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CONSIDERATIONS ABOUT THE APPARENT "SUPERLUMINAL EXPANSIONS" IN ASTROPHYSICS(o)

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ABSTRACT.- The ortodox models devised to explain the apparent "superliminal expansions" observed in astrophysics — and here briefly summarized and discussed together with the experimental data — do not seem to be too much successful. Especially when confronted with the most recent observations, suggesting complicated expansion patterns, even with possible accelerations.

At this point it may be, therefore, of some interest to explore the possible alternative models in which actual Superluminal motions take place.

To prepare the ground we start from a variational principle, introduce the elements of a tachyon mechanics within special relativity, and argue about the expected behaviour of tachyonic objects when interacting (gravitationally, for instance) among themselves or with ordinary matter.

We then review and develope the simplest "Superluminal models", paying particular attention to the observations which they would give rise to. We conclude that some of them appear to be physically acceptable and are statistically favoured with respect to the ortodox ones.

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1.- INTRODUCTION

The particular — and unreplaceable — role in Special Relativity (SR) of the light-speed, c, in vacuum is due to its invariance (namely, to the experimental fact that c does not depend on the velocity of the source), and not to its being of not the maximal speed[1].

The subject of Tachyons, even if still speculative[2], may deserve some attention for reasons that can be divided into a few categories, some of which we want to mention right now: (i) the larger scheme that one tries to build up in order to incorporate space-like objects in the relativistic theories can allow a better comprehension of many aspects of the ordinary relativistic physics, even if Tachyons would not exist in our cosmos as "asymptotically free" objects; (ii) Superluminal classical objects can have a role in elementary particle or quantum interactions; (iii) they may have a role even in astrophysics. Let us moreover recall that, in General Relativity (GR), space-like geodesics are "at home"; so that tachyons have often been implicit ingredients of GR[3].

In this paper let us fix our attention on the problem of the apparent "superluminal expansions" in Astrophysics.

2.- THE APPARENT SUPERLUMINAL EXPANSIONS

The theoretical possibility of Superluminal motions in astrophysics has been considered since long (Gregory[4], Mignani and Recami[4], and Recami[4]).

Experimental investigations, started long ago as well (see Smith and Hoffeit[5], and Knight et al.[5]), led at the beginning of the Seventies to the claim that radio-interferometric observations had revealed — at least in the two quasars 3C279, 3C273 and in the Seyfert Type I galaxy 3C120 — expansion of small radio components at velocities apparently a few times greater than that of light (Whitney et al.[6], Cohen et al.[6], Shaffer et al.[6], and Shapiro et al.[6]). The first claims were followed by extensive collections of data, all obtained by very-long-baseline-interferometry (VLBI) systems with many radio-telescopes; reviews of the experimental data can be found in Cohen et al.[7], Kellerman[7], and Cohen and Unwin[7]: see also Schillizzi and Bruyn[7]. The result is, grosso modo, that the nucleus of seven strong radiosources (six quasars, 3C273, 3C279, 3C345, 3C179, NRAO-140, BL Lac, and one galaxy, 3C120) consists of two components which appears to recede from each other with Superluminal relative speeds ranging from a few c, to a few tens c (cf. Ref.8). A result so puzzling that the journal Nature even devoted one of its covers (April 2, 1981) to the Superluminal expansion exibited by quasar 3C273. Simplyfying it, the experimental situation can be summarized as follows:

(i) the Superluminal relative motion of the two components is always a collinear recession ;

(ii) such Superluminal "expansion" seems endowed with a roughly constant velocity, which does not depend on the observed wave-length;
(iii) the flux density ratio for the two components, F_1/F_2, does depend on the (observed) wave-length and time.

Apparently, those strong radiosources exibit a compact inverted-spectrum core component (usually variable), and one extended component which separate from the core with Superluminal velocity. But it is not yet clear whether the compact core is indeed stationary of it too moves. The extended component seems to become weaker with time and more rapidly at high frequencies.

The most recent results, however, seem to show that — at least in quasar 3C345 — the situation may be more complex (Unwin et al.[9], Readhead et al.[9], Biretta et al.[9], Porcas[9]). In the same quasar an "extended component" does even appear to accelerate away with time (Moore et al.[10]; see also Pearson et al.[10]).

Many theoretical models were soon devised to explain the apparent Superluminal expansions in a ortodox way (Ree[11], Whitney et al.[6], Cavaliere et al.[11], Dent[11], Sanders[11], Epstein and Geller[11], and so on). Reviews of the orthodox models can be found in Blandfort et al.[12], Scheuer and Readhead[12], Marscher and Scott[12], Orr and Browne[12], and Porcas[9].

The most successful and therefore most popular models resulted to be:
a) The relativistic jet model: A relativistically moving stream of plasma is supposed to emanate from the core. The compact core of the "superluminal" sources is identified with the base of the jet and the "moving" component is a shock or plasmon moving down the jet. If the jet points al a small angle α towards the observer, the apparent separation speed becomes Superluminal since the radiation coming from the knot has to travel a shorter distance. Namely, if v is the knot speed w.r.t. the core, the apparent recession speed will be $[c = 1]$: $w = v \sin\alpha/(1 - v\cos\alpha)$, with $v \geq w/(1 + w^2)^{1/2}$. The maximal probability for a relativistic jet to have the orientation required for producing the apparent Superluminal speed $\bar{w}$ — independently of the jet speed v — is $P(\bar{w}) = (1 + \bar{w}^2)^{-1} < 1/\bar{w}^2$ (Blandford et al.[12], Finkelstein et al.[13], Castellino[14]). The relativistic jet models, therefore, for the observed "superluminal" speeds suffer from statistical objestions, even if selecting effects can play in favour of them (see e.g. Porcas[15], Science News[15], Pooley[15], Pearson et al.[10]).

b) The "Screen" models: The "superluminal" emissions are triggered by a relativistic signal coming from a central source and "illuminating" a pre-existing screen. For instance, for a spherical screen of radius R illuminated by a concentric spherical relativistic signal, the distant observer would see a circle expanding with speed $w \simeq 2c(R - ct)/(2Rct - c^2t^2)^{1/2}$; such a speed will be superluminal in the time-interval $0 < t < \frac{1}{2}(2 - \sqrt{2})\, R/c$ only. When the screen is a ring the observer would see an expanding double source. The defect of such models is that the apparent expansion speed will be $w \geq \bar{w}$ (with $\bar{w} \gg 2c$) only for a fraction $c^2/\bar{w}^2$ of the time during which the radiousource exibits its variations. Of course one can introduce "oriented" screens — or ad hoc screens —, but they are statistically unfavoured (Blandford et al.[12], Castellino[14].

c) Other models: many previous (unsuccessful) models have been abandoned. The gravitational lens models did never find any observational support, even if a new type of model (where the magnifying lens is just surrounding the source) has been recently suggested by Liaofu and Chongming[16].

In conclusion, the orthodox models are not too much successful, especially if the more complicated Superluminal expansions (e.g. with acceleration) recently observed will be confirmed.

It may be of some interest, therefore, to explore the possible alternative models in which actual Superluminal motions take place (cf.e.g. Mignani and Recami[15]).

To prepare the ground, in Sects. 3 and 4 we shall develope some Tachyon Mechanics within SR. Before going on, however, let us immediately put forth the following (simple, but important) remark, valid at least in two dimensions.

Let us consider in SR two (bradyonic = slower-than-light) bodies A and B that — owing to mutual attraction — for instance accelerate while approaching each other. The situation is sketched in Fig. 1, where A is chosen as the reference frame $s \equiv (t,x)$ and, for simplciity's sake, only a discrete change of velocity is depicted. From a Superluminal frame they will be described either as two tachyons that decelerate while approaching each other [as seen from the frame $S'' \equiv (t'',x'')$], or as two antitachyons[17,18] that accelerate while receding from each other [as seen from the frame $S' \equiv (t',x')$]. Therefore, we expect that two tachyons from the kinematical point of view will seem to suffer a repulsion, if they attract each other in their own rest frames (or in other frames in which they are subluminal); we shall however see that such a behaviour of tachyons can be still considered — from the more important dynamical and energetical point of view — as due to an attraction.

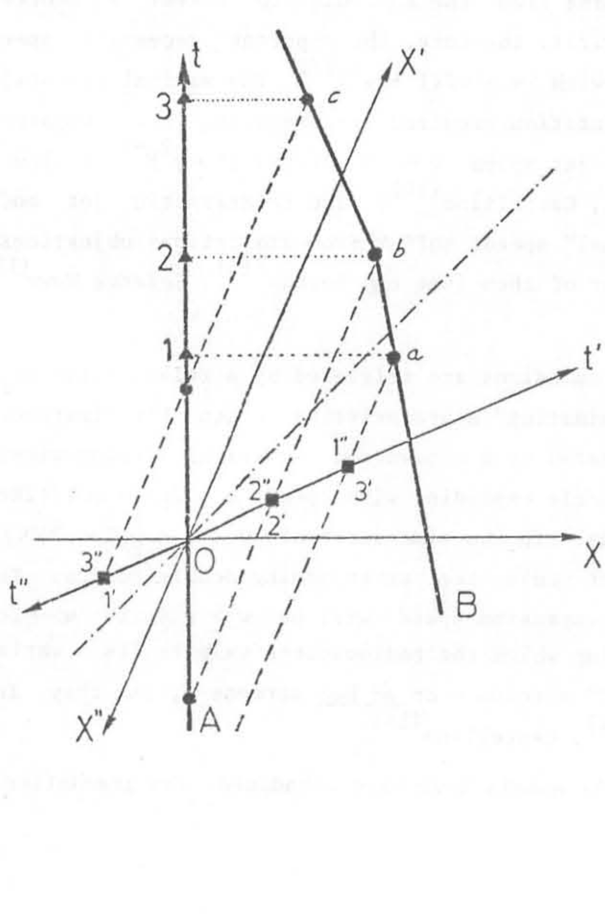

Figure 1 - Let us consider two braydonic (= = slower-than-light) objects A and B in two dimensions. Let B accelerate while approaching A, due to a mutual attraction. Then from a Superluminal frame they will be described: (i) either as two tachyons that decelerate while approaching each other [from the frame $S'' \equiv (t'',x'')$]; (ii) or as two antitachyons[17,18] that accelerate while receding from each other [from the frame $S' \equiv (t',x')$]. See also the text.

3.- SOME PRELIMINARY TACHYON MECHANICS IN SR

3.A.- On the Variational Principle: A Digression

Let us first consider the actions S for a free object. In the ordinary case it is $S = \alpha\int_a^b ds$; for a free tachyon let us, tentatively, write

$$S = \alpha\int_a^b |ds| . \tag{1}$$

By analogy with the bradyonic case, we might assume for a free tachyon the Lagrangian [c=1]

$$L = + m_o \sqrt{\vec{V}^2 - 1} \quad , \qquad [\vec{V}^2 > 1] \tag{2}$$

and therefore evaluate, in the usual way,

$$\vec{p} \equiv \frac{\partial L}{\partial \vec{V}} = + \frac{m_o \vec{V}}{\sqrt{\vec{V}^2 - 1}} \equiv m \vec{V} \tag{3}$$

which suggests that for tachyons

$$m = \frac{m_o}{\sqrt{\vec{V}^2 - 1}} . \tag{4}$$

If the tachyon is no more free, we can write as usual

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d}{dt}\left(\frac{m_o \vec{V}}{\sqrt{\vec{V}^2 - 1}}\right) . \tag{5}$$

By chosing the reference-frame, at the considered time-instant t, in such a way that $\vec{V}$ is parallel to the x-axis, i.e. $|\vec{V}| = V_x$, we then get

$$F_x = + m_o \left[\frac{1}{\sqrt{\vec{V}^2 - 1}} - \frac{\vec{V}^2}{\sqrt{(\vec{V}^2 - 1)^3}}\right] a_x = - \frac{m_o}{(\vec{V}^2 - 1)^{3/2}} a_x \tag{6a}$$

and

$$F_y = + \frac{m_o}{\sqrt{\vec{V}^2 - 1}} a_y \quad ; \quad F_z = \frac{m_o}{\sqrt{\vec{V}^2 - 1}} a_z . \tag{6b}$$

The sign in eq.(6a) is consistent with the ordinary definition of work $\mathcal{L}$

$$d\mathcal{L} \equiv + \vec{F} \cdot d\vec{\ell} \tag{7}$$

and the fact that the total energy of a tachyon increases when its speed <u>decreases</u> (as well-known[18]).

Notice, however, that the proportionality constant between force and acceleration does <u>change sign</u> when passing from the longitudinal to the transverse components.

The tachyon total energy E, moreover, can still be defined as

$$E \equiv \vec{p}\cdot\vec{V} - L = \frac{m_o c^2}{\sqrt{\vec{V}^2 - 1}} \equiv mc^2 \tag{8}$$

which together with eq.(4), extends to tachyons the relation $E = mc^2$.

However, the following comments are in order as this point. An ordinary time-like (straight) line can be bent only in a space-like direction; and it gets shorter. On the contrary, if you take a space-like line and, keeping two points on it fixed, bend it slightly in between in a space-like (time-like) direction, the bent line is longer (shorter) than the original straight line (see e.g. Dorling[19]). For simplicity, let us here skip the generic case when the bending is partly in the time-like and partly in a space-like direction (even if such a case looks to be the most interesting). Then, the action integral $\int_a^b |ds|$ of eq.(1) along the straight (space-like) line is minimal w.r.t. the "space-like" bendings and maximal w.r.t. the "time-like" bendings. A priori, one might then choose for a free tachyon, instead of eq.(2), the Lagrangian

$$L = - m_o \sqrt{\vec{V}^2 - 1} \quad , \tag{2'}$$

which yields

$$\vec{p} \equiv \frac{\partial L}{\partial \vec{V}} = - \frac{m_o \vec{V}}{\sqrt{\vec{V}^2 - 1}} \equiv - m\vec{V} \, . \tag{3'}$$

Eq.(3') becomes rather interesting, e.g., when tachyons are substituted for the "virtual particles" as the carriers of the elementary particle interactions[20]. In fact, the (classical) exchange of a tachyon endowed with a momentum antiparallel to its velocity would generate an <u>attractive</u> interaction.

$$\vec{F} = \frac{d\vec{p}}{dt} = - \frac{d}{dt} \left(\frac{m_o \vec{V}}{\sqrt{\vec{V}^2 - 1}}\right) \tag{5'}$$

and therefore, when $|\vec{V}| = V_x$,

$$\begin{cases} F_x = + \dfrac{m_o}{(\vec{V}^2 - 1)^{3/2}} a_x \; ; & (6'a) \\[2em] F_y = - \dfrac{m_o}{\sqrt{\vec{V}^2 - 1}} \; ; \quad F_z = - \dfrac{m_o}{\sqrt{\vec{V}^2 - 1}} a_z \, . & (6'b) \end{cases}$$

Due to the sign in eq.(6'a), it is now necessary to define the work $\mathcal{L}$ as

$$d\mathcal{L} \equiv - \vec{F} \cdot d\vec{\ell} \; , \tag{7'}$$

and analogously the total energy E as

$$E \equiv -(\vec{p}\cdot\vec{V}-L) = \frac{m_o c^2}{\sqrt{\vec{V}^2-1}} \equiv mc^2. \tag{8'}$$

3.B.- On Radiating Tachyons

Notice that the previous results in Sect. 3.A are quite independent of the eventual existence (or not) of Superluminal Lorentz transformations (SLT).

Here, as a further example of results actually independent of the very existence of SLTs, let us report the fact that a tachyon — when seen by means of its electromagnetic emissions (see Review I, and Baldo et al.(21)) — will appear in general as occupying two positions at the same time (Recami(4), and Barut et al.(22); see also Grøn(22)). Let us start by considering a macro-object C emitting spherical electromagnetic waves (Fig. 2c). When we see it travelling at constant Superluminal velocity $\vec{V}$, because of the distortion due to the large relative speed $|\vec{V}| > c$, we shall observe the electromagnetic waves to be internally tangent to an enveloping cone Γ having as its axis the motion-line of C (Recami and Mignani(23); Review I); even if this cone has nothing to do with Cherenkov's (Mignani and Recami(24)). This is analogous to what happens with an airplane moving at a constant supersonic speed in the air. A first observation is the following: as we hear a sonic boom when the sonic contact with the supersonic airplane does start (Bondi(25)), so we shall analogously see an "optic boom" when we first enter in radio-contact with the body C, i.e. when we meet the Γ-cone surface. In fact, when C is seen by us under the angle (Fig. 2a)

$$V \cos \alpha = c \qquad [V \equiv |\vec{V}|] \tag{9}$$

all the radiations emitted by C in a certain time-interval around its position C_o reach us simultaneously. Soon after, we shall receive at the same time the light emitted from suitable couples of points, one on the left and one on the right of C_o. We shall thus see the initial body C, at C_o, split in two luminous objects C_1, C_2 which will then be observed to recede from each other with the Superluminal "transverse" relative speed W (Recami et al.(26), Barut et al.(22)):

$$W = 2b\,\frac{1 + d/bt}{[1 + 2d/bt]^{1/2}} \quad ; \quad b \equiv \frac{V}{\sqrt{V^2-1}} \quad , \qquad [V^2 > 1] \tag{10}$$

where $d \equiv \overline{OH}$, and $t = 0$ is just the time-instant when the observer enters in radiocontact with C, or rather see C at C_o. In the simple case in which C moves with almost infinite speed along r (Fig. 2b), the apparent relative speed of C_1 and C_2 varies in the initial stage as $W \simeq (2cd/t)^{1/2}$, where now $\overline{OH} = \overline{OC_o}$ while $t = 0$ is still the instant at which the observer sees $C_1 \equiv C_2 \equiv C_o$.

We shall come back to this subject in the following.

Here let us add the observation that the radiation associated with one of the images of C (namely, the radiation emmited by C while approaching us, in the simple case depicted in Fig.2c) will be received by us in the reversed chronological order; cf. Mignani and

Recami[27], and Recami[27].

It may be interesting to quote that the circumstance, that the image of a tachyon suddenly appears at a certain position C_o and then splits into two images, was already met by Bacry[28] and Bacry <u>et al.</u>[28] while exploiting a group-theoretical definition of the motion of a charged particle in a homogeneous field; definition which was valid for all kind of particles (braydons, luxons, tachyons). Analogous solutions, simulating a pair-production, have been later on found even in the <u>subluminal</u> case by Barut[28], when exploring <u>non-linear</u> evolution equations, and by Sala[28], by merely taking account of the finite speed of the light which carries the image of a moving subluminal object. Sala[28] did even rediscover — also in subluminal cases — that one of the two images can display a time-reversed evolution.

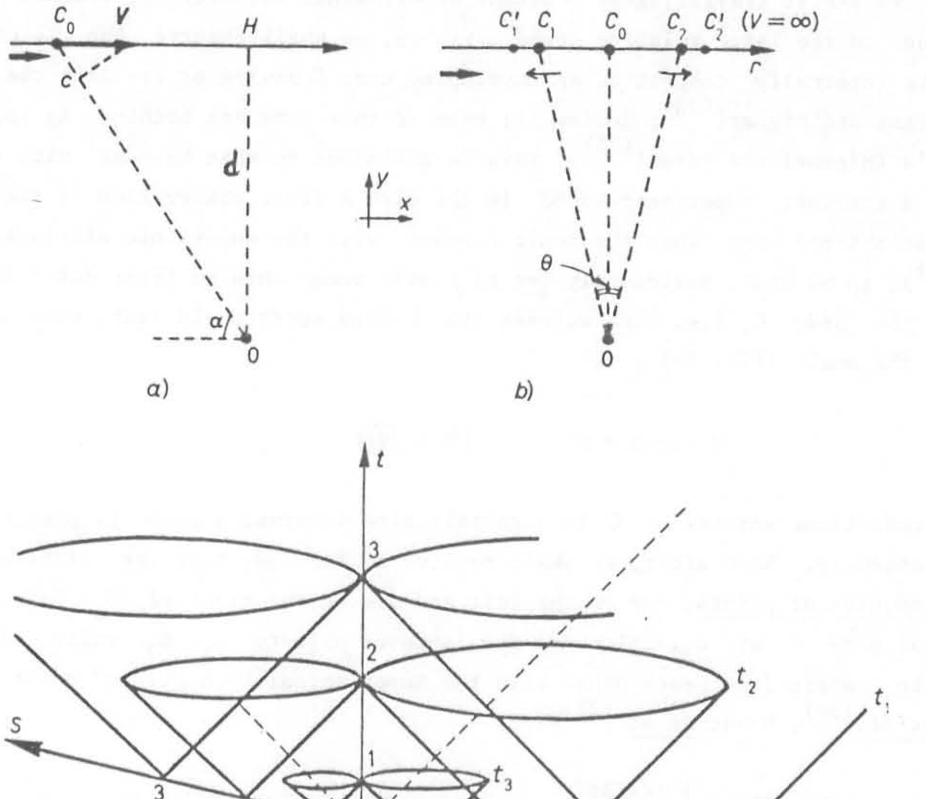

Figure 2 - A <u>unique</u> Superluminal object, observed through the radiation emitted by it, will appear as a <u>couple</u> of objects receding from each other with Superluminal relative speed. See the text.

4.- SOME MORE TACHYON MECHANICS IN SR

While the results in Sect. 3 do not depend at all on the eventual existence of SLTs, to go on we need now adopting the following Assumption. Namely, let us assume in this Sect. 4 that such "transformations" exist in four dimensions (even if at the price of giving up possibly one of the ordinary properties of the Lorentz transformations: see Refs. 29) that carry time-like into space-like tangent vactors, and vice-versa. Incidentally, they are known to exist in two [(1,1)] dimensions, as well as in (n , n) dimensions[(29)]. Their actual existence in four [(1,3)] dimensions has been claimed for instance by Shah[(30)] within the "quasi-catastrophes" theory (cf. also Smrz[(2)]). We shall call[(29)] Superluminal Lorentz transformations those "transformations"; let us repeat that, to proceed with, we need nothing but the previous Assumption. The laws of classical physics for tachyons could then be derived just by applying a SLT to the ordinary classical laws of braydons (cf. Parker[(31)], and Recami and Mignani[(18)]).

It is noticeable that tachyon classical physics can then be obtained in terms of purely real quantities. (Notice moreover that Sect. 4.A and 4.B below do contain improvements with respect e.g. to Review I).

4.A.- Tachyon Motion Equation

For example, the fundamental law of braydon dynamics reads

$$F^{\mu} = c \frac{d}{ds} (m_o c \frac{dx^{\mu}}{ds}) \equiv \frac{d}{d\tau_o} (m_o \frac{dx^{\mu}}{d\tau_o}) . \qquad [\beta^2 < 1] \tag{11}$$

Notice that eq. (11) in its first form is only Lorentz-covariant, while in its second form is G-covariant (cf. e.g. Review I).

Even for tachyons, then, we shall have[(18)]:

$$F^{\mu} = + \frac{d}{d\tau_o} (m_o u^{\mu}) \equiv + \frac{dp^{\mu}}{d\tau_o} , \qquad [\beta^2 > 1] \tag{12}$$

where m_o is the tachyon (real) rest-mass and we defined $p^{\mu} \equiv m_o u^{\mu}$ also for tachyons. Equation (12) is the relativistic Newton Law written is G-covariant form: i.e., it is expected to hold for $\beta^2 \lesseqgtr 1$. It is essential to recall, however, that u^{μ} is to be defined $u^{\mu} \equiv dx^{\mu}/d\tau_o$ [(18,29)]. Quantity $d\tau_o$, where τ_o is the proper-time, is of course G-invariant; on the contrary, $ds = \pm\, cd\tau_o$ for braydons, but $ds = \pm\, icd\tau_o$ for tachyons.

Equation (12) agrees with eqs. (5) and (5') of Sect. 3, where we set $\vec{F} = d\vec{p}/dt$, and suggests that for tachyons $dt = \pm\, d\tau_o/\sqrt{\beta^2 - 1}$ (see Review I), so that in G-covariant form $dt = \pm\, d\tau_o(|1-\beta^2|)^{-1/2}$.

For the tachyon case, let us notice the following. It at the considered time-instant t we choose the x-axis so that $V = |\vec{V}| = V_x$, then only the force-component F_x will make work. We already mentioned that the total energy of a tachyon decreases when its speed increases, and vice-versa; it follows that F_x when applied to a tachyon will actually make a positive, elementary work $d\mathcal{L}$ only if a_x is anti-parallel to the elementary displacement dx, i.e. if $\mathrm{sign}(a_x) = -\mathrm{sign}(dx)$. In other words, $d\mathcal{L}$ in the case of a force $\vec{F}$ applied to a tachyon <u>must be defined</u> (cf. Sect. 3.A) so that

$$d\mathcal{L} = -\frac{m_o}{(V^2-1)^{3/2}} a_x dx \tag{13}$$

where a_x and dx possess of course their own sign. Equation (13) does agree both with the couple of equations (6a), (7) and with the couple of equations (6'a), (7').

It is evident that, <u>with the choice</u> (Review I) represented by eqs. (7) and (2) of Sect. 3.A, we shall have $[v = v_x \; ; \; V = V_x]$:

$$F_x = +\frac{m_o}{(1-V^2)^{3/2}} a_x \qquad \text{for braydons;} \tag{14a}$$

$$F_x = \frac{m_o}{(V^2-1)^{3/2}} a_x \qquad \text{for tachyons.} \tag{14b}$$

On the contrary, still with the choice (7)-(2), we shall have

$$F_{y,z} = +\frac{m_o}{(|1-\beta^2|)^{1/2}} a_{y,z} \tag{14c}$$

for <u>both</u> braydons and tachyons. Actually, under our hypotheses $[v = v_x \; ; \; V = V_x]$, the transverse force-components $F_{y,z}$ do not make any work; therefore, one had no reasons a priori for expecting any change in eq.(14c) when passing from braydons to tachyons.

4.B.- Gravitational Interactions of Tachyons

In any gravitational field a braydon feels the (attractive) gravitational 4-force

$$F^\mu = -m_o \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{ds}\frac{dx^\sigma}{ds} \quad . \qquad [\beta^2 < 1] \tag{15}$$

In G-covariant form, then, eq. (15) [see Review I, Mignani and Recami[4], Recami and Mignani[18], and Recami[27]] are expected to write:

$$F^\mu = -\frac{m_o}{c^2}\Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\tau_o}\frac{dx^\sigma}{d\tau_o} \quad , \qquad [\beta^2 \gtrless 1] \tag{16}$$

since the Christoffel symbols behave like (third-rank) tensors under <u>any</u> linear transformations of the coordinates. Equations (16) hold in particular for a tachyon in any gravitational field (both when originated by tachyonic and by braydonic sources).

Analogously, the equation of motion for both braydons and tachyons in a gravitational field will still read (Review I), in G-covariant form,

$$a^{\mu} + \Gamma^{\mu}_{\rho\sigma} u^{\rho} u^{\sigma} = 0 \quad , \quad [\beta^2 \gtrless 1] \tag{17}$$

with $a^{\mu} \equiv d^2x^{\mu}/d\tau_o^2$.

Passing to General Relativity, this does agree with the Equivalence Principle: Braydons, photons and tachyons follow different trajectories in a gravitational field, which depend only on the initial (different) four-velocities and are independent of the masses.

Going back to eqs. (16), we may say that also tachyons are attracted by a gravitational field. However, such an "attraction" has to be understood from the energetical and dynamical point of view only.

In fact, if we consider for simplicity a tachyon moving radially w.r.t. a gravitational source, due do eq. (14b) [i.e., due to the couples of equations either (6a)-(7), or (6'a)-(7')] it will accelerate when recending from the source, and accelerate when approaching the source. From the kinematical point of view, therefore, we can say that tachyons seem to be gravitationally repelled. Analogous results were put forth by Vaidya(32), Raychaudhuri(32), Honig et al.(32), and so on.

In the case of a braydonic source, what precedes agrees with the results obtained within General Relativity: see e.g. Saltzan and Saltzman(33), Gregory(33), Hettel and Helliwell(33), Sum(33), Narlikar and Sudarshan(33), Narlikar and Dhurandhar(33), Comer and Lathrop(33), Maltsev(33), Ciborowski(33), Finkelstein et al.(13), Cao Shenglin et al.(33), etc.

4.C. About Doppler Effect

In the two-dimensional case, the Doppler-effect formula for a sub- or a Super-luminal source, moving along the x-axis, is (Mignani and Recami(27)):

$$\nu = \nu_o \frac{\sqrt{|1-u^2|}}{1 \pm u} \quad , \quad [-\infty < u < +\infty] \tag{18a}$$

where the sign - (+) corresponds to approach (recession). The consequences are depicted in figures like Fig. 23 of Review I. For Superluminal approach, ν happens to be negative, so as explained by our Fig.2c. Let us moreover observe that, in the case of recession, the same Doppler shift is associated both with $\bar{u} < c$ and with $\bar{U} \equiv c^2/\bar{u} > c$ (Mignani and Recami(34), and Recami(27)).

In the fourdimensional case, if the observer is still located at the origin, eq.(18a) is expected to generalize (Recami and Mignani(18,34)) into

$$\nu = \nu_o \frac{\sqrt{|1-u^2|}}{1 + u \cos\alpha} \; , \; [-\infty < u < +\infty] \tag{18b}$$

where $\alpha \equiv \widehat{\vec{u}\vec{\ell}}$, vector $\vec{\ell}$ being directed from the observer to the source. Let us notice from Sect. 3.B (eq.(9)), incidentally, that when an observer starts receiving radiation from a Superluminal pointlike source C (at C_o, i.e. in the "optic-boom" situation), the received radiation is infinitely blue-shifted.

5.- THE MODEL WITH A UNIQUE (SUPERLUMINAL) SOURCE

The simplest Superluminal model is the one of a unique Superluminal source. In fact we have seen in Sect. 3.B (see Fig. 2) that a unique Superluminal source C will appear as the creation of a pair of sources collinearly receding from each other with relative speed $W > 2c$. This model immediately explains some gross features of the "superluminal expansions"; e.g., why converging Superluminal motions are never seen, and the high luminosity of the "superluminal" component (possibly due to the optic-boom effect mentioned in Sect. 3.B; see also Ref. 27 and last Ref. 4), as well as the oscillations in the received overall intensity (perhaps "beats", cf. Recami[27]). Since, moreover, the Doppler effect will be different for the two images C_1, C_2 of the same source C (Sect. 4.C), a priori the model may even explain why F_1/F_2 does depend on the observed wavelength and on time (see Sect. 2, point (iii)).

Such a model for the "superluminal expansions" was therefore proposed long ago (see Recami, Refs. 4; Mignani and Recami[34]; Recami et al.[26]; Grøn[22]; and Barut et al.[22]). More details can be found in the M.S. thesis work by Castellino[14], where e.g. the case of an extended source C is thoroughly exploited.

5.A. - The Model

With reference to Fig. 2 and Sect. 3.B, let us first consider the case of an expanding universe (homogeneous isotropic cosmology). If we call $\overline{C_o0} \equiv s = db$, with $b \equiv V/\sqrt{V^2-1}$, the observed angular rate of recession of the two images C_1 and C_2 as a function of time will be

$$\dot{\theta}(t) \equiv \omega = \frac{2bc}{s} \frac{1 + A}{[1 + 2A]^{1/2}} \quad ; \quad A \equiv \frac{s}{b^2 ct} \quad , \tag{19}$$

provided that s is the "proper distance" between C_o and 0 at the epoch of the radiation reception by 0, and t is the time at which 0 receives those images. Let us repeat that ω is the separation angular velocity of C_1 and C_2, observed by 0, in the case of a space-time metric

$$ds^2 = c^2dt^2 - R^2(t) \cdot [dr^2 + r^2 d\Omega]$$

where $R = R(t)$ is the (dimensionless) scale-factor. Notice that $\dot{\theta}(t) \to \infty$ for $t \to 0$.

If we call t^* and t the emission time and the reception time, respectively, then the observed frequency ν (see Sect. 4.C and eq.(18b)) and the received radiation intensity I will be given of course by (Recami[34], Recami et al.[26], Castellino[14]):

$$\nu = \nu_o \frac{\sqrt{V^2 - 1}}{|1 - V\cos\alpha|} \cdot \frac{R(t^*)}{R(t)} \quad ; \quad I = \frac{(V^2 - 1)W_o}{4\pi s^2(1 - V\cos\alpha)^2} [\frac{R(t^*)}{R(t)}]^2 \quad , \tag{20}$$

where ν_o is the intrinsic frequency of emission and W_o is the emission power of the source in its rest-frame. Quantity s is again the source-observer "proper distance" (Weinberg[35], p. 415) at the reception epoch.

Let us pass to the case of a non-pointlike source C. Let for simplicity C be one-dimensional with size ℓ w.r.t. the observer 0 (Fig. 2a), and move with speed V in the direction r of its own length. Let us call x the coordinate of a generic point of r, the value $x = 0$ belonging to H. As in Sect. 3.B, be $t = 0$ the instant when the observer 0 enters in radiocontact with C.

Once the two (extended) images C_1 and C_2 get fully separated (i.e., for $t > \ell/V$), if the intrinsic spectral distribution $\Sigma(\nu_o)$ of the source C is known, one can evaluate the differential intensities $dI_1/d\nu$ and $dI_2/d\nu$ observed for the two images (Recami et al.[26], Castellino[14]). For the moment let us report only that, due to the extension of the moving images, for each emitted frequency ν_o the average observed frequencies will be

$$< \nu_1 > = \frac{2\nu_o}{\sqrt{V^2-1}\,(1-\alpha_2/\alpha_1)} \cdot \frac{R(t^*)}{R(t)} \quad ; \quad < \nu_2 > = \frac{\alpha_2}{\alpha_1} < \nu_1 > , \tag{21}$$

quantities α_1, α_2 being the observed angular sizes of the two images, with $\alpha_1 > \alpha_2$. Moreover $\ell/d = \frac{1}{2} V (\alpha_1 - \alpha_2)$.

5.B.- Corrections Due to the Curvature

Let us consider the corrections due to the curvature of the universe, which can be important if the observed expansions are located very far. Let us consider, therefore, a curved expanding cosmos (closed Friedmann model), were the length element $d\ell$ is given by $d\ell^2 = dr^2(1-r^2/a^2)^{-1} + r^2 d\Omega$, quantity $a = a(t)$ being the curvature radius of the cosmos. Again, some details can be found in Recami et al.[26] and Castellino[14]. For instance, the apparent angular velocity of separation $\dot{\theta}(t)$ between the two observed images C_1 and C_2 (cf. eq.(19)) becomes $[h \equiv r/a \ ; \ ct \ll r]$:

$$\dot{\theta}(t) \equiv \omega \simeq b\,\frac{1+bh}{b+h}\left[\frac{2c}{rt}\right]^{1/2}\left[1-h^2\right]^{1/4} \tag{22}$$

quantities r and a being the "radial coordinate" of C_o and the universe radius, respectively, at the present epoch [$r = \sin(s/a)$, where s is the "proper distance" of C_o; moreover $a = c/(H\sqrt{2q-1})$; $H \equiv$ Hubble constant; $q \equiv$ deceleration parameter]. Further evaluations in the abovequoted literature.

5.C.- Comments

The eq. (19) yields apparent angular velocities of separation two or three orders of magnitude larger than the experimental ones. It is then necessary to make recourse of eq. (22), which includes the corrections due to the universe curvature; actually, eq. (22) can yield arbitrarily small values of $\dot{\theta}(t)$ provided that $h \to 1$, i.e. $r \to a$. To fit the observation data, however, one has to attribuite to the "superluminal expansions" values of the radial coordinate r very close to a. Such huge distances would explain why the possible blue shifts — often expected from the local motion of the Superluminal source C (cf. end of Sect. 4.C) — appear masked by the cosmological red-shift. (Notice, incidentally, that a phenomenon as the one here depicted can catch the observer's attention only when the angular separation θ between C_1 and C_2 is small, i.e. when C_1 and C_2 are still close to C_o). But those same large distances make also this model improbable as an explanation of the observed "superluminal" expansions, as least in the closed models. One could well resort, then, to open Friedmann models. In fact, the present model with a unique (Superluminal) source is appealing since it easily explains: (a) the appearance of two images with Superluminal relative speed ($W > 2c$); (b) the fact that only Superluminal expansions (and not approaches) are observed; (c) the fact that W is always Superluminal and practically does not depend on ν; (d) the relative-motion collinearity; (e) the fact that the flux-densities ratio <u>does</u> depend on ν and t, since the observed flux differential intensities for the two images as a function of time are given by the formulae[14]:

$$\begin{cases} \dfrac{dI_i}{d\nu} = \dfrac{V^2 - 1}{4\pi d^2\, V L} \displaystyle\int_{\nu/M_i(t)}^{\nu/m_i(t)} \frac{\Sigma(\nu_o)\, d\nu_o}{\nu_o F}\,, \quad [i = 1,2] \\[2ex] F \equiv [V^{-2}(\sqrt{V^2 - 1}\; \dfrac{R(t)}{R(t^*)}\, \dfrac{\nu}{\nu_o} + 1)^2 - 1]^{1/2}\;; \end{cases} \tag{23}$$

the integration extrema being

$$m_{\substack{1\\2}}(t) \equiv K\{VG[VTG']^{-1/2} \pm 1\} \tag{24a}$$

$$M_{\substack{1\\2}}(t) \equiv K\{\frac{V(G - L)}{[VT(G' - 2L) + L(L - 2\sqrt{V^2 - 1})]^{1/2}} \pm 1\} \tag{24b}$$

where d is the "proper distance" $\overline{OH}$ at the reception epoch (Fig. 2a); $L \equiv \ell/d$; $T \equiv ct/d$; $K \equiv \sqrt{V^2 - 1}\, R(t^*)/R(t)$; $G \equiv \sqrt{V^2 - 1} + VT$; and $G' \equiv 2G - VT$. All eqs. (23)-(24) become dimensionally correct provided that V/c is substituted for V.

But the present model remains disfavoured since: (i) the Superluminal expansion seems to regard not the whole quasar or galaxy, but only a "nucleus" of it; (ii) at least in one case (3C273) an object was visible there, even before the expansion started; (iii) it is incompatible with the acceleration seemingly observed at least in another case (3C345).

Nevertheless, we exploited somewhat this question since: (A) in general, the above discussion tells us how it would appear a unique Superluminal cosmic source; (B) it might still regard <u>part</u> of the present-type phenomenonlogy; (C) and, chiefly, it must be taken into account even <u>for each one</u> of the Superluminal, far objects considered in the following models.

6.- THE MODELS WITH MORE THAN ONE RADIO SOURCES

Let us, first, recall that black-holes can classically emit (only) tachyonic matter, so that they are expected to be suitable classical sources — and detectors — of tachyons (Pavšič and Recami[36], De Sabbata et al.[36], Narlikar and Dhurandhar[36], Recami[36], Recami and Shah[36], Barut et al.[22]. Notice that, vice-versa, a tachyon entering the horizon of a black-hole can of course come out again from the horizon. As well known, the motion of a space-like object penetrating the horizon has been already investigated, within GR, in the existing literature.

We also saw in Sect. 2 (Fig. 1) and in Sect. 4.B that, in a "subluminal" frame, two tachyons may seem — as all the precedent authors claimed — to repel each other from the kinematical point of view, due to the novel features of tachyon mechanics (Sect. 4.A : eqs(14b,c)). In reality, they will gravitationally attract each other, from the energetical and dynamical points of view (Sect. 4.B).

From Sect. 4.B a tachyon is expected to behave the same way also in the gravitational field of a braydonic source. If a central source B (e.g., a black-hole) emits e.g. a Superluminal body T, the object T under the effect of gravity will loose energy and therefore accelerate away. If the total energy $E = m_o c^2/\sqrt{V^2 - 1}$ of T is larger than the gravitational binding energy $\overline{E}$, it will escape to infinity with finite (asymptotically constant) speed. (Since at infinite speed a tachyon possesses zero total energy —see Sect. 3.A —, we may regard its total energy as all kinetic). If on the contrary $E < \overline{E}$, then T will reach infinite speed (i.e. the zero total-energy state) at a finite distance; afterwards the gravitational field will not be able to subtract any more energy to T, and T will start going back towards the source B, appearing now — actually — as an antitachyon $\overline{T}$ (see Refs. 17 and 18). It should be remembered (e.g., from Refs. 17) that at infinite speed the motion direction is undefined, in the sense that the transcedent tachyon can be described either as a tachyon T going back or as antitachyon $\overline{T}$ going forth, or vice-versa.

We shall see, on another occasion, that a tachyon subjected e.g. to a central attractive elastic force $\vec{F} = -k\vec{x}$ can move periodically back and forth with a motion analogous to the harmonic one, reversing its direction at the points where it has transcedent speed, and alternatively appearing — every half an oscillation — now as a tachyon and now as an antitachyon. Let us consider, in general, a tachyon T moving in space-time (Fig. 3) along the space-like curved path AP, so to reach at P the zero-energy state. According to the nature of the force fields acting on T, after P it can proceed along PB (just as expected in the above two cases, with attractive central forces), or along PC, or along PD. In the last case, T would appear to annihilate at P with an antitachyon emitted by D and travelling along the curved world-line DP (see Refs. 17, 18, 37; see also Davies[37], p. 577).

It is clear that the observed "superluminal" expansions can be explained:
(i) either by the splitting of a central body into two (oppositely moving) collinear

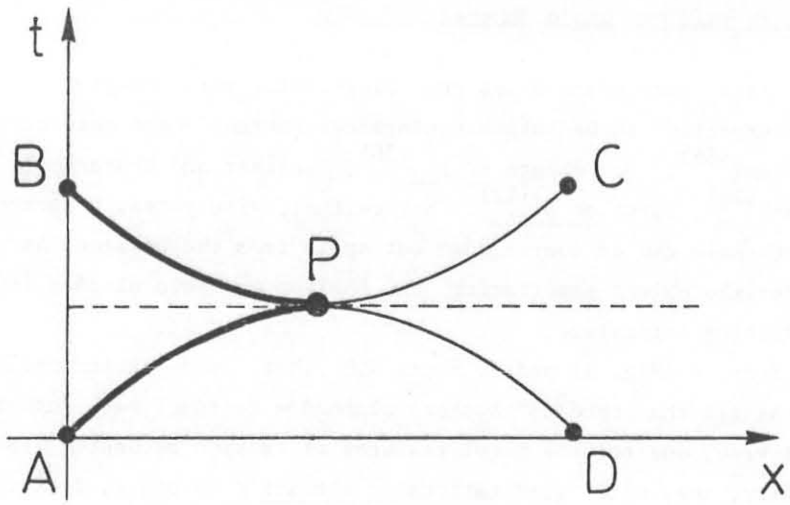

Figure 3 - See the text.

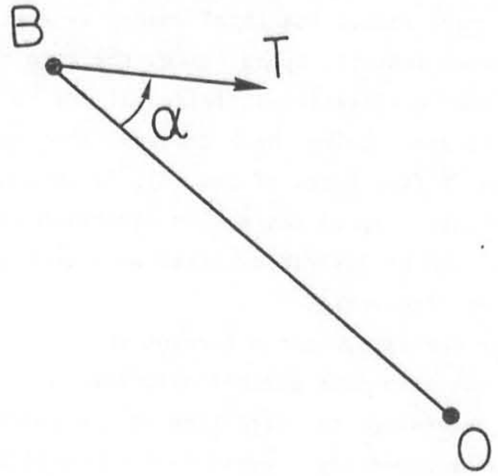

Figure 4 - A Superluminal object T is emitted by the source B. Point O is the observer's position. See the text.

tachyons T_1 and T_2; or by the emission from a central source B of: (ii) a tachyon T, or (iii) of a couple of tachyons T_1 and T_2 (in the latter case, T_1 and T_2 can for simplicity's sake be considered as emitted in opposite directions with the same speed). On this respect, it is interesting that Ne'eman[38] regarded quasars — or at least their dense cores — as possible white holes, i.e. as possible "lagging cores" of the original expansion.

For simplicity, let us confine ourselves to a flat stationary universe.

6.A.- The Case (ii)

In the case (ii), be 0 the observer and α the angle between BO and the motion-direction of T. Neglecting for the moment the gravitational interactions, the observed apparent relative speed between T and B will of course be (see Fig. 4):

$$W = \frac{V \sin\alpha}{1 - V\cos\alpha} . \qquad [V > 1] \tag{25}$$

Let us assume $V > 0$: then, $W > 0$ will mean recession of T from B, but $W < 0$ will mean approach. Owing to the cylindrical symmetric of our problem w.r.t. BO, let us confine ourselves to values $0 < \alpha < 180^o$. Let us mention once more that $W \to \infty$ when $\cos\alpha \to 1/V$ ("optic-boom" situation). If the emission angle of T from B w.r.t. BO has the value $\alpha = \alpha_b$, with $\cos\alpha_b = 1/V$ ($0 < \alpha_b < 90^o$; $b \equiv$ "boom"), tachyon T appears in the optic--boom phase; but the recession speed of T from B would be too high in this case, as we saw in the previous Section.

Incidentally, to apply the results got in Sect. 5 to the Superluminal object T (or T_1 and T_2 in the other cases (i), (iii)), one has to take account of the fact that the present tachyons are born at a finite time, i.e. do not exit before their emission from B. It is then immediate to deduce that we shall observe: (a) for $\alpha > \alpha_b$, i.e. for $\alpha_b < \alpha < 180^o$, the object T to recede from B; but (b) for $a < \alpha < \alpha_b$, the object T to approach B. More precisely, we shall see T receding from B with speed $W > 2$ when

$$\begin{cases} \dfrac{V - \sqrt{5V^2 - 4}}{2(V+1)} < \mathrm{tg}\,\dfrac{\alpha}{2} < \dfrac{V + \sqrt{5V^2 - 4}}{2(V+1)} \; ; \\[2ex] \arccos \dfrac{1}{V} < \alpha < 180^o \; . \end{cases} \tag{26}$$

It should be noticed that eq.(25) can yield values $W > 2$ whenever $V > 2/\sqrt{5}$: In particular, therefore, for all possible values $V > 1$ of V. Due to eqs. (26), the "emission-direction" α of T must be however contained inside a certain suitable solid angle: $\alpha_1 < \alpha < \alpha_2$; such a solid angle always including, of course, the optic-boom direction α_b. For instance, for $V \to 1$ we get $0 \leq \mathrm{tg}\,\frac{\alpha}{2} < \frac{1}{2}$; $\alpha \geq \alpha_b = 0$, wherefrom:

$$0 \leq \alpha < 53.13^o \quad ; \qquad [V \to 1] \tag{27}$$

in such a case, we shall never observer T approaching B. On the contrary, for $V \to \infty$ we get $\frac{1}{2}(1-\sqrt{5}) < \mathrm{tg}\,\frac{\alpha}{2} < \frac{1}{2}(1+\sqrt{5})$; $\alpha_b = 90^\circ \leq \alpha < 180^\circ$, wherefrom $-63.44^\circ < \alpha < 116.57^\circ$; $\alpha \geq 90^\circ$, that is to say: $90^\circ \leq \alpha < 116.57^\circ$. If we add the requirement, e.g., $W < 50$, in order that $2 < W < 50$, we have to exclude in eq. (27) — for $V \to 1$ — only the tiny angle $0 < \alpha < 2.29^\circ$, so that in conclusion

$$2.29^\circ < \alpha < 53.13^\circ \,. \qquad [V \to 1]$$

The same requirement $2 < W < 50$ will not affect — on the contrary — the above result $90^\circ \leq \alpha < 116.57^\circ$ for the case $V \to \infty$.

Similar calculations were performed by Finkelstein et al.(13).

The present case (ii) suffers some dificulties. First, for $\alpha > \alpha_2$ (for instance, for $53 \lesssim \alpha < 180^\circ$ in the case $V \to 1$) we should observe recession-speeds with $1 < W < 2$, which is not supported by the data; but this can be understood in terms of the Doppler--shift selective effects (see Sect. 4.C; and Blandford et al.(12)). Second, for $\alpha < \alpha_b$ one should observe also Superluminal approaches; only for $V \simeq 1$ ($V \gtrsim 1$) it is $\alpha_b \simeq 0$ and therefore such Superluminal approaches are not predicted.

In conclusion, this model (ii) appears acceptable only if the emission mechanism of T from B is such that T has very large kinetic energy, i.e. speed $V \gtrsim 1$.

6.B.- The Cases (i) and (iii)

Let us pass now to analyse the cases (i) and (iii), still assuming for simplicity T_1 and T_2 to be emitted with the same speed V in opposite directions. Be α again in the range $[0, 180^\circ]$. In these cases, one would observe faster - than - light recessions for $\alpha > \alpha_b$. When $\alpha < \alpha_b$, on the contrary, we would observe a unique tachyon $T \equiv T_1$ reaching the position B, bypassing it, and continuing its motion (as $T \equiv T_2$) beyond B with the same velocity but with a new, different Doppler-shift.

One can perform calculations analogous to the ones in Sect. 6.A; see also Finkelstein et al.(13).

In case (i), in conclusion, we would never observe Superluminal approaches. For $\alpha < \alpha_b$ we would always see only one body at a time (even if $T \equiv T_2$ might result as a feeble radiosource, owing to the red-shift effect): the motion of T would produce a variability in the quasar. For $\alpha > \alpha_b$, as already mentioned, we would see a Superluminal expansion; again, let us recall that the cases with $1 < W < 2$ (expected for large angles α only) could be hidden by the Doppler effect.

Case (iii) is not very different from the case (ii). It becomes "statistically" acceptable only if, for some astrophysical reasons, the emitted tachyonic bodies T_1 and T_2 carry very high kinetic energy ($V \gtrsim 1$).

7.- ARE "SUPERLUMINAL" EXPANSIONS SUPERLUMINAL?

If the emitted tachyonic bodies T (or T_1 and T_2) carry away a lot of kinetic energy ($V \gtrsim 1$), all the models (i), (ii), (iii) may be acceptable from the probabilistic point of view.

Contrariwise, only the model (i) — and the model (iii), if B becomes a weak radiosource after the emission of T_1, T_2 — remain statistically probable, provided that one considers that the Doppler effect can hide the objects emitted at large angles (say, e. g., between 60^o and 180^o). On this point, therefore, we do not agree with the conclusions in Finkelstein et al.[13].

In conclusion, the models implying real Superluminal motions investigated in Sect.6 seem to be the most probable for explaining the apparent "superluminal expansions"; especially when taking account of the gravitational interactions between B and T, or T_1 and T_2 (or among T_1, T_2, B).

Actually, if we take the gravitational attraction between B and T (Sect.4.B) into account — for simplicity, let us confine ourselves to the case (ii) —, we can easily explain the accelerations probably observed at least for 3C345 and maybe for 3C273 (Shenglin and Yongzhen[39]).

Some calculations in this direction have been recently performed by Shenglin et. al.[33] and Cao[40]. But those authors did not compare correctly their evaluations with the data, since they overlooked that — because of the finite value of the light-speed — the images' apparent velocities do not coincide with the sources' real velocities. The values W_o calculated by those authors, therefore, have to be corrected by passing to the values $W = W_o \sin\alpha/(1 - \cos\alpha)$; only the values of W are to be compared with the observation data.

All the calculations, moreover, ought to be corrected for the universe expansion. However, let us recall (Sect. 5) that in the homogeneous isotropic cosmologies — "conformal" expansions —, the angular expansion rates are not expected to be modified by the expansion, at least in the ordinary observational conditions. While the corrections due to the universe curvature would be appreciable only for very distant objects.

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