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Cryogenic systems for Long Duration Balloon experiments

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Abstract. We describe typical long duration cryostats, suitable for cooling large balloon-borne photometers for mm and sub-mm range. The idea, well tested in several experiments, is to thermally insulate the coldest part of the system from the room temperature shell by interposing layers with gradually decreasing temperature. In this way the heat load on the cold system is remarkably reduced. The target of a long hold time is achieved reducing the radiative loads by means of a super-insulation blanket for the nitrogen tank and a vapor-cooled shield for the helium tank. All the components are supported by fiberglass tubes. This class of cryostats operates autonomously without external power, for all the long duration balloon flight, that is typically longer than two weeks.

Key words. Cryostat – helium – nitrogen

1. Introduction

A cryostat is a vessel that mantains at cryogenic temperatures parts of an experiment, for all the duration of the measurements. In fact, only drastically reducing the temperature of the detectors and of the surrounding environment it is possible to reduce the sources of noise (Johnson noise, temperature noise, photon noise) contaminating the signal of interest. The typical way to reach low temperatures is by means of liquified cryogenic gases: the thermal contact between the liquid and the system allows to keep the low temperature until the whole liquid has evaporated under the thermal load. It is well known that there are three possible ways of heat transmission in a cryostat: conduction, convection, radiation. All must be reduced for optimal operation. The balloon environment makes no exception. The main cryogenic liquids used are nitrogen (77K at p=1atm) and helium (4.2K at p=1atm). One of the issues for long duration balloon-borne (LDB) experiment is the requirement that the cryostat has to operate autonomously for all the time of the measurements. In this sense, passive cryostats with cryogenic fluids represent the best option.

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2. The cryostat of OLIMPO

OLIMPO is a balloon-borne telescope devoted to cosmological and astrophysical surveys in the mm and sub-mm range (Nati et al. 2007). The principal aim of the experiment is the measurement of the Sunyaev-Zeldovich effect in clusters of Galaxies; OLIMPO will carry out a survey in four frequency bands centered at 140, 220, 410 and 540 GHz. The

OLIMPO cryostat must satisfy many requirements. Those characteristic of long duration ballooning are the duration, that has to be longer than two weeks, and the strength, which should be designed to withstand external thermal and mechanical stresses. The low external stratospheric temperature drives the design of vacuum seals in the outer shell of the cryostat, while the nominal 10g shock at parachute opening drives the design of the support system for the different inner tanks of the cryostat. The OLIMPO cryostat is part of a telescope: the inner frame, supporting both the mirrors and the cryostat housing the detector system, can be tilted to set the observing elevation from 0^o to 60^o. So the cryostat should operate in a wide range of directions of the gravity vector. Moreover, the cryostat must maintain with high stability the temperatures of the focal plane of the instrument and of the cold optics, respectively 0.3K and 2K, with drifts inferior to 0.1 mK/h (Masi et al. 1999). The experimental volume containing the cold optics, the fridge and the detectors, is a large cylinder (diameter of 450mm and height of 450mm) driving the overall dimensions of the system. It should be easy to remove the experimental insert, for preparation, optical alignments, and tests. Finally, during flight the cryostat has to operate automatically.

2.1. External shell and window

The external shell is an aluminum vessel that supports all the inner components of the dewar; it's the first shield against radiative load and allows the evacuation of the inner volume, reducing the convective load on the inner layers.

The radiation to be measured enters the cryostat and reaches the cold optics through a vacuum window made of UHMWPE (Ultra High Molecular Weight PolyEthilene); in order to remove interference due to internal reflections, the window is anti-reflection coated. The large diameter (d=130mm) is set by the configuration of the cold optics and by the large corrected throughput of the telescope. It has a thickness of 4 mm.

2.2. Nitrogen tank

It has a bell shape, and screens the inner parts absorbing most of the radiative load from the room temperature shell. Liquid nitrogen is well-suited for this aim: it has a latent evaporation heat of $L_{N_2} = 199kJ/kg$ at $p = 1atm$, much larger than those of ^4He and ^3He (respectively $L_{^4He} = 21kJ/kg$ and $L_{^3He} = 24.5kJ/kg$). Therefore, significant heat loads can be absorbed with the evaporation of a limited amount of liquid, resulting in a sufficient duration of the cryostat. The available volume of liquid nitrogen is of $65l$.

2.3. Superinsulation

The next layer is the *superinsulation*: it's composed of n layers made of film of *mylar*, covered by aluminum on one side to reduce both emissivity and transparency, and covered by an insulator on the other side to reduce the thermal contact between two consecutive layers (Chen 1994). The superinsulation is wrapped around the nitrogen tank. Given a surface of area A, the energy $\dot{Q}_{rad}$ emitted by radiation is given by the Stefan-Boltzmann law: $\dot{Q}_{rad} = \sigma\varepsilon AT^4$, where $\varepsilon = \varepsilon(\lambda, T)$ is the surface emissivity, equal to 1 in the case of black body, and $\sigma = 5.67 \cdot 10^{-8} Wm^{-2}K^{-4}$ is the Stefan-Boltzmann constant.

With n layers of superinsulation the radiative load it's reduced of a factor ($\sim n+1$):

$$\dot{Q}_{rad} = \left(\frac{1}{n+1}\right)\left(\frac{\varepsilon}{2}\right)\sigma \cdot A(T_{n+1}^4 - T_0^4)$$

In order to reach the goal of few W/m^2, the minimum number of layers is 30.

2.4. Comparison with BOOMERanG: need of fiberglass supports

The technology of the OLIMPO cryostat is quite similar to the one, well tested, of BOOMERanG (Masi et al. 1999, 2006), but with some distinctions due to the different geometry (OLIMPO is a Cassegrain telescope: a lateral window is needed) and scan strategy. The main difference is the use of fiberglass

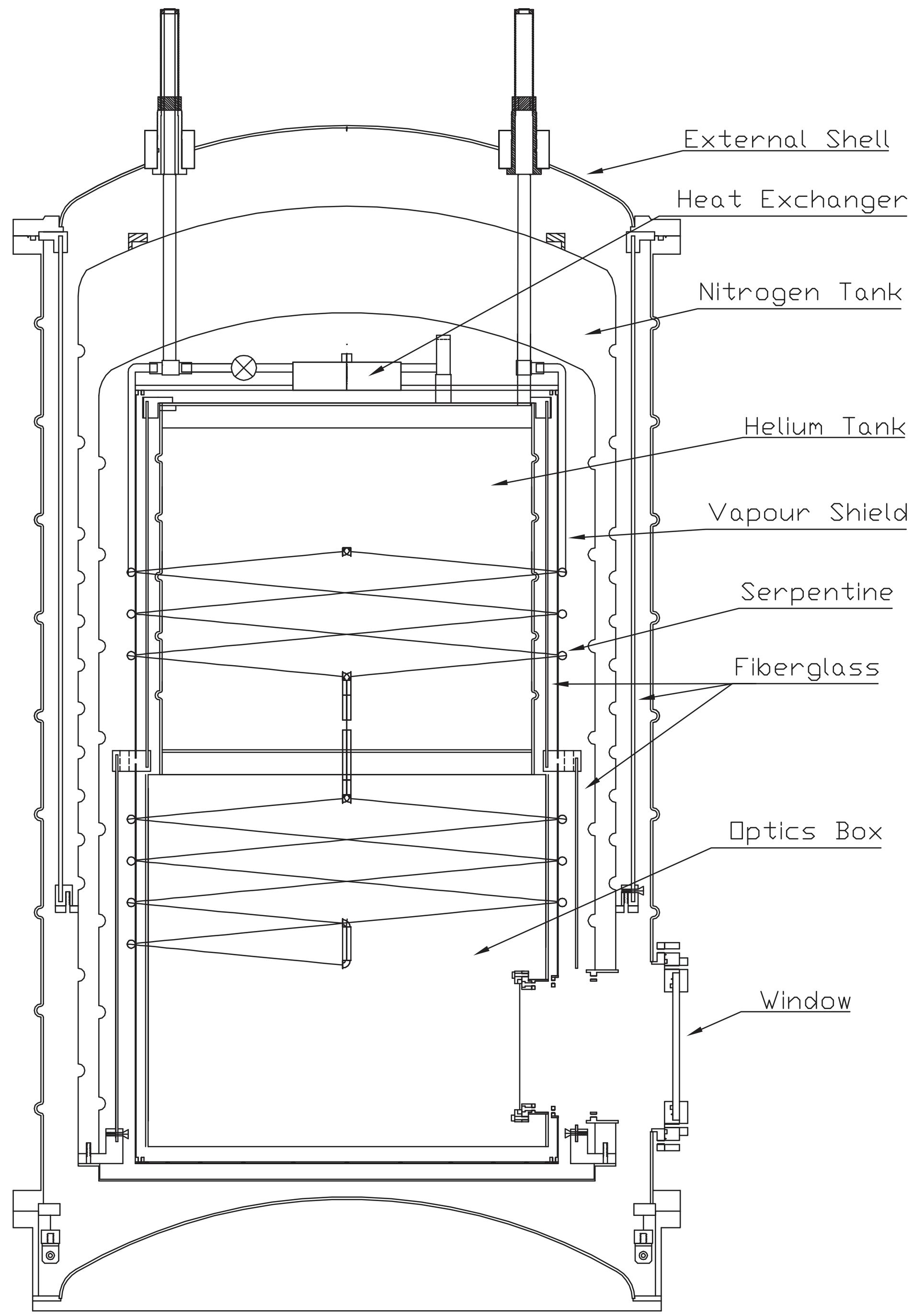

Fig. 1. Sketch of the OLIMPO cryostat: the thermal layers aimed at drastically reducing the heat load on the cold parts are labeled in the figure.

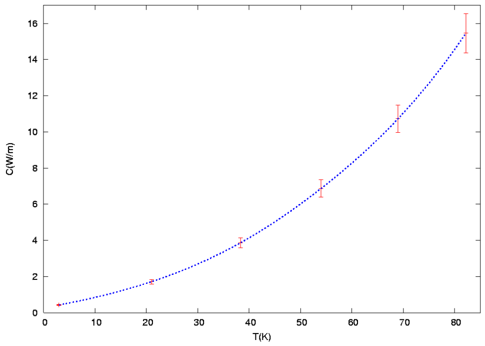

Fig. 2. Integral thermal conductivity of the OLIMPO fiberglass tubes.

Table 1. Temperature of the vapor shield vs. heat exchange efficiency with the evaporating He, for the OLIMPO cryostat. In the last column we report the corresponding hold time.

Efficiency	T_{shield}(K)	Days
0.1	46.0	8
0.2	41.0	10
0.3	37.0	12
0.4	35.0	13
0.5	33.0	14
0.6	31.0	16
0.7	29.0	17
0.8	28.0	18
0.9	27.0	19
1.0	26.0	20

cylinders to replace the kevlar cords suspending the nitrogen and helium tanks. Fiberglass cylinders provide higher stiffness to the system, which is a primary requisite to keep the detector arrays centered on the optical axis within the diffraction limits during operation at different elevations. Fiberglass has a low thermal conductivity; moreover, its stiffness is comparable to the stiffness of aluminium. Fiberglass is a composite material composed of glass fibers and epoxy resin: depending on the detail and structure, remarkable variations of the thermal conductivity can occur. In fig.2 is reported the result of the measurements of the integrated thermal conductivity κ_{int} between $2K$ and T of the fiberglass tubes of the OLIMPO cryostat.

2.5. ^4He stage

A way to reduce the temperature of a boiling cryogenic liquid consists in reducing the pressure of its vapors (Conte 1970). This is simple to obtain at balloon altitude: the low atmospheric pressure represents the best possible pump for the He bath, and its value (around 3 mbar) corresponds to a temperature of the He bath below the superfluid transition. For ^4He, a consistent part of the liquid is evaporated to cool down the remaining. The total volume of helium liquid that the helium tank can hold is of about 64 liters, but it becomes about a half after pumping on it, reaching a final temperature of $1.8K$. The vapor of the boiling liquid passes through a serpentine welded on a copper shield placed between the He and N tanks: in this way the vapor can absorb heat from the shield, reducing its temperature. T_{shield} is between about $20K$ and $40K$, depending on the efficiency of the heat exchange between shield and vapor. This is unity when $T_{shield} = T_{vap}$, where T_{vap} is the temperature of the vapors when they reach the external environment. The presence of this vapor cooled shield reduces the radiative load on the ^4He. A large impedance of the serpentine can generate pressure oscillations during the helium pumpdown. To mitigate this problem, a heat exchanger is added in parallel to the serpentine: it will reduce the impedance, even if the efficiency is reduced. A motorized valve regulates the flux of evaporating gas, allowing its passage through the serpentine rather than the exchanger.

2.6. Results

Numerical simulations for OLIMPO cryostat are reported in tab. 1, describing the variations of the temperature of the vapour shield and the hold time of the cryostat as a function of the exchange efficiency between vapour and shield. Cooldown data for the OLIMPO cryostat confirmed the results: after pumping on He bath, the hold time in the laboratory test is of at least 2 weeks. At float, the reduced air temperature will result in a lower temperature of the outer shell, extending the hold time.

3. PILOT cryostat

A similar philosophy has been adopted for the cryostat of the PILOT experiment. The aim of the PILOT experiment (Bernard et al. 2007) is the measurement of the polarized Far-IR and sub-mm brightness emitted by interstellar dust grain in our Galaxy.

The requirements for the cryostat are different from the ones for OLIMPO: a hold time of 2-3 days is sufficient; the cold volume needed for the optics has a diameter of 400mm and a height of 580mm; and the weight cannot exceed 120 Kg (much less than OLIMPO, that is almost 250 Kg).

In order to be light and compact, we have decided to use three He-vapor cooled shields (in place of the N_2-cooled shield), each surrounded by a superinsulation jacket of 20-30 layers. This is the standard design for space cryostats, like the ones used in COBE, ISO, IRTS, SPITZER. From numerical simulations, the temperatures of the 3 shields are expected to be around 38, 70 and 140 K, with efficiency of the heat exchangers of about 70%. This corresponds to a lifetime of about 4 days.

4. Conclusions

The OLIMPO cryostat successfully works: simulations done before construction have been confirmed by the tests on the dewar with both liquid nitrogen and liquid helium. The PILOT cryostat is under construction: the next step is to confirm the forecast obtained from the simulations making a test on the dewar. Several forthcoming missions will benefit of this know-how: in particular BB-Pol, a balloon experiment aimed at validating the B-Pol satellite mission for CMB polarization B-modes; also these technologies are useful to design the cryogenics system of Sagace, a satellite of the Italian Space Agency, now in phase-A, aimed at producing a large spectroscopic catalog of the Sunyaev-Zeldovich effect in clusters of galaxies and of primordial galaxies and AGNs.

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