The Cosmic Ray Electron Synchrotron Telescope (CREST)

S. Nutter*, **T. Anderson**†, **C. R. Bower**‡, **S. Coutu**†, **J. Gennaro**¶, **M. Geske**†, **D. Müller**§, **J. Musser**‡, **N. H. Park**§, **M. Schubnell**¶, **G. Tarlè**¶, **S. Wakely**§ **and A. Yagi**¶

**Northern Kentucky University, Highland Heights, KY 41099 USA*
†Pennsylvania State University, University Park, PA 16802 USA
‡Indiana University, Bloomington, IN 47405 USA
§University of Chicago, Chicago, IL 60637 USA
¶University of Michigan, Ann Arbor, MI 48109 USA

***Abstract*. The Cosmic Ray Electron Synchrotron Telescope (CREST) is a NASA-sponsored balloon-borne instrument for a long-duration flight from Antarctica during the austral summer of 2010-11. The instrument will measure the energy spectrum of multi-TeV electrons through detection of the x-ray synchrotron radiation emitted as the electrons traverse the Earth's magnetic field. These photons form a line typically extending many hundreds of meters when their trajectories intersect balloon altitudes. Thus the acceptance of the CREST instrument is many times its geometric area. The identification of electrons through synchrotron radiation also provides a natural discrimination against the large proton background in the cosmic radiation. The measurement of multi-TeV electrons will provide new insight into spatial distribution and abundance of nearby cosmic-ray sources, believed to be supernova remnants, and thus they are probes of the acceleration mechanisms within these remnants. An engineering flight of CREST took place from the continental US in spring 2009. An overview of the detector design, fabrication status, simulations, and test flight results is presented.**

***Keywords*: cosmic rays, electron detectors, balloons**

I. Cosmic-ray electrons

Evidence for the acceleration of cosmic-ray electrons in supernova remnants (SNRs) was first discovered in SN1006 by Kobayashi *et al.* [1], with electron energies possibly as high as 200 TeV at the source. While the nuclear cosmic-ray component is also believed to originate in SNRs, electrons do not penetrate into the galaxy as far from the source as the nuclear species due to the more dramatic effect of the energy-loss mechanisms of inverse Compton scattering and synchrotron radiation on the electrons. In a process similar to that of defining the GZK cutoff, one can define an electron horizon of about 1 kpc beyond which electrons originating with TeV energies are downgraded in energy to GeV energies. Any TeV electrons detected at Earth must have originated within this distance. Thus the detection of TeV electrons at Earth is a direct probe of SNR acceleration mechanisms.

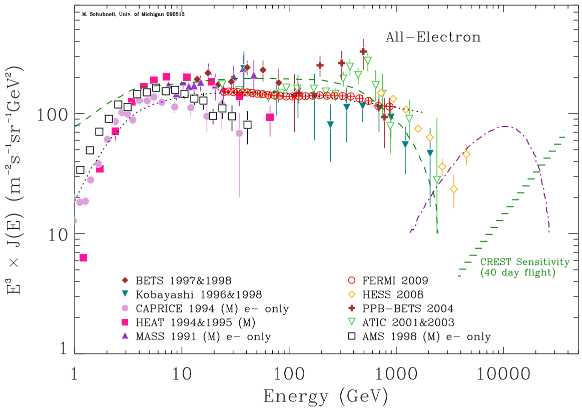

Fig. 1: Measurements and predictions of the all-electron flux. The marking (M) indicates the instrument used magnetic spectrometry. The dashed curve below 2 TeV is a prediction of the local flux from distant sources, while the dash-dot line shown above 1 TeV is for contributions from the Vela SNR with the parameters from Figure 5 in [2]. The dash-dot line below 2 TeV is a prediction using the GALPROP [4] model adjusted to fit the FERMI data. The expected CREST minimum measurable flux for a 40 day flight at 4 g/cm^2 overburden is shown.

A model predicting the electron flux at Earth due to the known local sources has been proposed by Kobayashi [2]. The model divides the electron flux at Earth into a distant component due to sources beyond the 1 kpc TeV electron horizon, and a local component from sources inside the horizon. The distant component drops off precipitously at 1 TeV. However, the parameter space for describing the local SNRs allows the predicted local component of the electron flux above 1 TeV to vary by more than an order of magnitude. The Vela SNR is expected to be the largest contributor to the local spectrum due to a combination of parameters (e.g., size, age, electron release time, diffusion coefficient, and distance from Earth). One possible prediction is shown in Figure 1, along with electron-flux measurements to date. The highest-energy measurement, extending to nearly 5 TeV, is by HESS, a ground-based system of imaging atmospheric Cherenkov telescopes [3]. However, the systematic uncertainties in the data due to the dominant background proton flux are quite large.

II. CREST INSTRUMENT METHOD

The CREST instrument is designed to measure the electron spectrum in the region above 2 TeV sensitive to local SNR sources. The detection technique concept, illustrated in Figure 2, utilizes the synchrotron radiation emitted by electrons as they bend in the Earth's magnetic field. Electron energy can be reconstructed by determining the average energy of detected synchrotron photons, which is related to the synchrotron radiation critical energy $E_c = 3\mu_B\gamma^2 B_\perp$. Here μ_B is the Bohr magneton, γ is the Lorentz factor of the primary electron, and $B_\perp$ is the perpendicular component of the Earth's magnetic field to the electron trajectory. This energy marks the midway point in integrated power radiated by synchrotron radiation. The strong dependence of E_c on the primary electron's energy makes the technique viable. $E_c \approx$40 keV and 16.6 MeV correspond to an electron energy of 2.5 TeV and 50 TeV, respectively. Strong atmospheric absorption of photons below 30 keV sets a natural lower energy threshold at 2 TeV for this technique at balloon altitudes.

The detection of synchrotron radiation from the primary electron has the advantage of completely eliminating the proton background that plagues most other measurements. In addition, this method has an acceptance larger than the geometric area. Since the highly relativistic electron beams the synchrotron photons forward, the intersection of the latter's trajectories as they pass through the balloon altitude forms a line which typically extends over several hundred meters. As E_c increases, the survival probability of a synchrotron photon in the atmosphere increases, and the acceptance increases with increasing electron energy. A long exposure time can be achieved through a long-duration balloon flight in Antarctica.

The signal is therefore a line of nearly simultaneous photons (within about 6 ns for CREST) arriving at the detector. Background is due to x-ray radiation from the decay of atmospheric shower secondaries and the diffuse galactic radiation and low-energy protons. Charged-particle backgrounds can be eliminated with a charged-particle detector surrounding the photon-detector volume. The background affects measurements primarily in two ways. First, chance coincidences of aligned, simultaneous background photons can create a 'fake' event. This is very rare, since the requirement that the hits be aligned is very stringent. Secondly, a background photon can arrive during the narrow time window of a primary event and masquerade as a primary synchrotron photon, or as a scattered primary photon. Both rates are highly dependent on the energy threshold setting of the instrument, since the background x-rays are softer than the signal photons. A 40 keV threshold combined with a 6 ns timing window and a minimum 4 co-linear crystal hits result in about one background event in a 30 day flight. Discrimination against background photons being mistaken for scattered photons is discussed in Section III-C.

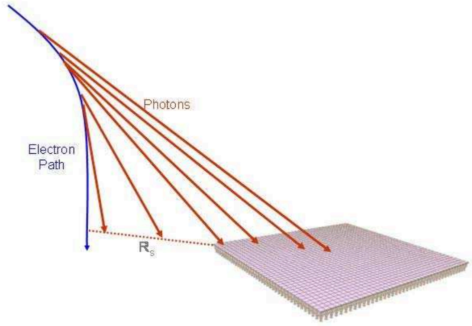

Fig. 2: CREST measurement technique concept. CREST will detect the synchrotron radiation emitted by cosmic-ray electrons as they bend in the Earth's magnetic field. See text for details.

III. CREST INSTRUMENT OVERVIEW

The CREST instrument is designed for launch with the NASA long-duration balloon vehicle. An instrument schematic is shown in Fig. 3. CREST consists of 1024 photon detectors (5 cm diameter by 2 cm thick BaF_2 crystals) individually viewed by photomultiplier tubes (PMTs) arranged in a 32 $\times$ 32 array, surrounded by charged-particle veto counters (plastic scintillator paddles). The array is 2.4 m on a side, and thus the crystals fill 40% of the geometric area. The design is mature and fabrication of all components is well under way. The large number of crystals provides the segmentation necessary to identify individual photons. Because Antarctic magnetic fields are close to vertical, the most probable detection zenith angle for an incident electron is about 60°. The crystals are arranged in a square array with a 1.5 crystal diameter pitch to take advantage of these highly inclined tracks. The crystal/PMT assemblies have a 0.4 cm$\times$6.25 cm lead wrapping with the top edge located 5 mm above the PMT faceplate surface to absorb Coulomb scattered photons (see Section III-C below). The veto counters cover more than 99% of the surface area surrounding the photon detector volume. The full instrument uses less than 800 W of power, provided by solar panels during flight.

The design is modular for ease of recovery in Antarctica. The 1024 crystal assemblies are arranged in 8 groups of 128. Each group is embedded in an Ethafoam matrix and placed on one aluminum alloy C-channel. The 128 crystals are arranged in groups of 16 for the electronics, for a total of eight digitization boards on each C-channel. The electronics is contained beneath the channel. PMT signals and power are fed through holes in the C-channel. Redundant communications are provided between each board and an 'Overlord' board, which collates the hit-

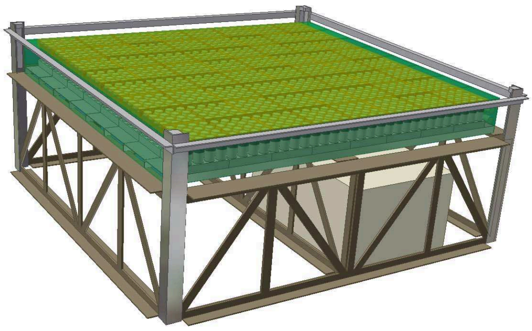

Fig. 3: CREST detector schematic showing the frame with communications box below, the 32×32 BaF_2 crystal array, and plastic scintillator veto counters surrounding the crystal volume.

timing information from all 64 crystal assembly boards on the instrument and searches for potential electron events. Each C-channel has a single communications and power cable, and is designed to electrically and physically disconnect from the instrument and be carried into an Antarctic recovery vehicle.

The acquisition system is 'triggerless' from a hardware perspective. The veto counters provide neither a trigger nor an anti-trigger. The Overlord system, consisting of a Xilinx multiprocessor board and software, defines a moving time window within which it searches for a threshold number of crystal hits. When that threshold is passed, it requests the digitized signals from the digitization boards and from any veto counters hit in the time window. It is important to note that *all* timing information is saved, while digitized signal information is recorded only for those crystal and veto hits considered involved in a potential event. More details are available in [6].

The system has an LED fiber optic calibration system to monitor timing offsets and gain changes during flight.

A. BaF_2 crystal assembly details and performance

The basic photon detector of CREST is a BaF_2 crystal 5 cm diameter by 2 cm thick, corresponding to one radiation length in vertical depth. The crystals are assembled onto Hamamatsu 2" R7724CW custom PMTs designed for an operating gain of 5×10^6. The final assembly achieves 1.15 photoelectrons (pe's) per keV of energy deposit. The energy resolution of the 662 keV line of ^{137}Cs is 13%. BaF_2 was chosen over BGO despite the higher x-ray cross section and density of BGO due to the faster timing and larger light yield available from BaF_2, which are essential in discriminating against background in CREST.

Of the pe's detected in the BaF_2 assembly, 15% is contained in a fast component, with an intrinsic rise time less than 30 ps, and a decay time of 800 ps [7]. The slow component decay time is 630 ns [8]. The first ns thus contains 0.12 (fast component) + 0.002 (slow component) pe/keV. For example, the 662 keV line has about 80 pe's in the first ns. Thus timing resolution of 1 ns is achievable. The fast component peak emission wavelengths are 195 and 200 nm, and the slow emission peak is at 310 nm. Since the peak output wavelengths of the fast component light are not efficiently transmitted by a standard borosilicate PMT window, a coating of TPB (tetraphenyl butadiene) on each side of the crystal converts the light to 400 nm. Additionally, the crystal is wrapped by PTFE (teflon) wrapping to aid diffuse reflection into the PMT face. The crystal is held in place and made light-tight with a 25 μm aluminum foil cap.

The PMTS are provided with vacuum potting, a low power ($\sim$30 mW) Cockcroft-Walton base powered by 5 V, and 0.1 mm mu-metal shielding appropriate for magnetic field strengths of as much as $\sim$5 gauss. The operating voltages are individually controlled with 0-2 V supplied by the instrument through the digitization boards. The PMT anode signal is split three ways for timing and a high and low gain signal digitization. A dynamic range of 1 keV to 10 MeV is achieved.

B. Veto counter details and performance

The veto system consists of 5 mm thick plastic scintillator with Kuraray 1.2 mm green waveshifting fibers embedded the length of the paddle and spaced 2 cm apart. The fibers are precisely aligned at each end with clear fibers, which are collected onto the face of a PMT. Each paddle is wrapped in three layers of diffusely reflecting PTFE and black 38 μm Tedlar (a DuPont product). The fiber optic light assemblies allow the paddles to be placed flexibly close together, which is essential in achieving the 99% area coverage. The veto system uses the same PMTs and electronics as the crystal assemblies. The PMTs are handpicked for a higher response in the green wavelengths. Tests of paddles assembled for the continental US engineering flight obtained 15-25 pe's per end for normally incident muons, with a nearly constant summed response of the two ends of about 40 pe's. The signal distributions are clearly separated from the pedestal. An end-to-end timing resolution of about 2 ns is obtained.

In order to realize the 99% area coverage, there are a total of 38 vetos paddles required, of which 11 are narrow (7.5 cm) paddles with 3 fibers intended to provide double coverage along joints between the larger ($\sim$28 cm wide) paddles. These narrower paddles perform similarly to the full-sized paddles, and are ganged together with their nearest larger neighbor. The system uses 54 PMTs, and 8 digitization boards.

C. Simulations

The results of simulations to verify the efficacy of the technique used by CREST to detect electrons and broadly characterize instrument response were reported earlier [9]. The simulations indicated that instrument sensitivity would begin at 2 TeV and increase dramatically with primary electron energy, due to the increase in average energy of synchrotron photons, to be about 10 times the detector area at 50 TeV. Energy is expected to be determined to about a factor of two.

Extensive simulations have continued. Both synchrotron generator and instrument simulations based on the GEANT4 package [10] exist. The output from the event generator can be input to the instrument simulation. Both codes have yielded further results affecting the design and performance of the instrument.

A simulation of instrument response to single incident photons led to the realization that multiple Coulomb scattering (MCS) of a photon from one crystal to another could lead to a misrepresentation of the number of synchrotron photons involved in the event, and thus a misestimation of the primary electron energy. To solve this problem, enough lead wrapping was added around the top of the PMT, below the crystal, to decrease the rate of scatters to below the naturally occuring background single crystal rate, so that any PMTs firing during an event that are not colinear with the others may be ignored. The 0.4 cm$\times$6.25 cm lead wrapping effectively eliminates MCS.

The synchrotron event generator simulations have resulted in the discovery that the atmospheric overburden is sufficient to produce bremsstrahlung photons in significant numbers. Their presence at balloon altitudes is primarily for two reasons. First, the brem photons from TeV electrons have typical energies in the GeV range, which penetrate further into the atmosphere than the softer MeV synchrotron photons. Secondly, brem photons are produced nearer to the instrument instead of all along the electron track, as are synchrotron photons. The result is that the end of the line of synchrotron photons, nearer to where the electron passes through balloon altitude, contains a number of brem photons. This is also where the synchrotron photon abundance is denser, since they had less atmosphere to travel through, and is thus the region of the track to which CREST is more sensitive. As an example of brem content, the average 10 TeV electron produces 50 times more synchrotron photons than brem. But only 10 times more synchrotron photons than brem survive to balloon altitudes. A typical event consists of both brem and synchrotron photons. Occasionally, an event will contain many crystal and veto hits due to a brem-induced particle shower, and the ability to distinguish crystals hit by synchrotron photons among the hits is lost, thereby losing the event. In the absence of the lead shielding, the brem photons more often pass through the detector without interaction, and the event is salvageable. However, the MCS problems mentioned above arise.

IV. ENGINEERING FLIGHT

An engineering flight took place from Ft. Sumner, New Mexico, on 5 May 2009. The test instrument consisted of one C-channel instrumented with four groups of 16-crystal assemblies. Two sets had the lead wrapping, while the other two had no lead wrapping to verify MCS rates with the different lead configurations. It is too early at this writing to include results. Overall, the instrument behaved well. The instrument was valved down through a range of altitudes corresponding to the likely overburden expected in an Antarctic flight.

V. CONCLUSION

CREST will measure the electron spectrum above 2 TeV, directly exploring the SNR acceleration mechanism. The experiment is not subject to the proton background of other methods.

Fabrication of detector components is underway. The Antarctic gondola is complete. More than 60% of the crystal assemblies have been manufactured and extensively tested in vacuum. All of the veto counters have had the waveshifting fiber laid. Fiber light guides are scheduled for completion by the end of the summer. Electronics fabrication and testing begins in earnest now that the engineering test flight results are in. An Antarctic flight is scheduled for the austral summer of 2010-2011. A follow-up flight is planned for the next available season.

This work is supported under NASA Grants NNX08AC42G, NNX08AC40G, NNX08AD08G, and NNG04WC34G, and the Kentucky Space Grant. We would like to thank the Columbia Scientific Balloon Facility and the CSBF launch crews for their excellent support of balloon missions. The collaboration also gratefully acknowledges the contributions of J. Ameel, M. Gebhard, R. Northrop, and C. Smith.

REFERENCES

[1] T. Kobayashi, *et al.* **Nature** 378 (1995) 255.
[2] T. Kobayashi, *et al.* **Ap. J.** 601 (2004) 340–351.
[3] F. A. Aharonian *et al.* **Phys. Rev. Lett.** 101 (2008) 261104.
[4] See http://galprop.stanford.edu/
[5] M. Schubnell *et al.* in the **Proceedings of the 30$^{\rm th}$ International Cosmic Ray Conference,** Merida, Mexico Vol. 2 (OG part 1) (2007) 305-308.
[6] G. Tarle *et al.* in the **Proceedings of the 30$^{\rm th}$ International Cosmic Ray Conference,** Merida, Mexico Vol. 2 (OG part 1) (2007) 313-316.
[7] S.E. Derenzo, *et al.* IEEE Trans Nucl Sci, **NS-47** (2000) 860–864.
[8] J.D. Valentine, *et al.* Nucl Instr Meth, **A325** (1993) 147–157.
[9] S. Nutter *et al.* in the **Proceedings of the 30$^{\rm th}$ International Cosmic Ray Conference,** Merida, Mexico Vol. 2 (OG part 1) (2007) 309-312.
[10] J. Allison *et al.* **IEEE Transactions on Nuclear Science** 53 No. 1 (2006) 270–278.