Multiphysics Simulation of Polymer-Based Filters for Sub-Millimeter Space Optics

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Abstract

This work focuses its analysis on polymer-based filters used in space-borne astronomical instrumentation for Cosmic Microwave Background Radiation and Far-Infrared observations. Most of these observatories mount quasi-optical elements made of such materials, due to their high transparency and low absorption in such wavelength ranges. Nevertheless, data from past missions have proven that thermal imbalances in the instrument (not caused by filters) can complicate the data analysis [1]. Consequently, for future, higher precision instrumentation, further investigation is required on any thermal imbalances embedded in such polymer-based filters. Particularly, the heating of Polypropylene filters is described, when operating at cryogenic temperatures in space.

To do so, a detailed thermal model was created using data and theoretical descriptions of their properties available in literature [2-9]. This information was then used to create an enhanced simulation of the filter heating using the software COMSOL Multiphysics®. Specifically, heat capacity and thermal conductivity were described using a Debye model for polymers and then used to precisely solve the heat conduction equation for the materials used in the simulation. In addition, full advantage was taken of the multiphysics capabilities of COMSOL, including the radiative heat transfer equations in the same model. This was done by adding radiosity-dependent variables so as to perform radiation transfer between the filter layers and external heat sources. Moreover, to improve the detail of the radiative transfer model, data from literature [10-12] were included to provide the values of the cryogenic optical constants of the polymer considered. The filters were designed considering the geometry suggested by the large format array instruments designed for future, post-Planck space missions, such as EPIC [13] and PRISM [14]. Further details described in these proposals [15] were also used to create two time-dependent heat source models, by taking into account the principal sources of thermal radiation such as planets and zodiacal light.

Subsequently, a quantitative data analysis was performed applying a modified lumped capacitance model to the results. It was found that all the filters reached a different equilibrium temperature depending on the model considered, with time constant values between 1000 and 1300 s and a maximum deviation from the initial condition between 0.09 K and 1.3 K. In addition, the periodic small-scale fluctuation caused by the heat source fluctuation was also quantified.

Overall, these simulations suggest that increasing the size of the optics and therefore filters,

would enhance this phenomenon enough to affect the measurements of objects that requires sensitivity of the order of few Jy, in the Far-Infrared or sub-mm band. Therefore, a detailed knowledge of the optical constants and thermal properties of the materials of which quasi-optical components are made of, is crucial to determine the order of magnitude of these effects. They also highlight the possible need for space instrument with large focal plane arrays to also employ (similarly to ground based instruments) some elements of thermal filters (thin film near-IR rejecting filters) prior to thick polymer optical elements.

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