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Cosmic rays and changes in atmospheric infra-red transmission

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ABSTRACT

Recent work by Aplin and Lockwood (2013) [1] was interpreted by them as showing that there is a multiplying ratio of order 10^{12} for the infra-red energy absorbed in the ionization produced by cosmic rays in the atmosphere to the energy content of the cosmic rays themselves. We argue here that the interpretation of the result in terms of infra-red absorption by ionization is incorrect and that the result is therefore most likely due to a technical artefact.

1. Introduction

Atmospheric molecular cluster ions (MCI) are bipolar charged species formed by ionization in the atmosphere. The absorption of infra-red radiation (IR) by such clusters is interesting since it could have an effect on the Earth's radiation budget and thereby allow the ionization from cosmic rays (CR) to affect the climate. Recently, an experiment has been described by Aplin and Lockwood (AL) in which they claim to observe a large absorption of IR by MCI produced by CR in the atmosphere [1].

In the AL experiment infra-red (IR) detectors are operated close to a small CR telescope. The IR band studied is 9.15 ± 0.45 μm, a region of reduced absorption by atmospheric greenhouse gases [2]. They observe an average decrease of $\sim$2.5 mW/m^2 in intensity over this wavelength range in a time duration of order 800 s following counts in the telescope. They assume that the decrease is caused by the absorption of IR radiation by MCI produced by CR showers, one particle of which gives the detected count (usually a muon). They claim that the ratio of the total IR energy absorbed by these showers to the energy in the CR itself is of order of 10^{12}.

This quite remarkable result needs careful independent analysis and this is what we propose to do. We will show that the interpretation of result as absorption of IR by MCI leads to impossible consequences and we conclude that this interpretation is wrong.

2. The reasons for believing that the AL interpretation is wrong

2.1. Most AL triggers are from low multiplicity events

AL propose that the absorption which they observe is from CR showers in the upper atmosphere. Their trigger is unselective and so they sample all primary CR energies. The energy spectrum of CR primaries falls roughly as E^{-3} so their triggers (mostly muons) will come mainly from low energy primaries. A calculation shows that the average primary energy sampled by their trigger is $\sim$12 GeV interacting at an altitude between 10 and 20 km [3]. The average multiplicity of secondary particles at this primary energy will be of order 10 [4]. The mean transverse momenta of the secondary tracks will be of order 0.5 GeV/c [4]. Together with the effects of multiple Coulomb scattering, this will spread the secondary particles over a radius of several hundred metres at the Earth's surface. There will be considerable fluctuations about these values but these will serve for the order of magnitude estimates we make here.

From this one sees that the majority of the CR triggers in the AL apparatus come from small low energy showers rather than the large high energy showers which they assume. A single low energy shower produces only a small instantaneous increase of the ion pair concentration in the atmospheric column above their IR detectors, as described below.

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2.2. The observed absorption is inconsistent with laboratory measurements

This is illustrated by a simple order of magnitude calculation. AL draw attention to the measurements of [5,6]. These show that laboratory measurements give rise to absorptions of 1–3% in two bands centred on wavelengths 9.15 and 12.3 μm with MCI columnar concentrations of 10^{13} m^{-2}.

CR muons deposit energy at the rate of 1.8 MeV per g cm^{-2} in the air [4]. The energy expended to create an ion pair is 35 eV [4]. So each muon produces $5.1 \cdot 10^4$ ion pairs per g cm^{-2} (i.e. 66 ion pairs per cm of air at ground level). A muon passing through the troposphere (lower 700 g/cm^2 of the atmosphere) will therefore produce $3.6 \cdot 10^7$ ion pairs. Let us assume that each muon is, on average, accompanied by of order 10 further muons over an area of order 100 m^2. This implies an ion columnar density of order 3.6 10^6 ion pairs per m^2.

Fig. 2 in the AL paper shows that the mean daily IR intensity is 350 W/m^2 in their broad band detector. The intensity in the region of their narrow band detector (9.15 ± 0.45 μm) will be approximately 5.5% of this figure i.e. 19 W/m^2. We make the conservative assumption that all this energy flux comes from the top of the troposphere.

From the laboratory measurements one would deduce, assuming that each ion of the pair produces a MCI (i.e. 2 MCI per ion pair), that the ionization from CR should absorb $2 \cdot (0.01 - 0.03) \cdot 19 \cdot 3.610^6/10^{13}$ i.e. 0.14–0.41 μW/m^2. This is 4 orders of magnitude smaller than AL actually observe. This absorbed energy is an overestimate since it assumes every IR photon passes through the column of ions in the shower. In fact only a fraction $\Delta\Omega/4\pi$ of the photons will pass through the column where $\Delta\Omega$ is the solid angle subtended by the shower at the IR detector. Hence the absorption should be even smaller than this estimate.

Furthermore, the time variation of the amplitude decrease seen by AL is incompatible with absorption by MCI. The MCI concentration should decay exponentially after formation with a time constant of order of their lifetime due to recombination. This lifetime could be as short as 50 s [7] but a more modern calculation would increase this to of order 500 s. In contrast, AL observe that the amplitude of their signal actually increases rather than decreases with time for 500–700 s and then decreases rapidly. Hence the time variation observed by AL is not an exponential decay and is therefore incompatible with the absorption of IR by MCIs.

In conclusion the magnitude of the AL signal is inconsistent with their laboratory measurements, and the time characteristics of the AL signal are inconsistent with those expected from the absorption of IR by ions produced by a CR shower.

2.3. Implied energy imbalance

The AL multiplying factor of 10^{12} should be seen against the fact that the total sunlight energy density is about 10^8 times that in CR (adopting the usual CR energy density of 0.5 eV cm^{-3} [4]). Their trigger is unselective and is sensitive to all muons which pass through its active solid angle. Hence, on average, each muon must behave in a similar way and the effect they observe must therefore be cumulative and linear. The implication is that their factor of 10^{12} then applies, on average, to all CR hitting the Earth. Hence the claimed absorption of IR energy by MCI from CR is of order 10^3 times the total from sunlight falling on Earth (assuming on average 10 muons per shower).

Hence, as well as the inconsistencies described in Section 2.2, the attenuation which AL claim to measure is also inconsistent with conservation of energy. Therefore, their interpretation of the result as attenuation of IR by ionization from CR must be wrong.

3. Consequences of the result being true

3.1. The absorption cross section for IR photons by multi cluster ions

3.1.1. The signal from a single muon

The laboratory measurements of [5,6] imply a measured cross section per MCI for absorption of IR photons of $1\text{–}3 \cdot 10^{-11}$ cm^2. A comparison is now made with the cross sections which can be deduced from the measured attenuations by AL assuming that it comes from absorption of IR by MCI produced by ionization from CR particles.

The probability of an IR photon to be directed towards the AL detector and to be absorbed by MCIs from a single ionizing track is given by geometry to be

$$P = \frac{I\sigma}{4\pi a}\left(\alpha_1 - \alpha_2 + \frac{1}{2}\sin 2\alpha_1 - \frac{1}{2}\sin 2\alpha_2\right). \quad (1)$$

This equation is derived in the Appendix. Here I is the number of MCI per unit length of the track, a is the perpendicular distance from a projection of the track to the IR detector and σ is the absorption cross section for an IR photon by a MCI. The angles α_1 and α_2 (see Fig. 1) are those between the line in the plane of the track through the detector perpendicular to the track projection and the line in the same plane from the detector to the start and end points of the track, respectively.

It can be seen from Eq. (1) that the absorption probability decreases linearly with the perpendicular distance, a, of the projection of the particle track to the detector. Hence the closest tracks to the detector are the most important ones for IR absorption. It can also be seen that for tracks which begin and end at high altitude the difference between the angles α_1 and α_2 will be small and therefore the absorption probability for such tracks is small. Hence, the contribution from high altitude absorption will be small except for the rather rare extensive air showers from very high energy primaries which produce large numbers of particles. Such events are rare since the primary CR spectrum falls roughly as $E^{-2.6}$ [8], where E is the primary energy. They are considered separately in Section 3.1.2. For a single muon, the quantity I will fall as the altitude increases due to the reduction of pressure with altitude. This is partly offset, however, by the increased ionization from the few other secondary tracks associated with the detected muon [3]. In fact, the decreasing rate of change of the angle α with altitude implies that most of the absorption takes place in the vicinity of the detector, so that the changes in I will be insignificant.

The absorption probability measured from the AL experiment is difficult to estimate precisely. However, rough order of magnitude estimates are possible as follows. Assuming that the principal source of IR is radiation from the lower atmosphere, the total source energy in their wavelength range will be 19 W/m^2 (350 W total with a fraction 0.055 in their wavelength range). If, however, the source is mainly radiation from the stratosphere, the total will be lower, implying a higher absorption probability (higher cross section). To obtain a conservative lower limit on the cross section we take the measured probability to be the ratio of the observed absorption of 2.5 mW/m^2 to the estimated source energy of 19 W/m^2 i.e. $1.3 \cdot 10^{-4}$, the smaller of the two probabilities.

The columnar density of MCI is computed from the rate of production of ionization by muons (see above) assuming that each ion pair produces a MCI. The absorption cross section is then computed from the AL observed attenuation and the density of MCI production as follows.

From Eq. (1) the absorption will be dominated by the track closest to the detector which in the majority of cases will be the trigger muon. In this case the angle α_1 is almost $\pi/2$ radians and the angle