COSMOLOGY, GALAXY FORMATION AND ASTROPARTICLE PHYSICS
ON THE PATHWAY TO THE SKA
Klöckner, H.-R., Rawlings, S., Jarvis, M. & Taylor, A. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

Relativistic particles in the Earth's atmosphere

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Abstract. The Earth's atmosphere is a large scale laboratory to study particles. Particles from stellar processes impinge on the top of the Earth's atmosphere and propagate downward. Particles from discharge processes at the bottom of the atmosphere propagate upwards into near-Earth space. The acceleration of both particle populations in the Earth's atmosphere produces electromagnetic radiation which is observed at remote distances. The observation of the electromagnetic radiation makes it possible to detect the particles and to determine their impact on the Earth's atmosphere. The quantitative description of the electromagnetic radiation enables an assessment of the photon rest mass.

1. Introduction

The paradigm of linear atmospheric electromagnetics is supplanted in favour of non-linear atmospheric electromagnetic processes. (1) Top down particles: Solar particles impinge on the top of the atmosphere and ionise the ambient air molecules. Soft particles travel down to ∼70-80 km height whilst relativistic particles reach down to ∼40-50 km height (e.g. Baker et al. 1993; Sentman 1990 and references therein). The particles ionise the air and thereby modify the sub-ionospheric propagation of radio waves. Magnetars are the source of strong γ-ray bursts, which produce short-lived ionospheric disturbances with oscillation periods of some seconds lasting for some minutes (Inan et al. 1999; Fishman & Inan 1988) . Ultra-high energy cosmic rays produce cascades of particles in the atmosphere which produce bursts of electromagnetic radiation for tens of nanoseconds. (e.g. Falcke et al. 2005; Huege & Falcke 2004 and references therein). (2) Bottom up particles: Lightning discharges during thunderstorms occasionally produce X-rays, where small scale electric fields inside the thundercloud act as mini particle accelerators (Dwyer et al. 2003; Dwyer 2003) . The large scale electric fields of lightning discharges act as maxi particle accelerators for electrons which propagate along the geomagnetic field lines into near-Earth space (Inan 2005). The accelerated electrons may produce an exotic kind of lightning above thunderclouds termed gigantic jets, blue jets and sprites (Füllekrug et al. 2006; Su et al. 2003; Neubert 2003; Pasko et al. 2002; Fishman et al. 1994; Sentman & Wescott 1993; Franz et al. 1990) . Whether terrestrial γ-ray bursts observed in near-Earth space are associated with regular lightning discharges or sprites is the topic of ongoing research (Dwyer & Smith 2005). (3) Strange particle: The photon has an impulse but seemingly no mass. Classical electromagnetism is described with Maxwell's equations with a zero rest mass of the photon. Proca's equations describe electromagnetism with a small, but finite rest mass of the photon (Tu et al. 2005). Which of the two theories describes electromagnetism correctly is not known. The Earth's atmosphere is a giant laboratory which is ideally suited to distinguish between the two theories. The comparison of large scale electromagnetic fields in the Earth's atmosphere with their theoretical description offers the unique opportunity to place a new upper limit on the photon rest mass (Füllekrug 2004).

2. Top down

Protons with energies up to ∼100 MeV are accelerated in the solar corona and their occurrence is often associated with solar flares. Proton emissions can last for many days, while the bursts of optical and X-ray radiation from solar flares usually last for less than one hour. The high-energy proton flux is often associated with the emission of electrons with energies >1 MeV following the flare. Another class of high-energy electrons is accelerated in the co-rotating interaction regions of the solar wind. These high-energy electrons preferentially occur with a periodicity of 26-28 days during minimum solar activity. No proton flux is associated with these high-energy electrons (Schlegel & Füllekrug 1999). The proton and electron flux with energies >1 MeV is continuously monitored on board the space environment system on the GOES satellites. The emitted particles travel through interplanetary space and penetrate deep into the Earth's atmosphere where they ionise the air molecules. This ionisation increases the conductivity of the atmosphere by an order of magnitude, superposed on the background ionisation from solar short wave (UV) radiation and soft (keV) particles accelerated in the Earth's magnetosphere (Baker et al. 1993; Sentman 1990). The increase of the atmospheric ionisation results in an absorption of radio waves which are produced by naturally occurring lightning discharges and man-made transmitters. The search for celestial sources of ionospheric disturbances resulted in the detection of an extremely intense hard X-ray/γ-ray flare from a soft gamma ray repeater located some thousands of light years away (Inan et al. 1999; Fishman & Inan 1988). The illumination of the terrestrial night side by this neutron star led to an increase of the atmospheric ionisation up to daytime levels at 60 km height. This ionisation exhibits a 5.16 s long cyclic variability which coincides exactly with the rotation period of the neutron star. Unknown celestial objects are the source of ultra-high energy cosmic rays with energies $> 10^{17}$ eV (Nagano & Watson 2000) . The largest cosmic ray energies observed to date are on the order of $\sim 10^{20}$ eV, i.e., some J, and occur sporadically, i.e., about one incidence per century per km^2. Using the Earth's atmosphere as a particle detector with an effective surface area of $\sim 500 \cdot 10^6$ km^2 results in ~ 10 occurrences on the global scale. Ultra-high energy cosmic rays produce cascades of electron-positron pairs which spiral around the magnetic field line and emit highly beamed electromagnetic radiation during the propagation of the air shower through the atmosphere (Huege & Falcke 2005). These bursts of electromagnetic radiation can reach peak electric field amplitudes ~ 1 V/m and decay away during some tens of nanoseconds such that they can be recorded with electric field antennas in the frequency range of some MHz (Falcke 2005). The radio signals are reflected by the highly conductive ground and the ionosphere and thus propagate to remote distances. The detection of cosmic rays over large distances is a new challenge for radio remote sensing.

3. Bottom up

The fundamental problem of atmospheric electricity is that the conventional breakdown electric field in the atmosphere needs to exceed $\sim 3 \cdot 10^6$ V/m to initiate a lightning discharge, but these large electric fields are not observed inside thunderclouds. It was speculated that the required electric fields within the thundercloud are highly localised in space and time and therefore remain undetected. However, balloon measurements of electric fields in thunderclouds suggest that the breakdown electric field is on the order of $\sim 10^5$ V/m, i.e., one order of magnitude smaller than the conventional breakdown threshold (Marshall et al. 1995). This observation is explained with the newly recognised phenomenon of relativistic breakdown in the atmosphere (Gurevich & Zybin 2005; Gurevich et al. 1992). The key point of relativistic breakdown is that the cross section of collisions between energetic electrons and neutral air molecules decreases during acceleration of the electrons by the electric field. In this way, the electrons 'run away' and subsequent avalanches of energetic electrons are produced. This new physical mechanism requires one energetic particle, e.g., a cosmic ray, $\sim 10^{16}$ eV to start the relativistic breakdown process (Gurevich & Zybin 2005). Positive feedback of runaway breakdown results from energetic photons and positrons which travel in opposite direction to the propagation of the avalanche and subsequently initiate additional electron avalanches (Dwyer 2003). The runaway breakdown process results in a population of particles with energies of some tens of MeV in the mixed phase region of the thundercloud at ~ 5 km height where the collisions of riming graupel and ice crystals result in the necessary charge separation to produce strong electric fields. About 50 % of the mass of the atmosphere is located below and above 5 km height such that the energetic radiation from runaway breakdown can be observed from the ground (Dwyer et al. 2005, 2003) and from space (Inan 2005; Smith et al. 2005). The observations of terrestrial γ-ray flashes on board of satellites are explained with a giant particle accelerator in the Earth's atmosphere which is produced by the lightning electric field above thunderclouds (Inan 2005). In this picture, a particularly intense lightning discharge deposits a charge of ~ 100 C inside the thundercloud. The resulting monopole electric field decays slower with height than the higher order multipole electric fields, while the runaway breakdown threshold falls off exponentially with height since it scales with the neutral gas density. The result is that the lightning electric field exceeds the relativistic breakdown threshold at some height in the atmosphere and accelerates free electrons to some MeV of energy producing bursts of terrestrial γ-rays resulting from bremsstrahlung radiation of the energetic electrons (Lehtinen et al. 1996). The electrons may produce a transient luminous (red-bluish) airglow above the thundercloud termed sprite (Yukhimuk et al. 1998; Fishman et al. 1994). The electrons propagate along the geomagnetic field lines into near-Earth space where they are trapped in the radiation belt and bounce back and forward between conjugate hemispheres while drifting eastward. The primary electron beam is highly localised in space ($\sim 10 - 100$ km) and time (~ 1 ms) such that the direct detection of the electrons with particle detectors on satellites is improbable. However, some of the injected electrons are predicted to form eastward drifting 'curtains' extending over $\sim 70^\circ$ in latitude within a few minutes after injection (Lehtinen et al. 2000). This spreading of the particles substantially increases the likelihood of detection before the particles dissipate by precipitating back into the Earth's atmosphere. A number of challenging space missions is now under way to simultaneously detect the electron beam, the emitted energetic radiation and the luminous manifestation of the particles in the form of sprites.

4. Strange

The photon is a strange particle. It carries an impulse but seemingly no mass. The current knowledge on the photon rest mass ultimately relies on experimental observations and their theoretical understanding putting an upper limit on the rest mass of the photon (Tu et al. 2005; Gul'yel'mi & Pokhotelov 1994; Goldhaber & Nieto 1971). Maxwell's equations are a cornerstone of modern physics to describe electromagnetic phenomena. Proca's equations are an extension of Maxwell's equations which include the effects of a massive photon to describe electromagnetic phenomena

$$\underline{\partial} \times B = \mu_0 \underline{J} + \mu_0 \varepsilon_0 \frac{\partial}{\partial t} \underline{E} - \mu_\gamma^2 \underline{A}, \tag{1}$$

$$\underline{\partial} \cdot \underline{B} = 0, \tag{2}$$

$$\underline{\partial} \cdot \underline{E} = \frac{\rho}{\varepsilon_0} - \mu_\gamma^2 \Phi, \qquad (3)$$

$$\underline{\partial} \times \underline{E} = -\frac{\partial}{\partial t}\underline{B} \qquad (4)$$

(Morse & Feshbach 1953). The mass of the photon $m_\gamma = \mu_\gamma \hbar / c$ is given by the characteristic length scale of the photon μ_γ, the Planck constant $\hbar$ and the speed of light c. It is not known if Maxwell's or Proca's equations describe electromagnetism correctly. The solutions of Proca's equations suggest a number of ways in which the effects of a non-zero photon rest mass might be measurable. The four most widely explored of these are: (i) a frequency dependence of the speed of electromagnetic radiation in vacuum, (ii) deviations from the inverse square law of electrostatics, (iii) changes to the form of the magnetic dipole field, and (iv) astrophysical measurements of magneto-hydrodynamic effects. The current upper limits for the photon rest mass derived from these four approaches are 3×10^{-49} kg, 8×10^{-51} kg, 8×10^{-52} kg and 1×10^{-52} kg respectively (Tu et al. 2005). Progress on the knowledge of the photon's physical properties is monitored by the Particle Data Group at Lawrence Berkeley National Laboratory in the United States (Eidelman et al. 'Particle Data Group' 2004). The effect of a non-zero rest mass becomes highly significant if the rest energy and the quantum energy of the photon become comparable, i.e., $mc^2 = \hbar\omega$. It is clear that the lower the frequency, the easier it becomes to observe the effects of a non-zero rest mass. Extremely low frequency radio waves are emitted by lightning discharges in the troposphere (Sentman et al. 1995) and gigantic transient luminous events above thunderstorms (Boccippio et al. 1995) termed sprites (Füllekrug et al. 2006). These radio waves propagate over long distances, reflected between the highly conductive Earth and the lower ionosphere, which together form a giant natural spherical capacitor. They have wavelengths as long as the circumference of the Earth (40,000 km) and frequencies as low as 10 Hz (Füllekrug 2005; Füllekrug & Constable 2000) . Using the above expression, it is easy to see that a photon mass on the order of 1×10^{-50} kg would have readily observable effects at 10 Hz. A more detailed analysis shows that the photon rest mass must be smaller than 4×10^{-52} kg to be consistent with observations, this upper limit being constrained by the natural variability of the conductivity within the Earth's ionised upper atmosphere (Füllekrug 2004; Füllekrug et al. 2002; Füllekrug 2000). The ultimate upper limit for the photon rest mass is given by the characteristic length scale of the photon which must be smaller than the size of the universe. This ultimate limit is given by $m_\gamma \approx h/Tc^2 \approx 10^{-69}$ kg, where $T \approx 10^{10}$ years is the age of the universe (Goldhaber & Nieto 1971). It is apparent that a whopping gap of 17 orders of magnitude remains between the current best upper limit and the ultimate upper limit for the photon rest mass which poses a challenge to all scientists using Maxwell's equations as a working hypothesis during their daily work.

5. Summary

The Earth's atmosphere is used as a large scale laboratory to study relativistic particles. Top down particles from stellar and celestial sources penetrate deep into the Earth's atmosphere where the particles ionise air and emit electromagnetic radiation. The variable ionisation of the atmosphere places an upper limit on the photon rest mass. The electromagnetic radiation of particles which almost reach the ground is used for detection of their location and for determination of their energy. Bottom up particles are accelerated by small scale electric fields inside thunderclouds and large scale lightning discharge electric fields above thunderclouds. The electromagnetic radiation of these particles is observed on the ground and in space. The radio waves emitted by relativistic runaway breakdown and the resulting electron beam in near-Earth space remain to be discovered. The determination of an upper limit for the photon rest mass currently leaves 17 orders of magnitude of wiggle-room for worries if Maxwell's or Proca's equations describe electromagnetism correctly, a charming potential which deserves to be fostered in the future.

Acknowledgements. I wish to thank Steve Rawlings and Hans-Rainer Klöckner for giving me the unique opportunity to present my views on relativistic particles in the Earth's atmosphere to an astronomy audience. I also wish to thank Antony C. Fraser-Smith, Umran Inan, Ute Ebert, Robert Roussel-Dupré, Heino Falcke, Tim Huege and the attendants of the sprite summer school for stimulating discussions.

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