LETTERS TO PROGRESS IN PHYSICS

Blackbody Radiation in Optically Thick Gases?

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In this work, the claim that optically thick gases can emit as blackbodies is refuted. The belief that such behavior exists results from an improper consideration of heat transfer and reflection. When heat is injected into a gas, the energy is primarily redistributed into translational degrees of freedom and is not used to drive emission. The average kinetic energy of the particles in the system simply increases and the temperature rises. In this respect, it is well-know that the emissivity of a gas can drop with increasing temperature. Once reflection and translation are properly considered, it is simple to understand why gases can never emit as blackbodies.

Supposing all the above conditions to have been verified, then the physicist's picture of the external universe has only one further requirement to fulfill. Throughout its whole composition it must be free from everything in the nature of a logical incoherence. Otherwise the researcher has an entirely free hand. [Intellectual freedom]... is not a mere arbitrary flight into the realms of fancy.

Max Planck, Where is Science Going? 1932 [1]

1 Introduction

In the laboratory, blackbodies are specialized, heated, and opaque enclosures, whose internal radiation is determined by the Planckian function [2, 3]. Not all cavities contain this type of radiation, even if Kirchhoff's law of thermal emission had dictated such an outcome [4, 5]. There are demonstrable shortfalls in Kirchhoff's ideas [6–15] and arbitrary cavities are not black. Everything is very much dependent on the nature of the walls [6–15].

Nonetheless, if can be shown that the interior of a cavity is lined with a nearly ideal absorber, or subjected to the action of a carbon particle [8–10], then it can support black body radiation [15]. It is also possible, under special circumstances, to drive the reflectivity of a cavity through a temporary violation of thermal equilibrium [15]. Under those conditions, a cavity, if it has walls which can support Lambertian radiation, might also come to be filled with black radiation. These are unique settings which do not ratify Kirchhoff's claims [15].

In its proper formulation, the law which governs radiation in arbitrary cavities [14, 15] under the limits set by Max Planck [2,3], combines the laws of Kirchhoff [4,5] and Stewart [16] (see Eq. 1 and 9 in [15]). These solutions include the effect of reflectivity, which can act to produce substantial deviations from the behavior expected for cavity radiation, as advanced in 1860 [4, 5]. That real materials possess reflectivity implies that they cannot generate a blackbody spectrum without driving this reflective component [15].

2 Optically thick gases

Finkelnburg [17] advocated that optically thick gases can also produce blackbody radiation [3–6], since he did not properly consider reflection and energy transfer within a gas. Real gases can never meet the requirements for generating a blackbody spectrum, as they possess both convection and reflection.

Relative to the claim that optically thick gases [17] can sustain blackbody radiation [2, 3], the arguments advanced [17] fail to properly address the question. It is easy to demonstrate that, if reflection is not considered, cavity radiation will always be black, independent of the nature of the walls [8–10, 15]. However, real materials, including gases, possess reflection. As a direct consequence, this property must be included.

In his classic paper [17], Finkelnburg makes the suggestion that even if gases are transparent at certain frequencies, they can come to absorb slightly over all frequencies because *"a thermally excited gas by necessity is ionized to a certain, though occasionally small degree"*. He continues, *"As a consequence of this ionization, a continuous spectrum resulting from the stopping of the free discharge electrons in the fields of the positive ions covers the whole spectral region. The same applies (with largely varying intensity) for a number of continuous spectra beyond the series limits where the emission results from recombination of free electrons with ions into different excited states of atoms. Even if any broadening of the discrete lines or bands emitted by the gas is disregarded the absorption coefficient of every luminous gas thus is different from zero for 'all' wave-lengths"* [17]. In this respect, Finkelnburg has overlooked that internal reflection within the gas is also likely to be different from zero at all wavelengths.

Finkelnburg failed to properly address the reflection. That is why he advocated that optically thick gases could emit as blackbodies. He made the assumption that surface reflectivity was negligible in a gas [17]. Yet, since gases have no surfaces, there can be little relevance in such statements.

The reality remains that all gases possess internal reflection over certain wavelengths and that this characteristic cannot be distinguished from emissivity.* Unlike the transmissivity, the reflective properties of a gas remain independent of path length and is an ever present property which cannot be ignored. Photons can be reflected within a gaseous system, even if no surface exists. This is not the same as if the photons were emitted because reflection is a driven phenomenon which involves an external source to drive the departure from thermal equilibrium [15].

It has recently been argued that, in order to obtain black radiation in an arbitrary cavity, the reflectivity of a material must be driven [15]. While gases cannot be characterized by reflectivity, since they do not have a surface, they do possess internal reflection. In order for a gas to gain a blackbody appearance, it is this reflection which must be driven.

Yet, there are only two ways in which reflection can be driven. The first method, adopted by Max Planck, involves placing a small carbon particle within the cavity of interest [15]. Obviously, this cannot be achieved when considering optically dense gases in space. The second method involves driving the reflection, by the addition of energy [15], without an associated change in temperature.†

For a gas to emit like a blackbody, it must be possible to channel energy into this system and produce an excess of emission over absorption. This must occur in a manner which can serve to drive reflection [16], rather than promote convection and increase temperature. However, within a gas, this is extremely unlikely to occur. Gases are known to increase their temperature in response to the inflow of energy. They do not easily increase their emissivity [18]. In fact, the emissivities of some gases are known to drop with increasing temperature, directly confirming this conclusion [18, p. 214–217]. Gases primarily respond to energy by channeling it into translational (not simply in their vibrational, rotational, or electronic) degrees of freedom. Gases increase their average kinetic energy, hence their temperature. When confronted with heat, the atoms of a gas do not simply conserve their kinetic energy in order to promote emission. Therefore, gases can never act as blackbodies, since they can easily access convection. This situation is completely unlike a solid, like graphite, which cannot invoke convection to deal with the influx of energy. Planck insisted that blackbodies have rigid walls [3]. There can be no convection.

As a side note, all experiments on pure gases on Earth involve some form of container. This places the gas within the confines of an enclosure, which though not necessarily opaque to photons, will act to permit gaseous atoms to experience collisional broadening. Such an effect can dramatically alter the conclusions reached, when studying gases in the laboratory versus how gases behave in the unbounded conditions of space. It is not possible for Finkelnburg to assert that *"Even if any broadening of the discrete lines or bands emitted by the gas is disregarded the absorption coefficient of every luminous gas thus is different from zero for 'all' wavelengths"* [4], as the experimentalist who is studying a gas remains restricted to his container and the effects which it imposes on his conclusions. Obviously, if no broadening of the lines can be observed, then the gas under study is even further from approaching the blackbody spectrum. If broadening does not occur, then the lines, by definition, remain sharp and this implies no absorption between the bands.

3 Discussion

When the interaction between a photon and a gas is considered, one must include the effect of reflection or scattering. Such processes are ignored in all derivations which lead to the conclusion that gases can act as blackbodies, when they are sufficiently optically thick [17]. A gaseous atom can interact briefly with a photon and this can result in diffuse reflection or scattering. This term prevents any mathematical proof that all gases, given sufficient optical thickness, can act as blackbodies. The proper equations for radiation in thermal equilibrium with an enclosure, even in the illogical scenario that a gas can be in thermal equilibrium with a self-provided enclosure, involves reflection [15]. The momentary loss of thermal equilibrium, associated with the injection of an infinitesimal amount of heat into a gas, is seldom associated with increased emissivity and the ability to drive reflection [15]. Rather, the additional energy is channeled towards the translational degrees of freedom.

Gases can easily support convection. That is why no gas can ever behave as a blackbody, even when "optically thick".

Long ago, Sir William Huggins and his wife, Margaret Lindsay Huggins [19], demonstrated that planetary nebula can manifest extremely sharp lines in spite of their great spatial extent [20, p. 87]. These findings provide strong evidence that astronomical gases do not emit as blackbodies.

As previously emphasized [6–15], condensed matter is absolutely required for the production of a thermal spectrum.

Dedication

This work is dedicated to Larry and Winifred, in thanksgiving for their friendship and encouragement.

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*When monitoring a gas, it is impossible to ascertain whether a photon which reaches the detector from the *"interior of the gas"* has been directly produced by emission, or whether the photon has undergone one or more reflections before arriving at the detector.

†This second method relies on a temporary departure from thermal equilibrium. In the case of real cavities, a situation such as $\epsilon_\nu = \kappa_\nu + \delta\rho_\nu$ must be considered, where ϵ_ν corresponds to emissivity, κ_ν to absorptivity, and $\delta\rho_\nu$ to that fraction of the reflectivity which has been driven [15]. In a gas, we can reformulate this relationship in terms of emissive and absorptive powers, E and A, and obtain $E = A + \delta R \cdot I$, where δR is the fraction of the internal reflection which has been driven by some function, I [15].

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