The Institute of Space and Astronautical Science
Report SP No.14, December 2000

Development of SiC Mirror for ASTRO-F

By

Hidehiro KANEDA*, Takashi ONAKA†, and Ryoji YAMASHIRO‡

(November 1, 2000)

Abstract: The development of the light-weight silicon carbide mirrors for the ASTRO-F mission is described in this paper. These mirrors are made of a sandwich-type SiC material, consisting of light porous core and dense CVD (chemical vapor deposition) coat of SiC. The primary mirror has a diameter of 710 mm and weighs only 11 kg. Combined with the secondary mirror of the same type, they form Ritchey-Chretien type telescope (F/6), which is cooled down to 5.8 K. Fabrication of the small-scale test SiC mirror has been successful which shows very little deformation of the figure at liquid-helium temperatures. Another type of the SiC coated mirror has been tested which has the same size as flight model, but of which core is made of graphite. At present, polishing of the flight-model primary mirror is going on. Construction of the flight model telescope system will be finished in 2001.

1. INTRODUCTION

The first Japanese infrared astronomy satellite, ASTRO-F, is scheduled for launch in 2004 (Murakami 1998). ASTRO-F telescope forms F/6 Ritchey-Chretien system with a primary mirror of 710 mm in diameter. In Figure 1, the structure of the telescope assembly is shown, the total weight of which is about 38 kg. The details of the telescope parameters are described in Onaka et al. (1998). The whole system of the telescope is cooled down to 5.8 K with a combined use of super-fluid liquid helium and newly-developed mechanical coolers.

The telescope system has to meet the severe weight constraint and launching vibration conditions. Hence, much attention has to be paid in making design and selecting materials for the cooled telescope. The telescope truss is made of beryllium, while the primary and secondary mirrors are made of silicon carbide, which is a new promising material for fabricating mechanically and thermally tough, light-weight, cooled mirrors. The mirrors are coated with Au and ZnS to have good reflectivity in the infrared region and to have strong surface to allow cleaning.

This paper describes the design and the characteristics of the telescope and refers to some of the cryogenic performances achieved experimentally.

* The Institute of Space and Astronautical Science, Kanagawa 229–8510, Japan; kaneda@ir.isas.ac.jp
† Department of Astronomy, University of Tokyo, Tokyo 113–0033, Japan; onaka@astron.s.u-tokyo.ac.jp
‡ Designing Department, Nikon Corporation, Mito Plant, Mito, Ibaragi 310–0843, Japan; YAMASHIRO.ryo@nikon.co.jp

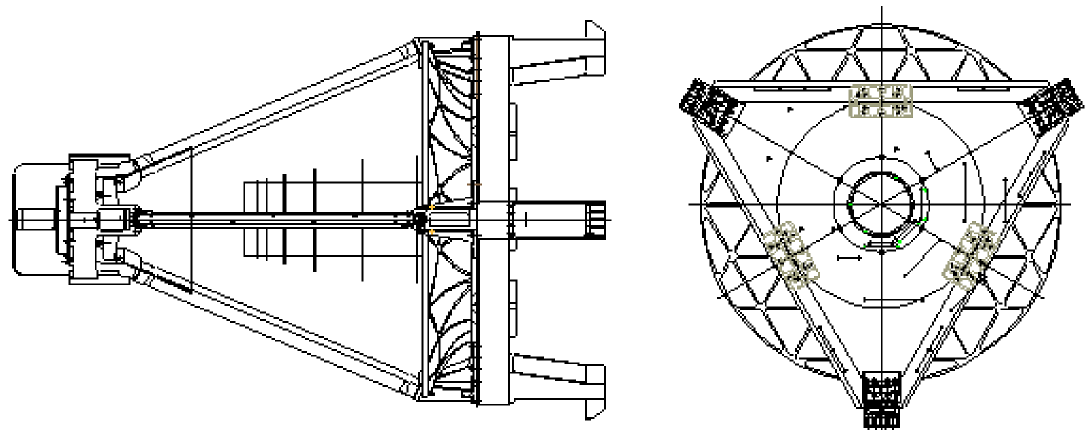

Fig. 1: ASTRO-F telescope design

Table 1: Material properties at room temperature

		Units	Porous SiC	CVD SiC	Be	Quartz
Young's modulus	:	GPa	147	490	287	74.5
Density	:	g/cm^3	1.85	3.21	1.85	2.19
CTE	:	ppm/K	4.4	4.5	11.3	0.5
Conductivity	:	W/m/K	31	67	216	1.4
Specific heat	:	J/kg/K	920	710	1925	750

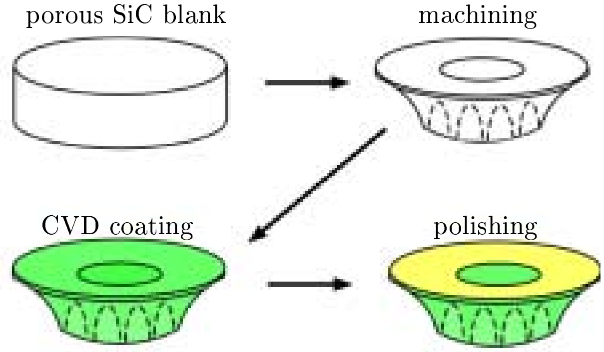

Fig. 2: Fabrication of sandwich-type SiC mirror

2. MATERIAL: SILICON CARBIDE

We have decided to employ silicon carbide (SiC) mirrors for the ASTRO-F telescope. In Table 1, basic material properties of porous SiC and CVD (chemical vapor deposition) SiC are displayed together with those of other representatives for comparison. As seen in the table, SiC has moderately good thermal conductivity compared to quartz, and smaller specific heat and CTE than those of metals such as beryllium. Furthermore, SiC has a large Young's modulus and thus can be polished to high precision. Above all, SiC is a very tough material against mechanical vibration/shock and cosmic ray hitting, which are inevitable for space application.

The weight of the mirror has been reduced very much by machining the mirror blank to the open-back structure and further adopting the sandwich structure of porous SiC (3 mm thick) and CVD coat (0.5 mm thick) on the rear and front surfaces. Porous core SiC plays an important role in realizing light weight and easy machining, while dense and strong CVD SiC enables us to polish to low surface roughness. With this combination, the total expected weight of the 710-mm diameter mirror is only about 11 kg. Figure 2 shows the process to fabricate such light-weight sandwich-type SiC mirror. It takes almost a whole year to complete the fabrication even if all the processes go perfectly.

3. 160 MMΦ SIC TEST MIRROR

3.1 Measurements of Cryogenic Performance

In order to estimate the cryogenic performance of the sandwich-type SiC mirror, test spherical mirrors of 160 mm in diameter of a similar structure as the primary mirror of the ASTRO-F telescope were fabricated. In total, four pieces were fabricated and tested at low temperature in a liquid-helium cryostat (Onaka et al. 1999). The changes in the surface figure were measured from outside the cryostat by an interferometer for the temperature range of 6 K to 280 K, while the mirror was being warmed up.

The surface figures thus obtained for the second and the fourth SiC test mirror at low and room temperature are shown in Figure 3, where the rms surface roughness is also indicated. A conspicuous local minimum was observed in the center for all the mirror figures, which is attributed to the presence of the vacuum-sealing window along the optical path, and thus the data were removed by masking the central region. During these fabrications and measurements, we have made lots of improvements; for the fourth test mirror, deformation due to the change of temperature is very small ($< 0.01\lambda$, hereafter, λ implies 6328 Å of He-Ne laser), and surface roughness at low temperatures itself is quite small (0.055λ rms). In the error budget of the ASTRO-F telescope design, $\lambda/10$ (rms) is allocated to the wavefront error due to the primary mirror, including the deformation at low temperatures. These results clearly demonstrate the promising applicability of this kind of SiC material to cooled telescope mirrors.

3.2 Selection of Glue

The primary mirror is designed to be supported by three bipod flexures made of titanium alloy which are fixed to the optical aluminum base-plate. The flexures are attached to the SiC mirror through the support structure made of super-invar. The deformation of the mirror surface due to thermal contraction of such support structure might become a serious problem.

Using the fourth SiC test mirror which showed the best cryogenic performance, selection of glues was performed by attaching the support structure to the rear surface of the mirror. If thermal contraction of the glue itself is very large, the deformation of the mirror may be more serious; otherwise if elasticity of the glue works even at lower temperatures, the deformation can be avoided to some extent. Hence, three kinds of cryogenic adhesive agents (stycast 2850FT, EC2216, EP007) were tested at three attaching points of the mirror. In Figure 4, the surface figures of the SiC mirror with support structure at low and room temperature are shown after subtraction of the mirror surface figure without support structure measured at a similar temperature. As can be seen in this figure, the effects of attaching the support structure are clearly seen, which are quite different among the three kinds of glues. Particularly in case of

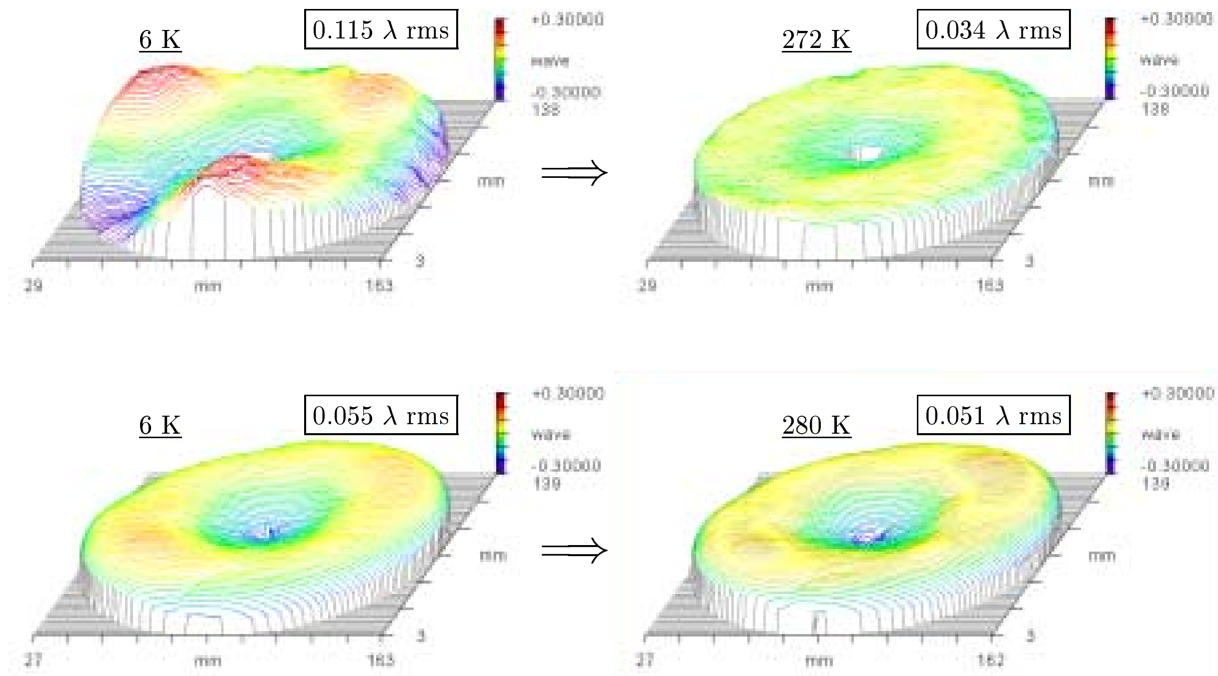

Fig. 3: The change of the surface figure for the second SiC test mirror (upper) and the fourth SiC test mirror (lower) with temperature. All figures are shown in the same scale.

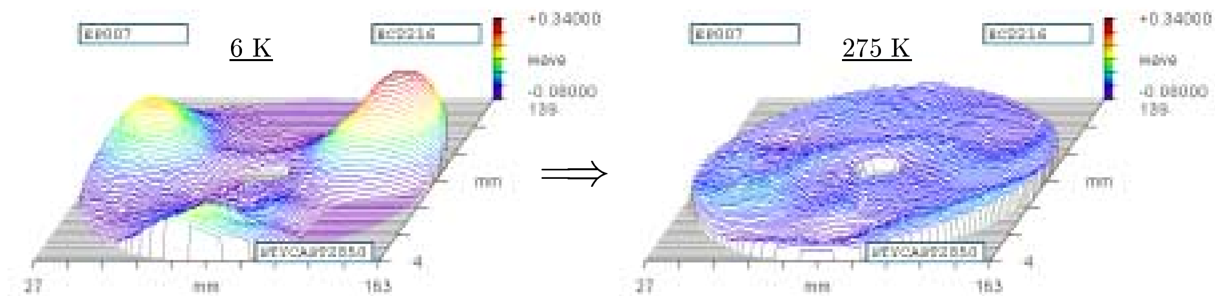

Fig. 4: The change of the surface with temperature: the fourth mirror + glue + super-invar (support structure)

EC2216, peak-to-valley value of the deformation reaches 0.3 λ at 6 K, which entirely consumes the error budget allocated for the surface roughness of the primary mirror. As a result, stycast 2850FT has turned out to be the best choice, yielding relatively small deformation at low temperatures.

4. 710 MMΦ SIC MIRROR

4.1 Measurements Using Cryogenic Test Chamber

As a next step, the surface figure of the 710-mm diameter mirror has to be measured at cryogenic temperatures. Cryogenic test chamber for such large mirrors has been constructed at ISAS in 1999. Figure 6a shows a picture of this facility which is about 4 m tall including the interferometer and various kinds of optical stages placed on the upper side of the cryostat. First, tests of cryogenic performance of the primary mirror will be performed, followed by measurements of the telescope assembly under the configurations shown in Figure 5.

In the left panel of Figure 5, the primary mirror is place on the tilt and X/Y cold stages. The surface figure of the mirror is directly measured by the interferometer through the null lens and vacuum-sealing window. The alignment of the optical axis of the mirror and the measurement system is monitored by the alignment telescope and adjusted by moving both the inner cold stages and the upper optical stages. In the right panel of the figure, the telescope assembly is suspended from the ceiling of the 4-K innermost radiation shield, while the 750-mm diameter reflecting flat mirror made of fused silica is placed on the cold stage. Assuming that the surface figure of the primary mirror is already known, what is measured under the latter configuration is the combination of the surface figures of the secondary mirror and the flat mirror. The extraction of the surface figure of the secondary mirror itself will be attempted by independently shifting the flat mirror up to ± 25 mm with the X/Y cold stage. The tilt of the flat mirror is monitored by the auto-collimator from outside of the cryostat and corrected to the level by moving the inner tilt stage every time the flat mirror is shifted.

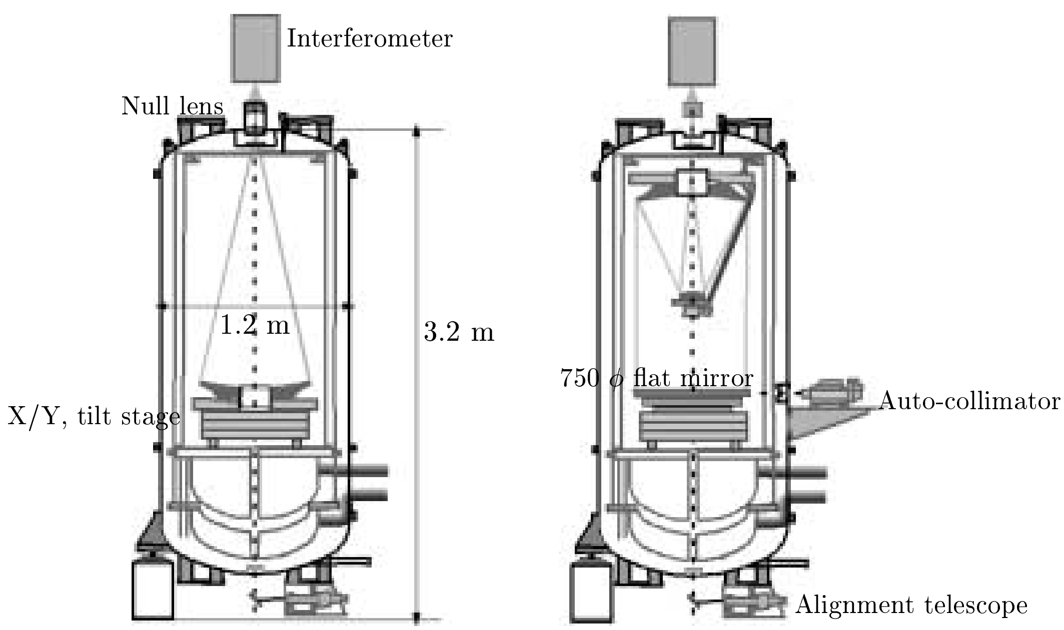

Fig. 5: Schematic view of measurements of mirror figures: primary mirror (left) and telescope assembly (right).

The telescope assembly has a function of the focus adjustment, so that the distance between primary and secondary mirrors is adjustable within the range of $\pm$ 0.4 mm, using the cryogenic stepping motor embedded in the secondary mirror support. During the latter measurement, the focus adjustment at cryogenic temperature will also be conducted before installation of the telescope assembly into the flight-model (FM) cryostat.

(a) (b)

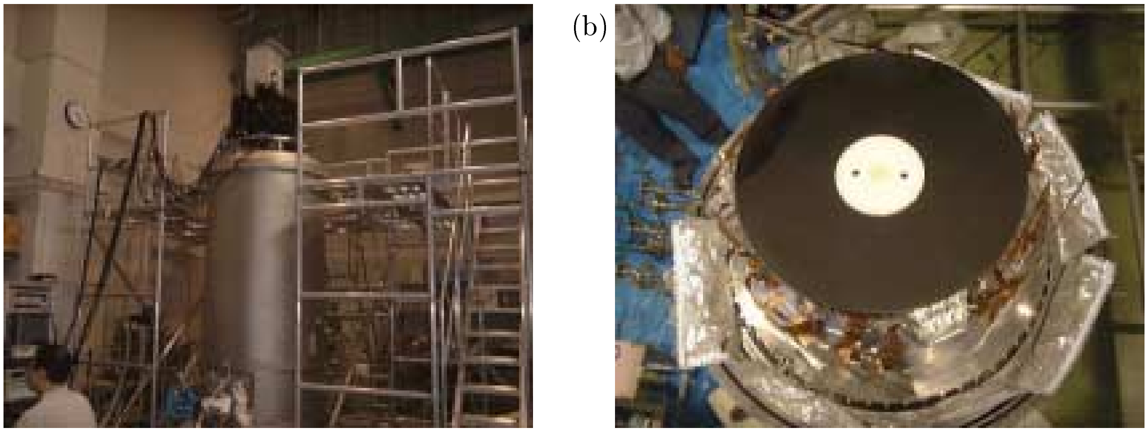

Fig. 6: (a) Cryogenic test chamber for 710-mm diameter mirrors. (b) Graphite-core-CVD-SiC-coat mirror placed at the cold stage inside the cryostat.

4.2 Graphite-core-CVD-SiC-coat Mirror

Prior to the fabrication of the porous SiC core mirror, a 710-mm diameter mirror with graphite core has been made in order to confirm the machining process. The graphite core mirror was coated with CVD SiC and ground/polished to qualify the polishing process.

Using the facility mentioned above, the graphite-core mirror figure has been measured at ambient temperature under the same configuration as shown in the left panel of Figure 5 (see also Figure 6b), and the fringe pattern of the mirror has been successfully observed by the interferometer. The surface roughness is, however, found to be too large to reproduce the mirror figure, since the polishing is not perfect. Although this is merely a rehearsal for tests of the FM mirror, the feasibility of the optical measurement utilizing this chamber is confirmed well.

4.3 Flight-model SiC Mirror

After lots of efforts, each fabrication process for the sandwich-type SiC mirror (see Figure 2) has been established very well. At present, two blanks of the SiC core with CVD coat have been successfully fabricated. One is mechanical-test-model (MTM) mirror and the other is FM mirror which is currently being polished (Figure 7). Polishing will be accomplished in October 2000. The third blank of the SiC core is also being fabricated as a back-up of the FM mirror. The MTM and FM mirrors, after both are ground, will be vibrated at the launch conditions and tested at liquid-helium or liquid-nitrogen temperatures using the chamber facility described above.

(a) (b)

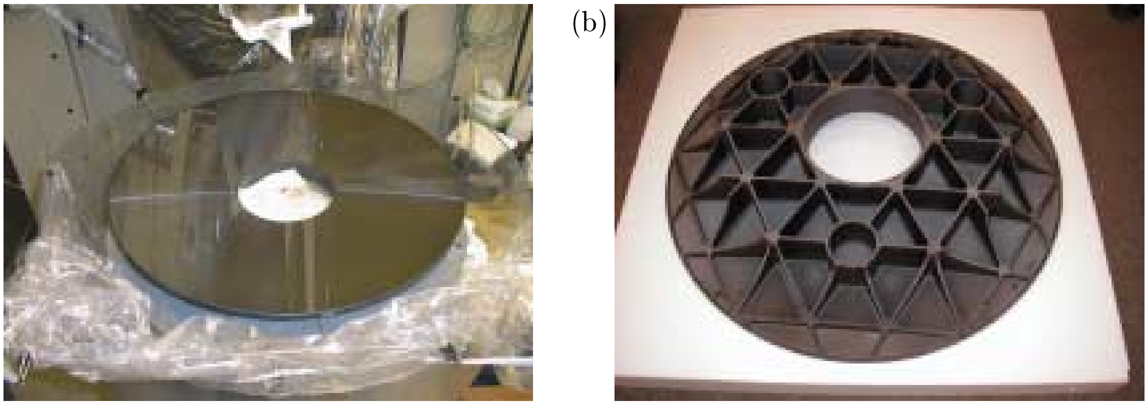

Fig. 7: Flight-model (FM) primary SiC mirror under polishing: (a) front surface and (b) rear surface.

5. CURRENT STATUS & FUTURE PLAN

The vibration test of the MTM primary mirror has recently been conducted, which resulted in no damage to the mirror. Hence, it is confirmed that the SiC mirror is quite durable under the launch conditions. The cryogenic test of the MTM primary mirror is now underway. This is the first time that SiC primary mirror of 710 mm in diameter is cooled down to cryogenic temperatures. The change of the mirror surface with temperature will be measured by the interferometer. As a next step, the MTM telescope assembly will be installed inside the prototype-model (PM) cryostat and the cryogenic vibration test will be performed this autumn.

After polishing of the FM mirror is completed, first, the FM primary mirror, and next, the FM telescope assembly will be cooled and tested successively. The results of the cryogenic tests of the FM mirror will be reported in near future.

REFERENCES

Onaka, T., Sugiyama, Y., & Miura, S. 1998, SPIE Proc., 3354, 900

Onaka, T. et al. 1999, in: Proc. of Ultra Lightweight Space Optics Challenge Workshop (http://origins.jpl.nasa.gov/meetings/ulsoc/papers/onaka.pdf)

Murakami, H. et al. 1998, SPIE Proc., 3356, 471