JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 22, No. 3, July–September 2008

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Thermal Design and Analysis of a Hard X-Ray Modulation Telescope

H. X. Zhang*
Chinese Academy of Sciences,
100080 Beijing, People's Republic of China
G. L. Huang†
University of Arkansas at Little Rock,
Little Rock, Arkansas 72204
and
J. Yang‡
University of West Ontario,
London, Ontario N6A 5B8, Canada

DOI: 10.2514/1.34467

Nomenclature

C_p = specific heat, J/kg °C
K = conductivity, W/m · K
α = absorptance
ε = emittance
ρ = density, kg/m^3

Introduction

THE Hard X-ray Modulation Telescope (HXMT) is a high-energy astrophysics telescope being developed to detect and analyze x rays in the range of 1–250 keV and to discover more super mass black holes and other high-energy celestial bodies. It is one of the main observatories that will be available in the next few years for astrophysicists to study the universe in the hard x-ray spectrum [1].

The HXMT is composed of 18 identical circularly arrayed detector units. Each detector unit has a collimator, a NaI/CsI crystal detector cell and a photomultiplier tube (PMT), as shown in Fig. 1a. The 18 detectors are supported by the top plate, the middle plate, the bottom plate, and supporting sleeves and lateral ribs, as shown in Fig. 1b. The plastic scintillators and plumbum rings are used for shielding the crystal detector cells from electronic charges and from side incident x rays coming from space, as shown in Fig. 1c. The HXMT weighs about 1 ton with dimensions of 1300 × 1300 × 920 mm. Each part of the HXMT is labeled in the key of Fig. 1.

The HXMT resides in the barrel supported by the satellite platform. The HXMT top half is exposed to space, as shown in Fig. 2a. The satellite provides electrical power, data recording, and attitude and thermal-control services to the HXMT. The planned service life is three years at an altitude of 500 km with a 43 deg inclination orbit. The mission is to provide full-sky scans, as well as long-time observation of hot spot areas. The HXMT satellite will rotate itself with angular steps at −30, −15, 0, 15, and 30 deg, covering most of the sky, as shown in Fig. 2b. The HXMT is able to remain at an arbitrary angle to keep itself inertially fixed on a hot spot area.

Because the exposed surfaces of the HXMT are covered with multilayer insulation (MLI), the barrel becomes the only part of the satellite platform that has significant thermal influences on the HXMT. Therefore, it appears in the HXMT model as a temperature boundary representing the satellite at different temperatures.

The internal heat sources for the HXMT include: 1) electronic heat dissipated by the PMTs, 1.5 W × 18; 2) heat dissipated in the plastic scintillators, 0.9 W × 12; 3) electronic heat dissipated in the collimators, 0.3 W × 18. These are shown in Figs. 3a–3c respectively.

The principle forms of environmental heating while the HXMT is in orbit are direct sunlight, sunlight reflected off of the Earth (albedo), and infrared energy emitted from the Earth. While the HXMT orbits the Earth, the beta angle β, which is defined as the minimum angle between the orbit plane and the solar vector, will vary continuously with time. This is due to the orbit nodal regression and the change in the sun's right ascension and declination over the year [2]. For this reason, environmental heat fluxes received by different parts of the HXMT will also change. Attitude of the HXMT in different scientific observation missions and Earth eclipses occurring while the HXMT orbits into the shadow of the Earth will also change the incident heat fluxes upon it. Therefore, numerical evaluations are needed to assess the effects of environmental heat flux variations on the HXMT component temperature and thermal gradient.

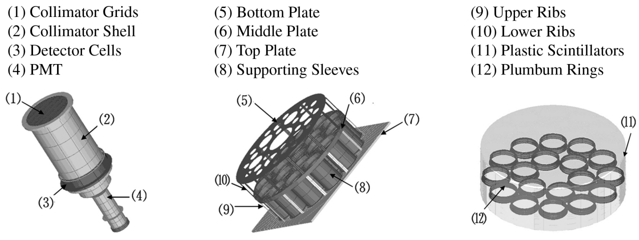
The thermal-control system should maintain the temperature of all HXMT telescope components within the allowable working limits for all mission design conditions. To enhance system reliability, the system uses passive design whenever possible. Overall, thermal control of the HXMT telescope is achieved by balancing the energy emitted by the telescope to cold space −270°C as infrared radiation against the energy dissipated by internal heat sources and the energy absorbed from the environment and the heat sink of the satellite barrel. In this paper, thermal control of the HXMT is established using common thermal-control hardware: thermal surface finishes, MLI, heaters, and thermal isolators. Typical thermal designs for the HXMT components are described in following section.

Thermal Design

The temperature of the 18 detector cells embedded in the middle plate should be controlled within 20 ± 2°C to achieve maximum sensing performance. Heater patches were used to raise and maintain the optimum temperature. However, the heater patches cannot be mounted directly onto the detector surfaces because the detector cells are entirely enclosed in the housing formed by their surrounding plumbum rings, the collimators, and the PMTs. This was done for the purpose of reducing signal noises coming from incident electrons and side incident x rays. There is only a 1 mm thickness gap left between the cell free surfaces and their surrounding parts. Because the shells of the detector cells and the PMTs are all made of

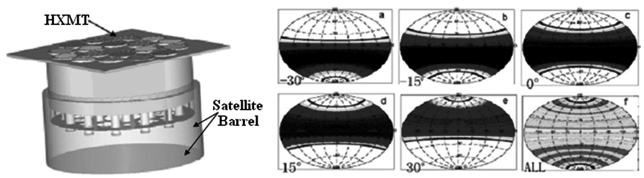
Received 6 September 2007; revision received 12 December 2007; accepted for publication 12 December 2007.

*Senior Engineer, Thermal Control Group, Academy of Opto-Electronics.
†Assistant Professor, Department of Systems Engineering; glhuang@ualr.edu.
‡Assistant Professor, Department of Mechanical Engineering.



a) b) c)

Fig. 1 Parts and structure of the HXMT.

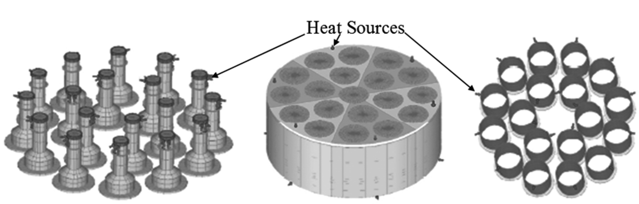


a) b)

Fig. 2 HXMT satellite (barrel) and its mission coverage.

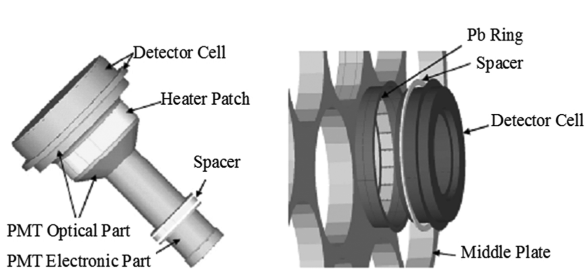
aluminum, heaters are mounted on the surfaces of the optical parts of the PMTs, as shown in Fig. 4a. The PMTs are well jointed with the detector cells to improve contact heat transfer between them. To prevent heat from flowing into the surrounding massive HXMT body and the heat-dissipating electronic part of the PMT (1.5 W per piece), fiberglass spacers and titanium bolts are used, as shown in Figs. 4a and 4b. Low-emittance aluminum tapes are attached on the external free surfaces of the detector cells and the inner cylindrical surfaces of the plumbum rings to minimize radiation heat transfer between the detector cells and their surrounding parts.

To control the thermally induced structural distortions of the HXMT, especially the distortion of the dense collimator grids resulting from environmental heat flux changes, the external surfaces of the HXMT that face toward space are covered with MLI. This includes the top surface where the hard x rays penetrate. This is done at the cost of some energy which will be lost in the MLI barrier. The top surface MLI thickness will be numerically evaluated to reach a compromise between the amount of hard x-ray energy lost and the thermal insulation efficiency of the MLI. Surfaces inside the HXMT are coated with a high-emittance white paint to improve radiation heat transfer between them.



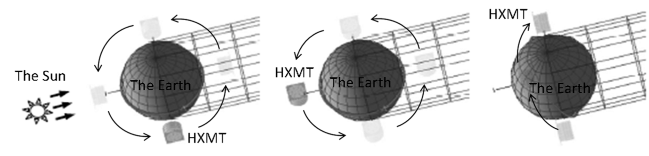
a) b) c)

Fig. 3 HXMT internal heat sources.



a) b)

Fig. 4 Detector cell thermal design.



a) b) c)

Fig. 5 Typical environmental heat fluxes of the HXMT.

The PMT electronic parts generate 1.5 W per detector unit. This energy is conducted through the PMT's aluminum shell, the aluminum bottom plate, the lateral ribs, and the middle plate. The body of the HXMT provides a massive heat sink for this energy. Fiberglass spacers are used to thermally isolate the PMT optical part from its electronic part. This can improve a detector cell's heating efficiency, as well as reduce temperature increase of the electronic elements in PMTs.

Analysis and Discussion

Numerical evaluations of the effect of the thickness of the top surface MLI on the amount of hard x-ray energy lost and the MLI thermal insulation performance were conducted [3]. As a result of those evaluations, a compromise of a five-layer MLI, instead of the 20-layer MLI mounted on a cylindrical external surface of the HXMT, is used as the radiation shield for the top surface of the HXMT.

The top surface that is covered with the five-layer MLI is the part of the HXMT that is the most sensitive to environmental heat flux changes. It is a key factor to be considered in the selection of the three typical analysis cases.

1) In orbit case 1, beta equals 0 deg and the HXMT's three axes are stabilized in the nadir pointing mode with the top surface pointing away from the Earth. In this case, the albedo and the infrared radiation from the Earth are shielded by the satellite platform. Therefore, the value of heat flux of direct sunlight on the top surface of the HXMT changes rapidly in an orbit cycle, as shown in Fig. 5a.

2) In orbit case 2, beta equals 0 deg and the HXMT's three axes are stabilized in the nadir pointing mode with the top surface parallel to its orbit plane. This is the coldest case, because the top surface receives no environmental heat flux, as shown in Fig. 5b.

3) In orbit case 3, beta is set at 66.4 deg and the HXMT's three axes are stabilized with the top surface pointing constantly toward the sun. This is the hottest case because the HXMT has the shortest eclipse time and the top surface receives the maximum amount of direct sunlight heating, as shown in Fig. 5c.

The 3-D thermal model is built in numerical software Thermal Desktop [4]. The radiation interchange factors among parts of the HXMT, view factors to space, solar, and planet fluxes, can be automatically calculated by Thermal Desktop. Contact conductance value is assumed to be 50 W/m^2 °C, which is the average measured heat transfer coefficient for typical mechanical interfaces in the HXMT. Material properties thermal finish solar absorptance α and infrared emittance ε data are listed in Table 1.

Because the exposed surfaces of the HXMT are entirely covered by MLI, the change of short-period environmental heat fluxes in each orbital cycle have little effect on the HXMT's temperature. This is

Table 1 Material properties and thermal finish data

	ρ	C_p	K	α	ε
NaI	3700	——	3.47	——	——
CsI	4510	201	1.1	——	——
Aluminum	2700	921	121	——	——
Beryllium	1850	1925	218	——	——
Plumbum	11,340	129	35	——	——
Plastics	2150	1172	0.14	——	0.91
White paint	——	——	——	0.17	0.87
MLI outer cover	——	——	——	0.38	0.79
Aluminum tape	——	——	——	0.04	0.1

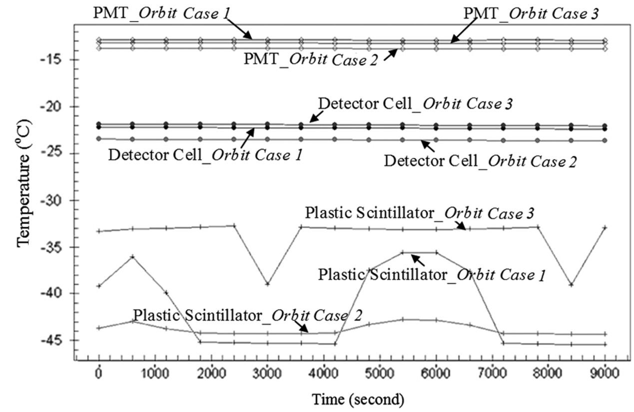
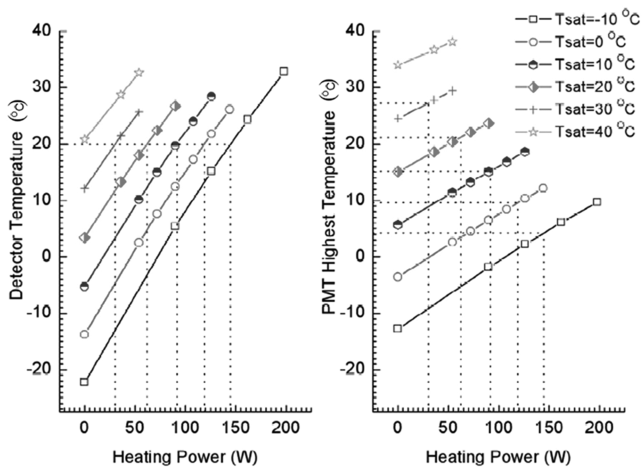


Fig. 6 Temperature profiles of main HXMT parts.



a) b)

Fig. 7 Prediction of heating power and temperatures.

especially true for the innermost parts of the HXMT, like the PMTs and the detector cells whose temperatures remain almost constant. Figure 6 shows the temperature profiles of the detectors, the PMTs, and the plastic scintillator for the three environmental heat flux cases within the orbit cycles. It should also be noted that the attitude adjustment, as well as the beta angle variation, will change the temperature level of the HXMT. However, the difference values are small due to the insulating effects of the MLI.

The amount of heat lost by radiation through the large exposed surface areas of the HXMT is significant even with the cover of MLI. The little heat that is dissipated inside the HXMT further contributes to the low temperature level. Patch heaters are used to increase the detector cells' temperature and to control it within 20 ± 2°C. The amounts of active heating power required are predicted at different satellite barrel temperatures and for the typical environmental heat flux cases. In these analyses, the barrel temperature (Tsat) was fixed at specific values ranging from -10 to $+40$°C with increases of 10°C. A maximum power of 150 W is predicted for the coldest case with the barrel temperature remaining at -10°C, as shown in Fig. 7a. The temperatures of the heat-dissipating electronic parts of the PMTs remain below $+30$°C for all analysis cases, as shown in Fig. 7b.

Large temperature differences exist in HXMT structure, but they result from contact resistance between mechanical interfaces. Temperature differences within each part of the HXMT are relatively small because it is made of high thermal conductivity aluminum. Therefore, structural distortion due to temperature flux is not a key problem in HXMT design.

Conclusions

The HXMT is a large on-orbit scientific sensor being developed in China. It is characterized by its large size, its low heat dissipation, the significant environmental heat flux changes in different missions, and the thin MLI mounted on its top surface to reduce hard x-ray energy loss. By using common temperature control hardware, including thermal surface finishes, MLI, heaters, and thermal isolators, thermal control of the HXMT has been accomplished. A numerical model of the HXMT was also built to evaluate the effects of MLI thickness and environmental heat flux changes on the HXMT temperature, and to predict the amount of power required for heating detector cells.

References

[1] Li, T. P., Zhang, S., and Lu, F. J., "Hard X-Ray Modulation Telescope (HXMT) Mission," *Chinese Journal of Space Science* (*Kong Jian Ke Xue Xue Bao*), Vol. 26, No. z1, 2006, pp. 30–41.

[2] Gilmore, D., *Satellite Thermal Control Handbook*, Aerospace Corp. Press, El Segundo, CA, 1994.

[3] Wu, B. B., and Zhang, H. X., "Thickness Effects of Top Surface MLI on Hard X-Ray Energy Lost and Thermal Performance," Chinese Inst. of High Energy Physics, HXMT-0312, June 2003.

[4] Panczak, T., Ring, S., Welch, M., and Johnson, D., "Thermal Desktop User's Manual", Ver. 4.8, C&R Technologies, Denver, CO, 2005.