HIGH ENERGY MONITORING INSTRUMENT FOR GAMMA-RAY BURST STUDIES

Kyle M. Holmes[(1)], Brian C. Schratz[(1)], Sven G. Bilén[(1)]

[(1)]The Pennsylvania State University, 332 Electrical Engineering East, University Park, PA 16802, USA

ABSTRACT

Students of the Student Space Programs Laboratory at The Pennsylvania State University are developing the High Energy Monitoring Instrument (HEMI) to investigate the high energy spectrum of gamma-ray bursts. HEMI is a "student collaboration" instrument included as part of the Joint Astrophysics Nascent Universe Satellite (JANUS) mission proposed to NASA's Small Explorer (SMEX) program. Student development of HEMI through all aspects and phases of the mission facilitates the training of the next generation of NASA engineers and scientists. The inherent simplicity of HEMI coupled with the instrument's science contribution allows the student team to be a self-driven and integral part on JANUS. HEMI will allow for the measurement of the peak energy, enabling the calculation of the total energy output of the burst. Also, measurement of these values will enable tests of several proposed luminosity indicators for GRBs.

HEMI is using high altitude balloons as a technology-development path to prepare for the JANUS mission. We are proposing to fly HEMI on a long duration, high altitude balloon from NASA's Antarctic balloon facility well in advance of integration with JANUS. This balloon flight will serve as a platform to test the capabilities of HEMI prior to integration into JANUS. This balloon flight will build upon HEMI's heritage gained through a short duration, high altitude balloon (NASA's High Altitude Student Platform), which was launched in September 2008.

1. INTRODUCTION

The prompt emission of gamma-ray bursts (GRBs) is a broad-band phenomenon that has been detected by various instruments and for various bursts with energies from below keV to greater than GeV, i.e., regimes spanning eight, or more, orders of magnitude in photon energy. The full nature of the physical processes powering the burst-prompt emission remains elusive, but their spectra are commonly parameterized as a Band function, with two distinct power-law segments joining at the peak energy, E_{peak}, in a νF_ν energy distribution—that is, the photon energy that characterizes the bulk of the burst's energy output. Within the BATSE burst catalog, peak energies range from 40 keV, roughly the low energy cutoff for BATSE, up to 1 MeV, with a typical value of $E_{peak} \approx 300$ keV.

JANUS, which is now in Phase A, is a follow-on mission to the very successful *Swift* mission, and is designed to capitalize and expand on *Swift*'s objective to use GRBs to study the early Universe. Since its launch in November 2004, *Swift* has only detected two bursts from the reionization era (GRB 050904 at $z = 6.3$ and GRB 090423 at $z = 8.3$ [1, 2].

Over the course of its two-year baseline mission, JANUS will detect and observe on the order of 50 bursts from $z > 5$, including an estimated seven bursts from $z > 8$, out to a highest measureable red shift of $z = 12$; and identify more than 400 quasars from $z > 6$, out to a maximum red shift of $z = 10$.

JANUS will investigate the causes of reionization through star rate formation, quasar number density, change in luminosity over the reionization period (red shift of $5 < z < 12$), and the contribution of stars and quasars to ionizing the interstellar medium. Identifying GRBs and quasars from the period of the early Universe will give rise to a greater understanding of reionization. By measuring the distribution of GRB redshifts, JANUS can form an accurate model of star formation over the range $5 < z < 12$, which contributed to the reionization of the interstellar medium.

JANUS, illustrated in Fig. 1, will use the X-Ray Flash Monitor (XRFM) to detect GRBs and localize the burst position to sub-arcminute resolution—a large improvement over the *Swift* Burst Alert Telescope (BAT), which had an accuracy of one-to-four arcminutes [3]. Within minutes, JANUS will focus its

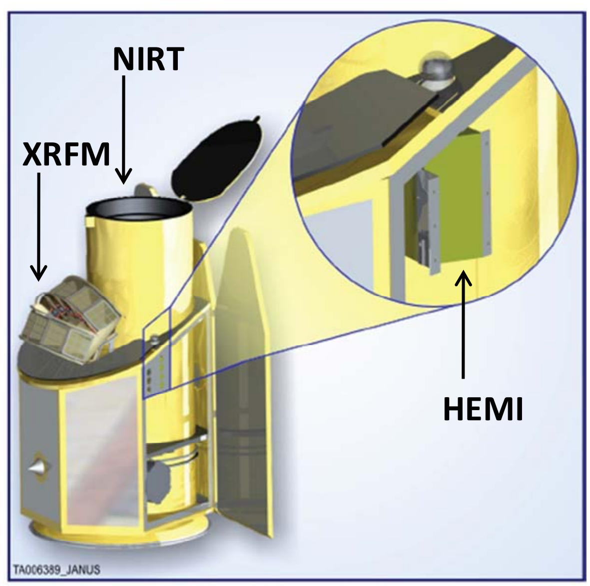


Figure 1. The JANUS Satellite

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

Near-Infrared Telescope (NIRT) on the burst afterglow to measure the brightness and redshift (for $z > 5$) to 7.5% precision. The combination of the XRFM, the NIRT, and quick response make JANUS an extremely capable instrument for the study of the early Universe.

HEMI will gather data on the high energy spectrum of the bursts just outside the XRFM's band pass. From this data, the E_{peak} of the GRB will be obtained, along with data that can be used to construct time-resolved and energy-resolved spectra of the GRBs.

2. SCIENTIFIC YEILD

Over the baseline of the JANUS mission, HEMI is predicted to detect ~25 GRBs within its 6-sr field of view. HEMI will collect data on the burst, and 60 s before and after the burst, with 10% energy resolution and 1-ms time resolution. This data will be used to construct the light curve of a GRB.

HEMI does not have the capability to localize the origin of detected GRBs. This means that there will be an error of about 45% in the energy measurement. However, if the XRFM or another satellite localizes the same burst, HEMI will be able to use this data to reduce the error in the effective area of the scintillator for that specific GRB.

Including HEMI in the JANUS mission will accentuate the science return from the XRFM and the NIRT through broader spectral coverage. From this, several science objectives become achievable.

First, HEMI will allow for the measurement of E_{peak}, which can lie outside the XRFM band pass, even for high red-shift GRBs. This measurement of E_{peak}, provided by HEMI, enables the calculation of the total energy output of the burst, E_{iso}. Measuring the energy output of the brightest and highest red-shift bursts, while not necessary to exploit burst afterglows for cosmology, is of great interest from the standpoint of physical models, which must explain how it is possible to release these extreme energies in a short amount of time. Indeed, the high red-shift GRB 050904, with $z = 6.3$ and $E_{\text{peak}} > 150$ keV [1], was found to have an extraordinary energy output, more than ten times the typical value for $z \approx 1$ bursts [4, 5].

Second, measurement of the burst E_{peak} and E_{iso} will enable tests of several proposed luminosity indicators for GRBs [6]. While it is not clear that cosmological constraints can be derived from these relations in a non-circular fashion [7], this application will hold for bursts at any red shift, so long as the red shift is measured via either JANUS or ground-based observations.

Finally, the presence of a detector of $E > 20$ keV photons onboard JANUS will enable XRFM detection and localization of additional spectrally hard bursts that would otherwise lie below the XRFM threshold. Based on detection of a burst of high energy photons, the XRFM software can relax its threshold for identification of new sources. While this approach is not expected to lead to the discovery of any additional high red-shift bursts (these are relatively soft and slow evolving), it may enable real-time localization of additional short, hard bursts, an intriguing subset of the GRB population that may result from compact object merger events [8].

3. IMPLEMENTATION

HEMI will be a small instrument designed to fly within the margins of the spacecraft. JANUS has allocated HEMI 10 × 10 × 20 cm volume, 5 kg mass, 5 W power, and 5 MB/day average data volume for the instrument. A contingency of 30% for each allocation, excluding volume, will be held at the instrument level.

Table 1. HEMI Allocation

Physical Envelope	10 × 10 × 20 cm
Mass	5 kg
Power	5 W average
Data	5 MB/day average

3.1. DETECTOR

The HEMI detector consists of a single sodium–iodide (NaI) scintillator (5.08 cm in diameter by 5.08 cm in length) coupled to a photomultiplier tube (PMT). Scintillator/PMT–based detectors have been used in GRB studies since the 1970s and continue to be used in modern instruments. In particular, NaI scintillators have been used on BATSE's Spectroscopy Detectors and continue to be used on *Fermi*'s GLAST Burst Monitor (GBM).

NaI has been widely used in gamma ray spectroscopy due to its high light yield. By using a scintillator with a height-to-length ratio of 1, HEMI gains favorable light collection properties. Therefore, the material and geometry of the scintillator make HEMI capable of accurate measurements of photons at the lower end of the energy spectrum.

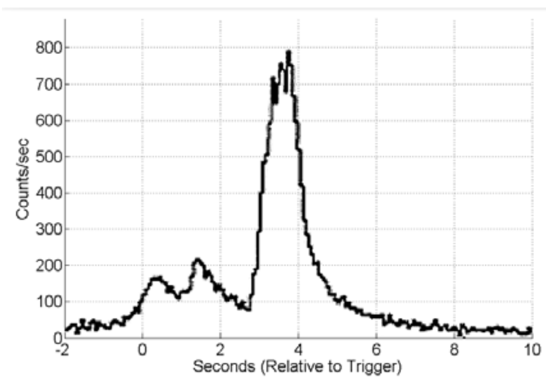
As a means of constant in-flight calibration, HEMI will contain a 10-nCi Cs–137 radiation source. This calibration source will provide HEMI with a constant emission line of 662 keV at a rate of 166 photons/sec. This radiation source will indicate how the performance of the instrument varies after long exposure to the radiation environment.

3.2. TRIGGERING

The success of HEMI heavily depends on the instrument's ability to determine when a GRB has occurred and, once HEMI has detected one, when the burst is over. This directly causes the instrument to change between transmitting background data and burst data.

3.2.1. BURST DETECTION

A substantial increase in the flux of high energy photons, as shown by the simulated HEMI data product shown in Fig. 2, is characteristic of a GRB event. This fundamental characteristic is utilized to determine when a GRB has occurred.



Fiaure 2. Simulated HEMI Data

HEMI will monitor the rate at which photons are detected across multiple short timescales (4, 64, 256, and 1024 ms). HEMI will also monitor the current background radiation environment across a long timescale, nominally 15 s, for comparison. When the rate determined on one of the short timescales exceeds a specified, standard deviation threshold, nominally 5.5 σ, HEMI will determine a GRB has occurred, and start transmitting burst data.

The fundamental process used on HEMI to detect bursts has been the standard for scintillator-based experiments for the last three decades. The GRB detector on the Pioneer Venus Orbiter used a similar technique, and it is currently in use by the *Fermi*'s GBM.

This detection method will inevitably result in the instrument triggering on a celestial event that is not a GRB. Some significant sources as recorded by BASTSE include solar flares, particle precipitation, entrance into the South Atlantic Anomaly (SAA), and Cygnus X-1 [10]. These events can be differentiated from a GRB by their spectra when processed by post-flight analysis software.

To maximize the quality and quantity of the data provided on GRBs, there is an interface between HEMI and the XRFM. If HEMI detects a GRB, and the XRFM does not, the XRFM will scan its coded mask with its imaging capability to see if there is a burst lying below its detection threshold. Similarly, if the XRFM detects a GRB, and HEMI does not, HEMI will view this as a valid trigger, and begin transmitting burst data and running through its burst termination algorithm.

3.2.2. BURST TERMINATION

After detecting a GRB, HEMI will monitor the rate at which photons are detected in 4-s intervals. When three of these time intervals are within 2σ of each other, HEMI will determine that the burst is over. This will be overridden by an automatic limit of 500 s, in case the background environment contains some source that is causing a constant variation in the background radiation.

If the XRFM detects a burst that causes the spacecraft to slew, HEMI will receive a trigger when the slew begins and ends. HEMI will wait 60 s after the slew is over to start sampling the background radiation to determine if the burst has ended. If the XRFM does not detect the burst and, therefore, the spacecraft does not slew, HEMI will wait 60 s from the time it triggers to determine if the burst has ended.

All of these parameters will be adjustable in order to maximize the efficiency of this algorithm once the instrument is in operation.

4. BACKGROUND DATA

HEMI will constantly collect data on the background radiation environment. This data will be transmitted for four energy channels across the energy range and will have one-minute time resolution. This data can be used to form a model of the background radiation environment, which can be used to increase the instrument's sensitivity. This also provides the opportunity to look through data at any point, to look for a GRB on which HEMI failed to trigger, but which was detected by another instrument.

This data will also be used to monitor the long term drift in the instrument. By keeping track of where the Cs-137 line and the 511-keV positron emission line occur, it will be possible to monitor changes in the instrument's performance.

5. STUDENT SPACE PROGRAMS LABORATORY

HEMI is being developed by The Pennsylvania State University's Student Space Programs Laboratory (SSPL). SSPL [11] is comprised primarily of undergraduate students and graduate students with oversight from faculty members. Furthermore, SSPL has mentorship from various industrial sources and Penn State faculty.

SSPL focuses on engaging students in space missions to train and motivate the next generation of space scientists and engineers. In the past decade, Penn State students have participated in four sounding rocket payloads, four microgravity experiments, two high-altitude balloon instruments, and two nanosatellites.

Students involved in SSPL have access to facilities operated by both SSPL and other labs on campus (including the Communications and Space Sciences Lab within Electrical Engineering) in order to fabricate and test flight equipment. Such facilities include a clean room, vibration tables, a machine shop, thermal–vacuum, cryo chambers, and solder reflow facilities.

6. HERITAGE

The inclusion of HEMI on JANUS enhances the JANUS mission by contributing meaningful science. Also, as a student collaboration instrument [12], the development of HEMI will expose undergraduate and graduate students to the processes and procedures of building spaceflight hardware and will better prepare this future generation of scientists and engineers for future careers in the aerospace industry.

Developing an instrument to the standards and requirements of the JANUS mission is a tremendous learning opportunity for a predominantly undergraduate student group. In preparation for the initial JANUS proposal, PSU's SSPL quickly decided on a technology-development plan that would mature the HEMI technology in accordance with the JANUS schedule. High altitude balloons were chosen as the best platform. Incorporating balloon missions has several advantages. Balloons provide a cost-effective maturation path for HEMI. They provide an end-to-end system test of the flight instrument, operation, and data analysis. Each flight serves as a step in the development process as HEMI will evolve from a low cost prototype into an instrument qualified for spaceflight. Each step will build on the lessons learned from the prior flight.

Furthermore, short turn-around times provide compelling opportunities to students who would not otherwise see the later testing or flight of HEMI on JANUS. Pathfinder flights maintain a constant excitement among students and aid in recruiting and retaining students to ensure that knowledge is maintained and transferred across the dynamic student workforce.

Therefore, a preliminary pathfinder instrument was developed for a short-duration flight (~20 hours) on NASA's High Altitude Student Platform (HASP) [13] operated by the Louisiana State University (LSU). Based on lessons learned from HASP, another, more advanced prototype is planned for flight on a long duration (>20 days) high altitude balloon approximately two years after the HASP launch.

Because GRBs do not occur very frequently—on average there are one to two per day—and the typical HASP balloon launch duration is roughly 20 hours; then it was not very likely that a GRB would be detected by HEMI during the HASP flight. Taking this into account, and keeping in mind that the ultimate goal is studying GRBs, this first flight was intended to be a test of preliminary hardware as well as the student organization. On this HASP flight, the instrument, shown in Fig. 3, was used to detect cosmic rays as a precursor to studying GRBs. HEMI collected information on the number of particles and their energies during time intervals. The data processing algorithms for cosmic rays will differ from those for GRBs. However, the detection and data collection hardware will be similar between the two instruments.

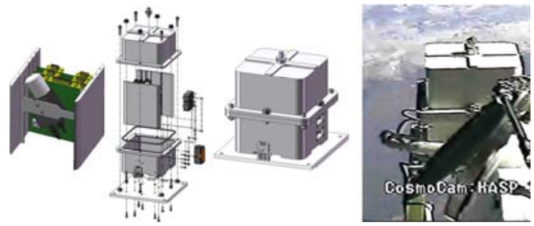


Figure 3. HEMI Pathfinder Instrument Design (left) and in Flight on HASP (right)

The short duration pathfinder balloon experiment developed and analyzed by the students provided valuable experience to the students working on HEMI. Students were engaged throughout the mission life cycle from proposal to fabrication and were directly involved in the launch and data analysis.

Through this balloon project, students have been introduced to issues very similar to those they will encounter during the development of the satellite instrument. Students have become familiar with issues that arise in the use of PMTs, testing procedures, calibration, and data analysis from the PMT.

Students have provided a thermal analysis and suggested solutions for thermal issues. They have designed and built circuits for command and data handling, power, signal conditioning, and health and status monitoring. As part of command and data handling, the HEMI team now has experience in the area of pulse peak detection. This experience will provide a foundation as the students begin developing peak detection algorithms for a light curve of a GRB. The power and communication interfaces are also very similar to those of JANUS.

The HEMI team has also been introduced to the process of integrating an instrument into a host flight system, systems engineering, project management documentation, interfaces, and scheduling. In addition, this effort gave students significant experience in the end-to-end life cycle including data analysis and has better prepared them for the more complicated iterations to come.

7. CONCLUSIONS

HEMI will provide valuable data on the E_{peak} of GRBs during the JANUS mission and may provide triggers to assist JANUS in the detection and localization of additional GRBS. Student development of the HEMI through all aspects of the mission facilitates training of the next generation of NASA engineers and scientists. The inherent simplicity of the HEMI design coupled with the instrument's science contribution allows the student team to be a self-driven and integral part of the JANUS mission. Furthermore, a technology development plan using high altitude balloons has reduced the development risk of HEMI will continuing to engage students.

8. AFTERWORD

On 19 June 2009, NASA announced the selection for the next round of small explorer (SMEX) class mission opportunities. JANUS did not receive a flight opportunity. Nonetheless, SSPL retains the capability to perform all aspects of missions similar to that of HEMI and will look for future opportunities.

9. REFERENCES

1. Band *et al*., "BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity," *The Astrophysical Journal*, vol. 413, pp. 281–292, August 1993.
2. Personal correspondence with Derek Fox, 30 May 2009.
3. Barthelmy *et al*., "The Burst Alert Telescope on the Swift MIDEX mission," *Space Science Reviews*, vol. 120, pp. 143–164, 2005.
4. Frail, D. A., *et al*., "An Energetic Afterglow from a Distant Stellar Explosion," *The Astrophysical Journal Letters*, vol. 646, pp. L99–L201, August 2006.
5. Gou, L. J., Fox, D. B., and Mészáros, P., "Modeling GRB 050904: Autopsy of a Massive Stellar Explosion at $z = 6.29$," *The Astrophysical Journal*, vol. 668, p. 1083, 2007.
6. Liang, E., and Zhang, B. "Calibration of Gamma-Ray Burst Luminosity Indicators," *Monthly Notices of the Royal Astronomical Society: Letters*, vol. 369, pp. L37–L41, MNRAS, 269, L37, 2006.
7. Butler, N. R., *et al*., "A Complete Catalog of Swift Gamma-Ray Burst Spectra and Durations: Demise of a Physical Origin for Pre-Swift High-Energy Correlations," *The Astrophysical Journal*, vol. 671, pp. 656–677, December 2007.
8. Fox, D. B., *et al*., "The Afterglow of GRB 050709 and the Nature of the Short-Hard Gamma Ray Bursts," *Nature*, vol. 437, pp. 845–850, 2005.
9. Knoll, Glenn F., *Radiation Detection and Measurement*, Wiley, New York, 2005.
10. Fishman, G., *et al*., "The first BATSE gamma-ray burst catalog," *ApJ Supplement Series*, vol. 92, p. 229, May 1994.
11. DeVore, Steven M., Kummer, Allen T., Schratz, Brian C., and Bilén, Sven G., "The Student Space Programs Laboratory: Fostering Student Space Systems Education and Research within a University Environment," 19th ESA PAC Symposium, June 2009.
12. CoBabe–Ammann, E., and Klumpar, D., editors, Final Report of the NASA Program Definition Team for Student Collaborations, NASA, 2008.
13. Schratz, Brian C., "Development and Analysis of the High Energy Monitoring Instrument Pathfinder for the Janus Satellite," The Pennsylvania State University, M.S. Thesis, Fall 2008.