Recent Results and Future Plans for the Gamma Ray Polarimeter Experiment (GRAPE)

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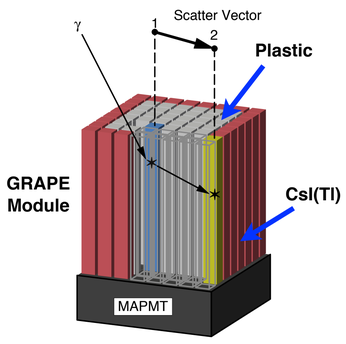
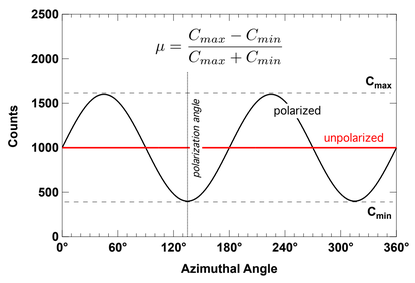
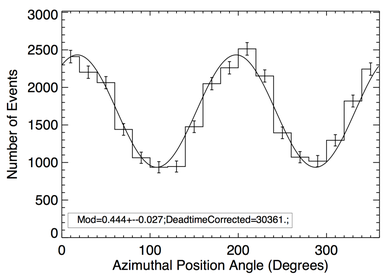
The Gamma-RAy Polarimeter Experiment (GRAPE) is a Compton polarimeter designed to measure the polarization of astronomical sources in the soft gamma-ray band (50 - 500 keV) from a high-altitude balloon platform. Although designed primarily for studies of gamma-ray bursts over the entire sky, the instrument can also be combined with a collimator for pointed observations. The first science flight of the payload, in the collimated configuration, was launched from Ft. Sumner, NM, on September 23, 2011 by NASA's Columbia Scientific Balloon Facility (CSBF). Although the polarization sensitivity was limited by several factors, the instrument and payload performed well during 26 hours at float altitude, performing observations of the Crab Nebula and two M-Class solar flares. We describe the instrument, payload, science observations, and data analysis procedures, and present our upper limits for the soft gamma-ray polarization of the Crab and the solar flares. A second flight, with greatly improved sensitivity, is currently scheduled for the Fall of 2014.

Compton Polarimetry

Compton polarimetry exploits the fact that photons tend to scatter at right angles to their polarization vector:







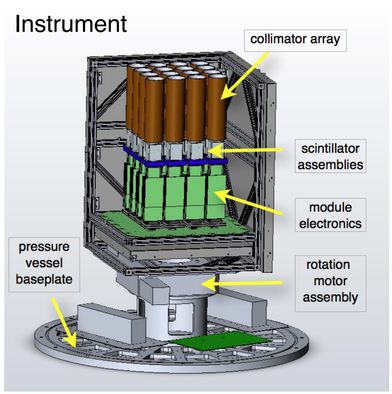
A suitable arrangement of scintillators records the azimuthal scattering vector of incident gamma rays. Organic (plastic) bars are used for scattering elements, and inorganic (CsI:Tl) bars for calorimeter elements.

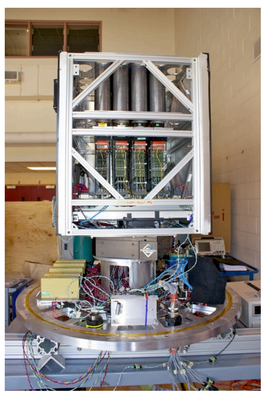
Polarized radiation produces a sinusoidal azimuthal scatter distribution. The modulation μ is proportional to the **degree of polarization**, and the minimum of the distribution gives the **polarization angle**.

95% polarized radiation at ~98 keV is produced in the lab by scattering 122 keV photons at 90° from a plastic block. The modulation histogram recorded by the integrated GRAPE instrument (below) is shown.

GRAPE Instrument and Payload

Instrument





The **GRAPE instrument** consists of

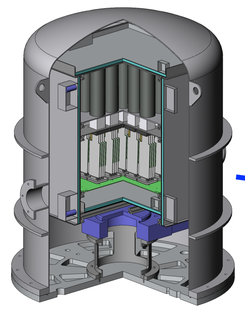
- A 4 × 4 array of polarimeter modules, each with 64-element scintillator array, readout MAPMT, and electronics
- Shielding, both passive (0.8 mm Pb/0.8 mm Sn) and active (6 mm plastic)
- An array of cylindrical collimators, providing a ~20° field of view
- Power board, module interface board, and instrument computer w/ flash hard drive
- Rotation table: entire instrument is rotated in 4° steps every 13 s to average out geometric asymmetries

The **GRAPE balloon payload** consists of

- A two-piece pressure vessel consisting of a flat base plate and upper dome
- Gondola frame constructed out of 80/20 extruded aluminum
- Attitude control system: ADU 5 differential GPS for azimuth determination, azimuthal control rotator (provided by CSBF), and inclinometer/ elevation control motor. Azimuth stability is ~1° RMS
- Thermal control via commandable heaters
- Command and telemetry via the CSBF mini-SIP and low- and high-rate science transmitters

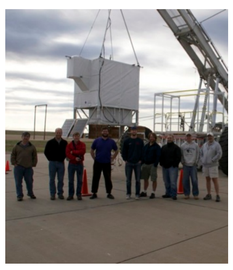
CSBF Rotator

Pressure Vessel

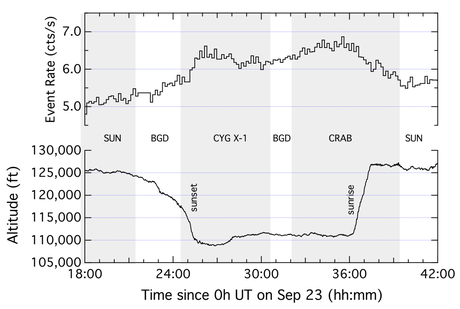


Gondola

September 2011 Science Flight



The GRAPE Balloon Payload was Launched on Sept. 23, 2011, from Ft. Sumner, NM

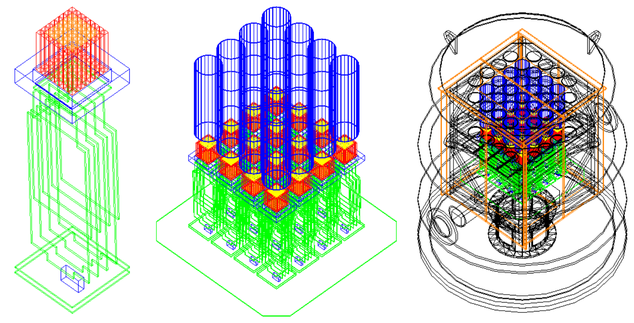


The payload spent 26 hours at float. The float altitude ranged between 3.5 gm cm^{-2} (126,000 ft) to more than 7 gm cm^{-2} due to day/night variations in solar heating. Pointed observations were performed of the Sun, Cyg X-1, and the Crab Nebula, interspersed with blank-field background pointings. The instrument and payload performed well, and were recovered in good condition in the Texas panhandle.

Data Analysis

Geant4 Simulations

The analysis of the GRAPE data relies heavily on Geant4 Monte Carlo simulations to derive the instrument's energy and polarization response. Shown left to right are the Geant4 mass model of the polarimeter module, instrument array, and pressure vessel interior.

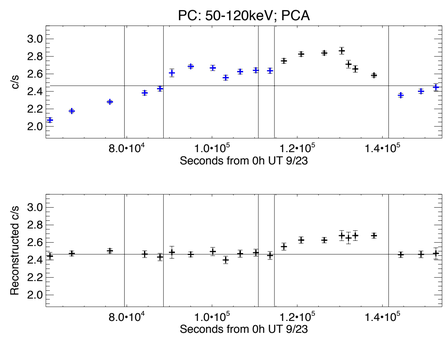


Two types of data were simulated and analyzed:

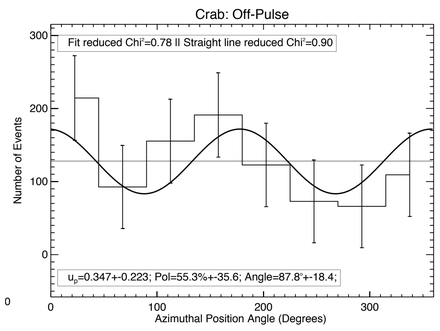
- **PC Events**: plastic-to-calorimeter scatter events, used for polarization and spectroscopy analysis
- **C Events**: single hits in the calorimeters, used for spectroscopy only

Crab Nebula Analysis

Both the PC and C counting rates varied considerably over the course of the flight, dependent on atmospheric depth and temperature. A **Principal Component Analysis (PCA)** was used to find the relation between the counting rates and these variables, using the plastic shield rates as a proxy for atmospheric depth. This allowed the variation due to these factors to be removed, revealing the count rate due to the Crab (left). Repeating this procedure in multiple energy bands produces a count spectrum, which which can be used in spectral analysis.

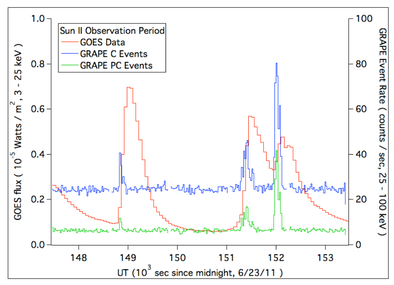


Events were binned according to the phase of the Crab Pulsar. Off-pulse (i.e., Nebula) events were selected from the phase range 0.5 - 0.88, following Dean et al. (2008, Science, 321, 1183). An analysis of the modulation histogram from these events, in the 50 - 120 keV band, was unable to constrain the polarization of the Crab Nebula (right). **A combination of reduced altitude at nighttime and insufficient passive shielding resulted in reduced source counts and increased background counts**. The **minimum detectable polarization (MDP)** for this observation was 109%.



Solar Flare Analysis

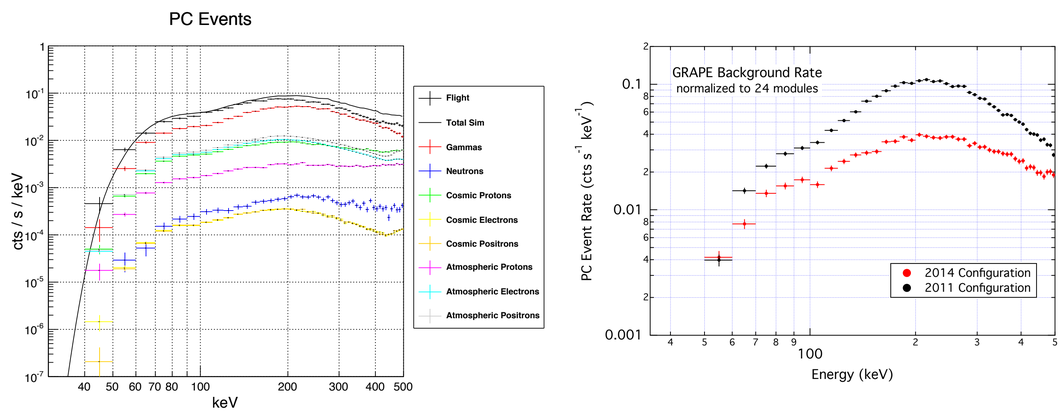
The Sun was very active during our observations, and two M-Class solar flares were observed just before the end of the flight (left). For transient events, background subtraction is trivial.No modulation was observed in the 40 - 110 keV band (right); preliminary analysis indicates that the MDP for this flare was 29% (at the 99% confidence level). For further details see presentation 118.03D.



Plans for 2014 Balloon Flight

The GRAPE payload is scheduled to fly a second time from Ft. Sumner, NM, in the Fall of 2014. Several modifications are being made, the most important of which include the following:

- The instrument array will be expanded to 24 polarimeter modules
- The passive shields and collimators will be upgraded to add several mm of lead



Simulations of the in-flight background have been developed, based on data from the 2011 balloon flight (left). The shielding modifications being implemented for the 2014 balloon flight will reduce the background per module by a factor about 2.5x (right).

With these improvements we expect to achieve a MDP level of ~20% for the Crab Nebula (off-pulse), in the 50-150 keV energy band, at the 99% confidence level.

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