

A Demonstration of the Infrared Activity of Carbon Dioxide

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Abstract

Before they can talk meaningfully about anthropogenic climate change, students need to grasp basic principles of *natural* planetary climates, for example, the key role of trace atmospheric gases in setting surface temperature. We describe a dramatic demonstration that scales well for large audiences and that requires as little as ten classroom minutes to show the crucial difference between room air and carbon dioxide gas. Beyond its significance for public policy, the demonstration can serve as a springboard to motivate discussion of important physics concepts such as rotation and vibration spectra.

1 Introduction

Climate is a topic of great concern to students, but it remains difficult to discuss scientifically. We are bombarded daily by emotional messaging for and against the proposition that human activities are altering the climate in ways that may have catastrophic effects. But it often seems that those predictions rest entirely on massive computer simulation models, which the listener is not in a position to evaluate. We wished to find an aspect of the puzzle that could be directly experienced, and that would therefore give us a solid starting point for discussion. Here we describe a dramatic lecture demonstration that scales well for large audiences and that requires as little as ten classroom minutes to show an important difference between room air and carbon dioxide gas. Beyond its significance for public policy, the demonstration can serve as a springboard to motivate discussion of important physics concepts such as molecular rotation and vibration spectra.

It is easy to find demonstrations of this effect described in social media (and in this journal). Many, however, involve a vessel containing gas and a thermometer that is irradiated with infrared light for a long time, for example 30 minutes. Besides being an inconvenient wait for a class demonstration, this slow pace leads to difficult questions of what is going on during that period, including heat transport out of the container and so on.

We developed a demonstration that uses an infrared camera, does not rely on convection, and yields a result after just 1–2 minutes of irradiation (Fig. 1). Although the cost of a suitable infrared camera is appreciable, many physics departments already own one because such cameras can be used for many other instructional purposes [1, 2]. Moreover, we find that merely brandishing such an instrument and showing its basic properties already sparks student interest, leaving an audience in a receptive state.

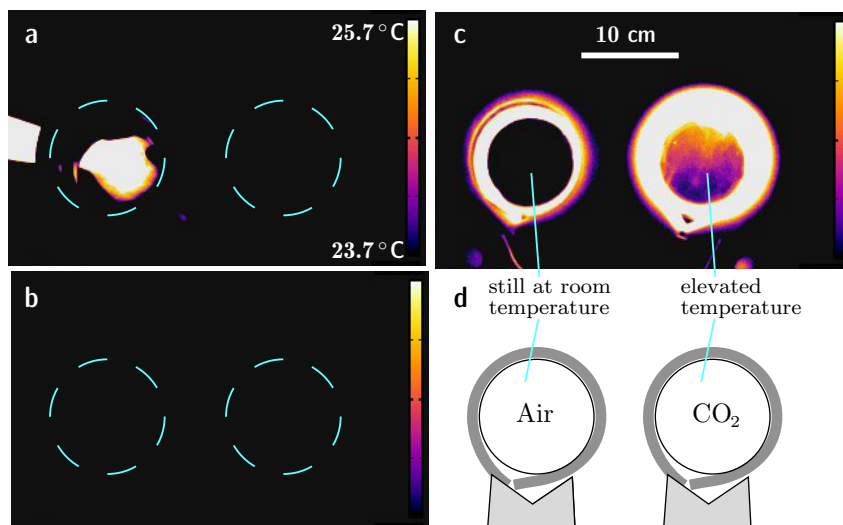


Figure 1: (Infrared photographs.) Energy absorption by an infrared-active gas. Two identical cylindrical chambers (“tubes”) with transparent ends were viewed in the wavelength band shown in Fig. 2. False color indicates radiance in this band (reds are higher than blues); the scale bar is labeled with approximate inferred temperature in degrees Celsius. The chamber on the left contains dry air. The one on the right contains carbon dioxide. Both are cylinders viewed end-on. (a) Tubes before irradiation. A human hand is viewed through the left chamber. *Dashed teal lines* were added to show the locations of the chamber walls. (b) The tubes were invisible before irradiation because they matched the ambient room temperature. The backdrop was independently measured to be at about 24°C, which agreed with the camera. (c) The tubes were exposed to infrared light for two minutes. After irradiation was stopped, the one containing CO₂ was observed to be slightly warmer for about one minute. That is, the apparent temperature when looking through this chamber was higher than either the backdrop or the other chamber. The bright rings are the steel cans themselves and their insulating blankets. (d) Cartoon showing the approximate positions and thicknesses of the foam insulation blankets (*dark gray*). An artifact of the infrared camera makes the warmer right-side insulation appear thicker in (c) than the identical left layer.

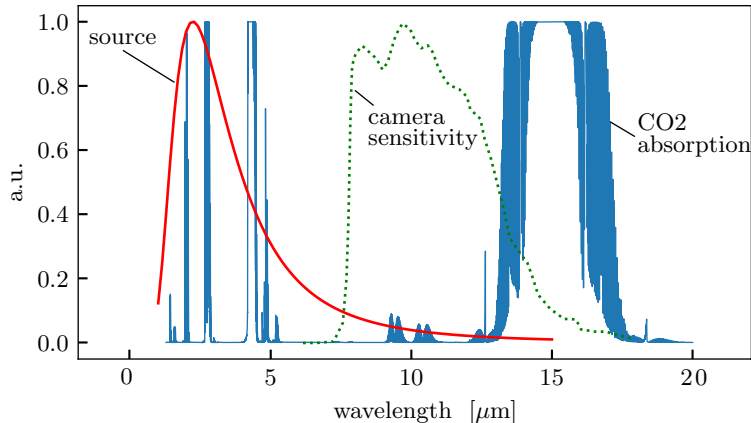


Figure 2: Three infrared spectra. The entire visible spectrum corresponds to a small sliver to the left of all the curves shown (0.4–0.7 μm). *Blue curve*: Absorptivity of a 23 cm deep column of carbon dioxide at atmospheric pressure and room temperature. (Data courtesy Eugene Clothiaux; see [3, Fig. 2.12].) *Green dotted curve*: Spectral sensitivity of the camera we used, from manufacturer’s specifications [4]. The main peaks of CO_2 absorption lie mostly outside this wavelength band. *Red curve at left*: Planck spectrum at temperature 1300K. We inferred this estimated value from the orange color of our infrared source’s glowing filament [5].

2 Demonstration

Instrument We used the FLIR E60 infrared camera (www.flir.com), which contains an uncooled microbolometer array with spectral sensitivity shown in Fig. 2. The camera has video output that can be projected in real time for audience viewing; it can also export still images. Other cameras may work as long as they have similar sensitivity and spectral sensitivity range, and allow manually fixing a narrow false-color scale. A tripod is helpful.

Materials See Fig. 3.

- Four identical coffee cans with both ends removed. Ours were 11.5 cm diameter steel. Optional: we joined pairs of such cans to get two cylindrical chambers (“tubes”) of length 23 cm.
- Sheer plastic food wrap (“Glad Wrap/Handiwrap/Saran Wrap”).
- Fire extinguisher or another source of dry CO_2 [6].
- Two identical sources of infrared radiation, for example, 1000 W ceramic heating elements.
- Apparatus to hold the cans in place (wooden V-blocks, lab jacks, etc).

Procedure

1. Cover tube one with food wrap at both ends, secure with rubber bands, and set aside. Cover tube two with food wrap on just one end and secure with rubber band. Prepare a square of food wrap for the last window but do not attach it yet.

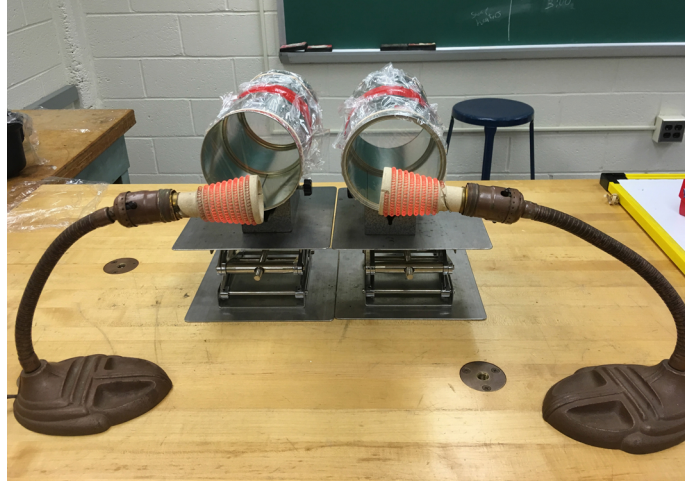


Figure 3: Setup. After irradiation from the two heat lamps (*foreground*), the two cans were viewed by an infrared camera placed on the far side (near the chalkboard). *Not shown*: For the trial shown in Fig. 1, each cylindrical can was wrapped in a blanket of foam insulation (except for its ends).

2. Set up the tubes with their cylinder axes horizontal (Fig. 3), with nothing behind them for at least a meter, and something uniform beyond that (typically a wall of uniform temperature). This horizontal arrangement will later reduce convective heat transfer from the sources to the cans.
3. Turn on the camera and focus on the cans. Align the tubes and camera so that the camera looks straight down each tube's axis. Make sure that what the camera sees when looking through each tube is the uniform wall. Then override the automatic temperature scale and manually adjust it so that the wall is at the low end of the scale displayed and the upper end is not more than 3°C higher.
4. Place tube two on the floor with open end up and flood it with dry CO_2 gas. Quickly cover it loosely with the remaining food wrap window and wait for any solid CO_2 snow to sublimate, then seal it and return it to its position (Fig. 3). Wait for everything to come to room temperature.
5. Image the cans. The experimenter's own emission will create an artifact when specularly reflected from the tube windows, so practice standing to the side to avoid this. Most rooms contain other warm objects, such as computers, so identify and avoid their reflections. For the same reason, audience members should not be too close. [Optionally, it may also be worthwhile to do the demonstration in a darkened room to minimize potential reflections.] Confirm that, with these precautions, both cans appear the same to the infrared camera.
6. Move the sources into position and irradiate the cans for 2 minutes. Point out to the audience that one can easily feel radiation passing out the far ends of each can—at least some wavelengths go right through.
[Caution: Some cameras can “burn in” an image of the hot filament, which will last for

some time after removing the sources. To avoid this, block the camera from directly viewing the sources during irradiation.]

7. [Optional: In some trials, we placed a reflecting metal sheet behind the sources during irradiation. This redirects some more energy back toward the cans, and protects the wall of the room from being heated, if space limitations force it to be close to the sources. Alternatively, heat lamps equipped with their own reflectors can be used.]
8. [Optional: In some trials, including the one shown in Fig.1, we blanketed both tubes with foam insulation to obstruct energy loss through the walls. As expected, this change increased the steady-state temperature difference observed after irradiating the cans, but our effect was apparent even without this step.]
9. Suddenly remove the sources (and reflecting sheet if any) and immediately uncover the camera. Image the tubes and observe that the interior of the tube with CO₂ appears warmer than the can with air for at least a minute. More precisely, the apparatus adds its own emission to any wall emission seen through the back end of the can.
10. Controls: While practicing the demonstration, it is worthwhile to exchange the positions of the cans, exchange which can gets which gas, exchange the infrared sources, and so on. We found that in every case the only variable relevant to the observed difference was the presence of CO₂ gas.

3 Interpretation

The demonstration shows that CO₂ gas differs from air in a directly measurable way. For some audiences, that remark is already enough. For more advanced audiences, however, various other points can now be addressed.

We are all familiar with the sensation of warmth from the radiation emitted by a heat lamp, or the hot wall of a building shortly after sundown. Like air, carbon dioxide gas transmits visible light with hardly any absorption or scattering (both cans appear transparent). In fact, a few centimeters of CO₂ or dry air also transmit most wavelengths of infrared radiation; for example, we can feel it by placing a hand on the far side of the can from the source during irradiation. The infrared camera we used also sees clearly through air and CO₂: The emission from a finger can be seen equally well when viewed through either tube.

Unlike molecular oxygen or nitrogen, however, CO₂ *does* strongly absorb in a wavelength band around 4.3 μm . A broad-spectrum infrared source, for example, a heat lamp, carries some of its energy in this band. We multiplied the incoming radiation (red curve in Fig.2) by the absorptivity (blue curve in the figure), and found that the area under the resulting curve was about 2.3% of the total power in the incoming radiation. That is, about 2.3% of the energy traveling down the tube axis is absorbed by 23 cm of pure CO₂ at standard temperature and pressure. In contrast, dry air contains about 350 ppmv CO₂; repeating our calculation, we found that only 0.05% of the IR energy would be absorbed in this case, an immeasurably small effect for our apparatus.

Why are O₂ and N₂ so different from CO₂? The difference is that, while none of these molecules has an electric dipole moment in its ground state, a triatomic molecule like CO₂ can *gain* a nonzero dipole moment by deformation, whereas the others cannot. Emission of

electromagnetic radiation, and its inverse, absorption, are much more probable when an electric dipole moment operator can participate. Thus, some vibration modes of CO₂ can strongly couple to light of the appropriate wavelength, whereas those of O₂ and N₂ cannot. (Mixing with rotational states further splits the resulting spectral lines.)

The energy of absorbed infrared light can, in turn, be emitted as light in the same 4.3 μm band. That band is not visible to our camera. But the absorbed energy can also end up as infrared light at other wavelengths via thermal emission. This can happen when excited gas molecules collide with one another, but they also constantly collide with the windows of the chamber. Those windows, in turn, can radiate in a broad spectrum including that observed by our camera [7]. The camera estimates the total energy in its wavelength band, then reports the temperature of a source that would thermally emit that quantity of radiation.

That is, the thin windows of our tubes amount to a “thermometer” read out by the IR camera. To support that interpretation, we note that when imaging the tube containing CO₂ we usually see static irregularities, possibly arising from imperfections in the window material, even though the gas itself is highly uniform in this small volume. Such an ultralow mass thermometer can rapidly come to a steady state with even a very low-mass sample (the gas in the tube).

Some potential pitfalls are avoided in our measurement because we are comparing a nonzero quantity (absorption of infrared by CO₂) to nearly *zero* (absorption of infrared by dry air, containing CO₂ at 350 ppmv). Thus, the qualitative result is unaffected by normalization details such as whether the sources are exactly identical and so on. Similarly, differences in heat-transport properties between CO₂ and air, which are an important confounding factor for some measurements [8], are immaterial in our demonstration because negligible energy is being deposited in the tube with air.

In fact Wagoner et al. argued that molecular mass differences dominated the experiment that they analyzed. Following their suggestion, we repeated our measurement with argon gas in place of CO₂. The argon gas behaved similarly to air, that is, differently from CO₂. We interpreted this result as meaning that the molecular mass of CO₂, which is similar to the mass of an Ar atom, was not the relevant factor in our demonstration. The infrared absorption of CO₂ does differ from that of either dry air or argon, pointing to its role in what we observed.

Other previously published demonstrations have (*i*) used illumination by the Sun instead of an IR source; (*ii*) allowed the illumination to be absorbed by a flat-black wall, observing the “trapping of heat” supposedly due to the presence of CO₂; and/or (*iii*) used moist CO₂ gas evolved from solution (for examples, see [9, 10, 11]). In contrast, the experiment reported here shows directly the absorption of energy from IR irradiation by pure CO₂ itself. Once demonstrated, this phenomenon can be *one element* of a more complete discussion of the roles of IR absorption and convection in setting a planet’s surface temperature.

4 Implications

We see that a gas can be quite transparent to visible light, yet absorb some kind(s) of IR, and that different gases can differ markedly in this respect, in a way that is partly predictable from quantum mechanical ideas.

A planet such as Mercury (or our Moon) has little or no atmosphere. Its mean temperature is set by a balance between absorption of incoming solar radiation and emission back out to space. A simple calculation shows that this argument succeeds well in explaining the temperature of

Mars and the Moon, yet predicts a mean Earth temperature below the freezing point of water [12]! And the same calculation fails even more spectacularly for Venus.

Much of the solar radiation energy arriving at Earth's upper atmosphere is in the visible and near-IR range, and mostly passes through the atmosphere to the surface (or is reflected by clouds). The energy arriving at the surface must ultimately exit to space, because the surface is in a roughly steady state when averaged over time and position [13]. Some energy is shed as thermal (or "blackbody") radiation emitted at the surface temperature, but that radiation is largely in the infrared range, so infrared-active gases will absorb certain wavelengths on their way out. Energy absorbed in this way will again be radiated, but *some fraction is directed back down toward Earth*. A planet clothed in infrared-active gases must therefore maintain a higher surface temperature (compared to a rock with no atmosphere) in order to come to energy balance [12, 14].

We must emphasize that our demonstration is not a literal model of the Earth system, for example, because it mainly illustrates absorption of light around $4.3\ \mu\text{m}$, whereas terrestrial infrared emission peaks at longer wavelengths. Nevertheless, Fig. 1 does illustrate the point that an atmospheric component can be transparent at some wavelengths yet optically dense at others. A much stronger version of this effect keeps the surface temperature of Venus hot enough to melt lead [15], despite the fact that its orbit is not much smaller than Earth's and its reflectivity (albedo) is much higher. A planet's habitability is a delicate matter.

5 Vistas

It is remarkable that detailed measurements of the infrared activity of gases goes back to the 19th century [16, Lecture X]; in a sense, our demonstration is just an update of Tyndall's work with convenient modern technology. It can be used to support lessons on several levels:

- Students with little background may be surprised that CO_2 , which is transparent in the visible range, nevertheless can interact strongly with infrared light. If we can get a dramatic effect from just a few centimeters of optical path, then it may be plausible that over tens of kilometers of atmosphere a small-seeming concentration change may be significant.
- Other students may be well aware of the infrared absorption of CO_2 , yet are surprised to learn that it actually selects only a few narrow bands of the spectrum.
- Still others may harbor misconceptions rooted in the popular phrase "greenhouse effect." A real greenhouse is indeed warmed by solar energy with easy entry. However, the main loss mechanism impeded by a greenhouse (or any house) is by air convection. That mechanism does not apply to a planet! The form of planetary energy loss impeded by an atmosphere is infrared radiation emitted to space.

Finally, many students are unaware that naturally occurring water vapor is also an infrared-active gas. So the question of anthropogenic emissions becomes one of how a quasisteady state *changes* when such emissions are added. The answers are not simple, but the demonstration we have described can be a starting point to introduce the results of the detailed predictions. Students may wish to study this topic further, possibly even as a career choice.

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- [4] flir.custhelp.com/app/answers/print/a_id/932.
- [5] For example, see en.wikipedia.org/wiki/Red_heat, archived as perma.cc/6PQA-X8VX.
- [6] Some alternative sources: (a) Insert dry ice pellets into a plastic bag in advance, close it until they have sublimated, then pour the gas into the tube. (b) Obtain a CO₂ tire inflator and cartridge from a bike shop (e.g. ridepdw.com/). (c) Ref. [8, footnote 13] has another suggestion. Chemically generating CO₂ (or letting it escape from a bottle of soda) has the disadvantage of producing gas saturated with water vapor, as was immediately apparent when we tried it and observed water condensation inside our tube. No such condensation was observed with our CO₂ source.
- [7] Food wrap absorbs, and therefore emits, significantly through much of the camera’s wavelength range (Roger Tobin, private communication). Absorption of radiation from the source will warm the windows of both tubes, but this effect is transient; the energy associated with the elevated temperature of the window is rapidly transferred by contact with the cool room air as soon as we remove the infrared sources, too rapidly for us to track it. In contrast, energy deposited in the interior of the CO₂ tube is slower to find its way out, and on its way out it warms the window, leading to a slowly-decaying temperature trace in only the CO₂ tube.
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