Ultrarelatvistic Rockets And The Ultimate Future of the Universe

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ABSTRACT:

Traversing cosmological scale distances will require ultrarelativistic rockets, i.e., rockets for which $\gamma = (1-v^2/c^2)^{-1/2} >> 1$. I outline the theory of high γ rockets, showing that (1) the expansion of the universe can be used to slow the rocket, thus drastically reducing the initial mass ratio: (2) proton-antiproton annihilation is the favored rocket propellent. (I develop the theory of rockets with such propellent); (3) the Standard Model of particle physics allows baryon number conservation to be violated, making it easier to manufacture antiprotons; (4) payloads will probably weigh less than a kilogram, because virtual humans will be the only humans ever to engage in interstellar travel; (5) constraints imposed by the universe's ultimate future must be taken into account in *any* analysis of interstellar travel. I show that these ultimate future constraints imply the top quark mass is 185 ± 20 GeV and the Higgs boson mass is 220 ± 20 GeV.

I. INTRODUCTION:

At this conference we've seen many proposals for

(1) Propellantless Propulsion

(2) Faster-Than Light Interstellar Travel

I proved a number of Theorems in the late 1970's (Tipler (1976, 1977a, 1977b, 1978a, 1978b) showing that faster-than-light travel is impossible unless we have a violation of the Timelike/Null Convergence Condition ($R_{\mu\nu}U^{\mu}U^{\nu} \geq 0$, where $R_{\mu\nu}$ is the Ricci tensor and U^{μ} is a timelike or null vector respectively), or a violation of the Averaged Null Convergence Condition (ANCC):

$$\int_{-\infty}^{+\infty} R_{\mu\nu}U^{\mu}U^{\nu} \geq 0 \qquad (1.1)$$

integration over complete null geodesics. The most recent evidence (Ford & Roman, 1996, 1997) strongly suggest that the ANCC holds even if the Casimir Effect causes a violation of the other two conditions. BUT -- suppose the evidence is misleading. Suppose that we CAN build a propellantless spaceship or a faster-than light (FTL) drive.

WHY BOTHER?

That is, think *carefully* about the implications of these proposed devices. I want to challenge the TACIT assumptions of this conference.

In Section II, I shall show that an antimatter rocket can effectively move a spaceship as close to the light cone as could a propellantless engine. As regards a FTL drive, it is well known (e.g. Tipler 1974) that such a device is equivalent to a time machine. This means that if such a device is possible, then superbeings from the universe's future can travel to us now, and restrict our actions to ensure their survival. In Section III, I shall outline the physics of the Ultimate Future, and show it will not be in the superbeings' interest to allow us to use FTL drives.

II. ULTRARELATIVISTIC ROCKETS:

A relativistic spacecraft is one whose cruising speed is comparable to the velocity of light c. For "short" interstellar distances, there is really no point in going faster than 0.9c, because at such a speed the transit time relative to the universal rest frame is 90% of the minimum transit time, whereas going faster than than 0.9c is extremely costly in terms of energy. For "large" interstellar distances a spacecraft needs a high initial speed in order to avoid being slowed down during transit by the expansion of the universe. I shall summarize the basic theory of spacecraft traveling at relativistic speeds; see (Tipler 1994b, 1996) for details.

The General Theory of Relativistic Rockets

If the mass of the payload is M_p and the mass of the entire rocket is initially M_i, then the ***mass ratio*** is $r \equiv M_i/M_p$. Defining $\beta \equiv v/c$, $\gamma \equiv (1-\beta^2)^{-\frac{1}{2}}$, we recall that the total energy E of the spacecraft is given by $E = \gamma mc^2$, where m is the *rest mass* of the spacecraft. In this paper, *all* masses will be rest masses. All modern textbooks in relativity written by professional relativists, use the term "mass" to refer only to rest mass, because this is the only concept of mass that is independent of the reference frame.

It will be essential to introduce a less familiar concept, that of the ***rapidity*** ω defined by

$$\cosh\omega \equiv \gamma \equiv \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \tag{2.1}$$

$$\sinh\omega \equiv \frac{\beta}{\sqrt{1-\beta^2}} = \frac{\frac{v}{c}}{\sqrt{1-\frac{v^2}{c^2}}} \tag{2.2}$$

and so $\tanh\omega = \beta = \frac{v}{c}$.

The reason for introducing the rapidity is that rapidities, unlike velocities, add linearly. That is, we have $\omega_E = \omega_r + \omega_q$, since $\tanh(\omega_r + \omega_q) = \frac{\tanh\omega_r + \tanh\omega_q}{1+\tanh\omega_r\tanh\omega_q}$ is both the standard velocity addition formula and an identity of hyperbolic functions.

To compute the mass ratio, suppose a rocket having initial mass $\tilde{M}$ moves forward by expelling a burst of gas with infinitesimal mass Δm at exhaust velocity v_s (as measured in the rocket's instantaneous rest frame), leaving the rocket with mass M and infinitesimal forward velocity dv. Then $d(\frac{v}{c}) = d\beta = \tanh(d\omega)$.

Conservation of energy in this situation is given by

$$\Delta mc^2\cosh\omega_s + Mc^2\cosh(d\omega) = \tilde{M}c^2 \tag{2.3}$$

and the conservation of momentum by

$$-\Delta mc\sinh\omega_s + Mc\sinh(d\omega) = 0 \tag{2.4}$$

Since $d\omega$ is infinitesimal, we have $\cosh(d\omega) \approx 1$, and $\sinh(d\omega) \approx d\omega$; putting in these approximations and dividing the momentum equation (2.4) by the energy equation (2.3) gives

$$\frac{\sinh\omega_s}{\cosh\omega_s} = \tanh\omega_s = \frac{v_s}{c} = \frac{M\,d\omega}{\tilde{M}-M} \tag{2.5}$$

But the change in the rocket rest mass is $dM = M - \tilde{M}$, so

$$d\omega = -\frac{v_s}{c}\frac{dM}{M} = -\beta_s\frac{dM}{M} \tag{2.6}$$

Now rapidities add linearly, so (2.6) can be integrated to give

$$\omega = \beta_s \ln\left(\frac{M_i}{M_p}\right) \tag{2.7}$$

which implies

$$\tanh\omega = \frac{v}{c} = \tanh\ln\left(\frac{M_i}{M_p}\right)^{\beta_s} \tag{2.8}$$

where v is the final velocity of the rocket in the rest frame of the Earth. After a little algebra, this expression gives

$$\frac{M_i}{M_p} = \left[\frac{1+\frac{v}{c}}{1-\frac{v}{c}}\right]^{\frac{c}{2v_s}} = \left[\frac{c+v}{c-v}\right]^{\frac{c}{2v_s}} \tag{2.9}$$

Since $\frac{v}{c} = \sqrt{1-\frac{1}{\gamma^2}}$, then if $\gamma \gg 1$, we have $\frac{v}{c} \approx 1 - \frac{1}{2\gamma^2}$, so the mass ratio is approximately

$$\frac{M_i}{M_p} \approx (2\gamma)^{\frac{c}{v_s}} \tag{2.10}$$

For photon rockets ($v_s = c$), this means that, in the ultrarelativistic limit ($\gamma \gg 1$), the ratio of the initial total energy of the rocket, including the fuel, to the final total energy of the payload is just

$$\frac{M_i c^2}{\gamma M_p c^2} = \frac{2\gamma}{\gamma} = 2$$

Photon rockets are thus a quite efficient means of obtaining a high γ: the total initial mass-energy needed to accelerate the rocket to the final velocity v is only twice the final total energy the payload has in the rest frame of the Earth. However, once the rocket's velocity has reached $0.9c$, it becomes extremely costly to decrease significantly the travel time as measured in the universal rest frame. When $v = 0.9c$, we have $\gamma = 2.3$, whereas $v = 0.99$ corresponds to $\gamma = 7.1$; the total rocket energy must be increased by a factor of 3 in order to decrease the transit time by only 10%. This is expensive, since for photon rockets the mass ratio is 4.4 for a velocity of $0.9c$ but 14.1 for a velocity of $0.99c$.

Since *any* spacecraft acceleration mechanism will require at least $E = (\gamma - 1)mc^2$ of energy to be imparted to the spacecraft, the photon rocket is within a factor of 2 of the most efficient acceleration mechanism.

Using the Expansion of the Universe to Slow a Rocket

A high γ spacecraft will be useful only if the spacecraft is going so far that the expansion of the universe becomes significant — as would be the case, for example, if one wished to go to the opposite side of the universe. In such a situation, the spacecraft would appear to be going slower and slower relative to the galaxies farther and farther away, since these galaxies are moving faster and faster away from us, by Hubble's law. The FRW metric is

$$ds^2 = -dt^2 + R^2(t)[d\chi^2 + \Sigma^2(\chi)(d\theta^2 + \sin^2\theta d\phi^2)] \tag{2.11}$$

Since this spacetime is spatially homogeneous and isotropic, a geodesic initally moving entirely in the the radial (χ) direction remains without velocity in either the θ or the ϕ directions. Thus a radial geodesic moves in the 2-dimensional space defined by the metric $ds^2 = -dt^2 + R^2(t)d\chi^2$. Since the metric components do not contain χ explicitly, this means that the momentum in the χ direction, p_χ, is a constant of the motion. But $p_\chi = g_{\chi\chi}p^\chi = g_{\chi\chi}d\chi/d\lambda$, where λ is the affine parameter if the particle we are following is a photon, and is equal to the particle's proper time per unit rest mass along the particle's trajectory if the particle is timelike (as it would be if it is a spacecraft).

If we compute the momentum in the radial direction in the local Lorentz rest frame of observers at rest in the FRW coordinates — such observers have constant χ, θ, ϕ, and they are the observers at rest with respect to the cosmological background radiation — we get (letting p^χ_{Local} be this momentum):

$$p^\chi_{Local} \equiv p^{\hat{\chi}} \equiv \langle \omega^\chi, p\rangle = \langle g^{1/2}_{\chi\chi} d\chi, p\rangle = g^{1/2}_{\chi\chi} p^\chi = g^{1/2}_{\chi\chi}\frac{d\chi}{d\lambda}$$

where ω^χ is a local orthonormal basis 1-form, and p is the 4-momentum vector. But since $g_{\chi\chi}d\chi/d\lambda$ is a conserved quantity, and since $g_{\chi\chi} = R^2(t)$, we have shown that $R(t)p^\chi_{Local}(t)$ is a constant, independent of cosmic time. Thus

$$\frac{p^\chi_{Local}(t_{now})}{p^\chi_{Local}(t)} = \frac{\gamma_{now}v_{now}}{\gamma(t)v(t)} = \frac{R(t)}{R(t_{now})} \tag{2.12}$$

where $p^{x}_{Local}(t_{now}) = \gamma_{now} m v_{now}$ is the relativistic momentum the spacecraft has in the rest frame of the stellar system which launches it, and $R(t_{now})$ is the scale factor of the universe the day the spacecraft is launched.

The crucial thing to note about equation (2.12) is that it says we can in effect use the expansion of the universe itself to slow down the spacecraft; we need not carry along any fuel to accomplish this. This is extremely important for high gamma spacecraft, because if all the velocity of transit had to be killed, the initial mass ratio given above would have to be *squared*. If the spacecraft is to reach the antipodal point at a time when the universe is 3×10^5 its present size, we would need an initial $\gamma_{now} = 5 \times 10^5$ for a photon rocket if the travel is to be relativistic the whole trip. (Having $\gamma(t_{max}) = 2$ is a sufficient condition for the entire trip to be relativistic, where t_{max} is the time of maximum expansion.) If we had to use the rocket to slow down from $\gamma = 5 \times 10^5$, we would have to have an initial mass ratio of 1×10^{12}. Instead, only $(3.7)(2)(5 \times 10^5) = 3.7 \times 10^6$ is necessary. (The extra factor of 3.7 is required to slow the payload from $\gamma = 2$ down to $\gamma = 1$.)

The Theory of Proton-Antiproton Rockets

However, a realistic relativistic rocket would probably not be a photon rocket, because the only known method of converting mass entirely into energy involves matter-antimatter annihilation. Thus the rocket fuel has to consist of half matter and half antimatter. The reaction $e^+ + e^- \rightarrow 2\gamma$ gives only photons, but there is no known method of storing large amounts of positrons, except as part of anti-atoms. So most of the antimatter mass would be antiprotons, which does not annihilate directly into two photons. Proton-antiproton annihilation generally proceeds (Cassenti 1988) by decay into pions:

$$p + \bar{p} \rightarrow m\pi^0 + n(\pi^+ + \pi^-)$$

where $m \approx n \approx 1.60$. None of the pions are stable, and the neutral pion usually decays via the reaction $\pi^0 \rightarrow 2\gamma$. The gamma rays from the neutral pions are lost, carrying away energy, but the charged pions will travel about 20 meters before they decay, and thus can provide thrust by having their trajectories bent by magentic fields so that they go out the rocket exhaust. The neutral pions carry away on the average zero net momentum in the rocket's instantaneous rest frame.

If some of the energy in the annihilation is lost, then equations (2.3) and (2.4) have to be modified. If a fraction $\eta\Delta mc^2$ of the propellent rest mass gets rapidity ω_s, and another fraction $\delta\Delta mc^2$ just disappears in the reaction, then equations (2.3) and (2.4) respectively become

$$\eta\Delta mc^2\cosh\omega_s + \delta\Delta mc^2 + Mc^2\cosh(d\omega) = \tilde{M}c^2 \tag{2.13}$$

$$-\eta\Delta mc\sinh\omega_s + Mc\sinh(d\omega) = 0 \tag{2.14}$$

Proceeding as in the derivation of equation (2.5), we get

$$\frac{\eta\sinh\omega_s}{\eta\cosh\omega_s + \delta} = \frac{Md\omega}{\tilde{M} - M} = -\frac{Md\omega}{dM} \tag{2.15}$$

where I have inserted the change in the rocket rest mass, $dM = M - \tilde{M}$. Integrating equation (2.15) gives

$$\omega = \left[\frac{\sinh\omega_s}{\cosh\omega_s + \frac{\delta}{\eta}}\right]\ln\left(\frac{M_i}{M_p}\right) \tag{2.16}$$

where now v_s is the velocity of the charged pions in the $p - \bar{p}$ annihilation reaction. Solving equation (2.16) for the mass ratio yields

$$\frac{M_i}{M_p} = \left[\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}\right]^{\frac{c}{2v_s}\left(1 + \frac{\delta}{\eta\gamma_s}\right)} \tag{2.17}$$

where $\gamma_s = \cosh\omega_s$.

But by conservation of energy we have

$$\eta\gamma_s = \delta$$

which reduces equation (2.17) to

$$\frac{M_i}{M_p} = \left[\frac{1+\frac{v}{c}}{1-\frac{v}{c}}\right]^{\frac{c}{v_s}} \tag{2.18}$$

For $\gamma \gg 1$, we have

$$\frac{M_i}{M_p} \approx (2\gamma)^{\frac{2c}{v_s}} \tag{2.19}$$

instead of equation (2.10). Equation (2.19) differs from equation (2.10) by an extra factor of 2 in the exponent.

Conservation of energy gives 2 × 938 − 4.8 × 139 MeV divided more or less evenly among 4.8 pions, so each charged pion has a kinetic energy of 252 MeV. The ratio of kinetic energy to rest mass is $\gamma - 1$, so each pion has $\frac{v_s}{c} = 0.935$. Equation (2.19) thus becomes

$$\frac{M_i}{M_p} \approx (2\gamma)^{2.14} \tag{2.20}$$

With the initial $\gamma_{now} = 5 \times 10^5$ required to reach the antipodal point by the time of maximum expansion, we would need an initial mass ratio of 1×10^{14}. (Remember that an extra factor of 17 is required, because the rocket must be used to reduce $\gamma(t_{max}) = 2$ down to $\gamma = 1$.)

Now the term "payload" in the mass ratio includes not only the payload proper, but also the fuel tanks and the rocket engines. The key to reducing both the mass of the payload proper and the masses of the tanks and engines is nanotechnology (Drexler 1992). I have argued elsewhere (Tipler 1994b, Section N) that the mass of the payload proper need be no greater than 100 grams. If we use molecular-size universal constructors to reshape the rocket and the engines as it accelerates, then in principle, the tanks and the motors can be made out of fuel; the tanks and motors will then make *zero* contribution to the payload mass. If this is done, then a matter-antimatter annihilation rocket capable of traveling, at relativistic velocities the whole way, from the Earth to the other side of the universe by the time of maximum expansion, would have a mass of ten billion metric tons.

Using the Standard Model to Reduce the Energy Cost of Making Antimatter

The current cost of five billion tons of antimatter is enormous. A large fraction of this enormous cost is due to the baryon and lepton number conservation law, which requires that a proton be created along with each antiproton. This means that at least half of the energy must go into creating useless protons. The same conservation law restricts nuclear energy to less than 1% efficiency: less than 1 % of the rest mass of nuclei can be converted into energy, whereas if the law did not hold, possibly all the mass could be converted into energy.

However, in 1976, Gerard t'Hooft showed that the law can be violated in the Standard Model of particle physics. The predicted violation is tiny, and has never been observed, but if the Standard Model is correct — and all experiments indicate that it is — then this violation must occur. A number of physicists (Tipler, 1994b, Section N) since 1976 have discovered ways in which the effect can be enhanced, but our mathematics is too primitive to analyze the details of the effect in the absence of experiments.

Why Virtual Humans will be the Only Humans Ever to Engage in Interstellar Travel

Recall that nanotechnology allows us to code one bit per atom in the 100 gram payload, so the memory of the payload would sufficient to hold the simulations of as many as 10^4 individual human equivalent personalities, at 10^{20} bits per personality. This is the population size of a fair sized town, as large as the population of "space arks" that have been proposed in the past for interstellar colonization. Sending simulations — virtual human equivalent personalities — rather than real world people has another advantage besides reducing the mass ratio of the spacecraft: one can obtain the effect of relativistic time dilation without the necessity of high γ by simply slowing down the rate at which the spacecraft computer runs the simulation of the 10^4 human equivalent personalities on board. One needs the large γ in the trip to the universal antipode in order to get there by the maximum expansion time, not to reduce the time experienced on board the spacecraft.

A third advantage of using virtual human equivalent personalities rather than real world humans is that it solves the problem of radiation shielding. Protons in the interstellar medium have the same γ in the spacecraft's rest frame as the spacecraft has in the medium's rest frame, and the resulting intense radiation from the protons in the interstellar medium has often been cited as proving the impossiblity of high γ spacecraft. One indeed needs thick shielding: 2 meters thickness of aluminum is required to stop 1 GeV protons ($\gamma = 2$). However, if the spacecraft has a cross-sectional area of $1mm^2$, then only 5 grams of aluminum is required.

A fourth advantage of virtual humans in a virtual environment over real humans is that the virtual humans will experience the simulated acceleration of the virtual environment rather than the real acceleration of the rocket. If a rocket accelerates at 155 gravities, real humans would be converted into jelly, while virtual humans on the same rocket would experience their choice of accelerations: the usual 1 gravity or less. Since there is no difference between an emulation and the machine emulated, I predict that no real human will ever traverse interstellar space. Humans will eventually go to the stars, but they will go as emulations; they will go as virtual machines, not as real machines.

III. THE ULTIMATE FUTURE OF THE UNIVERSE:

I shall show that the mutual consistency of *all* the laws of physics in the Ultimate Future imply: (1) the universe must be closed, with S^3 spatial topology; (2) the universe will expand to a maximum size, then collapse to a final singularity; (3) the universe must be nearly homogeneous and flat, with $\Delta T/T < 6 \times 10^{-5}$ and $4 \times 10^{-6} < \Omega_0 - 1 < 4 \times 10^{-4}$, where T, ΔT, and Ω_0 are the temperature and temperature variation of the Cosmic Background Radiation (CBR), and the density parameter resepctively; and finally the top quark and Higgs boson masses must be 185 ± 20 GeV and 220 ± 20 GeV respectively.

I shall then show that the ultimate future implied by the laws of physics is unlikely *unless* life expands to engulf the entire universe, and to control it, forcing event horizons to disappear. A spacetime without event horizons is called an Omega Point universe, and the theory of such a universe the Omega Point Theory. I shall show that this universe-engulfing behaviour of life is equivalent to the constructability of a "universal" computer, a computer that can emulate any other computer. Finally, I shall show life can survive in the far future only if FTL drives are never used. I shall only outline the proofs of these claims here. A full demonstration would require a book, which I've written: *The Physics of Immortality* (Tipler, 1994b).

Hawking has shown that if black holes (BHs) completely evaporate — which they will if the universe expands forever — then *some* information inside the BH will be lost, since event horizon can end only in singularities. This loss of information will necessarily cause unitarity to be violated. (I can show, but do not have the space to do so here, that this violation of unitarity cannot be circumvented by invoking quantum "hair" or the standard d-brane mechanisms.) But unitarity is a fundamental physical law. Hence, if astrophysical BHs exist — which they do — then the universe cannot expand forever. This means, if gravity is always attractive, that the universe must topologically be S^3 spatially, a universe which expands to a maximum size, and then recontracts to a final singularity (Barrow *et al* 1985, 1986).

The entropy of the universe is bounded below by the entropy in the CBR. By the Second Law of Thermodynamics, this entropy cannot decrease. But the Bekenstein Bound (See Tipler (1994b) for an analysis of this Bound; it's basically the Heisenberg Uncertainty Principle in relativistic guise) says if there are event horizions present:

$$Entropy < Information\, in\, Universe < \frac{\pi R^2}{L_{Planck}^2 \ln 2} \tag{3.1}$$

where R is the scale factor of the universe, and L_{Planck} is the Planck length (10^{-33} cm.). We have a contradiction with the Second Law if there are event horizons, since $R \to 0$ in the contracting phase of the universe. (The CBR entropy contradicts (3.1) when the CBR temperature reaches 10^4 GeV in the contracting phase.) However, if there are no event horizons present, then the Bekenstein Bound is not (3.1) but

$$Entropy < Information\,in\,Universe < \frac{2\pi ER}{\hbar c \ln 2} \tag{3.2}$$

where E is the total non-gravitational energy in the universe. It can be shown that *if* life (and/or computers) has engulfed the universe, then the available energy in the contracting phase increases as R^{-3}, so the righthand side of (3.2) diverges to infinity as $R \to 0$, thereby avoiding Second Law violation.

So life must become ubiquitous near the final singularity, and event horizions must disappear if the laws of physics are to remain consistent. But — it is well-known that S^3 homogeneous solutions of Einstein's equations without event horizons are of measure zero in the space of all solutions. It is exceedingly implausible that the entire universe could be evolving toward a measure zero state, so if such were to occur it would mean that some essential physics was being left out.

A universe with no event horizions is measure zero, however, *only* if the actions of *life/computers* are left out of the analysis. But if life is present, its effect on a large physical system cannot be ignored. Consider the Earth's atmosphere. If we ignored the effect of life, we would infer that it would have to consist of 95% carbon dioxide, the same as the atmospheres of Venus and Mars. Life has completely changed Earth's atmosphere: carbon dioxide has been removed by green plants and they have introduced free oxygen. The oxygen is sustained by the continual action of plants. So it will be with the universe as a whole. Life in the far future will expand and engulf the universe, and eliminate event horizions, something life *must* do if it is to survive. Further, life must be present in the ultimate future for the mutual consistency of the physical laws. As I show below, taking life into account makes the elimination of horizons necessarily present in the space of all *physically reasonable* solutions of Einstein's equations. In such a space of solutions, those solutions without event horizons are of normalized measure one, not measure zero.

In the preceeding discussion, I have identified life with computers. Let me now justify this, and rederive the Omega Point Theory from a computer science postulate (Tipler 1986): A UNIVERSAL COMPUTER CAN BE CONSTRUCTED.

The reason for believing a Universal Computer is not only fundamental in computer complexity theory, but its constuctability is also possible physically comes from the Feynman/Deutsch view of physical processes (Deutsch 1997), according to which computations and physical processes are in one-to-one correspondence: not only are all computations physical processes (obviously!) but conversely, all physical processes are really computations. In particular, the evolution of the universe is just a gigantic computation! Life also must be a form of computation, one in which the information is preserved by natural selection. The Oxford University zoologist Richard Dawkins (1976, 1987) has independently defended this computer defintion of life. This view of physics — regarding computer science and physics as being in 1-1 correspondence — has lead Feynman and Deutsch to invent the quantum computer, which justifies the view experimentally.

The ultimate limit to computation is therefore a fundamental physical law, the fundemantal limit on the complexity of physical processes. Computer science has already determined the most natural limit to the complexity of a computer, namely a universal computer.

Recall some key facts about universal computers. First, by the Church-Turing Thesis (see Deutsch 1997 for a discussion of this thesis), all universal computers are equivalent (not surprising, since by definition a universal computer is one which can emulate all other computers.) I shall need two theorems about universal computers: (1) they all have an infinite memory, and (2) each bit of this memory is always accessible to the central processor. See Minsky (1967) for the proofs of these theorems. These theorems have the following three implications for cosmology if a universal computer can be constructed:

(A) computation must continue in the universe until the end of time, since for all events p and q in a deterministic spacetime, $J^+(p) \cap J^-(q)$ is compact, where $J^\pm(q)$ is respectively the causal future (+) and causal past (-) of the event q (Hawking & Ellis 1973). A compact set *cannot* contain an infinite computer memory.

(B) the computer must process an infinity of bits between now and the end of time (since the computer is infinite), and

(C) the computer must store a diverging amount of causally connected bits of information as end of time is approached (causally, since each bit of the memory must be always accessible).

A universal computer cannot be constructed in an open (or inflationary) universe because all structures decay, and such universes expand too fast to use available energy to re-construct them (Tipler 1992). A universal computer cannot be constructed in a flat universe because there would not be enough energy available to send an infinity of signals back and forth across the universe an infinity of times (which must happen if all bits are to always be causally accessible). Thus we PREDICT that the universe must be closed. Recall that each bit of information *irreversibly* processed requires expending kT of free energy. By Implication (B), we must have

$$Total\,Information\,Processd = \int_{now}^{end\,of\,time} \frac{dE/dt}{kT}\,dt = +\infty \qquad (3.3)$$

The energy density ρ available in an appropriate asymmetric collapse of the universe increases as $\sim R^{-6}$, the total available energy as $\sim \rho R^3 \sim R^{-3}$ (as I stated above) the temperature increases as $\sim R^{-1}$, and $R \sim t^{1/3}$, where t is the proper time until the final singularity is reached at $t = 0$. Thus in a closed universe, there is MORE THAN ENOUGH ENERGY to process an infinity of bits.

PROVIDED event horizions disappear, so computer operations can be carried out over the entire universe. Note that the disappearance of event horizions also guarantees that each bit stored in memory is always available for further processing. The absence of event horizons means that in Penrose's c-boundary construction (Hawking & Ellis 1973; Tipler 1994b), the future c-boundary consists of a single point: call it the *Omega Point*, and this theory of the universe's Ultimate Future *The Omega Point Theory*.

Since the temperature of the universe is going to infinity as the final state is approached (recall $T \sim 1/R$), information must be stored in some other form than the chemical bonds now used. In general, information is stably stored if it is coded in energy levels with energy greater than kT. Such storage can be accomplished if we store info as standing waves with the universe itself as the bounding box, since the collapse of the universe would itself increase the energy of the waves as $E \sim 1/R$. Transferring the information from its present matrix of chemical bonds to standing waves is easiest if universe slows its collapse before the temperature reaches the chemical bond energy of $\sim 1/100$ eV. The Standard Model of particle physics minimally coupled to gravity says such a slowing force must exist, and *may* be of sufficient magnitude to work. The slowing effect is *maximized* and hence the likelihood of successful info transfer is maximized if (PREDICTION [Tipler 1994a,b]):

mass of top quark $= 185 \pm 20$ **GeV**, and **mass of Higgs boson** $= 220 \pm 20$ **GeV**

Computers will not be able to eliminate event horizions if all matter condensces into giant BHs before the matter can be reached by ultrarelativistic rockets. The only way this can be prevented is for irregularities to not have grown too large before other parts of the universe are reached by such rockets. Projecting this back on the CBR gives (PREDICTION): $\Delta T/T < 6 \times 10^{-5}$.

Setting up the conversion from information storage in present-day chemical bonds to universe-sized standing waves requires that computers/life have already engulfed the universe, and further, have been in causal contact before the standing waves are set up. It can be shown (Tipler 1994b) that this requires, in addition to approximate homogeneity at that far future time, (PREDICTION): $4 \times 10^{-6} < \Omega_0 - 1 < 4 \times 10^{-4}$.

The energy from asymmetric collapse of the universe does not become available until after the recollapse of the universe has begun. Until then, the conversion of matter into energy will be the primary source of energy. The causal structure of the universe actually prevents this matter-energy from being used too fast: in a matter-dominated universe, the universal antipodal point cannot be reached by $v < c$ rockets until after the time of maximal expansion. But a FTL drive would permit life to use resources too fast, and thus far future life would intervene to stop the use of FTL drives. With the above Ω_0, virtual humans would arrive at antipode 10^{18} years from now (when $R(t)/R(t_{now}) = 3 \times 10^5$), and our Sun would have long since left the Main Sequence. However, if Earth and the other planets in the universe are downloaded in computers before they are destroyed, virtual humans can eventually return to (emulated) Earth and/or all other planets at any time they choose. In short, every virtual human can personally see everything in the present day universe there is to see. FTL spaceships are unnecessary!

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