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Explaining Global warming through Quantum Mechanics

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ABSTRACT

In the current world scenario, it is no surprise that glaciers are melting, sea levels are rising, forests are dying and the wildlife are losing almost all their habitat. We often call the result - Global Warming.

Keywords: *Quantum Mechanics, Climate Change, Spectroscopy, Environment, Global Warming*

1. INTRODUCTION

It has become clear that humans have caused most of the past century's warming by releasing heat-trapping gases as we power our modern lives. Such gases are commonly known as 'greenhouse gases (GHGs)' and result in the 'greenhouse effect'. Anthropogenic activity being the major contributor to global warming and climate change, has resulted in greenhouse gas levels being higher now than at any time in the last 800,000 years.

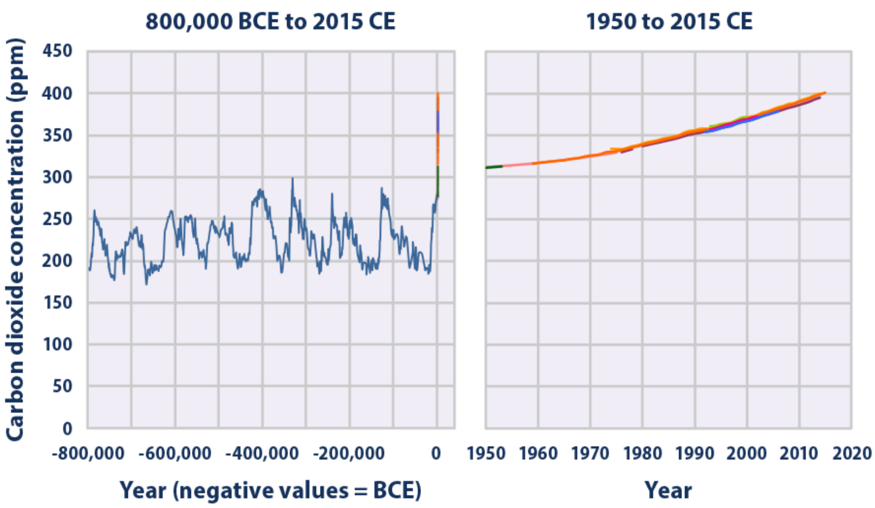

Fig. 1

While many people tend to use global warming and climate change as synonyms, scientists use the term 'climate change' when describing the complex shifts now affecting our planet's weather and climate systems. Climate change encompasses not only rising average temperatures but also extreme weather events, shifting wildlife populations and habitats, rising seas, and a range of other impacts.

In simple terms, the greenhouse effect is the warming of the Earth's surface when the GHGs namely - carbon dioxide (CO_2), methane (CH_4) , water vapour and chlorofluorocarbons (CFC's) trap and radiate the sun's energy back into the atmosphere. The natural greenhouse effect is essential as it helps maintain an optimum temperature on the Earth's surface, without which the temperature would be about 60 degrees Celsius cooler. However, with the increase in concentration of GHGs, the greenhouse effect is enhanced, eventually leading to global warming and climate change.

The rapid rise in greenhouse gases is a major issue because it's changing the climate faster than some living organisms can adapt to. In addition, a new and more unpredictable climate would pose unique challenges to all life. Thus, there exists a pressing need to gain a better understanding of global warming and climate change in order to provide solutions to the same.

It is well known that anthropogenic activity including burning of fossil fuels and large-scale industrialization, are some of the major factors causing global warming. However, human activity isn't the only factor that affects Earth's climate. Volcanic eruptions, variations in solar radiation from sunspots, solar wind, the Earth's position relative to the sun and large-scale weather patterns such as El Niño, all play a role. The extent to which such factors play a role in contributing to global warming, varies. Volcanic eruptions, for example, emit particles that temporarily cool the Earth's surface and the effects of the same, lasts just a few years. Events such as the El Niño also work on fairly short and predictable cycles. On the other hand, the types of global temperature fluctuations that have contributed to ice age, occur on a cycle of over thousands of years.

A lesser known factor contributing to global warming and climate change, lies in the Earth's atmosphere, particularly in the troposphere. The Earth's atmosphere has been divided into five major layers and several secondary layers. Going from the lowest to highest, they are - troposphere, stratosphere, mesosphere, thermosphere and exosphere. The Earth's troposphere is a very shallow layer tasked with holding all the air plants require to perform photosynthesis and animals require to respire. The tropopause is the boundary between the troposphere and the stratosphere. In the troposphere, temperatures typically decrease as one goes higher, since most of the heat found in the troposphere is generated by the transfer of energy from Earth's surface.

Surface warming results in an upward shift of the tropopause. When carbon dioxide (CO2) levels increase with fixed surface temperature, a warmer tropopause mainly results from the direct radiative effect of carbon dioxide increase. With surface warming, the largest contribution to the tropopause warming comes from the radiative effect of the warmer troposphere, which is partly cancelled by the radiative effect of the moistening at the tropopause. Strengthening of the stratospheric circulation following surface warming cools the lower stratosphere dynamically and radiatively via changes in ozone. These two effects are of comparable magnitudes and this circulation change is the main cause of temperature changes resulting in global warming.

Global warming and climate change are resulting in direct changes to our planet. Though the changes may seem small, the impacts are huge. For example, the Earth's temperature has already increased by 1 degree Celsius compared to pre-industrial levels. The impact of the same may potentially be disastrous because the amount of extra energy required to increase the average surface temperature would also rise in turn force-feeding the global climate system. Commonly known effects of global warming include rising sea levels, more frequent extreme weather events, warming and acidification of oceans, species extinction, droughts, coral bleaching and of course, damage to human health and habitats. With the knowledge of the same, it is imperative that we explore solutions that help mitigate or reduce the impacts of global warming in order to protect our planet from further deterioration.

This increase in the average temperature can be understood with the help of quantum mechanics and principles of radiative transfer. The earth absorbs 1.22×10^{17} joules of energy from the sun every second. If the earth had no way of getting rid of the energy, the temperature would rise to 800,000 Kelvin in one billion years, so it's evident that the earth needs to get rid of this energy. The way that earth gets rid of this excess energy from the sun, is through the emissions of infrared radiation. The atmosphere is a gaseous mixture of matter and photons. As planets are significantly less dense compared to other celestial objects, the photons do not interact with each other. One of the key principles of radiative theory is that radiation is produced by quantum transitions. The momentum of photons is too small to observe any significant change in the kinetic energy. Therefore, the momentum of the photons is used to change the internal quantum states of the molecules in the atmosphere as they absorb photons from visible light. Given that molecular energy levels are discrete, when they are hit by infrared radiations that have photons carrying the amount of energy which is equal to the difference between the energy levels of that particular molecule they gain energy and move to a higher energy level. However, at higher energy levels these molecules are highly unstable and have an innate tendency to fall back to a lower energy level. As they fall back to a lower energy level, they must release the energy that they previously gained by emitting infrared radiations back into the atmosphere due to conservation of energy. The radiations emitted scatter around in all directions – some of them are emitted back into outer space while some of them are emitted back into the earth, thereby increasing the temperature.

Planck's law dictates that solar radiation can be described as radiations emitted from a black body at a temperature of nearly 6,000 Kelvin. The energy available for the earth is given by the equation:

$$E_a = \pi r_E^4 (1 - \alpha) S_0$$

where S_0 is the solar constant, r_E is the radius of the earth and α is the albedo of the planet. The albedo α, can be defined as the ratio of the total power scattered to the total incident power. All bodies that have some absolute temperature (temperature above 0K) radiate energy in the form of electromagnetic waves. The power radiated by the body can be governed by the Stefan-Boltzmann law, which is defined by the following equation:

$$P = e\sigma A T^4$$

The energy absorbed and remitted can be defined in accordance to the Stefan-Boltzmann law as follows:

$$E_t = 4\pi r_e^2 \sigma T_e^4$$

In the above equations, σ is known as the Stefan-Boltzmann constant and has a value of $5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$. Furthermore, it should be noted that the Planck's law has been integrated over all frequencies and angles and the values of the temperature and albedo used for computation are mean values.

The primitive equation for radiative transfer is

$$I_v = I_v(0)e^{-\tau_v} + I_V^B[1 - e^{-\tau_v}]$$

From this fundamental equation, we can calculate the radiation intensity for an object with negligible optical density, $\tau_v \ll 1$. The intensity of an optically thin body is now defined by the equation: $I_v = \tau_v I_V^B$. For an optically thin body the intensity of the radiation is much smaller compared to that of a black body at a particular frequency as shown in the figure 2.

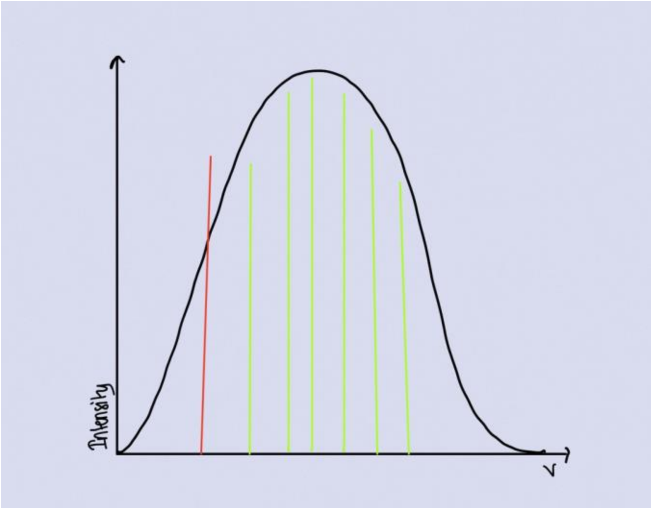

Fig. 2: Black body radiation

Note: The figure is just a rough diagram of the radiation pattern from a black body.
Note: A black body is a theoretical body that has an emissivity of the surface equal to one and is a perfect absorber as well as radiator.

It should be noted that the black curve gives the shape of a black body radiation and all the lines drawn in green are possible radiations, however, the line in red is forbidden as no object can have radiations at an intensity greater than that of a black body.

Absorption and emissions are discrete and are functions of the frequencies due to the nature of the energy levels of a particular element where there will be a transition from one energy level to the other only when the photon carries energy that is equal to

$$E_{\Delta n} = -13.6 \times \frac{z^2}{n_2^2} - -13.6 \times \frac{z^2}{n_1^2} \text{ ev}$$

where z is the atomic number of the element undergoing transition and n is the energy level number also called the principle quantum number. It should be noted that it is not mandatory for an electron to fall back to the ground state, it can fall back to any of the energy levels that lie below the excited energy level.

2. QUANTUM THEORY OF RADIATION

For the sake of conceptual understanding, assume that there is a 2 level atom in a radiation field $\mathrm{U(v)}$ where the energy level 'm' is greater than the energy level 'n'. The rate of transition from the upper level m to the lower level n can be given by

$$[\mathrm{A} + \mathrm{CU(v)}]\mathrm{N(m)}$$

Where A is the Einstein coefficient for spontaneous emission, C is the Einstein coefficient for stimulated emission and $\mathrm{U(v)}$ is the energy density. Einstein said that an atom will jump from level 'm' to level 'n' even if it is not prompted by an external radiation field due to vacuum fluctuations. Similarly, the rate of stimulated absorption can be given by

$$[\mathrm{BU(v)}]\mathrm{N(n)}$$

Where B is the Einstein coefficient for stimulated absorption.
From symmetry,

$$\mathrm{B} = \mathrm{C}$$

And for thermal equilibrium to occur,

$$\frac{\mathrm{N(m)}}{\mathrm{N(n)}} = e^{\frac{-\mathrm{E(m)}-\mathrm{E(n)}}{kT}}$$

$$= e^{\frac{-hv}{kt}}$$

At equilibrium, the rate of emission must be equal to the rate of absorption

$$[\mathrm{BU(v)}]\mathrm{N(n)} = [\mathrm{A} + \mathrm{CU(v)}]\mathrm{N(m)}$$

Therefore yielding,

$$\mathrm{U(v)} = \frac{\mathrm{A\,N(m)}}{\mathrm{B(N(n) - N(m))}}$$

$$\mathrm{U(v)} = \frac{\frac{\mathrm{A}}{\mathrm{B}}}{e^{\frac{-\mathrm{E(m)}-\mathrm{E(n)}}{kT}} - 1}$$

From quantum mechanics the values of A and B can be found as follows:

$$\mathrm{A} = \frac{8hv^3\mathrm{B}}{c^3}$$

$$\mathrm{B} = \frac{4\pi^2 e^2}{3h^2}|x_{mn}|$$

Therefore, Einstein conclusively proved that whenever there is a stimulated emission, there has to be spontaneous emission.

3. SPECTROSCOPY OF GREENHOUSE GASES

The compounds that play the most important role in explaining the heating effect is water vapour and carbon dioxide. The absorption cross section for carbon dioxide and water vapour is a function of the wavenumber, which is directly proportional to the frequency v.

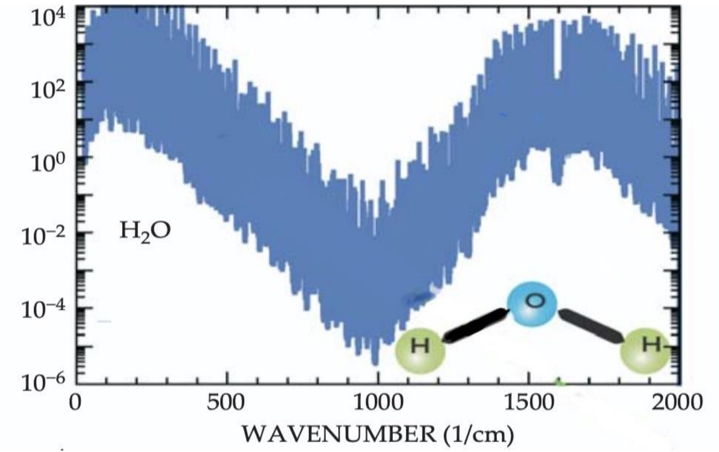

Fig. 3: Cross sectional absorption spectra for water vapour

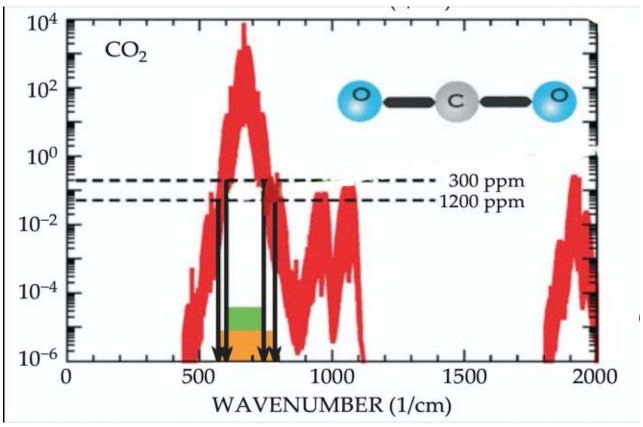

Fig. 4: Cross sectional absorption spectra for carbon dioxide

Note: These spectra are obtained from the HITRAN database.

These spectra are computed at an atmosphere pressure of about 5×10^4 Pa which is similar to the middle of earths atmosphere. As seen by the spikes in Figure 4, carbon dioxide has four main regions of absorption. From these four regions, the most earth like is the one that has a wavenumber of about 670/cm. As seen in the above spectral diagrams, the water vapour molecule is able to absorb at a much broader range of frequencies in comparison to the carbon di-oxide molecule. This is due to the polar nature of the water vapour molecule. The continuous spectrum obtained from gaseous collisions can be explained as the colliding molecules act as a singular complex molecules each of which has a transition of its own. For modern day earth like conditions, the most important spectra is that of water vapour at about the $1000cm^{-1}$range. The earth's atmosphere is heated partly from its own surface due to the absorption of internal heat. The lower layers of the atmosphere are primarily regulated through convection and the fluid motions, and the constant lifting produce a region of lower temperature as we go up in the atmosphere. As we go higher up the atmospheric movement is primarily governed by radiative transfer as opposed to convection. At higher regions, the temperature roughly constant or decreasing at a very slow rate.

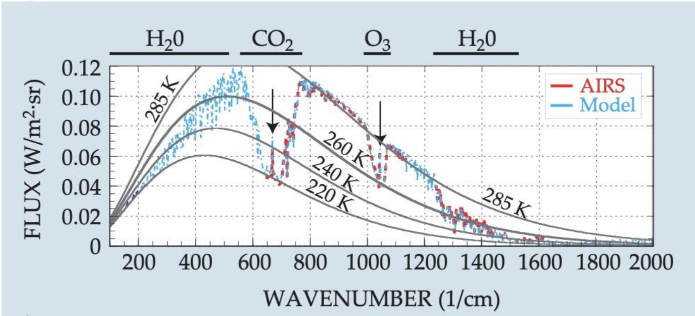

Fig. 5

The data observed by the Atmospheric Infrared Sounder (AIRS) is shown in figure 5 by the red lines and the predictions made by the model are given by the blue lines. The AIRS satellite collected data for a wavenumber of 650 and beyond, however, the predictions theorized earlier hold just as true for values less than 650. As seen in the above figure, the similarity between the theorised model and observed data is a near perfect match, thereby validating the spectroscopy, radiative transfer theory and physics behind climate change.

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