# JBIS

Journal of the British Interplanetary Society

VOL. 52 No. 9/10 SEPTEMBER/OCTOBER 1999


CONTENTS



* * *


PUBLISHED AS TWO COMBINED MONTHLY ISSUES

ISSN 0007-09-4X

**PROBLEMS AND PERSPECTIVES IN INTERSTELLAR EXPLORATION**

# PROBLEMS AND PERSPECTIVES IN INTERSTELLAR EXPLORATION

G. Vulpetti
Telespazio SpA, Via Tiburtina 965, 00156 Rome – ITALY
E-Mail: giovanni_vulpetti@telespazio.it

**Abstract** - This paper is the continuation of an effort started by a previous paper [1], that included major aspects issued up to September 1998 relevant to the feasibility of the problem known as The Interstellar Flight (**TIF**) - as far as present human knowledge with reasonable extrapolations is concerned. The present work represents (1) a significant revision also including comments and questions from many distinguished investigators on different areas/fields of space flight & exploration, (2) a focus on new meaningful concepts that are reported and discussed.

## 1. INTRODUCTION

The Nineties represent the fifth decade in which many space researchers throughout the world have been investigating about the feasibility or unfeasibility of TIF. Some of the past and present investigators have been affected to some extent by science fiction literature, including famous movies and novels, in proposing new concepts for travelling through the vast distances between stars. In this paper, we shall follow an approach with the following characteristics:

1. Only the present state of scientific knowledge and its potential development will be used as prime considerations; that include reasonable extrapolations of technology and some envisaged new lines for research. Science fiction, technology-fiction and any relationship to the so-called unidentified flying object are completely excluded from our line of reasoning
2. A multidisciplinary policy will be followed not only because a flight machine to the stars is quite a complex system, but also (and mainly) since TIF should involve everything we know and will know, in practice.
3. Many of the considerations in this paper are meant to contribute to fostering advanced research fields that are important in themselves, not only for spaceflight, though this one is given here a major emphasis and is potentially able to cast further light to the conventionally-conceived fields of basic research.

## 2. HISTORICAL BLOCKS

The past four decades saw an intense investigation on the possibility of interstellar flight (re-defined in section 5). We have summarised it in the following decade-based structure:

<u>THE FIFTIES</u>: Special Relativity was applied to very preliminary concepts of rockets using nuclear or antimatter energy to approach the speed of light for exploiting the Lorentz contraction in travelling very far from the solar system. Rockets were given very high acceleration just as a parameter assumed generally constant during thrusting. Meaningful results about optimal mass ratio were obtained. Some investigators pictured very complex devices to deal with nuclear and annihilation power on board. A meaningful example was the Project Orion that spanned over Sixties too.

<u>THE SIXTIES</u>: researchers gave more attention to the propulsion system; rocket concepts for very deep space exploration were endowed with parallel and series stages to be able to achieve very

high terminal speeds. Parametric mission studies were the majority. Space ramjet was also considered for interstellar flight, but only from a dynamical viewpoint.

THE SEVENTIES: a strong and systematic investigation in USA and Europe delivered detailed spaceship models, including power and propulsion systems, propellant and payload systems, and telecommunication & navigation systems. Smart missions with relativistic trajectories to nearby stars were conceived and optimised by the most advanced methods of control theory. Nuclear fission and fusion dominated the propulsion stage. Technology and mission analysis were considerably stressed to try to find a *reasonable* starship. The celebrated Project Daedalus by The British Interplanetary Society represented a big joint effort that both fostered new investigation areas and highlighted the need for studying TIF from multidisciplinary viewpoints.

THE EIGHTIES: many non-rocket spacecraft and propulsion methods were studied. A rocket starship turned out to be too much massive, even if powered by fission and/or fusion. The interstellar fusion-based ramjet resulted in an unfeasible device. Thus, laser-driven and microwave-driven vehicle concepts appeared as promising designs to overcome the rocket drawbacks. Space sailing received a particular attention for one-way spaceships, small or large. Rocket, however, had its return match because in this decade there was an enormous investigation about matter-antimatter annihilation for potential space use. Very clever concepts for exploiting the basic properties of the annihilation reaction were set up in States and Europe. Although roughly, an envisaged rocket-based starship could exhibit two of the fundamental properties for fast and long-range missions: high specific energy and high specific power. However, still today the so-called antiproton and positron technologies are too far from producing the big amounts of antimatter to be stored onboard an interstellar ship.

In those decades, most investigators essentially searched for complex systems, trajectories and missions to star systems by using known physics and extrapolated technology smartly. New concepts of spaceship, ways to exploring and methods for getting information at the various targets were analysed deeply. It was realised that intelligent life plays an increasing role in space exploration from many different viewpoints ranging from biology to philosophy, from ethics to sociology.

In the Eighties people from the space community proposed *precursor* interstellar missions. Besides the high cost of an interstellar mission, many investigators realised that it is meaningless to try a jump by many orders of magnitude if one is not able to accomplish a much smaller scale mission. Instead, speculative investigation could continue *in parallel*. Such an approach is still in progress.

THE NINETIES: during their first half, some funding policy changes and a certain disenchantment in the public opinion for space flight slowed down the general research towards TIF, although a number of *valuable collections* of ideas proceeded in certain national institutions for research and technology. The new general approach to space has been considering low-cost high-information-return projects. In July 1997, NASA re-launched the initiative to explore the feasibility and possibly building a roadmap to an interstellar probing mission. There are many targets of high scientific importance in the heliosphere and beyond, in the range of hundreds or thousands of Astronomical Units (AU). Thus, one of the medium term challenges is to build a practical propulsion system that allows us to send *fast* probes beyond the planetary range. For instance, the Kuiper belt, the heliopause, the unperturbed interstellar medium and the solar gravitational lens represent high-interest targets.

Many investigators identified three important items: (a) current knowledge of the physical laws (CKPL) does not seem sufficient to implement TIF *conceptually*; (b) even though CKPL were to give some hope for a few light-year flight lasting a human-job span or 3-4 decades (e.g. by nuclear fusion and antimatter propulsion), its cost for a full development may be quite outside the current capabilities (and wills) of one space agency; (c) multidisciplinary areas have to progress simultaneously in order to understand systems, as the natural ones as the advanced artifacts, for space exploration. Consequently, an active research is in progress with the unhidden hope to find out some breakthrough in Science and/or Technology. Perhaps the current years may be considered – in a historical perspective – as a sort of resetting from a number of viewpoints: scientific, technological, economical and managerial. In such a general framework, speculative research has been continuing. Thus, in this second half-decade there is an international revival about TIF and its implications, but with a significant change with respect to the general trend of the past decades. A number of researchers from basic physics in USA, Japan and Europe apply advanced concepts and methods of Relativity and Quantum Field Theory (QFT) to investigate new ways for accomplishing space travel and/or re-evaluate old ideas. In addition, Nano-Technology and Robotics are going to provide new insights and perspectives.

References [2,3] are recommended for deepening the above historical vision through the original contributions to essential concepts of TIF.

## 3. MAY BASIC PHYSICS BE DRIVEN BY ASTRONAUTICS?

Section 3 of [1] received attention by many readers. Here, the author would like to first summarise it (sect. 3.1) and then to reply to the most valuable comments (sect. 3.2).

Normally, basic physics makes advances and big jumps whenever a number of critical experiments show aspects of nature not explainable by and/or in contrast to the current accepted models. Crucial data come from experiments (usually performed on ground) or from astronomical observations. So far, Astronautics has been considered a complex set of technological disciplines, each driven by basic physics, to allow humankind to accomplish space exploration. Even astrodynamics is related to technology. Space propulsion is one of the smartest applications of basic knowledge on fundamental interactions, energy, entropy, materials and so on. In addition, progresses on electronics and robotics, micro technology, sensors, software engineering and so forth reinforce the general idea that spaceflight is only an application, though wonderful, of basic knowledge.

### 3.1 CONSCIOUS-LIFE EXPANSION PRINCIPLE: THE STRONG FORM

It is certainly true that Astronautics derives from plenty of human knowledge; nevertheless, one can speculate whether spaceflight may (*a*) be a source of basic knowledge, (*b*) intrinsically be a fundamental discipline. Point-*a* has been evolving whenever an important finding or discovery is accomplished by means of a space mission. Point-*b* is debatable, but represents one of the guiding paths of this paper. To be clearer, we make the following hypothesis:

*An intelligent and self-aware species evolving on a planet is able to set about space exploration eventually. This enterprise is neither an option nor a casual event in the species' history, but it represents an obligatory way to diffusion of high-level life outside the normal place where it developed.*

We call such a hypothesis the Conscious-Life Expansion Principle (CLEP). In the above statement, by life development we mean what is necessary to allow a primitive Conscious Intelligent Life (CIL) to achieve a level of knowledge such that it can overcome the gravitational potential well of its planet. At this point of its history, this living kind should have a number of options, in principle. The *strong* CLEP states simply that, apart from a brief interval of time necessary to get further knowledge, this species recognises *inevitably* that there is no other alternative to the exploration of Space. This principle may be also viewed to some extent as a generalisation of the "grand strategy for the species" described in [4], where manned interstellar flights and the search for extraterrestrial intelligence can proceed in parallel without conflicts. In [4], starting from a biological behaviour (whereupon a species responds to inputs coming from the environment), it is stated substantially that the activities of the human species have to be stretched to include Space. CLEP does not need any environmental push on a CIL for its application; though its road to a general expansion could be shorten by environmental pressures. This is not a subtle difference.

Conceiving Astronautics in a way compliant with CLEP (or some future equivalent formulation) entails a universal aim (accomplishable through and for Life), even because CLEP would apply to every eventual CIL in any galaxy hosting high-level life. According to many evolutionists of the 20$^{th}$ century, intelligent life is very improbable on any other planet of the visible universe (chap. 3 of [5]).  Even in this extreme (unproven!) case, CLEP would remain valid simply because it pertains to *this* life on *this* planet: it is an established feature of life, here, to expand everywhere.

Someone may be induced to confuse this CLEP with the Weak Anthropic Principle (WAP) [5]. In reality, WAP does not imply that observers of the Universe shall explore space by sophisticated artifacts different from ground telescopes (of various types), or send (self-replicating) robots throughout a galaxy, or colonise stellar systems by slow world ships. A CIL that could decide to observe the external universe by remaining on its planet (where laboratory experiments are performed) would be compliant with the WAP, but certainly not with the CLEP. This difference is simply immense.

Our astronautics perhaps moved its first significant steps into a CLEP context when even physicists from basic research began by considering spacecraft in their *gedanken* experiments. Nowadays, after long-range spaceprobes and space-telescope generations, the studies on permanent lunar bases and on the human exploration of Mars, there is no doubt that at least a partial realisation of the CLEP has taken place or is in a probable further progress. However, what about the interstellar flight? If the *strong* CLEP is true, then two corollaries follow:

I. Laws for Universe have to allow any conscious life to accomplish interstellar flight

II. This capability has to hold in any galaxy where conscious life has appeared, regardless of the number of inhabited stellar systems at some cosmic time.

According to the latest inflationary-universe theory [6], the whole universe might consist of a 'sea of self-reproducing domains' (or inflationary bubbles), each of which may host its own type of life and natural laws.  Therefore, one may argue that CLEP does not hold in this enlarged universe. However, it is sufficient that it holds in any universal region where life is able to achieve the stage of consciousness and will for investigating, learning and designing. Although such lives will never contact each other - for the simple reason that one would not be allowed in the other's bubble - what matters is that at least one CIL obeys the expansion principle in its bubble. If one of the *properties* I and II does <u>not</u> exist, <u>no</u> conscious life (regardless of its peculiar capability of processing information and knowledge) could explore Space beyond, perhaps, the stellar 'sphere' of its central sun (that is, the heliosphere for the humankind).

At first glance, one might identify CLEP with the Final Anthropic Principle (FAP), extensively discussed in [5]. FAP and CLEP share that intelligent life *can* spread out from the limited region of its birth. *Strong* CLEP, in addition, entails that CIL *must* expand into space. Again, such a difference is very big. Furthermore, there is no infinite-type condition to be satisfied for *strong* CLEP may hold. Also, event horizons can exist in a universe where intelligent life is CLEP-compliant. The most important difference between FAP and CLEP is the following: FAP has been often tied to intelligent species the members of which are viewed essentially as instances of sophisticated computer programs. CLEP should be applied to a CIL conceived with both information-processing capability and many important consciousness-related manifestations other than computability [7]. These latter features are dominant too. Contrarily to FAP, CLEP has not been yet explored in its details; one may not exclude that both principles may entail some common consequence, perhaps with regard to physical eschatology.

### 3.2 Conscious-Life Expansion Principle: The Weak Form

Now, let us discuss some of the most significant comments got on CLEP. Allen Tough suggested softening the strong claim that a CIL has no alternatives to its expanding into Space. If there are many conscious lives in galaxies, "a few civilisations may have very good reasons for not exploring space", Tough adds[1]. In a previous paper [8, sect. 4], Tough highlights some basic motivations of a civilisation for sending interstellar probes, whereas in [8, sect. 5] he discusses the alternatives, radio or probes, for exploring and knowing. One may think of an advanced civilisation using more than one method for communicating, but with the free choice not to moving itself physically into other star systems. Hansson[2] starts his considerations from the above corollary-I. He comments: "... we should be open for the possibility that the Universe we observe is the result of a natural process as astronomers do, but a mixture of such processes and conscious engineering. In fact it is possible to solve for the so-called dark-matter problem by such an assumption!". Although such a consequence may appear too strong, however there would be some likelihood that an obliged way to expansion may lead, in the very long term, to some universal consequence that can be conflicting with some observations (even though the observable Universe now might be not sufficiently old to allow CILs to affect or dominate its evolution). The following *weak* form of CLEP is suggested:

*Universal Laws are life-oriented. As a very special case, they allow Conscious Life to accomplish interstellar flight. Each civilisation could be strongly motivated to either exploring Universe without leaving its solar birth system or expanding itself to other star systems.*

Let us examine a few essential features of this CLEP statement. *First*, it re-highlights the role of conscious life in the universe and a high universal aim is implicit as in the strong form. Life is not considered an improbable event throughout galaxies, but an unavoidable consequence of the universal laws. In the contrary case, there would be no need for conceiving of universal laws admitting interstellar flight or for giving the interstellar expansion a huge importance and relevance in the universe history. *Second*, a civilisation shall carry out its free will (presumably diluted over a particular period) whether to either limit its space evolution to its solar system or steer itself to a long-term expansion

[1] A. Tough, private communication, Oct. 1998

[2] A. Hansson, private communication, Dec. 1998

throughout stars. *Third*, many civilisations may exhibit some common well-substantiated motivation ultimately pushing them to contact each other someway. *Fourth*, the differences (as outlined above) between WAP & FAP and weak CLEP persist.

Moreover, it is improbable that galaxy-oriented conscious lives may alter the evolution of the universe as a whole, but only locally: CIL cannot change the basic laws. Therefore, the presence of any such civilisation should not be detected by another civilisation, developing only in its solar system, by astronomical observations.

A final consideration: one might object that, since CLEP regards a system of the utmost complexity (namely, any CIL), no long-term statement would seem possible. This is true in general. However, a very complex system produces stability and this is just what CLEP implicitly requires. Many paths to or about a stability region are possible: the *strong* CLEP does not claim to predict which particular way shall lead to the expansion by CIL into space. Such an expansion is not a sequence of particular (maybe unpredictable) events. Rather, it regards a general time-persistent feature (like a physical law), although knowledge may proceed through different modes in various historical periods.

In this line of thought, also, we are about to discuss different (and potential) types of interstellar flight.

## 4. WHY INTERSTELLAR FLIGHT

The first remark on why a CIL should expand into Space consists of recognising that a CLEP-like statement contains sufficient reasons to push it to go. Nevertheless, if one admits that more than one civilisation may exist somewhere in the space-time (regardless of interstellar communication), then it is possible that some specific reasons to exploration & expansion (E&E) are different from a civilisation to another one. Concerning the CIL on Earth, we may arrange a list of major items as follows:

1. A Virtually Unlimited Extension of Scientific Knowledge
2. Utilisation of Resources not Restricted to a Planet
3. Overcoming Limits to Growth
4. Human-Life Expansion
5. Higher-Quality Life
6. Search & Communication with Extraterrestrial Intelligent Life
7. Physics and Metaphysics Connection

Obviously, each point could encompass many other important issues, as dealt with extensively in the literature [2,3]. The above listing does not reflect any rank; it is subjective at both individual and national levels. Moreover, it could depend on some global context in the specific period when some international community wants to foster, plan and realise a big space project. Boundary of any motivation is somewhat fuzzy and overlaps the other ones. Many of the above items are not new. Often, in the past centuries or millennia, people were pushed by one or more of the above reasons for bringing forth enterprises that have affected a significant piece of the human history. For instance, (local) reasons similar to points 2 and 5 induced ancient populations to migrate passing through wide lands and oceans. Those expansions lasted and employed several human generations and were not risk-free. It sounds realistic that all above points may hold and enlarge their validity in the next centuries. Thus, in addition to a general principle like CLEP, Humankind has a set of robust reasons (SRR) to fully justify its big efforts to TIF.

## 5. Definition of Interstellar Flight

What does going to the stars mean? What does the related expansion into space (and time) involve? The former point is less difficult to describe. A CIL begins its evolution on some appropriate planet. Eventually, it reaches a stage where something like CLEP and specific SRR induces that living species to progressively send artifacts and representatives outside its planet. It starts by exploring the 3D space and using the third dimension *actively*. Before such jump, information could be only received from the external space (via photons and particles) and there was no way to explore something far *in situ*. Subsequently, instruments for knowledge can be delivered far; in addition, instrumentation concepts get enormous benefit from spaceflight technologies. The original CIL learns that it can live in suitable non-planetary *habitats* and utilise some of the resources (in the most general meaning) of its planetary system.

Interstellar flight may begin when spaceprobes are sent for exploring the interstellar medium well beyond the region of interaction of the stellar wind with the interstellar wind (in the reference frame of the considered star). For the solar system, this is the heliopause and the related bow shock. The heliopause and the bow shock should have a nose and a gradually farther tail, namely, its distance depends on the radial direction to escape from the solar system. It is expected that the heliopause (or the star-pause, more generally) shrinks or swells according to the solar-activity cycle. A definition may also be given in terms of a mission to the stellar gravitational lens (SGL); however, only the lower bound (i.e. 550 AU for Sun) may be employed. It is expected that incoming photons, with an impact parameter of a fraction of the stellar radius from the photosphere, be strongly refracted in passing through the plasma of the stellar corona, thus moving the lowest focal distance further out. The new-focus distance increases with decreasing photon energy [9]. In addition, the non-spherical corona symmetry may change the ideal spherical SGL shape normally considered. Analogous definition difficulties are found if the planetary range or the focal distances for gravitational waves are used instead. In the literature, missions like those ones (and other to non-stellar objects such as the Oort cloud) are usually considered as *precursors* to true interstellar missions. One could take such a concept if the cruise speed of precursory spacecraft overcomes a certain mission-class-dependent lower limit. This is due to the need to keep mission & vehicle cost and time at reasonably low levels. For example, a total project time (that is design time + flight time + payload mission time) amounting to not more than a half of the normal human job-time would be high desirable. Once the precursor missions are defined and accomplished, TIF may be well regarded as the physical attaining of stars or stellar systems. Such an achievement entails either a fly-by to or the insertion into a closed orbit about the target star, or, more deeply, the probe capture by the gravitational well of some planet. This is a minimum set of requirements. Landing on a planet and/or escaping the stellar system represent(s) a further need as missions evolve. Note that the specific payload mission is not deemed as a sort of threshold for flight feasibility. (Nevertheless, payload and telecommunication systems are required to work at destination, of course). This is the **space** part of the interstellar-flight definition.

Suppose to build a probe launched with a small positive (potential + kinetic) energy with respect to the solar system. The vehicle will cruise with a speed of 100 AU/yr (about a factor 30 with respect to the current humankind standards), so reaching the first star after 27 centuries (supposed that the essential systems still work!). May such a mission be considered a true interstellar one? On the other side, many concepts of world-ship entail inter-star journeys measurable in thousands of years. This introduces us to the **time** part of the interstellar-flight definition.

The space component of TIF is related to the distance between stars, whereas the time component is tightened to the characteristic time scales of the travellers. In the sole case we know, we have a number of reference time scales: (a) the averaged human lifetime, (b) the (estimated) time of the human history, (c) some multiple of a time division, in our calendar, considered particularly meaningful. All these intervals are either changing with time or somehow arbitrary. Nevertheless, since an interstellar craft is a special type of transportation, travel times are normally referred to (a). This chiefly affects the interstellar-flight type through propulsion. Engines could be designed for either non-relativistic or relativistic speed trajectories; thus, the time part of an interstellar flight could require a strong "time detachment" at destination between the travelers and their contemporaries at departure. This is a probable new feature of such type of exploration with respect to any other conceived or realised previously. (Section 7.1 expands such considerations).

By using the concept of world-line from Special Relativity (SR), one can combine what just said together with the considerations of section 4 and then issue the following definition:

*The Interstellar Flight is a multidisciplinary multipurpose high-knowledge global enterprise that accomplishes by space-time world-lines the endpoints of which have enormous space separation and, possibly, are very different in length (the proper time).*

Then, the next step is to investigate which ways we may follow for realising such a concept.

## 6. Ways to Expansion

We follow the principle of *progressive* technological capabilities and exploration complexity to describe different ways to realise the human expansion to the physical space much beyond the solar system. It is obvious that these ways start from our levels of knowledge and technology capability. This is not a limitation for a general view of spaceflight; this means that the number of ways to exploration could be, for another civilisation, lower or higher than our ways.

In the past decades many concepts more or less related to TIF appeared in the specialised literature. Here, we exclude ideas regarding what the humankind may begin after thousands or more of years from now; scenarios for TIF - in the current period or in a reasonably foreseeable future - can be grouped in the classes here below. Comments on each specific class are added in the same subsection.

### 6.1 One-Way Fast Flights and Progressive Exploration, Type-1

Humankind achieves both the physical knowledge and technological ability sufficient to build space probes capable to reach the nearest stars in less than the human lifetime. One-way missions can be designed to start a systematic exploration by robot to within, say, a 10-ly sphere centred on the Sun. The cruise speed should then be as high as 0.08 - 0.12 c. The current level of physics seems adequate, but the areas related to thermonuclear fusion, antimatter production & handling and very powerful laser systems in orbit are far to be realisable. Advances in nanotechnology, quantum computing and communication shall be necessary for making an efficient complete starprobe. By a multiple-target single-launch strategy [10], a 10-ly exploration may be accomplished in a couple of centuries. However, humankind should endow itself with a cultural background for funding such missions and waiting for its results, since the initial designers and scientists may be passed away when the first target information reaches Earth. There is another drawback. While such a vehicle proceeds to nearby star(s), probably humankind's physical knowledge could exhibit some leap(s) inducing breakthrough(s) in space propulsion technology. Consequently, a much faster starcraft may be conceived, made and launched in a time much shorter than the flight time of the previous starprobe. The new starprobe could reach the same target well in advance of the old one. In any case, the previous programme becomes obsolete from this point of view. From scientific and technological standpoints, there would be no strange situation because the latest program would act as a natural continuation or generation of the already-started program. The true problem is the cost of the "obsolete" project. On this basis, it is hard to convince financiers to spend an enormous amount of money, probably both public and private, for decades. The strategy "waiting for better times" may prevail even because the scientific return could not appear to them as strong as it could do to scientists. In addition, when a big expensive scientific programme is proposed, there are likely other scientific communities disagreeing on this plan requiring so a large fraction of the national budgets devoted to research and development. Thus, such attitudes may be a further cause of program rejection. Such drawbacks are not sure events, but they are expected to happen and, therefore, may in advance influence this interstellar flight strategy.

### 6.2 ONE-WAY FAST FLIGHTS AND PROGRESSIVE EXPLORATION, TYPE-2

Basic knowledge and technology evolution could eventually allow us to perform missions to nearby stellar systems in times considerably less than the human lifetime. The starprobe cruise speed should be higher than 0.5 c. By such a capability, a detailed exploration of many nearby systems can be accomplished in some decades. It is then possible to design missions the scientific return of which can be got within a normal job time. This stage of space exploration probably involves a large-scale utilisation of the solar system. The one-way character of Type-2 consists of the following major items:

1. Exploration is based on one star-vehicle per one star-system. Similarly to Type-1, this does not exclude using one launch from the solar system to deliver k starprobes to as many stellar systems, with $k > 1$; even $k=2$ would result in a considerable saving of flight time. Once a starprobe achieves its target star, it is unable to go to another star. In particular, it will not go back to the solar system. This entails that any information got by the probe on its target can be known to the humankind only via an interstellar-range communication.

2. A starprobe is fully automated, can decelerate and park on some orbit about a planet of the target star. Smaller expendable probes can be then delivered onto the planetary surface. No sample return to the solar system is allowed.

3. Some of the propulsion system concepts envisaged in the Eighties and Nineties – antimatter propulsion, ultra-high power laser/microwave propulsion, fusion propulsion and magnetic sailing (for deceleration) – should be realised at sufficiently low cost to allow a systematic exploration of most of the nearby stellar systems. This could require a technology breakthrough from some meaningful evolution (not revolution) of physics.

4. A starprobe of this class has to be equipped with communication and computer systems with performance orders of magnitude higher than the present ones. However, this is not enough. With regard to the computer, a distributed self-repairing system is highly desirable or, perhaps, mandatory for a successful flight. Because targets are located at some light-years, there would be no need for searching for a new physics. Instead, unconventional compression techniques, very long range signal coherence, ultra-high pointing accuracy and precision, ultra-dense storage devices, ultra-high rate of information processing and

the capability to in-flight update scenarios are some of the challenges of starprobe technology. Progresses in the emerging Quantum Communication and Quantum Computing [11] together with Nanotechnology [12,13] advances appear as excellent candidates for translating a starprobe into reality. Such advancements should be the natural evolution of what is under active investigation in the present years (section 8.3). By such theoretical and practical tools, interstellar navigation should not represent a showstopper.

### 6.3 Round-Way Fast Missions and Progressive Colonisation

The round-trip capability of this type of interstellar flight regards the human flight essentially. In principle, it should not be strictly possible to define a cruise speed (in the way we are used to), but rather a sort of *effective* speed accounting for all relativistic effects that will drive such rapid flights (section 7.1). The two conflicting schools of thought – one claiming that more and more complex robots are necessary and sufficient to perform Cosmos exploration and the other one deeming that the human presence at the targets is essential – should agree on this type of flight. The basic reasons are as follows:

i. A manned starship able to perform such flights should be composed essentially by computing systems and highly specialised robots emulating many human skills;

ii. CLEP excludes that robots act for human beings in every respect. Full space expansion is ultimately for conscious life, not for artifacts no matter how sophisticated they will be made by their human designers;

iii. At an unknown target, robots may carry out dangerous tasks more reliably and faster than the human counterparts;

iv. Human beings, as during the flight as at the target, shall contribute to the mission success because of their capabilities of thought, judgment, creativity and beauty to appreciate knowledge and the desire to augment it.

Points (i) and (iv) will allow a step-by-step colonisation of worlds both suitable for human life and uninhabited by another eventual conscious life. Main psychological problems, well in advance with respect to the scientific and technological bases for TIF, should be overcome by people devoted to beginning a new life on a planet different from their mother-planet. This is important not only for them, but also for their descendants living there. These last ones should not receive any suffering syndrome related to staying there and not on the distant planet of origin. Similarly to the experience of emigrants or pilgrims in the past centuries, people colonising new worlds may feel themselves appointed to create a new society, ideally deprived of many detrimental items afflicting plenty of generations on Earth. Such a mission is quite compliant with CLEP. It could find many supporters, even in the present day and near– future. On the opposite side, other people could think that, in the very long term, a federation of planets (among which an incredible number of trade opportunities may be established) could represent a very strong spring to large-scale colonisation, especially on considering the exhaustion of the Earth resources.

### 6.4 Slow Expansion: Robotic Replication and Diffusion

The mentioned CLEP entails that a CIL should participate directly to any activity (grouped by class of objectives) outside its planet through a sequence of non-space-oriented cultures. If one agrees to extend the practical means CLEP should be implemented by, then the following strategy may either be realistic or become part of a larger many-piece scenario towards exploration and expansion for which the originating CIL plays the central role.

One can conceive a starprobe consisting of three main systems: ($\alpha$) an engine system (including any eventual distinct power system and propellant), ($\beta$) a communication system, ($\gamma$) a general self-reproducing constructor. The third system is a sophisticated fully automated machine able to make any type of item necessary for replicating the original starprobe, including itself. This assumes that humankind will manage to realise some emulation – from the construction activity viewpoint – of its prototype individual. This is conceptually possible and represents the kernel of the $\gamma$-system design. This system can analyse and process the materials it finds on the selected planet of the target star. The outcome of such a process is at least one exact copy of the starprobe arriving at that planet. Such new starprobes are then launched towards other stellar systems, reasonably close to the current one. Thus, such travelling self-replicating systems render many resources of the various stars available to the CIL that designed those robots. What just mentioned is the essential scenario. Many variations may be thought, but all they share a certain number of basic things and are subject to some critical issues. It is worth mentioning both groups explicitly.

1. Replication should take place only on those planets where landing and quiet robot operations are possible. Jupiter-like planets seem to be completely excluded. Some stellar systems – to be analysed only in the latest approaching phase, presumably – may have giant planets alone instead of a rich planetary spectrum like the solar system. In such cases, the starprobe should go to another stellar system for replicating itself, thus rendering the problem to transport a probe to a star much more complicated.
2. The above-mentioned availability of the new planetary resources to the probe designers is strongly limited, in practice. For instance, if new living species and/or new materials and/or abundant resources are found on a certain planet, then some actions could require a human decision. This may come only after a long time, otherwise should be the robot to make a choice.
3. A replicating machine with the general function to construct any device necessary to build a copy of the landed vehicle, no matter which ambient may actually find, should be to controlled by a very complicated code. There is no exhaustive or conclusive test showing that a complex code is error-free. Even the human cell has a non-zero probability to be replicated imperfectly.
4. It is hard to know a-priori how and how much even a little error, somewhere in the replicating process, propagates into the subsequent replication at the different stages of starprobe diffusion. That may be viewed also in the light of a sort of ecology at galactic scale.
5. The control code, validated on a number of stellar systems, may be not fully appropriate for other systems, essentially because a high number of things are unknown before the exploration starts or goes on.
6. To overcome points 4-5, the replicating system should communicate back to earth its self-detected faults so that it may be re-programmed. This request to the descendants of the original programmers may happen plenty of time after the first starprobe launch. The transmission of the program *patches* may involve a very high number of bits across interstellar distances. In any case, no matter how many bits are transmitted, there is no

possibility to perform a full test on the new code version accurately, simply because that planet has resulted much different from Earth.

The above points are not to be viewed as show stoppers for this exploration strategy. Rather, they highlight some of the enormous difficulties to be overcome for its success. Perhaps, the human component to E&E implicit in the CLEP is definitive, even on an extended robot-assisted diffusion. Such a consideration brings us to the last type of the today-envisaged interstellar flights.

### 6.5 Slow Expansion by Large Human Expeditions: The World-Ships

The author has to warn that he is going to mention a moderate scenario in terms of onboard population, construction energy, launch time, travel time and so on. Extreme concepts of world-ship (WS) and their related very long-term diffusion times (i.e. hundreds of thousand or million years, or even more in certain cases) will be carefully avoided here for the simple reason that many pieces of such visions are today not realistically predictable. Some considerations supporting such policy are discussed.

Once the solar system resources become available to Humankind, it may be planned and decided to build large space vessels hosting many thousands (or more) of women and men that will live there and generate descendants that continue to work and evolve in space. Such ships should be endowed with propulsion systems capable to achieve cruise speeds in the range 0.005-0.02 c, depending on the mission class. Each ship (out of a fleet), sent to another selected stellar system, is a closed self-sufficient ecosystem resembling Earth, from its internal resources standpoint. It should allow its inhabitants to live normally during the very long journey to the stars. A target star is selected for having some Earth-sized or Jupiter-sized planet. This should be possible by space telescopes and interferometers of very high resolution in the Earth-Moon or solar system and, probably, by telescopes sent to the solar gravitational lens region. This point adds to the resource availability pre-requirement and then puts a lower limit on the WS launch time, presumably not before a couple of centuries from now. (One should note that in this period the humankind could build and send a probe to a nearby star, according to what said in 6.1-6.2).

The approaching phase to the chosen star should confirm whether the Earth-sized planet(s) are Earth-like type or not. In the *positive* case, the world-ship will decelerate down to some orbit about the chosen planet. People should then colonise the planet and refurbish/replenish the ship. This, of course, can insist on decades or, better, on some generations. In addition, many improvements could be made to the original ship. The arrival generation, to which the leaving ancestors transferred the mission to expand life on a new planet, probably wants to stay on the new planet. The new generations, if their culture does not change, could attend the next journey to another life-hosting stellar system. Thus, after a number of decades, the WS is ready to be propelled to another star. A proliferation strategy should be planned in order to carry out a true expansion. Thus, another (not necessarily contemporary) WS should be built and leave that stellar system. In the *negative* case (which may include some Jupiter-like planets), WS people has three options: (a) to decelerate and orbit about a Jupiter-like planet (since the spectroscopic analysis reveals that the planet may be a replenishment source for the WS), (b) to continue to run without decelerating and point to the next planetary system (of course, the original travel plans contained such a possibility), (c) to decelerate and orbit the central star in a near-circular orbit of appropriate semimajor axis (so becoming a new small component of the planetary system). Options a-b seem quite reasonable. Option-c may be useful, for instance, if the crew recognised that utilising a high rate of energy (by selecting the distance) from the current star for a certain time interval (in terms of human generations, probably) is safer than proceeding to another star directly.

Although a WS has to contain several machines with artificial intelligence, there is no need to design an utmost complicated program – and the related hardware – like that necessary in the full-autonomous multiple-replication scenario. Actually, a WS already contains an entity endowed with a code for efficient reproduction and construction capabilities, at least: the human being or, more exactly, the representative of an evolved CIL. There is a very big advantage: it is proved that a living species can evolve; in this case, the conscious entity living in a WS can keep on developing mentally and physically. In contrast, an analogous feature is not proven achievable by the scenario-4 actors.

What is the smallest world-ship capable to travel a prefixed distance from the solar system? The concept is quite complicated; nevertheless, let us try to infer something in a simple manner. In the spiral-arm region where the Sun is co-located, the density and the class distribution of stars is such that, inside a sphere of radius 70 ly, one can find about 100 stars from the G1-class to the G3-class. Such star classes are believed to host some Earth-sized planets (in addition to Jupiter-sized planets that should be more probable). Now, noting that the time elapsed from the first use of written information up to the first WS may amount to roughly 6000 years, the above question translates into what is the smallest world-ship (of a fleet) capable to colonise the planets inside 70 ly in 6000 yr. Seventy light-years represent more than one order of magnitude with respect to the mean star distance in our galactic region. Clearly, this depends on the quantitative meaning of the action "colonising a planet". This, in turn, is linked to how many people will continue the exploration in WS. Another issue consists of using a *dry* or *wet* world-ship. In the first case, no sea-like quantity & arrangement of water are present. A dry WS would have a mass much lower than a wet WS, also because the presence of an onboard ocean requires much larger power & propulsion systems, much more propellant and structural mass etc. Such masses add to the ocean mass. On the other side, a WS should model the Earth as closely as possible for rendering the life of generations a natural one (though in a body running a rectilinear path instead of a body following a quasi-periodic free-fall about a star). Scaling down considerably the very big WS analysed in [14], a suitable unit for a wet WS mass should be $10^8$ tonnes (100 MT), whereas that for the travelling people may be $10^4$. A 100-MT world-ship with a cruise speed of 0.02 c (compliant with the previous figures of distance and time) could then be thrusted by an antimatter-triggered fusion system. The initial acceleration would be about 0.0015 g for an acceleration time of 10 years. After a deceleration phase (most of which may be accomplished by non-rocket devices such as an electrostatic scoop or a magnetic sail) to the stellar system, this WS would deliver a habitat of 10-15 million tonnes and a high-performance reusable chemical rocket for going up from and down to the planetary surface. This rough example has the only purpose to show that things do not appear unreasonable in terms of physics, technology, resources and time not too much ahead of nowadays.

We have to mention some special issues out of many related to a WS: (**i**) population stability, (**ii**) social health, (**iii**) decision making. Such problems appear to be interrelated and crucial to the WS mission success (to be defined appropriately). Point-i would entail some degree of birth and death control. If one excludes the second one on both ethical and practical reasons, the birth control is the only viable. However, this results in a delicate task not only for the ethic itself, but also because a seemingly full liberty for procreation could induce a disastrous consequence on the ship resources. A way to "optimise" between different conflicting thrusts and requests might be that of designing a 10-thousand WS with 100 people as the initial crew. If the mean distance (24 ly) between stars of class G1-G3 is crossed at 0.02 c (by each WS) then WS population should be bound to 10,000 individuals for 12 centuries. That entails a (birth-death) annual rate of 0.38 percent. Point-ii is related to the so-called social attitudes or, more generally, to the social and cultural mentality. It is unrealistic that the intermediate WS generations replicate the same line of thought of the travel beginners. In particular, the arrival generations will exhibit many differences with respect to their ancestors. The role of such middle generations is expected to be critical. They shall guarantee the continuity of social and individual values, the advancement of knowledge, the transmission of the motivations that drove the design and construction of their world-ship. Point-iii regards a peculiar expression of the flying society. Taking for granted that, at a certain time, the community accepts general principles for living in a world-ship, how to perform a long-term control that avoids new attitudes/mentalities deemed objectively dangerous for the WS mission as a whole? Of course, this shall not be in contrast with the freedom of any individual on the WS. These points, though mentioned just a bit, however represent problems of so a significant complexity and importance that, probably, the most difficult tasks related to a WS will not come from physics and/or technology.

Finally, the two following considerations justify some of the basic features put inside the limited WS scenario above described.

(α) Some authors [5], starting from the WAP and the absence of evidence (which is different from evidence of absence) of extraterrestrial intelligent beings in the solar system, develop a reasoning with the conclusion that, very probably, ours is the only civilisation in the Galaxy. In such thinking, the principle of mediocrity and additional assumptions intervene; some of such hypotheses consist of simple statements since no other information is available today. Therefore, one evolved CIL can expand into the Galaxy. Models of galactic colonisation by one technological civilisation claim a time ranging from fifty million to a thousand million years for the complete expansion. Now, we want to neither discuss such models nor defend a presence of extraterrestrial life at any cost. More simply, if one of the fundamental assumptions - made "to prove" that extraterrestrial intelligence is very improbable – were wrong or merely relaxed, then the number of potential galactic civilisations would be greater than one. What this would entail is too long to be dealt with here even at a simplified level. In such a case, the concept of full galactic colonisation by one or more evolved civilisations would lose its original meaning, all the more if any truly intelligent CIL disagrees on the concepts of star war, galactic empire and so on.

(β) During its long journey through the interstellar space, WS people will not cease to evolve, much presumably, even because they keep on communicating with Earth at least during the first part of the travel. Then, it is reasonable that they could do or become aware of discoveries about new faster and more efficient ways of exploring space. Thus, once arrived at a suitable planet, travellers of a WS could organise their society oriented to a broader space exploration, namely, well beyond what would be accomplishable by the old refurbished and replenished WS. Some generations will live on the colonised planet and go on exploring space, for instance, by some strategy like that described in 6.3 . All this would represent an evolution of what requested by point-ii.

Points $\alpha$ and $\beta$, essentially, have induced us to conceiving of realistic 'short-range' WS as the "beginner" of an E&E. An extended expansion may evolve in an unpredictable (although reasonable) way. Thus, to begin an expansion programme by the construction of very large WS could be inefficient and useless from several viewpoints.

### 6.6 SLOW/FAST EXPANSION BY HUMAN HIBERNATION

In another paper of this JBIS special issue, hibernation is dealt with appropriately. Here, we mention only a few items. Especially in the Nineties, the idea to send frozen human cells or adult individuals in suspended animation mode (or both) onboard spaceships or baby world-ships, respectively, has been receiving a greater attention. (Suspended animation and hibernation entail different levels of reduction of the normal metabolism; hypothermia is a way to accomplish them. Some considerations for TIF are discussed in [15]). It is not excluded that, technically speaking, the human hibernation and restoring to normal life may become possible. There is also the advantage to avoid those big social and psychological problems relevant to the generations on a world ship. In addition to some ethical objection to be carefully analysed, there is the aspect that the crew recalled to a hot life finds itself evolution-lagged with respect to the mission designers, especially if crew traveled on a slow ship. If communication with Earth was interrupted (for different reasons, including some conceptual/technological limit to the communication system), then astronauts has no way to learn the last-decade or last-century advancement made by the humankind in the solar system. No information was able to arrive to the onboard computer. A mission of such a kind can be planned as if knowledge were blocked at some time after the launch.

### 6.7 OTHER SCENARIOS

In the specialised literature, particularly in [2, 4], one can find other proposals to accomplish interstellar exploration, with or without galactic colonisation. Generally speaking, these ones: (1) can be viewed as different versions of the scenarios 1 through 6, (2) entail detailed predictions of so a long time compared to human eras that, in the author's opinion, any consideration and its opposite may have an equal probability to happen, (3) require concepts and/or means that sometimes appear to be more appropriate to the realm of science fiction. Thus, consistently with what is said in section 1, such schemes for TIF have not been included in the present paper.

## 7. INTERSTELLAR-FLIGHT DIFFICULTIES

This section is a review (sub-section by sub-section)) of section 7 in [1]: we highlight the most important aspects and add meaningful points not present in [1].

### 7.1 TECHNOLOGICAL COMPLEXITY

Problems regarding technology for TIF can be generally obvious, but also specifically less obvious. Very powerful propulsion, vehicle complexity, high reliability and cost belong to the former class. For instance, a spacecraft travelling at a speed equal to 0.1 c has a specific kinetic energy equal to 453 TeraJoules (TJ) per each kilogram (of starcraft mass);

at 0.9 c this quantity rises to 116,300 TJ/kg. The latter category can encompass: (a) space infrastructures close to Earth (for instance, for pushing small sails by laser or maser), in the Earth-Moon system, elsewhere in the solar system for utilising some resource (e.g. mining $He^3$ before making an efficient fusion starship), (b) a revolution in antimatter production, cooling and storing on ground before attempting to make a true annihilation-based rocket ship. These are few examples of "external-to-ship" conditions for practical starprobes.

Major problems related to the spacecraft propulsion design can be summarised by few general figures of merit (as far as current physics is concerned), that have to meet mission requirements. Each specific design has additional peculiar parameters, of course. In general, a propulsion system (PS) consists of a system for power generation (PGS) plus an engine system (ES), the eventual reaction mass being a separate system. In some propulsion concepts, the functions of ES and PGS are carried out by one system. The following quantities are particularly important for the mission design:

i. Specific Power (W), namely, the ratio of the kinetic power (K) of the ejection beam, related to the thrust process by the ES, on the total PGS+ES mass. K may be much less than the total power released by PGS.

ii. Exhaust Speed (U), namely, the *true* speed that the jet achieves when its interaction with the ES ceases (in practice, when it is no longer accelerated by the engine). Its value enters the equation for the kinetic beam power, which can be calculated by SR. (In the classical approximation $\eta_d$ K = T U / 2 where T is the actual thrust developed by the ES and $\eta_d$ denotes the beam divergence factor).

iii. Mass-Energy Utilisation Efficiency ($\eta_m$), that is the ratio of the total[3] beam power on the total energy rate related to the mass flow rate into the PS. The total flow is composed by active and inert mass, in general. What does not go to the beam is lost at zero total momentum with respect to the spacecraft reference frame. In the classical approximation, such quantity reduces to the well-known ratio of the mass actually ejected on the mass from the tank into the engine. The product $U_e = \eta_d \eta_m U \equiv \eta U$, called the *effective* jet speed, strongly determines the dynamical spacecraft output. (Usually, $\eta_d$ is sufficiently close to unity to be neglected in a preliminary analysis).

iv. Regular-working time ($\tau$), a suitable fraction of the time interval from the first engine start-up to the system crash.

v. Controllability factors (number of restarts, thrust direction control, throttling, etc)

Such performance parameters, normally referred to rocket (or pseudo-rocket) systems, can be extended somehow to non-rocket systems. For instance, for a solar sail the specific power could be defined as the ratio of the sail irradiance on the sail loading. Such a parameter varies with the Sun-sailcraft distance and sail attitude. This has not to be compared *straightforward* with advanced-rocket specific-power figures simply because the solar sail thrust decreases rapidly with the distance. (Of course, U = c, but now $\eta$ is to be referred to thrust in a somewhat complicated manner). A short list of the major propulsion concepts so far envisaged for deep-space exploration is arranged in Table-1. Some remarks are necessary to read this Table. *First*, the figures reported for effective jet speed are upper limits. *Second*, the specific-power values depend on current (conceptual) designs. Anyway,

[3] The adjective "total", referred to energy and to energy rate, is to be meant in relativistic sense, namely, rest + kinetic energy.

we reported some projected values that fit our present context very well. *Third*, concerning antimatter-based propulsion, the exhaust speed of any engine cannot be 1, although the matter-antimatter annihilation is believed to be a full mass-to-energy conversion. In the case of proton-antiproton, annihilation generates photons, massive leptons and mesons that decay by chain; some of their final products are neutrinos. In addition, a considerable fraction of the high-energy photons cannot be utilised as jet energy. Both carry off about one third of the initial hadronic mass. Thus, it is not possible to control such amount of energy. *Fourth*, at the present there is no design of rocket propulsion system that exhibits very high specific energy and very high specific power at the levels *necessary* for an interstellar mission, even of the type described in section 6.1.

Table 1. Major propulsion concepts for deep space missions. The symbol (=) at the right of the Type column indicates a particular version for which the power comes from the mass to be ejected. The label (IS) refers to a propulsion concept entailing infrastructures in space. Reported figures should be meant as theoretical limits, where applicable.

| | Propulsion | Type | Specific Power [ kW/kg ] | Effective Exhaust Speed [ C ] | Spacecraft Complexity |
|---|---|---|---|---|---|
| *A* | Solar Electric | pseudo-rocket | 0.1 (1 AU) | 1.E-4 | medium |
| *B* | Nuclear Electric | rocket | 1 | 3.E-4 | high |
| *C* | Magnetic sail | non-rocket | | 1.E-3 | medium |
| *D* | Solar Photon Sail | non-rocket | 900 (1 AU) | 1 | low |
| *E* | Laser-driven Sail | non-rocket | (IS) | 1 | low |
| *F* | Microwave-Driven Sail | non-rocket | (IS) | 1 | low |
| *G* | Nuclear Fission | rocket (=) | 50 | 0.02 | very high |
| *H* | Nuclear Fusion | rocket (=) | 200 | 0.04 | very high |
| *I* | Matter-Antimatter | rocket (=) | 1.0E4 | 0.5 | very high |
| | Laser + Fusion<br>Laser + Antimatter<br>Antimatter + Ramjet | equivalent rocket | 1.E6 | ~ 1 | ? |

One of the ways to overcome such problems is to resort to a ultra-high power laser/microwave system. A sufficiently light, simplified sailcraft could receive the necessary momentum from an external source and get relativistic. Big problems in such concept are: (a) the presence of large orbital infrastructures, (b) collimating and focusing a photon beam at great distance, (c) appropriate spacecraft materials. Laser-pushed sailcraft and microwave-driven sails (or starwisps [16]) are very interesting concepts that, like rocket concepts, do not require a new physics. Unfortunately, considering the complexity of the problems to be solved, it is not yet excluded that some showstopper might be found in some of them. It has been suggested to use a “plasma of nano-systems (10-100 millions of atoms encompassing sensors and actuators)” able to steer themselves to the sailcraft. Another way might consist of a runway of pre-deployed propellant that a fusion spacecraft should capture and burn along its path. Studies are in progress on both concepts that obviously appear very complicated [49].

Finally, the last row in Table 1 indicates what SR would allow us to do if, for a moment, one assumed that humankind will manage nuclear fusion, macroscopic amounts of antimatter, ultra-high power photon beams, and perhaps antimatter-augmented ramjet in space. By using the concept of equivalent rocket [17], in principle a combination of the different propulsion concepts would allow an orbiter mission to Proxima Centauri by a 15-year flight. Some tonnes of antimatter and laser system with many tens of TW would be necessary to deliver a payload of the order of 1 tonne.

There is another significant problem in devising very fast vehicles. One realises that mass must be reduced as much as possible. Even if it is possible to envisage low-mass telecommunication systems and scientific instruments, nevertheless any propulsion system that was investigated for interstellar flight cannot be scaled down arbitrarily. Highly exothermic reactions give rise to high-energy particles with different ranges, decay times and interaction cross sections. Mass and size of propulsion systems have to be sufficiently high to trap and direct their energy into some beam. This holds even for non-rocket systems (though to a lesser extent) as soon as one thinks that using force fields onboard entails some material source.

With this background in mind, it should be easier to understand why the theoretical investigation on TIF (summarised in 7.2) is given a considerable importance.

### 7.2 Reasons from Basic Physics

Let us first consider the fast interstellar flight. The main problem could be summarised in one word: *Time*. This point, better expressed, means Special Relativity. Better again, this signifies the Lorentz-Einstein transformations (LET). It is known that all SR is based on three ingredients:

1. the Principle of Relativity
2. the homogeneity of Space and Time, the isotropy of Space
3. the invariance of a speed limit (for transporting energy and momentum), that coincides with the speed of light in vacuum

Even though LET are much more favourable to TIF than Galilean transformations (because of space contraction), nevertheless the increasing slowing-down of Time in a spacecraft moving faster and faster turns into an infinite barrier of energy to get the speed of light. Why does this happen? Because – essentially - SR is a linear theory. Why is SR a linear theory? SR is a linear-transformation-based theory simply because both space and time are homogeneous entities. That is, all points in spacetime are equivalent from the LET viewpoint. Thus, for instance, although speed affects time intervals and lengths, in every frame of reference the length[4] of any rod (either at-rest or moving) is independent of where the rod is located. In the framework of SR, one has that

(i) the metric of the four-dimensional Minkowski space is globally constant,

(ii) this metric cannot be changed,

(iii) LET are applicable to moving objects of any size and mass.

Point-i has been overridden by General Relativity (GR, that allows a space-time to be asymptotically flat). On-ground, big accelerators show that point-iii is correct in dealing with any known high-energy particles. In addition, some important consequences of SR have been proven for macroscopic objects. Then, if elementary particles obey SR, then it is so for any type of objects. Now, let us try to express point-ii differently. When gravitation is

[4] measured by making the difference between the space coordinates of its ends simultaneously time-tagged in that frame

negligible, does SR cover all aspects of Space-Time? In other words, does one continue to observe that (*a*) the Lorentz factor diverges for a massive body as its speed approaches c, (*b*) the Minkowski metric remains unchanged no matter high the body mass and speed may be, namely, the Lorentz Group is yet an isometric transformation group? Question-b may be put into the form: is the LET isometry valid for macroscopic objects and/or hypothetical particles much denser than the nuclear density? The first part of the above question would mean: might a macroscopic body (i.e. a spacecraft, not a massive particle), achieving some threshold speed (close to the speed of light), modify its spacetime neighbourhood so that its *local* metric changes? Assuming a 'yes' for a moment, would the speed-of-light still be a time barrier between the SR dynamics and a more general dynamics? Here, we call this set of questions the non-Lorentzian conjecture (NLC) for a further deeper investigation of SR. (Of course, no test of such a kind has been performed. In astrophysics, the seeming super-luminal galactic jets can be re-interpreted in the SR view to give a sub-luminal speed. Such jets are composed of particle plasma and therefore they are sufficiently separated in space that they should not form a macroscopically dense body. Thus the above question does not apply there).

In the latest years, some concepts have been revisited. Additional ideas, supported by calculations, emerged and have been debating by the basic-physics community. One may arrange such modern concepts as follows: extension of SR, Space Drives, Spacetime-induced Drives, New View on Inertia. Because the fundamentals of such areas are conceptual, we include them as basic-physics items. We are about to discuss each of the above classes. The purpose is <u>twofold</u>. *First*, one can be aware that a considerable research has been continuing to understand better what might seem fully ascertained and, in parallel, to investigate potential extensions & generalisations. *Second*, one can better recognise various levels of difficulty in trying to implement a very fast mission to nearby stars.

#### 7.2.1 Extension of Special-Relativity

In Reference [1], one can find many considerations about the past studies on super-luminal physics. No meaningful revision is necessary here. Although CLEP does not put any restriction on actual physics, we limit ourselves to report that the claimed spaceflight implications from the <u>current</u> tachyon views and CLEP are not consistent with each other. A different situation might stem from eventual positive results in the line hinted in section 8.1.

#### 7.2.2 Space Drives

S*pace-drive* propulsion, as defined here, would mainly utilise the fundamental properties of the 3D physical space. Usually, such concepts are based on QFT and/or GR. Space-time metric is of types known in GR. In contrast to concepts described in sub-section 7.2.3, engines are envisaged to affect the state of the 3D space. In addition, they do not expel reaction mass-energy to get a thrust. Since such a propulsion system uses some field to excite space, confusion might arise with the so-called *field* propulsion concept [18][5]. Perhaps, the most investigated and calculation-

[5] Actually, this concept is more general than space drive; as a point of fact, a field propulsion system can be very classical, like a magnetic-sail device driven by the solar wind or an artificial plasma. Some authors call this space drive the *bias* drive [19] meaning that some basic property of space (for instance, the gravitational constant) might be changed locally.

supported concept of space drive is that proposed in [20,21]. It consists essentially of the following conceptual items:

(a) Space is a continuum endowed with two main states: the elastic solid phase (in the present universe) and the visco-elastic liquid phase (in the early universe). Space can undergo a phase transition governed by the Gibbs free energy function corresponding to the Higgs potential function for vacuum in QFT. This transition corresponds to symmetry breaking. Space retains these properties up to the current event horizon.

(b) Space can be excited by some tensor field that increases the vacuum expectation value of the underlying scalar field. The energy-momentum tensor of the exciting field induces a space (Gaussian) curvature through the GR equations, in particular by the double time-like component of the Ricci tensor. The curvature, in turn, causes an inward normal stress on the curved surface. A 3D region of space - conceived of a succession of parallel 2D slices along a certain direction - is subjected to a curvature that renders the connections-dependent piece of the geodesic equation different from zero. Then, a body in that space region would undergo acceleration.

(c) A body (spaceship) hosting a device (engine) producing a field (for instance, a very strong magnetic field) cannot self-accelerate if this field is stationary or slow varying with time. This, of course, is forbidden by the action-reaction principle applied to the space + body + field system. However, if the magnetic field is switched off and on, then - during the interval the source is off - there is a region nearby the engine where the curvature is zero, while space is still curved in a farther region. This would be so because of the finite strain rate of space. The ship would be partially immersed in a non-zero curvature volume; the most important thing, the spacecraft would see the volume field as an external field. Thus, a non-vanishing net acceleration would act on the spaceship during the engine-off time interval. The cycle can be repeated. Therefore, this space-drive concept is a pulsed propulsion system.

An important claim of such propulsion concept would consist of simultaneously accelerating the vehicle structures and any other separated object inside the ship. Another issue is that a magnetic field of several and more orders of magnitude higher than any field realisable on ground is required to curve space appreciably. This is not only a technological problem, but a conceptual one as well. In any case, producing a high-intensity field over a finite region of space entails a device to either transform some mass into energy or tap energy directly from an external source. Another substantial point is whether the acceleration may be kept as the vehicle increases its speed progressively. An evolution of the above concept of space drive is presented in [22].

### 7.2.3 Spacetime-induced Drives

A propulsion system concept may be based on particular properties of both space and time. In principle, one might think of inducing <u>local</u> changes in the spacetime metric and use the ship engines to insert and keep the vehicle into this region. Of course, this spacetime volume has to move in order to transport the ship far away. In addition, the complexity in managing a special curvature of spacetime must be fully justified by an unusual dynamical performance of the spaceship. Before discussing some suggested examples of this envisaged propulsion type, it is useful to summarise very shortly what is known as the Quantum Inequalities (QI) in literature. In contrast to classic physics, in QFT states are allowed to exhibit *negative* energy density[6] (NED, also called the *exotic matter*) that may result unbounded at a four-dimensional point. In an inertial frame, an observer might see a NED, but there exist inequalities to be satisfied. QI represent uncertainty-principle-like constraints on both duration and density of negative energy. In particular, there exists an inequality for NED in a finite neighbourhood of a generic point along the world line of an observer. QI have been carried out for the cases of massless scalar field, massive scalar field and the electromagnetic field, all in the Minkowski spacetime [23,24]. Extensions to curved spacetime are discussed in [25]. The 'tt' component of the energy-momentum tensor and the sampling interval of the observer's proper time (ST) both enter the energy density QI. If the ST is large enough, then one gets back to the well-known averaged weak energy condition. Roughly speaking, if an observer experiences NED in a region close to her/him, then such energy cannot persist too long.

With QI, the envisaged wormhole-based travel [26] and the negative-mass propulsion [27] should be somewhat improbable, if not ruled out. However, considering the great complexity of these topics, both theoretical and observational (where applicable) aspects deserve a deeper investigation. We like to tell just few words about wormholes. First of all, let us note that they are categorised as either Euclidean or Lorentzian. The former class stems from quantum field theories and it is a very strange object living in a non-real[7] time. The latter class is more popular. By a Lorentzian wormhole, one generally means particular solutions to the GR equations; it is found that it is possible to connect two regions ("mouths") of spacetime a way like tunnels. Such a passageway is attractive because, in some cases, the time necessary to travel from a mouth to the other one, *through* it, is much briefer than the time interval for the trip in the normal space. Wormholes are a generalisation of the Einstein-Rosen bridge between two copies of the black hole geometry. They are part of a more general problem known as the determination of spacetimes with compactly generated chronology horizons. Normally, a spacetime hosts world lines which are open; however, particular circumstances (for instance, infinite distributions of matter, universe rotation, etc.) can induce a spacetime structure that contains closed timelike curves (CTC)[8] over some zone, called a non-chronal region. A CTC may originate from an infinitely extended distribution of rotating matter inducing a particularly strong drag of the inertial frames. Zones of spacetime free of CTC are called the chronal regions. Chronal and non-chronal regions are bounded by special zero-length geodesics, called the chronology horizons (CHs). These CHs can be either *past* or *future*. In principle, one may pass from a usual chronal region to a non-chronal one through a future CH and live in a CTC (that originates from this CH). Conversely, a CTC dies at a past CH where spacetime becomes chronal. Inside a non-chronal region, there are smoothly closed null geodesics that represent *asymptotic* geodesics for the world lines that generate a CH (i.e. the horizon generators). These "asymptotes" are called the *fountains*. They are particularly important because –

[6] not to be confused with antimatter

[7] By this phrase, one means that time is represented by a non-real number.

[8] In a CTC, the future wraps into or interconnects to the past because the light cone is progressively and strongly tilted by matter

along them – the total stress-energy tensor of matter and field has to satisfy an integral inequality. This constraint, obtained by combining GR and geometric optics[9], violates the averaged null energy condition (ANEC); namely, it is negative. This entails that only exotic matter might produce CTCs. A problem arises since QFT does not forbid a violation of the ANEC. Therefore, in principle, somebody claims, a CTC might be used by an advanced civilisation for building a time machine! Now, this would provoke a number of significant problems, perhaps the best known being the "grandfather paradox". What is the mechanism that apparently forbids going back into time? It seems that quantum instability occurs on a future CH in any spacetime. If an event in the chronal region approaches a future chronology horizon, then NED diverges due to accumulation of the fluctuations associated with the vacuum of some quantum field. The same line of thought induced Hawking to formulate his chronology protection conjecture (CPC). According to it, if one achieves so an advanced level of knowledge to allow the management of large amounts of NED (if it exists), then a wormhole might be built and kept open by this matter[10]. However, putting a particle inside turns into a destabilisation of the wormhole itself, and so fast that it is not possible to use it. Here, we like to point out that there is yet no evidence for NED matter, although there are proposals to investigate it via astronomy. On the other side, nobody knows a firm law stating how/why chronology is protected. Many details can be found in [28,29].

A special case of spacetime-induced motion was suggested in [30]. Suppose that, by means of exotic matter one manages to generate a sphere-like region in the Minkowski spacetime. On an edge, the spacetime is contracted while on the opposite edge it expands. This bubble can then move, even at the speed of light, along the direction from the expanded or back edge to the contracted or front edge. These sides have a finite thickness. For simplicity, one may assume that the bubble has a spherical corona. As internally as externally, the corona space is flat; however, whereas far from the bubble spacetime metric is Minkowskian, the metric of the internal spacetime is non-diagonal. In the corona, metric depends on the internal bubble radius R and the wall thickness $\delta$ and is non-diagonal again. In the same reference frame where such spacetime perturbation propagates, let us consider a spaceship at rest and distant from the bubble with an impact parameter $0 \leq q < R+\delta$. As soon as the ship penetrates the bubble corona, it starts accelerating with respect to far observers at rest. Inside the bubble and out of the corona, the ship has a speed that depends on its distance from the bubble centre. When the vehicle crosses the back edge, it begins decelerating. Once the spacetime perturbation is sufficiently far, the ship returns to rest, but now it is shifted forward (with respect to its initial inertial position) along the bubble motion direction. The maximum displacement would happen when $q=0$. If one chooses a function (controlling the motion inside the bubble) constant and equal to unity, then the ship speed for any $q<R$ equals the bubble speed, thus avoiding any tidal effect on a real finite-size vehicle. Because the propagation of a spacetime perturbation may equal c, this would be the speed of the ship with respect to distant inertial observers (on the Earth for simplicity). This is the

[9] In the approximation of geometric optics, a photon travels on null geodesics.

[10] A wormhole might be used to travel from space to space or through time.

first amazing result from the proposed metric. There is a second intriguing property of such transportation: the proper time interval in the ship frame equals the time elapsed on the Earth. Is then the conceptual problem of Time for TIF solved in such a manner? No decidedly. In fact, one has to put a big amount of NED in the bubble corona. The t-t component of the energy-momentum tensor is negative for any choice of the controlling function. That stems from the first integral of the ship's geodesic as sensed by a distant observer. Therefore, QI apply. The result is the following [31,32]: (i) the wall thickness is of the order of the bubble speed times the Planck length or less; (ii) the total NED mass, necessary to make a bubble containing a spacecraft of some tens of meters, is greater than the mass of the known universe. If QI do not apply, then one should manage NED matter of the order of the solar mass, at least. Apparently, a metric exhibiting the above properties could not be conceived as a standalone GR object. Some related considerations can be found in Section 8.1.

### 7.2.4 A New View on Inertia

One knows that mass is one of the big spaceflight problems in general, not only for TIF. In the last years, a new very interesting theory has been issued about the nature of inertia. The work is still in progress, but in a stage sufficiently advanced to make considerations and see many theoretical consequences. Starting from a well-known conjecture, it is suggested in [33-35] that a material body may sense the zero-point fluctuations of different fields: the electromagnetic, weak and strong interaction fields. These body-vacuum interactions, occurring ultimately at level of leptons and quarks, are the cause of inertia when an external agent (or force) drives a body to change its momentum with respect to an inertial frame of reference (IF, where the force is measured). An observer (or instrument) sees the zero-point field scattered isotropically when the body has zero velocity in IF. There is no net energy flux (N) and momentum density (**J**) of the zero-point field (ZPF) flowing across the volume of the body. If a body moves at a constant velocity **V** with respect to IF, then it senses N=0 and **J**=0 in its own frame of reference. However, an observer in IF detects **J** = constant ≠ **0** with **J** // -**V** ($|\mathbf{J}|=N/c^2$) for the body. Then, the object is given a linear momentum $\mathbf{P} = \mathbf{J}*\upsilon/\gamma_V$, where $\upsilon$ is the body's proper volume and $\gamma_V$ denotes the Lorentz factor evaluated at V=|**V**|. When an external force begins acting on the body, the ZPF <u>reacts</u> by inducing a net flux of its momentum (now time-dependent) across the object in the direction exactly opposed to the external acceleration vector. That appears to an inertial observer who is tracking the body. In IF, the time derivative $d\mathbf{P}^{zpf}/dt$ of the ZPF momentum received by the accelerating body is no longer zero. By using stochastic electrodynamics (SED) applied to objects sensible to em-fields, but in a way independent of the particular body-vacuum interaction, it is shown in [34,35] that $d\mathbf{P}^{zpf}/dt$ is proportional to the opposite of the acceleration through a scalar coefficient having the dimension of a mass. This coefficient - called the object's mass - depends on both the body's proper volume and an integral over the ZPF spectrum, weighted by a frequency-dependent function expressing the fraction of ZPF energy trapped by the body. As the ZPF spectrum is Lorentz-invariant, mass is a true scalar. In addition, these results can be proved relativistically valid, as far as Special Relativity is concerned. If one excludes Mach's view about inertia (that entails an instantaneous action at a distance), the new view sets the force as a fundamental concept, in contrast with the Newtonian concept of mass as intrinsic property of a microscopic or macroscopic body. The role of the em-ZPF is not only to be responsible for an acceleration-dependent reaction force (through the scattering of the ZPF radiation by the interacting object), but also to retain, in a body-comoving neighbourhood, both momentum and kinetic energy the external agent is imparting to the body and that the object should transmit to the interacting field.

A significant consequence of such an inertia concept is that negative mass (which is claimed to exhibit negative inertia) should not exist. This enforces some considerations based on SR that exotic mass, if existed, could not be stable.

From an astronautical viewpoint, the following question arises. Supposing that one understands inertia completely and find a way to control it to some extent (if any), there would be any benefit for a spaceship? Although it is premature to make any conclusion, nevertheless one may conjecture of a rocket ship that onboard has an inertia-decreasing device that allows the inertial ship mass $M_S$ to be reduced by a factor $0 < \kappa < 1$. This regards any mass inside the ship, of course. The rocket thrust is well known to be expressible as $\mathbf{F} = -\eta\ (dM_P/dt)\ \mathbf{U}$, where the term in parentheses represents the time rate of total propellant (i.e. active + inert components) driven into the engine system. However, even $M_P$ scales down by $\kappa$, whereas the ejection velocity retains its value because it comes from the energy conservation equation. The total utilisation efficiency $\eta$ is not affected by mass scaling. As a result, the ship acceleration history $\mathbf{F}(t)/[M_S(t_0) - M_P(t)]$ does not change. Therefore, a device controlling inertia should be useless for a rocket-propelled spacecraft. A different result may come from a sail-based spacecraft.

### 7.3 HUMAN & SOCIAL DIFFICULTIES ON GROUND

It is reasonable to think that one space agency cannot probably manage an enterprise such as a true interstellar mission. An international joint venture should be much more adequate for the following main reasons:

1. This endeavour regards all humankind, especially if relied on CLEP (section 3)
2. it is better to collect ideas coming from different viewpoints & expertise and then select solutions in order to avoid biases that could invalidate part of the mission
3. the cost is shared among many nations, thus making the approach to TIF affordable or, at least, less subject to critic and cancellation

Potential drawbacks contrast the above advantages. The design and construction of a starprobe should be more rapid if performed in an ideal ambient of collaboration. However, often non-scientific and non-technological reasons slowdown a big international program. Therefore, a world-wide scale co-operation, working for many years or decades, should be set up with sufficient stability against economic and political changes in every attending nation. Because it is unrealistic to hope that changes of such a type do not occur on our planet, the only way to successfully deal with an interstellar mission is to provide humankind for a background culture. Human mentality, it is known, is rather slow to modify. A star-oriented vision can be gained during presumably some decades, provided that interstellar precursor missions become: (1) progressively successful, (2) showing that there is a real benefit for all people (not only for scientists and technologists) and peoples through several spin-offs affecting the every-day life positively. A permanent lunar base or the human exploration of Mars could contribute to such a mentality efficaciously. Obviously, the very high cost of an interstellar mission should not be subtracted to large social-oriented programmes, simply because that would not be right. It would be a strange contradiction to try to raise the human life quality and prove its meaning in the Life-in-the-Universe context by starting with life degradation in the origin planet!

A mistake in approaching an official interstellar mission design would be to wait for the achievement of quasi-ideal conditions to start. Many things can pave the way to the first mission. Many technological activities require a long time so that a widely spread initiative could keep the international interest "awake" for the necessary decades until a true project is ready to start.

Throughout this section, one can recognise how much difficult is to reach the stars. One might find the "obliged way" item of the strong CLEP conflicting with the clause "provided that..." repeatedly used here. This simply means that humankind may be far from the minimal conditions for actually set up interstellar missions. However, it is already on the road, according to the weak CLEP.

## 8. Searching for Potential Solutions

From what said in section 7, there is no doubt that we have to resort to basic physics for hoping to realise the fastest classes of interstellar exploration. We have to reason in a different way to overcome what appears as a sort of barrier to our need to expand into Space. In order that a new scientific theory represents a true extension of knowledge, the following requirements should be satisfied[11]:

1. It has to show an internal consistency
2. It has not to deny what has been experimentally obtained; in particular, the past accepted theories have to be retrieved if some condition(s)&situation(s) go to a limit(s)
3. It has to indicate new characteristic experiments
4. Outcomes from such experiments have to be explained unambiguously.

If some mathematical/physical construction is a candidate for a fundamental theory, then it should be universal too. The above points should be regarded as the necessary conditions to accept a scientific theory. As a point of fact, a theory can be falsified; another matter is to show that it is true!

In the context of TIF, none of the emerging theories satisfy all the above necessary conditions, even because most of them are too new (and still in their infancy) to be either accepted or rejected.

An initiative by NASA Headquarters started in 1997. In March 1998, some researchers of JPL presented a technology evaluation for interstellar precursor missions [36] as the preliminary answer to this NASA commitment. Of course, the realisation of a precursor mission is quite important from many standpoints.

Another research programme, as a task to formulate a 25-year (or more) investigation for very advanced propulsion, is detailed in [37, 38] and summarised in [39]. It is named breakthrough

[11] Of course, this assumes that there exist Laws of Nature, quite in contrast to some extreme consequences of the so-called chaotic gauge theories.

propulsion physics (BPP). It regards three major branches to future spaceflight that – in the context of this paper – may be cast as follows:

A. The problem of Spacecraft Mass. It aims at investigating new eventual propulsion modes that reduce the mass of propellant dramatically or hopefully get rid of any need of ejection mass for primary propulsion[12]. An example of this solution class might be the space drive concept of section 7.2.2.

B. The problem of Spacecraft Speed. It fosters research for the achievement of the highest possible speed for a spaceship. What summarised in sections 7.2.3 through 7.2.4 may act as a guideline to search for real solutions.

C. The Energy problem (for spacecraft and/or space infrastructures in orbit). This problem is an essential issue to the others. In fact, although one looks for methods that ultimately may lead up to an ideal spaceship travelling ultra fast without propellant consumption, however some form and amount of energy must be managed.

Problems A-B-C have much physics in common. However, even if humankind achieves a degree of comprehension in one point (e.g. the mass problem), however this does not automatically entail that one can control it[13].

Two important features of such a long-term program consist of proving credible and measuring the progress made step by step, each step being a set of near-term tasks. BPP, initially thought for the USA context, has been progressively extending to the international scientific and technological community (see [37] for details).

### 8.1 Research on Special Relativity

SR should not be considered a closed chapter for knowledge. In addition to the four conditions mentioned above, an eventual extension of SR should perhaps pass through techniques like those of GR, but not limited only to a mathematical manipulation of spacetime properties. Instead, some new profound meaning should be attached to the objects interested by the extension itself. SR enters both GR and QFT heavily. However, an extended SR might be formulated not as a base over which putting other formulations of Nature, but rather in conjunction with different theories. This method has been already followed in many explanations or re-interpretations of some relativity paradoxes, especially when the principle of causality is involved. It should be investigated whether an extended SR might include an additional dimension to the four-dimensional tissue that hosts events and is affected by them. However, this dimension should be neither space nor time, according to [40]. Substantially, a dimensional structure consisting of three space dimensions plus one time dimension, or a (3+1) spacetime, has a high probability to contain *observers* sufficiently complex and stable to be able to understand the universe they live in. That would be due to: (1) a spacetime with (n+1, n<3) dimensions would entail a world with too a low complexity, (2) a (n+1, n>3) spacetime would not permit a sufficient stability, (3) the physical laws would not allow observers to make predictions in a

[12] That is in the context of very high speed, of course, inasmuch as such goal can be achieved by solar sail for missions in the heliosphere (100-300 AU) and by slower flights beyond.

[13] For instance, one knows the behaviour of spin and at-rest lifetime of particles, but nobody knows how to change (if it were conceptually possible) their values if it were necessary for achieving some high purpose (for instance, the construction of large-scale reactors based on the muon-induced fusion).

(3+m, m≠1) spacetime. Here, we add that the CLEP is perfectly compliant with the (3+1) space-time properties, although it does not exclude a higher dimensional manifold including some dimension different from space and time. The NLC, suggested in Section 7.2, might involve a higher dimensionality, which then should be inferred from a deep analysis of the normal spacetime. The NLC should be ascribed to high-speed massive body (made of normal matter) that would induce a modification to the properties of its neighbouring spacetime, something like what happens to the air environment around an aircraft approaching the speed of sound. In contrast, the warp-drive propulsion concept, discussed in Section 7.2.3, regards a ship caught by a moving spacetime perturbation, caused by something else.

### 8.2 Research on General Relativity

An overview of the research on GR together with investigation lines for the future can be found in [41]. They regard binary pulsars (for the behaviour of strong gravitational fields), the nature of singularities (by numerical-relativity methods and/or modern techniques of partial differential equations), cosmology (inflationary models, strings and other topological defects, etc.), quantum gravity (QG). Since its onset, researchers have been dealing with QG by trying to formulate a quantum theory of GR essentially via either a covariant approach (by particle physicists) or a canonical approach (by general relativists). Although a big work has been done, however there are many basic issues still unsolved in both methodologies. In particular, in new approaches QG should naturally emerge as a theory *asymmetric* with respect to Time. A research devoted to space propulsion breakthrough has not yet been accomplished, apart from a few cases of GR formalism applied to space objectives (for instance those discussed in sections 7.2.2-3). Since concepts closely related to the structure of the spacetime or higher-dimension universal tissues are fundamental for a general knowledge, there is no doubt that insights gained in advanced GR investigation could give space researchers a precious aid.

### 8.3 Research on Quantum Field Theory and QM Applications

It is not excluded that developments of QFT might disclosure aspects relevant to TIF, especially the problem of managing enormous amounts of energy. For instance, the Casimir effect should be more deeply investigated experimentally to ascertain whether it originates from either vacuum fluctuations or, for instance, some special behaviour of the intermolecular forces [42]. In addition, QG may provide the researchers in advanced Astronautics for interpretations that can cast a new light on any of the basic flight problems: mass, energy, speed and time.

Propulsion is not the only basic requirement for E&E. Immediately below, communication between the starship(s) and the celestial departure body is mandatory in any type of interstellar flight, at least during a non-negligible fraction of the flight. Classical communication may evolve technologically to cover many hundreds or a few thousands of AU, but this is insufficient for a large-scale exploration of several stellar systems, especially if Physics were to allow fast interstellar missions from a propulsion viewpoint. A conceptual leap has to be eventually done for mastering interstellar communication. The present status of physics has begun with giving us a potential way to face with this problem [43]. In this decade, a significant advancement in the fundamentals of quantum computing and quantum communication has been made. Only recently, researchers have realised that the unusual features of systems governed by QM - mainly, the complementary principle, the superposition principle and the entanglement – could be used for potential revolutions in cryptography, communication and computing [44]. Such emerging disciplines not only share basic principles, but also are expected to be strongly interlaced in applications. In the first half of $20^{th}$ century, besides GR and QM, the classical theory of information represented a third revolution (although often considered as only a branch of engineering). It deals with storing, transmitting and processing information. More fundamentally, an information theory views the physical world (and its related systems) under the general aspects of internal data content, data transmission, insight and knowledge by observers. In the latest years, a *programme* just started: reconsidering the laws of physics from the information theory viewpoint. Information is intimately related to the structure of the Universe, very meaningfully (though partially) expressed by the statements "no information without physical means or representation" and "any organised structure (system) must have an *amount* of information stored and can exchange it with other systems". Many efforts have been made to *link* thermodynamics to the classical information theory. There is one simple linear equation relating thermodynamic entropy to information entropy (they are conceptually different from each other). Classic information theory, in turn, can be generalised to quantum information theory, where a two-state system is still basic for defining the information content of any quantum system. This content represents the minimum number of 'elementary' two-state systems (quantum bits or *qubits*) necessary for transmitting or storing the state of the general system under consideration. There are many additional and amazing features. First, if one builds an ordered set of qubits, say n, by means of which $2^n$ numbers can be stored, then by superposition one potentially has *all* these numbers simultaneously storable and accessible, not one at a time as in the classic case. Second, quantum entanglement allows one to compress *two* bits into one. Third, the evolution of *any* physical system could be simulated on a quantum machine, apart from eventual problems arising from violation of the central paradigm of computer science. Thus, this decade of investigation in quantum information established some of the basic pieces necessary to develop (in the long term) quantum computers[14], quantum transmitters and receivers (quantum *teleportation* systems included). It is worth mentioning that the QM non-locality does not allow one to use entangled states to send signals (information) faster than light[15]. Perhaps, the most challenging problem in realising a quantum information processing system is *decoherence*. Therefore, a principal objective is to learn how to avoid its effects. How and how much quantum communication systems might be useful for interstellar missions is not known today. Its contribution may be indirect. For instance, robots delivered to or released inside a stellar system may communicate via "quantum antennas" with a channel capacity much higher and error correction codes much more efficient than those ones foreseeable by classic methods. In addition, computer systems for interstellar flight may well achieve a computational power measurable in thousands of TeraFLOPS on memory densities many orders of magnitude higher than today and requiring

[14] Key pieces for such computers are the quantum gates. Currently, there are two types of gates (type U and type M). A working type-U gate could be realised by the so-called (solid state) quantum dot physically represented by a single ion in a many-atom trap. By lasing this system appropriately in frequency and time, one could get the states $|0\rangle$, $|1\rangle$ or $a_0\,|0\rangle + a_1\,|0\rangle$ ($a_0^2 + a_1^2 = 1$). One may also note the smallness of such a memory type.

[15] The strict explanation is a little long, but, essentially relies on the fact that neither the transmitting nor the receiving system (even if humans) can control the stochastic nature of the outcomes from a measurement process [46].

very low power. Moreover, according to recent significant studies [45], molecular nanotechnology will eventually be able to use the internal molecule energy to prime molecular transformations. New materials endowed with multi-function and regeneration properties may become a reality. These and many other items represent potential space applications for nanotechnology. Though difficult, it is not a branch of engineering only: it deals with basic aspects of QM. In addition, its applications are potentially countless in fields different from spaceflight.

#### 8.4 HIGHER-LEVEL RESEARCH INVOLVING BOTH GR AND QM

Since its early steps, QM has been exhibiting a number of interpretations for what is known as the state vector reduction (SVR, or the wave function collapse) of a quantum system. The attitude of scientists in this basic area is considerably diversified. In particular, a school of thought deems that the *unitary* time-evolution (UTE) of a quantum system, described by Schrödinger's equation, exhausts the whole story. That, for instance, results in the *many-worlds* picture. Some other authors set up a theory [47] which, relying on the concept that - in a quantum system - the *conditional* entropy of an *entangled* sub-system may be negative, gives the overall measurement process no SVR. In such a view, the measuring device has no special role. In contrast, many other physicists think that UTE and SVR are real both. It should be stressed that such different attitudes are not a mere problem of interpretation; rather, they reflect a profound difference in conceiving the current physical models. Some physicists think that, apart from an eventual refining, the general QM structure has not to be changed, corroborated by the great successes QM accumulated hitherto. Other scientists deem that the internal QM problems are a symptom of something much deeper than a re-interpretation need. In particular, Roger Penrose has been working on a concept [7 and Refs. inside] in which, by assuming the SVR (that he calls the ***R***-process) is truly *asymmetric* with respect to time, the role of gravity is fundamental. A (quantum) system to be measured and the measuring device, each with its *environment*, generally are in a state of *superimposed* other states, according to QM. Each state has a probability amplitude and the QM rules tell us how to calculate each amplitude. For simplicity, let us consider a two-state superposition here. Roughly speaking, one can say that each state is characterized also by its own mass distribution (no matter how this may appear small with respect to the usual standards). One can then calculate the *gravitational self-energy* (say, $E_S$) of the difference between the two mass distributions. According to the uncertainty principle, the superimposed system state may be given a mean life $\tau \approx \hbar / E_S$. The system then decays into only one of its basic states and this represents the outcome of the measurement process. Penrose has proposed an interesting space experiment [48] that may reveal the objectivity of the gravity-induced wave-function collapse through an unambiguous signature. The related setup should be detailed for ascertaining whether it could be implemented by current or near-term technology. Such an experiment (that would anyway result in meaningful information) may – in the positive case – indicate the right way for unifying the physical phenomena falling in either QFT or GR domain, perhaps under a new view of quantum gravity.

Astronautics has been generally viewed as a set of (advanced) engineering branches necessary to build a space vehicle, namely, a sophisticated tool delivering scientific instruments far from Earth where an appropriate environment can be found to make science. Most scientists working in universities and in laboratories are used to utilizing space means (satellites or deep-space probes) according to such a conception. In addition, many of them think too that without their payloads the space vehicle and its design would lose their meaning and money. From this point of view, Section 3 of this paper is rather provocative. If the (role and range of the) laws of the universe are a function of its observers (via WAP, CLEP or something else deeper), then even space exploration and expansion shall act as "basic" disciplines.

## 9. CONCLUDING REMARKS

By taking into account what has been discussed in the previous sections, it should be clear that today it is not easy at all to answer the question: "is the Interstellar Flight viable" by either yes or no. Nevertheless, we try to arrange a short summary as follows:

If one means the very slow diffusion of life through human generations and artifacts in a rather limited region of the galaxy (as discussed in section 6.5) then the answer can be "it's possible"[16]. Time frame may be the 22nd century, once the culture of the Earth inhabitants evolves. A big point of the culture of generations inhabiting planets in the *intermediate* stages of expansion should rely on the fact that they originated in another (far) stellar system and that some of their descendants and artifacts shall continue to explore and expand into the galaxy.

On the other extreme side, if we mean fast round-trip travels (with all consequences one can envision such as federation of planets, interstellar commerce, eventual small and big conflicts and so on), then present-day knowledge and technology tell us "very improbable". However, considering that our models of Nature and its Laws evolve rapidly and noting that just in this decade the general scientific community debates about TIF on a multidisciplinary basis, a more appropriate answer should be "maybe". If a principle like CLEP is true, then our efforts shall certainly arrive at a "yes", although we do not know "when". Again, this type of interstellar flight will require an appropriate culture of the humankind. Such a culture could evolve significantly during the periods of nearby-star mission and receive new impetus as soon as each mission is completed.

In the middle of the feasibility interval, we find scenarios of type 1 and 2 (section 6) that may give a meaning to the question "when the first *precursor* interstellar mission"? In July 1998, JPL organized a workshop [49] for compiling and publishing a set of recommendations to NASA headquarters. Next decade may regard: (1) scientific goals and requirements of a robotic interstellar mission (including its precursor mission), (2) the assessment of candidate propulsion concepts that sound viable together with some definition of mission infrastructures and their interaction with the scientific requirements, (3) the appraisal of the potential industrial participation in a long-term programme. The author's hope is that such an eventual programme may be international.

## ACKNOWLEDGEMENTS

The author thanks the following authorities (*in alphabetic order*) for their precious comments and questions (to his starting paper [1]) resulting in additional aspects to the present revision:

Dr. Anders Hansson (European Institute of Quantum Computing, UK), Dr. Roger Penrose (Mathematical Institute, Oxford - UK), Dr. Marco Quadrelli (JPL, USA), Dr. Salvatore Santoli (INT, Rome - Italy), and Prof. Allen Tough (University of Toronto, Canada).

---

[16] In the present context, 'possible' is given less uncertainty than 'probable'

## 10. References

Due to the enormous literature in the fields dealt with in this paper, we also included a few items containing a very large collection of references.


1. G. Vulpetti, *On the Viability of the Interstellar Flight*, paper IAA-98-IAA.4.1.05, 49th Congress of the International Astronautical Federation, Melbourne, 28 Sept - 2 Oct, 1998. Also, AA Special Issue for the Congress proceedings, 1999
2. Z. Paptrony, J. Lehmann and J. Prytz, *Interstellar Travel and Communication Bibliography - 1986 Update*, JBIS Vol. 40 No. 8, pp. 353-364, August 1987
3. Journal of the British Interplanetary Society (JBIS): INTERSTELLAR STUDIES issues in the Seventies, Eighties and Nineties (up-to-date)
4. M. A. G. Michaud, *A Grand Strategy for the Species*, 33rd IAF Congress, Rome, Sept. 1981
5. J. D. Barrow and F. J. Tipler, *The Anthropic Cosmological Principle*, Oxford University Press, Oxford 1990
6. A. Linde, *The Self-Reproducing Inflationary Universe*, Scientific American Special Issue, March 1998
7. R. Penrose, *The Large, the Small and the Human Mind*, Cambridge University Press, 1997
8. A. Tough, *Small Smart Interstellar Probes*, JBIS 51, pp. 167-174, 1998
9. J. L. *West, Design Issues for a Mission to Exploit the Gravitational Lensing Effect at 550 AU*, Proceedings of the 2nd IAA Symposium on Missions to the Outer Solar System and Beyond, Aosta, 29th June-1st July, 1998
10. G. Vulpetti, *Relativistic Astrodynamics: The Problem of Payload Optimization in a Two-Star Exploration Flight with an Intermediate Powered Swing-by,* Journal of the British Interplanetary Society, Vol. 37 pp. 515-521, Dec. 1984
11. C. P. Williams and S. H. Clearwater, *Explorations in Quantum Computing*, Springer-Verlag, 1997
12. S. Santoli, *Nano-to-Micro Integrated Single-Electron Bio-Macro-Molecular Electronics for Miniaturised Robotic "Untethered Flying Observers"*, Acta Astronautica vol. 41, No.'s 4-10, 279-287, 1997
13. S. Santoli, *Hyper-Interspersed Nano/MEMS-Architecture Design for New Concepts in Miniature Robotics for Space Exploration*, Proceedings of the 2nd IAA Symposium on Missions to the Outer Solar System and Beyond, Aosta, 29th June-1st July, 1998
14. Special Issue of JBIS/Interstellar-Studies on World Ships, Vol. 37, June 1984
15. E. F. Mallove and G. L. Matloff, *The StarFlight Handbook*, John Wiley & Sons, 1989
16. R. L. Forward, *Starwisp: an Ultralight Interstellar Probe*, JSR, vol. 22, 1985
17. G. Vulpetti, *Multiple Propulsion Concept for Interstellar Flight: General Theory and Basic Results*, JBIS, Vol. 43, pp. 537-550, 1990
18. H. D. Froning, Jr, *Field Propulsion for Future Flight*, AIAA Joint Propulsion Conference, Sacramento, 24-26 June 1991

19. M. G. Millis, *Challenge to Create the Space Drive*, Journal of Propulsion and Power, Vol. 13, pp. 577-582, Sept-Oct 1997

20. Y. Minami, *Possibility of Space Drive Propulsion*, IAA-94-IAA.4.1.658, 45th Congress of the International Astronautical Federation, Jerusalem, 9-14 October 1994

21. Y. Minami, *Spacefaring to the Farthest Shores: Theory and Technology of a Space Drive Propulsion System*, JBIS Vol. 50, pp. 263-276, 1997

22. H. Hayasaka and Y. Minami, *Repulsive Force Generation Due to Topological Effect of Circulating Magnetic Fluids*, STAIF-99 Congress, Albuquerque (NM), USA, Jan. 31 – Feb. 4, 1999

23. L. H. Ford and T. A. Roman, Physical Review D, **53**, p. 5496, 1996

24. L. H. Ford and T. A. Roman, *Restrictions on Negative Energy Density in Flat Space-Time*, Physical Review D, pp. 2082-2089, 15 Feb. 1997

25. M. J. Pfenning and L. H. Ford, Physical Review D, **55**, p.4813, 1997

26. M. Morris and K. S. Thorne, *Wormholes in Spacetime and Their Use for Interstellar Travel: a Tool for Teaching General Relativity, American Journal of Physics*, **56**, pp. 395-412, 1988

27. R. L. Forward, *Negative Matter Propulsion*, Journal of propulsion and Power, **6**, pp. 28-37, 1990

28. K. S. Thorne, *Closed Timelike Curves*, Proceedings of the 13th International Conference on General Relativity and Gravitation, Cordoba, Argentina, 28 June – 4 July 1992

29. M. Visser, Lorentzian Wormholes – from Einstein to Hawking, AIP Press, Woodbury (NY), 1995

30. M. Alcubierre, *The Warp Drive: Hyper-Fast Travel within General Relativity*, Classical and Quantum Gravity, **11**(5), pp. L73-L77, May 1994

31. W. A. Hiscock, *Quantum Effects in the Alcubierre Warp-Drive Space-Time*, , Classical and Quantum Gravity, **14**(11), pp. L183-L188, Nov. 1997

32. M. J. Pfenning and L. H. Ford, *The Unphysical Nature of 'Warp Drive'*, Classical and Quantum Gravity, **14**, pp. 1743-1751, 1997

33. B. Haisch and A. Rueda, *An Electromagnetic Basis for Inertia and Gravitation: What are the Implications for 21st Century Physics and Technology*?, Space Technology & Applications International Forum, Albuquerque, NM, Jan. 25-29, 1998

34. A. Rueda and B. Haisch, *Inertia as Reaction of the Vacuum to Accelerated Motion*, Physics letters A, 240, pp. 115-126, Feb. 1998

35. A. Rueda and B. Haisch, *Contribution to Inertial Mass by Reaction of the Vacuum to Accelerated Motion*, pre-print, Foundations of Physics (in press), 1998

36. R. H. Frisbee and S. D. Leifer, *Interstellar Mission Overview*, Ninth Advanced Space Propulsion Workshop, Pasadena, March 11-13, 1998

37. M. G. Millis, http:// www.lerc.nasa.gov/WWW/bpp/

38. M. G. Millis, *Breakthrough Propulsion Physics Research Program*, NASA TM 107381, Lewis Research Center (1997).

39. M. G. Millis, *NASA Breakthrough Propulsion Physics program*, Proceedings of the 2nd IAA Symposium on Missions to the Outer Solar System and Beyond, Aosta, 29th June-1st July, 1998

40. M. Tegmark, *On the Dimensionality of Spacetime*, Classical and Quantum Gravity, **14**, L69-L75, 1997

41. R. M. Wald, *The Present Status of General Relativity*, Proceedings of the 13th International Conference on General Relativity and Gravitation, Cordoba, Argentina, 28 June – 4 July 1992

42. P. W. Milonni, *Casimir Effect: Evidence and Implications,* Los Alamos National Labs, Los Alamos, New Mexico, 1994

43. The Physics of Quantum Information, European Research Network, index of selected publications, http://info.uibk.ac.at/c/ c7/c704/qinet/index,html

44. C. P. Williams and S. H. Clearwater, *Explorations in Quantum Computing*, Springer-Verlag, 1997

45. S. Santoli, *Molecular Nanotechnology – Rethinking Chemistry, Computation and Interstellar Flight*, this JBIS issue

46. G. Ghirardi, *Un'Occhiata all Carte di Dio*, (in Italian), Ed. Il Saggiatore, Milan, 1997

47. N. J. Cerf and C. Adami, *Quantum Mechanics of Measurement*, KRL preprint MAP-198 (12 Feb 1997), quant-ph/9605002 v2)

48. R. Penrose, *A Proposed Space Experiment*, invited paper to the Interstellar Space Exploration Symposium at the 50th IAF Congress, Amsterdam, Oct. 1999

49. *Robotic Interstellar Exploration in Next Century*, NASA/JPL, Pasadena, July 28-31, 1998; workshop summary, May 1999.