Cosmic Ray Energetics And Mass

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Abstract

The Cosmic Ray Energetics And Mass balloon-borne experiment has had two successful flights from Antarctica, with a cumulative duration of 70 days. High energy cosmic-ray data were collected in a wide energy range, from ~ 10^{10} to > 10^{14} eV, at an average altitude of ~38.5 km with an average atmospheric overburden of ~3.9 g/cm^2. All elements from H to Fe are clearly separated with excellent charge resolution. Preliminary analysis indicates an increase in the abundance of helium nuclei relative to protons compared to previous lower energy data. The payload recovered from the first flight was refurbished and is being integrated in preparation for the next launch, scheduled for December 2007. The project status including preliminary results from the ongoing analysis and future plans are reported.

1. Introduction

The Cosmic Ray Energetics And Mass (CREAM) experiment was designed and constructed to measure cosmic ray elemental spectra for Z = 1 - 26 nuclei. The goal was to extend direct measurements of cosmic-ray composition to the highest energies

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practical with balloon flights. Precise measurements of the energy dependence of elemental spectra from ~10^{12} to ~ 10^{15} eV, where the rigidity-dependent supernova acceleration limit could be reflected in a composition change, provide a key to understanding cosmic-ray acceleration and propagation. Secondary cosmic rays produced in the nuclear interactions of primary cosmic rays with the interstellar medium hold a key to understanding the cosmic-ray propagation history. In order to obtain the spectra at the source where cosmic rays are accelerated, the measured spectra must be corrected for propagation effects. Simultaneous measurements of the relative abundances of secondary cosmic rays (e.g. B/C) and the energy spectra of primary nuclei will allow determination of cosmic-ray source spectra at energies where measurements are not currently available.

2. Record-Breaking LDB Flights

The first payload was launched from McMurdo, Antarctica on 16 December 2004, and it subsequently circumnavigated the South Pole three times before being terminated on 27 January 2005 [1]. Both the distance traveled (~14,000 nautical miles) and the time duration (41 days 21 hours 36 minutes) were records for an Antarctic LDB flight. The second launch occurred on 16 December 2005 exactly 1 year after the first launch. A cumulative duration of 70 days within 13 months, another LDB record, was achieved when the second flight completed its 28-day journey on 13 January 2006 after twice circumnavigating the South Pole [2].

The flight operations were unique in several aspects: (1) CREAM was the first LDB mission to transmit all the prime science and housekeeping data (up to 85 kbps) in near real-time through the Tracking and Data Relay Satellite System (TDRSS) via a high-gain antenna, in addition to having an onboard data archive. To fit the data into this bandwidth, science event records excluded information from channels that had levels consistent with their pedestal value. This "data sparsification" reduced the average high energy shower event record size by nearly 95%. (2) The instrument was shipped to Antarctica fully integrated to minimize the flight preparation time on the Ice, and flight readiness was achieved within 2 weeks after the crew arrived. (3) The science instrument was controlled from the science operation center at the University of Maryland throughout the flight after line-of-sight operations ended at the launch site. Primary command uplink was via TDRSS, with Iridium serving as backup whenever the primary link was unavailable due to schedule or traversing zones of exclusion. The nearly continuous availability of command uplink and data downlink allowed rapid response to changing conditions on the payload (e.g., altitude dependent effects) throughout the flight. See Refs. [3] and [4] for more details about flight operations and the data acquisition system.

The balloon float altitude was between ~125,000 and ~130,000 ft (~38 and ~40 km) throughout most of the flight. The diurnal altitude variation due to the Sun angle change was very small, < 1 km, near the Pole, i.e. at high latitude, although it increased as the balloon spiraled outward to lower latitudes. The temperature of the various instrument boxes stayed within the required operational range with daily variation of a few °C, consistent with the Sun angle. A total of 60 GB of data including ~ 4×10^7 science events were collected from the first flight and 57 GB including ~ 2.7×10^7 science events were collected from the second flight.

3. The CREAM Instrument

The instrument was designed to meet the challenging and conflicting requirements to have a large enough geometry factor to collect adequate statistics for the low flux of high-energy particles, and yet stay within the weight limit for near-space flights. It consists of complementary and redundant particle detectors to determine the charge and energy of particles. They include a Timing Charge Detector (TCD), a Transition Radiation Detector (TRD) with a Cherenkov Detector (CD), and a calorimeter module comprised of a Silicon Charge Detector (SCD), a carbon target, scintillating fiber hodoscopes (S0/S1 and S2), and a stack of tungsten plates with interleaved scintillating fiber layers. A detailed description of the instrument has been published elsewhere [5].

The carbon target induces hadronic interactions in the calorimeter module, which measures the shower energy and provides tracking information to determine which segment(s) of the charge detectors to use for the charge measurement. Tracking for showers is accomplished by extrapolating each shower axis back to the charge detectors. The hodoscopes S0/S1 and S2 provide additional tracking information above the tungsten stack. Tracking for non-interacting particles in the TRD is achieved with better accuracy (1 mm resolution with 67 cm lever arm, 0.0015 radians). The TRD determines the Lorentz factor for $Z \geq 3$ nuclei by measuring transition x-rays using thin-wall gas tubes. The TRD and calorimeter (which can also measure the energy of protons and He) have different systematic biases in determining particle energy. The use of both instruments allows in-flight cross-calibration of the two techniques and, consequently, provides a powerful method for measuring cosmic-ray energies. Multiple charge measurements with the TCD, CD, SCD, and S0/S1 layers of scintillating fibers accurately identify the incident particles by minimizing the effect of backscattered particles from the calorimeter. The TCD is based on the fact that the incident particle enters the TCD before developing a shower in the calorimeter, while the backscattered particles arrive several nanoseconds later. A layer of scintillating fibers, S3, located between the carbon target and the tungsten calorimeter provides a reference time. The SCD is segmented into pixels to minimize multiple hits of backscattered particles in a segment. Individual nuclei are measured with excellent charge resolution (e.g. $\sigma \sim 0.2e$ for p & He) as shown in the SCD charge histograms in Fig. 1.

The CREAM ballooncraft, i.e., all hardware attached to the mobile launch vehicle, is an integrated assembly of the science instrument and the support systems. In contrast to most balloon payloads, the science instrument was not pressurized, in order to be more robust for Ultra Long Duration Balloon (ULDB) flights. The main support system was the Command and Data Module (CDM), which was developed at the NASA Wallops Flight Facility – WFF [6]. This is also in contrast to typical LDB payloads, which utilize the Support Instrumentation Package (SIP) provided by the Columbia Scientific Balloon Facility (CSBF). Two CREAM instruments have flown as LDB payloads with all ULDB systems except for the balloon vehicle. The 40 MCF-lite conventional balloon carried a total suspended weight of 6,000 lb, including ~2,500 lb for the science instrument, ~400 lb support structure, and ~1,100 lb of ballast for the first flight. The suspended weight for the second flight was 5,676 lb including ~1,200 lb ballast. The large amount of ballast played an important role in maintaining high altitude of the zero-pressure balloons throughout the flights, especially when they drifted northward. The power consumptions of the instruments for the two flights were 379W and 355W, respectively.

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The exceptional performance of both the science instrument and the flight support systems can be attributed to the fact that they were developed for 100-day ULDB missions. Details of the performance of the instruments flown on the first two flights can be found elsewhere: TRD/TCD performance [7, 8, 9], Calorimeter performance [10, 11, 12], SCD performance [13, 14, 15].

4. Data Analysis and Results

The highly segmented detectors comprising the instrument have about 10,000 electronic channels. The instrument was calibrated in a series of beam tests at the CERN SPS, which provides the highest energy test beam particles available. As discussed in Refs. [16, 17, 18, 19] the beam test data are in good agreement with the simulations. The instrument was also exposed to A/Z = 2 nuclear fragments of a 158 GeV/n indium beam. Figure 2 shows the energy deposit as a function of mass number. The heaviest fragments correspond to ~ 9 TeV, as indicated by the corresponding incident energy scale on the right vertical axis. Monte Carlo simulations show that the calorimeter response is quite linear over the CREAM measurement range and that its energy resolution is nearly energy independent [20].

Preliminary spectra of heavy nuclei from the TRD and calorimeter from flights 1 and 2 are reported in our papers elesewhere [21, 22, 23]. The CREAM results span ~ 4 decades in energy from ~ 10^{10} eV to ~ 10^{14} eV. For the high energy triggered events, i.e., for the particles with significant energy deposit in the calorimeter, the shower axis is reconstructed by a linear fit of the scintillating fiber strip with the maximum energy deposit in each layer. This reconstructed trajectory is required to traverse the SCD active area and the bottom of the calorimeter active area. Considering the tracking resolution, the SCD pixel with the highest signal within 7 × 7 pixels (each pixel 2.1 cm^2) centered at the extrapolated position was selected for the charge measurement. The signal in that pixel is then corrected for the reconstructed incidence angle for the charge determination. The particle energy was determined from the energy deposit in the calorimeter.

Figure 3 compares the CREAM-I Proton and He spectra in energy per particle with previous measurements (RUNJOB [24], JACEE [25], Ryan et al. [26], ATIC-1 [27], ATIC-2 [28], Ichimura et al. [29], SOKOL [30], and Zatsepin et al. [31]). Also shown is a dashed line representing Hörandel’s empirical model [32]. The shaded area indicates the range of ground based indirect measurements produced from various hadronic interaction models in the atmosphere, such as QGSJET and SIBYLL. The calorimeter calibration and the details of the analysis are reported elsewhere [33, 34]. The energy deconvolution is still preliminary, and the energy dependent shower leakage corrections for the energy scale have not yet been made. The absolute flux has large uncertainties, not shown in the plot, but the results are in agreement with the previous measurements. The proton spectrum seems to follow a power law without much change up to ~ 100 TeV. Compared to lower energy data, there seems to be an increase in the abundance of helium nuclei relative to protons.

At the current stage of analysis, the CREAM measurements show good agreement with Hörandel’s empirical model which is based on complied data of previous measurements. Future flights will extend the CREAM energy reach to higher energies to distinguish hadronic interaction models, such as QGSJET and SIBYLL used for KASCADE data and other indirect measurements.

The CREAM flight duration exceeds the cumulative flight time of either JACEE or RUNJOB. The number of protons measured by CREAM is more-or-less equivalent to the total of all the prior experiments. JACEE reported only 656 protons above 6 TeV [25], despite the fact that the flight duration was about 60 days, while CREAM estimates >1700 protons from its 70 day flight. This is, in part, because less than half of the JACEE collected data was analyzed and, in part, because of the detection efficiency which was apparently low. RUNJOB had about the same flight duration, but only 40% of the exposure due to a smaller detector area.

The CREAM payload is relatively light as an LDB payload (2000 – 2500 lb), and it maintained high altitude. The corresponding atmospheric overburden was 3.9 g/cm^2. That implies about 6.8 g/cm^2 for the maximum angle acceptance, which is smallest among comparable experiments. For example, the average vertical depth for RUNJOB was more than twice that of CREAM, due to its low flight altitude. Considering the RUNJOB acceptance of particles at large zenith angles, its effective atmospheric depth is as large as 50 g/cm^2. For that depth, large corrections are required to account for the fact that 41% of protons and 84% of Fe nuclei would have interacted before reaching the detector.

The trigger geometry factor of the CREAM TRD is 2.2 m^{2}sr. The effective geometry of the calorimeter, after taking into account the interaction fraction, is about 0.3 m^{2}sr for protons and increasingly higher for heavier nuclei, due to their higher interaction probability. The collecting power of CREAM is about a factor of two larger than that of ATIC for protons and He and, considering the much larger geometry factor of the TRD, about a factor of 10 larger for heavier nuclei. TRACER has a larger geometry factor than CREAM, but a smaller dynamic charge range ($Z = 8 – 26$) was reported for its 10-day Antarctic flight. Its dynamic charge range was improved to $Z = 3 – 26$ for its ~ 4-day flight from Sweden to Canada in 2006. We estimate that the latter should have approximately the same amount and quality of data as CREAM for precise high-energy B/C measurements.

5. Refurbishment and Upgrades for CREAM-III and CREAM-IV

The instruments used for the first two flights survived landing of the payloads almost intact. Even the fragile 380 μm thick silicon sensors were well protected. However, some parts of the instrument had to be cut during recovery to go through the Twin Otter door. For example, the honeycomb pallet had to be cut into two pieces, the calorimeter optics were destroyed, and some tungsten plates were damaged, etc. Reassembly of the calorimeter optics was one of the major refurbishment efforts. For the CREAM-III calorimeter, the optics were replaced with multi-clad fiber ribbons to enhance the light signal. New readout electronics boards reduce noise even further than the previous low-noise version. These improvements allow increased sensitivity to low energy showers. The fully refurbished calorimeter from CREAM-I was recalibrated at the CERN SPS in October 2006 for the anticipated launch of CREAM-III in December 2007. The construction of the calorimeter and tests of its optical and electronic components are reported in paper [35].

Another improvement was a new “quartet” structure for better survival of optical components in the recovery after the flight. The light-tight wall around the stack has been replaced by a structure of inter-connected aluminum parts that allow the calorimeter to be disassembled in sections, each with 4 tungsten plates, which are thus called “quartets.” This structure is planned to work with a set of ground support equipment recovery frames to protect the optical layers during recovery, and allow them to be reused in an eventual fifth flight.

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A significant upgrade for CREAM-III is the addition of a Cherenkov imager (CherCam) optimized for charge measurements [36]. It consists of a silica aerogel Cherenkov radiator plane and a photon detector plane with an array of 1600 1-inch diameter photomultiplier tubes (PMT's). The planes are separated by a 10 cm ring expansion gap to ensure that most Cherenkov photons are collected in 8 tubes surrounding the tube hit by the incident particle. Since upward moving particles will be absorbed in the radiator, the CherCam will provide efficient discrimination against backscattered particles. With CherCam, in addition to the TCD based on timing, and the SCD based on pixelation, the CREAM-III instrument implements virtually all possible techniques to minimize the effect of backscatter on charge measurements in the presence of the calorimeter. We are striving to achieve charge measurements with the highest possible accuracy.

Another major improvement for CREAM-III will be a redundant Science Flight Computer, which was a potential single point failure for the previous flights. Two computers will be accommodated with a USB interface [37]. New software developed for the USB interface was successfully tested during the 2006 accelerator calibration of the calorimeter. The instrument integration is nearing completion as shown in Fig.4. After complete functional tests the instrument will be integrated with the support sub-systems at NASA's Wallops Flight Facility. This will be followed by shipping to Antarctica for launch.

The fourth flight will incorporate a calorimeter essentially identical to CREAM-III, a similar detector to S3, the same graphite targets that flew in CREAM-II, a refurbished SCD, a new TRD, a CD similar to that flown before, and the same TCD design as in the prior flights. A significant improvement for CREAM-IV is a recoverable pallet. Using two halves of the CREAM-I and CREAM-II pallets, a CREAM-IV pallet is being constructed using a piano hinge concept. This will allow the recovered pallet to go through the Twin Otter door and be re-flyable through simple reassembly, as long as damage is not severe. The CREAM-IV calorimeter optics are already under construction with over 1500 ribbons fabricated, of which over 1000 have been cut and polished. The calorimeter calibration is planned for September 2007 at CERN. Flight readiness is planned for December 2008.

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Fig. 1. Distribution of the charge (in units of the elementary charge e) of cosmic-ray nuclei measured in the first flight with SCD.

Fig. 2. Test data (red squares) from 158 GeV/n indium beam fragments are compared with Monte Carlo simulations using FLUKA (blue diamonds).

Fig. 3. Preliminary CREAM-I (a) Proton and (b) He spectra in energy per particle are compared

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with previous direct measurements (symbols described in text), Hörandel's empirical model (blue dashed line), and ground based indirect measurements (shaded area).

Fig. 4. A photograph of the CREAM-III instrument (left) during the integration at the UMD lab in March 2007 and a schematic view of the instrument configuration (right).

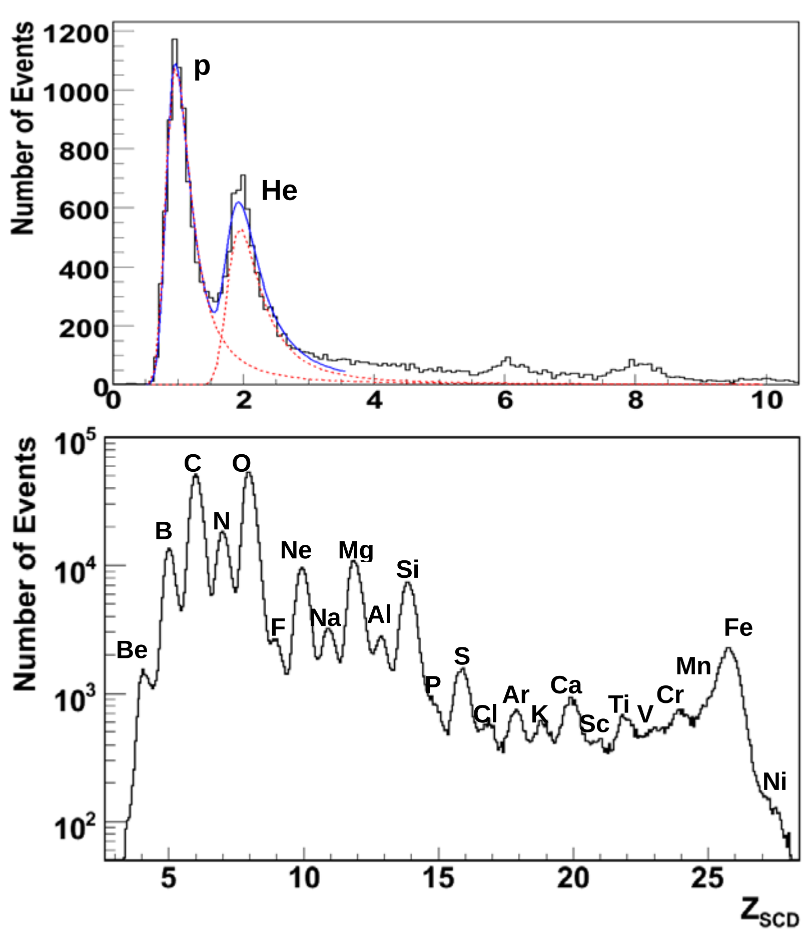
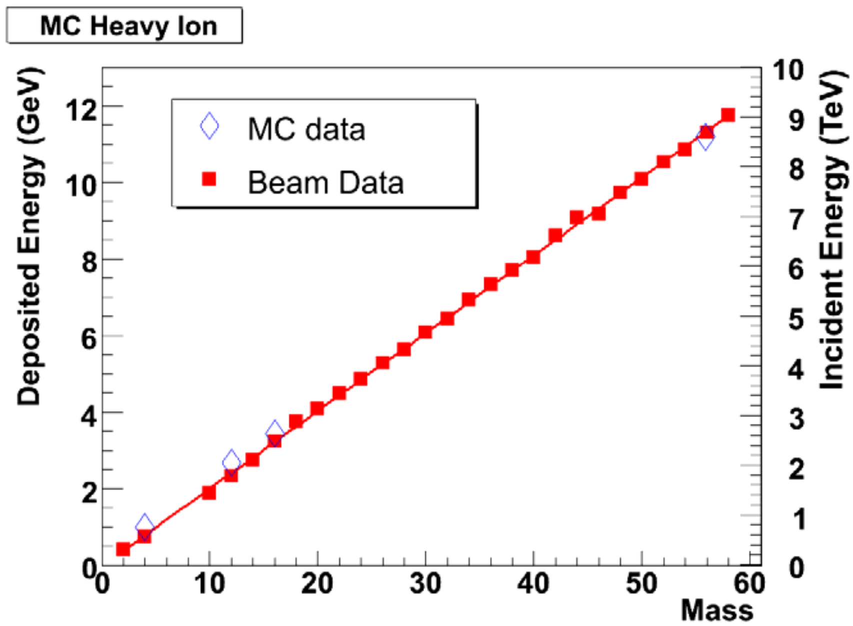


Fig. 1.



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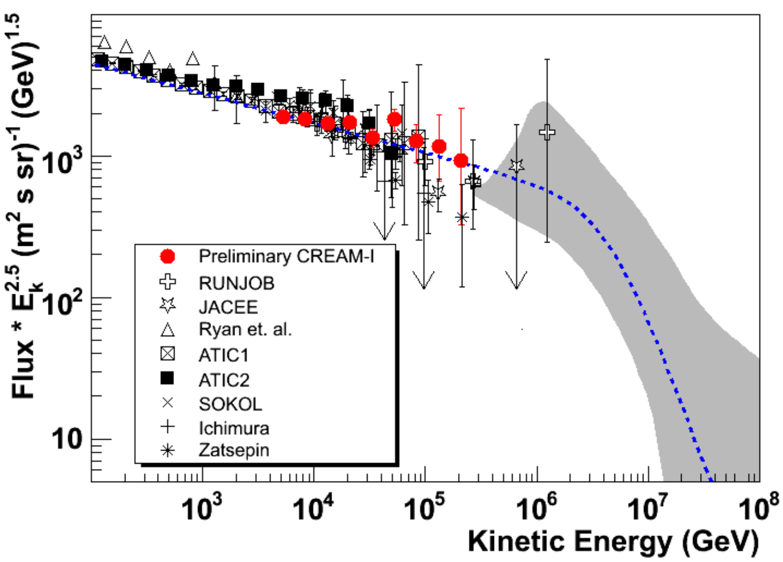

Fig. 3a

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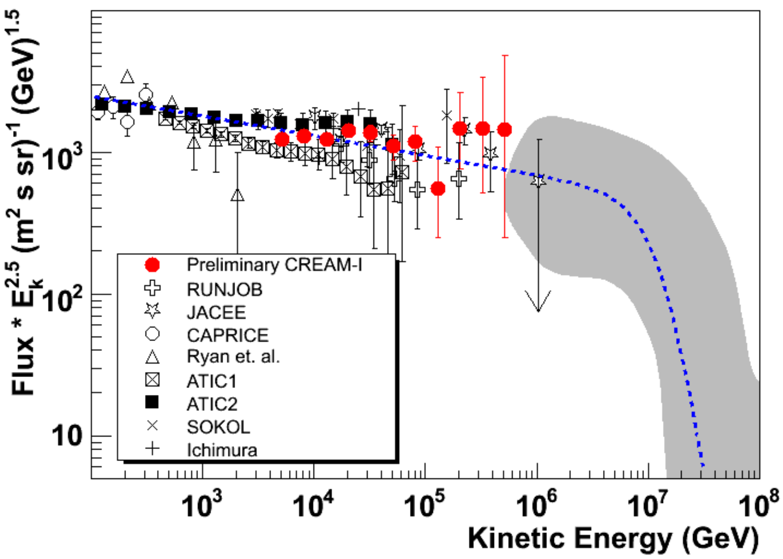
Flux * $E_k^{2.5}$ $(m^2\ s\ sr)^{-1}$ $(GeV)^{1.5}$
10
10^2
10^3
Preliminary CREAM-I
RUNJOB
JACEE
CAPRICE
Ryan et. al.
ATIC1
ATIC2
SOKOL
Ichimura
10^3
10^4
10^5
10^6
10^7
10^8
Kinetic Energy (GeV)

Fig. 3b

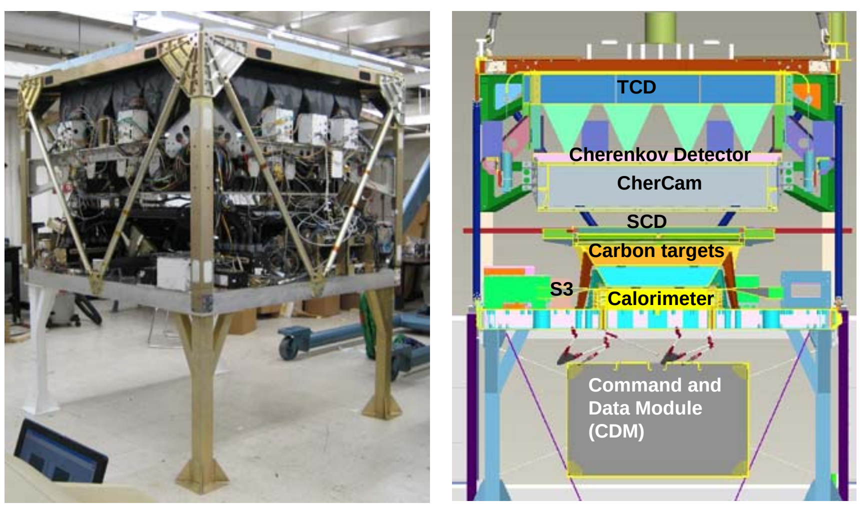
TCD
Cherenkov Detector
CherCam
SCD
Carbon targets
S3
Calorimeter
Command and
Data Module
(CDM)

Fig. 4.