scattered proton tracks. In both cases the original CCD image is shown on the left. On the right, the calibrated mask was used to determine fiber locations and boundaries. Light intensities were averaged for each fiber, and an average background was subtracted. "Dark" fibers were assigned a non-zero brightness level to reveal the layout of fibers in the bundle. Note the increasing light intensity towards the end of the proton tracks (top of image). This shows our ability to discriminate between the beginning and the end of a proton track.

The dynamic range of fiber brightness expected from a 11 MeV proton is ~2, consistent with Fig. 9. The relative intensities of proton and muon track images are in agreement with our calculations.

Since determination of both the proton track direction and orientation becomes feasible above 10 MeV (~5 fibers), our threshold for SONTRAC neutron measurements lies at 20 MeV.

VI. CONCLUSIONS

The SONTRAC prototype developed by UNH and SAIC has demonstrated all key features of the technique not addressed in earlier work. The prototype is limited to tracking in two dimensions. Self-triggered tracks from (minimum-ionizing) cosmic-ray muons, as well as proton tracks from 14 MeV neutrons, are clearly resolved. Extending this concept to 3-D tracking in a full flight instrument promises unprecedented capabilities for the study of solar flare neutrons.

ACKNOWLEDGMENTS

We would like to thank Dr. Patrick Papin and David Smith at the San Diego State University neutron generator for their help. We also want to thank Janis Baltgalvis and Aaron Polichar at SAIC for their efforts in assembling the SONTRAC prototype and software.

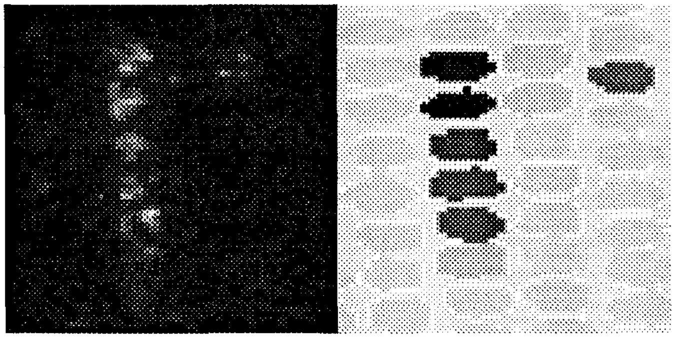

Fig.9: ~ 11 MeV proton track generated by 14 MeV neutron incident from bottom. "Raw" CCD image (left) and light intensities averaged over each fiber (right). Bright fiber to the right is probably a related second scatter, although this cannot be confirmed near energy threshold and without 3-D track knowledge.

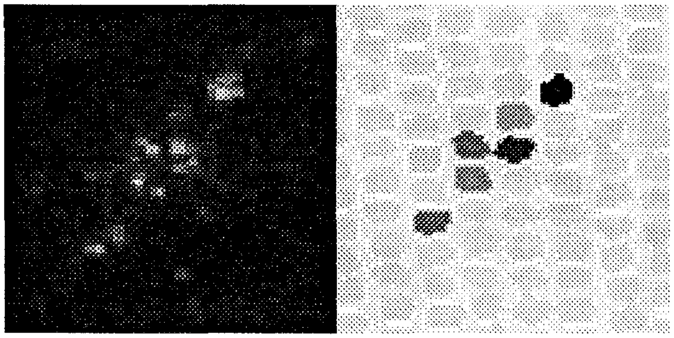

Fig.10: ~12 MeV proton track generated by 14 MeV neutron incident from the lower left corner of the image.

REFERENCES

[1] Lockwood, J.A., et al., Solar Physics **173**, p 151, 1997.
[2] Herzo, D., et al, Nucl. Instr. Methods **123**, p 583, 1975.
[3] Kanbach, G., et al., J. Geophys. Res., **79**, p 5159, 1974.
[4] Lockwood, J.A., et al., J. Geophys. Res., **81**, p 6211, 1976.
[5] Ryan, J.M., et al., in "Data Analysis in Astronomy IV," p 261, Plenum Press, NY, 1992.
[6] Morris, D. J., et al., topical meeting Radiation Protection and Shielding, p 227, 1996.
[7] Debrunner, H., et al., ApJ **479**, p 997, 1997.
[8] Chupp, E.L., ApJ (Suppl.) **73**, p 213, 1990.
[9] Rank, G., 1996 PhD thesis, Max Planck Institut, Technische Universität München, Germany.
[10] Nieminen, P., 1997 PhD thesis, Physikalisches Institut, Universität Bern, Switzerland.
[11] Frye, G.M., et al., 19th ICRC, **5**, p 498, 1985.
[12] Ryan, J.M., et al., San Diego SPIE proceedings, 1997.