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A Continuous 100-mK Helium-Light Cooling System for MUSCAT on the LMT

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Abstract The MUSCAT instrument is a large-format camera planned for installation on the Large Millimeter Telescope (LMT) in 2018. MUSCAT requires continuous cooling of several large-volume stages to sub-Kelvin temperatures, with the focal plane cooled to 100 mK. Through the use of continuous sorption coolers and a miniature dilution refrigerator, the MUSCAT project can fulfil its cryogenic requirements at a fraction of the cost and space required for conventional dilution systems. Our design is a helium-light system, using a total of only 9 litres of helium-3 across several continuous cooling systems, cooling from 4 K to 100 mK. Here we describe the operation of both the continuous sorption and the miniature dilution refrigerator systems along with the overall thermal design and budgeting of MUSCAT to enable this large-format camera to be compatible with our proposed compact continuous cooler. MUSCAT will represent the first deployment of this new technology in a science-grade instrument and will prove the concept as a viable option for future large-scale experiments such as CMB-S4.

1 Introduction

The Mexico UK Sub-mm Camera for AsTronomy (MUSCAT) will be a 1.1-mm receiver consisting of 1,800 lumped-element kinetic inductance detectors (LEKIDs) operating at the photon noise limit. MUSCAT is scheduled to be installed on the Large Millimeter Telescope (LMT) (Puebla, Mexico) in 2018, after the LMT has completed the current upgrade of the primary mirror from 32 m to 50 m. MUSCAT will be one of the first new instruments to be installed on the 50-m LMT. To enable optimum operation of MUSCAT, a cryogenic system has been designed capable of continuously cooling the focal plane of MUSCAT to a

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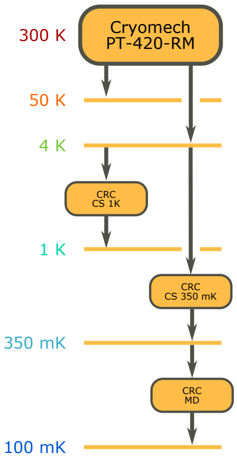

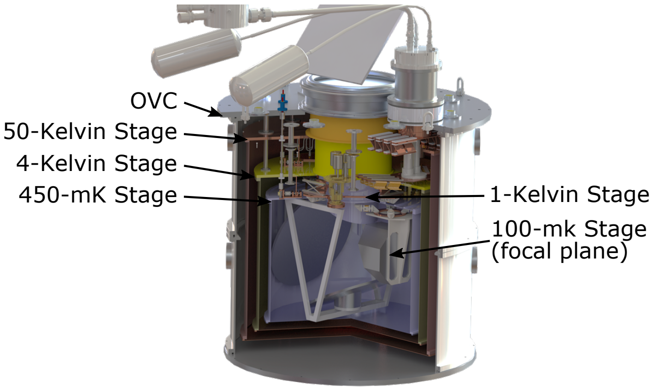

Fig. 1 (a) The MUSCAT cooling system from room temperature (300 K) to the focal plane (100 mK). (b) Cross-sectional view of the CAD design for the MUSCAT cryostat. The 50-Kelvin, 4-Kelvin, and 450-mK stages are coloured for illustration only. (Colour figure online.)

temperature of order 100 mK, as well as cooling the structure of the MUSCAT cryostat and providing appropriate heat-sinking stages.

2 Cooling Chain

The MUSCAT cooling chain contains a total of four separate cooling systems, namely: a Cryomech Inc.[i] PT-420-RM Pulse Tube Cooler (PTC), two Chase Research Cryogenics Ltd[ii] (CRC) continuous sorption (CS) coolers, and a final Chase Research Cryogenics Ltd miniature dilution (MD) refrigerator.

The pulse tube cooler is used to cool two stages of the cryostat; the first of these operates at a nominal value 50 K and is used as a heat sinking point and to cool a thermal radiation shield; the second stage is cooled to a nominal temperature of 4 K and contains an additional radiation shield, readout amplifiers and is also used as the thermal bath for the two continuous sorption coolers. The two continuous sorption coolers (operating the 4-Kelvin stage) cool separate stages down to temperatures of 1 K and 450 K, both of these stages fluctuate in temperature during operation however this is not seen as an issue for MUSCAT. The 1.1-Kelvin stages provides heat sinking for readout and housekeeping cabling whereas the 450-mK stage contains the final radiation shield and acts as the condensing point for the miniature dilution refrigerator. The MUSCAT cooling chain is illustrated in Figure 1a.

3 MUSCAT Design

In simplistic terms, the MUSCAT cryostat consists of and outer vacuum can (OVC) followed by three further radiation shields, all of which fit together like a set of Russian dolls. Each

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radiation shield is mounted of a thermal stage, decreasing in temperature towards the centre of the cryostat. In addition to the three stages from which the radiation shield are mounted, there are two further temperature stages which do not incorporate radiation shield. The full mechanical design of the MUSCAT cryostat is described by Castillo-Dominguez et al.[2] but is outlined in Figure 1b.

4 The Continuous Sorption Coolers

The first two sub-Kelvin stages of MUSCAT are cooled by continuous sorption (CS) coolers. Each of these systems operate essentially as two separate subsystem cycled in anti phase with each other. Both subsystems cool the same final-stage head which contains a small amount of a helium-3 ballast gas. The first of systems contains two helium-4 pumps and is designed to achieve a minimum an operating temperature of approximately 1 K.

The second CS system, used to cool the 450-mK stage of MUSCAT, consists of two pairs of helium-4 and helium-3 pumps. The performance of a similar system has been described previously and has been shown to operate at a temperature of 300 mK for in excess of three months with minimal thermal loading.[4] Our system is expected to operate at a higher temperature due to the presence of a thermal load, as described later. The temperature at the final head of the CS cooler fluctuates naturally during its operation due to the constant recycling of the system. These fluctuations can be seen in Figure 2, which shows the first five cycles of each subsystem over the a period of approximately 20 hours under minimal loading. The black line in Figure 2 (shown zoomed in in the lower panel) shows the temperature of the final head of this system, it is seen that for the first two cycles of each subsystem the minimum temperature achieved decreases for each cycle but the final performance is not achieved until the third cycle of the A (red) system (the red or blue traces in the upper panel are low when that system is being pumped upon). In the *steady state* (after the first two cycles of each subsystem) the temperature of the final stage fluctuates between 255–290 mK. It has been shown that through PID control of a heater mounted to this head, the achieved temperature can be stabilised at 365.0 ± 0.1 mK in the presence of a 20-μW thermal load (designed to represented the device load for a particular application).[4]

In order to operate at the levels of thermal loading anticipated for MUSCAT, a rapid-recycling scheme has been developed. Using this scheme a load curve for a prototype of each of the two CS coolers has been measured. These load curves are shown in Figure 3 and the stated temperatures correspond to the maximum temperature observed during the steady-state fluctuations.

5 The Miniature Dilution Refrigerator

As discussed earlier, the final cooling stage of MUSCAT will be a miniature dilution (MD) refrigerator. This system works through the same principle of moving helium-3 molecules across the phase boundary between a He^3-rich phase and a He^3-poor phase as a conventional dilution refrigerator.[3,5] Unlike the conventional dilution refrigerator, our system is fully contained within the structure of the cryostat and requires no mechanical pumps or large gas-handling systems. Instead the flow of He^3 is driven by a temperature difference between the evaporator (also referred to as the *still*) of the dilution refrigerator and a condensing point. So long as the condenser is cooler than the still, He^3 molecules evaporated in the still from the He^3-poor phase will preferentially flow to the condenser and are then returned as liquid

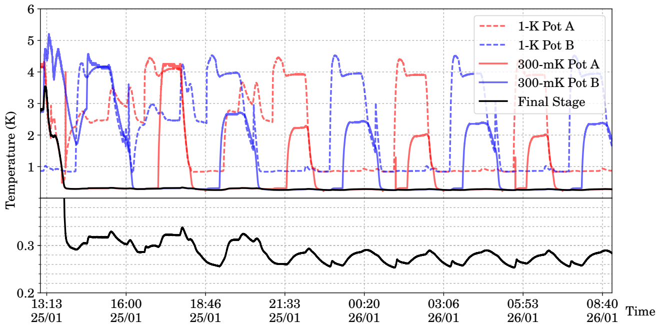
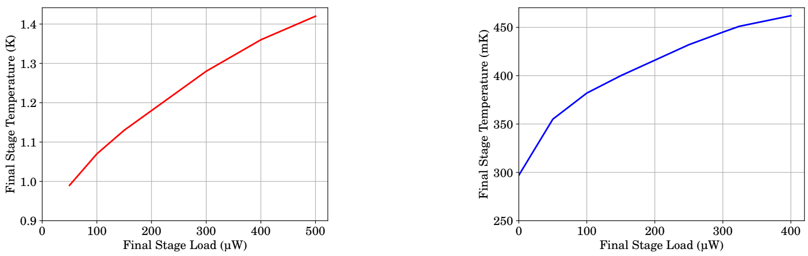


Fig. 2 Initial cycles of the two systems (red and blue lines) of the second MUSCAT continuous sorption cooler, used to cool the 450-mK stage. For this tests the system was under minimal loading. The final stage temperature is shown by the black line. When the coloured lines are high, that system is being charged with gas, when the lines are low that system is being pumped upon and is cooling the final head. (Colour figure online.)



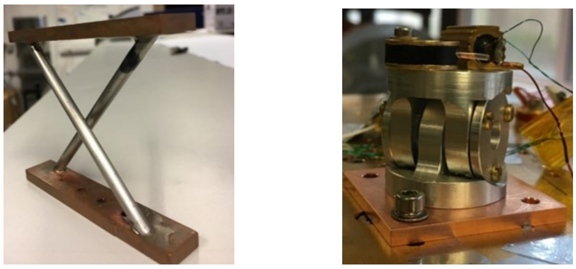
(a) (b)

Fig. 3 Measured load curves for the two continuous sorption coolers used by MUSCAT. (a) 1-Kelvin cooler; (b) 450-mK cooler. (Colour figure online.)

to the He^3-rich phase. A key advantage of this architecture is that the helium-3 requirement for a miniature dilution refrigerator is of order only 2 L, a factor of fifteen less than some conventional dilution refrigerators. MUSCAT plans to utilise a second-generation miniature dilution refrigerator from Chase Cryogenics Ltd (CRC), this unit is currently undergoing the finally stages of commissioning however a first-generation CRC miniature dilution refrigerator has been run in a general-purpose testing cryostat at Cardiff. This system achieves a minimum temperature of 77 mK under minimal load and a sustained temperature of 88 mK under a 5-μW thermal load.

6 Thermal Supports

Prior to modelling the thermal behaviour of MUSCAT, it is necessary to characterise the thermal supports used between the coldest stages of the cryostat. Two supports have been identified for use at these stages of MUSCAT these are a thin-walled stainless steel cross-beam and a crushed-sapphire joint as developed for the SCUBA-2 instrument.[1] These supports are shown in Figure 4.



(a) (b)

Fig. 4 Mechanical supports select for use between the final stages of MUSCAT. (a) thin-walled stainless steel cross beam, (b) crushed-sapphire joint (shown with thermometer and heater installed for characterisation). (Colour figure online.)

In order characterise the performance of these supports at in the sub-Kelvin range, one end of each support was mounted to the 100-mK plate of a cryostat cooled by a miniature dilution refrigerator, a temperature-stable heater and germanium thermometer were mounted on the other end of the support (the *isolated* end, as seen in Figure 4b) to apply a known thermal load and measure the temperature difference across the joints. Measurements were taken for three heat-sink temperatures of 100 mK, 350 mK, and 1.2 K corresponding to the nominal temperatures of the three MUSCAT stages of interest. At each bath temperature, numerous powers were applied through the load heater and these data have all been combined to plot the thermal conductance of the two supports, as shown in Figure 5.

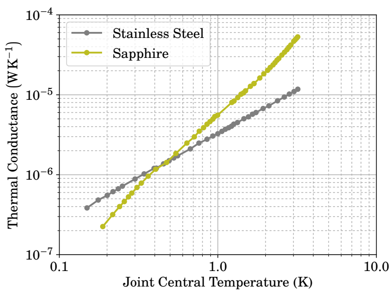


Fig. 5 Comparison of the thermal conductance of a thin-walled stainless steel crossbeam (grey) and crushed-sapphire joint (yellow). It is clear that for configurations where the central temperature of the joint will be less than 450 mK the use of the crushed-sapphire joint is preferable. (Colour figure online.)

7 Thermal Model

To verify the plausibility of the cooling chain presented here, we have modelled the expected thermal load on each stage of MUSCAT, the results of this are presented in Table 1. A complete description of the structure and interfaces between stages is given by Castillo-Dominguez et al.[2]

Table 1 Summary of thermal modelling for MUSCAT

	Stage				
Consideration	**50 K**	**4 K**	**1 K**	**250 mK**	**100 mK**
Mech. load through supports	8.92 W	64 mW	116 μW	12.4 μW	1.04 μW
Rad. load from previous stage	25.68 W	7 mW	-[1]	30.0 μW	0.005 μW
Opt. load from filters	3.10 W	32 mW	-[1]	22.3 μW	0.019 μW
RF Cabling	0.50 W	10 mW	22 μW	16.1 μW	0.14 μW
DC cabling	0.17 W	8 mW	28 μW	14.6 μW	0.23 μW
RF amplifiers	-	125 mW	-	-	-
Cooling Systems	-	0.2–1.2 W[2]	-	300 μW	-
Sky load	-	-	-	-	1.65 μW
Total Load	38.37 W	0.5–1.6 W	166 μW	395.4 μW	3.08 μW
Expected Temperature	44 K	2.8–4.1 K	1.10–1.15 K[3]	440–460 mK[3]	$<$ 88 mK

[1] 1-K stage has negligible surface area
[2] Load on 4-K stage fluctuates during cycling of CS coolers due to operation of heat switches
[3] Natural fluctuation of CS cooler (as seen in Figure 2) without the use of PID stabilisation

8 Helium-3 requirements

The final three cooling systems of MUSCAT require quantities of helium-3 in order to operate the cost of which is currently in excess of 2,000 USD per STP-litre of gas. All the cooling technologies selected for MUSCAT are designed to minimise this requirement. A summary of the helium-3 requirement for MUSCAT is given in Table 2.

Table 2 Helium-3 requirement for the MUSCAT cooling systems

Component	**Required He^3(L_{STP})**
1-K CS final stage ballast	1.5
450-mK CS pumps	2
450-mK CS final stage ballast	1.5
MD Refrigerator	2
Total	**9**

9 Conclusion

We have designed a cooling chain capable of cooling the focal plane of MUSCAT to below 100 mK continuously. The total requirement for helium-3 in the entire cooling chain is only 9 L_{STP}, substantially reducing the cost of MUSCAT's cooling system compared to more conventional systems capable of comparable performance. The individual cooling systems are currently undergoing the final stages of commissioning and verifications and will be installed in the MUSCAT cryostat in the coming months.

Acknowledgements

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