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Cryogenics in space

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Abstract

Cryogenics plays a key role on board space-science missions, with a range of applications, mainly in the domain of astrophysics. Indeed a tremendous progress has been achieved over the last 20 years in cryogenics, with enhanced reliability and simpler operations, thus matching the needs of advanced focal-plane detectors and complex science instrumentation. In this article we provide an overview of recent applications of cryogenics in space, with specific emphasis on science missions. The overview includes an analysis of the impact of cryogenics on the spacecraft system design and of the main technical solutions presently adopted. Critical technology developments and programmatic aspects are also addressed, including specific needs of future science missions and lessons learnt from recent programmes.

Introduction

H. Kamerlingh-Onnes liquefied ^{4}He for the first time in 1908 and discovered superconductivity in 1911. About 100 years after such achievements (Pobell 1996), cryogenics plays a key role on board space-science missions, providing the environment required to perform highly sensitive measurements by suppressing the thermal background radiation and allowing advantage to be taken of the performance of cryogenic detectors.

In the last 20 years several spacecraft have been equipped with cryogenic instrumentation. Among such missions we should mention *IRAS* (launched in 1983), ESA's *ISO* (launched in 1995) (Kessler et al 1996) and, more recently, NASA's *Spitzer* (formerly *SIRTF*, launched in 2006) (Werner 2005) and the Japanese mission *Akari* (IR astronomy mission launched in 2006) (Shibai 2007). New missions involving cryogenics are the ESA missions *Planck* (dedicated to the mapping of the cosmic background radiation) and *Herschel* (far infrared and sub-millimetre observatory), carrying instruments operating at temperatures of 0.1 K and 0.3 K, respectively (Crone et al 2006). In the 10 K to 100 K temperature range, many missions are operational, including military reconnaissance satellites (*Helios*), Earth observation and meteorological satellites (*Meteosat* Second Generation), with IR detectors operating at about 85 K (Cihlar et al 1999). For science missions, we

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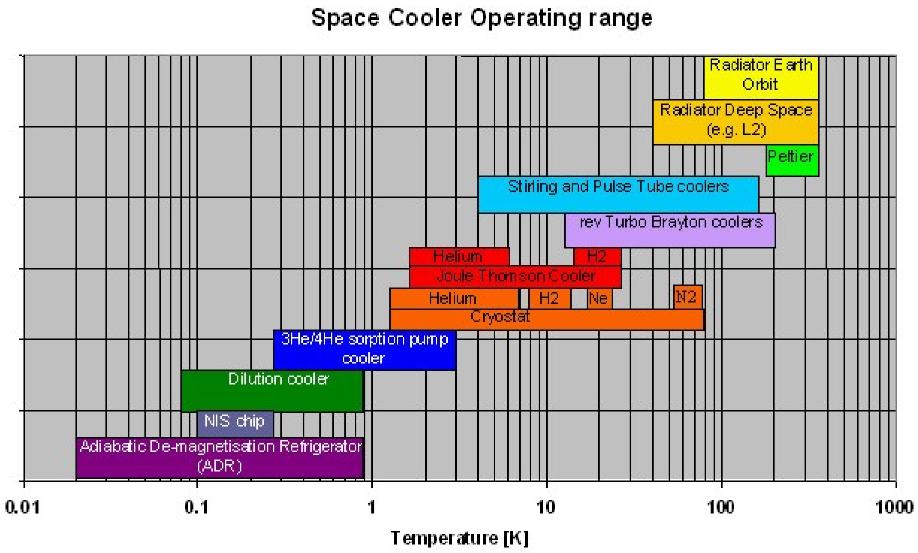

Figure 37.1: Operating temperature range of different space coolers.

should quote the ESA mission *INTEGRAL* (launched in 2002), with Stirling coolers maintaining the detectors of the spectrometer at 80 K (Winkler 2004). Different cryogenic techniques are available depending on requirements, in particular operating temperature and cooling power. Figure 37.1 provides an overview of the different cooling approaches as a function of base temperature. The different cryogenic techniques and the required technology developments will be addressed in the following sections.

Applications of cryogenics in space

Science missions in operations / post-operations

The first cryogenic missions, such as *IRAS*, launched in 1983 (Langford et al 1983), *COBE* (COBE 1992), launched in 1989, and *ISO*, launched in 1995 (Kessler et al 1996), were based on liquid He cryostats, with the bath temperature regulated by adjusting the vapour pressure. Lifetime was correspondingly limited by the amount of cryogen, typically to about 12 to 18 months. More recently, the same approach has been used by *Spitzer* (Figure 37.2, left). *Spitzer*, thanks to an optimised cryogenic system (passive radiation, use of helium gas enthalpy, orbit choice), was designed to provide a minimum lifetime of 2.5 years, using only 360 litres of superfluid He. *WIRE* (launched in 1999 and lost during commissioning), had a two-stage, solid-hydrogen cryostat maintaining the optics below 19 K and the Si:Ga detector array below 7.5 K, with a lifetime of four months (Elliott et al 1994). A hybrid, solid-neon / liquid-helium design was adopted by *ASTRO-E I*

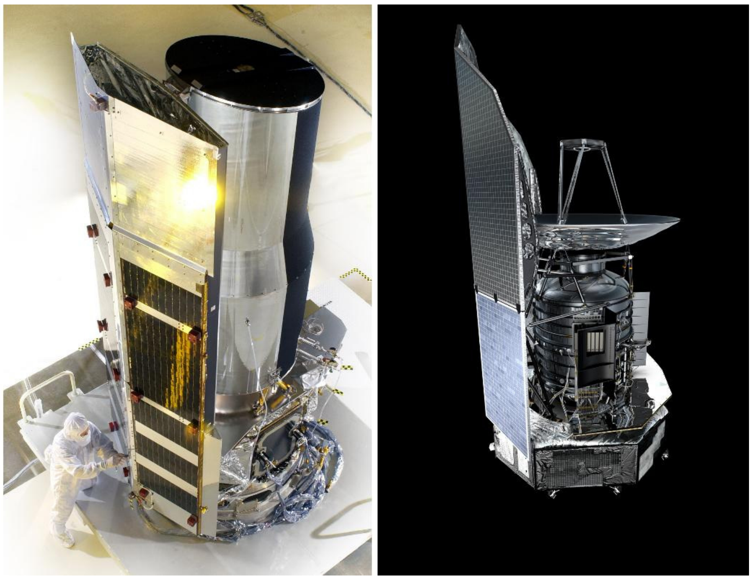

Figure 37.2: Left: *Spitzer* spacecraft during final testing (NASA). Right: *Herschel* spacecraft (artist view – ESA).

and *ASTRO-E II*, renamed *Suzaku* (launched in 2000 and 2005, respectively), two ISAS (Japan) satellites for X-ray astronomy (Ogawara 1998). The *ASTRO-E* spectrometer used calorimeters operating at 65 mK via an adiabatic demagnetisation refrigerator (ADR), hosted in a liquid-helium cryostat and thermally shielded by a solid-neon cooled outer jacket. Predicted lifetime was two years. Finally, the Japanese mission *ASTRO-F* (an IR observatory launched in 2006 and renamed *Akari*) represents a follow-on from the *IRAS* mission, performing an all-sky survey between 6 µm and 180 µm, with a 180 litre He cryostat, working in combination with Stirling coolers (Shibai 2007).

In the temperature range above 50 K, we should mention NICMOS, the Near Infrared Camera and Multi-Object Spectrometer (0.8 µm to 2.5 µm), installed on *HST* in 1997. The detectors were cooled down to 60 K via 120 kg of solid nitrogen, replaced in 2002 by a reverse turbo-Brayton cooler. In this temperature range mechanical coolers (turbo-Brayton, Stirling), replaced the use of cryogens (Thompson et al 1998). In fact, ESA's *INTEGRAL*, dedicated to spectroscopy and imaging between 15 keV and 10 MeV, uses space-qualified Stirling cryo-coolers (Winkler 2004), maintaining the germanium detectors of the spectrometer at 82 K. Similarly NASA's *RHESSI* mission, launched in 2002, also uses a Stirling cooler, maintaining the Ge detectors at 80 K (Hannah et al 2007).

Among the main recent cryogenic missions we should mention ESA's *Planck* and *Herschel*. *Planck*'s objective is to map the temperature anisotropies of the cosmic microwave background over the whole sky (Crone et al 2006). The cryogenic system of *Planck* is based on passive pre-cooling to 50 K to 60 K (telescope), cooling to 20 K via an H_2 Joule-Thomson (JT) cooler (adsorption compressors), cooling to

4 K with a He Joule-Thomson cooler (mechanical compressors) and final cooling (bolometer detectors) to 0.1 K with an open-loop dilution refrigerator (DR). Its nominal mission lifetime is 15 months. The *Herschel* mission (Figure 37.2, right side) is a far-infrared and sub-mm multi-user observatory (85 µm to 600 µm), based on a superfluid helium dewar at 1.65 K (lifetime of 4.5 years) (Pilbratt 2008). The scientific goals will be achieved with three instruments operating at 2 K (heterodyne receiver based on SIS mixers, see Chapter 31, Wild 2010), 1.7 K (photometer based on photo-conductors) and 0.3 K (photo-spectrometer using bolometers and a ^{3}He sorption cooler, respectively). ESA developed the two spacecraft together, and launched them to L2 on a single *Ariane 5* in May 2009.

Science missions under development and under study

An important role will be played by NASA's *JWST* (Gardner et al 2006). This large programme, scheduled for launch in 2013, is based on a 6 m diameter passively cooled telescope enabling observations in the near and medium-IR, from 1 µm to 30 µm. The science instruments are an NIR camera and two Europe-led instruments, ESA's NIR low-resolution spectrograph (NIRSpec) and a MIR camera-spectrograph combination (MIRI). The first two instruments operate at 30 K (passive cooling), while MIRI makes use of a Joule-Thomson cooler, pre-cooled by a 3-stage pulse tube to achieve a base temperature of about 6 K. Other space missions with cryogenic equipment are being studied. On the ESA side we should mention *Darwin*, a near-infrared space observatory dedicated to the search of planets. In Japan the mission *SPICA* (a medium- and far-IR observatory scheduled for launch in 2017) is under study, assuming a cryogenic chain entirely based on mechanical coolers, with a 3.5 m diameter mirror operating below 5 K (Sugita et al 2006). Recently, ESA's *XEUS* (Rando et al 2006) and NASA's *Constellation-X* (Petre et al 2006) have been merged into *IXO*, an ESA-JAXA-NASA project. An overview of the main scientific cryogenic space programmes is given in Table 37.1.

Earth-observation satellites and telecom applications

Earth-observation missions require cryogenics because of the utilisation of medium infrared detectors (typically operating around or just below 100 K). Although in some cases cryogens have been used, for instance on NASA's *UARS*, launched in 1991 (Reber 1990), a growing number of missions are making use of mechanical coolers. ESA's *ERS-1* & *-2* (launched in 1995 and 1999) and *Envisat* (launched in 2000) make use of Stirling coolers (Aminou et al 1998). The next-generation missions are likely to take advantage of the progress made in the field of pulse-tube refrigerators (Barnes et al 1998).

The recent progress in the area of high-temperature superconductors may open new perspectives for radio-frequency superconducting devices (filters, delay lines, resonators), of interest also for space applications. For instance, YBCO (yttrium-barium-copper-oxide) at a temperature of 77 K and at a frequency of 10 GHz has a surface resistance which is 30 times lower than that of copper, implying the possibility to improve the energy efficiency of telecommunications systems or to significantly reduce their size and weight (Chaloupka et al 1993).

Table 37.1: Summary of main scientific cryogenic space programmes.

Mission	Science domain	Type/class	Launch year	Cryogenic system	In-flight T/K	Lifetime	Orbit	Status
IRAS (NASA, NIVR, SERC)	IR	satellite (surveyor)	1983	^{4}He (λ) cryostat	3	290 d	near polar	post-ops.
COBE (NASA)	IR	satellite (surveyor)	1989	^{4}He (λ) cryostat	1.4 – 1.6	305 d	near-Earth	post-ops.
ISO (ESA)	IR	satellite (observat.)	1995	^{4}He (λ) cryostat	1.8	840 d	HEO	post-ops.
HST (NASA)	NIR	Nicmos, instrument	1997	sN_2 cryostat	60	700 d	LEO	post-ops.
WIRE (NASA)	IR	satellite (surveyor)	1999	dual, sH_2 cryostat	< 7.5	120 d	LEO	post-ops/lost
INTEGRAL (ESA)	γ-ray	instrument (observat.)	2002	Stirling cooler	85	2–5 a	HEO	operat.
RHESSI (NASA)	solar phys.	satellite (observat.)	2002	Stirling cooler	85	> 5 a	LEO	operat.
Spitzer (NASA)	IR	satellite (observat.)	2006	^{4}He (λ) cryostat	1.4	2.5 a	Earth trailing	operat.
Rosetta (ESA)	planet. sci.	instrument (probe)	2003	Stirling cooler	80	10 a	heliocentr.	operat.
Suzaku (ISAS, NASA)	X-ray	satellite (observat.)	2005	sNe+^{4}He cryost.+ADR	0.065	730 d	LEO	lost
Akari (ISAS)	IR	satellite (observat.)	2006	^{4}He (λ) cryost.+ cooler	1.8	550 d	LEO	operat.
Herschel (ESA)	FIR	satellite (observat.)	2009	^{4}He (λ) cryost.+^{3}He SC	0.3 & 1.7	4.5 a	Sun-Earth L2	developm.
Planck (ESA)	sub-mm	satellite (surveyor)	2009	H_2&^{4}He JT + DR	0.1 & 20	460 d	Sun-Earth L2	developm.
JWST (NASA)	NIR	satellite (observat.)	2013	passive rad.+ cooler	4 – 40	5–10 a	Sun-Earth L2	developm.
SPICA	MIR-FIR	satellite (observat.)	2017	passive rad. + cooler.	4.5	5 a	Sun-Earth L2	study
IXO (ESA, JAXA, NASA)	X-ray	instrument (observat.)	2020	Stirling cool.+ADR	0.05–0.3	> 5 a	Sun-Earth L2	study

Technology-demonstration missions

A number of space missions have been dedicated to the validation of specific cryogenic technological issues. In particular NASA has flown a number of cryogenic payloads on several space shuttle flights (*STS-77, 79* and *87*), including studies of superfluid helium (Chui et al 1994), test facilities (Bowman et al 1997) and coolers (Lipa et al 1996).

Cryo-electronics and large-scale applications

Electronics systems operating at cryogenic temperature have found application on board spacecraft. For example, in the case of ISOPHOT (on board *ISO*), a specific MOS IC (metal oxide semiconductor integrated circuit) was developed for the instrument front-end which demonstrated low-noise, low-dissipation, multiplexed operations, operating at cryogenic temperature (Dierickx et al 1996).

Another category of cryogenic device is the SQUID (superconducting quantum interference device). Such a device is the most sensitive magnetometer known to date, reaching sensitivities of the order of a few femtotesla per square root of hertz at frequencies of a few hertz. SQUIDs are used in very sensitive gravity gradiometers, fast digital electronics and detector read-out circuitry (Braginski 1999). Large-scale applications involving cryogenics in space include energy storage and gas storage for life support systems and propulsion purposes. Energy can be stored in the form of an intense magnetic field generated by a superconducting magnet to cope with sudden demands for large amounts of energy, which cannot be supplied by the combination of solar cells and batteries used on board spacecraft. The storage of gases in liquefied form is well known and offers obvious advantages for storage of large amounts in a limited volume tank. In addition this technique is relevant to life support systems for inter-planetary missions (e.g., future missions to Mars) or for the *ISS* (Kohout 1989). Required operating temperatures are less demanding in comparison with other cryogenics applications, depending on the different gases (H_2, N_2 and O_2), ranging between 20 K and 90 K.

Cryogenics and spacecraft engineering

Architecture of cryogenic spacecraft

A spacecraft is usually composed of a satellite bus (or service module) and a payload module. The payload module carries one or several instruments used to process signals coming from Earth or space, with either individual or common optics (main telescope) (Wertz and Larson 1999). Cryogenic installations have a strong impact on the architecture of both spacecraft and instrument. Key design factors are:

- A cooling system must be used with performances (heat lift, base temperature and hold time) compatible with both instrument requirements and spacecraft resources.

- The low-temperature equipment must be properly supported, insulated from the room temperature satellite bus and protected from solar, Earth or planet radiation.
- The cold parts have to be accessible (e.g., optical access to the focal plane) and wiring needs to be routed between cold payload and satellite bus.
- Cryogenic ancillary equipment is required to operate the cryogenic payload (e.g., heat links, heat switches, filters, thermometry).
- Activities related to assembly, integration and test (AIT) of cryogenic equipment must be taken into account already during the design phase.
- The complete system must survive the vibrations induced by the launcher.
- The cooler has to operate in zero gravity for a period of the order of a few years.
- The lifetime of the equipment should exceed the mission duration.

Space coolers

Coolers provide a cold heat sink, by removing the heat in the cold area and dissipating it into the warm area. Either the energy is directly radiated to space (via **radiators**), or work has to be performed to pump the energy between two temperature levels, from a cold to a warm level to then be more easily radiated away. Such an operation can be done using an open-cycle configuration or in a closed cycle.

The open cycle corresponds to the use of **stored cryogens**, where the work is performed before the mission, on the ground, by a liquefier. The cold heat sink is provided by evaporation of liquid or solid cryogens. The closed cycle corresponds to the use of **mechanical coolers**, where the work is done continuously during operations. Existing space coolers can provide about 1 W of cooling power in the temperature range 50 K to 100 K (Stirling coolers, pulse tubes), about 100 mW in the range 15 K to 20 K (double-stage Stirling), or a few milliwatt at 4 K (Joule Thomson). Very low-temperature coolers (e.g., ^{3}He cryo-sorption refrigerators, dilution or ADR) rely on the pre-cooling systems mentioned above to reach temperatures between 50 mK and 1 K. For base temperatures above 50 K a single stage can be sufficient. At lower temperature, multiple-stage systems with various types of coolers have to be used.

Types of coolers

Radiators are the most efficient, simplest and reliable space coolers. They are based on the fact that all objects emit infra-red radiation proportionally to their area S, emissivity ε, and to the fourth power of their temperature T, and on the fact that the ambient temperature (deep space) is very cold (black-body at $T_0 = 2.73$ K). The net cooling power is thus

$$Q_{\mathrm{rad}} = \sigma\, S\, F\, \varepsilon\, (T^4 - T_0^4) \cong \sigma\, S\, F\, \varepsilon\, T^4 \quad , \tag{37.1}$$

where σ is the Stefan constant and $F \cong 1$ is the shape factor (Bard 1984). Radiators are efficient above 100 K, but have limited performance at low temperatures and limitations related to their size (a few square metres on a spacecraft) and orientation: they need to be shaded from the solar radiation (1.4 $kW\,m^{-2}$), and from the Earth or planet infra-red and albedo radiation (about 300 $W\,m^{-2}$ for the Earth) and looking at dark space in order to efficiently radiate. For low Earth orbits, the temperature limit is about 100 K, with a cooling power lower than 1 $W\,m^{-2}$. For far-away orbits (e.g., Lagrangian points), the radiator architecture becomes simpler, with lower temperature and better performance. In the case of *Planck*, it is expected to have a cooling power of about 2 W at about 50 K.

A **stored-cryogen cooler** is composed of a cryogen tank, a vacuum vessel (isolating the cryogen tank before and during launch), filling and venting lines, heat shields / multilayer insulations (MLI), and some interface or volume for instrument accommodation. In the absence of gravity, the fluid needs to be maintained inside the tank by a phase separator. Space dewars, to withstand the launch loads, have specific supports and a separate venting line to efficiently use the gas enthalpy to cool the shields, and to release the gas without applying momentum to the spacecraft. In space it is also possible to cool the whole vacuum vessel by radiation to space and by the venting line (the *Herschel* vessel is expected to be at 77 K). The bath equilibrium pressure is not 1 bar as on ground, but it is vented to the space vacuum. This allows to pump on the cryogen bath and to use solid cryogens, which usually have a sublimation heat much larger than their latent heat. The proper design of the exhaust nozzle allows tuning the base temperature (vapour pressure) of the cryogen bath by adjusting the pressure drop. The volume of cryogen to be carried depends on the mission duration and on the heat input. The choice of the cryogen to be used depends on the base temperature required. The most widely used are superfluid or supercritical helium, solid H_2 and solid Ne. Bi-cryogen systems, such as N_2/He, or H_2/He, optimise the cooler mass, but their design is more complex, as all lines and valves have to be doubled. Coolers based on cryogens are cooled on ground and topped up just prior to the launch, while the low vapour-pressure is maintained by pumping on the bath through the vent line.

In a **mechanical cooler** mechanical work is transformed into refrigerating power. Active coolers can be categorised into *regenerative cycles* (Stirling, pulse tube, Gifford coolers) and *recuperative cycles* (Joule-Thomson or Brayton coolers). *Regenerative coolers* are based on a pressure wave generated by a compressor (usually mechanical), and a cold finger, using a mobile (Stirling, Gifford) or a fixed (pulse tube) regenerator. The heat is extracted at the cold end when the gas expands, and rejected at the warm end when the gas is compressed. The recuperative cycles use the enthalpy difference between high- and low-pressure gas. The Brayton-cycle coolers use a cold turbine to expand the gas, whereas the Joule-Thomson coolers use the expansion through an orifice, and the properties of real gas. The JT cooler (normally coupled to Stirling units) is less efficient than the Brayton, but it is simpler. A lifetime of five years is a typical requirement for most space applications (Ross 1990). A typical power allocation for a space cryo-cooler is between 50 W and 200 W. Most mechanical coolers (typically based on the Stirling cycle) have an efficiency of the order of 2 % to 5 % of the ideal Carnot cycle, implying a cooling power of a few milliwatt at 4.2 K with an input power of about

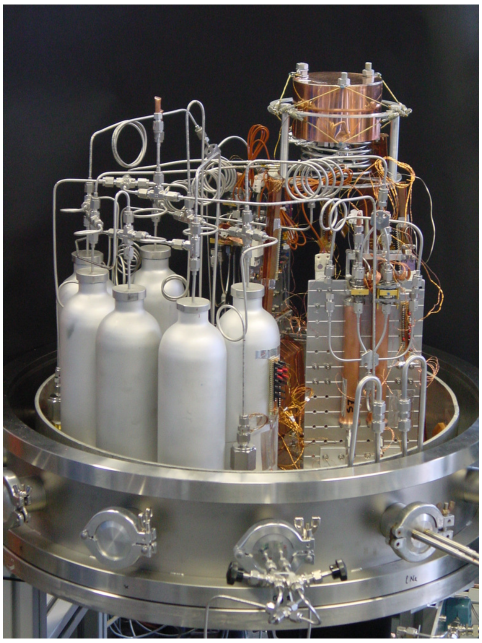

Figure 37.3: 4 K sorption-cooler prototype under development (Univ. Twente).

100 W. Mass also is a critical parameter in the evaluation of space coolers, since the typical allocated values are of the order of 100 kg to 150 kg. Coolers should not export vibrations degrading the performance of the instruments. To date most space mechanical coolers are based on the Stirling cycle or on the Joule-Thomson expansion, but more recently pulse-tube refrigerators have become an interesting alternative. Finally, we should mention the closed-cycle, hydrogen or helium-filled sorption coolers, an interesting alternative to mechanical coolers, such as the one developed by JPL (US) for the *Planck* mission (base temperature of 20 K, no moving parts) (Jones et al 1990) and a similar unit being developed by ESA (Figure 37.3) (Burger et al 2002).

Very low-temperature coolers ($T < 1$ K)

In many scientific satellite applications it is necessary to achieve temperatures well below 1 K. Such a temperature (cf., Figure 37.1) can be achieved by using closed-cycle ^{3}He sorption coolers (down to 250 mK), by dilution refrigerators (50 mK to 100 mK) and by adiabatic demagnetisation refrigerators (50 mK to 300 mK).

^{3}He sorption coolers offer simplicity of operations, lack of moving parts and closed-cycle operations with an efficient duty cycle (^{3}He condensation phase vs. hold time at base temperature). Typical cooling power is of the order of 10 µW at 300 mK. Sorption coolers have flown aboard balloons (Boomerang, Maxima, Archeops), sounding rockets and on the satellite *SFU* (IRTS, Infrared Telescope in Space instrument) (Freund et al 1998). Sorption coolers are also used on board *Herschel* instruments SPIRE and PACS.

Dilution refrigerators, based on the quantum-mechanical properties of ^{3}He–^{4}He mixtures, are routinely used on ground to achieve temperatures below 100 mK, with cooling power exceeding 100 µW. This technique has been adapted for space applications for *Planck* (cooling power $\approx$ 0.1 µW, Benoit and Pujol 1991), avoiding circulation pumps by working in open loop, thus requiring a very large amount of gas mixture with a lifetime limited by the gas reservoirs. A closed-loop approach is under study.

Adiabatic demagnetisation refrigerators have been already used on board sounding rockets and scientific satellites (*ASTRO-E*) (Hagmann and Richards 1995). They produce base temperatures of the order of 50 mK to 100 mK by reducing the entropy associated with the electronic spins of the atoms of paramagnetic salt, aligned by a magnetic field of the order of a few tesla. Cooling powers of about 1 µW to 10 µW are achieved (Pobell 1996). ADRs offer very low base temperatures with simple operations and good duty cycle efficiency. The main challenges are the need for large magnetic fields and for high performance and high-reliability thermal switches. The use of an ADR system is proposed for a number of future science missions, including *IXO* and *SPICA*.

Solid-state coolers, equivalent to Peltier elements but operating below 1 K, are being investigated. Based on normal metal-insulator-superconductor (NIS) junctions, they provide cooling of the lattice by relying on phonon-electron coupling and removing the hottest electrons present in the normal metal electrode of the device (Nahum et al 1994). Cooling of membranes from 0.3 K to 0.1 K has already been achieved. Such coolers are developed with the aim of building self-cooling detectors (e.g., bolometers), capable of operating with simpler pre-coolers (e.g., ^{3}He sorption coolers instead of ADR).

Insulation technology and ancillary cryogenic equipment

Thermal insulation is used to limit the heat loads (due to conductive and radiative coupling) on the cold stage to a level compatible with the heat lift of the cooler.

Low-conductive supports are key elements of the structure of any cryogenic payload, in view of the launch loads. Steel and titanium alloys are still frequently utilised, but Kevlar, glass and carbon fibre based materials find ever more applications. Struts, tension straps, are used to support dewars and cold stages. Kevlar strings are preferred to ensure a high degree of stiffness combined with small contact surfaces. A review of cryogenic structural supports and materials can be found in Reed and Golda (1990).

Multilayer insulation is commonly used on ground as well as in space. MLI consists of a stack of polyester (Mylar) or polyamide (Kapton) foils which are embossed, crinkled or separated by a spacing material, such as a thin net. The foils are aluminised on one or both sides to reduce the radiative transfer, thus protecting the spacecraft from intense solar radiation and insulating the low-temperature stages (Bapat 1990).

V-groove shields are based on a few (< 5) angled and highly-reflective solid plates, open to space, rejecting radiation after a number of reflections between the angled shields (rather than trapping it between layers as with MLI). V-grooves play a critical role on *Planck*. Additional details can be found in Bard (1987).

Cryogenic ancillary equipment plays a critical role during ground testing as well as in flight. We list here the key items required on board spacecraft.

High thermal conductivity links ($K > 1$ W/K) are required to link the focal plane to the cold stage of the cooler. Such links need to be flexible and electrically insulating as well as damping any cooler vibrations. Cryogenic heat pipes are under development (Gilman et al 1995).

Heat switches have a key role in several units, including ^{3}He sorption coolers and ADR systems. To date gas-gap switches (cryo-sorption based) and electro-mechanical switches are used, but their performance and reliability need improvement (Torre and Chanin 1984).

Pressure, level and flow meters are required to monitor the performance of cryogenic equipment on board spacecraft. There are almost no such devices that are space-qualified.

Space-qualified temperature sensors are a critical item, especially at $T <$ 1 K. An overview of cryogenic thermometry is provided in Rubin (1997).

Cryogenic cables with low thermal conductivity, low electrical resistance and low capacitance are crucial for space instrumentation, especially at $T < 1$ K. Ribbon cables can provide 1000 lines (metal or superconductor), with a resistance $< 20\,\Omega$ and a total load at the lowest temperature stage of less than 20 µW at 0.3 K (Cunningham et al 1995).

Key technologies and programmatic aspects

Based on typical applications, a number of critical technologies can be identified. A short description of the main development needs is provided below.

Passive radiators (40 K $< T <$ 100 K) play a major role, reducing the requirements imposed on active cooling systems. Further improvements are needed to ensure high emissivity at low temperature and better thermal isolation solutions.

Active cooling systems — the few existing space-qualified coolers are very expensive (on the order of a million euros) and heavy; they remain a major source of vibrations and their efficiency needs to be improved.
20 K coolers are essential pre-cooling stages. Stirling coolers are difficult to accommodate, while Joule-Thomson coolers are less efficient. Modularity and cooling power scalability need to be improved. Cryo-sorption systems (e.g., H_2 based) are a valid option and need further development.
2 K to 4 K coolers should provide greater cooling power (> 50 mW) to support lower temperature stages. Minimisation of vibrations is required for very low-temperature systems, sensitive detectors and high-accuracy spacecraft pointing and/or positioning (e.g., interferometry applications).

Very low-temperature coolers ($T < 1$ K) are essential to future space missions. A large effort is required to develop closed-loop, space-qualified coolers (such as ADR, DR, sorption coolers), offering reliable performance and long lifetime (>5 years).

Finally the development of ancillary equipment and devices (e.g., heat pipes, heat switches, thermometry and cryogenic mechanisms) should not be neglected. The use of cryogenics in space projects also has a number of important programmatic implications. The complexity, duration and cost of integration and end-to-end test activities are key examples, with a large impact on any space project. In fact, typical turn-around times of complex cryogenic systems and test facilities are of the order of several weeks. In order to simplify the verification phase, timely development of the cryo-chain units is required (by the end of phase B). On this basis, a thorough scrutinity of the requirements and a vigorous technology demonstration plan are essential activities during the assessment study phase (phase 0 / phase A). Adequate resources must be made available in order to raise the technology readiness of key units in the early phases of the programme.

Conclusions

The use of cryogenic detectors on board spacecraft has allowed unprecedented results, especially in the field of astrophysics. Over the last 25 years, several missions have demonstrated the advantages of cryogenic instruments, although at the expense of additional system complexity, increased development risk and increased cost.

Cryogenics will continue to play a key role on board science missions. In fact, future astrophysics applications require large-format detectors operating at ≈ 50 mK to 100 mK, with cryogenic front-end electronics, and, in the case of medium and far infrared, cold-entrance optics. The development of such complex cryogenic payloads calls for a truly system approach, involving the complete spacecraft design from the assessment phase. Clear examples are set by several space-science observatories, which are built around their cryogen tanks, or by the crucial role played by mission operations control in the case of passively cooled instruments. Significant development effort is required to further improve the performance of cryogenic systems, to enhance cooling efficiency and reliability, and to reduce resource demands as well as cost. Such development must be undertaken in the early project phases, based on actual flight requirements, so as to minimise the risks during phase C/D when the impact of design changes is largest. The effort produced in this field by the leading space organisations shows without any doubt that cryogenics is going to play a strategic role on board future space missions.

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