FIRST RESULTS FROM HETE-2

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HETE-2 is a compact spacecraft entirely dedicated to the study of GRBs. This paper describes the first year of the mission with a presentation of the payload, the in-flight performance of the spacecraft and a few selected scientific results.

1 The HETE-2 Mission

Gamma-ray bursts (GRBs) are the trace of powerful explosions taking place at cosmological distances. The study of these events is expected to provide new insights into the physics at

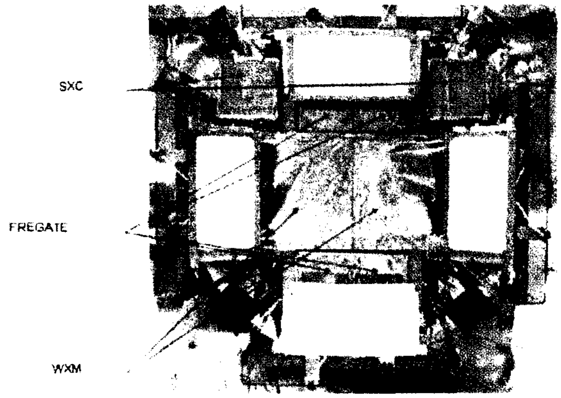

Figure 1: Top view of HETE-2, showing the three instruments.

work in regions where huge amounts of energy are dissipated and into the star formation and evolution at remote epochs. The High Energy Transient Explorer (HETE-2 [a]) is a dedicated mission to study the early phases of GRBs at X-ray and γ-ray wavelengths. This mission was brought to life by an international consortium (see the list of authors) under the PI-ship of G. Ricker from the MIT Center for Space Research. HETE-2 (hereafter HETE for simplicity) was launched in October 2000.

A unique feature of HETE is its capacity to detect GRBs, quickly localize them on-board and disseminate this information within seconds of the trigger. For the purpose of detecting and localizing GRBs, HETE carries three instruments: a γ-ray spectrometer (FREGATE) based on a NaI detector and two spectro-imaging X-ray cameras (WXM and SXC). WXM is based on Position Sensitive Proportional Counters (PSPCs) viewing the sky through a coded mask. SXC is a set of CCIDs viewing the sky through a coded mask. All three instruments have wide fields of view (FOVs), in order to increase their probability to detect gamma-ray bursts. This instrumental suite provides broad-band coverage of the prompt GRB phase (from 1 keV to 400 keV), with good temporal and spectral resolution. Fig. 1 shows how these instruments are laid out on one face of the spacecraft. HETE is on an equatorial orbit at an altitude of about 600 km, like BeppoSAX. This orbit is well suited for high energy instruments thanks to its very low background. HETE has been designed to look in the antisolar direction, and the instruments and the solar panels are on two opposite faces of the spacecraft. This orientation divides the life of the spacecraft into daytime and nighttime (see Fig. 2). During *daytime* the instruments look at the Earth while the solar panels see the Sun and charge the batteries. During *nighttime* the instruments look at the sky for high energy transients. Daytime and nighttime are roughly 45 minutes long each. Fig. 3 illustrates the operation of HETE over a 24 hour period. It should be noted that the spacecraft can also accomodate some head nodding (a few ten degrees) during nighttime in order to keep the moon out of the field of view of the star trackers and/or to remove bright X-ray sources (SCO X1) from the field of view of the instruments.

For the purpose of disseminating the alerts quickly, the HETE collaboration has set up a dedicated network of ground stations distributed in longitude near the equator in such a way

[a]HETE-1, launched in 1996, was lost due to a failure of the Pegasus launcher.

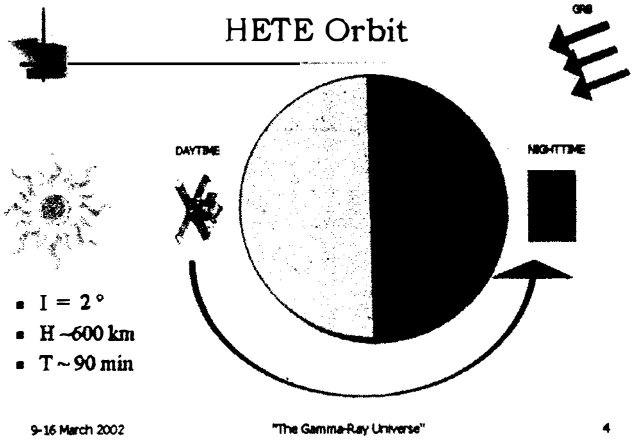

Figure 2: Schematic view of the attitude of HETE, showing the daytime and nighttime portions of the orbit.

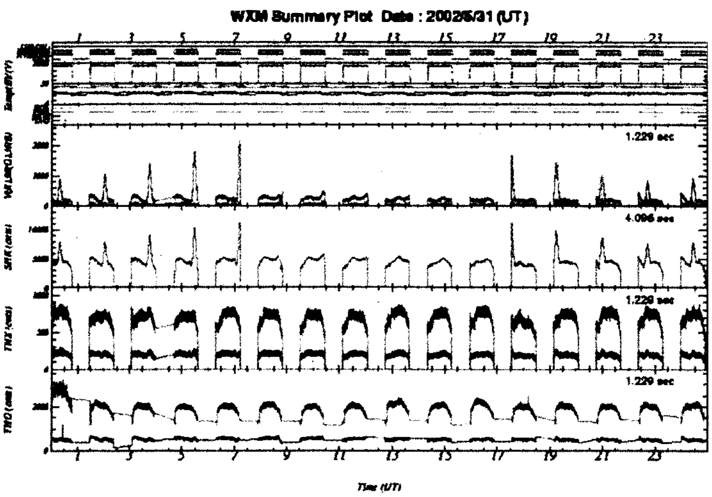

Figure 3: Typical daily HETE operation. This plot, called the WXM summary plot, is built by the WXM operation team and continuously updated as new data are received from HETE. The upper four panels show the status of the WXM detectors, the fifth panel shows events which are likely due to particles and the sixth panel shows the total cout rate recorded by the WXM. The lower two panels show the count rates in two energy bands for the WXM (top) and for FREGATE (bottom). It can be seen that FREGATE and the WXM are switched off during approximately half of the orbit, when HETE looks at the Earth (daytime). In 24 hours, HETE does 16 revolutions around the Earth.

Table 1: FREGATE instrumental characteristics.

Built by	CESR (France)
Instrument type	Cleaved NaI(Tl) + PMT
Energy range	6 - 400 keV
Effective Area	160 cm^2
Spectral resolution	13% @ 81 keV
	10% @ 356 keV
Timing resolution	10 μs
Passively collimated field of view	$\sim$ 4 sr
Sensitivity, 6 σ, 50-300 keV	$\sim 1 \times 10^{-7}$ erg cm^{-2} s^{-1}
Background count rate in 25-100 keV	100 c s^{-1} per detector

that HETE is almost always within range of one of these stations. When a burst is detected and localized, its position is broadcasted by the on-board VHF antenna. The 14 ground stations are continuously listening. When they receive a message from HETE, this message is sent to the MIT Control Center where it is processed and eventually relayed to the GCN to be distributed to the community.

An extensive description of the HETE mission can be found in the proceedings of the Wood-sHole conference on "Gamma-Ray Burst and Afterglow Astronomy", which contain detailed descriptions of the mission [1,2,3] of the instruments [4,5,6] and of the ground segment [7,8].

2 In-flight calibration and performance

2.1 FREGATE

The verification phase of FREGATE consisted of *i)* the measure of the background spectrum and adjustment of the gains, *ii)* the verification of the trigger performance, the measure of the sensitivity to GRBs and of the rate of false alarms, and *iii)* the verification of the spectral response with the Crab nebula. These verifications demonstrated that FREGATE is working as expected,[4] with a very low rate of false triggers due to the requirement of coïncident excesses on independent detectors. The trigger sensitivity is of the order of 10^{-7} erg cm^{-2} s^{-1}, and FREGATE detects about 40 confirmed GRBs per year within its field of view. [10] The occultation of the Crab nebula by the Earth allowed to check the spectral response of the instrument in flight, in the energy range 6-200 keV.[9] In-flight performances of FREGATE are given in Table 1.

2.2 WXM

The verification phase for the WXM consisted of *i)* the measure of the background spectrum and adjustment of the gains, *ii)* the verification of the on-board trigger sensitivity, *iii)* the verification and calibration of the localization capability (in real time and on the ground) *iv)* the validation of the spectral response with the Crab nebula. After few months used to optimize the localization software and to perform astrometric calibrations (with the Crab nebula, SCO X1, and a few XRBs and SGRs), the WXM now fully meets its specifications.[5,13,19] The spectral response has been validated with the Crab, and the consistency of WXM and FREGATE spectra has been checked. Since the launch of HETE to the end of May 2002, the WXM has localized 18 GRBs, 6 SGR bursts from SGR1900 and SGR1806 and about 200 X-Ray Bursts from known galactic bursters. In-flight performances of the WXM are given in Table 2.

Table 2: WXM instrumental characteristics.

Built by	RIKEN (Japan) and LANL (USA))
Instrument type	PSPC + coded mask
Energy range	2 - 25 keV
Effective Area	175 cm^2 (each of two units)
Spectral resolution	25% @ 20 keV
Detector QE	90% @ 5 keV
Timing resolution	1 ms
Field of view (FWZM)	1.6 sr
Sensitivity, 10 σ, 2-10 keV	$\sim 8 \times 10^{-9}$ erg cm^{-2} s^{-1}
Localization accuracy	19' (5σ burst)
	2.7' (22σ burst)

Table 3: SXC instrumental characteristics. The loss of half of the optical blocking filters in the first months of the mission led to degraded performance which are given in column 3.

Built by	MIT-CSR (USA))	
Instrument type	CCID-20	
Energy range	0.5 - 14 keV	1.3 - 14 keV
Effective Area	74.4 cm^2	37.2 cm^2
Spectral resolution	46 eV @ 0.5 keV	
	129 eV @ 5.9 keV	300 eV @ 5.9 keV
Timing resolution	1.2 s	1.2 s
Field of view (FWZM)	1.9 sr	1.3 sr
Sensitivity, 5.5 σ	1.0 cts cm^{-2} s^{-1}	1.2 cts cm^{-2} s^{-1}
Localization accuracy (90%)	43"	43"

2.3 SXC

The verification phase of the SXC was perturbated by the loss of the optical blocking filters covering half of the CCDs.[8] The two SXC cameras include a total of 4 CCD detectors, two of which were covered with polyimide optical blocking filters (OBFs) and two with beryllium OBFs. Three months after launch it appeared that the polyimid OBFs were being destroyed by atomic oxygen (whose concentration at an altitude of 600 km greatly depends on the solar activity). As a consequence, Two CCDs were unusable and the other two were contaminated by light leakage. The consequence of the light leakage was to reduce the use of Be covered CCDs to 20 dark days per lunar month and to decrease their spectral resolution.[16] Despite this loss, the detection efficiency and the localization capability of the SXC have been checked with quiescent (Crab and SCO X1) and transient X-ray sources (8 X-Ray Bursts and 1 burst from SGR1806-20).[15] The precision of localization is 20" rms, giving a radius of 43" for a two dimensional 90% error region. With a reduced sensitivity, the SXC is now expected to localize 2-3 GRBs per year. In-flight performances of the SXC immediately after launch and after the loss of the Optical Blocking Filters are given in Table 3.

2.4 ground trigger

In complement of the on-board trigger, HETE data are searched for excesses as soon as they arrive on the ground[12,14] (i.e. with a delay of a few minutes to 90 minutes). This ground trigger has proven very efficient to detect long faint GRBs which are missed by the on-board trigger.

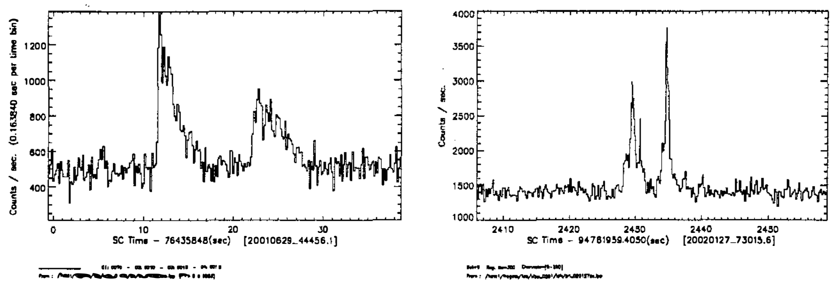

Figure 4: Light curves of GRB010629 and GRB020127 detected by FREGATE and localized by the WXM within 6.5 and 1.8 hours after the burst, respectively.

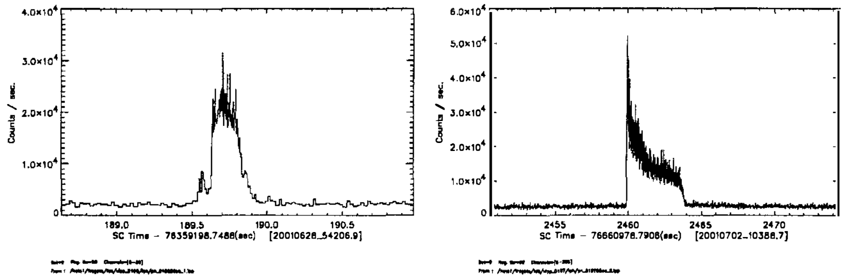

Figure 5: Light curves of two bursts from SGR1900+14. The spectrum of the second burst is shown in Fig. 10.

Several X-Ray Flashes have been discovered in this way.

3 Selected scientific results

3.1 High Energy Transients Detected by HETE

During its first year of operation, HETE has detected 34 confirmed Gamma-Ray Bursts,[b] 30 bursts from Soft Gamma Repeaters, above 300 X-Ray Bursts, and several solar flares reflected by the atmosphere of the Earth. Additional triggers were due to fast fluctuations of SCO X1 and to electrons trapped in the magnetic field after large solar flares. A remarkable feature of HETE is its low rate of noise triggers due to the observation of the same region of the sky with independent detectors. Fig. 4, 5 and 6 show some examples of GRBs, SGRs and XRBs detected by HETE. Fig. 7 displays the number of GRBs, SGR bursts and XRBs detected by FREGATE during its first year of operation. The GRB detection rate is 40 GRB/yr with FREGATE (75% of which are within the FOV), 15-20 GRB/yr with the WXM (nearly all localized), and 2-3 GRB/yr with the SXC.

Real-time localizations. To the end of March 2002, the flight software had succesfully localized 6 GRBs, 7 SGRs et 27 XRBs in near real time (i.e. in seconds after the trigger). The majority of these positions were NOT distributed to the astronomical community for one of the following reasons: lack of real time aspect (e.g. due to full moon) - temporary loss of the alert network on the ground - S/N ratio judged too small by the on-board software. Only 1 SGR and

[b]plus 8 probable but unconfirmed GRBs

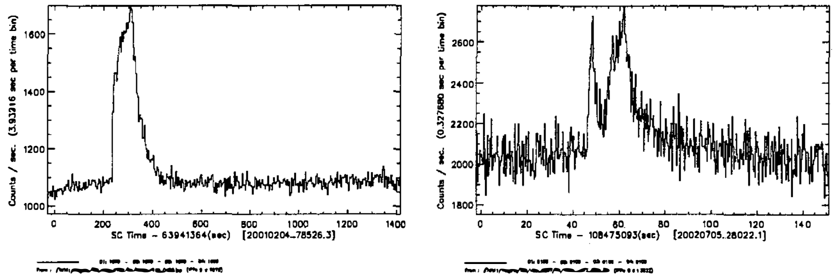

Figure 6: Light curves of two bright X-ray Bursts, respectively from 4U0614+091 and X1812-121.

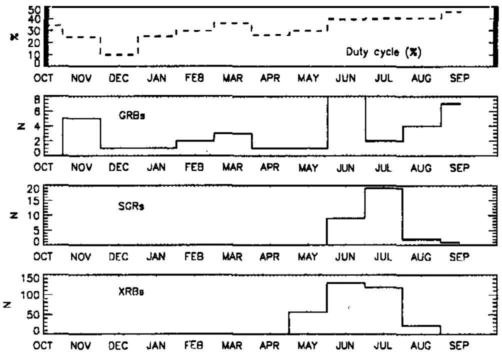

Figure 7: FREGATE monthly detection number of various types of high energy transients from October 2000 to September 2001. From May to August, the Galactic bulge was in the field of view of FREGATE. Note the scale of the XRB plot.

2 XRB real time localizations were distributed to the astronomical community. The experience gained by the HETE team has resulted in a much increased reliability of the various components of the HETE mission. It now appears reasonable to expect a few real time GRB positions in 2002 and in the following years.

3.2 Gamma-Ray Bursts

Localizations. From its launch to the end of May 2002, HETE/WXM has localized 18 GRBs, including a few X-Ray Flashes [22,27] and the short hard burst GRB020531.[30] The positions of four GRBs were distributed within less than 2 hours of the event, which was never done before. HETE localizations have led to the discovery of 5 afterglows. Optical afterglows were identified for GRB010921[23,24,25] (see Fig. 8), GRB020124, GRB020305 and GRB020331, while GRB020127 had an X-ray afterglow and a radio afterglow (these informations can be found on the GCN site http://gcn.gsfc.nasa.gov or on J. Greiner's site http://www.aip.de/People/JGreiner/grbgen.html). The low redshift of GRB010921 (z=0.45), provided favorable conditions for the detection of a poosible underlying supernova. An extensive followup of the afterglow with the HST, showed no evidence for a supernova and provided the strongest constraints to date on the luminosity of a supernova associated with a GRB.[26]

Gamma-Ray Bursts and X-Ray Flashes. HETE broad-band energy coverage allows comparative studies of the population of classical GRBs and of the population of X-Ray Flashes

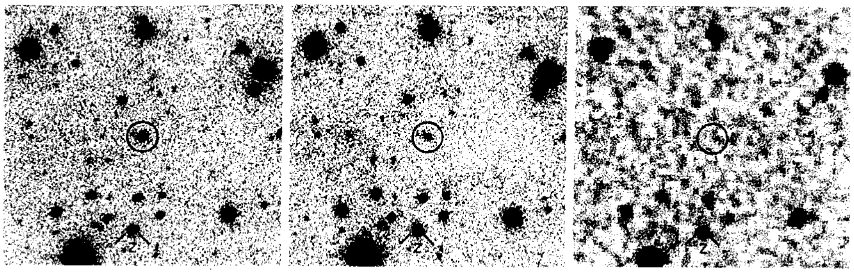

Figure 8: Identification of the afterglow of GRB010921. Left and middle panels: Images taken on 2001 September 22 and 27, respectively, with the LFC (r' filter) on the Palomar Hale 200 inch telescope. Right panel: same field from the DSS-2. Each image is 1.5' on a side, with north to the top and east to the left (from Price et al. 2002).

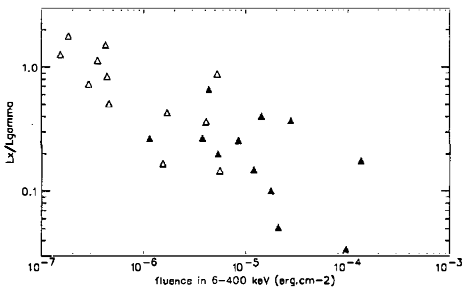

Figure 9: FREGATE observation of 24 GRBs/XRFs. This plot displays the fluence ratio (6-30 keV / 30-400 keV) as a function of the fluence in the range 6-400 keV. XRFs are in the upper left corner. This figure suggests a continuous evolution from GRBs to XRFs (from Barraud et al. 2002a).

(XRFs)[22,29]. A recent analysis of 24 GRBs/XRFs spectra recorded by FREGATE seems to show a continuous distribution of events from classical GRBs to XRFs, rather than two classes[27,28] (see Fig. 9). With improving statistics HETE will help us to better understand the GRB population as a whole. With more than 15 GRBs detected each year by WXM and FREGATE, HETE will also contribute to characterize the X-ray emission during gamma-ray bursts.

3.3 X-Ray Bursts

The strength of HETE is that any particular source of the galactic bulge is within the field of view of the WXM during an average of 3 10^6 sec every year (except for sources in the vicinity of SCO XI [c]). This allows to monitor the source activity of several tens of objects at a time and permits the detection of rare events. We note for instance that the WXM has detected and localized over 200 XRBs and that FREGATE has detected two bursts from 4U0614∓091, from which only one half dozen bursts were previously known.

[c]Starting in 2002, the head nodding capability of HETE has been used to exclude SCO X1 from the field of view of the WXM.

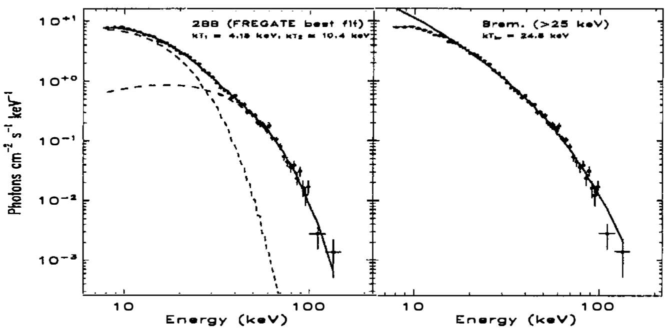

Figure 10: FREGATE spectrum of a bright burst from SGR1900+14. This plot shows that the standard description of SGR burst spectra by a thermal Bremsstrahlung law (right panel) becomes unacceptable when we observe energies below 20 keV. The left panel assumes a fit with two blackbodies.

3.4 Soft Gamma Repeaters

The broad energy coverage of HETE (down to 6 keV for FREGATE and to 2 keV for the WXM) makes it particularly sensitive to Soft Gamma Repeaters: during its first "galactic season", in the summer 2001, FREGATE detected 30 short and soft bursts typical of SGRs. Two of these bursts were localized by the WXM to SGR1806-20 and four to SGR1900+14, and it is most probable that the others also came from these sources. The WXM has the galactic bulge within its field of view during about 3 month, but if SGR-like activity is detected within 1.5 month before or after this period, HETE can easily change its nominal (anti-solar) orientation to monitor the galactic bulge region. This possibility effectively increases the SGR observing window to about 6 months. Overall, HETE has a real potential for discovering new SGRs (if any).

Observations performed in 2001 have already brought an interesting result. A preliminary analysis of a high fluence burst from SGR1900+14 shows that a simple Bremsstrahlung spectral shape does not fit the data,[21] and that a new model must be found for this burst. The need for a new characterization of SGR burst spectra is the direct consequence of the broad-band energy coverage of HETE.

4 Conclusion

After a few months of on orbit calibrations and software adjustment, HETE reached a fully operational status in June 2001. 18 GRBs have been localized by the WXM till may 2002, including a few X-Ray Flashes and one short hard GRB. These localizations have led to the identification of five afterglows. The study of the afterglow of GRB010921 has provided the strongest constraints to date on an underlying supernova. HETE has distributed to the community real time localizations of 1 SGR and 2 XRBs; a much larger number of real time localizations were done correctly, but could not be distributed to the astronomical community for various reasons. We expect the first real time localization of a GRB to arrive soon now (this is written on July 12, 2002).

On another plan HETE has already observed more than 60 GRBs, 30 SGRs and 300 XRBs over a broad energy range, and is accumulating a wealth of information on high energy transients which we just begin to analyze. Two examples of this richness have been illustrated by the spectral analysis of a bright burst from SGR1900+14 (which exhibits a previously unknown spectral shape) and by a detailed comparison of the properties of GRBs and XRFs. The huge amount of data accumulated by HETE must benefit to the community and it is the willingness of the HETE team to make these data available to the widest audience. We encourage anyone having some interest in HETE data to get in contact with members of the Investigator Team (see http://space.mit.edu/HETE).

Acknowledgments

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