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Review

Matter-antimatter models in cosmic and biologic systems

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The leading theories suggest that in the first fractions of the second following the Big Bang, equal amounts of matter and antimatter were formed, and annihilated. Therefore, the asymmetry of matter and antimatter, and formation of the visible universe is one of the major unsolved problems in physics. Surprisingly, when the major characteristics of the cosmic matter- antimatter interactions, were compared to the biologic body- antibody system, unexpected similarities were observed. They relate to the outcomes of weak and strong interactions, their specificities, annihilation of most of the antimatter, excess of matter over antimatter, difficulty in producing antimatter, early deletion of antimatter, and the material nature of the antimatter. Based on these similarities, it is suggested that a mechanism, different from the charge- parity symmetry (CP) violation, allowed the formation and preservation of the visible universe. This hypothesis could have far reaching consequences on basic concepts in cosmology.

Key words: Visible universe, CP symmetry violation, matter, antimatter, cosmology.

INTRODUCTION

There is considerable speculation as to why the observable universe is apparently composed almost entirely of ordinary matter, as opposed to a more symmetric combination of matter and antimatter. Neither the standard model of particle physics, nor the theory of general relativity provides an obvious explanation for why this should be so, and it is a natural assumption that the universe be neutral with all conserved charges. This asymmetry of matter and antimatter in the visible universe is one of the greatest unsolved problems in physics (Kolb and Turner, 1988; Bigi, 1997; Sather, 1999; Canetti et al., 2012).

In particle physics, antimatter is material composed of antiparticles, which have the same mass as particles of ordinary matter but have opposite charge (charge parity symmetry, or CP-symmetry). CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C symmetry), and then its spatial coordinates are inverted ("mirror" or P symmetry). Encounters between particles and anti-particles lead to the annihilation of both (Dirac, 1928; Anderson, 1933; Utpal, 2007; Close, 2009).

During the period of baryogenesis, when the universe was extremely hot and dense, matter and antimatter were continually produced and annihilated (Kolb and Turner, 1988; Shaposhnikov and Farrar, 1993; Trodden, 1998). The presence of remaining matter, and absence of detectable remaining antimatter, (baryon asymmetry), is

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attributed to CP-violation, a violation of the CP-symmetry relating matter to antimatter. The exact mechanism of this violation during baryogenesis remains a mystery. However, as of yet, no theoretical consensus has been reached regarding this, and there is no experimental evidence of an imbalance in the creation rates of matter and antimatter (Kolb and Turner, 1988; Wolfenstein, 1989; Bigi, 1997; Trodden, 1998; Utpal, 2007; Sozzi, 2008; Canetti et al., 2012).

Recently, astrophysicists, cosmologists, biologists and philosophers suggested that there are similarities, analogies between cosmic and biologic systems. For instance it was suggested that the cosmos underwent an evolutionary Darwinian-like development , a cosmological natural (artificial) selection, in which, black holes may be mechanisms of universe reproduction within the multiverse, an extended cosmological environment in which universes grow, die, and reproduce (Smolin, 1992; Harrison, 1995; Gardner, 2000; Barrow, 2001; Balaz, 2005; Ellis, 2007; Vidal, 2010; Krioukov et al., 2012). Additional similarities have been suggested, in basic principles and mechanisms (Kleinmann 2008, 2016) and in holographic models (Amjamrooz et al., 2011). Therefore, it was intriguing to compare the matter-antimatter model in two different systems, in the cosmic, and the biologic systems.

DESCRIPTION OF MATTER- ANTIMATTER MODELS

The cosmic model: Matter-antimatter

There are competing hypotheses to explain the matter-antimatter imbalance that resulted in baryogenesis, but there is as yet no one consensus theory to explain the phenomenon (Sakharov, 1967; Kolb and Turner, 1988; Trodden, 1998; Canetti et al., 2012). The Big Bang should have produced equal amounts of matter and antimatter, and if CP-symmetry was preserved, there should have been total cancellation of both-protons should have cancelled with antiprotons, electrons with positrons, neutrons with antineutrons, and so on. This would have resulted in a sea of radiation in the universe with no matter and no life (Kolb and Turner, 1988). Since this is not the case, after the Big Bang, physical laws must have acted differently for matter and antimatter, that is, violating CP-symmetry. It was suggested that this is due to differences in the strength of matter antimatter interactions (Sakharov, 1967; Kuzmin et al., 1985; Wolfenstein, 1989; Bigi, 1997; Trodden, 1998; Utpal, 2007; Sozzi, 2008; Canetti et al., 2012; Turner, 2013):

1. The strong interactions seems to be invariant, the CP-symmetry is preserved and as a result, matter and antimatter are reciprocally annihilated (Wolfenstein, 1989; Utpal, 2007; Sozzi, 2008; Close, 2009).
2. The CP-symmetry is slightly violated during week interactions (Kuzmin et al., 1985; Trodden, 1998). As a result some matter escapes annihilation, and this allows the existence of visible universe, and of life.

The discovery of CP violation plays an important role both in the attempts of cosmology to explain the dominance of matter over antimatter in the present Universe, and in the study of weak interactions in particle physics (Sakharov, 1967; Kuzmin et al., 1985; Shaposhnikov and Farrar, 1993; Turner, 2013). However, as yet, no theoretical consensus has been reached regarding the exact nature of the CP-violation, and the exact mechanism of this violation during baryogenesis remains a mystery. In addition, there is no experimental evidence of an imbalance in the creation rates of matter and antimatter (Sakharov, 1967; Kolb and Turner, 1988; Trodden, 1998).

The biologic model: Body-antibody

The biologic body-"antibody" model is provided by the immune system. This is a highly complex, complicated and sophisticated system (Roitt and Delves, 2004*)*. However, since this is an attempt to compare basic principles of cosmic and biologic phenomena, we are going to relate only to their major, basic characteristics. For instance, under the general term of "antibody", we will relate to all the different types of immune responses and their components, which provide the body with a self - defense mechanism. Following is a brief description of the principles governing the immune system (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In the cosmic model, the matter is composed from particles and antiparticles. In the biologic model, the matter is composed from bodies and "antibodies". Each body has his own, specific antigens - the self-antigens that are different of antigens from another body - the foreign antigens.

Very early in body's development, the immune system will produce "antibodies" against billions of self and foreign antigens. These antigen-"antibody" interactions should lead to their reciprocal annihilation, resulting in destruction of the body, and preventing the existence of biologic matter and life (Roitt and Delves, 2004; Christopher et al., 2005; Abbas et al., 2014; Chapel et al., 2014). Therefore, the question is how life is possible in spite of these reactions. The biologic systems provide some interesting answers that might be relevant to the cosmic systems. It is interesting, that the outcomes of the reactivity of the immune system, to the self, or to the foreign antigens are different, and depend on the strength of their interactions (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

1. Components of the immune system, which interact self-reacting components of the immune system are eliminated, leaving only those with capacity of reacting against foreign antigens (Shortman, 1990). A few self-

Table 1. Comparison of cosmic and biologic matter-antimatter models.

Characteristics	Cosmic	Biologic
Cosmic/biologic	Matter-antimatter	Body-"antibody"
1) Antimatter/"antibody" annihilation	Yes (99%)	Yes (96-99%)
2) Weak interactions-allow existence of matter/body	Yes	Yes
3) Strong interaction eliminate anti self-antimatter/"antibody"	Yes	Yes
4) Difficulty in producing anti self-antimatter/ "antibody"	Yes	Yes
5) Self-tolerance. Existing antimatter/"antibody" does not react with self-matter/body	Yes	Yes
6) Early deletion of antiself-antimatter/"antibody"	Yes	Yes
7) Excess of matter/body over antimatter/"antibody"	Yes	Yes
8) Antimatter/"antibody" are made out of matter	Yes	Yes
9) Antimatter/"antibody" is specific to matter/body	Yes	Yes

reacting components, that have escaped the above filtration, are later deleted in the peripheral organs (peripheral tolerance) (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

2. The immune system components that interact weekly with self-antigens, are allowed to exist, and they are responsible for reactivity against foreign antigens (Liu et al., 1995). The interaction of the anti-foreign "antibodies" with their corresponding foreign antigen, will lead to their annihilation, protecting and preserving the body (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014)

Therefore, the immune system has a dual function. From one hand, it induces a state of tolerance to self-antigens (matter) that prevents its own destruction, and allows the body (matter) and life to exist. On the other hand, it protects, preserves the integrity of body (matter) from invasion, destruction, by foreign antigens (matter). Altogether, it allows existence of life and its preservation.

DISCUSSION

The universe is made chiefly of matter, rather than consisting of equal parts of matter and antimatter as might be expected. The Big Bang should have produced equal amounts of matter and antimatter and if CP-symmetry was preserved, there should have been total cancellation of both. This would have resulted in a sea of radiation in the universe with no matter. Since this is not the case, physical laws must have acted differently for matter and antimatter, i.e. violating CP-symmetry (Kuzmin et al., 1985; Kolb and Turner, 1988; Wolfenstein, 1989; Trodden, 1998; Bigi, 1997; Utpal, 2007; Sozzi, 2008; Canetti et al., 2012) (Table 1). The cosmic matter-antimatter, and biologic body –"antibody" systems, seem to share several major similarities, that perhaps could help us understand why matter prevails. Following there is a discussion of the similarities, their meanings, consequences, predictions and ways of testing (Table 1).

Antimatter annihilation

Theoretically, the Big Bang should have produced antimatter against all the matter of the universe. However, over 99% of it is annihilated during baryogenesis. It was suggested, that even if only one particle in a billion escapes annihilation, it would be enough to account for the entire visible universe (Kolb and Turner, 1988; Bigi, 1997; Canetti et al., 2012; Utpal, 2007; Trodden, 1998; Wolfenstein, 1989; Sozzi, 2008; Kuzmin et al., 1985).

Similarly, in the biologic model, the immune system produce reactants against every antigen. However, 96-99% of them are deleted (Christopher et al., 2005; Shortman, 1990). These are the ones with anti-self reactivity, the remaining components reacting only against foreign antigens. This mechanism allows the existence of the body and the life. In addition, the immune components left, possessing anti-foreign antigen activity, preserve and protect the body from annihilation by foreign bodies (viruses, bacteria, parasites) (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In both systems , the existence of the matter, is allowed, is possible due to the existence of weak interactions between matter-antimatter, or between body –"antibody"

The CP violation during the weak interactions, allow some of the matter to escape the annihilation by the antimatter (Bigi, 1997; Canetti et al., 2012; Utpal, 2007; Trodden, 1998; Wolfenstein, 1989; Sozzi, 2008; Kuzmin et al., 1985). As a result a very complex, diverse and visible universe is formed. Similarly, in the biologic system, the fact that the weakly interacting components of the immune system do not react against self-antigens, allow the existence of the body, and of life (Liu et al., 1995).

In both systems, strong interactions lead to the deletion of anti self reacting antimatter or "antibody"

In the cosmic system, the strong interacting antimatter is deleted (Bigi, 1997; Canetti et al., 2012; Utpal, 2007; Trodden, 1998; Wolfenstein, 1989; Sozzi, 2008; Kuzmin et al., 1985). The traces of antimatter remaining do not react with self-matter, and perhaps are reactive only against foreign matter, matter from other planetary/galactic/cosmic systems. Therefore, it is suggested that there are two types of antimatter, anti self and anti-foreign. Self-matter belonging to our planetary/galactic/cosmic system. Foreign matter it is most probably of other planetary/galactic/cosmic systems.

According to the multiverses hypothesis, parallel universes could exist, with different composition, and physical/chemical laws (Tegmark, 2003). Their matter could be the foreign matter. However, it has also been suggested that galaxies made of anti-matter could exist. Therefore, foreign matter will be considered as one from other planetary/galactic/cosmic systems. To test this assumption, antimatter from our galaxy/universe, should be mixed with matter from other galaxy or universe. In addition, matter from our planet, such as a rocket or a space ship could be annihilated by antimatter from other planetary/galactic/cosmic systems.

Similarly, in the biologic systems, the components of the immune system, interacting strongly with self-antigens, are deleted (Roitt and Delves, 2004; Robey and Fowlkes, 1994; Starr et al., 2003; Abbas et al., 2014; Chapel et al., 2014). The components remaining after deletion do not react with self-antigens, but only against foreign antigens (substances, viruses, bacteria, parasites, other bodies) (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al.,2014).

In both systems is very difficult to produce anti self reacting substances

Antimatter is produced only under extreme conditions, very small amounts, and is immediately eliminated. For instance, high-energy cosmic rays impacting Earth's atmosphere (or any other matter in the Solar System) produce minute quantities of antiparticles in the resulting particle jets, which are immediately annihilated by contact with nearby matter (Moskalenko et al., 2002). Similarly, in biologic systems, under normal conditions there is no production of anti self "antibodies". In certain conditions, when such" antibodies" are produced, they are immediately eliminated (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In both systems there is a state of self tolerance

The deletion of anti self-antimatter, and the difficulty to produce antimatter (see above) suggests that there is astate of cosmic self-tolerance. It is suggested that this is the reason why, the antimatter left in our galaxy, does not react against its own components, such as our planetary system. Therefore, antimatter against matter from our planetary/galactic/cosmic system should be found in other planetary/galactic/cosmic systems.

Similarly, in the biologic systems, there is also a state of self-tolerance. The "antibodies" left after deletion of the strongly interacting components of the immune system, react only against foreign antigens (Klein et al., 2009; Kappler et al., 1987; Schwartz, 1989).

In both systems, the deletion of anti self-reacting substances, occurs at their very early phases of development

The self-reacting antimatter is eliminated in the first seconds after the Big Bang (Kolb and Turner, 1988). The anti self-reacting "antibodies" are also deleted very early, during the embryonic and newborn, phases of life (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In both systems there is much more matter than antimatter

Most of the antimatter, reacted with matter during the first seconds after the Big Bang, and was eliminated at the birth of universe. Any anti self-antimatter left was continuously eliminated. Therefore only a small amount of it, the anti- foreign antimatter, was left. At the same time, the matter kept proliferating, and thus an excess of matter was produced. This resembles the biological systems, where most of the self-reacting "antibodies" were deleted in the early phases of its development; however the body kept proliferating, increasing. The "antibodies" left, constitute only a very small portion of the body (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In both systems, the antimatter and the "antibody", are made out of matter

The antimatter is made out of matter, however they are not identical. One major difference is that they have opposite charges and different lepton and baryon number (Dirac, 1928; Anderson, 1933; Utpal, 2007; Close, 2009). The "antibody" is also made out of matter (complex molecules), however is not identical to the antigen. The antigens could range from simple elements to complex molecules (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

In both systems, there is specificity

The antimatter has specificity to particles or atoms. For example, electrons to positrons, protons to antiprotons, and neutrons to antineutrons (Dirac, 1928; Anderson, 1933; Close, 2009; Cork et al., 1956; Chamberlain et al., 1955). However, such specificities have been shown even to more complex structures such as to nuclei of helium and atoms of hydrogen (Star Collaboration, 2011; Amoretti et al., 2002)."Antibodies" also have specificity to antigens. There are "antibodies" specific to billions of different antigens, starting from simple elements (silver, nickel), and up to very complex biochemical structures (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

The existence in our galaxy/universe of antimatter that does not react with self-components, suggests the existence of additional, different, foreign matter, that exist outside of our galaxy, universe

In biologic systems, the existence of "antibodies" that do not react with self-components, but only to foreign antigens, indicate the existence of foreign substances (antigens), belonging to other individuals (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014). Similarly, the existence of antimatter that does not react with self-matter suggests the existence of foreign matter, in other planetary/ galactic/cosmic (multiverses) systems.

The antimatter of our planetary system would not react with matter from Earth, since is it has been depleted from "anti-self-antimatter". For instance our rackets traveled through the solar system, from Mars to Pluto, without being annihilated. Therefore, most of the antimatter in our planetary system is "anti-foreign antimatter". However, a space ship traveling to other planetary/galactic/cosmic systems, could be annihilated, by their "anti-foreign antimatter". It was suggested that galaxies composed of antimatter could exist in the universe (Close, 2009). Collisions of galaxies are considered to be very traumatic events. Perhaps part of it is due to the powerful foreign matter- anti foreign antimatter reactions. The need for a mechanism of self-defense against foreign antimatter, and preservation of self-matter, implies the existence of additional universes.

The constitution, the structure, the properties of antimatter from our galaxies/universe, could indicate what is the nature, the composition the structure of matter from other galaxies/universe

There is CP- symmetry between the matter-antimatter. Therefore, the matter from other galaxies/universes, should be a mirror image of our anti-foreign antimatter, but with opposite charges (electron and positron, neutron and antineutron), and perhaps different lepton and baryon numbers (Dirac, 1928; Anderson, 1933; Utpal, 2007; Close, 2009). Since the antimatter in our galaxy is directed against matter from other galaxy/universe, finding its matter equivalent could teach us about the components, composition of other galaxies/universes.

In biologic systems, since the "antibody" has specificity to antigen, its combining sites could indicate the composition of the corresponding structure on the antigen (epitope). However, this is a much more complex interaction, involving additional features (electrical, structural, space configuration) (Roitt and Delves, 2004; Abbas et al., 2014; Chapel et al., 2014).

The matter-antimatter symmetry is a basic feature of the cosmos. It is suggested that similarly to the body-" antibody" system, its purpose is to defend, preserve its units (planetary/galactic/cosmic), from foreign matter of other planetary/ galactic/cosmic systems

It was suggested that the Big Bang created the universe (Kolb and Turner, 1988; Turner, 2013). Therefore, it does not seems logical, that immediately, in the first fractions of a second of its existence, an orderly matter –antimatter symmetry is produced, just for the sake of reciprocal annihilation? Could it be a programmed self-destruction, a cosmic "death wish", or just a pyrotechnical game? Or perhaps it is a mechanism of defense, preservation of the uniqueness of each cosmic entity (planetary/galactic/ universe), from destruction by foreign matter or antimatter? The biologic model , provides an explanation for the excess of matter and existence of life, based on a logical process, and not due to a mistake, or a violation of the laws of the nature. It also suggests that the purpose of matter-antimatter symmetry is not annihilation, but to the contrary, its defense and self-preservation. This, since only the self-reacting antimatter is destroyed, leaving our galaxy/universe with anti-foreign antimatter, thus protecting it from matter from foreign galaxies/ universes.

The similarities of cosmic and biologic mechanisms (Table 1), suggests that prevalence of the matter, and the existence of the visible universe and of life, is not the result of a violation of the CP-symmetry. It is not a violation of an existing law of physics, but rather it is a new, additional law. It is the law that allows the existence of matter, and rules the deletion of self-reacting antimatter, the induction of tolerance to self-matter, and the protection from foreign matter. It is the law of the "cosmic immune system". The aforementioned suggested similarity, could by one of the many other similarities between the biologic and cosmic systems, that have been previously suggested (Smolin, 1992; Harrison, 1995; Gardner, 2000; Barrow, 2001; Balaz, 2005; Ellis, 2007; Vidal, 2010; Krioukov et al., 2012). Recently, these similarities have been discussed also at the cellular level. For instance, it has been suggested that there are similarities between the production and the life cycles of cells and stars (Kleinmann, 2008). The cellular universe, a new cosmological model based on the holographic principle, suggests that all that exists in the macro universe is mirrored in a biological cell as a microuniverse (Amjamrooz et al., 2011). Finally, similarities were suggested at almost all of the major principles and mechanisms during the birth and life span of the universe (Kleinmann, 2016).

The possibility that the existence of matter and life, is not due to a mistake (one extra matter particle in a billion), or a violation of the physical laws (CP symetry), but to a well-defined mechanism, could make the difference between the concept that the universe is the result of a random, casino like event, to a the concept that it is the result of an orderly, logic, new physical law. This new concept could have far reaching consequences on cosmology.

Abbreviations: "Antibody"- a general term for all the different types of immune response and their components, that provide the body with a self-defense mechanism; CP, symmetry - charge parity symmetry.

Conflict of interests

The authors have not declared any conflict of interests.

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Full Length Research Paper

Determination of the characteristic parameters for the modified Bessel-Gauss beams

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Some characteristic parameters of the Bessel- Gaussian beam were determined theoretically by direct analytical calculations. Variation of the final beam radius (ω) with the starting beam radius (ω_o) was studied. The Rayleigh range of a Bessel-Gauss beam was calculated for each value of the minimum starting beam radius. The beam wavefront radius of curvature (*R*) was calculated as a function of starting beam radius at different distances from the source. A modified Bessel-Gauss beam was also considered. The beam intensity was calculated in the waist plane. The variation of the intensity near the center depends on whether the radius (*a*) equal, less than or greater than the starting beam radius (ω_o).

Key words: Bessel- Gauss beam, beam radius, waist plane, intensity.

INTRODUCTION

Bessel beam optics have attracted many researchers in the past few decades because of its interesting characteristics and applications. Bessel beams represent a class of diffraction free solutions to the Helmholtz equation, and have been studied extensively since the work of Durnin (1987) and Durnin et al. (1987) and recently by Lukin (2012, 2014); McGloin and Dholakia (2005); Mikutis et al. (2013); Turunen and Friberg (2010) and Trappe et al. (2005).

Durnin et al. (1987) have used an annular aperture in the focal plane of a lens to produce an approximate Bessel beam. Although successful in generating a Bessel beams, this method is highly inefficient since the aperture absorbs most of the incident radiation. This reduction in the available energy is unsuitable for applications where high intensities are needed. An axicon, or conical lens element is perhaps the most convenient and cost-effective way to generate Bessel beam (Indebetouw, 1989) (Figure 1).

When a Gaussian beam with a flat phase front is incident on the axicon, the focusing property of the axicon produces strong interference effects in the region where the deflected beam overlaps with itself (Laycock and Webster, 1990). The profile of the generated interference pattern remains invariant over the overlap region. The axial symmetry of the system results in the beam pattern having an amplitude profile that is approximated by a Bessel function of order zero (Bagini et al., 1996). Beyond the overlap region the on-axis beam amplitude falls rapidly to zero.

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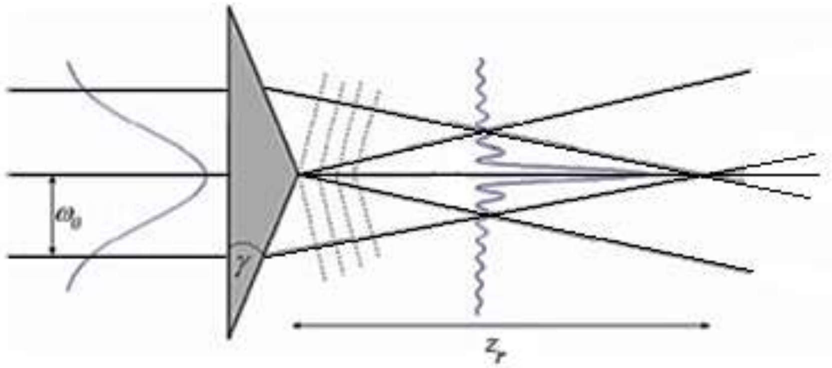

Figure 1. Propagation of a Bessel beam generated by axicon.

In this work, direct analytical calculations of some characteristic parameters of Bessel-Gauss beam are carried out. The calculations use the model proposed by Bagini et al. (1996). The intensity of the modified Bessel-Gauss beam at waist plane is also considered.

THEORETICAL BACKGROUND

The model used in this work is based on the situation that a Bessel beam is created by illuminating a Gaussian beam onto an axicon, Figure 1. In the plane z = 0 of a cylindrical reference frame (r, ϑ, z), Let us consider a field of the form (Bagini et al., 1996);

$$v_o(r,\vartheta,\alpha) = A(\alpha)\exp\left(-\frac{r^2}{\omega_o^2}\right)exp[i\beta r cos(\alpha-\vartheta)] \quad (1)$$

where ω_o is the starting beam radius and A is the amplitude. This equation represents a Gaussian beam whose mean wave vector has a projection β on the z = 0 plane, forming an angle α with respect to the x-axis, Figure 2.

The amplitude *A* is a function of α. When α varies, the wave vector describes a cone of semiaperture φ such that $sin\varphi = \beta/k$, where k is the wave number. The superposition of all Gaussian beams of Equation 1 form the Bessel-Gauss beams of order *n.* After propagating a distance *z* from the axicon, the radius of the beam $\omega(z)$ and the wavefront radius of curvature $R(z)$ are given by Bagini et al. (1996):

$$\omega^2(z) = \omega_o^2\left[1+\left(\frac{z}{Lcos\varphi}\right)^2\right] \quad (2)$$

$$R(z) = \frac{z}{cos\varphi} + \frac{L^2 cos\varphi}{z} \quad (3)$$

Where

$$L = \frac{\pi}{\lambda}\omega_o^2 \quad (4)$$

and ω_o is the starting beam radius at plane of *z* = 0. Let us consider a superposition of Gaussian beams, having mean wave vectors parallel to the longitudinal z direction, but whose centers are placed on a circumference of radius *a* around the z axis. In this case we obtain a superposition of beams that we call modified Bessel-Gauss beams of order *n*.

The modified Bessel-Gauss beam of zero order may show a central region of uniform intensity in the waist plane. The intensity distribution of the modified Bessel-Gauss beam can be obtained by Bagini et al. (1996)

$$F(r) \approx exp\left(-2\frac{a^2}{\omega_o^2}\right)\left[1+\frac{2r^2}{\omega_o^2}\left(\frac{a^2}{\omega_o^2}-1\right)\right] \quad (5)$$

If we consider the zero order term, the intensity as a function of *r* and *z* can be formulated as;

$$F(r,z) = \left(\frac{\omega_o}{\omega(z)}\right)^2 exp\left(-2\frac{a^2}{\omega^2(z)}\right)[1+2r^2\Delta(z)] \quad (6)$$

where

$$\Delta(z) = \left[\frac{1}{\omega^2(z)}\left(\frac{a^2}{\omega^2(z)}-1\right)\right] - \left(\frac{ka}{2R(z)}\right)^2 \quad (7)$$

It is seen from these equations that the intensity may

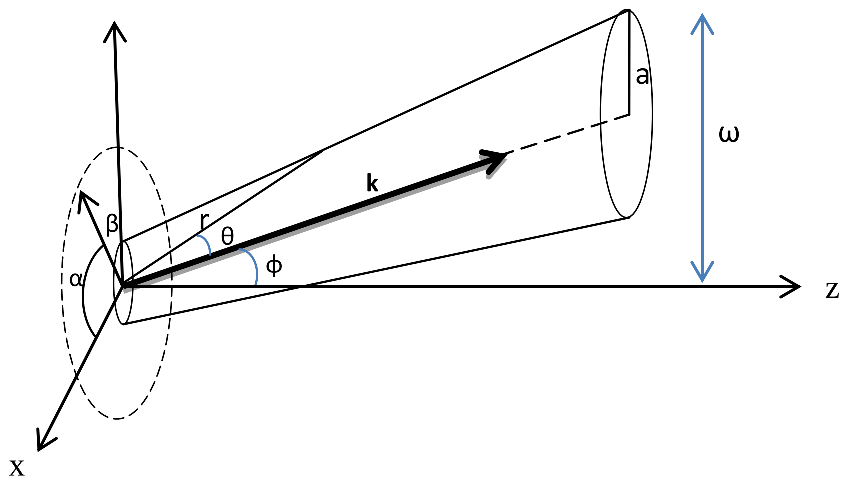

Figure 2. Illustration of the Bessel-Gauss beams.

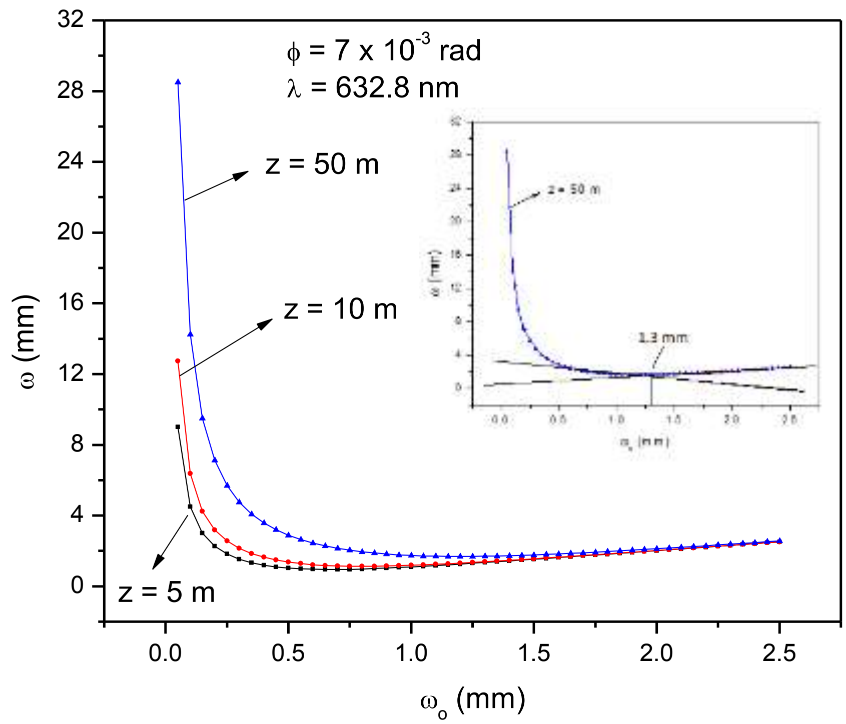

Figure 3. Beam radius as a function of starting beam radius at distances 5, 10 and 50 m from the axicon calculated from Equations 2 and 4.

show a maximum, a plateau or a minimum near $r = 0$ depending on whether Δ is negative, null or positive.

RESULTS AND DISCUSSION

Direct calculations were carried out to determine some characteristic parameters of the Bessel-Gaussian beam. The final beam radius (ω) was calculated as a function of the starting beam radius (ω_o) at a fixed distance (z) using Equations 2 and 4. Figure 3 shows the variation of the final beam radius with the starting beam radius at distances 5, 10 and 50 m from the axicon. From the figure one can notice that the beam radius reaches a

Table 1. The optimum values of the starting beam radius and the Rayleigh range at different distances.

z (m)	5	10	50
$(\omega_o)_{opt}$ (mm)	0.56	0.7	1.3
z_r (mm)	10.98	13.73	25.49

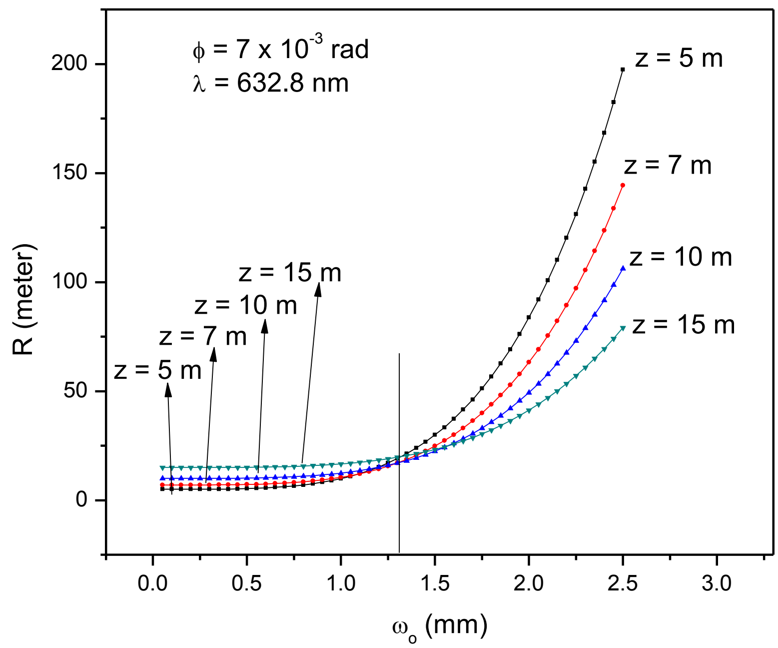

Figure 4. Wavefront radius of curvature versus starting beam radius calculated using equations 3 and 4 at distances 5, 7, 10 and 15 m.

minimum value at a certain starting beam radius. The initial beam radius corresponding to minimum beam radius over the distance (z) is known as optimum starting beam radius $(\omega_o)_{opt}$. For example at Z = 50 m, the optimum starting beam radius $(\omega_o)_{opt} \approx 1.3$ mm and this may represent the best combination of minimum beam diameter and minimum beam spread over a distance 50 m, see inset of Figure 3.

The Rayleigh range of a Bessel-Gauss beam can then be calculated for each value of the optimum ω_o from the relation (Duocastella, and Arnold, 2012):

$$z_r = \frac{(\omega_o)_{opt}}{(n-1)\gamma} \tag{8}$$

where n is the refractive index of the axicon and γ is the opening angle of the axicon. The Rayleigh range represents the largest distance after the axicon in which Bessel-Gauss beam will propagate where the central maximum will not exhibit diffractive spreading. The optimum ω_o values as well as the Rayleigh range at different distances z are listed in Table 1 (taking γ = 0.1 rad and n = 1.51). Figure 4 represents a plot of the wavefront radius of curvature (R) versus starting beam radius at different distances using equations 3 and 4. It is noticed that R increases with the increase of ω_o.

The change of the wavefront radius of curvature with the distance z is somehow irregular. Before approximately $\omega_o = 1.3\ mm$, R increases as the distance is increased while after $\omega_o = 1.3\ mm$ the radius of curvature decreases with the increase of z. Therefore $\omega_o = 1.3\ mm$ may represent a suitable value of the starting beam radius at which the beam radius of curvature is being a constant regardless of the distance apart the beam source.

Figure 5 demonstrates the variation of the beam radius

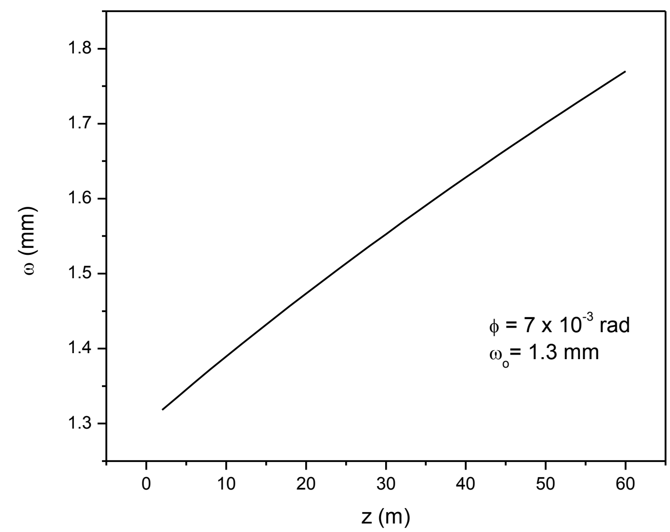

Figure 5. Variation of the beam radius with the distance at fixed value of the starting beam radius.

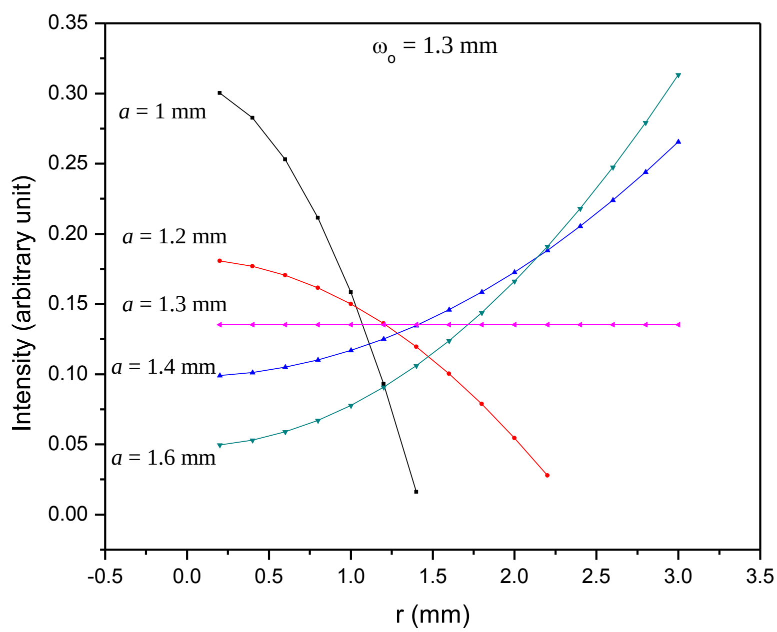

Figure 6. Intensity distribution of the modified beam of zero order on the waist plane as a function of r, for ω_o = 1.3 mm and different values of a. The calculations were carried out using Equations 6 and 7.

with the distance until 60 m from the axicon at fixed value of the starting beam radius. The relationship between the two parameters is linear indicating that as the beam travels apart from the source, it will spread out.

The intensity of the modified Bessel-Gauss beam of zero order is considered. Calculation of the beam intensity in the waist plane using Equations 6 and 7 was carried out. Figure 6 represents the beam intensity as a function of (*r*) at different values of (*a*). The starting beam radius (ω_o) was kept at 1.3 mm. From the figure one can deduce that if the radius *a* equals ω_o, the intensity near the axis is constant. If ω_o is greater than *a*, the intensity will decrease by raising of *r* while the intensity will increase when ω_o is less than *a*. This can be explained by considering that when the radius *a* is increased, the maxima of the constituent Gaussian beams recede from one another so that a central dip appears.

Conclusion

The parameters characterizing the Bessel-Gaussian beam were determined. It was found that the beam radius reaches a minimum value at a certain starting beam radius at any distance. The change of the wavefront radius of curvature with the distance *z* is somehow irregular. It was concluded that starting beam radius equals 1.3 mm represents the suitable value of the starting beam radius at which the beam radius of curvature is being a constant regardless of the distance from the beam source. Calculation of the beam intensity of the modified Bessel-Gauss beam in the waist plane was proceeded. The results are dependent on weither *a* is smaller, equal or greater than ω_o.

Conflict of interests

The authors have not declared any conflict of interests.

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