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Thermal analysis and expected performance of the low energy instrument on board the HXMT satellite*

WANG Yu-Sa(王于仨)[1;1] CHEN Yong(陈勇)[1] XU Yu-Peng(徐玉朋)[1] WANG Juan(王娟)[1]
CUI Wei-Wei(崔苇苇)[1] LI Wei(李炜)[1] HAN Da-Wei(韩大炜)[1] ZHANG Zi-Liang(张子良)[1]
CHEN Tian-Xiang(陈田祥)[1] LI Cheng-Kui(李承奎)[1] YANG Yan-Ji(杨彦佶)[1,2]
LIU Xiao-Yan(刘晓艳)[1,2] HUO Jia(霍嘉)[1,3] ZHANG Jun-Min(张俊敏)[1,4] ZHENG Yi-Qian(郑伊茜)[1,4]

[1] Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences (CAS), 19B Yuquan Road, Beijing 100049, China
[2] College of Physics, Jilin University, No.2519, Jiefang Road, Changchun 130023, China
[3] College of Electrical and Control Engineering, XI'AN University of Science and Technology, No.58, Yanta Road, Xi'an 710054, China
[4] School of Instrument Science and Opto-electronics Engineer, Beihang University, Beijing 100191, China

Abstract The Low Energy X-ray Instrument (LE) of the Hard X-ray Modulation Telescope (HXMT) uses the Swept Charge Device (SCD) to detect the X-rays in 1–15 keV. The performance of SCD is vulnerable to temperature. We analyzed the thermal condition of LE at different satellite working attitudes with the Finite Element Method (FEM). It is shown that the angle between the sunlight and the normal line of the barrier should be less than 26°, to keep the SCD detectors working in the required temperature range, i.e. −40 ℃ to −80 ℃. We find that the performance of LE is very stable in this temperature range, with a typical energy resolution of 160 eV at 5.9 keV.

Key words LE, HXMT, satellite attitude, thermal calculation

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1 Introduction

The Hard X-ray Modulation Telescope (HXMT) is the first dedicated astronomy satellite of China [1–3] consisting of three X-ray instruments, the High Energy X-ray Instrument (HE), the Medium Energy X-ray Instrument (ME), and the Low Energy X-ray Instrument (LE) (Fig. 1). LE is sensitive in 1–15 keV containing three Swept Charge Device (SCD) detector arrays. Being sensitive to the low energy X-ray, LE is responsible for low energy X-ray all sky survey, cosmic X-ray background and pointed observations. These objectives need high time resolution, low noise and good energy resolution. Considering the above facts, SCD is selected here because its readout speed is much higher than that of normal CCDs, it also has high energy resolution and low noise.

Unfortunately, the performance of SCD is vulnerable to temperature. The dark current of SCD increases with temperature. Until the temperature is below about −45 ℃, the dark current can not be neglected. The signal amplitude of SCD decreases with temperature. Our experiment shows that the noise of SCD decreases greatly at temperatures below −45 ℃ compared with that at room temperature (Fig. 2). In addition, cooling SCD can improve its performance after SCD is irradiated by the solar protons and other particles [4]. Therefore, to keep SCDs operating at a low and stable temperature is critical for LE. The operational temperature range of SCD is determined, from −50 ℃ to −80 ℃. Thermal simulation and design of the thermal structure are presented here to satisfy the temperature requirement of SCD. Here simulation is carried out in the FEM software I-DEAS TMG (Integrated Design Engineering Analysis Software, Thermal Modeling Generator). TMG

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* Supported by HXMT Project
1) E-mail: wangyusa@mail.ihep.ac.cn

is a full thermal module in I-DEAS containing conduction, radiation, convection, fluid flow and phase change, which provides rapid and accurate thermal modeling and simulation. TMG's radiation calculation is based on the Oppenheim's method [5] of constructing radiative exchange matrix and sparse matrix solver. The greatest advantage of TMG is the perfect radiation calculation with visual complicated satellite attitude [6], which can meet the complex radiation conditions of LE exactly.

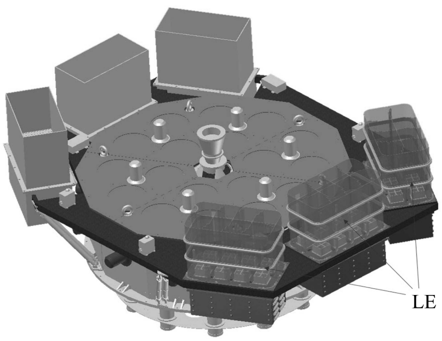

Fig. 1. LE's position on the HXMT satellite.

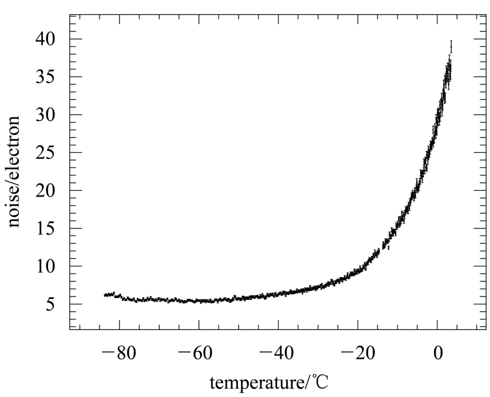

Fig. 2. The SCD's readout noise calibrated by an ^{55}Fe radioactive source as a function of the temperature.

2 Thermal scenario

The orbit of HXMT is circular with an altitude of 550 km and an inclination angle of 43°. The thermal radiation environment of HXMT is complex when all sky survey and pointed observation are carried out under this kind of orbit. This thermal environment is a little bit different from that of Chandra [7] or XMM-Newton [8]. The detectors of Chandra and XMM-Newton are concentrated in the deep of telescopes and their detector areas are small. The orbits of them are so high that the Earth albedo and infrared heat fluxes are negligible. Moreover, their grazing incidence structures are helpful to thermal control. So passive thermal scenario is mainly adopted for Chandra and XMM-Newton. Both of their passive means of thermal control are achieved by using MLI (Multi-Layer Insulation) and radiators. Nevertheless, the detector area of HXMT is much larger and the structure is open without extra thermal insulation. The solar thermal radiation, the Earth infrared heat fluxes and the Earth albedo all take effect. These kinds of thermal radiation depends on the distance and direction to HXMT, which can cause fluctuation of the thermal flux to HXMT. Considering the serious external heat flow and high request of the temperature, a classic thermal scenario: first passive thermal radiation; active heating secondly, is applied. The passive thermal radiation is adopted to emit the inside heat. The active heating is responsible for reducing thermal fluctuation caused by periodic variation of radiation, heating SCD without too low temperature. Also the active heating could improve the performance through annealing SCD after SCD is irradiated by protons and neutrons. Under this scenario a low and stable temperature could be achieved for LE.

3 Thermal structure and material

As shown in Figs. 3 and 4, there are eighteen cylindrical detectors of the HE located in the central region of HXMT, surrounded by three ME instruments and other three identical SCD detector arrays of LE. The pointing directions of the three instruments are the same, which is required for the pointed observation. The barrier is used to shelter LE, ME and HE from the sunlight, helping to make a fine thermal environment, overall. It is 1.5 m high and 2.0 m wide. The angle between the barrier normal and the vector from the top of the barrier to the top of the LE1 is 21.6°. There is an angular constraint in pointed observation, 15° [9], which is the angle between the sunlight and the barrier normal. Because the angular constraint in pointed observation is less than 21.6°, the barrier size can keep the sunlight from LE, ME and HE, completely. The material of the barrier is one kind of MLI which varies from the front to the back of the barrier. The material of the front is aluminum-backed Teflon which can reflect the sunlight and minimize the solar absorption. The material of the back is aluminum foil which can give off as little as possible thermal radiation. This paper is mainly about the thermal control of LE, so the HE and ME are simplified into effective thermal units without detailed structures. An FEM model of one SCD array is presented in Fig. 5. The loop heat pipes are laid outside the cover for strengthening heat exchange, and also for avoiding thermal deformation of the cover. The cover is the main radiator used to emit the most heat from SCD and its driving circuit. The material of the cover's surface is second-surface mirrors which have both high emittance and reflectance. The inner heat is transferred to the cover through the inner heat pipes shown in Fig. 6. There are eight SCDs above the three curved heat pipes and four straight heat pipes. These heat pipes could transfer the heat of SCD quickly to the cover with negligible temperature gradient. The active heaters below SCD are responsible for heating SCD to keep temperature stable.

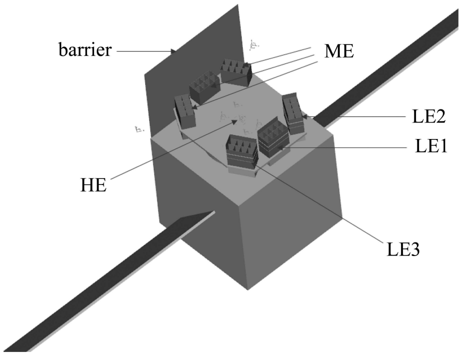

Fig. 3. The solid model of HXMT. Three ME detector arrays are behind the barrier, and three LE detector arrays are at the other side. The HE is simplified to a heat unit in the central region. The barrier is used to keep the three instruments from the sunlight, and its size is 1.5 m high and 2.0 m wide.

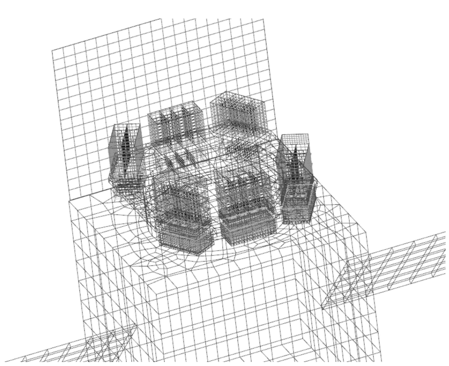

Fig. 4. The FEM model of HXMT.

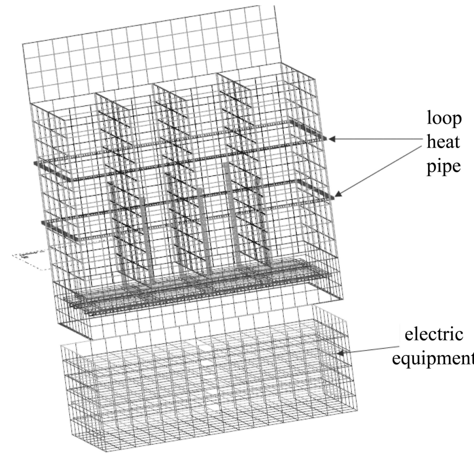

Fig. 5. The FEM model of one detector array of LE. The loop heat pipes are outside of LE detector array, balancing the temperature in the cover.

Many kinds of materials are applied in the model, such as aluminum, copper and aluminum nitride (AlN). The parameters [10] of these materials are listed in Table. 1. The mechanical structure adopts aluminum mainly. The copper is used where fast heat flow is required. The materials named Board and Battery are for the surface of the satellite platform and the solar battery, respectively. Likely the Barrier stands for the material used in the barrier. The AlN is the package material of SCD.

Table 1. The materials used in the simulation. The Emissivity and Absorption are the parameters for the non-solar thermal radiation calculation. The Solar Specular Reflectivity and Solar Absorption are for the solar thermal radiation, especially.

parameters	aluminum	copper	board	battery	AlN	barrier
mass density/(kg/m^3)	2.7×10^3	8.9×10^3	2.7×10^3	4×10^3	3.26×10^3	1.9×10^3
thermal conductivity/(J/(m·K·s))	121	185	121	10	120	10
specific heat/(J/(kg·K))	805	285	905	200	737	285
emissivity	0.6	0.6	0.3	0.1	Null	0.8
absorption	0.2	0.2	0.5	0.8	Null	0.1
solar specular reflectivity	0.8	0.8	0.5	0.2	Null	Null
solar absorption	0.2	0.2	0.5	0.8	Null	0.8

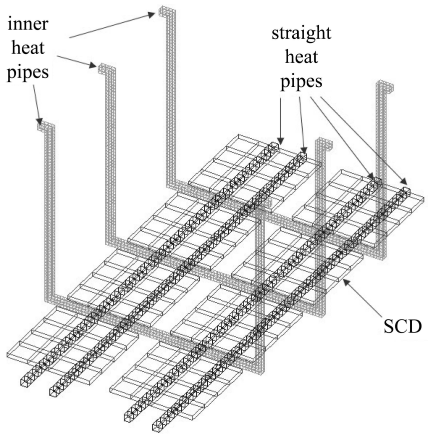

Fig. 6. The inner model of one detector array of LE. There are three inner heat pipes and four straight heat pipes below the eight SCD modules. Through the heat pipes the heat of SCD could be transferred to the cover quickly.

4 Satellite attitudes and simulation results

HXMT is a three-axis-stabilized satellite. This type of satellite is characterized by a box-shaped body and deployable solar panel arrays [11]. The pointed observation is carried out when HXMT's pointing direction is fixed on one star and the barrier is adjusted to keep out as much sunlight as possible. When the normal of the barrier is pointed to the Sun and HXMT is kept rotating 360° every orbit period on the axis of the barrier normal, the sky survey is carried out. In this way, all sky survey could be completed in half a year. Two reasonable attitudes are selected for different interesting sky regions, scanning the Galactic Plane with barrier normal towards the Galactic Pole, and scanning all the sky. The pointed observation is not presented here because the barrier could keep out sunlight according to the angular constraint in pointed observation. In this case, the results should be similar to those of all sky survey. In addition, the power of all SCD detector arrays is 72 W under these attitudes, and the simulation time of one attitude is five or ten orbit periods (5733 seconds per orbit period).

4.1 Scanning the Galactic Plane

The X-ray source distribution on the Galactic Plane is important in high energy astrophysics. However, according to the coordinates of the Galactic Pole, the scanning observation to the Galactic Plane can only be carried out at the time around Spring Equinox and Autumnal Equinox. And LE will be subjected to the sunlight in some way, which can cause increase of the temperature of SCD and the electronic equipment. In fact, scanning the Galactic Plane at Autumnal Equinox is the same with that at Spring Equinox. So only the result of scanning the Galactic Plane at Spring Equinox is presented. The steady calculation under the attitude is simulated firstly and the result is saved as the initial condition for the next transient calculation. The simulation time of the transient calculation is five orbit periods at Spring Equinox. The simulation result is output every 60 seconds and the temperature-time curve is for SCD in the LE1 in Fig. 3. As shown in Fig. 7 the temperature of SCD is in the range of −45 ℃ and −60 ℃ with obvious periodical fluctuation under the attitude of scanning the Galactic Plane at Spring Equinox.

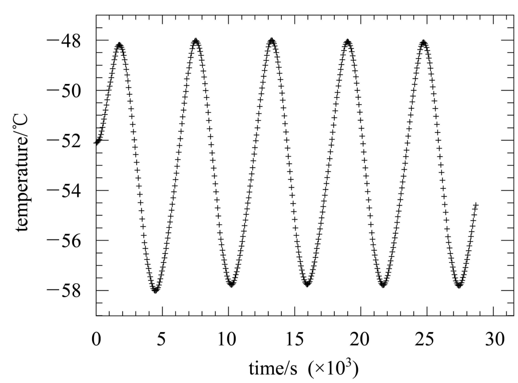

Fig. 7. The SCD's temperature under the attitude of scanning the Galactic Plane with the barrier normal towards the North Galactic Pole at the Spring Equinox as a function of time. The periodical fluctuation is evident.

4.2 All sky survey

The main objective of HXMT is the all sky survey, so it is critical to ensure the three instruments working normally under the mission of all sky survey. Under the attitude of scanning all the sky, HXMT will rotate on the axis which is the barrier normal, so LE can be out of irradiation of the Sun, completely. The result of the steady calculation under this attitude is saved as the initial condition for the next transient calculation too. The simulation time of the transient calculation is ten orbit periods, and the result is output every minute too. As expected, the SCD's temperature under this attitude is below −60 ℃ in Fig. 8, which is in the operational temperature range. The temperature fluctuation is obvious even if there is no sunlight, and there is about 2 ℃ difference among the SCDs. It indicates that the effect of the Earth infrared and albedo play an important part in the temperature fluctuation. This attitude is suitable to the all sky survey on the whole. However it is difficult to keep LE from the sunlight all the same. Sometimes the normal of the barrier is not parallel with the sunlight, but with a small angle.

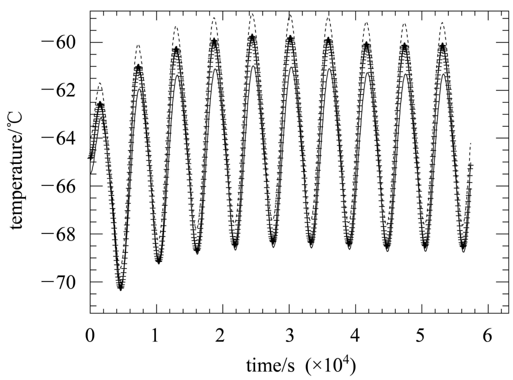

Fig. 8. The SCD's temperature under the attitude of all the sky survey as a function of time. The angle between the barrier normal and the sunlight is zero. The solid line with "+" is the temperature-time curve of SCD in LE1, the dotted line without mark and the solid line without mark represent those of LE2 and LE3, respectively.

Firstly the sunlight over the side of the barrier is presented. When only one detector array is exposed to the Sun, the angle is about 30°, the sunlight affects the special array greatly. As the dotted line shows in Fig. 9, the SCD's temperature is out the operational temperature range. Until the angle is less than 26°, the temperature of SCD is not in the operational range, as the dotted line shows in Fig. 9. So the turning angle is 26° over the side of the barrier. If it is over 26°, the performance of SCD will deteriorate because of the increase of the temperature. The sunlight over the top of the barrier is calculated, secondly. When HXMT is under the sunlight over the top of the barrier, the temperature increases with the increasing angle between the sunlight and the barrier normal too. The turning angle over the top of the barrier is about 26.5°. As shown in Fig. 10, the SCD's temperature is in the operational temperature range. It is coincident that the turning angle from the side and the top of the barrier is similar. It could be explained by the structure HXMT, which makes the sunlight from the side or the top of the barrier nearly the same.

As shown in the above results the temperature fluctuation is dominated by the Earth infrared and albedo, while the sunlight and the power of electronic equipment dominate the average temperature. The heater included in the thermal scenario is absent in the model because the thermal calculation is the main focus in this paper and the final temperature could be evaluated from the simulation result and the power of the heater. Anyway, the final temperature will be a little bit higher than the average value −59 ℃ shown in Fig. 10, but the fluctuation could be decreased. Therefore, SCD could obtain a stable and low temperature with heating.

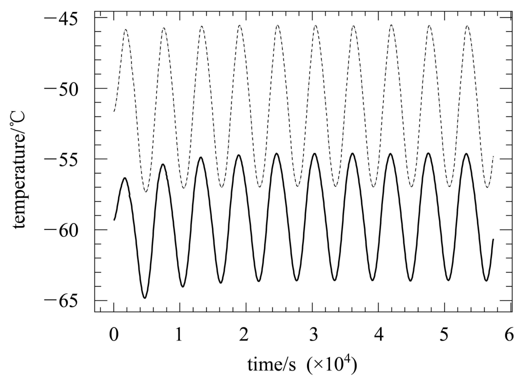

Fig. 9. The SCD's temperature under the attitude of all the sky survey with 26° (solid line) and 30° (dotted line) between the barrier normal and the sunlight over the side of the barrier as a function of time.

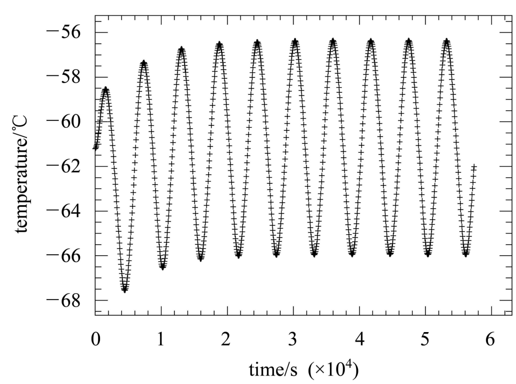

Fig. 10. The SCD's temperature under the attitude of all the sky survey with 26.5° between the barrier normal and the sunlight over the top of the barrier as a function of time.

5 Performance of detector in the expected operational temperature range

The above simulation shows that the operational temperature of SCD is in the range of −45 ℃ to −75 ℃, which is marginally consistent with the nominal operational temperature (−50 ℃ to −80 ℃). In order to estimate the performance of SCD in this temperature range, we investigated the readout noise, peak position and energy resolution from −40 ℃ to −80 ℃ (Figs. 11, 12 and 13). The SCD's readout noise is about 6e$^-$, approaching its intrinsic readout noise (5e$^-$). The peak position at 5.9 keV increases about 0.08% when the temperature decreases one degree (Fig. 11). The observed energy resolution at 5.9 keV is much lower than the required value (450 eV), and its range is from 155 to 176 eV (Fig. 12). Here the energy resolution at 5.9 keV is a little worse than the value calculated from the readout noise. This is because the temperature variation and charge transfer efficiency also contribute to the fluctuation of the peak position at 5.9 keV, despite the readout noise. This problem will be investigated in more detail in future publication.

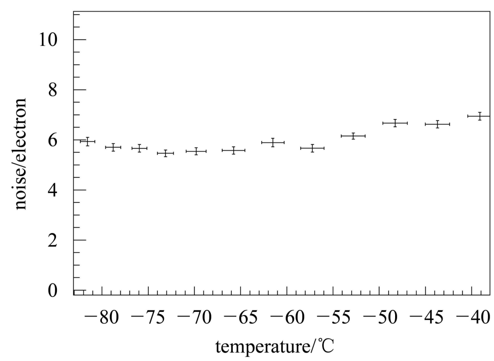

Fig. 11. The SCD's readout noise tested with an ^{55}Fe radioactive source as a function of the temperature.

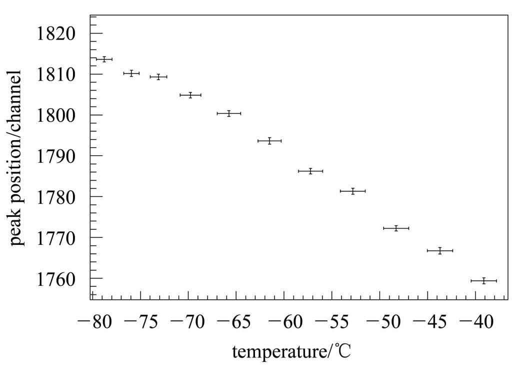

Fig. 12. The SCD's peak position at 5.9 keV tested with an ^{55}Fe radioactive source as a function of the temperature.

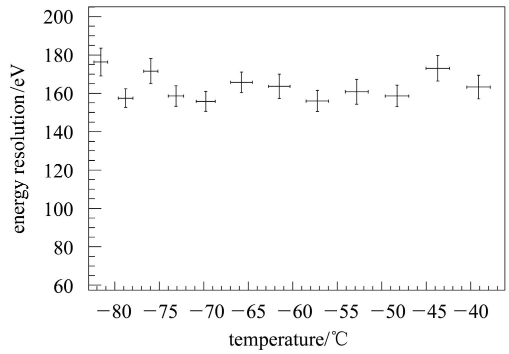

Fig. 13. The SCD's temperature and the energy resolution at 5.9 keV tested with an ^{55}Fe radioactive source as a function of the temperature.

6 Conclusion

We presented thermal simulation of LE considering thermal conduction, thermal radiation, thermal radiation of the Sun and the Earth. The reasonable attitude for all sky survey is scanning the all sky with the barrier normal towards the Sun, and the angle between the barrier normal and the sunlight must be less than about 26°, when the barrier is 1.5 m high and 2.0 m wide. The SCD's temperature of scanning the Galactic Plane is also within the operational temperature range. Similarly, the pointed observation is reasonable, because the barrier could keep out the sunlight. The spectral resolution of LE remains unchanged in the expected temperature range, while the peak position changes significantly with temperature. A detailed calibration of LE's in-orbit response as a function of temperature is needed in order to get reliable observational results. Overall, the thermal scenario is reasonable and suitable to the thermal requirements of LE.

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