MOMENTUM LOSS FOR ANTIMATTER METEORS

P. M. PAPAELIAS

Laboratory of Astrophysics, Dept. of Physics, National University of Athens, Panepistimiopolis, Athens, Greece

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Abstract. The momentum loss for a possible antimatter meteor entrance can be described by the combination of two terms. One which can be characterized by the mechanism of annihilation and a second one, the well known mechanism, which is common for all koinomatter (ordinary) meteors. That is, the momentum loss caused by the air molecules swept up by the moving object. We discuss, in this paper, the contribution of the rocket effect caused by the action of the secondaries which can be produced by the annihilation interactions of the antiatoms with the air molecules. The momentum loss of an iron type meteor made of antimatter, as a function of its equivalent radius R, can be described by the formula, ΔJ (MeV/c) = $8R$ (cm), for values of R within the range $1\ \mathrm{cm} < R < 5\ \mathrm{cm}$ and can be resulted by a single annihilation interaction of a nucleon-antinucleon pair.

1. Introduction

The existence of antimatter is still a matter of intensive and careful study. Theories supporting the symmetric model in cosmology, are standing since a long time (e.g., Alfvén, 1962) against other hypotheses which support exactly the opposite (Steigman, 1976), although the latter are based on careful analysis of critical experimental results. The most recent experiments that detected antimatter have shown both positive (Buffington, 1981) and negative (Strittmatter, 1987) results. However, different techniques such as the use of superconducting magnets in those experiments may show differences, which probably could be proven critical in future. The promising ASTROMAG experiment (Ormes, 1988) which will be established in the space station (1990), could probably give us an answer about this problem, for it should be 1000 times more sensitive, than previous experiments about the search of antimatter had shown.

In view of such contradicting results, but primarily in view of the consequences which may follow such an entrance (Libby, 1965), we are obliged to study carefully the possible case of an antimatter meteor entrance, even if the experimental results for the existence of antimatter are negative.

Some confusion had been raised, when the term antimatter meteoroid was first used (Papaelias, 1987). By the term meteoroid (*μετεωροειδές*) = meteor (*μετέωρο*) + oid (*είδος* = kind) and consequently antimatter meteoroid, we introduced a new classification of meteors which although we suppose that it has the same general properties to those described by the word itself, there are however substantial differences to distinguish them from the general classification of the majority of meteors (Papaelias, 1987) and therefore, does not necessarily apply only to the special case of koinomatter meteoroids – as it was considered

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by Beech (1988) – which may vary from ordinary meteors, only in structure or the size. A small antimatter meteor may release energy thousand times greater than that of a large koinomatter meteor and the curves describing its velocity – height behavior may greatly differ from those of typical koinomatter meteoroids. To avoid such a confusion, the term meteor will only be used, despite that the small koinomatter meteors and the dustgrain ones are abundant among meteors and the same should be expected for those small meteors made of antimatter.

As it was mentioned recently (Papaelias and Apostolakis, 1990), Cowan *et al.* (1965) argue that obviously, nothing is known about the interactions of heavy antiatoms with atmospheric constituents like nitrogen and oxygen. The simplest case of matter-antimatter annihiliation is that of $p\bar{p}$. Even in this case, the annihilation is not limited to s states, and the process becomes complex, due to the various possible angular momentum states in the initial system and the various charge states in the final states. In view of such obvious difficulties, one is obliged to neglect factors related with the structure as proposed by Beech (1988) and therefore is obliged too, to use the classical theory of koinomatter meteors (e.g., Buchwald, 1975), as this is the only tool available to use for studying the Physics of the antimatter ones.

2. Analysis of the Method

The velocity-height relation for a probable antimatter meteor entrance which we presented recently (Papaelias 1983, 1987), was described by the formula,

$$\frac{v_z}{v_\infty} = \exp\left[\frac{B}{\alpha}\exp(-\alpha z)\right] - \frac{C}{Bv_\infty}\left\{1 - \exp\left[-\frac{B}{\alpha}\exp(-\alpha z)\right]\right\},$$

where v_z and v_∞ are the velocities at a given height z and before entrance respectively, B is a factor proportional to the drag factor, α^{-1} is the scale height and C a factor proportional to the annihilation cross-section which experimentally is unknown (Papaelias and Apostolakis, 1990). The above formula covers also the cases of koinomatter meteors because in such a case the value of the annihilation cross-section is zero – in other words when there are no annihilation interactions – and thus the factor C which is proportional to the annihilation cross-section is, therefore, zero. The parameter C is also proportional to the momentum loss ΔJ caused by the rocket effect of the secondaries produced by the annihilation interactions of the atmospheric atoms with the antiatoms of the compact object.

The products of the annihilation of antiatoms with atoms are mostly charged and neutral pions (Horowitz *et al.*, 1959; Papadopoulou, 1978), produced by interactions of nucleons of atoms or molecules and antinucleons which can be assumed that antimatter meteors are consisting of. Photons can also be produced by the e^+e^- annihilation interactions. The momentum loss caused by the photons of the latter case, is a small fraction in the process, and therefore it is neglected, and only those secondaries produced by the annihilation interactions of the nucleons with the antinucleons ($N\bar{N}$) are taken into consideration in our calculations.

In the case of an antimatter meteor entrance, a fraction of the annihilation secondaries, may enter in the interior of the object, and may depose a fraction of the energy carried by them. Those secondaries are moving from the point where they are generated, towards any direction in the surrounding atmosphere. Depending on the size of the antimatter meteor, a fraction of those secondaries may penetrate the object, while the rest may be escaped away.

3. Calculations

Because of the large number of the annihilation secondaries, that can be produced and move randomly in any direction at a relatively low height, it can be assumed that equal number of secondaries are moving at the same time to opposite directions. If p_1, p_2, p'_1, p'_2 are such two pairs of equal mass and equal initial kinetic energy, which may be produced on the same point of the antimatter meteor and assuming that they are moving on the same plane, and the angle of their motion with the motion of the object is ϑ (Figure 1a), then the energy ΔE which can be deposed by the particle p'_1 is equal to that of the particle p'_2.

The temperature of the object may be increased by the secondary particles which may penetrate it, as long as their energy and consequently their momentum may be reduced due to the ionization and Bremmstrahlung effects. In the x and

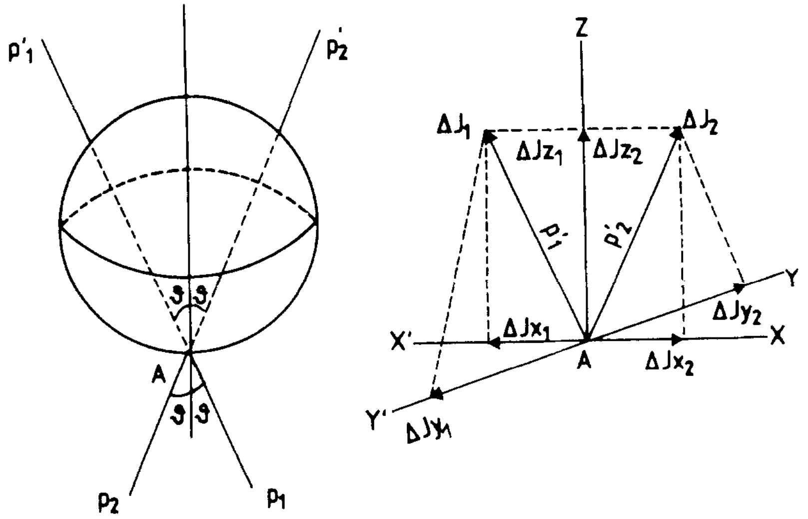

Fig. 1. (a) Particles p_1, p_2, p'_1, p'_2 are produced on the same point A of the antimatter meteor and move onto the same plane in opposite directions. (b) Momentum analysis of the particles p'_1 and p'_2 in x, y, z directions.

y directions (Figure 1b), the momentum of the particles p_1 may be cancelled by the momentum of the particle p_2, but towards to the z direction – which here is the direction of motion of the antimatter meteor – the component of the momentum loss for both particles remains the same and their direction is opposite to that of the antimatter meteor's motion. Thus, $\Delta J_1 = \Delta J_2 = J_1 - J'_1 = J_2 - J'_2 = \Delta J$, where J'_1 and J'_2 are the momentum of the particles p'_1 and p'_2 after their penetration through the antimatter object. The contribution of the particle p_1 or p_2 in the momentum loss of the antimatter meteor is $\Delta J_z = J_{z_1} - J_{z'_1} = \Delta J \cos\vartheta$.

The momentum loss for the charged particles, when moving through an object with a velocity v is equal to $\Delta J = \Delta E/\beta$, where $\beta = v/c$, and c is the velocity of light. By using the Bethe Bloch formula, one can estimate the energy deposition ΔE of the charged pions and consequently the momentum loss for both positive and negative pions. By using simulation techniques, such as the computer program EGS CODE, one may also estimate the contribution of the neutral pions in the momentum loss of the antimatter meteor caused by the passing of the photons produced by the decay of those π^0s. Thus, the momentum loss $\langle\Delta J\rangle$ of the antimatter meteor due to the rocket effect of the annihilation secondaries is the sum of the following three terms

$$\sum\langle\Delta J\rangle = \sum\langle\Delta J\rangle^+ + \sum\langle\Delta J\rangle^- + \sum\langle\Delta J\rangle^0 ,$$

where by $+$, $-$, 0 the contribution of the charged and neutral particles are denoted.

The spectrum of the charged and neutral pions produced by the nucleon – antinucleon interactions lies between approximately 0 and 1000 MeV and can be described by a Maxwell-Boltzmann function while the mean multiplicity of the $\pi^\pm$ mesons of the $p\bar{p}$ annihilation interactions is 3.22 ± 0.18 (Horowitz *et al.*, 1959). The mean multiplicity of the $\pi^\pm$ mesons was described by a Gaussian distribution with a standard deviation $\sigma = 1.3 \pm 0.1$ (Papadopoulou, 1978) and estimation of the same mean multiplicity increases slightly that value to 3.5 ± 0.2. The difference could be explained, because interactions between antiprotons annihilated by neutrons were also included in the second experiment. Consequently, the momentum loss of the charged particles can be calculated by the formula

$$\langle\Delta J\rangle^\pm = \sum \Delta J_i^\pm = \sum_i \sum_j \nu_i^\pm (\Delta E_i^\pm / \upsilon_i) \cos\vartheta_j ,$$

where the term $\nu_i^\pm$ is the relative frequency of the charged pions with energy between $E_i^\pm$ and $E_i^\pm + \Delta E_i^\pm$. Here, the term ΔE_i is the deposited energy of them in the interior of the antimatter meteor.

Neutral pions of the secondary products can be decayed mostly in two photons which may have energies between $E_1 = (W - E')/2$ and $E_2 = (W + E')/2$ where $E' = \sqrt{W^2 - \epsilon^2}$. Here W is the total energy of the neutral pion and ϵ its rest mass equal to $134\ \mathrm{MeV/c^2}$.

When such photons penetrate the antimatter object, their energy can be con-

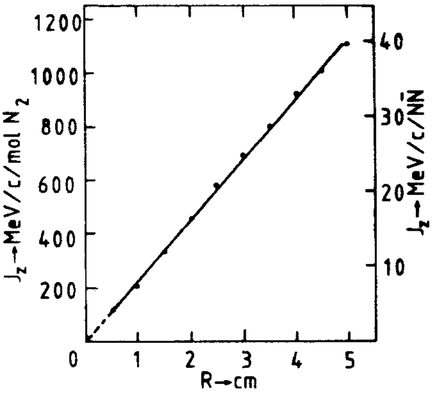

Fig. 2. Momentum loss of an antimatter meteor caused by the annihilation of a N_2 molecule (left axis) as a function of the radius of the object. The annihilation interactions occur on the surface of the meteor. The right axis shows the momentum loss caused by a nucleon-antinucleon annihilation.

verted to particles due to the electromagnetic shower effect and therefore a number of electrons positrons and photons of smaller energy can be produced after penetration of a distance which usually can be measured in radiation lengths. In *A* approximation this means that a photon of initial energy E_0, after passing a number t of radiation lengths through the object, it can be converted into a shower of particles the number of which is $N = 2^t$, while the energy E of each of them becomes equal to $E_0 2^{-t}$. The radiation length t_0 is given by the formula

$$\frac{1}{t_0} = 4\alpha' r_0^2 \frac{N_0}{A'} Z(Z + \xi) \ln(183 Z^{-1/3}) ,$$

where A' is the mass number of the absorber, Z is its atomic number, r_0 the classic radius of the electron which is equal to 2.8176 Fermi, $\alpha' = 1/137$ the fine structure constant, and $\xi = \ln(1440 Z^{-1/3})/\ln(183 Z^{-1/3})$ (Stenheimer, 1953). For more accurate results we have used a Monte Carlo simulation program (Ford and Nelson, 1978) known as the EGS Code.

For the photons produced by the decay of the neutral pions, the momentum loss becomes

$$\langle \Delta J \rangle^0 = \sum \Delta J_i^0 = \sum_i \sum_j v_i^0 (\Delta E_i^0 / c) \cos \vartheta_j ,$$

where the term v_i^0 is the relative frequency of the photons with energy between E_i^0 and $E_i^0 + \Delta E_i^0$.

In the above equation, if the energy loss of a photon is equal to ΔE_i^0 then the corresponding momentum loss is equal to $\Delta E_i^0/c$, while the corresponding momentum loss for the charged pions is equal to $\Delta E_i^{\pm}/v$.

If we assume that, for a spherical antimatter meteor, the annihilation interactions occur on the spot, and the number of the secondary particles which can be produced by the annihilation interactions is N, then the number of particles N' which may penetrate and heat the object within the solid angle $\Delta\Omega$, can be given by the relation

$$N' = \frac{N}{2}(\cos\vartheta_2 - \cos\vartheta_1)\,,$$

where ϑ_1 and ϑ_2, can be determined by the solid angle

$$\Delta\Omega = \int_{\vartheta_1}^{\vartheta_2}\int_{0}^{2\pi} \sin\vartheta\,\mathrm{d}\vartheta\,\mathrm{d}\varphi\,.$$

If $r = \mathrm{d}N/(\mathrm{d}S_1\,\mathrm{d}t)$ is the rate of annihilation of nucleon antinucleon interactions per unit area, then $N = 4\pi R^2 r\,\Delta t$ is the number of annihilation interactions on the total surface of the sphere, during the time interval Δt. Thus, the above equation becomes

$$N' = 2\pi R^2 r\,\Delta t(\cos\vartheta_2 - \cos\vartheta_1)\,.$$

The cross-sectional area of an object having a spherical shape, which may enter the Earth's atmosphere as a meteor, is equal to 1/4 of its total surface and by using all the above we get

$$N' = \frac{1}{2}\pi R^2 r\,\Delta t(\cos\vartheta_2 - \cos\vartheta_1)\,.$$

By summing the momentum loss for all particles penetrating the object, one may calculate the total momentum loss of an antimatter meteor due to the annihilation interactions caused on its surface by the atmospheric molecules swept up by the object.

The total momentum loss due to the annihilation of secondaries rocket effect, for a meteor which has a radius between 1 cm and 5 cm is drawn in plot 2. The graph shows the momentum loss of the antimatter meteor which may be caused by the annihilation of 1 N_2 molecule (left axis) or a nucleon-antinucleon annihilation interaction (right axis). This momentum loss should be added to the momentum loss caused by the action of atmospheric molecules, which is a common feature for all koinomatter meteors. From the plot we can see that ΔJ_z (MeV/c) $= 8R$ (cm) per each nucleon-antinucleon annihilation interaction.

4. Summary and Discussion

Even if the momentum loss due to the annihilation rocket effect is known, we are still unable to draw the velocity-height curve for an antimatter meteor with known geometric and other characteristics. The reason is that the annihilation cross-section of an atom – antiatom annihilation interaction is still unknown and the theoretical predictions in case of the existence of a repulsive potential between them (Papaelias and Apostolakis, 1990) may reduce its value several orders of magnitude, lower than it is expected in the case in which there is no repulsive potential between them.

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