The Scintillating Optical Fiber Calorimeter Instrument Performance (SOFCAL)

M.J.Christl[1], C.M.Benson[1], F.A.Berry[1], W.F.Fountain[1], J.C.Gregory[2], J.S.Johnson[1*], R.B. Munroe[3], T.A.Parnell[2], Y.Takahashi[2], J.W.Watts[1]

[1] Marshall Space Flight Center/NASA, Huntsville AL. 35812
[2] University of Alabama in Huntsville, Dept of Physics, 35899
[3] University of Mobile, Mobile AL.
**University Space Research Association*

Abstract

SOFCAL is a balloon-borne instrument designed to measure the P-He cosmic ray spectra from ~200 GeV/amu - 20 TeV/amu. SOFCAL uses a thin lead and scintillating-fiber ionization calorimeter to measure the cascades produced by cosmic rays interacting in the hybrid detector system. Above the fiber calorimeter is an emulsion chamber that provides the interaction target, primary particle identification and in-flight energy calibration for the scintillating fiber data. The energy measurement technique and its calibration are described, and the present results from the analysis of a 1 day balloon flight will be presented.

1 Introduction:

The galactic cosmic ray (GCR) proton and helium spectra contain signatures of their source(s) and the galactic environment in which they are confined. The known cosmic ray spectrum extends from few×100 MeV to more than 10^{20} eV. A pronounced bend or *knee* in the all-particle spectrum near 10^{15}eV is likely caused by an upper limit for acceleration by SN shocks (Lagage,1983). Biermann (1993) has explored acceleration by both type-I and type-II SN. A difference in the composition from each SN type may be observable even at low energies by comparing the proton and helium spectra and ratio. The Scintillating Optical Fiber Calorimeter (SOFCAL) was designed to measure the proton and helium spectra from 0.2 to >10 TeV, along with a limited number of heavier nuclei. SOFCAL is a hybrid instrument that comprises a passive emulsion chamber with target and emulsion calorimeter and a thin ionization calorimeter utilizing scintillating fibers and lead plates (SciFiCal). The data analysis described below is from a 20-hour flight, from FT. Sumner, NM. to Phoenix, AZ., on May 20,1997.

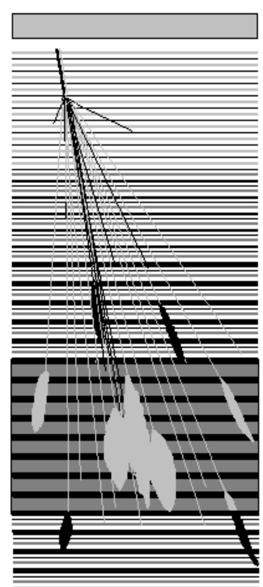

Fig.1 SOFCAL configuration.

2 Instrument Configuration:

The SOFCAL instrument contains four modules used in complement to measure the energy and charge of GCR nuclei. Figure 1 shows the arrangement of modules and further details are in the references (Christl,1996).

- ➢ A Cerenkov counter at the top of the instrument contains a 50×60×1.27 cm^3 Teflon™ radiator in a light diffusion box which functions as a part of an event trigger.
- ➢ Below the Cerenkov counter is an emulsion chamber (EmCal) that is nominally divided into “target” and “calorimeter” sections that perform both charge and energy measurements. It is a standard emulsion chamber design using nuclear emulsion plates, acrylic plates, lead plates and x-ray films (Burnett,1986). EmCal is 0.22 proton mean-free-paths (MFP) thick and has 5.8 radiation lengths (rl) of lead vertically.
- ➢ Below EmCal is the SciFiCal which is a thin calorimeter (7.1 rl) comprising 10 lead plates 0.4cm thick with two orthogonal layers (designated X,Y) of 0.5mm square scintillating fibers below each plate. The fibers for each axis are mapped on the input of separate image-intensified-CCDs (II-CCD). The images contain three-dimensional information about the cascades.
- ➢ The bottom module is another emulsion calorimeter with 1.7 rl depth.

The CCD pixel data range from 0 to 255 (8-bits). Corrections to the raw data were made for dark count, optical distortion, intensity variations over the FOV, and the decay time of the phosphorous screen in the II-CCDs (Christl,1998). Figure 2 shows the X and Y images of a cascade.

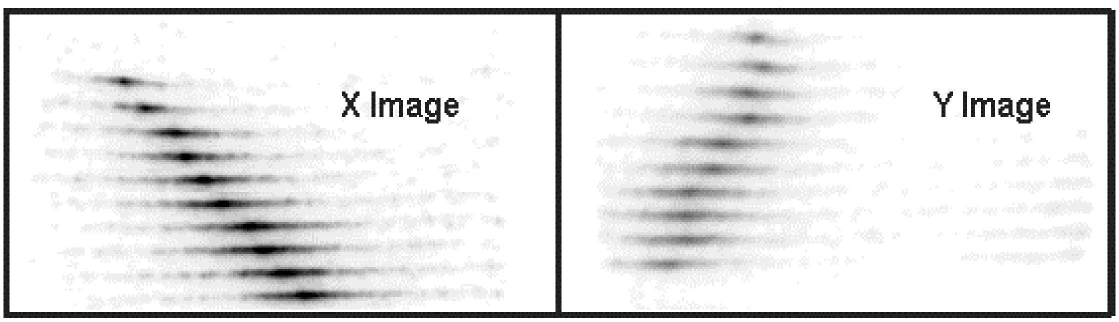

Fig. 2 Raw images of a cascade in SciFiCal (reverse video). The width of each image corresponds to a continuous segment in the detector 5cm wide. Some blurring of the image was seen which is characteristic of the II-CCDs used.

3 Cascade Measurements:

The signal proportional to the energy deposition for each layer in SciFiCal was determined by summing the CCD-pixel intensities of that layer. The resulting layer signals were then corrected for pathlength differences through the fibers (cos(θ)) and light attenuation down the lengths of the fibers. The scintillation signal for each layer in the X,Y images was normalized to the range 0.01 to 10.0. An analytical function (Roberts,1989) was used to fit the cascade from which the maximum intensity (I_{max}) of the cascade could be determined (Figure 3).

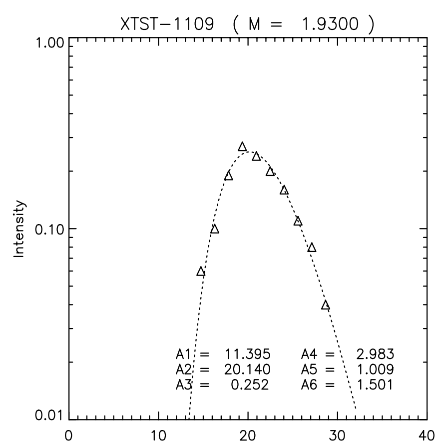

Fig.3 Transition curve of an event detected in SciFiCal. The event is inclined (tan(θ)= 1.93).

The procedure was also applied to simulated cascades and the curve fitting routine proved exceptionally good for a large class of events. Fitting for events having cascade maxima above SciFiCal or events with azimuth angles ≥68° proved unreliable and were removed from the analysis. The final data set of SciFiCal data consisted of 1356 cascades. The simulations were used to calculate the geometry efficiency factors to derive the primary flux.

3.1 Energy Calibration:

The hybrid design of SOFAL was developed to provide an in-flight energy calibration of the novel SciFiCal technique using proven emulsion chamber methods (Burnett,1986). The scintillation signals of the thin SciFiCal are not a direct measure of the primary energy of the incident hadron, but rather that of the produced cascades ($\Sigma E\gamma$). That signal is dominated by the electromagnetic cascade from the first interaction and is closely related to the measurement by the emulsion technique. The emulsion technique uses electron counts and optical density measurements of x-ray films to determine the cascade energy (Takahashi,1998).

Twenty-six high energy events (~20% of the EmCal cascades with energy $\sum E\gamma>1$ TeV) identified in both EmCal and SciFiCal were used to evaluate the scintillation signal and energy relationship. Most of the events used in the calibration had cascade energies ($\sum E\gamma$) between 1.5 and 5.0 TeV. To form a single comparison for the calibration, the data from the Y camera was normalized to that from the X camera which was determined by a direct comparison between the two respective data sets. The two highest energy calibration cascades only used data from the Y camera because the X camera had a considerable amount of saturation. The calibration data are shown in Figure 4. A linear fit was used for the cross-calibration of the cascade energy and scintillation signal.

$$\sum E\gamma = 1.11\times \mathrm{Imax}\ (\mathrm{TeV})$$

The scatter in the calibration data results from the resolution (errors) of the two measurement techniques and some differences between the two measurement techniques. The EmCal measurements are made on high energy electrons in the core ($r<100\mu m$) of the shower fitted to energy-electron count curves (Burnett,1986). The SciFiCal technique is also sensitive to the full width of the cascade (a few centimeters) and includes more effects of secondary interactions. Simulations of the average response in the SOFCAL configuration demonstrated that the comparison of the two techniques is adequate.

A determination of the instrumental dispersion of the SciFiCal can be made without introducing artifacts of the EmCal analysis. Since the X and Y camera systems perform independent cascade measurements, their comparison includes the total dispersion introduced by the measurement technique. This comparison gave a relative dispersion of 30%, which includes both cascade fluctuations and instrumental effects. A further contribution to energy resolution not included in that comparison results from variations in the 1st interaction position that was determined with simulations to be 7.2%. Taking the shower to shower fluctuations for protons to be 18% (Asakimori, 1998), the resolution for protons in the energy range covered by SciFiCal is estimated at:

$$\sigma_{\mathrm{SciFiCal}} = (0.072^2+0.18^2+0.30^2)^{1/2} = 35\%$$

The EmCal calibration affects the absolute accuracy of the SciFiCal energy calibration. This accuracy is affected by the resolution of the two chambers, which includes the fit accuracy to intensity data, electron counting and optical measurements in EmCal. Future calibrations of the SciFiCal technique will rely on signal intensity relative to that produced by minimum ionizing particles.

3.2 Measured Spectrum:

The measured $\sum E\gamma$ all-particle spectrum was determined from the data set after correcting for the detection and interaction efficiencies and instrument dead-time. The

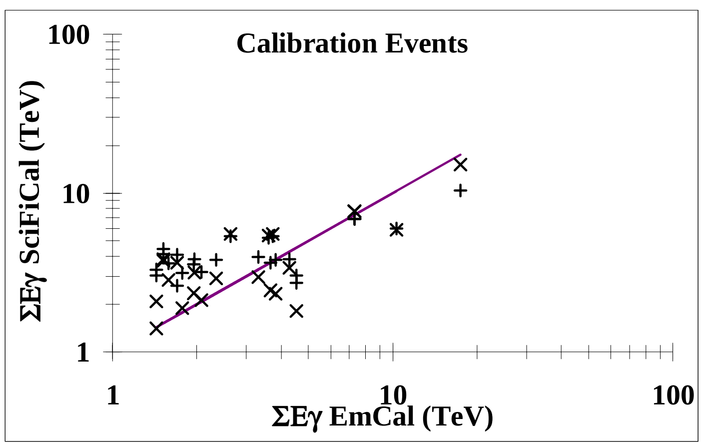

Fig.4 Comparison of cascade energy determined by EmCal and SciFiCal for 27 events used in calibration. (The cross(×) are the X camera data and the plus(+) the corresponding Y data.)

differential spectrum was assumed to be a single power law, and the spectral index for the ∑Eγ data was determined by a least-squares-fit to the data. When including all events with ∑Eγ>355 GeV, the spectral index was 2.66. The measured spectrum overestimates the actual intensity because of the energy resolution of the detector and the steep nature of the spectrum. If the true spectrum was g(∑Eγ), then the measured spectrum f(∑Eγ) is a convolution of the energy resolution function and incident spectrum. Assuming a gaussian distribution function, with σ=35%, the intensity is reduced by 7%. The corrected spectrum is shown in Figure 5 with data binned in graduated intervals (constant width on a log scale). The error bars indicate the level of statistical fluctuations and energy resolution.

3.3 Cerenkov Counter Analysis:

The Cerenkov counter provided event triggering along with two layers of scintillating fibers in SciFiCal. The pulse height data from the counter showed no clear charge peaks above that due to minimum ionizing particles. Calculations of back-scatter from the calorimeter performed post-flight verify that the counter response is consistent with relativistic electrons hitting the Cerenkov radiator. Those simulations used 1 TeV protons incident on SOFCAL and showed the counter was not useful for charge measurements or detector geometry (Munroe,1998). The emulsion chamber tracing will be performed to yield the P/He ratio for the highest energy events.

4 Discussion:

The SOFCAL instrument has provided a first step in the application of scintillating fiber sampling calorimetry to cosmic ray energy measurements. The image data from the II-CCD required a number of corrections peculiar to intensified video images, but all proved treatable. The SciFiCal was constructed as a monolithic instrument and some non-uniformity existed in the fiber performance. The II-CCD systems contributed to image blurring. However, as comparison of X and Y image data has demonstrated, the combined instrumental and physical variations of 35% was acceptable. This can be significantly improved in future instruments.

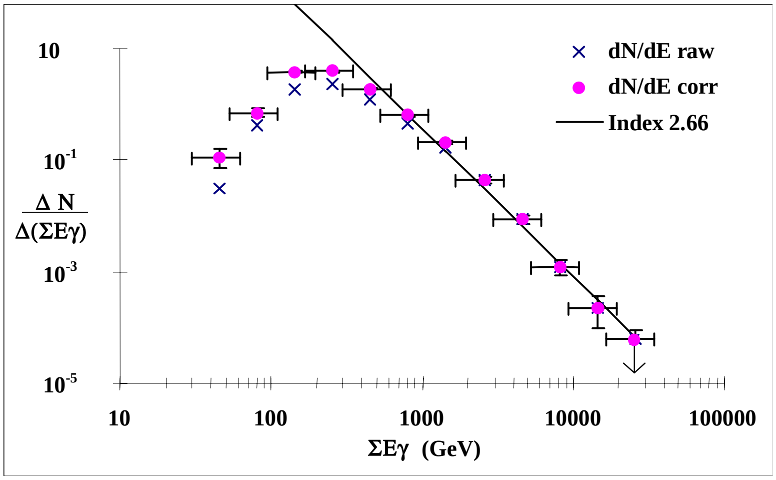

Fig.5 Differential spectrum measured by SciFiCal. The crosses indicate the measured spectrum and the solid circles have been corrected for the detection efficiency (Christl,1998).

A follow-on balloon instrument utilizing a thicker, larger area, calorimeter with improved uniformity and readout devices has been considered to make additional GCR spectra measurements. Currently, the NASA concept study for the Advanced Cosmic-ray Composition Experiment on the Space Station (ACCESS) is underway. Some candidate instruments are based on scintillating fibers and thin calorimetry.

References

Asakimori, K. et al., ApJ. , **501**, 278 (1998)
Biermann, P.L. et al., Astron. Astrophys., **271**, 649, (1993)
Burnett T.H. et al., NIM, **A251**, 583(1986)
Christl M.J. et al., Proc. of SPIE, **V2806**, 155, (1996)
Christl M.J., Ph.D. Dissertation, University of Al. In Huntsville, Huntsville, Al., 35899 (1998)
Lagage, P.O. et al., Astron. Astrophy., **125**, 249 (1983)
Munroe, R.B., NASA/ASEE Summer Faculty Fellowship Program, MSFC/NASA (unpublished) (1998)
Roberts, F.E. et al., Rapid Fitting of Particle Cascades, NASA Technical Memorandum TM-100368 (1989)
Takahashi, Y. et al., Nuclear Physics B (Proc. Supl.), **60B**, 83, (1998)