Final Technical Report

Title:
1) Solar Microflare Detection-UNH (SPRH),
2) COMPTEL Burst Detection and Rapid Response-UNH and NMSU and (SPRF),
3) Solar Flare and Earth Albedo Neutron Studies-UNH, UCR and Glasgow (SPRI).

Type of Report: Final

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Period covered: 9/1/93 to 2/28/98

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Grant Number: NAG5-2350

The work conducted under this grant is comprised of three independent research efforts and the funding was awarded through three independent proposals to the Compton Gamma Ray Observatory Guest Investigator Program.

The work entitled Burst Angular Distribution was conducted in collaboration with Clemson University. The work at Clemson was subcontracted to them under the direction of Dr. Dieter Hartmann. The results of the collaborative effort were published as a Ph.D. thesis of Dr. R. Marc Kippen and subsequently published in the *Astrophysical Journal*, a reprint of which is attached.

The results of the work on Solar Microflares were presented at the 1997 Spring American Geophysical Union meeting in Baltimore (Arndt, Biesecker and Ryan 1997) by Martina Arndt. She received the award for the outstanding student paper of the meeting. A copy of the abstract is attached. There were no written proceeding of this meeting. Work continues on the project, the results of which will be published at either (or both) the Solar Physics Division of the American Astronomical Society in June 1999 or the Fifth Compton Symposium in September 1999.

The work entitled Solar Flare and Earth Albedo Neutrons was conducted in collaboration with the University of California at Riverside and the University of Glasgow. UCR was under contract with UNH to perform simulations of the COMPTEL instrument as it responds to neutrons. Glasgow, with its own funding, performed the deconvolution necessary to produce the neutron spectrum from the data. Attached is a report from Glasgow that uses the results of the UCR calculations to model the neutron spectrum from the 11 June 1991 solar flare. Work continues on this effort with the results to be presented at the Fifth Compton Symposium in September 1999.

Cormack Research Project: Glasgow University

Susan Skinner

August 1998

Abstract

The aim of this project was to investigate and improve upon existing methods of analysing data from COMPTEL on the Gamma Ray Observatory for neutrons emitted during solar flares. In particular, a strategy for placing confidence intervals on neutron energy distributions, due to uncertainties on the response matrix has been developed. We have also been able to demonstrate the superior performance of one of a range of possible statistical regularisation strategies. A method of generating likely models of neutron energy distributions has also been developed as a tool to this end. The project involved solving an inverse problem with noise being added to the data in various ways. To achieve this pre-existing C code was used to run Fortran subroutines which performed statistical regularisation on the data.

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1 Background

A solar flare is a huge release of energy within the sun which results in a sudden brightening of a small part of the sun's upper chromosphere. The flare's brightness increases dramatically over a short period of time, usually of the order of a few minutes. The flare's brightness then slowly decays over a longer timescale, usually of the order of an hour. The energy is released by the flare in various forms including both particles and penetrating radiation. This project dealt with data from neutrons emitted during such a flare. These in turn are a product of reactions between mildly relativistic ions and ambient ions. Thus they may reveal aspects of the energy and time-dependence of flare particle acceleration.

2 COMPTEL

COMPTEL is the imaging COMPton TELescope currently in orbit on the Gamma Ray Observatory. It is used to detect spectra of neutrons emitted during solar flares which have energies between approximately 20 and 120 MeV.

COMPTEL uses elastic scattering to measure the incident neutron's direction and energy and consists of two arrays of detectors, one at the front and one at the rear, both of which are surrounded by charged particle detectors. The forward detectors consist of a liquid organic scintillator which has a low carbon to hydrogen ratio. This is necessary to ensure that as many of the incident neutrons as possible scatter from hydrogen rather than carbon. These detectors are also designed so that the incident neutron should scatter only once before leaving the detector. The telescope can also be used to detect γ-rays but it is relatively simple to discriminate between neutrons and γ-rays because neutrons scatter protons in the first detector and γ-rays scatter electrons. These give rise to current pulses of different durations in the charged particle detectors. It is also possible to measure the time-of-flight of the neutron or photon from the forward detectors to the rearward detectors which also helps to distinguish between them as neutrons will take a longer time to reach the second detectors than photons travelling at the speed of light. The rearward detectors consist of NaI and are also surrounded by charged particle detectors. An ideal telescope event is when the neutron scatters elastically on hydrogen only once in a forward detector and is fully absorbed in a rearward detector.

The amount of energy deposited by the neutron in the forward detector E_1 can also be obtained from the current pulse generated in the charged particle detectors. The energy, E_2, that the neutron retains after it has been scattered in the first detector can be inferred from the time-of-flight between forward and rearward detectors. By adding the two amounts it is possible to calculate the total energy of the incident neutron.[1]

$$E_{total} = E_1 + E_2$$

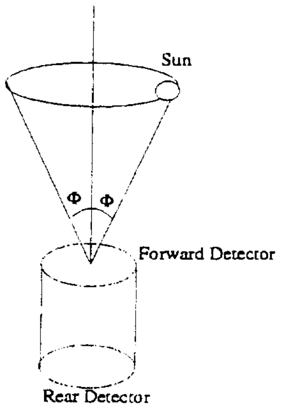
If we assume that the neutron is scattered elastically, then from kinematics we can deduce that the scatter angle of the neutron is given by

$$\phi = \tan^{-1}(E_1/E_2)$$

where ϕ is the scatter angle.[2] This allows us to check that the incident neutron has been emitted by the sun because if we check the position of the sun at the moment when the neutron was recorded, it ought to appear in or near an imaginary cone whose sides lie at angle ϕ. See Figure 2.

All of the above is true if the neutron scatters elastically from hydrogen. Of course, other

Figure 1: Checking the sun's position



events are possible, for example, if the neutron scatters from carbon rather than hydrogen, but these are recognisable from the shapes of the current pulses in the charged particle detectors which are very nearly 100% efficient at identifying charged cosmic rays. This project assumed that the data being analysed had been "cleaned up" and only results which had been identified as elastic scattering events were included. However, it would be possible to use the methods described in this report to analyse data which included obviously erroneous results. However a different choice of statistical regularisation method may have to be made .

COMPTEL is unique in that it has a high signal-to-noise ratio for neutron detection, giving it greater spectroscopic capabilities than have previously been available. It also has a field-of-view of 90° for neutron detection, which is quite large compared to previous detectors. For solar flares this should increase the number of flares which give usable data. It also opens up possibilities for studying Earth 'albedo' neutrons.

3 Statistical Regularisation

The task of analysing data received at COMPTEL in order to reproduce what was actually emitted at the sun is an inverse problem which has the form

$$\mathbf{x} = M.\mathbf{s} + \epsilon$$

where: $\mathbf{x}$ is the data from the telescope i.e. $\mathbf{x}_i$ is the number of neutrons in the energy bin from E_i to E_{i+1}; M is the response matrix of the telescope (see Section 4); $\mathbf{s}$ is the data as it was at the source i.e. what it is that we are actually trying to find; ϵ is the noise on the data. It is the noise on the data which makes inverse problems difficult to solve. If there was no noise and the problem was just of the form [3]

$$\mathbf{x} = M.\mathbf{s}$$

then we could simply invert the matrix and the solution would be

$$\mathbf{s} = M^{-1}.\mathbf{x}$$

However, such straightforward inversion amplifies any noise on the data and gives totally misleading results. Hence, we must use another method known as statistical regularisation. This involves compromising between an exact fit to the data, which is what straightforward inversion gives, and a uniform, featureless spectrum.

The particular statistical regularisation technique used in this project was Maximum Entropy. In order to perform this smoothing technique on the data, the Glasgow University Inversion Problem Subroutines (GUIPS) were used. These Fortran subroutines give various choices of 'smoothness' measure but we concentrated on the Maximum Entropy method. This gave us four possible options, either the Global Maximum Entropy smoothness constraint or the Local Maximum Entropy smoothness constraint could be used in conjunction with either a chisquared or Bayesian smoothing parameter. The Global Maximum Entropy smoothness constraint is of the form

$$\Phi(\hat{f}) = \sum_{i=1}^{n} \hat{f}_i - m_i - \hat{f}_i \log(\hat{f}_i/m_i)$$

where m_i is a 'prior estimate' of $\hat{f}$ which the function is smoothed towards. The Local Maximum Entropy constraint is of the form

$$\Phi(\hat{f}) = \sum_{i=1}^{n-1} (\hat{f}_i - \hat{f}_{i+1})(\log(\hat{f}_i) - \log(\hat{f}_{i+1}))$$

This modification removes the need for the prior m. To then solve the problem it is necessary to find the $\hat{f}$ which minimises

$$\chi^2 + \lambda\Phi(\hat{f})$$

where

$$\chi^2 = \sum_{i=1}^{m} \left[\hat{g}_i - \sum_{j=1}^{n} H_{ij} f_j \right]^2$$

and λ is the smoothing parameter. The choice of a Bayesian smoothing parameter puts $\chi^2 - \lambda\phi = m\sigma^2$ where m is the number of data points and σ^2 is the noise variance on the data. Choosing the chisquared smoothing parameter puts $\chi^2 = m\sigma^2$. For this project the GUIPS routines were treated as 'black boxes' and the actual details of the numerical strategy used to optimise $\chi^2 + \lambda\phi$ were not tampered with.

4 The Response Matrix

The response matrix M_{ij} gives the probability of a neutron in energy bin j being incorrectly counted in energy bin i. The matrix that was used in this project was generated by Monte Carlo simulations at the University of California and is shown below.

$$\begin{bmatrix} 139 & 26 & 37 & 9 & 5 & 1 \\ 5 & 181 & 37 & 8 & 1 & 3 \\ 1 & 4 & 126 & 32 & 8 & 1 \\ 5 & 2 & 8 & 101 & 45 & 11 \\ 4 & 2 & 3 & 7 & 45 & 31 \\ 0 & 2 & 1 & 1 & 2 & 13 \end{bmatrix}$$

The matrix should be read as follows: 139 neutrons which had a total energy of 13 MeV were counted in the first energy bin; 5 were counted in the second bin; 1 was counted in the third bin etc. The energy bins which were used are shown in the following table.

Bin Energy	Bin Width
13	8.5 - 17.5
22	17.5 - 26.5
32	26.5 - 37.5
50	37.5 - 62.5
77	62.5 - 91.5
100	91.5 - 108.5

Approximately 180,000 neutrons at each of the six energies, 13, 22, 32, 50, 77, 100 MeV, were 'injected' into the detector. Only those events which gave a signal consistent with single elastic scattering were retained and the results were binned according to their energies. It was assumed that all neutrons arrived at an angle of 15° to the detector axis. This is consistent with the large solar flares that occurred in July 1991.[4] The matrix is not a unit diagonal matrix because, particularly at low energies, there is a non-negligible chance of a neutron scattering more than once in the forward detector. This means that the actual energy deposited in the forward detector will be underestimated, although the event itself will still resemble an elastic scatter event. There is also a possibility that an inelastic scatter event could masquerade as an elastic event, giving a spurious result. Also only a small fraction of the incident neutrons scatter into the range of solid angles that includes the rearward detector. The response matrix is inherently noisy because, as can be seen from the matrix itself, there are only small numbers of neutrons in the bins. The matrix was used to generate the fake data required and then the data was convolved back through the matrix during the statistical regularisation process in order to reconstruct a spectrum so that it could be compared to the original fake spectrum.

5 Details of the Project

5.1 Simulation of Data

The code which this project used had four basic steps. It read in the response matrix and other details from a file, generated a fake spectrum, performed statistical regularisation on the fake data and then outputted the reconstructed spectrum. Originally, the code generated a perfectly flat spectrum using the formula detailed below,

$$y = \exp\left\{\frac{\mathrm{K}\sqrt{mass}\sqrt{1-2e/mass}}{\sqrt{2e}}\right\}$$

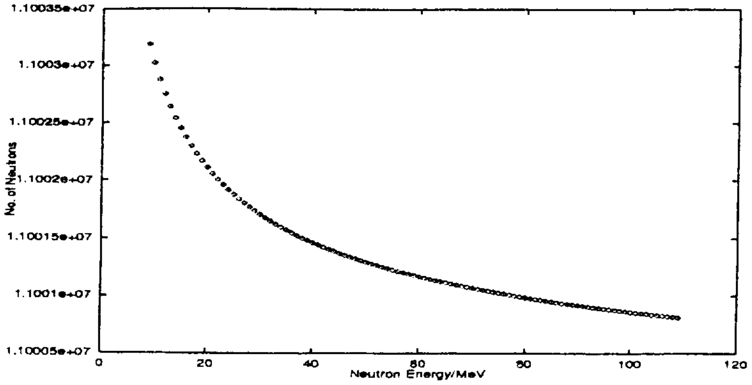
where K is a constant, *mass* is the mass of the neutron in MeV and *e* is the energy of the bin in MeV i.e. 13, 22, 32, 50, 77 or 100. However, since this does not correspond to what is actually recorded, the first task in this project was to change the code so that the generated spectrum better resembled the actual data received from COMPTEL. This meant incorporating the decay time of the flare into the calculations for the spectrum so that the spectrum had the form of an exponential decay. This is important because the decay times of the flares are of the same order of magnitude as the e-folding time of the neutrons, so some of them will have decayed before they reach the telescope i.e. observations over a finite time interval monitor an energy-dependent interval of the actual flare. The revised formula is

$$y = \exp\left\{((1/t)-(1/\tau))\left(\frac{\mathrm{K}\sqrt{mass}\sqrt{1-2e/mass}}{\sqrt{2e}}\right)\right\}$$

where K, *mass*, e are as above, t is the decay time of the flare and τ is the e-folding time of the neutron. The flare decay time used during this project was 1000s and the e-folding time of the neutron was 930s. The spectrum which was used is shown in Figure 2. This spectrum does actually resemble data which is available from the large flares which occurred in July 1991.[5]

The fake data was also perfectly 'quiet' but unfortunately attempts to add substantial noise directly to the data were unsuccessful. We used a poisson noise routine in C[6] to generate random noise which was added to our data points. Because we were adding poisson noise to data which was of the order of tens of millions the noise, being the square root of the data, was negligible. Reducing the total number of neutrons to increase the noise on the data did not help because the Fortran subroutines seemed unable to cope with a total number of neutrons below approximately one hundred thousand neutrons, at which stage poisson noise is still negligible. Various attempts were made to reach a compromise between non-negligible noise and a suitable total number of neutrons or to resolve the difficulties in the Fortran routines but this proved to be beyond the scope of this project.

Figure 2: The Fake Spectrum



Instead of adding noise to the data directly, we used the generated data normalised to high count rates, to concentrate attention on the uncertainty arising from the poisson noise on the response matrix, implicit in the Monte Carlo method. To do this we generated many alternative poisson realisations using the response matrix using a shell script. For each of these we first convolved the fake data through the response matrix and then reconstructed the solution using each of the four possible regularisation methods. However, an unexpected difficulty arose: certain realisations of the response matrix resulted in unstable behaviour in the GUIPS routine, in which counts in some energy bins were effectively set to zero. See Figure 3. Investigation of this effect proved to be beyond the scope of this project. We proceeded to put the necessary procedures in place by artificially suppressing the response matrix noise level by multiplying the numbers in the noisy response matrix by a factor of 100 and then dividing the resulting fake data by the same factor to compensate. This effectively reduced the noise level on the matrix by a factor of 10. See Figure 4. A complete investigation of the problem was deferred for future work.

Figure 3: Using a 'Noisy' Response Matrix

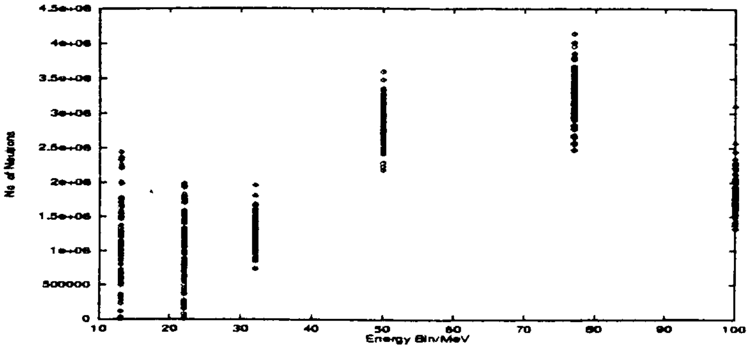
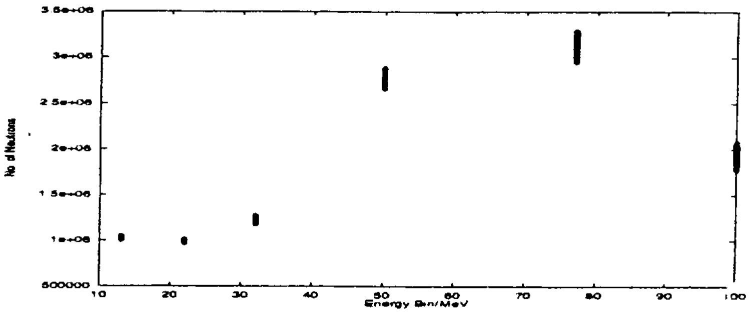


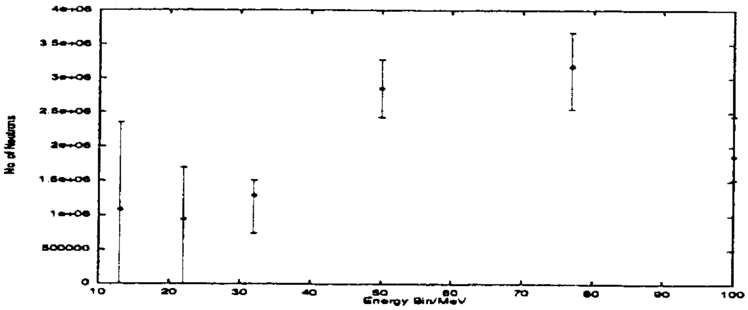
Figure 4: Using a 'Less Noisy' Response Matrix



5.2 Confidence Intervals for the Various Methods

So that an average spectrum could be plotted, more code was written in C to calculate the weighted mean of the total number of neutrons for each energy bin, as well as the length of error bar required. The error bars on Figure 5 show the region of 90% probability, i.e. 90 out of the 100 realisations gave a value for the total number of neutrons which was between these two points for that particular energy bin. Figure 5 must obviously be treated with care due to the small counts generated by the Fortran routines in some bins for certain realisations.

Figure 5: The Mean Spectrum using a 'Noisy' Response Matrix



5.3 Choice of Regularisation Strategy

In order to choose which of the methods of statistical regularisation was best, the shell script was used to create 100 realisations for each of the four possible choices. We used the noisiest response matrix for this so that we could see which of the methods were most sensitive to this. Figures 6, 7, 8 and 9 show the mean spectra obtained from these realisations, with the error bars showing the region of 90% probability. The original data is also plotted here (denoted by a +). From these graphs it can be seen that, while still returning spurious results in some energy bins for some realisations, the best choice of regularisation method

Figure 6: Local Maximum Entropy with Chisquared Smoothing Parameter

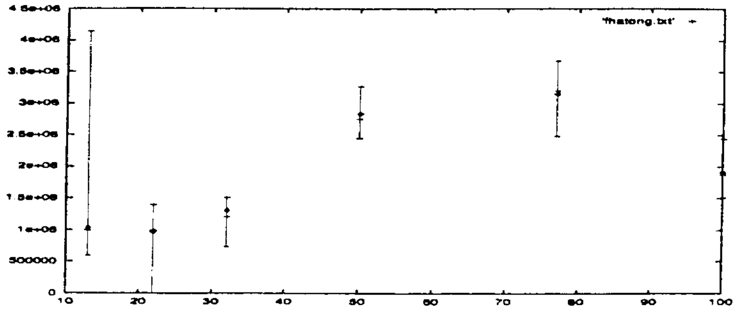


Figure 7: Local Maximum Entropy with Bayesian Smoothing Parameter

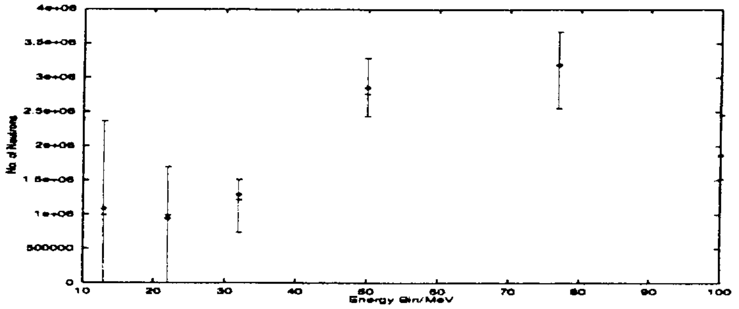


Figure 8: Global Maximum Entropy with Chisquared Smoothing Parameter

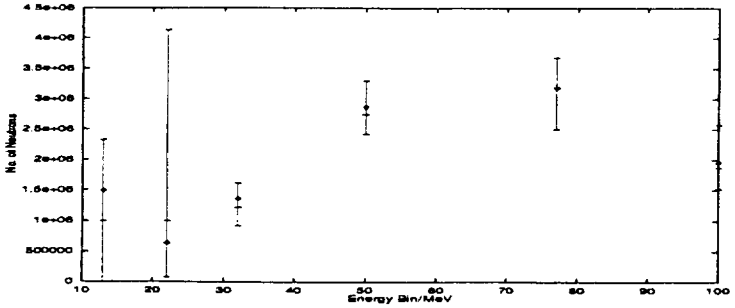
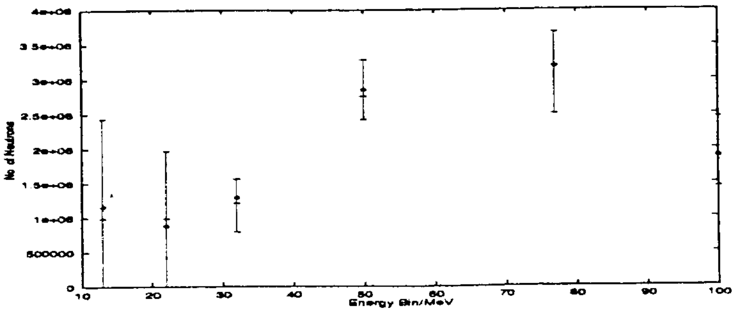


Figure 9: Global Maximum Entropy with Bayesian Smoothing Parameter

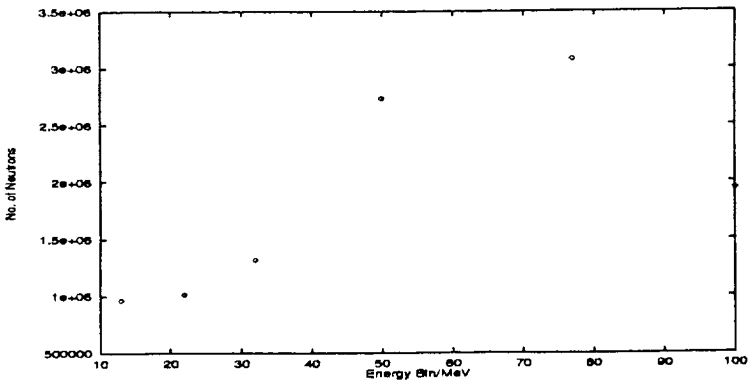


is the Local Maximum Entropy Constraint with a Bayesian choice of smoothing parameter. The Global Maximum Entropy smoothing constraint is more sensitive to possible features at the edges of the spectra than the Local Maximum Entropy smoothing constraint, which means for this particular case that it is more to susceptible to noise in these areas. Choosing the chisquared method tends to produce a larger than optimum smoothing parameter, which results in the data being over-smoothed. The Bayesian choice selects a smoothing parameter which is slightly smaller than the optimum value but in this case this had no adverse effects on the final result.

6 Conclusions

The main conclusion of this project was establishing the procedures, as detailed above, for generating true neutron energy distributions incident on COMPTEL. In particular, we have demonstrated that the Local Maximum Entropy 'smoothness' constraint, in conjunction with a Bayesian choice of smoothing parameter yields the best data fit, and is least sensitive to noise on the response matrix. Figure 10 shows the mean spectrum obtained using the Local Maximum Entropy constraint with a Bayesian choice of smoothing parameter and the response matrix with reduced noise.

Figure 10: The Mean Spectrum Using the 'Less Noisy' Response Matrix



7 Further Work

A further investigation into ways of adding noise to the data itself, while still operating within the constraints of the Fortran subroutines, should produce some helpful results on exactly how accurate a solution for the inverse problem we can obtain. This would possibly be better effected by altering the constraints on the Fortran routines so that they could cope with reduced numbers of neutrons, to allow the poisson noise to reach reasonable levels. It will also be necessary to investigate why the subroutines give strange results for the first two energy bins. Another interesting experiment would be to run the reconstructions with real data from COMPTEL to see what sort of features the actual spectrum has. It is important to remember that it is not only neutrons which are emitted during flares and it would also be useful to collate information gathered on γ-rays and X-rays with the information available on neutrons to form a more complete picture of what happens in the sun during a flare. However, a lot of work still has to be done before an absolutely complete spectrum from a solar flare can be obtained.

8 References

1. J. Ryan et al., Comptel as a Solar Gamma Ray and Neutron Detector
2. M. McConnell, AIP Conference Proceedings 294, (Waterville Valley, 1993), pp 21-25
3. Inverse Problems in Astronomy, I.J.D. Craig & J.C. Brown, Adam Hilger
4. G. Rank et al., AIP Conference Proceedings 294, (Waterville Valley, 1993), pp 100-105
5. J. Ryan et al., AIP Conference Proceedings 294, (Waterville Valley, 1993), pp 89-93
6. Numerical Recipes in C, Press, Teukolsky, Vetterling & Flannery, Cambridge University Press
7. A.M. Thompson, J.C. Brown, I.J.D. Craig & Fulber C., Astron. Astrophys., 265, pp 278-288, (1992)[9]
8. I.J.D. Craig & J.C. Brown, Astrophysics & Space Science, vol. 70, no. 2,pp 425-432,(July 1980) [9]
9. http://cdsads.u-strasbg.fr/