The Herschel space telescope

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Celestial objects such as stars, planets, galaxies, interstellar gas or interstellar dust emit light or general electromagnetic radiation of very different wavelengths. In order to investigate them as accurately as possible we need measuring instruments that are sensitive to the various wavelength ranges or spectral ranges. Very cold objects, for example, emit the majority of their light in the infrared range of the electromagnetic spectrum. The radiation of very distant celestial bodies is also best observed in the infrared.

The Herschel space telescope (Fig. 1) has been developed as an important European contribution to the study of very cold and very distant objects. The device will be able to very accurately measure infrared radiation coming from space and map objects that emit infrared radiation. The focus of this space mission is on the range of the ‘far infrared’. Now, with Herschel, this part of the infrared spectral range with the longest wavelengths can now be observed for the first time!

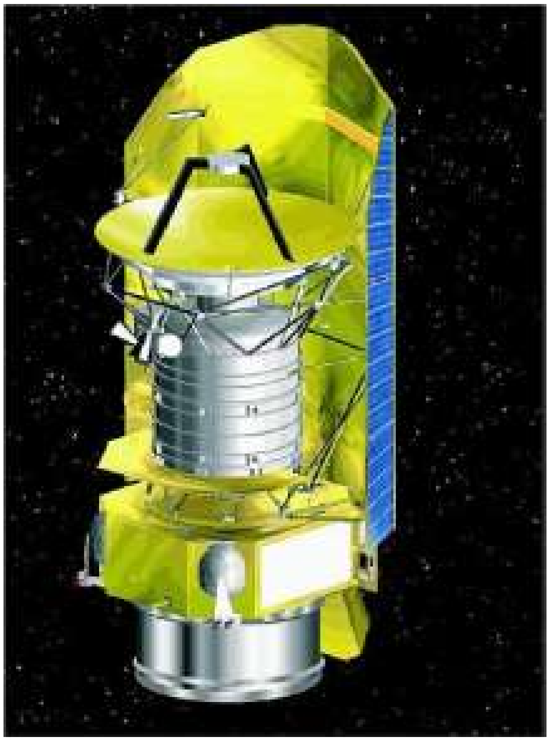

Fig. 1: The Herschel space telescope. (Picture: http://www.mpe.mpg.de/PIFICONS/herschel.jpg)

The following **tasks** should help us to understand why certain celestial bodies emit infrared radiation or why they are ‘visible’ in this spectral range in particular. Furthermore we will examine what **problems** arise during the construction of measuring instruments for infrared radiation and **how they can be solved.** To ensure that such devices work, they must be very significantly cooled, i. e. to just above absolute zero in this case. Above all we will deal with the question of why the device must be cooled to such a degree and how it works.

Overview of references		
Astronomy	Space travel, applied astronomy, diffuse medium, cosmos	Electromagnetic spectrum, cold objects, infrared radiation, objects in the early universe, cosmological redshift, interstellar matter
Physics	Thermodynamics	Thermal radiation (heat radiation), intensity, radiant power, black body , temperature radiation , Planck’s radiation law , radiation curves, Wien's displacement law, heat conduction, cryophysics
Related disciplines	Astro / physics	

1. Why do we need space telescopes and infrared astronomy?

When we use our eyes or use photographic methods we can only perceive a very small part of the electromagnetic radiation that comes from space: the visible light or, expressed more scientifically, the optical spectral range (Fig. 2). By far the largest part of the electromagnetic spectrum, the short-wave gamma, X-ray and UV radiation and the long-wave infrared, microwave and radio radiation, remains invisible to us.

In addition there is the fact that the Earth's atmosphere swallows almost all of the short-wave and therefore high-energy and dangerous radiation as well as the majority of the harmless infrared radiation (Fig. 2). It simply remains lodged in the higher layers of the atmosphere, more or less like the UV light in the ozone layer. In contrast, the majority of the longer-wave microwave and radio radiation that is not dangerous to life on Earth passes unhindered to the surface of the Earth.

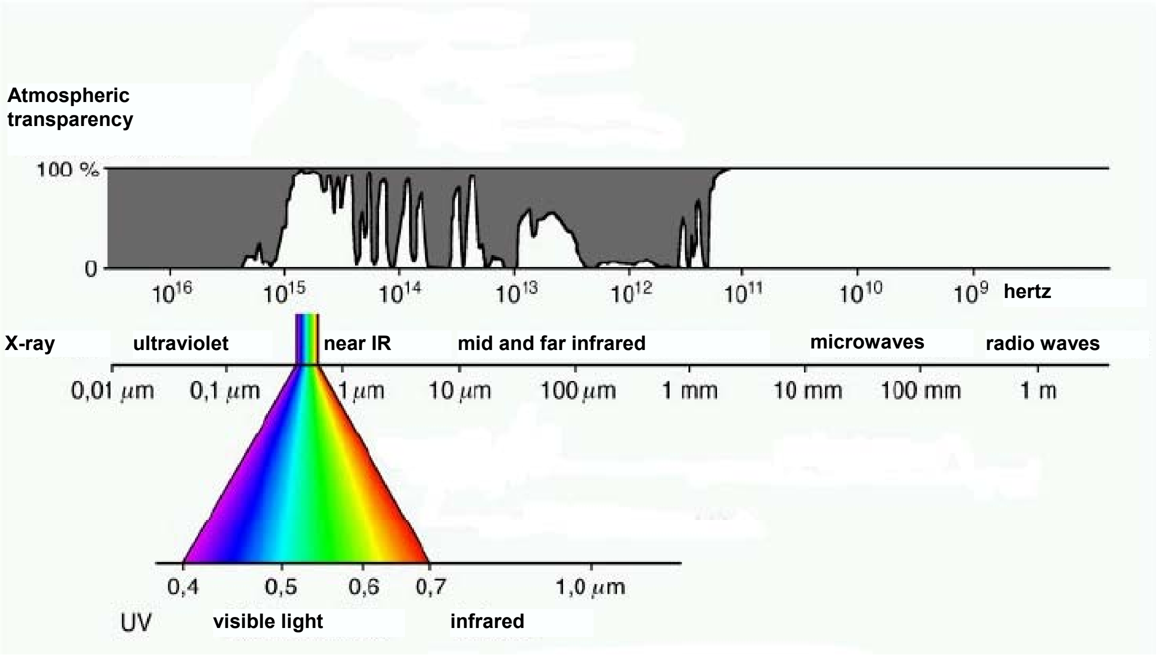

Fig. 2: Spectrum of electromagnetic radiation and transparency of the Earth's atmosphere for the different wavelengths (in metres) and frequencies (in hertz). The white areas show what percentage of the radiation of a certain wavelength or frequency hitting the atmosphere reaches the Earth. (Picture: www.fe-lexikon.info/images/Spektrum.jpg)

If we limited ourselves to the study of visible light many of the processes in space would remain hidden to us. In order to understand how the universe 'really works', we must study all of the electromagnetic radiation and therefore all wavelength ranges coming from space accordingly. The Herschel space telescope developed by the European Space Agency ESA is an important step in this direction. It will examine even more closely those parts of infrared light that have already been measured and for the first time open up the range of the far infrared that until now has not been accessible to observations.

Bodies emit electromagnetic radiation due to their temperature. This radiation is called 'thermal radiation', 'temperature radiation' or 'heat radiation'. Stars are so hot that they emit the majority of their heat radiation in the range of UV radiation and visible light. Therefore depending on the temperature they appear bluish-white to us (very hot, up to 50 000 K[1]), yellow, orange-coloured or red (very cool, not more than 2.500 K).

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[1] In physics and therefore also in astrophysics the temperature is measured in the unit of Kelvin (K). Zero on the Kelvin scale is absolute zero temperature. If a body were to have a temperature of 0 Kelvin it would possess absolutely no kinetic energy. 0 degrees Celsius equals 273.16 Kelvin.

If bodies such as stars emit light due to their temperature the same must apply in principle to all other objects, regardless of whether they have an extremely high or an extremely low temperature. And this is exactly the case. However we can only ‘see’ the heat radiation of very cold objects with the help of special detectors such as the measuring devices on the Herschel space telescope. This is because very cold objects emit the majority of their heat radiation in the infrared spectral range that is invisible to us.
But it is not only very cold objects that are best observed in the infrared: the same applies to very distant objects also. Here we mean the first stars and galaxies that were formed in the earliest period of the universe (Fig. 3). These celestial bodies also emitted in the optical spectral range a majority of the light that reaches the Earth today after a journey of several billions of years. Nonetheless, we are unable to observe them in this spectral range. They have ‘disappeared’ from the range of visible light, so to speak. What appears to be paradoxical at first glance can be understood when we examine what happens to the light during its long journey through space towards the Earth (keyword: ‘cosmological redshift’).

Exercise 1.1: What ranges is infrared radiation divided into and which wavelengths does each range cover?

Exercise 1.2: Why is infrared light best able to be observed using space telescopes?

Exercise 1.3: Cold interstellar dust clouds also emit heat radiation due to their temperature. What is their temperature? What wavelength λ_{max} does their radiation maximum have? Accordingly, in which spectral range do they emit most light? (see appendix: ‘black body ’)?

Exercise 1.4: What does ‘redshift’ mean? How is it defined? What does ‘highly redshifted’ mean? What causes high redshifts?

Exercise 1.5: Why is the far infrared used to investigate both cold and dust-covered as well as highly redshifted radiation sources? Have these two types of object undergone similar physical processes or are they fundamentally different?

Exercise 1.6: What does the term ‘early universe’ mean? Why is it possible to use Herschel to investigate the ‘early universe’?

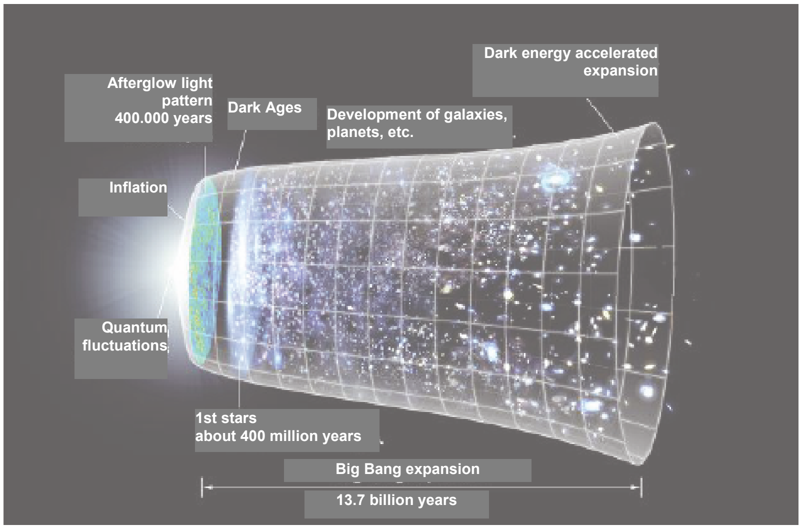


Fig. 3: Chronological development of the universe from the Big Bang until today (from left to right). Important development phases are marked. The first stars were formed around 400 million years after the Big Bang. (Picture: http://map.gsfc.nasa.gov/m_mm.html).

2. Requirements when building infrared telescopes: cooling

Measuring instruments for the infrared radiation are special devices that must satisfy special requirements. The following exercises are intended to clarify the practical problems that arise during construction and how they are solved. The cooling of the detectors that make measuring the infrared radiation possible in the first place is especially important.

Exercise 2.1: Estimate how much energy from the Sun reaches Herschel. The telescope corresponds to a cylinder with a diameter of 4 m and a height of 7.5 m (Fig. 4). The Earth receives a radiant power of 1370 W per m^2 from the Sun. Herschel is around 1 % further away from the Sun than the Earth. (The intensity received is proportional to $1/r^2$)

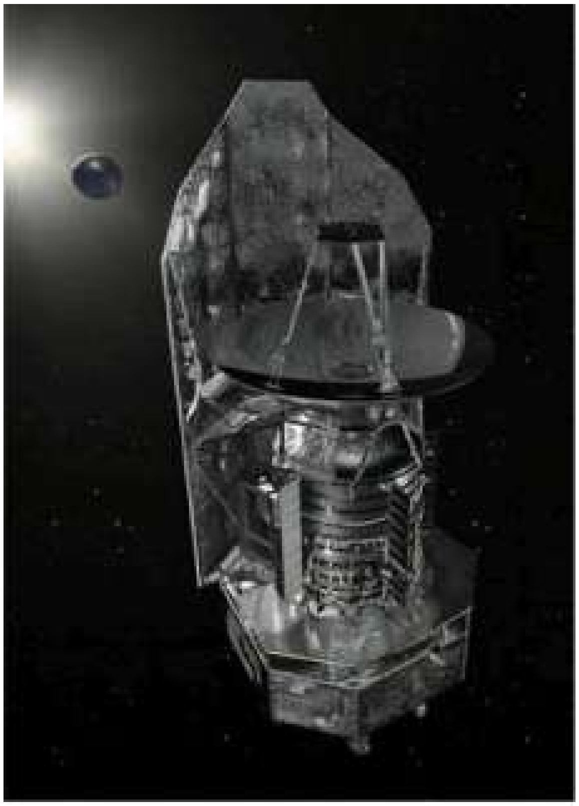


Fig. 4: The space telescope Herschel in space (artist's impression).
(Picture: http://regmedia.co.uk/2007/09/20/artist_view.jpg)

Exercise 2.2: Estimate how much energy in the form of heat radiation from the Earth reaches Herschel. The Earth emits just as much energy into space per second and per cm^2 as a 'black body' that has a temperature of 256 K (see appendix). For this reason we say: 'The Earth has an effective temperature T_{eff} of 256 K.' The total amount emitted by the Earth in the form of heat radiation is:

$$I_{\mathrm{total}} = 4\pi R_{\mathrm{earth}}^{2} \sigma T_{\mathrm{eff}}^{4} \quad \text{(where } R_{\mathrm{earth}}\text{: radius of the Earth)}$$

Calculate the radiation I_{total}. A black body with a temperature of 300 K emits a heat radiation of 46 mW per second and per cm^2 into all of space. Explain the terms 'black body ', 'albedo' or 'reflectivity ' and 'absorptivity ε' (see appendix). Why can we use a black body as an object of reference for the Earth or other objects that emit heat radiation?
Herschel will be located at a distance of r = 1.5 mill. km from the Earth. When the space telescope picks up the radiation coming from the Earth each second with the area F and the absorptivity ε it receives the radiant power $I = (I_{\mathrm{total}}\, \varepsilon F) / (4\pi r^2)$ from the Earth. Calculate the radiant power I picked up by Herschel. For ε , $\varepsilon = 1$.

Exercise 2.3: How does the telescope's large radiation shield work (Fig. 5. left)? Because the Sun and the Earth lie in the same direction as seen from Herschel (Fig. 4), the radiation shield effects a shadow for both the radiation from the Sun and the radiation from the Earth. If we assume that the radiation shield picks up 5 % of the radiant power reaching it from the Sun and the Earth (ε = 5 %) it increases its temperature until the amount of radiation that is emitted due to heat radiation from the front side (Fig. 5. left), ε = 5 %, and from the reverse side (Fig. 5. right), ε = 1 %, is exactly the same as the amount of radiation that has been picked up. What temperature does the radiation shield then have and what radiant power does it subsequently release to the telescope?

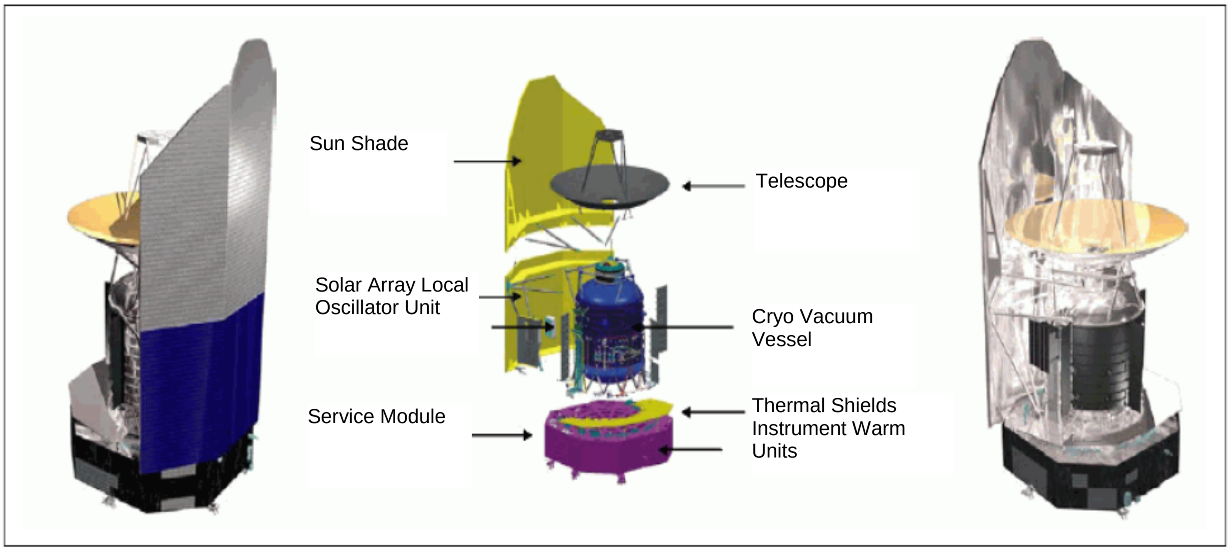
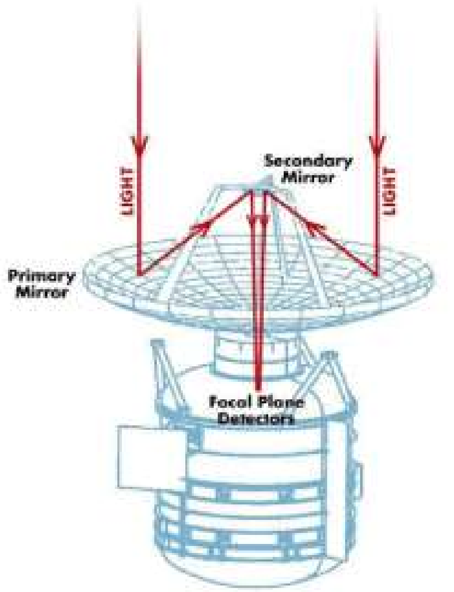


Fig. 5: Construction of the Herschel space telescope. Left: 'warm ' side, i.e. the side turned towards the Sun and the Earth; centre: Overview of the individual components; right: 'cold' side, i.e. the side of Herschel that is turned away from the Sun and the Earth. (Picture: http://herschel.esac.esa.int/Docs/Herschel/html/ch01.html)

Exercise 2.4: Estimate the radiation intensity I_{mirror} that the telescope emits due to its own temperature. For the primary mirror with a diameter of 3.50 m, $\varepsilon = 0.8\ \%$. If: $I_{\mathrm{mirror}} = \pi\, r_{\mathrm{mirror}}^2\, \varepsilon\, \sigma\, (80\ \mathrm{K})^4$. How large is the portion of the heat radiation caused by the primary mirror itself that falls onto the secondary mirror and is directed from there into Herschel's interior (Fig. 6)?



Exercise 2.5: The wavelength maximum $\lambda_{\max}$ for the heat radiation shifts with the temperature T: $\lambda_{\max} = 0.002898\ \mathrm{mK}/T$ (Wien's Displacement Law, Fig. 9). At what temperatures T would this maximum lie in the range of wavelengths that can be observed by Herschel's instruments (60 µm - 600 µm)?

Fig. 6: Schematic diagram of the Herschel space telescope: The light coming from the celestial bodies is collected by the primary mirror and guided to the secondary mirror. From here it enters the cryostat in which the measuring devices are located. (Picture: http://herschel.jpl.nasa.gov/ spacecraft.shtml)

Exercise 2.6: Based on exercises 2.4 and 2.5 explain why the measuring instruments on board Herschel must be cooled to such an extent.

Exercise 2.7: Why are we able to draw conclusions about the temperature of an object by comparing measurements in different wavelength ranges with radiation curves of black bodies?

Exercise 2.8: Herschel's measuring devices are located in a thermos flask, the cryostat (Fig. 7 and 8). This is built such that as little heat as possible is able to leak from the outside to the inside. The inner part is cooled by the evaporation of liquid helium. It is enclosed in three additional shells, i.e. the radiation shields.

The helium, which evaporates at 2.8 K, is routed to the three radiation shields through a series of pipelines. When it reaches the outer shell it is emitted into space. At the first radiation shield the helium will have reached a temperature of 15 K, at the third radiation shield it is 150 K. When it leaves the telescope it will have heated to 200 K. What quantity of heat will 1 litre of liquid helium have absorbed a) when evaporating internally, b) as a gas by the time it reaches the first radiation shield, c) by the time it reaches the third radiation shield and d) by the time it leaves the telescope?

Exercise 2.9: The external shell and the radiation shields also emit energy in the form of heat radiation internally. Estimate the power that the 1st radiation shield, the 3rd radiation shield and the outer shell release internally if for their respective surfaces $\varepsilon = 1\ \%$.

Fig. 7: Cryostat and service module of the Herschel space telescope. (Picture: http://www.esa.int/esaSC/ SEM0ZJJPK6F_index_0.html)

Exercise 2.10: The cold inner part of the cryostat must be attached to the outer shell of the device such that the device is able to withstand the vibrations during the launch of the carrier rocket. Heat is of course able to enter internally via these attachments. For this reason these attachments should be as thin as possible. In the case of a bicycle the spokes are very thin but also attach the hub to the wheel in a way that guarantees tensile strength. The inner part of the cryostat is attached to very thin spokes in a similar manner. Estimate how much heat flows through a spoke of this type that is 1m long and has a cross sectional area of 1mm^2 if one end has a temperature of 2.8 K and the other 15 K. What would be the level of heat exposure if the spoke was attached to an outer shell with a temperature of 200 K?

How does the level of heat exposure via the spoke vary if we double the length of the spokes or triple the cross sectional area?

Exercise 2.11: At what helium vapour pressure do we attain a temperature of 1.6 K? How can this low pressure be generated?

Exercise 2.12: An absorber (zeolite or activated carbon) binds ^3He to itself, thus pumping it away. How high does the vapour pressure of ^3He have to be in order to attain a temperature of 0.3 K?

Exercise 2.13: What amount of ^3He do we need if we want to attain a heat output of 10 μW over 45 hours?

Exercise 2.14: Why is the chopper able to improve the signal-to-noise relationship?

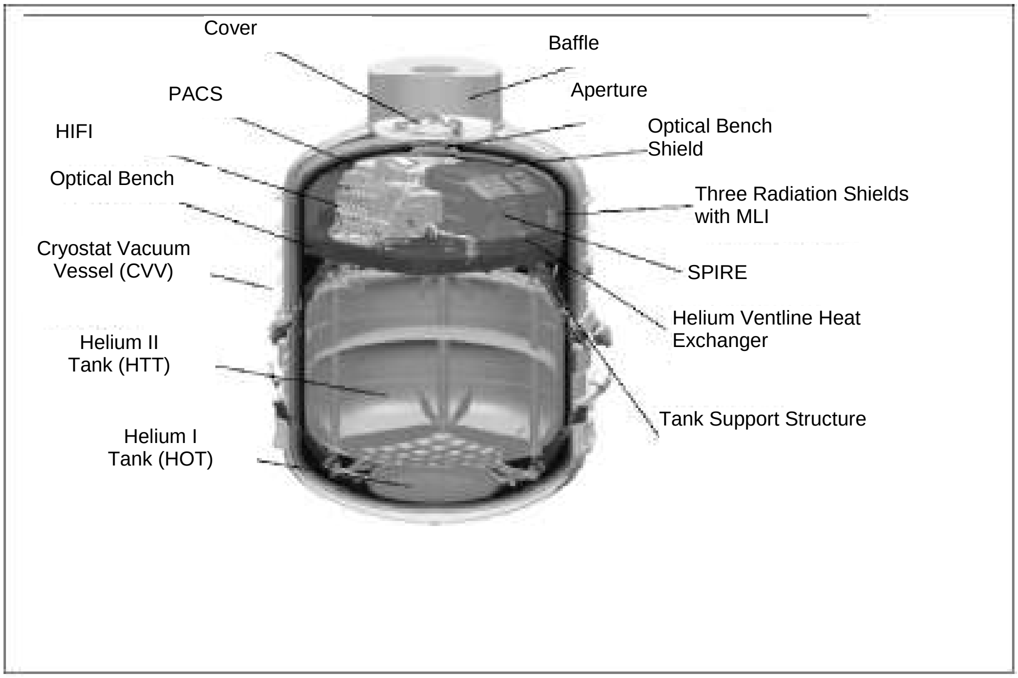


Fig. 8: The measuring instruments and the radiation shields required to cool them, as well as the tanks for the cooling agent helium, are located in the cryostat of the Herschel space telescope. The tanks hold almost two thirds of the cryostat. (Picture: http://herschel.esac.esa.int/Docs/Herschel/html/ch01.html)

Appendix

The black body

Each body emits heat radiation due to its temperature. The intensity of this radiation depends very strongly on the wavelength λ (the colour) of the radiation and on material properties of the body. In addition, the size of the angular range dΩ in space in which the heat radiation is emitted and the wavelength range dλ that is being studied are also important.

A body that is able to absorb all of the radiation that hits it (which has an absorptivity of $\varepsilon = 100$ %) and which can completely emit this radiation back (which has a reflectivity or albedo of 100 %), is an ideal radiator, a ‘black body’. The intensity I that is emitted from a part of the surface of the black body (dA) is obtained using Planck's radiation law:

$$I = \frac{2 \cdot h \cdot c^2}{\lambda^5} \cdot \left[\frac{1}{\exp\left(\frac{h \cdot c}{k \cdot \lambda \cdot T} \right) - 1} \right] \cdot d\lambda \cdot d\Omega \cdot dA.$$

The heat radiation emitted by a black body with a temperature T has its maximum at wavelength $\lambda_{\max}$ (Wien’s displacement law):

$$\lambda_{\max} = 0{,}0029 \text{ m} \cdot \text{K} / T$$

The black body is an idealised body that does not exist in nature. In experiments we can only approximately realise its characteristics within limited wavelength intervals. Because it emits its heat radiation in accordance with Planck's radiation law which in turn depends solely on the temperature, material characteristics are irrelevant.

The radiation pattern of a black body, i.e. the radiation intensity I (amount of radiation emitted per unit of time and per unit of area) or the radiant power P (amount of radiation emitted per unit of time) per wavelength λ at a given temperature T can be calculated exactly (Fig. 9). Because of these idealised characteristics (only dependent on temperature) we can use black bodies to investigate the heat radiation emitted by real bodies (‘grey bodies’ - not purely dependent on temperature!) and to determine the amount of energy that is emitted at least approximately.

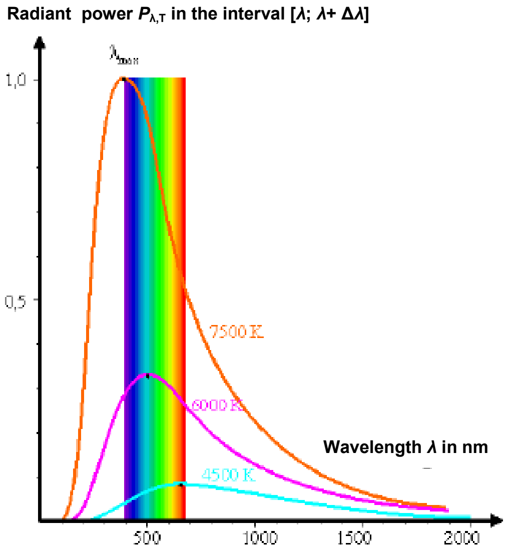


Fig. 9: Radiation pattern of a black body (Planck's radiation curves): As the temperature increases the total amount of the heat radiation emitted also increases. The wavelength at which most of the radiation is emitted ($\lambda_{\max}$) moves to decreasingly shorter wavelengths as the temperature increases. The amount of radiation that falls on a certain area per unit of time is called radiant power P or intensity I. The range of visible light is marked in colour. (Picture: http://leifi.physik.uni-muenchen.de)

Table 1: Characteristic data of ^{3}He (helium-3) and ^{4}He (helium-4)

	Helium-3	Helium-4
Gas density under standard conditions	0.135 kg / m^3	0.179 kg / m^3
Density of the liquid at boiling point	0.058 kg / l	0.125 kg / l
Heat of vaporisation (V enthalpy)	8.302 kJ / kg	20.43 kJ / kg
Boiling point	3.2 K	4.2 K

Table 2: Energy content (enthalpy) H from gaseous helium-4

T in K	4.2	15	50	100	150	200
H in (kJ / kg)	0	4.8	15	30	45	59

Table 3: Vapour pressure above liquid helium-3

T in K	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
p in hPa	0.0016	0.009	0.037	0.21	0.72	1.84	3.85	7.06

Table 4: Vapour pressure above liquid helium-4

T in K	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8
p in hPa	0.16	0.83	2.88	4.80	16.63	31.69	53.94	84.39	124.96	177.27

Re: heat conduction

If a rod has length l and cross sectional area A, and if one of its ends has the temperature T_1 and its other end has the temperature T_2 the heat $Q = \kappa \cdot (T_2 - T_1) \cdot A / l$ flows through it. The following applies for nylon:

T in K	0.4	1.0	4.0	10.0
κ in (mW / cm K)	0.006	0.025	0.125	0.390

For a rod made of nylon we can also find a table that specifies the amount of heat Q that flows from the end with the temperature T_2 to the end with the temperature $T_1 = 4$ K: $Q = W(T_2) \cdot A / l$

T in K	6	10	20	40	60	80	100	120	140	160	180	200
W in W/cm	0.321	1.48	8.23	38.5	85.9	142	204	269	336	405	475	545

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