Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 50 (2012) 346–350

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Passive cooling of superconducting magnetic systems in space

Piero Spillantini *

INFN branch and Physics Department of the Firenze University, Via Sansone 1, I-50019 Sesto Fiorentino, Firenze, Italy

Received 21 November 2011; received in revised form 29 March 2012; accepted 5 April 2012
Available online 17 April 2012

Abstract

The equilibrium temperature of a system in space can be lowered by a suitable choice of its geometry and its attitude. This remark is important for devices based on medium temperature and high temperature superconducting materials, and offers the possibility of their fully passive cooling without or with a marginal recourse to active systems. General parameterizations are given and simple schemes discussed. The adopted geometrical configuration and the attitude can enhance the role of passive cooling of the large superconducting magnetic systems required for protecting from ionizing radiation manned habitats in deep space. A specific example based on MgB_2 cable for protecting large volume habitats (500 and 1000 m^3) is treated. The systems can be run in deep space at equilibrium temperatures around 20 K mainly by passive cooling, provided that their geometry and attitude would be suitably chosen.

Keywords: Passive cooling; Superconducting magnets; Radiation shielding; Manned missions

1. Introduction

The equilibrium temperature of a system in space is obtained by matching the absorbed heat with the heat radiated to space. Its role was considered twenty years ago (Cocks, 1991) for the DHTSC (Deployable High Temperature Superconducting Coil) for the protection from ionizing radiation of habitats in deep space. When the Sun can be accounted as the only source, as it is far away from celestial bodies, the absorbed heat is proportional to the sun constant (1.35 kW/m^2 @ 1 AU), the absorptive constant α and the area A_a of the absorbing surface. The radiated heat depends on the Stefan–Boltzmann constant σ and is proportional to the emissivity constant ε, the area A_e of the radiating surface and the forth power of the equilibrium temperature T_{eq}. By their matching (and neglecting the temperature of the CMB, to be considered between 3 K and 7 K, depending on the cosmic dust around the Sun, and indeed from the distance from the Sun (Kelsall et al., 1993)):

$$T_{eq}^4 = (S/\sigma) * (\alpha/\varepsilon) * (A_a/A_e) = (S/\sigma) * R_{ae}/R_A$$

In the hypothesis that the system could be considered in static equilibrium, without temperature differences among different parts (i.e. a 'point-like' system) this relation can be used to construct the plot of Fig. 1, relating T_{eq} to the ratio A_e/A_a between the radiation and absorption areas, parameterized for several values (1, 0.1, 0.01, 0.001 and 0.0001) of the total insulation from the sunlight $R_{ae} = \alpha/\varepsilon$ (including the heat absorption and heat radiation constants, and considering the whole absorbed heat released to space at the same T_{eq}).

The value $R_{ae} \cong 0.01$ can be reached by an optimal reflection of the incoming sunlight; a multilayer insulation (MLI) can add two further orders of magnitude allowing reaching $R_{ae} \cong 0.0001$. Values $R_{ae} = 0.001$ and $R_{ae} = 0.0001$ can be considered the conservative and 'advanced' limits of a 'realistic' range, whereby the corresponding limits for the range of T_{eq} are:

$$T_{eq} = 69.9\ \mathrm{K}/\sqrt[4]{R_A} \quad \text{for} \quad R_{ae} = 0.001$$

$$T_{eq} = 39.3\ \mathrm{K}/\sqrt[4]{R_A} \quad \text{for} \quad R_{ae} = 0.0001$$

---

* Tel.: +39 055 4572261/+39 335 395941; fax: +39 055 4572367.
E-mail address: spillantini@fi.infn.it

0273-1177/$36.00 © 2012 COSPAR. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.asr.2012.04.006

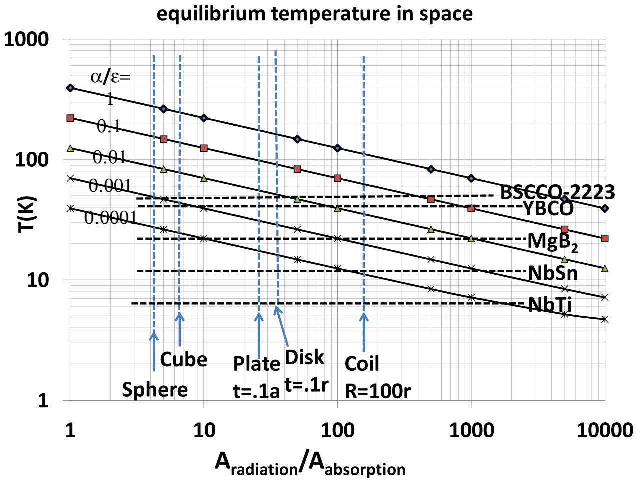


Fig. 1. Equilibrium temperature as a function of the ratio R_A between the radiating and absorbing areas for several values of the insulation from sunlight. Horizontal dashed lines indicate the critical temperature at a few tesla of the superconductors of Table 1. Vertical dashed lines indicate the possible ratio R_A between the radiating and absorbing areas for the different geometrical configurations reported in Fig. 2.

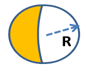
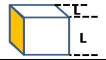
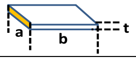
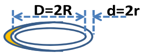
		$A_{absorption}/A_{radiator}$	T_{eq}(K) for $R_{ae}=10^{-4}$
(a) - Sphere		**$\pi R^2/4\pi R^2 = 0.25$**	**27.8**
(b) - Cube		**$L^2/6L^2 = 0.133$**	**23.7**
(c) - Plate		**at/(2ab+2a+2b) t=0.1a, a=b → R_A =1/24**	**17.8**
(d) - Disc		**2rt/(2πr2+2πrt) t=0.1r → R_A =1/34.5**	**16.2**
(e) - Ring		**(4Rr)/((4π²Rr)+2πR²= R=100r → R_A =1/160**	**11.2**

Fig. 2. Equilibrium temperatures for simple geometries exposed to sunlight from left, as indicated in the figure. In principle in the radiating area also the absorbing area must be accounted, also if in practice it is difficult to be achieved.

In the following the 'advanced limit' will be used considering the fact that our examples are for the far future, when the required technical progress could allow this value to be reached.

2. Role of passive cooling in superconducting systems

The role of passive cooling in space is one of the main ingredients of the thermal analysis of spacecrafts, and a quantity of literature and computer codes exists. Its early consideration is very important because it can drastically change the picture for how to lay out the structure and attitude of the space system and the mission profile. This importance is nowadays highlighted in view of the necessarily large electromagnetic systems that will be operated in space in the future interplanetary missions and interplanetary stations. Furthermore it acquires a particular role in the light of the progress in the production of new superconducting materials in the last two decades.

Main properties of the currently produced superconductor cables are summarized in Table 1. Some of these superconductors can be operated at temperatures much higher than those of the 'traditional' low temperature superconductors NbTi and NbSn. The critical temperatures of the superconductors reported in Table 1 operated at a few tesla are indicated in Fig. 1 by horizontal dashed lines. It can be noted that T_{eq} suitable to maintain superconductivity in the low temperature superconductor NbTi can be reached only for extreme values of the R_A ratio (>10^3) and for the NbSn low temperature superconductor R_A values exceed 10^2, which could be difficult to be obtained by configurations and attitude in space. See in fact Fig. 2, where T_{eq} that can be reached by some simple configurations are reported. Their possible R_A values are reported by vertical dashed lines in Fig. 1. It is clear from the figure that the medium and high temperature superconductors offer more possibilities for reaching equilibrium temperature lower than their critical temperature by suitable configurations of the system and suitable attitude in space. With $R_{ae} \approx 0.0001$, temperatures lower that 40 K, suitable for the operation at a few tesla of high temperature superconductors YBCO and BSCCO-2223, can be reached for any value of the ratio R_A between the emission and absorption areas. For what concerns the medium temperature MgB_2 superconductor (Nagamatsu et al., 2001; Dou et al., 2006), operating temperatures ⩽20 K can be reached for geometries such as plates, disks or rings. For cases (c)–(e) of Fig. 2 the ratio between the geometrical dimensions of the system parallel to the Sun direction and those transverse to the Sun direction cannot be pushed to very high values because the Sun itself, as seen from the system, is not a point, but a disk spanning an angle (9.3 mrad @ 1 AU), what limits the ratio between the two perpendicular views to about ⩽100 @

Table 1
Main characteristics of the currently available superconductors.

s.c. material	Critical temperature (K)	Critical field @ 4.2 K (T)	s.c. density (g/cm^3)	Production (km/year)
NbTi	9	10	6	>100,000
NbSn	18	25	7.8	10,000
MgB_2	39	>40	2.5	>1000
YBCO [$Yba_2Cu_3O_7$]	90	>100	5.4	50
BSCCO-2223 [$Bi_{1.8}Pb_{0.2}Sr_2Ca_2Cu_3O_{10}$]	108	>200	6.3	80

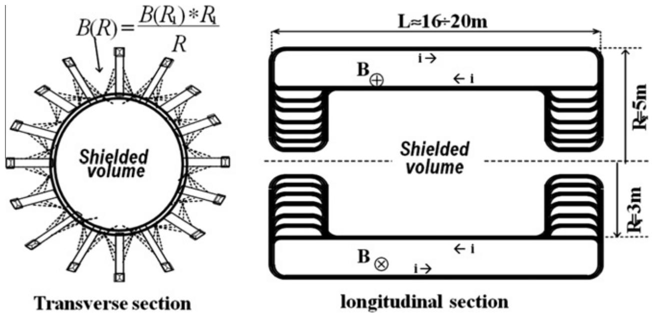


Fig. 3. Toroidal configuration assumed (Fig. 2 from Spillantini (2011)) for evaluating the protection of a 6 m diameter cylindrical habitat.

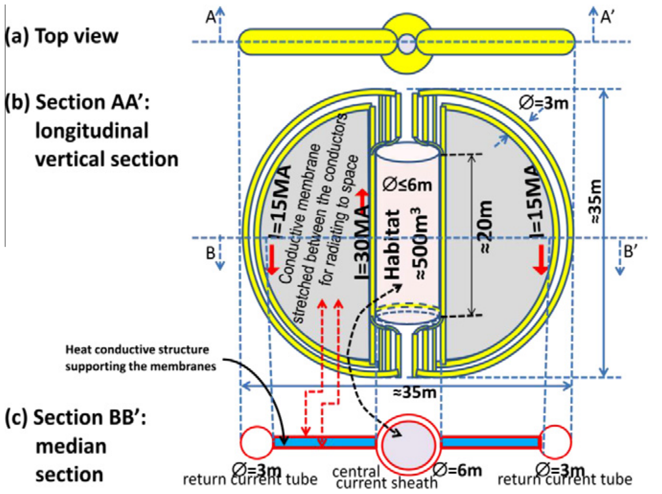


Fig. 4. (a) Top view (as seen from Sun) and (b) vertical longitudinal cross section of the two-D toroid for the protection of a 500 m^3 habitat. As represented in the transversal section (c) all conductors are envisaged as continuous very thin sheets, shaped as a central $\varnothing = 6$ m cylindrical tube and two $\varnothing = 3$ m tubes for the two return conductors.

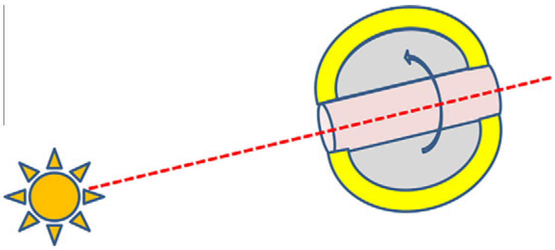


Fig. 5. Attitude of the system with respect to sunlight: the axis of the system points to the direction of the Sun. The arrow indicates that the system can rotate around its axis if needed for dynamical stabilization.

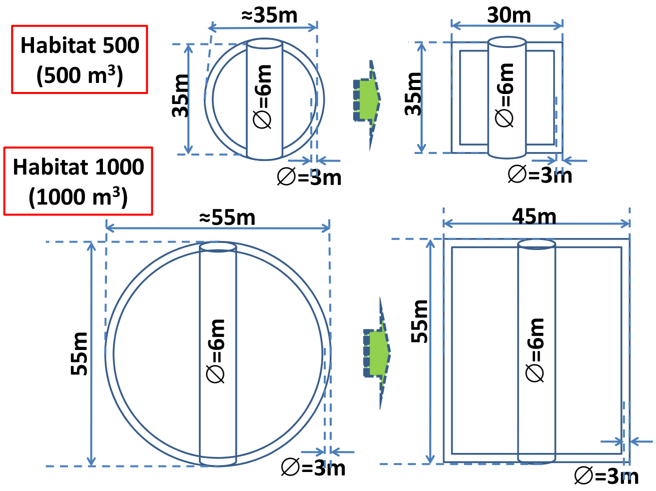


Fig. 6. Schematics of the rectangular coils assumed for approximating the D-shaped coils of the two-D toroids used for simplifying the evaluations of the equilibrium temperature of the system.

1 AU (i.e. plates and discs cannot be too thin and rings cannot have a too large radius in order to not affecting the T_{eq} value). For this reason, at 1 AU, T_{eq} values lower than 10 K cannot be reached by passive cooling, i.e. purely or mainly passive cooling concept cannot be applied to superconducting systems based on low temperature materials NbTi and NbSn.

3. Passive cooling of s.c. magnetic systems for protecting large habitats in space: two examples

Let's apply this recipe to the toroidal superconducting magnetic systems for the protection of large 'habitats' in deep space (Spillantini, 2010, 2011). Let us consider Fig. 3 (reproduced from Fig. 2 of Spillantini (2011)) with internal radius of the system $R_1 = 3$ m but a very large external radius, $R_2 \geqslant 12$ m. With this choice the number of outer return conductors can be drastically reduced, from 16 as in Fig. 3 to two only, realizing the 'two-D toroid' configuration already considered in the past for the Astromag facility (Basini et al., 1988; Green et al., 1988). This choice is schematically represented in Fig. 4 for the case of the protection from ionizing radiation of a large habitat 500 m^3 in volume.[1] Fig. 3(c) represents the vertical longitudinal cross section of the system to be considered. Heat is radiated to space mainly by conductive membranes stretched between the conductors. Membranes and their deployment and supporting structures must be highly heat conductive in order to ensure that the whole system, as it reached the same T_{eq}, could be considered a point-like structure. The whole scheme is oversimplified because the aim is to investigate the limit T_{eq} that can be reached under ideal (although rough) assumptions. The attitude of the system relatively to the Sun is represented in Fig. 5: the axis of the system points to the direction of the Sun, and the system can rotate around its axis if needed for dynamical stabilization. In the embodiment of Fig. 4 a total current of 30MA was assumed (divided in two return current of 15MA in each of the two return conductors). For the superconducting cable it is considered the MgB_2 cable produced in a titanium sheath and

---

[1] Obviously the two-D toroidal scheme implies that, while the habitat and the enveloping central column of current could be launched as a unique piece, the two return current conductors have to be deployed or assembled in space.

Table 2
Equilibrium temperatures of the superconducting two-D toroidal systems protecting large habitats (see Section 3).

	Point Sun	Extended Sun (9 mrad @ 1 AU)	Return current: $1 \times 6\ \mathrm{m}^2$ cross section	$1 \times 6\ \mathrm{m}^2$ return current cross section + extended Sun
Habitat 500 m^3	18.6 K	18.8 K	16.3 K	16.6 K
Habitat 1000 m^3	18.5 K	19.1 K	15.9 K	16.4 K

Table 3
Equilibrium temperatures of the superconducting two-D toroidal systems protecting large habitats (see Section 3) also considering the leakage of heat from the habitat to the toroidal system.

	Point Sun	$1 \times 6\ \mathrm{m}^2$ return current cross section + extended Sun	+leakage from the 10 kW in the habitat, with insulation $R_{ae} = 0.0001$	+leakage from the 10 kW in the habitat, with insulation $R_{ae} = 0.001$
Habitat 500 m^3	18.6 K	16.6 K	17.1 K	19.5 K
Habitat 1000 m^3	18.5 K	16.4 K	16.8 K	19.2 K

stabilized outside by aluminum (Alessandrini et al., 2006), that has a low specific mass (2.96 g/cm^3). By using this cable at 20 K and with 1 kA/mm^2 current density (1.3 safety factor respect to the critical current density at 20 K and $B = 2T$), and if the conductors are assumed to be 'continuous sheets' 1.59 mm thick,[2] the maximum field in the superconductor is $B \leqslant 2T$ everywhere.

The total mass of needed cable for the whole system amounts to 5.7t, to which it must be added the mass of the supporting mechanics and of the systems for the deployment and for supporting the pressure of the magnetic field gradient. The masses of these additive parts are supposedly much greater, and anyway depend from a detailed design.

In order to simplify the evaluation the two-D-shaped coils can be schematized by rectangular coils. The geometrical dimensions used for the evaluation are reported in Fig. 6 for two cases of the protection from ionizing radiation of large habitats of 500 m^3 and 1000 m^3. As for the two-D toroid of Fig. 4, in both cases the rectangular-shaped two-D toroid is supposed to be realized by the same MgB_2 superconducting cable and operated in the same $T \leqslant$ 20 K and $B = 2T$ conditions, which allows the same 1 kA/mm^2 current density and the same 1.59 mm thickness of the continuous current sheet. In the most straightforward embodiment of the coil the central conductor can be schematized as a 6 m diameter 1.59 mm thick sheath enveloping the $\leqslant$6 m diameter habitat and the two return conductors as 3 m diameter 1.59 mm thick tubes, maintaining the same $B = 2T$ maximum field in the conductor, and the same current density. As for the two-D toroid of Fig. 4, the attitude is that of Fig. 5 and heat is radiated to space mainly by conductive membranes stretched between the conductors. The T_{eq} results to be 18.6 K for the 500 m^3 habitat and 18.5 K for the 1000 m^3 habitat. At 1 AU these values must be respectively increased by about 0.3 K and 0.6 K for taking in account the finite angular dimension of the Sun.

A suitable distribution of the current in non-circularly shaped tubes of the current return conductors can maintain the magnetic field $B \leqslant 2T$ in the conductor, and therefore the corresponding current density, what allows minimizing the area exposed to sunlight. For example, by a suitable distribution of the current, cross section of the return current conductors could be 'quasi-oval', about $1 \times 6\ \mathrm{m}^2$, with the 1 m side exposed to sunlight. The above quoted T_{eq} values for the 500 m^3 and 1000 m^3 habitats diminish to 16.3 K and 15.9 K respectively, increasing to 16.6 K and 16.4 K for the finite angular dimension of the Sun. All these values are summarized in Table 2. These T_{eq} values are lower than the assumed 20 K operation temperature. However it must be stressed that they must be considered as 'minimum limit values', since in practice in a project the thermal inertia of the mechanical and electrical structures and possible other internal heat sources must be taken into account.

In previous space missions in deep space (such as Plank (Planck collaboration, 2011) and Spitzer (Gehrz et al., 2007) missions) in order to reach temperatures lower than 30 K, passive cooling had to be integrated by cryogenic fluids and active cooling devices. It must however be considered that the geometry of these apparatus, including shields and radiators, is compact and not mainly turned to the optimization of the passive cooling contribution. It is reasonable to expect that the above reported 'minimum limit values' could be approached in future by technological progresses and designing of an appropriate geometry and an appropriate attitude in space.

4. Passive cooling of a s.c. magnetic system for protecting large habitats in space: some comments

Three comments need to be made for the above application to the protection of large habitats in space:

I – For the above evaluations the system was considered in deep space, i.e. far away from any celestial body. The

---

[2] Except at the caps of the habitat where the 6m diameter cylinder is subdivided in thinner cylinders in order to protect the two ends of the habitat still maintaining $B \leqslant 2T$.

evaluations for habitats near celestial bodies are more complex: the total sunlight input could be reduced by the shadow of the celestial body, but its albedo light, also if less intense of direct sunlight,[3] must be taken into account; furthermore T_{eq} is difficult to be managed by acting on the attitude of the system.

II – Inside the habitat the temperature should be about 300 K, needed for the life of astronauts and maintained by the metabolism of astronauts themselves and the electric equipment. If the insulation between the habitat and the superconducting conductor could be pushed to $R_{ae} \approx 0.0001$ (as for the direct sunlight), the contribution to the T_{eq} of the superconducting magnetic system would be of secondary importance, 2.65 mW/m^2 for each kW dissipated inside the 500 m^3 habitat and 1.37 mW/m^2 for the 1000 m^3 habitat, and the T_{eq} would be slightly modified according to Table 3. However the distance between the external wall of the habitat and the internal face of the superconducting sheath must necessarily be small for not jeopardizing the volume of the habitat, and could constitute a problem for reaching such very low R_{ae}. By assuming $R_{ae} = 0.001$ the contribution to the superconducting system increases 10 times and T_{eq} results considerably modified (increased by about 3 K, see last column of Table 3) also if still in the limits of the superconducting operational parameters.

III – T_{eq} values given in Tables 2 and 3 are evaluated considering a CMB effective temperature of 7 K. It must be again stressed that they are ‘minimum limit values’, approachable but difficult to be reached in practice. Technical progress can be envisaged in near future for large screens against solar radiation, treatment of reflecting surfaces and efficiency of insulating materials that could facilitate this approach. They also depend from many other practical issues, such as the not enough high heat conductivity of the whole mechanical structure that prevents from considering an identical temperature on the whole radiating surface, the difficulty in maintaining a precise attitude of the system, the difficulty in disposing of the residual heat contribution from the habitat (see above paragraph II), and the needed mechanical interconnections between the habitat (where an internal pressure of about 1atm is required) and the external superconducting tube subject to the strong pressure of the magnetic field gradient.

5. Conclusions

In conclusion large magnetic systems based on MgB_2 superconducting cables can be mainly operated by passive cooling with marginal recourse to active devices for complementary cooling, for guaranteeing temperature margins to operate the superconductor and for redundancy and backup. The role of passive cooling can be enhanced by a suitable choice of the geometrical configuration and attitude in space. This observation has the potentiality of greatly simplifying the problem of the protection of large habitats by superconducting magnetic systems in deep space. This conclusion is even more valid for the high temperature superconductors that also could be a valid choice for space applications provided that their higher specific mass would not affect the total mass of the system too much.

References

Alessandrini, M., Fang, H., Hanna, M., Putman, P., Zhou, Y.X., Salama, K. High critical current of Ti-sheathed MgB2 wires for AC and weight critical applications. Supercond. Sci. Technol. 19, 129, 2006.

Basini, G., Bernabei, R., Bongiorno, F., Codino, A., DePascale, M.P., Green, M.A., Menichelli, M., Meschini, M., Morselli, A., Occhigrossi, M., Picozza, P., Ricci, M., Spillantini, P., Torresi, A., Valentini, S., Wang, Y.F. A double-dee toroidal field for a space spectrometer. Il Nuovo Cimento, 102B (5), 1988.

Cocks, H. DHTSC (Deployable High Temperature Superconducting Coil). J. British Interplanet. Sci. 44, 99–102, 1991.

Dou, S.X., Collings, E.W., Shcherbakova, A. Aluminum stabilized superconductor. Supercond. Sci. Technol. 19, 333–337, 2006.

Gehrz, R.D., Roellig, T.L., Werner, M.W., et al. The NASA Spitzer Space Telescope. Rev. Sci. Instrum. 78, 011302, 2007.

Green, M.A., Basini, G., Ricci, M., Codino, A., Spillantini, P., Rosatelli, F. The two-coil toroidal magnet an option for Astromag. IEEE Trans. Magn. 24 (2), 1988.

Kelsall, T., Hauser, M.G., Berriman, G.B., et al. Investigation of the Zodiacal Light from 1 to 240 mm using Cobe Dirbe data. SPIE Conf. Proc. 2019, 190, 1993.

Nagamatsu, J., Nakagawa, N., Muranaka, T., Zenitani, Y., Akimitsu, J. Superconductivity at 39 K in magnesium diboride. Nature 410, 63–64, 2001.

Planck collaboration. Planck early results. II. The thermal performance of Planck. A&A 536 (A2), 2011.

Spillantini, P. Active shielding for long duration interplanetary manned missions. Adv. Space Res. 45, 900–916, 2010.

Spillantini, P. Superconducting magnets and mission strategies for protection from ionizing radiation in interplanetary manned missions and interplanetary habitats. Acta Astronaut. 83, 1430–1439, 2011.

---

[3] The albedo near the Earth (bond albedo) is ≈30% of the value of the solar constant @ 1 AU, and decreases with distance as the inverse of the square of the distance from the center of the Earth. The albedo of the Moon is 11%, also decreasing with the inverse of the square of the distance from the center of the Moon, and that of Mars is 15% of the solar flux in the Mars orbit, also decreasing as the inverse of the square of the distance from the center of Mars.