PRELIMINARY THERMAL DESIGN ANALYSIS OF LARGE-SIZED INFRARED TELESCOPE FOR SPICA

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Abstract

The conceptual SPICA mission is ambitiously intended to make high-resolution infrared astronomical observations. The spacecraft is to be launched by the H-IIA rocket into a halo orbit around S-E L2. Long-term observation with a large mirror is realized by advanced cryogenic technologies. The primary mirror is to be cooled to 4.5 K by modern mechanical cryocoolers with the assistance of effective radiative cooling. In this paper, numerical 3-D analyses are carried out to study basic thermal characteristics of the infrared telescope system. As a result, technical requirements for the mission have become clear.

Key words: Orbits: S-E L2 – Size: 3.5 m diameter – Missions: SPICA – Cryogenics: mechanical cryocooler

1. Introduction

The SPICA (Space Infrared Telescope for Cosmology and Astrophysics) concept is a mid- and far-infrared telescope to be launched by the H-IIA rocket in 2010. An epoch-making astronomical surveys will be hopefully carried out in a halo orbit around one of the Sun-Earth Lagrangian libration points (S-E L2) as shown in Figure 1 (Nakagawa et al. 2000). The conceptual telescope system is equipped with a large mirror of 3.5 m and state of the art infrared detectors, which make it possible high-resolution observations for a long period of 5 years or longer. (See Figure 2.) These excellent features are attributed to the effective radiative cooling and the innovative cryocooling system. The primary mirror and focal plane instruments (FPI) must be cooled down to 4.5 K without massive cryogen. Thus, the whole telescope system should possess efficient structure for thermal radiation.

On the other hand, we have been developing a mechanical cooling system for 4 K, consisting of the 2-stage-Stirling (2ST) cooler and the Joule-Thomson (JT) circuit with the ^{4}He gas (Narasaki & Tsunematsu 2000). The same type of mechanical cryocooler will be used to cool down a superconductive detector for the atmospheric observation mission "SMILES" (Superconducting Submillimeter-Wave Limb-Emission Sounder) and be technically validated. Besides, SPICA is equipped with a far-infrared detector of stressed Ge:Ga operated at 1.7 K. Based on technologies developed for the 4 K cryocooler, an advanced mechanical cryocooler for 1.5 K, where the ^{3}He gas is used in the JT circuit, is experimentally researched with a prototype model.

In this paper, we carry out axial and radial temperature predictions, considering the aperture ratio, the radiation area, the shield thickness and materials as design parameters. We are aiming to obtain thermal characteristics of this infrared telescope for the detailed design.

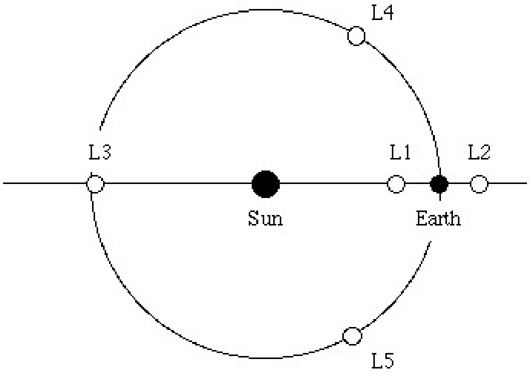


Figure 1. Sun-Earth Lagrangian libration points

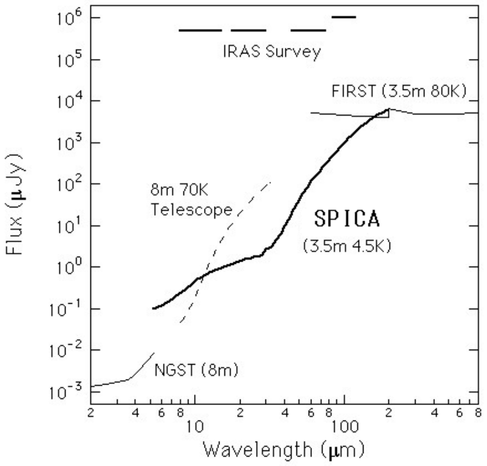


Figure 2. Point-source sensitivity

2. Telescope configuration

At S-E L2 point the spacecraft is exposed to heat fluxes from the sun and the earth in the same direction. That means that the earth albedo is negligible and the thermal design for radiative cooling becomes relatively simple. In order to cool down the primary mirror and the FPI to 4.5 K, we need to combine radiative cooling and mechanical cooling effectively (Murakami & Narasaki 2000). A proposed conceptual configuration of SPICA is depicted in Figure 3. The telescope with the sun shield is located at the upper part of the figure, while the bus module with the solar array paddle is mounted in the lower part.

As shown in Figure 4, the primary mirror and the FPI are surrounded by the baffle and by the telescope shell. The heat flow from the outside can be blocked by the sun shield and by three shields. However, each component is thermally connected through structure supports and wire harnesses. The heat flow between cold stages is mainly determined by the thermal conduction, since the thermal radiation becomes much smaller than between hot stages due to small absolute values of temperatures. MLI (Multi-Layer Insulator) is also effective for blocking the heat transfer from a hot stage.

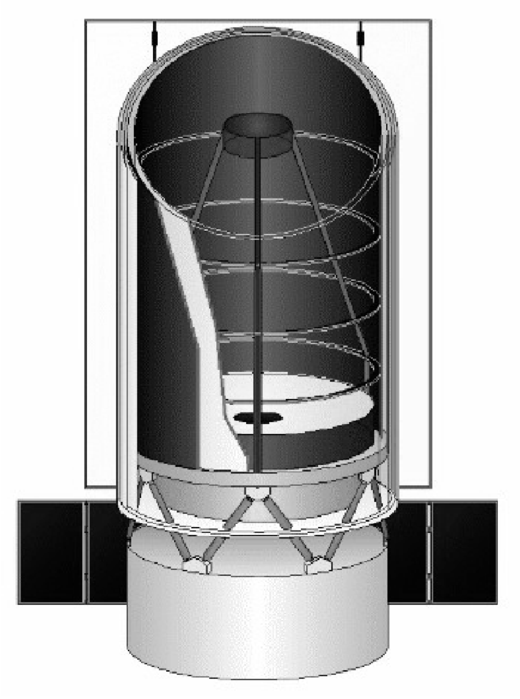


Figure 3. Conceptual Configuration of Telescope

3. Thermal design analysis

The cryogenic system in SPICA has been investigated by Hirabayashi et al. (2000). Some ideas were proposed and discussed for thermal design. However, the configuration of SPICA has not been completely determined. It is important to study various cases with different parameters such as size, shape, layout, material and so on.

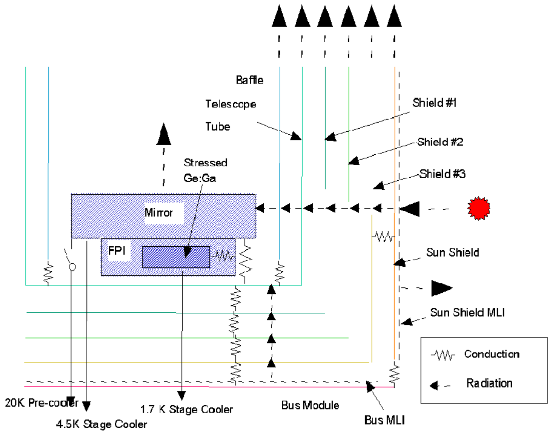


Figure 4. Schematic Drawing of Cryogenic System

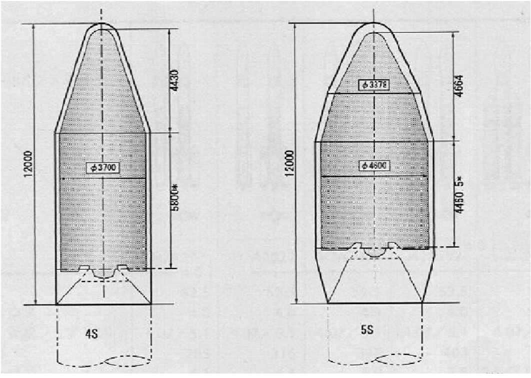


Figure 5. H-IIA rocket fairings

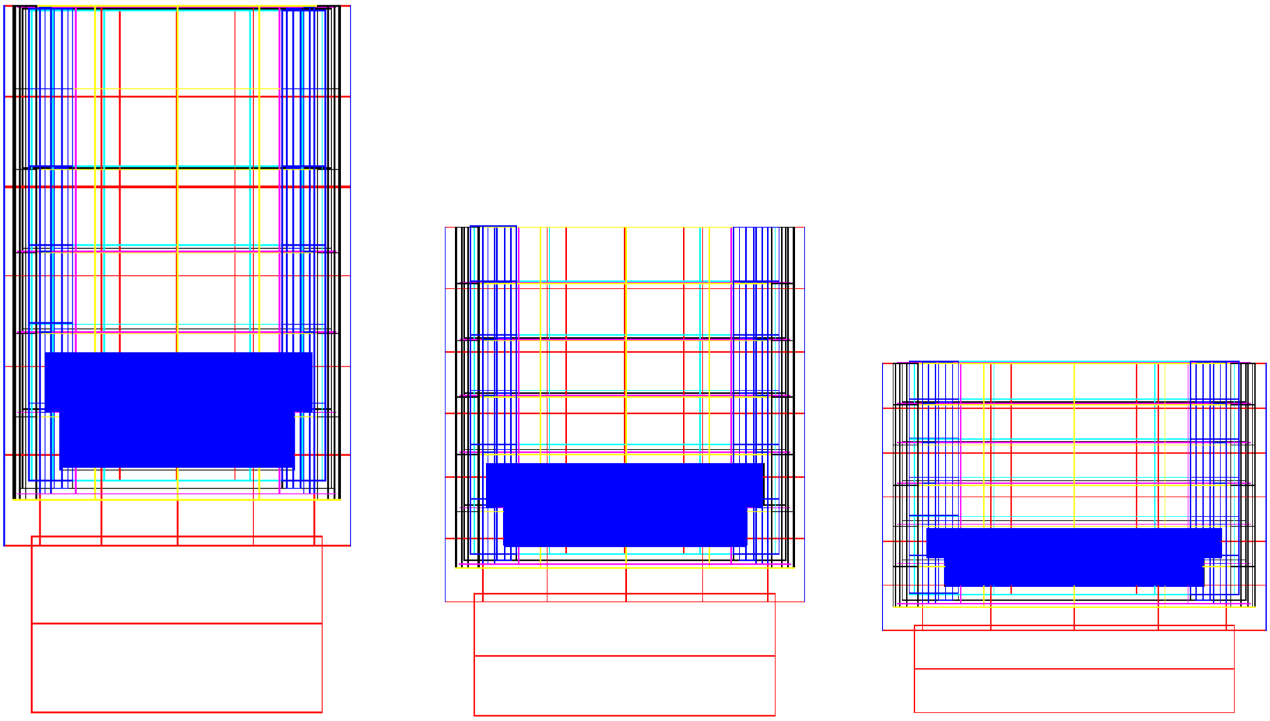
In this paper, we first construct 3-D mathematical models for the telescope system, and execute preliminary thermal design analyses for different sizes of telescope, validating the mission feasibility numerically.

3.1. Analytical model

A basic analytical model for thermal analyses is created, considering requirements as below.

1. The telescope must be fitted to a fairing size of the H-IIA rocket for the launch.
2. The aperture of telescope should be maximized for enhancement of the observation ability.
3. The heat transfer into the 4.5 K stage must be less than 15 mW due to ability of mechanical cryocooler.

Here, the 5S-type fairing is supposedly chosen in Figure 5. Three types of analytical models are depicted in Figure 6. The basic analytical model of Figure 6(b) is designed for the 5S-type fairing, where the maximum width,



(a) Slim type (b) Basic type (c) Flat type

Figure 6. Analytical models

the height and the mirror diameter are 4.4 m, 6.0 m and 3.4 m, respectively. As for the slim type, the basic type is expanded by 1.2 in the vertical direction and is shortened by 0.8 in the horizontal direction. The flat type is configured in the opposite way. Both the slim and the flat types are used for comparison of the telescope size.

3.2. ANALYTICAL CONDITIONS

Boundary conditions are indicated in Table 1, where temperatures of the bus module, the primary mirror and the FPI are fixed in analyses. It is assumed that the heat flux from the sun enters to the sun shield vertically, and structural components such as the shields, the telescope shell and the baffle are made of the aluminum alloy. It is also noted that the thermal conduction through structure supports of CFRP and wire harnesses of Manganin is considered.

3.3. RESULTS

A three-dimensional thermal analysis for the basic-type telescope was performed. A temperature distribution of SPICA is shown in Figure 7. It shows that radiation cooling works well on the sides of shields exposed to the deep space.

Table 1. Boundary conditions

Parameter	Value
Bus module	250 K
Mirror and FPI	4.5 K
Space background	3 K
Solar heat flux density	1.4 kW/m^2
Solar absorptivity α	0.3
Emissivity of radiator ϵ_{rad}	0.9
Emissivity of MLI surface $\epsilon_{\mathrm{surMLI}}$	0.04
Effective emissivity of MLI $\epsilon_{\mathrm{effMLI}}$	0.015

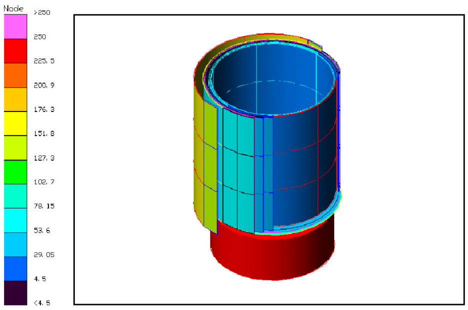


Figure 7. 3-D temperature distribution

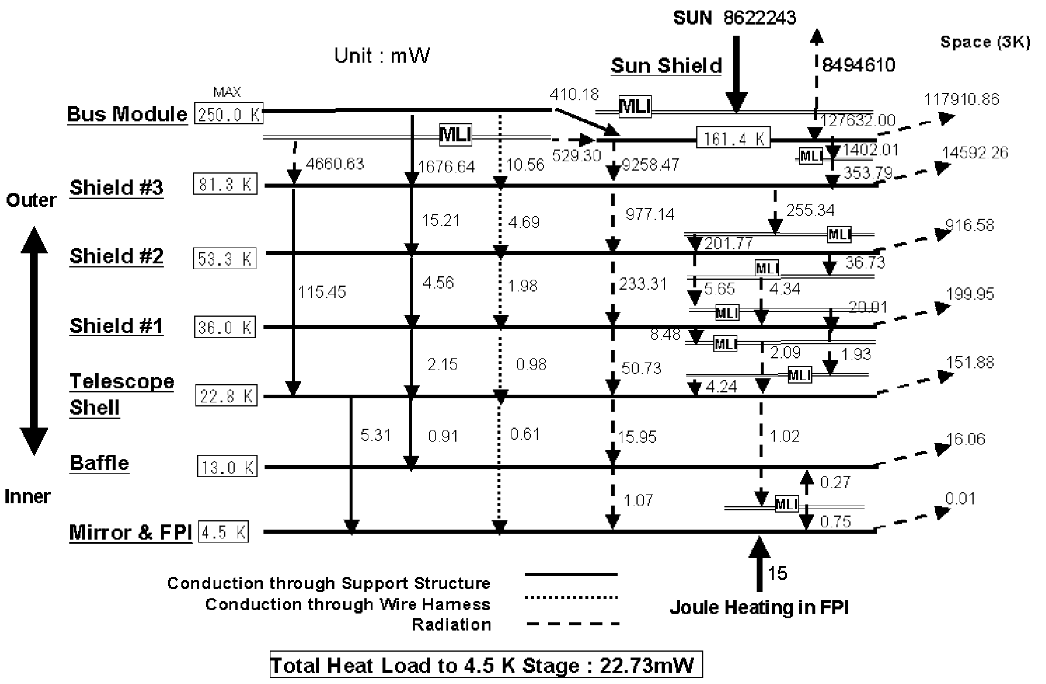


Figure 8. Heat flow in the telescope system

The heat flow of the whole system is calculated as depicted in Figure 8. It reveals that the thermal radiation is dominant at hot stages, while the thermal conduction becomes remarkable at cold stages. It is because thermal radiation is proportional to the fourth power of temperature. Hence, the heat transfer to colder stages should be shielded with MLIs at hotter stages. In fact, MLIs are attached to the bottom parts of the shell and the shields as illustrated in Figure 8.

As a result, the heat load to the 4.5 K stage (i.e. the primary mirror and the FPI) is approximately 23 mW by assuming the Joule heating of 15 mW in the FPI. That means that the heat load must be removed from the 4.5 K stage by mechanical cryocoolers. That requirement seems technically feasible, because the ^{4}He Joule-Thomson circuit combined with the 2-stage-Stirling cooler for 20 mW@4.5 K has been developed for the SMILES mission, which will begin operations at the Japanese Experimental Module "Kibo" of ISS in 2004.

Other 2 types of models were also analyzed. The heat loads to the 4.5 K stage were 22 mW in the slim type and 25 mW in the flat type, respectively. It was made clear that the heat transfer from the bus module is closely related to the heat load to the 4.5 K stage.

4. CONCLUDING REMARKS

Numerical 3-D analyses were carried out to investigate the basic thermal characteristics of the infrared telescope "SPICA".

It was found that the configuration of thermal shields and of MLIs strongly influences the temperature distributions in the whole system. However, the effective radiative cooling reduces the heat flow into the 4.5 K stage significantly. As a result, it was shown that modern mechanical cryocoolers ensure the mission feasibility without massive cryogens. In that sense, improvement in reliability of mechanical cryocoolers is indispensable for the success of mission.

It should be noted that mirrors deform at low temperature. Therefore, in order to obtain the detailed design of SPICA, we need to carry out thermal-structural combined analyses with a complicated mathematical model including cryocoolers.

In addition, time-dependent calculations are necessary for further discussions of the cooling time and of variations in temperatures.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. M. Hirabayashi of Sumitomo Heavy Industries, LTD. for providing low-temperature material data.

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