The Archeops Cryostat : A Dilution Refrigerator For A Balloon Experiment.

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Abstract

We present here the design of an open cycle dilution refrigerator able to reach a temperature of 0.1 K on a balloon-borne experiment. It was used to cool down the bolometric detectors of the Archeops experiment dedicated to measuring the microwave background radiation anisotropies (observation at millimeter wavelength with a 1.5 m telescope). The system maintains the low temperature with a high temperature stability for a flight up to 48 hours. A liquid helium bath is used to cool down the radiation shields and the entrance window. The input gas used for the dilution are precooled on the helium bath and the output dilute mixture is stored in a charcoal pump. We present a technical description of this cryostat followed by its in-flight perfomance. A similar open cycle dilution system will be used on the Planck ESA satellite, it is dedicated to a higher resolution measurement of the microwave background radiation anisotropies.

INTRODUCTION

The radiation we are aiming to measure was emitted when the Universe was about 300,000 years old and its temperature was 3000 K. Today, with the expansion of the Universe, this temperature fell to 2.735 K and the typical wavelength of the radiation is 1 mm. Measuring the anisotropies of this radiation requires a very high sensitivity which can be achieved with bolometers at very low temperature. It consists in measuring the temperature increase of an absorber heated by the incoming radiation. As the bolometer temperature decreases, the detector noise decreases. We do not need temperatures below 100 mK as the noise is then dominated by the intrinsic photon noise of the radiation, this is why we chose to work at this temperature.

To limit the pollution from atmospheric signal the instrument is carried by a stratospheric balloon at 35 km altitude. A more sensitive way to measure the radiation is to use a telescope on board of a satellite : this will be done in 2007 by the ESA satellite Planck which will use the same cooling technique.

To reach such low temperature, we use an open cycle dilution refrigerator developped for space applications[1]. We present here its application to the Archeops balloon borne experiment which has particular constraints. The main difference comes from the heating of the cold optics by infrared emission of the residual atmosphere through the entrance window.

PRINCIPLE OF AN OPEN CYCLE DILUTION REFRIGERATOR

The dilution of ^{3}He in ^{4}He is a well known process to obtain temperature as low as a few millikelvin. The originality of the open cycle refrigerator is that pure ^{3}He and ^{4}He gas are separately injected under pressure into the cryostat. They are pre-cooled, liquefied and injected in a heat exchanger. They mix together at low temperature, producing cooling by dilution of the liquid ^{3}He in liquid ^{4}He. The dilute mixture is extracted without separation of the two components. Therefore, the process does not need an evaporator to separate the ^{3}He from the mixture. The concentrated phase forms bubbles in the dilute phase and the dilution is done at the phase separation at the surface of the bubble. The process is fully independent of gravitation and can be used on a satellite.

The dilution process can start from a temperature higher than 2 K but will not work efficiently at 4.2 K. A Joule Thomson expansion of the helium mixture at the output of the dilution stage is used to cool down an intermediate stage at 1.6 K. This requires a gas output at low pressure (< 10 hPa) and allows the sytem to work from a helium bath at 4.2 K.

Such cryostat can stay below 100 mK for months, as long as pure ^{3}He and pure ^{4}He is being supplied and the mixture is pumped out. The purification of the mixture can be realized in the laboratory. After disconnection of the cryostat from the external supply, the running time depends only on the volume of gas under pressure carried with the experiment.

APPLICATION TO THE ARCHEOPS EXPERIMENT

The whole instrument is described in a technical paper[2]. We present here the cryogenics specifications and performances.

The helium bath consumption

One important heat load on the cryostat comes from the optics window of 15 cm diameter. It receives a power from 250 mW to 500 mW, depending on the temperature of the atmosphere. To keep the helium consumption reasonable, the cold optics is cooled between 8 and 10 K by the helium vapor exhaust. The helium bath is itself protected by two vapor cooled screens (but with a large hole at the position of the optics window). This results in a consumption of 0.4 liter/hour of liquid helium and an autonomy of 48 hours for the 20 liter dewar.

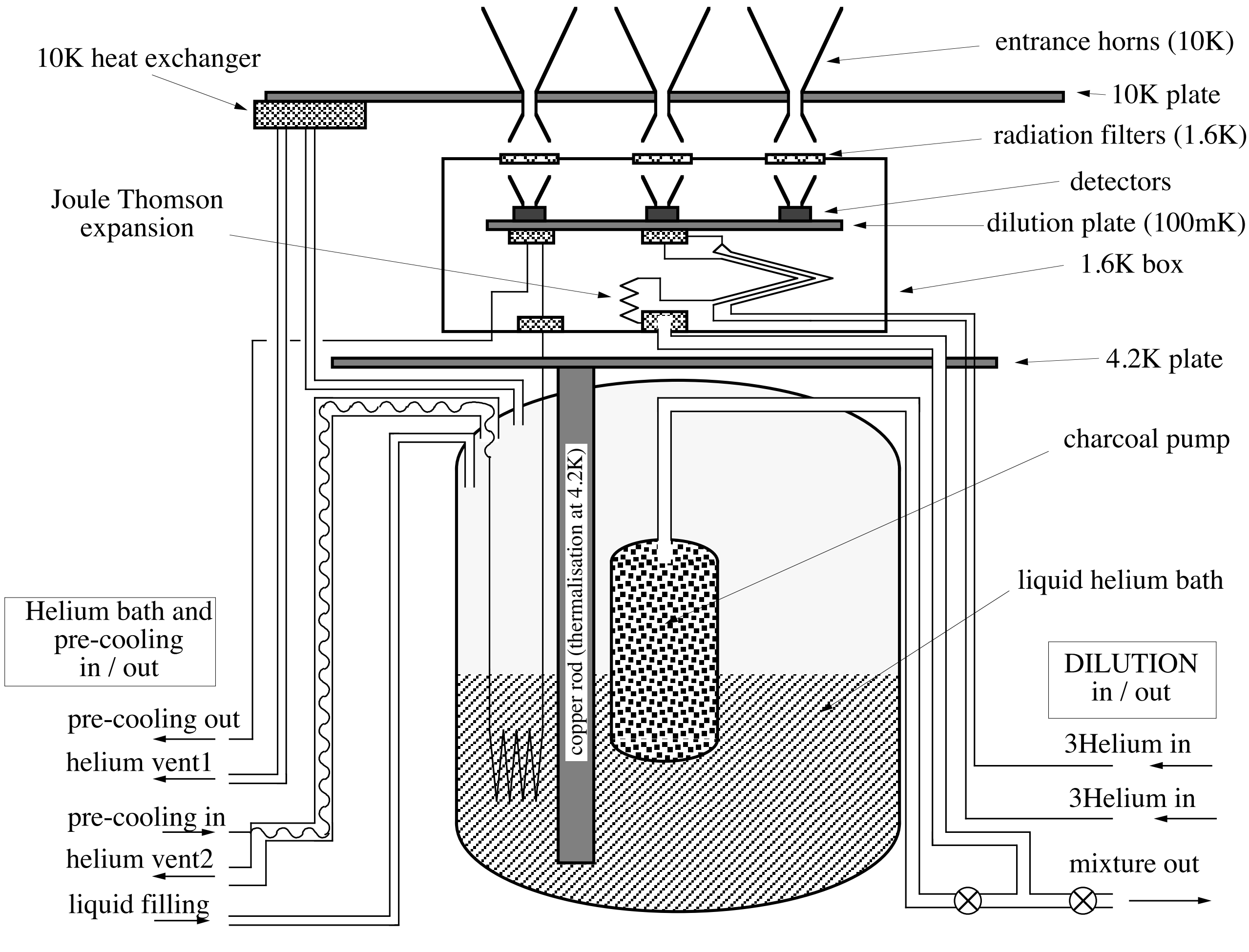

Figure 1: Scheme of the Archeops cryostat

When the instrument is carried by the balloon, during the ascent, the outside pressure decreases and if we do not take any precautions, the helium bath temperature decreases down to superfluid temperature (atmospheric pressure goes down to 3 hPa). This consumes a lot of helium and would reduce the duration of the experiment. To avoid this effect, we use an electronic pressure regulator to maintain a constant pressure of 1 bar on the helium bath.

The pre-cooling

A pre-cooling is necessary to cool the cryostat down to about 10 K. A capillary of 0.5×0.9 mm in CuNi brings helium gas at a pressure of 50 bars, up to the dilution stage. We use a second gas exhaust, as shown in figure 1 (helium vent2), in order to cool down the pre-cooling gas in the cold vapors coming from the bath. The cold gas is used to thermalize the 1.6 K box and the dilution stage. The thermalization is done through a heat exchanger made with 2 m of capillary rolled on a copper rod. A simple calculation shows that with a perfect heat exchanger, we need 2 m^3 of He gas to cool down the 1.6 K box and the detectors ($\sim$ 4 kg). In practice, we typically use 2.5 m^3 to cool down the system at 10 K in about 4 hours. The gas is pumped out before it reaches 4 K to make sure no superfluid helium is left inside the capillary. This would cause an extra heat flux going to the 100 mK stage which would unable it to reach its nominal temperature.

The dilution stage

The dilution fluids arrive through two capillary tubes of 0.5 mm internal diameter (except a small part of 60 μm diameter to cut the conduction of superfluid helium) from ambiant temperature down to 1.6 K. Then, we use 1 m length of 40 μm diameter and 3 m of 300 μm diameter as part of the heat exchanger between 1.6 K and 100 mK. The mixture exits through a third capillary of the same diameter. The three tubes, two extra capillaries for pre-cooling (0.5 mm diameter) and the electric wires for measuring the detectors (9 shielded cables with 12 conductors each) are soldered together, forming a continuous heat exchanger disposed around the 100 mK stage (see pictures on figure 2). With a flow rate of 24 and 6 μmol/s for ^{4}He and ^{3}He respectively, the theoretical power available at 100 mK is 1 μW. Most of this power is used to compensate heat losses from conduction by the supports (kevlar chords) and by viscous heating in the capillaries. We measure a residual available power of 200 nW at 100 mK. The lowest temperature obtained is 75 mK.

The Joule Thomson expansion

The output mixture is expanded at 1.6 K through a 13 μm diameter capillary in order to produce a Joule Thomson expansion. At nominal flow, the theoretical cooling power is around 1.8 mW. A heat exchanger is used to thermalize a cold box at 1.6 K supporting filters for the measured radiation and shielding the dilution stage from all other thermal radiation. The low pressure gas is pumped out at room temperature through a 3 mm diameter tube.

The flow control

The isotopes are stored in pressurized 1 liter bottles (typically 50 bars for ^{3}He and 100 bars for ^{4}He) and we need to maintain a flow of 24 and 6 μmol.s^{-1} for ^{4}He and ^{3}He respectively. The helium input flow of ^{4}He and ^{3}He needs to be precisely controlled for the dilution cryostat to work properly. A mass-flow regulator (distributed by Brooks) is used to control the flow. It works correctly on ground but is very sensitive to the outside pressure and temperature. In order to control its calibration during the flight, the on board computer calculates the gas flow by measuring the pressure drop on an impedance and the derivative of the pressure in the container. This allows an automatic correction of the flow-meter set point.

Output mixture pumping

On ground, the mixture coming from the cryostat with a classical primary pump in order to maintain a pressure lower than 5 hPa on the Joule Thomson expansion. The gas is then stored for later purification. Before the flight, we switch to a charcoal pump inside the main helium bath (1 liter charcoal pump). This pump can not be recycled without warming all the cryostat but its volume is large enough to pump the mixture for more than 3 days continuously at nominal flow.

CONCLUSION

The Archeops experiment has been launched from the Esrange base near Kiruna (Sweeden) during the artic night. On ground, the cryostat was maintained at low temperature, waiting for good launch conditions. The experiment accomplished two successful scientific flights (January 2001 and February 2002), flying once for 7 hours and once for 19 hours at ceiling. After a small warm up (120 mK) due to vibration during take off, the cryostat reached 100 mK during the ascent and stabilized near 85 mK during the flight. The cryogenic chain worked perfectly in a totally automatized way. The focal plane temperature was stabilized by a thermal filter made with an HoY alloy [3] in order to limit the temperature fluctuations of the detectors.

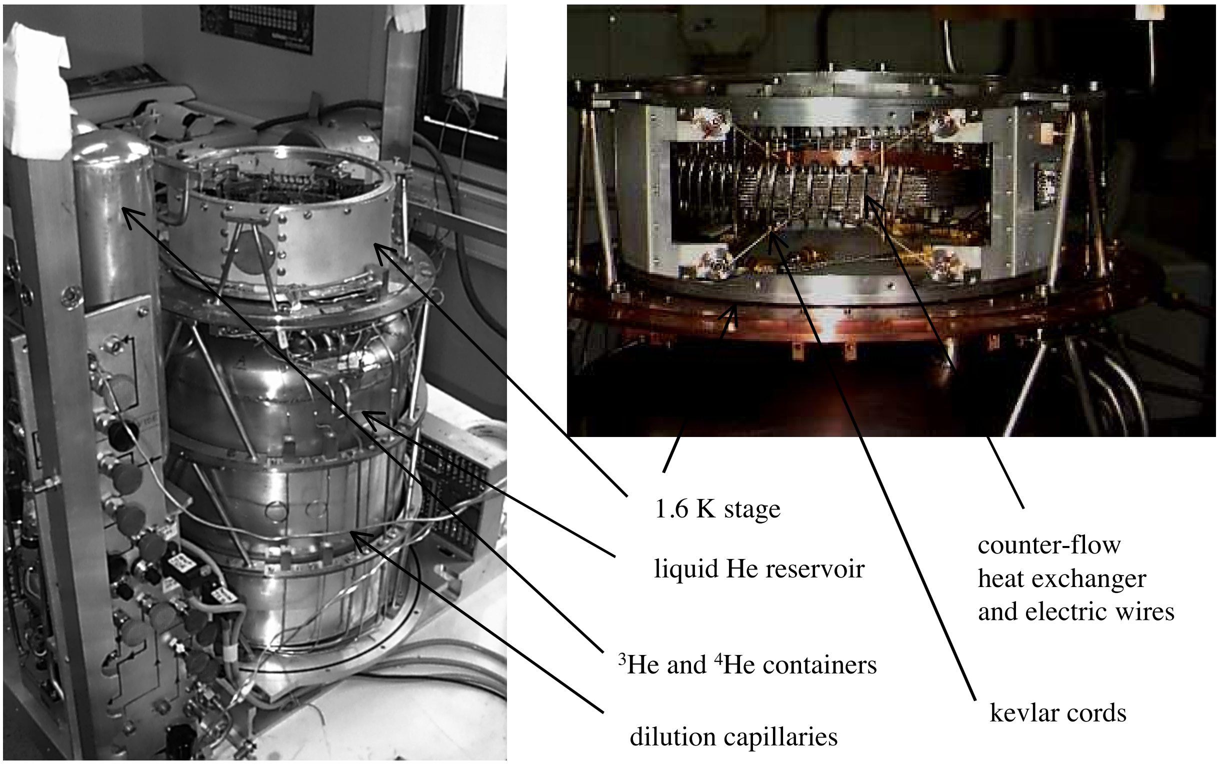

Figure 2: Pictures of the Archeops cryostat.

The data taken during these flights is currently being analysed and the results seem very promising.

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