THE ASTROPHYSICAL JOURNAL, 511:429–431, 1999 January 20

HOW RARE ARE EXTRATERRESTRIAL CIVILIZATIONS, AND WHEN DID THEY EMERGE?

MARIO LIVIO
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
Received 1998 May 15; accepted 1998 August 21

ABSTRACT

It is shown that, contrary to an existing claim, the near-equality between the lifetime of the Sun and the timescale of biological evolution on Earth does not necessarily imply that extraterrestrial civilizations are exceedingly rare. Furthermore, on the basis of simple assumptions it is demonstrated that a near-equality between these two timescales may be the most probable relation. A calculation of the cosmic history of carbon production that is based on the recently determined history of the star formation rate suggests that the most likely time for intelligent civilizations to emerge in the universe was when the universe was already older than about 10 Gyr (for an assumed current age of about 13 Gyr).
Subject heading: extraterrestrial intelligence

1. INTRODUCTION

With the recent discovery of several extrasolar planets (and brown dwarfs) around solar-type stars (e.g., Mayor & Queloz 1995; Butler & Marcy 1996; Basri, Marcy, & Graham 1996; Cochran et al. 1997), the question of the potential existence of extraterrestrial "intelligent" civilizations has become more intriguing than ever. While this topic has been the subject of extensive speculations and many ill-defined (often by necessity) probability estimates, at least one study (Carter 1983) has examined it from a more global, statistical perspective. That study concluded, on the basis of the near-equality between the timescale of biological evolution on Earth, τ_l, and the lifetime of the Sun, $\tau_\odot$, that extraterrestrial civilizations are exceedingly rare, even if conditions favorable for the development of life are relatively common.

The conclusion on the rarity of extraterrestrial intelligent civilizations (Carter 1983; see also Barrow & Tipler 1986) was based on one crucial *assumption* and one *observation.* The assumption is that the timescale of biological evolution on a given planet, τ_l, and the lifetime of the central star, τ_*, are a priori entirely independent quantities. Put differently, this assumes that intelligent life forms at some random time with respect to the main-sequence lifetime of the star. The observation is that in the Earth-Sun system $\tau_l \sim \tau_*$ (to within a factor 2; for definiteness I will from now on take τ_l to represent the timescale for the appearance of land life). For completeness, I will reproduce the argument briefly here. If τ_l and τ_* are indeed independent quantities, then most probably either $\tau_l \gg \tau_*$ or $\tau_l \ll \tau_*$ (the set of $\tau_l \sim \tau_*$ is of very small measure for two independent quantities). If, however, $\tau_l \ll \tau_*$ *generally*, then it is very difficult to understand why in the first system to exhibit an intelligent civilization (the Earth-Sun system), it was found that $\tau_l \sim \tau_*$. If, on the other hand, *generally* $\tau_l \gg \tau_*$, then it is clear that the first system found to contain an intelligent civilization is likely to have $\tau_l \sim \tau_*$ (since for $\tau_l \gg \tau_*$ a civilization would not have developed). Thus, according to this argument, one has to conclude that typically $\tau_l \gg \tau_*$, namely, that *generally* intelligent civilizations will not develop and that the Earth is an extremely rare exception. What I intend first to show in the present work is that this conclusion is at best premature, by demonstrating not only that τ_l and τ_* may not be independent, but also that $\tau_l/\tau_* \sim 1$ may in fact be the *most probable* value for this ratio. This is done in § 2. In § 3 I use the recently determined cosmic star formation history to estimate the most likely time for intelligent civilizations to emerge in the universe.

2. THE RELATION BETWEEN τ_l AND τ_*

Superficially it appears that τ_l (which is determined mainly by biochemical reactions and the evolution of species) and τ_* (which is determined by nuclear burning reactions) should be independent. However, to realize that τ_l may in fact depend on τ_*, it suffices to note that light energy (from the central star) exceeds by 2–3 orders of magnitude all other sources of energy that can drive chemical evolution in the prebiotic environment (e.g., Deamer 1997; note that the statement that intelligent life will not develop for $\tau_l \gg \tau_*$ also constitutes a qualitative dependence). Below I identify a specific physical process that can, in principle at least, relate the two timescales. First I would like, however, to point out the following *general* property. Imagine that we find that the ratio τ_l/τ_* can be described by some function of the form $\tau_l/\tau_* = f(\tau_*)$ and that we further find that the function f is monotonically increasing (at least for the narrow range of values of τ_* corresponding to stars that allow the development of life; see below). This situation is shown schematically in Figure 1. Since for a Salpeter initial mass function (Salpeter 1955) the distribution of stellar lifetimes behaves like $\Psi(\tau_*) \sim \tau_*$ (because for main-sequence stars, $L \sim M^{3.45}$ [e.g., Allen 1973]), it is immediately clear (since the number of stars increases as we move to the right in Fig. 1) that it is *most probable* that in the first place that we encounter an intelligent civilization, we will find that $\tau_l/\tau_* \sim 1$. Therefore, if we can show that some processes are likely to produce a monotonically increasing (τ_*; τ_l/τ_*) relation, then the fact that $\tau_l \sim \tau_*$ in the Earth-Sun system will find a natural explanation and will not have any implications for the frequency of extraterrestrial civilizations.

I should note, though, that if the breadth of the "band" in Figure 1 becomes extremely large, this is essentially equivalent to there being no τ_l-τ_* relation, and Carter's argument is recovered.

I will now give a simple example of how a τ_l-τ_* relation may arise. I should emphasize that this is not meant to be understood as a realistic model but merely to demonstrate that such a relation *could* exist.

Nucleic acid absorption of UV radiation peaks between 2600 and 2700 Å and that of proteins between 2700 and

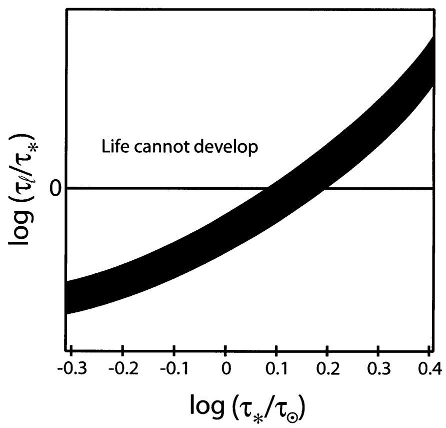

FIG. 1.—If the ratio of the timescale for biological evolution, τ_l, to the stellar lifetime, τ_*, is a monotonically increasing function of τ_*, then the most likely relation is $\tau_l \sim \tau_*$ (see text).

2900 Å (e.g., Davidson 1960; Sagan 1961; Caspersson 1950). Absorption in these bands is highly lethal to all known forms of cell activity (e.g., Berkner 1952). Of all the potential constituents of a planet's atmosphere, only O_3 absorbs efficiently in the 2000–3000 Å range (e.g., Watanabe, Zelikoff, & Inn 1958). It has in fact been suggested that the appearance of land life has to await the build up of a sufficient layer of protective ozone (Berkner & Marshall 1965; Hart 1978). Thus, it is important to understand the origin and evolution of oxygen in planetary atmospheres. While clearly only a limited knowledge of all the processes involved exists (and even that only from the Earth's atmosphere), this will suffice for the purposes of the present example. Two main phases can be identified in the rise of oxygen in planetary atmospheres (Berkner & Marshall 1965; Hart 1978; Levine, Hays, & Walker 1979; Canuto et al. 1983). In the first (which on Earth lasted $\sim 2.4 \times 10^9$ yr), oxygen is released from the photochemical dissociation of water vapor (this probably led on Earth to oxygen levels of ~ 0.001 of the present atmospheric level [PAL]). In the second phase (which on Earth lasted $\sim 1.6 \times 10^9$ yr), the amounts of O_2 and O_3 reach levels ~ 0.1 PAL, sufficient to shadow the land from lethal UV and allow the spread of life to dry land (the UV extinction is normally expressed as $I_x = I_0 e^{-kx}$, where I_0 is the impinging intensity, k is the absorption coefficient, and x is the path length in the atmosphere). The important point to note (Berkner & Marshall 1965; Hart 1978) is that the duration of the first phase is inversely proportional to the intensity of the radiation in the range 1000–2000 Å (significant peaks in H_2O absorption exist in the 1100–1300 Å and 1600–1800 Å ranges). Thus, for a given planetary size and orbit, the timescale for the development of shielding (which we identify approximately with τ_l) is dependent on the stellar spectral type and therefore on τ_*. For typical main-sequence star relations, $(L/L_\odot) = (M/M_\odot)^{3.45}$, $(R/R_\odot) = (M/M_\odot)^\beta$ (with β in the range 0.6–1 for spectral types F5–K5; see below), and empirical fractions of the radiation emitted in the 1000–2000 Å range (Stecker 1970; Carruthers 1971), a simple calculation (e.g., Livio & Kopelman 1990) leads to an approximate relation of the form

$$\tau_l/\tau_* \simeq 0.4(\tau_*/\tau_\odot)^{1.7} . \quad (1)$$

Clearly with the existence of a relation like equation (1), which is monotonically increasing, the highest probability is to find $\tau_l \sim \tau_*$, and hence the near-equality of these two timescales in the Earth-Sun system cannot be taken to imply that extraterrestrial civilizations are rare.

I should note again that the detailed evolution of the atmosphere is surely more complicated than a simple dependence on the intensity of UV photons. In particular, it may be that the different phases of the evolution have different dependences on the properties of the central star. The important point, however, is that, as the above example shows, the *existence* of a τ_l-τ_* relation is not implausible, and $\tau_l\,(\tau_*)$ *could* increase faster than linearly.

3. WHEN DID INTELLIGENT CIVILIZATIONS EMERGE IN THE UNIVERSE?

Given that extraterrestrial "intelligent" civilizations may not be exceedingly rare after all, one may ask what is a likely time in the history of the universe for such civilizations to emerge. I will restrict the discussion now to carbon-based civilizations. Assuming a principle of "mediocrity," one would expect the emergence to coincide perhaps with the peak in the carbon production rate. The main contributors of carbon to the interstellar medium are intermediate-mass stars (Wood 1981; Yungelson, Tutukov, & Livio 1993) through the asymptotic giant branch (AGB) and planetary nebula (PN) phases. Recent progress has been made in understanding the cosmic history of the star formation rate (SFR) (e.g., Madau et al. 1996; Lilly et al. 1996; Madau, Pozzetti, & Dickinson 1998). Assuming for simplicity that all the galaxies follow the same SFR history and stellar evolution processes, we can calculate the rate of formation of planetary nebulae (and hence the rate of carbon production) as a function of redshift. For this purpose, a population synthesis code has been used that follows the evolution of all the stars (assumed to be mainly in binaries) and includes all episodes of mass exchange, common envelope phases, etc. (for details see Yungelson et al. 1993; Yungelson et al. 1996; I am grateful to Lev Yungelson for carrying out the simulations). Figure 2 shows the assumed SFR as a function of redshift (taken as an approximation to the results in Madau et al. 1996) and the obtained PN formation rate as a function of redshift. As can be seen, the peak in the PN rate is somewhat delayed (to $z \simeq 1$) with respect to the peak in the SFR, and it is much more shallow at $z \lesssim 1$ owing to the build up of a reservoir during the previous epochs. Realizing that continuously

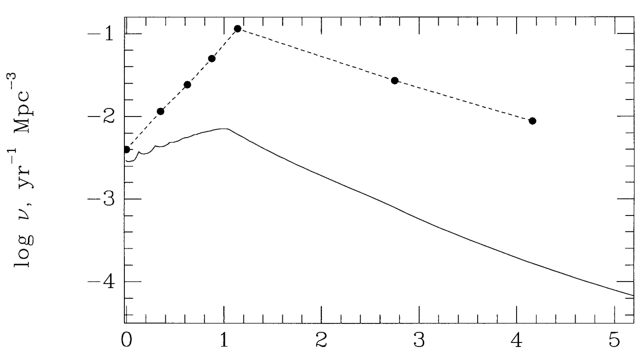

FIG. 2.—Dependence of the planetary nebula formation rate on redshift. *Dashed curve*: the star formation rate; *solid line*: planetary nebula formation rate.

habitable zones (CHZs) exist only around stars in the spectral range of about F5 to mid-K (e.g., Kasting, Whitmore, & Reynolds 1993) and that in general the biochemistry of life requires rather precise conditions, carbon-based life may be expected to start (with the assumed SFR history) around $z \sim 1$; this corresponds to an age of the universe of 5.6×10^9 yr for $\Omega_0 = 0.2$, as seems to be indicated by recent observations (e.g., Garnavich et al. 1998; Perlmutter et al. 1998; Reiss, Press, & Kirshner 1996; Carlberg et al. 1997 and a present age of $t_0 = 13$ Gyr). Given the fact that the time required to develop intelligent civilizations is $\tau_l \sim \tau_*$, as I have shown in the previous section, it is expected that civilizations will emerge when the age of the universe is $\gtrsim 10$ Gyr or maybe even somewhat older, since the CHZs around K stars are somewhat wider (in log distance) than around G stars. A younger emergence age will be obtained if the star formation rate does not decline at redshifts $1.2 \lesssim z \lesssim 5$ but rather stays flat (as is perhaps suggested by the recent *COBE* Diffuse Background Experiment; Hauser et al. 1998; Calzetti & Heckman 1999).

Finally, I should note that the arguments presented in this paper should definitely not be taken as attempting to imply that extraterrestrial intelligent civilizations do exist. Rather, they show that the conclusion that they do not is, at best, premature (see also Rees 1997 for discussions of related issues).

This work has been supported in part by NASA grant NAG5-6857. I thank the referee for his careful reading of the manuscript.

REFERENCES

Allen, C. W. 1973. Astrophysical Quantities (London: Athlone)
Barrow, J. D., & Tipler, F. J. 1986, The Anthropic Cosmological Principle (Oxford: Clarendon)
Basri, G., Marcy, G. W., & Graham, J. R. 1996, ApJ, 458, 600
Berkner, L. V. 1952, in Proc. Conf. on Ionospheric Physics (Geophys. Res. 12) (Cambridge: Air Force Cambridge Research Center), 13
Berkner, L. V., & Marshall, K. C. 1965, J. Atmos. Sci., 22, 225
Butler, R. P., & Marcy, G. W. 1996, ApJ, 464, L153
Calzetti, D., & Heckman, T. M. 1999, ApJ, submitted
Canuto, V. M., Levine, J. S., Augustsson, T. R., Imhoff, C. L., & Giampapa, M. S. 1983, Nature, 305, 281
Carlberg, R. G., Morris, S. L., Yee, H. K. C., & Ellingson, E. 1997, ApJ, 479, L19
Carruthers, G. R. 1971, ApJ, 166, 349
Carter, B. 1983, Philos. Trans. R. Soc. London, A 310, 347
Caspersson, T. O. 1950, Cell Growth and Cell Function: A Cytochemical Study (New York: Norton)
Cochran, W. D., Hatzes, A., Mary, G. W., & Butler, R. P. 1997, ApJ, 483, 457
Davidson, J. N. 1960, The Biochemistry of the Nucleic Acids (New York: Wiley)
Deamer, D. W. 1997, Microbiology and Molecular Biology Reviews, 61, 239
Garnavich, P. M., et al. 1998, ApJ, 493, L53
Hart, M. H. 1978, Icarus, 33, 23
Hauser, M. G., et al. 1998, ApJ, 508, 25
Kasting, J. F., Whitmore, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Levine, J. S., Hays, P. B., & Walker, J. C. G. 1979, Icarus, 39, 295
Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1è
Livio, M., & Kopelman, A. 1990, Nature, 343, 25
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Madau, P., Pozzetti, L., & Dickinson, M. 1997, ApJ, 498, 106
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Perlmutter, S., et al. 1998, Nature, 391, 51
Rees, M. 1997, Before the Beginning (Reading: Addison-Wesley)
Reiss, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 88
Sagan, C. 1961, Radiat. Res., 15, 174
Salpeter, E. E. 1955, ApJ, 121, 161
Stecker, T. P. 1970, ApJ, 159, 543
Watanabe, K., Zelikoff, M., & Inn, E. C. Y. 1958, Adv. Geophys., 5, 153
Wood, P. R. 1981, in Physical Processes in Red Giants, ed. I. Iben, Jr., & A. Renzini (Dordrecht: Reidel), 205
Yungelson, L., Livio, M., Truran, J. W., Tutukov, A., & Fedorova, A. 1996, ApJ, 466, 890
Yungelson, L. R., Tutukov, A. V., & Livio, M. 1993, ApJ, 418, 794