SOLAR SYSTEM OBJECTS AS COSMIC RAYS DETECTORS

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ABSTRACT

In a recent Letter, Jupiter is presented as an efficient detector for Ultra-High Energy Cosmic Rays (UHECRs), through measurement by an Earth-orbiting satellite of gamma rays from UHECR showers produced in Jupiter’s atmosphere. We show that this result is incorrect, due to erroneous assumptions on the angular distribution of shower particles. We evaluated other solar system objects as potential targets for UHECRs detection, and found that the proposed technique is either not viable or not competitive with traditional ground-based UHECRs detectors.

Key words: astroparticle physics – cosmic rays – gamma rays: general – planets and satellites: individual (Jupiter, Moon, Earth)

1. JUPITER AS A COSMIC RAY DETECTOR

A recent Letter (Rimmer et al. 2014) claims that a gamma-ray detector on an Earth-orbiting satellite, e.g., Fermi (Atwood et al. 2009), would be sensitive to Ultra-High Energy Cosmic Rays (UHECRs) interacting in Jupiter’s atmosphere. The satellite instrument would detect gamma rays from the shower of particles (electrons, positrons and photons) induced by UHECRs skimming Jupiter’s atmosphere, which may emerge from the atmosphere in a beam pointing to Earth. This result can be shown to be incorrect by a simple argument.

For a UHECR shower to be detectable, the number of gamma rays, \( n_\gamma \), reaching the satellite must be greater than one:

\[
n_\gamma = \frac{N_\gamma f_\gamma(\theta_b)A}{\pi(D\theta_b)^2} > 1,
\]

where \( N_\gamma \) is the number of gamma rays in the shower at its exit point from the atmosphere, \( f_\gamma(\theta_b) \) is the fraction of gamma rays emitted within a solid angle of half-angle \( \theta_b \), \( D \) is the distance between Earth and Jupiter (≈5AU), and \( A \) is the area of the satellite detector (≈1m²). For a 10²⁹ eV proton shower exiting Jupiter’s atmosphere at its maximum development, the number of electrons⁵ at the shower maximum is \( N_e \approx 6 \times 10^{11} \) (Heck et al. 1998; Kalmykov et al. 1997). The corresponding number of photons \( N_\gamma \) was obtained by numerical integration of the solutions of the shower cascade equations (Rossi & Greisen 1941; Lipari 2009). For a minimum gamma ray energy of 20MeV (the lower detection limit in Rimmer et al. 2014), we found \( N_\gamma = 1.3 \times N_e \approx 8 \times 10^{11} \). From Equation (1), we then derive:

\[
\frac{f_\gamma(\theta_b)}{\theta_b^2} > 2 \times 10^{12} \text{rad}^{-2}.
\]

The inequality is fulfilled for \( \theta_b < 7 \times 10^{-7} \text{ rad} \) and \( f_\gamma(\theta_b) = 1 \) (or for an even smaller \( \theta_b \) if \( f_\gamma(\theta_b) < 1 \)). Such an angular distribution is incompatible with the known properties of cosmic ray showers. In fact, the average angle of shower particles at the maximum of shower development is given by \( \approx E_e/E_c \), where \( E_s = 21 \text{ MeV} \) and \( E_c \) is the critical energy of the medium where the shower develops (Gaisser 1990; Grieder 2010). For Jupiter’s atmosphere, \( E_c = 340 \text{ MeV} \) (Rimmer et al. 2014), which results in an angle of \( 6 \times 10^{-2} \text{ rad} \), five orders of magnitude larger than \( \theta_b = 7 \times 10^{-7} \text{ rad} \). Thus, we conclude that the condition expressed by Equation (2) is never fulfilled by a realistic shower, and UHECR interactions in Jupiter’s atmosphere cannot be detected by an Earth-orbiting satellite instrument.

Indeed, the results of (Rimmer et al. 2014) are affected—in addition to other questionable approximations—by an erroneous assumption on the angular distribution of cosmic ray shower particles, namely that photons produced by an electron of energy \( E_e \) have an average angle \( \approx m_e/E_e \) with respect to the shower axis, where \( m_e \) is the electron mass. In fact, \( m_e/E_e \) is representative of the angular scales occurring in the elementary processes that drive the shower development (bremsstrahlung, Compton scattering and pair production). Instead, the angular distribution of both electrons and photons in a shower is dominated by multiple scattering of the electrons (Rossi & Greisen 1941) with a characteristic angle of \( \approx E_e/m_e^2 \). In the oversimplified treatment of (Rimmer et al. 2014), the flux of photons is thus overestimated by a factor \( (E_e/m_e^2)^2 \).

2. THE EARTH AND OTHER SOLAR SYSTEM OBJECTS

It may be interesting to evaluate other solar system objects as potential cosmic ray detectors. In the following, we analyze in more details UHECRs skimming the atmosphere of the closest object, Earth.

With a better approximation than Equation (1), the condition to detect a UHECR shower can be written as:

\[
n_\gamma(\theta_b) = \int_{\Delta \Omega} d\Omega \frac{df_\gamma}{d\Omega}(\theta_b) > 1,
\]

where \( df_\gamma/d\Omega \) is the normalized photon angular distribution and \( \Delta \Omega = A/D^2 \) is the solid angle subtended by the satellite instrument. Detectable showers come from directions close to the satellite horizon, corresponding to a distance \( D \approx 2500 \text{ km} \) for an orbit of 500km altitude. The angular distribution of photons follows closely the angular distribution of electrons in the shower (Rossi & Greisen 1941). To estimate \( df_\gamma/d\Omega \), we convoluted the electron angular distribution, parameterized in (Lafebre et al. 2009) as a function of the electron energy, with the electron energy spectrum at shower maximum as given in

⁵ For the sake of simplicity, in the following we will use the term electrons to indicate both electrons and positrons.
function of the angle of photon emission \(\theta_b\) (Nerling et al. 2006). A minimum electron energy of 20 MeV was required for consistency with Section 1. Also, we took \(N_e \approx 8 \times 10^{11}\), corresponding to a 10\(^{21}\) eV UHECR (see Section 1). In Figure 1, \(n_\gamma\) is shown as a function of the angle \(\theta_b\). The detectability condition expressed by Equation (3) is fulfilled up to a maximum angle \(\theta_b^{\text{max}} \approx 4^\circ\).

Thus, a UHECR shower skimming the Earth atmosphere is in principle detectable by a satellite instrument. However, it remains to be proven that a significant statistics of UHECRs may be collected with this technique. To estimate the aperture of an orbiting satellite, we performed a Monte Carlo simulation. A uniform distribution of the shower’s impact point was generated over the Earth atmosphere taken as a spherical surface. The shower direction was then generated according to an isotropic distribution. For each shower, the column density along its path in the atmosphere was calculated using the US Standard Atmosphere model (U.S. Stand. Atm. 1976). To ensure enough particles at the exit point, only showers with a column density between 600 g cm\(^{-2}\) and 1200 g cm\(^{-2}\) were further considered (within this range, \(4 \times 10^{11} \leq N_e \leq 8 \times 10^{11}\) for a 10\(^{21}\) eV proton shower). A shower was considered to be detected when the satellite was within an angle \(\theta_b\) from the shower direction, with the vertex of the detection angle located at the point where the shower exits the atmosphere. In Figure 2, the geometrical aperture estimated from the simulation is shown as a function of \(\theta_b\). The aperture for \(\theta_b = \theta_b^{\text{max}} \approx 4^\circ\) is found to be \(\approx 500\) km\(^2\) sr. Lower UHECR energies will result in smaller apertures: for example, a 10\(^{19}\) eV shower would have \(\theta_b^{\text{max}} \approx 0.1^\circ\) (see Figure 1) and a corresponding aperture of only \(\approx 0.2\) km\(^2\) sr (see Figure 2). For comparison, the geometrical aperture of the Pierre Auger Observatory (Abraham et al. 2004), the largest ground based UHECR facility, amounts to \(\approx 7000\) km\(^2\) sr for all UHECR energies above 10\(^{18.5}\) eV.

We also evaluated the case of UHECRs skimming the Moon surface, where the shower develops in the lunar regolith before exiting the surface. The corresponding aperture was found to be even smaller than that obtained for Earth. Other solar system objects were excluded as effective cosmic ray detectors by similar calculations. UHECR interactions with the solar atmosphere have also been studied by (Andersen & Klein 2011), who found very small particle fluxes undetectable by a satellite instrument. Notice that the aperture in Figure 2 is valid for any beamed emission from UHECR air showers. In particular, our findings apply to radio emission from UHECR showers, which has similar angular scales (Motloch et al. 2014). Thus, we also exclude that the radio synchrotron mechanism proposed by (Rimmer et al. 2014) may be used to efficiently detect UHECRs.

3. CONCLUSIONS

We have critically reviewed the claim (Rimmer et al. 2014) that Jupiter can be an efficient detector for UHECRs. We found that the number of gamma rays from a UHECR shower skimming Jupiter’s atmosphere is too low to be detectable by an Earth-orbiting satellite. We also investigated the potential of such a technique for other solar system objects. In the best case of Earth, we found that UHECRs skimming the Earth atmosphere are in principle detectable, but the aperture of an orbiting satellite is much smaller than traditional ground arrays. This result is also valid for beamed radio emission from UHECR showers, including the synchrotron mechanism proposed by (Rimmer et al. 2014). We conclude that this technique is not worthwhile further attention.

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