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**Cosmic rays and changes in atmospheric infra-red transmission**

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Abstract

Recent work by Aplin and Lockwood [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 $9.15 \pm 0.45 \mu m$, 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 seconds 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.

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 $\mu$m with MCI columnar concentrations of $10^{13} \text{m}^{-2}$.

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 $5.1 \times 10^4$ ion pairs per gm 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 $3.6 \times 10^7$ 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 $3.6 \times 10^6$ 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 ($9.15 \pm 0.03 \pm 0.45 \mu$m) 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 $2 \cdot (0.01 - 0.03) \cdot 19 \cdot 3.6 \times 10^6/10^{13}$ i.e. 0.14-0.41 $\mu$W/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 seconds [7] but a more modern calculation would increase this to of order 500 seconds. In contrast, AL observe that the amplitude of their signal actually increases rather than decreases with time for 500-700 seconds 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 aborption 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 $0.5 \text{ eV cm}^{-3}$ [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 $1-3 \times 10^{-11}$ 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

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

(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 \( \sigma \) is the absorption cross section for an IR photon by a MCI. The angles \( \alpha_1 \) and \( \alpha_2 \) (see figure 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 equation 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 \( \alpha_1 \) and \( \alpha_2 \) 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 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 \( \alpha \) 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. \( 1.3 \times 10^{-4} \), 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 equation 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 \( \alpha_1 \) is almost \( \pi/2 \) radians and the angle \( \alpha_2 \) will be the angle of the muon track to the vertical which is usually small since the muon angular distribution peaks around the vertical direction [8]. Substituting these values into equation 1 the absorption cross section for IR photons will then be of order \( 3 \times 10^{-3} \) cm\(^2\) per MCI. Allowing for IR photons produced below the level of the track or the fact that not every ion pair produces a MCI will increase the value of this estimated cross section. Hence this value is a lower limit on the cross section necessary to satisfy the AL observations. This lower limit is 8 orders of magnitude greater than the measured cross section [5, 6].

We have attempted to be conservative to find this lower limit on the cross section for absorption of an IR photon by MCI. Some of the numbers are debatable and adjustments to the
numbers could be made which may decrease it by a small factor. However, it will be impossible to reduce the implied cross section by the 8 orders of magnitude needed to be compatible with the laboratory measurements.

Hence, the cross section implied by the AL measurements is again incompatible with the laboratory measurements and it is also unphysically large for a molecular process.

3.1.2 The signal from CR showers

AL [9] propose that the majority of the absorption is by showers at high altitude. Such showers dissipate most of their energy as lower energy secondary particles at altitudes between 5 to 15 km. Hence the term in $\alpha_1 - \alpha_2$ is of order $10^{-3}$ for such particles, assuming that the value of $a \sim 300$ cm. The atmospheric pressure at this altitude is roughly 1/3 that at ground level. Hence the number of ion pairs will be of order 20 per cm per secondary particle. We assume that the cross section for the absorption of IR photons is the measured value of $2 \times 10^{-11}$ cm$^2$ [5,6]. Substituting these values into equation 1 shows that the probability for the absorption of IR photons at this altitude is of order $10^{-16}$ per secondary particle. We showed above that the total absorption probability for IR photons implied by the AL measurements is of order $10^{-4}$. Hence one needs showers containing of order $10^{12}$ particles to produce the absorption which they observe.

Extrapolating from shower measurements at lower energies, the primary particle energy needed to produce this number of secondary particles is of order $10^{12}$ GeV. Such an energy CR primary is greater than the maximum energy currently being observed and these events are very rare indeed, with fluxes of order 1 per square kilometre per century [10]. This is too rare to influence the average from randomly selected muons.

AL imply that their result could be due to absorption in CR showers at high altitude [9]. As we show above in section 3.1.1 most of the absorption should, instead, be attributable to single or small numbers of particles passing close to the IR detector. Events which give large enough numbers of particles to produce significant absorption in the upper atmosphere are extremely rare as shown above. Thus large CR showers cannot be responsible for the AL result.

3.2 Implications of the detected signals

Yet another way of looking at the consequence of the signal in the AL experiment being true is simply to consider the contribution to the IR absorption of all the other CR muons which arrive within the temporal and spatial window of the IR detector.

Equation 1 shows that most of the absorption occurs from muon tracks within a few metres of the IR detector. The total number of muons in 1 second passing through a disk of radius $R$ is $\sim \pi R^2 I_{CR}$ where $I_{CR} \sim 80$ m$^{-2}$sr$^{-1}$s$^{-1}$ [8] is the observed vertical CR muon rate at the Earth’s surface. This gives a total of 6300 muons passing through a disk of radius 5m each second. According to the AL measurements each muon absorbs $\sim 2.5$ mJ in each second for a time of 800 seconds. So the total IR energy absorbed in any 1 second by muons in the vicinity of their detector is $\sim 0.0025 \cdot 6300 \cdot 800 \sim 12600$ J i.e. the total IR power which would be absorbed is of order 12.6 kW in the 9$\mu$m band. However, there are only $\sim 350$ W of power available over the whole IR spectrum. Hence again the result of the AL experiment implies an unphysical value.
4 Likely explanations and conclusions

We have demonstrated that the results of the AL measurements, as interpreted by AL, lead to impossible consequences. What then could be the reason for the result?

It might be thought that an explanation is that it is due to some new unknown process. This seems highly unlikely since the contributing processes involve rather low energy electromagnetism. Furthermore, there would still be the inconsistency with their own laboratory measurements.

A more likely explanation is that the result is due to a bias or `cross-talk’ between the CR and IR detectors. Averaging noisy signals to produce a small observed deviation from zero such as is done in the AL experiment is very sensitive either to the presence of an apparatus bias or to such cross talk.

It is evident that an independent analysis of IR signals associated with CR is needed before the dramatic results of AL are considered further. Such analysis should include the careful monitoring of atmospheric conditions and searches for apparatus biases eg by an equal study of random triggers and CR triggers.

5 Appendix

Probability of absorption of an IR photon by a single ionizing track

The geometry of the single ionizing track is shown in figure 1. Take a small element of the track of length $dL$ at distance $L$ from the point on the perpendicular between the detector and the track (line AB in figure 1). This line subtends an angle $\alpha$ to the element. Assuming an isotropic distribution of IR photons, the probability of a downward-going photon moving in the direction of the detector traversing this element of track is $d\Omega/2\pi$ where $d\Omega = \pi w^2 \sin \alpha / r^2$ is the solid angle subtended by the element at the detector. Here $w$ is the radius of the element and $r$ is its distance to the detector. The probability that this photon is absorbed in the element $dL$ is $dx/\lambda$ where $dx = dL / \sin \alpha$ is the thickness of the element traversed and $\lambda = 1/\nu \sigma$ is the mean free path of the photon in the sea of MCI around the track. The mean density of MCI in the element is $\nu = I / \pi w^2$ with $I$ the number of MCI per unit length produced by the track and $\sigma$ is the absorption cross section for an IR photon by a MCI. Here it is assumed that the ions drift outwards by Brownian motion to fill a cylindrical column of radius $w$ ($w >> dL$) at a certain time. Hence the probability that the IR photon is absorbed in the element is

$$dP = \frac{d\Omega}{2\pi} \frac{dx}{\lambda} = \frac{\pi w^2 \sin \alpha}{2\pi r^2} \frac{dL}{\lambda \sin \alpha} = I \sigma dL \frac{\sin \alpha}{2\pi r^2}$$

(2)

The unknown track radius $w$ cancels so that the value of $dP$ does not depend on time.

Substituting that $L/r = \sin \alpha$ so that $dL = r \cos \alpha d\alpha$ and $a/r = \cos \alpha$ gives

$$dP = \frac{I \sigma}{2\pi a} \cos^2 \alpha d\alpha,$$

(3)

here $a$ is the perpendicular distance of the track to the detector (see figure 1). Integration of equation (3) over the length of the track (AD in figure 1) i.e. between the angular limits $\alpha_1$ and $\alpha_2$ gives the total probability for an IR photon to be absorbed by the track which is given in equation (1).
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Figure 1: (a) CR track starting at point D and ending at point C. The detector is at point B. The line AB is a perpendicular from the detector to the line of the track. Angle ABD is $\alpha_1$ and ABC is $\alpha_2$. (b) As (a) but showing a small element of the track, thickness $dL$, radius $w$ containing the ions. The element is at distance $L$ from point A and subtends angle $\alpha$ to the perpendicular AB.

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