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BACKGROUND LIMITED INFRARED AND SUBMILLIMETER INSTRUMENTS

J.-M. LAMARRE, F.-X. DÉSERT, T. KIRCHNER
Institut d'Astrophysique Spatiale
Bât 121, Université Paris XI,
91405 Orsay Cedex France

Abstract. The temperature and emissivity of infrared and submillimeter telescopes are basic parameters that drive the optical and thermal design of astronomical space projects. They determine also, among other parameters, the self-emission of the instrument and the photon noise produced by this radiation on the detectors. By comparing the telescope brightness with that of the sky in the 1μm–1 cm wavelength range, general conditions for background limited photometry are derived. For $\lambda < 0.4$ mm, temperature is the driving parameter, and for $\lambda > 0.4$ mm, temperature and emissivity have equivalent importances. It can be shown on actual projects that these two regimes determine different optical and thermal concepts. Although based on a simplistic approach, this work intends to help designers to handle some basic system parameters of infrared and submillimeter instruments.

Key words: Space instrumentation – Visible and Infrared diffuse backgrounds

1. Introduction

The fundamental limit to the sensitivity of observations is the photon noise of the detected radiation, i.e. the statistical variation with time of the number of photons that can be detected in a given measurement process. These intensity fluctuations are due to the quantum nature of photons and are part of the radiation itself. In laboratory experiments, it is possible to reduce their amplitude, at the expense of increased phase fluctuations. In the case of astronomical observations, they seem to be the ultimate limit to the precision of radiation measurements: the fluctuation of the part of the emitted radiation which is collected by a telescope is the smallest possible noise with this telescope. This ideal photometry (BLIP, or background limited photometry) can be met if the detector noise is smaller than the photon noise, which is possible now in infrared astronomy due to the significant advances that took place in the domain of detector technology in the one micrometer to one millimeter wavelength range. BLIP operation is therefore a commitment for new astronomical instruments unless other requirements, such as the presence of atmosphere for ground-based telescopes, or the difficulty of cooling large antennas for space projects, forbid it.

In the "phase space" of relevant parameters of space infrared to radio instruments, this paper addresses only the temperature and the emissivity of the instrument and from only one point of view, which is the photon noise. Other questions, such as angular or spectral resolution appear only as

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external constraints. From this simplistic approach, we expect to reach conclusions general and consistent enough to be a guideline for the astronomers who design (or just dream of) future instruments.

In the next section, we study how photon noise is related to the power reaching the detector and derive a condition on the temperature and the emissivity of the instrument for BLIP operation for a given background. In section 3, the astronomical background is described, and the corresponding photon noise is derived. In section 4, we study the emissivity of instruments and in section 5 we derive a maximum instrument temperature for BLIP conditions, depending on wavelength and instrument emissivity. Section 6 is dedicated to comments on the position of projects under study with respect to the BLIP condition.

2. Photon noise

Two sources producing the same power on a detector do not necessary produce the same photon noise. The noise equivalent power produced by photon detection statistics in a given detection process with a thermal source is (Lamarre, 1986):

$$NEP_{\rm ph}^2 = \frac{2}{\eta^2}\int h\nu Q_\nu \, d\nu + \frac{(1+P^2)}{\eta^2}\int \Delta(\nu) Q_\nu^2 \, d\nu, \qquad (1)$$

where η is the quantum efficiency of the detector, Q_ν is the power reaching the detector per unit of optical frequency, P is the polarization degree of this radiation, and $\Delta(\nu)$ is its partial coherence factor.

$\Delta(\nu)$ is usually expressed, as a first approximation, as the inverse of the number of space modes of the instrument, i.e. $A\Omega/\lambda^2$, where $A\Omega$ is the beam throughput of the measurement process and λ the wavelength. This is one of the difficulties of this formula: the source producing the incident power may occupy only a small part of the instrument beam throughput. In other terms, it may produce coherent radiation ($\Delta(\nu) = 1$) in a multimoded instrument ($\Delta(\nu) \ll 1$). The opposite situation is often verified in real instruments. Nevertheless, if the beam throughput of the detector pixels is of the order of magnitude or smaller than λ^2, all types of sources will produce with these detectors nearly coherent detection processes. No significant difference in photon noise is to be expected for equal incident powers. A second source of difference is the possible polarization of the incoming radiation with a maximum consequence on the photon noise of a factor $\sqrt{2}$.

In consequence, for two different reasons, equal powers coming from the source and from the instrument itself may produce different photon noises. They are nevertheless expected to be small for imaging instruments and not very polarized sources. In the following part of this paper, it will be assumed that equal powers produce equal photon noise, while keeping in mind that this is only an approximation acceptable for the study of orders of magnitude.

Stating that the photon noise is dominated by the sky is then equivalent to writing the condition:

$$I_{\nu,\,\mathrm{instr}} = K I_{\nu,\,\mathrm{bg}}, \tag{2}$$

where $I_{\nu,\,\mathrm{instr}}$ and $I_{\nu,\,\mathrm{bg}}$ represent the specific "background" intensity produced respectively by the instrument itself and by the source on the detector, and K is an arbitrary constant smaller than one. When $K = 1$, the background power cannot be lowered by more than a factor of two, which, at best yields a factor of two on the photon noise. Spending energy to still reduce that noise may not be worth.

If we consider the instrument as a greybody of emissivity $\epsilon(\nu)$ and of temperature T, it produces a specific intensity

$$I_{\nu,\,\mathrm{instr}} = \frac{2\epsilon h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}. \tag{3}$$

Then, the condition expressed by equation (2) becomes:

$$T = \frac{h\nu}{k}\frac{1}{\ln(1 + \frac{2\epsilon h\nu^3}{c^2 K I_{\nu,\,\mathrm{bg}}})}, \tag{4}$$

which defines the maximum temperature that keeps the photon flux produced by the instrument itself (in the absence of other sources) to a value equal to K times the sky background. This equation is based on an approximation. It does not take into account the intrinsic noise of the detectors or any other limitations such as confusion. It has nevertheless the advantage of simplicity. It gives the occasion to handle two basic parameters of instrumentation (temperature and emissivity) with a very clear criterion that does not depend on angular resolution, spectral resolution, detection principles, number of pixels, and so on.

3. The astronomical background

Although space experiments get rid of the strong atmospheric disturbances (opacity and emission), they still face faint but present foregrounds and backgrounds (Figure 1a). Interplanetary dust which pervades the inner Solar System scatters the Sun light in the near infrared and emits a thermal spectrum throughout the mid infrared as observed by IRAS (Hauser et al, 1984). Faint stars make a near infrared galactic background (Puget, 1976) and interstellar dust emission throughout the infrared (Boulanger & Pérault, 1988) produces a highly structured background (the so-called cirrus clouds) even at high galactic latitudes and which probably contains mid–infrared spectral features (Sellgren et al., 1985). The submillimeter background is due to the 3K cosmic background radiation.

The photon noise produced by these backgrounds is not negligible. Let us consider a perfect instrument with a transmission and a quantum efficiency equal to one, with a beam throughput equal to that of the diffraction limit, and with spectral resolutions of resp. 4, 10^2, and 10^4. As shown in Figure 1b, the corresponding NEPs are in the range of 10^{-17} to 10^{-20} W Hz$^{-1/2}$, which is reached by the most recent IR and submillimeter detectors. Therefore, the question of BLIP operation for astronomical space IR instruments is not a purely academic one. It is a requirement or a design goal that must be, and that is effectively at the center of the design of these instruments.

4. Instrument emissivities

4.1. TELESCOPE DESIGNS

Is it necessary to design low emissivity IR instruments? When looking at current IR and submillimeter projects, it is clear that different answers have been given to this question. Since it is the largest part in instrument design, the telescope is often also its warmest optical part. The focal optical system is usually cooled to temperatures low enough to give insignificant contributions to the general backgrounds. Therefore, the designs differ mainly by the telescope. In order to quantify the impact of instrument emissivities on their required temperature, we have chosen three different designs with supposed emissivities that cover the range of realistic ones.

a) High emissivity instrument based on a Cassegrain telescope. The baffles have been designed in order to minimize straylight, which may lead to significant obscurations by emissive elements. SIRTF (Werner & Simmons, 1994) may be an example of this design. We suppose that in this case the telescope has an emissivity of 0.1 plus that of the two mirrors:

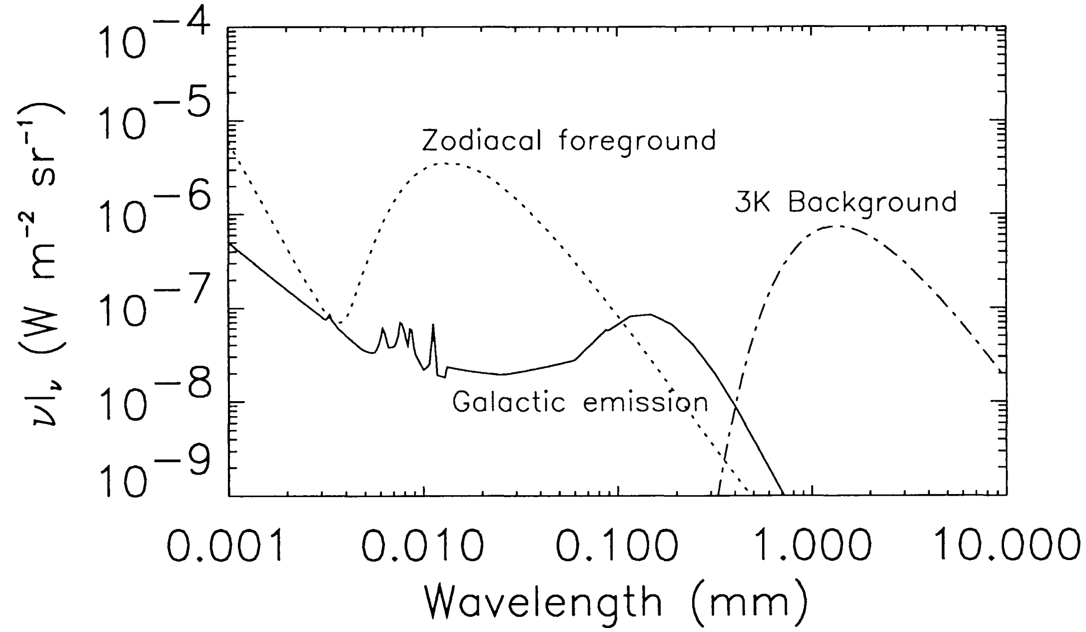
$$\epsilon_{\mathrm{tel}} = 0.1 + 2\epsilon_{\mathrm{m}}, \tag{5}$$

where ϵ_{m} is the mirror emissivity.

b) Low emissivity Cassegrain telescope. For mechanical or size reasons, a Cassegrain design was chosen, but in the same time, low emissivity was a design goal, and emissive items have been reduced to the strict minimum, such as the legs of the spider, and/or part of the obstruction by the secondary mirror. FIRST (Beckwidth et al., 1993) may be an example of this design. The emissivity of this type of telescope may be given by:

$$\epsilon_{\mathrm{tel}} = 0.03 + 2\epsilon_{\mathrm{m}}. \tag{6}$$

c) Low emissivity off-axis telescopes. An example of this type of telscope is the tilted off-axis Gregory design of the SAMBA or FIRE projects (e.g.



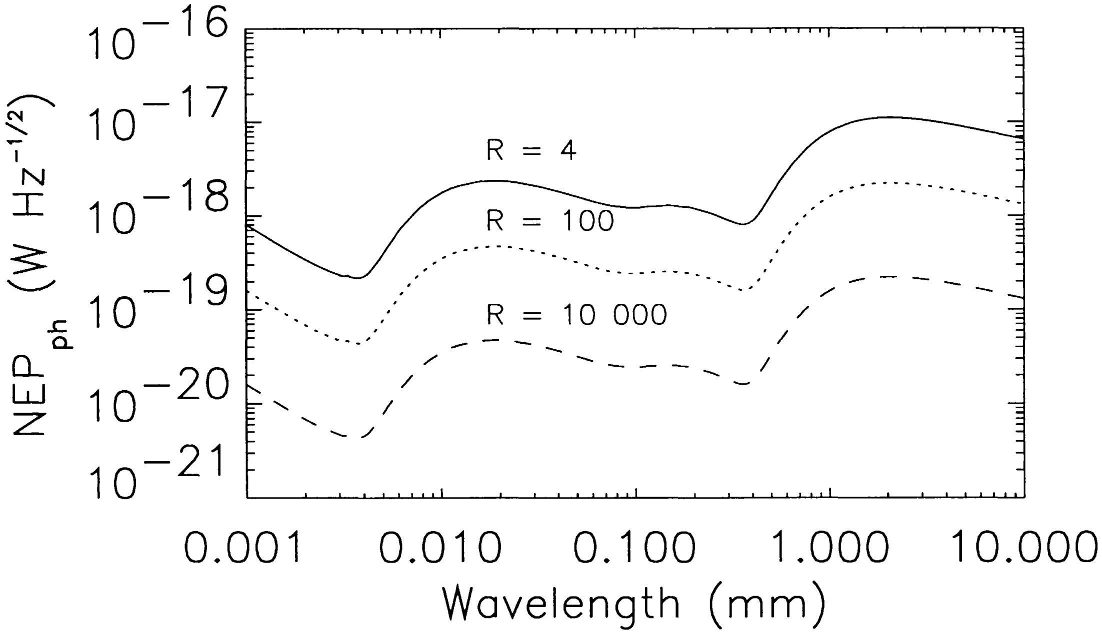


Fig. 1. a) Various foregrounds and backgrounds that space experiments are facing. The zodiacal foreground is a lower limit obtained only when observing near the ecliptic poles. b) Noise Equivalent Power as a function of wavelength due to the astronomical background (shown in Figure 1a) outside the atmosphere for a perfect instrument at the diffraction limit with a resolution of resp. 4, 10^2, and 10^4.

Lange et al., 1994). There is no obstruction, and the design of the focal optics includes a cold Lyot stop that reduces the instrument signal to that of the oversized telescope mirrors.

$$\epsilon_{\mathrm{tel}} = 2\epsilon_{\mathrm{m}}. \tag{7}$$

4.2. MIRROR EMISSIVITIES

The reflectivity R of bulk polished metal is given, following the theory of Hagen & Rubens, by Born & Wolf (1990):

$$R_{\mathrm{m}} \approx 1 - 2\sqrt{\frac{\nu}{\sigma}} + \ldots \tag{8}$$

where ν is the optical frequency and σ the DC current resistivity of the metal. Following Kirchhoff's law, for bodies in local thermal equilibrium, emissivity is equal to absorptivity, and in this case, to $1 - R_{\mathrm{m}}$.

$$\epsilon_{\mathrm{m}} \approx 2\sqrt{\frac{\nu}{\sigma}} + \ldots \tag{9}$$

Nevertheless, several factors such as imperfect layers of metal, contamination, and micro-roughness can increase the emissivity of actual mirrors. For the LDR studies, P. Swanson (1982) found that a large number of measurements of different metallic samples could be fitted by a common law:

$$\epsilon_m = 0.1\lambda_{\mu\mathrm{m}}^{-1/2}. \tag{10}$$

This formula is based on reflectivity measurements of gold, silver, and aluminum made by several authors (Touloukian & Dewitt, 1970, Weiss, 1980, and Otoshi & Thom, 1981) between a few microns and several centimeters of wavelength. The equal figures found for different metals seem to demonstrate that phenomena other than pure resistivity are dominant. The emissivity is simply taken, by supposing that scattering is negligible, as equal to one minus the reflectivity, which maximizes ϵ. The loss of resistivity of metals at low temperature is not taken into account, in spite of the fact that telescopes of IR and Submm space projects are usually cooled by cryogenic fluids or passively. The derived emissivities are several times larger than the theoretical value of equation (9) or than the best experimental results (Toscano & Cravalho, 1976, and Padalka & Shklyarevskii, 1961). This estimation is therefore pessimistic for freshly made clean mirrors, but may be a realistic approach for actual space projects submitted to different types of contamination all along their life. P. Swanson's law will be used in the following sections of this paper.

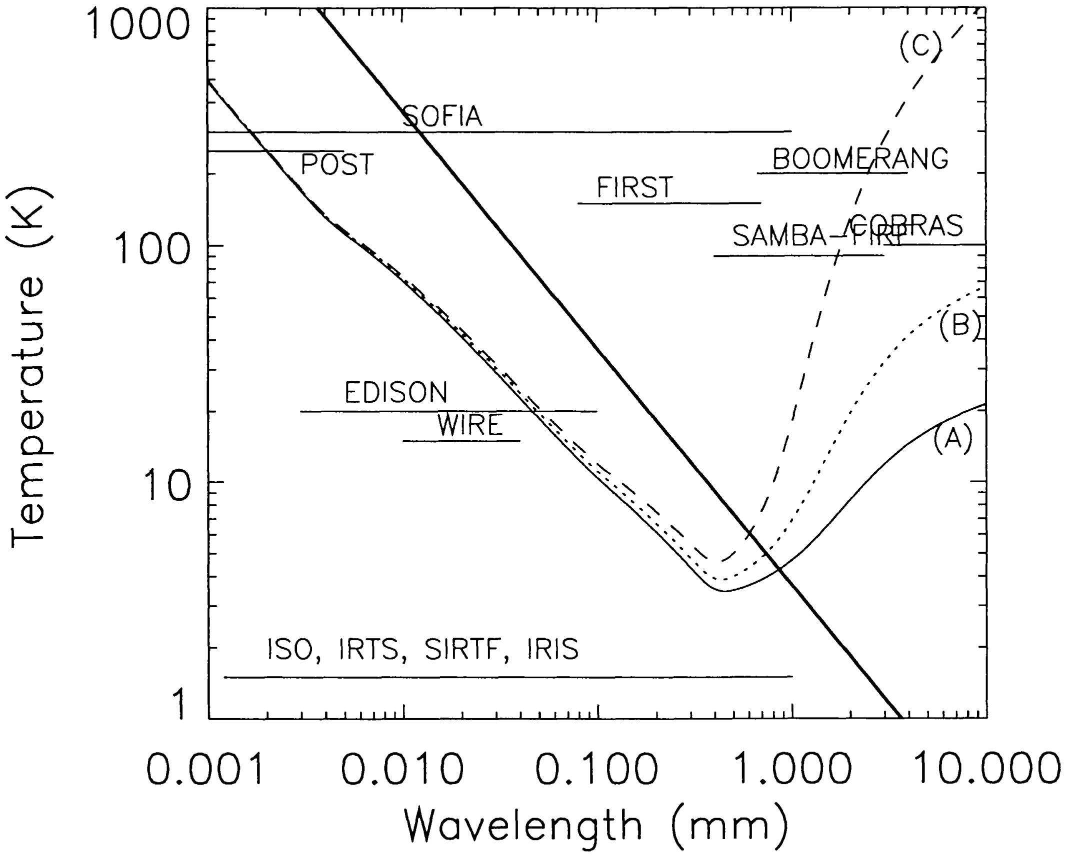


Fig. 2. Maximum allowed instrument temperature for the experiment to be background limited. A rough working range of wavelengths and temperature for a series of planned experiments are also indicated, see this conference proceedings for more details. Lines A, B, and C refer to Section 4.1 concerning the telescope configuration (equations 5, 6, and 7 resp.). The thick line represents Wien's displacement law for the maximum of νI_ν of a blackbody

5. Results

Figure 2 is obtained by applying equation (4) with $K = 1$ to the three cases defined in Section 4.1. The curves show the temperatures of the three types of telescope that produce backgrounds equal to that of the sky. These curves present a pronounced minimum around 400 μm. The features of the sky background cannot be easily recognized. The general shape of the curves is driven by Planck's function (PF) that varies much more than the sky background. This fact determines two regimes corresponding to the well known limit cases of the blackbody radiation, the Wien and the Rayleigh-Jeans (R–J) regimes.

The left part of the curve $\lambda \leq 400\,\mu$m corresponds to the short wavelength cut–on of the PF, which is very steep. Due to Wien's displacement

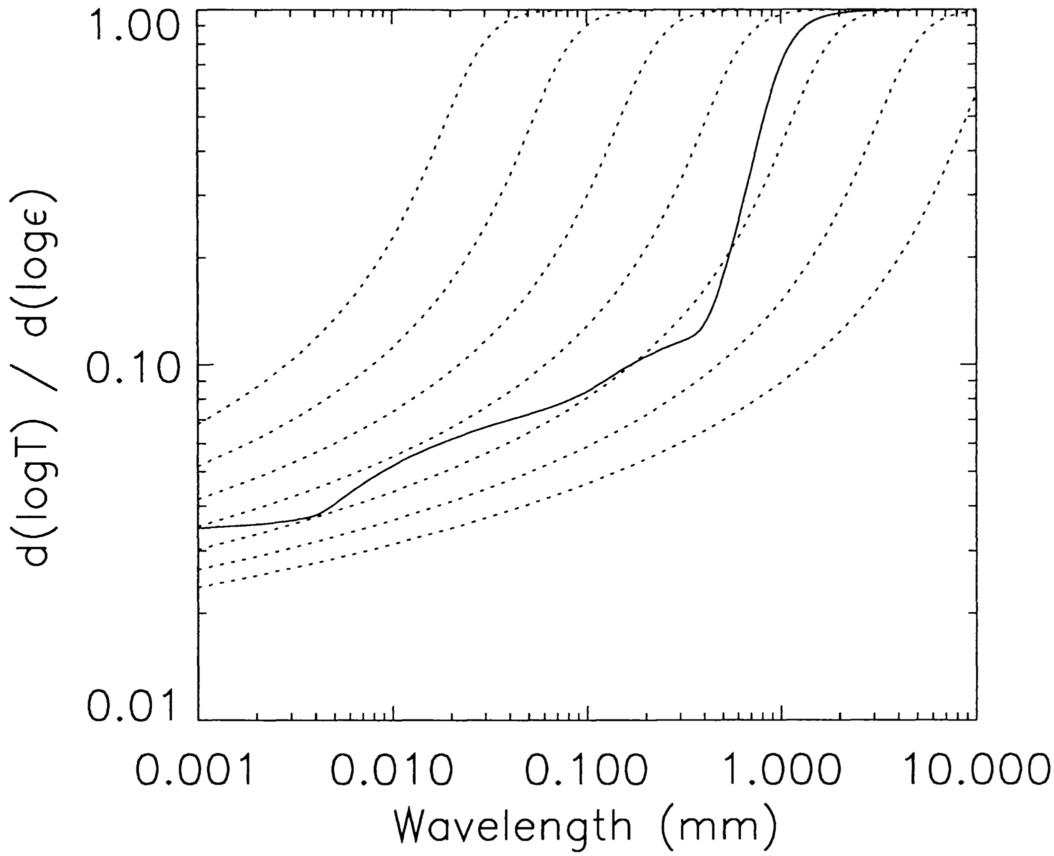


Fig. 3. The relative influence of temperature and emissivity in having a background limited instrument. The parameter R (see eqn. 11) is shown as a function of wavelength for a background going from 10 $\mathrm{Wm^{-2}sr^{-1}}$ (upper dashed curve) to 10^{-11} $\mathrm{Wm^{-2}sr^{-1}}$ (lower dashed curve) by powers of 100. The solid line corresponds to the sky background met by space experiments (see Figure 1a). All the curves were evaluated for a C configuration (see Section 4.1).

law, at each temperature corresponds a cut–on wavelength that does not change significantly with the telescope emissivity. The longwave part of the curve corresponds to the smoother R–J regime, where the emissivity and temperature have identical effects and where the three curves show diffferent behaviors. The relative influences of emissivity and temperature on the instrument self–emission can be represented on Figure 3, where the ratio of the derivatives of the self–emission with respect to the emissivity and the temperature is plotted:

$$R(\lambda, \nu I_{\nu,\mathrm{instr}}) \equiv \frac{\partial \ln(\nu I_{\nu,\mathrm{instr}})/\partial \ln \epsilon}{\partial \ln(\nu I_{\nu,\mathrm{instr}})/\partial \ln T} = \frac{y}{(1+y)\ln(1+y)}, \qquad (11)$$

where $y = 2\epsilon h\nu^3/(c^2 K I_{\nu,\,\mathrm{instr}})$. The dotted lines represent R for values of $(\nu I_{\nu,\,\mathrm{instr}})$ taking constant values from 10^{-11} to $10\,\mathrm{W m^{-2} sr^{-1}}$. They show that $R \approx 1$ at long wavelengths and $R < 0.1$ at short ones. The solid line represents the value of R for the sky background of Figure 1a.

Figures 2 and 3 help to define the two regimes concerning the efficiency of temperature and emissivity to meet the BLIP condition:

a) For $\lambda \leq 400\,\mu$m the temperature is the dominant parameter. The needed temperature is nearly proportional to the radiation frequency and independent of emissivity. This demonstrates that in this domain, reducing the emissivity is not and efficient way of meeting the BLIP condition. Very low temperatures are mandatory and directly related to the maximum wavelength of the project.

b) For $\lambda \geq 400\,\mu$m, the emissivity and temperature parameters have effects of the same order of magnitude. In this regime, one must put in balance the reduction of temperature and emissivity. Low emissivity designs must be used.

These two types of experiments have been designed and presented during this conference. Figure 2 represents, together with the BLIP limit curves, the temperature and spectral coverage of many of these experiments. The data used for this diagram may be subject to some errors due to the changing nature of projects and to the use of oral information (see this proceedings for more precise values). Nevertheless, it is possible to distinguish three families of experiments, two of which corresponding to the two regimes of the BLIP condition, and the third one not being background limited.

The "shortward BLIP" instruments include POST, EDISON, WIRE, ISO, IRIS, SIRTF and IRTS. They are usually not designed for a low emissivity. The warmest experiments (POST and EDISON) are not background limited in their whole spectral range. In this case, it will not be possible to meet the BLIP condition by decreasing their emissivity. Nevertheless, if it is not possible to cool them to lower temperatures, a low emissivity design will reduce the photon noise and increase the sensitivity. These instruments compete with warm ones, and may be more efficient for given modes of an observation.

The "longward BLIP" instruments are COBRAS, BOOMERANG, SAMBA and FIRE. All of them have low emissivity designs using off–axis tilted gregorian telescopes. SAMBA–FIRE and BOOMERANG do not meet the BLIP condition in the complete spectral range, since this condition would necessitate to cool the balloon–borne BOOMERANG experiment down to 30K and the SAMBA–FIRE telescope to 2K, changing the cost class of these projects.

The "non–BLIP" instruments are the airborne SOFIA telescope and the space FIRST experiment. The SOFIA telescope takes the temperature of the atmosphere at the flight altitude and it would not be possible to build a cryostat around a 3 meter class FIRST telescope. A low emissivity design would reduce the photon noise in these two projects but would be more difficult to implement in the case of the airborne telescope.

6. Conclusions

The analysis of the conditions for Background limited photometry of astronomical instruments by using only emissivity and temperature as parameters proved to successfully describe the situation of infrared and submillimeter instruments with respect to these two parameters. Three classes of instruments have been found, two of which corresponding to the two regimes of background limited photometry. General information that could be used to improve the instrument design were derived from this study that does not take into account confusion problems, detector type, and spectral resolution.

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