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Demonstration

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Adapting Three Classic Demonstrations To Teach Radiant Energy Trapping and Transfer As Related to the Greenhouse Effect

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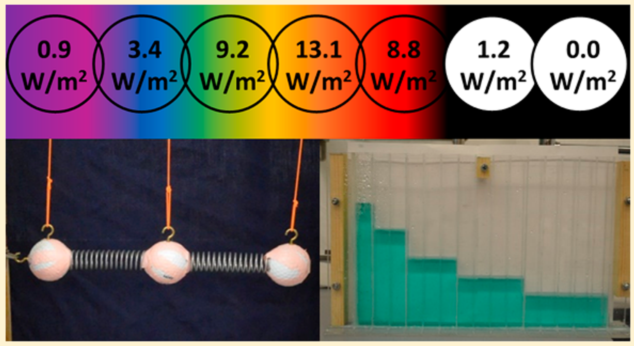
S *Supporting Information*

ABSTRACT: Three concepts necessary for understanding the greenhouse effect are infrared radiation, absorption of infrared radiation by greenhouse gases, and steady-state energy flow. Herein, we describe adaptations to three classic demonstrations for teaching these concepts. William Hershel's discovery of infrared radiation has been adapted into a fast and reliable demonstration using a pyranometer. We provide guidelines for building a ball-and-spring model of carbon dioxide that demonstrates the absorption of IR and the three fundamental vibrational modes of carbon dioxide and their relative frequencies. Finally, we describe an adaptation of Blanck's plastic water-flow device to demonstrate how adding greenhouse gases can alter the steady-state flow of energy through the atmosphere.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Upper-Division Undergraduate, Environmental Chemistry, Hands-On Learning/Manipulatives, Atmospheric Chemistry, Demonstrations, Resonance Theory, Molecular Modeling, IR Spectroscopy*

■ INTRODUCTION

The teaching of climate change and global warming has become a staple in our educational system.[1,2] In this context, we were approached by Irene Porro of the Christa C. McAuliffe Center for Integrated Science Learning at Framingham State University in collaboration with the Museum Institute for Teaching Science to participate in their 2017 Summer Professional Development Institute for Middle and High School Educators. Our task was to present the chemical-physics of radiant energy trapping and transfer through the atmosphere (i.e., the greenhouse effect) in a way that the teachers could take back to their students. Three key concepts connected to this subject are infrared radiation, absorption of infrared radiation by carbon dioxide, and steady-state energy flow.[3] Herein, we describe adaptations to three classic demonstrations for teaching these concepts.

■ DEMONSTRATIONS

Discovery of Infrared Radiation

To demonstrate the existence of infrared radiation, we intended to reproduce William Herschel's 1800 experiment where a thermometer placed just beyond the red portion of the visible light spectrum had a higher temperature than the thermometers placed in the visible spectrum.[4,5] Herschel's experiment, however, is not a practical classroom demonstration as the observed temperature changes are slight, the position of the sun constantly changes, and the time required to equilibrate the mercury thermometers is long. To overcome these challenges, we used a 300 W, 120 V theater spotlight as a light source and a pyranometer (Vernier, PYR-BPA[6]) to measure irradiance in place of thermometers, which measure temperature. An equilateral glass prism (105 mm long with side length of 35 mm) was used to disperse the light and create the rainbow. An overview of the setup is depicted in Figure 1. Additional details for setting up the demonstration can be found in Supporting Information.

At a distance of 1.0 m from the prism, the rainbow was resolved with approximately 1 cm wide violet and red "bands", making it easy for the audience to observe the color landing on the detector surface. The detector was attached to a ring stand and positioned so that the detecting surface was in the violet, where the first irradiance reading was made. The ring stand was moved in six 1 cm increments through the visible spectrum, with irradiance measurements recorded at each position. The fifth increment placed the detector surface in the shadow at the red edge of the spectrum. Moving the detector through the different parts of the rainbow clearly showed different irradiance values (Figure 1). Obtaining a signal in the fifth increment demonstrates the existence of infrared radiation. It should be noted that our peak signal occurred in a different region of the spectrum than was measured by Herschel. This

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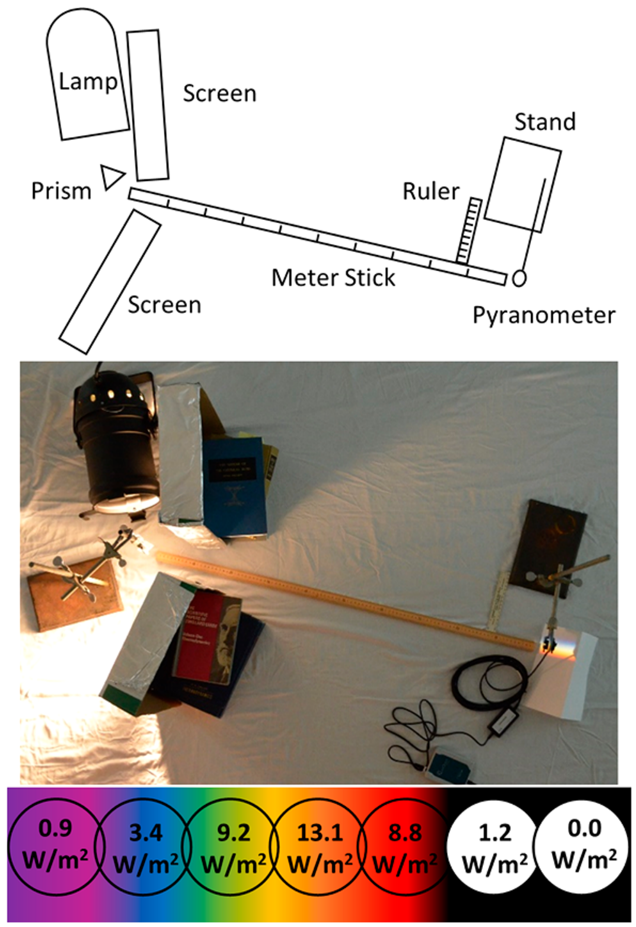

Figure 1. Diagram (top) and photograph (middle) of our modified Herschel experiment. The bottom image shows observed irradiance values superimposed on a rainbow as measured 1.0 m away from the prism. The irradiance values are 0.9, 3.4, 9.2, 13.1, 8.8, 1.2, 0.0 W/m^2, respectively.

can be explained by our use of poorly collimated light in comparison to solar radiation. While Herschel's experiment can be painstakingly reproduced, the use of a pyranometer simplified the demonstration with real time data-collection.

Absorption of Infrared Radiation by Carbon Dioxide

In the atmosphere, carbon dioxide absorbs infrared radiation at specific frequencies that correspond to the vibrational frequencies of the molecule itself.[7] Of particular importance is the bending vibrational mode of 2.0×10^{13} Hz, which corresponds to the absorption of infrared radiation with a wavelength of 15 μm. This is significant because if the Earth is treated as a blackbody emitter with an average surface temperature of 15 °C, its wavelength of maximal emission (λ_{max}) will be approximately 18 μm.[3,8] Carbon dioxide's symmetric stretch is infrared inactive, so it does not contribute to global warming. The antisymmetric vibration is infrared active but contributes little to global warming because the planet emits very little IR with the frequency needed to access this vibrational mode.[9] To demonstrate the microscopic vibrational motions of carbon dioxide, we chose to utilize a ball-and-spring model. Such models have been used since the 1930s to understand and demonstrate how molecules absorb infrared radiation and store energy.[10,11]

In a film produced in 1962 for use in the California University System, the three fundamental vibrational modes of carbon dioxide were clearly demonstrated.[12] In reproducing this demonstration it became exceedingly clear that achieving the correct ratio between mass and spring constant was difficult using ordinary objects. We determined that golf balls and compression springs (Hillman 540156 #52) can be used to build a system that will mimic carbon dioxide's vibrational behavior. In theory, it is possible to use any size balls with appropriate springs, but it is essential that the diameter of the compression springs be more than half the diameter of the ball; otherwise, the ball will twist with respect to the spring. The compression springs were mounted to the golf balls using strips of tape. Small cup-hooks were used to hang the balls on strings. Once suspended, the end ball of the model was attached by a flexible wire to a screw located off-center in the face of a rotating disk (Figure 2). Our rotating disk consisted of a #6 cork stopper mounted onto the drive shaft of a 12 V dc motor. The motor speed was controlled by a variable output dc power supply. The specific motor and power supply used are not critical as long as a steady rotational frequency between 4 and 40 Hz can be maintained. Step-by-step instructions for

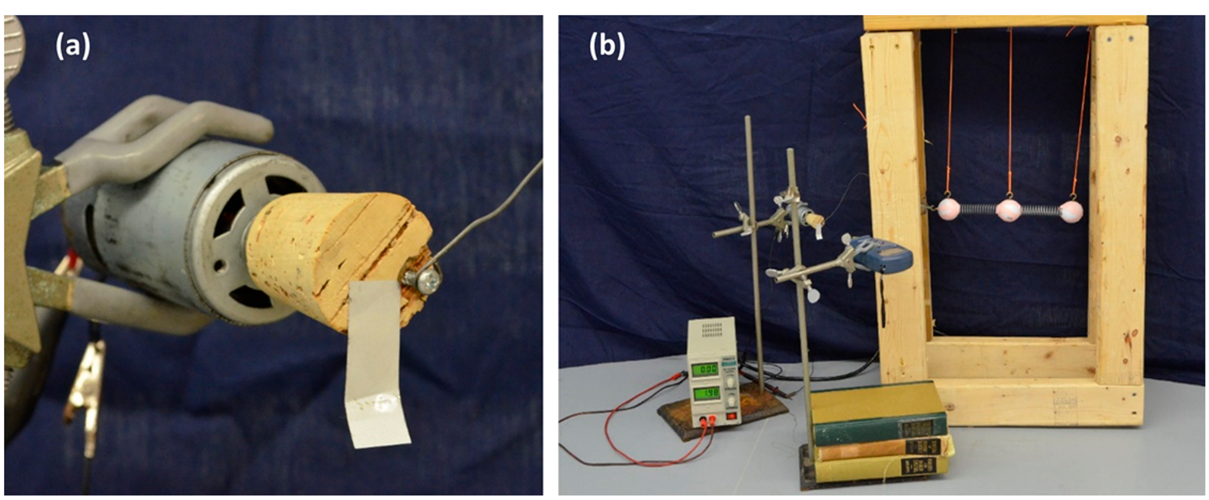

Figure 2. (a) The 12 V dc motor, rotating disk, and loose wire. (b) Our ball-and-spring system. The mass of the balls and the strength of the spring need to be well-matched, and the diameter of the springs must be at least half the diameter of a ball.

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constructing the model can be found in Supporting Information.

With our specific system, we were able to demonstrate the bending mode at 5.2 ± 0.1 Hz, symmetric stretch at 17.5 ± 0.2 Hz, and antisymmetric stretch at 30.0 ± 0.1 Hz. At higher frequencies the model would occasionally demonstrate combination vibrational modes. At all other frequencies the model moves only slightly or erratically, this being equivalent to carbon dioxide not absorbing other frequencies of radiation. In addition to demonstrating the relationship between radiation and microscopic motion, it also demonstrates that the bending mode is lower in frequency (energy) than the symmetric stretch, which is lower in frequency (energy) than the antisymmetric stretch. Finally, it demonstrates the absorption of infrared radiation by carbon dioxide through resonance coupling. The frequency of the spinning disk has to match the natural frequency of the model system for smooth and regular vibrational modes to appear.

Steady-State Condition and Changes to Steady-State

After carbon dioxide has absorbed infrared radiation, it can either transfer the energy to the local surroundings by collisions with other molecules, or it can re-emit infrared radiation. The re-emitted radiation is emitted upward or downward where it can either be reabsorbed/re-emitted by the atmosphere or ground or, eventually, be emitted into space. It is important to note that, as energy is transmitted back and forth throughout the atmosphere, the rate at which infrared radiation is emitted into space must match the rate at which solar energy is absorbed by the Earth's surface; otherwise, the total energy (and thus temperature) of the Earth would experience a change. This condition of equal rates of energy absorption and emission by the planet is known as a steady-state.[13] Our goal was to demonstrate how adding more carbon dioxide to the atmosphere would change the steady-state condition and result in an increase to the amount of energy temporarily trapped on the planet, and thus the planet's temperature.

A plastic water-flow device has previously been built by Blanck to demonstrate the concept of steady-state in the context of energy flow.[14,15] Our design was similar in size and materials of construction, but instead of having a fixed number of partitioning walls, our apparatus utilized partitions that could be inserted and/or removed as needed to mimic the addition of carbon dioxide to the atmosphere (Figure 3). Each of the partitions included an approximately 1 mm diameter hole located approximately 2 mm from the bottom edge to allow water to flow between chambers. Step-by-step instructions on how to build the device are available in Supporting Information.

In analogy to steady-state energy transfer through the atmosphere, the total quantity of water in each chamber represents the temporarily stored energy at a particular altitude in the atmosphere, and the height of the water column in each chamber represents the temperature of the atmosphere at a particular altitude. Just as a pressure difference between columns (created by different column heights) causes water to flow in our apparatus, the temperature difference between different levels in the atmosphere results in a net transfer of energy (heat). Similarly, just as individual partitions will impede the flow of water as it travels from the first chamber, through each partition, and finally to the drain, the transfer of energy from the surface of the planet, through the atmosphere, and into space will be impeded by the presence of greenhouse gases such as carbon dioxide. Adding partitions thus represents increasing the concentration of carbon dioxide and the optical depth of the atmosphere.

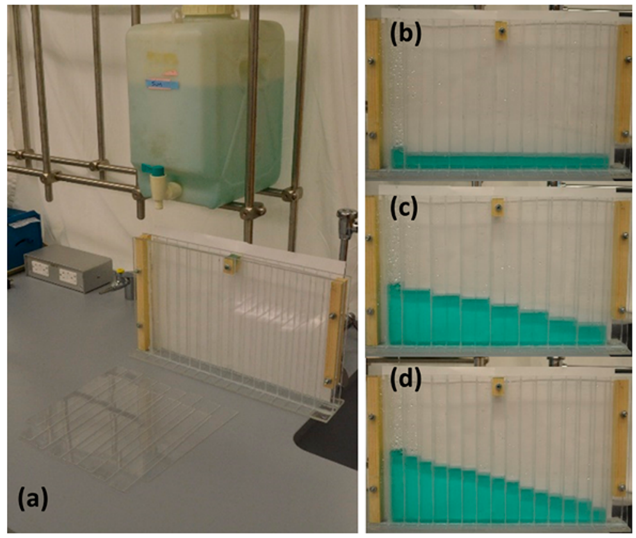

Figure 3. (a) Plastic water-flow device with all partitions removed. The picture sequence demonstrates steady-state for (b) 2, (c) 8, and (d) 15 partitions inserted, which represents an increase in the concentration, or number of "layers", of carbon dioxide. Note how the height of water in the first cell increases while the height of water in the last cell remains approximately constant. The same flow rate into the model was used for each of the pictures.

To begin our demonstration, all of the partitions were removed, and dyed water from a carboy (representing radiation from the sun) was added at a fixed flow rate. As no partitions were present to impede the flow of water, water immediately left the device at the same rate it entered. This represents a planet with a perfectly reflective surface with no atmosphere. To model the Earth as a blackbody absorber without an atmosphere, a single partition was added. Steady-state flow of water was achieved when the level of the water in the first chamber rose until the pressure created by the rising column of water was great enough to push water through the 1 mm hole at a rate equal to the input rate.

Addition of the next partition represented the addition of a "layer" of atmosphere that contains greenhouse gases. Initially, there was a temporary decrease in the rate of water flowing out of the device as the water levels in the first two cells increased to re-establish steady-state. The height of the water column in the first cell approximately doubled, and the height in the second cell rose to the level originally obtained by the first cell (Figure 3b). Each subsequent addition of a partition represented another "layer" of greenhouse gases in the atmosphere (Figure 3c,d). Addition of each subsequent partition resulted in a momentary decrease in the output flow rate followed by an increase in the water heights in all of the cells (most notably in the first cell) until a new steady-state was established. This is analogous to how adding greenhouse gases to the atmosphere causes the surface temperature of the planet to increase. Adding more carbon dioxide to the atmosphere is equivalent to increasing the number of layers of atmosphere between the surface of the planet and outer space that infrared radiation has to pass through.[3] A video of the change between the steady-states represented in Figure 3c,d is available to view online.[16]

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What our model does not take into account is the exponential decrease in concentration of a gas as a function of elevation (due to a pressure decrease). At higher elevations, radiation can travel farther before being absorbed than it can when it is close to Earth's surface.[8] This can be mimicked using our device by placing partitions in the 1st, then 3rd, 6th, 10th, and 15th grooves, resulting in a profile that roughly reflects decreasing concentrations of gases with increasing elevation, i.e., fewer layers at high altitude (Figure 4).

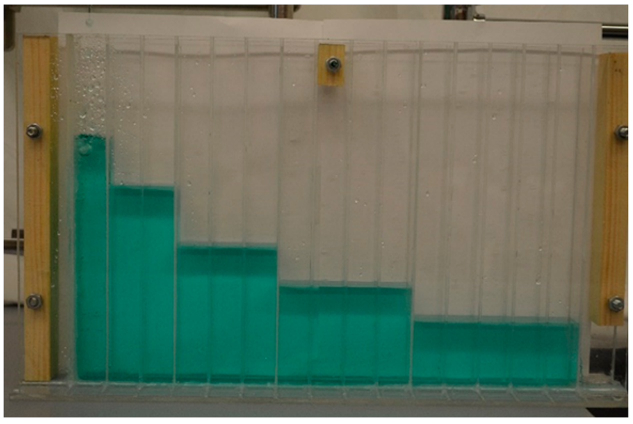

Figure 4. Plastic water-flow device with partitions at the 1st, 3rd, 6th, 10th, and 15th positions to represent steady-state through an atmosphere with diminishing concentrations of a greenhouse gas as a function of altitude.

As a teaching tool, our system demonstrates steady-state and changes in steady-state due to an increased amount of a greenhouse gas. It takes the emphasis off of *additional absorption* as being the cause of global warming and emphasizes climate change as being a change in a steady-state. Finally, our model can serve as a reminder that gas concentration decreases exponentially as a function of elevation.

CONCLUSION

We have provided some pragmatic suggestions with regard to three classic demonstrations that model aspects of radiant energy transfer through an atmosphere containing greenhouse gases. The use of a pyranometer made Herschel's experiment quick and easy. Golf balls and compression springs from the local hardware store produced a system with three fundamental vibrational modes similar to those of carbon dioxide and demonstrated resonance coupling. Finally, inserting movable partitions into a water-flow device provided flexibility when teaching steady-state and, more specifically, changes to steady-state.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00626.

Materials lists, instructions for setup, special considerations and tips (PDF)
Ball-and-spring video, bending (MPG)
Ball-and-spring video, symmetric stretch (MPG)
Ball-and-spring video, antisymmetric stretch (MPG)

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Notes

The authors declare no competing financial interest.

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