Icarus **151**, 307–313 (2001)
doi:10.1006/icar.2001.6607, available online at http://www.idealibrary.com on IDEAL®

An Estimate of the Age Distribution of Terrestrial Planets in the Universe: Quantifying Metallicity as a Selection Effect

Charles H. Lineweaver

School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
E-mail: charley@bat.phys.unsw.edu.au

Received September 13, 2000; Revised January 17, 2001; Posted online April 23, 2001

Planets such as the Earth cannot form unless elements heavier than helium are available. These heavy elements, or "metals," were not produced in the Big Bang. They result from fusion inside stars and have been gradually building up over the lifetime of the Universe. Recent observations indicate that the presence of giant extrasolar planets at small distances from their host stars is strongly correlated with high metallicity of the host stars. The presence of these close-orbiting giants is incompatible with the existence of Earth-like planets. Thus, there may be a Goldilocks selection effect: with too little metallicity, Earths are unable to form for lack of material; with too much metallicity, giant planets destroy Earths. Here I quantify these effects and obtain the probability, as a function of metallicity, for a stellar system to harbor an Earth-like planet. I combine this probability with current estimates of the star formation rate and of the gradual buildup of metals in the Universe to obtain an estimate of the age distribution of Earth-like planets in the Universe. The analysis done here indicates that three-quarters of the Earth-like planets in the Universe are older than the Earth and that their average age is 1.8 ± 0.9 billion years older than the Earth. If life forms readily on Earth-like planets—as suggested by the rapid appearance of life on Earth—this analysis gives us an age distribution for life on such planets and a rare clue about how we compare to other life which may inhabit the Universe. © 2001 Academic Press

Key Words: **terrestrial planets; extrasolar planets; cosmochemistry; planetary formation; planets.**

1. AIMS

Observations of protoplanetary disks around young stars in star-forming regions support the widely accepted idea that planet formation is a common by product of star formation (e.g., Beckwith *et al.* 2000). Our Solar System may be a typical planetary system in which Earth-like planets accrete near the host star from rocky debris depleted of volatile elements, while giant gaseous planets accrete in the ice zones ($\gtrsim$4 AU) around rocky cores (Boss 1995, Lissauer 1995). When the rocky cores in the ice zones reach a critical mass ($\sim$10 m_{Earth}) runaway gaseous accretion (formation of Jupiters) begins and continues until a gap in the protoplanetary disk forms or the disk dissipates (Papaloizou and Terquem 1999, Habing *et al.* 1999). The presence of metals is then a requirement for the formation of both Earths and Jupiters.

We cannot yet verify if our Solar System is a typical planetary system or how generic the pattern described above is. The Doppler technique responsible for almost all extrasolar planet detections (Mayor and Queloz 1995, Butler *et al.* 2000 and references therein) is most sensitive to massive close-orbiting planets and is only now allowing detection of planetary systems like ours, i.e., Jupiters at $\gtrsim$4 AU from nearby host stars. The Doppler technique has found more than 40 massive ($0.2 \lesssim m/m_{Jup} \lesssim 10$) extrasolar planets in close ($0.05 \lesssim a \lesssim 3$ AU), often eccentric orbits around high metallicity host stars (Schneider 2000). I refer to *all* of these giants as "hot Jupiters" because of their high mass and proximity to their central stars. Approximately 5% of the Sun-like stars surveyed possess such giant planets (Marcy and Butler 2000). Thus there is room in the remaining 95% for stars to harbor planetary systems like our Solar System.

It is not likely that giant planets have formed in situ so close to their host stars (Bodenheimer *et al.* 2000). It is more likely that after formation in the ice zone, these giants moved through the habitable zone, destroyed nascent Earths (or precluded their formation), and are now found close to their host stars (Lin *et al.* 1996). How this migration occurred is an active field of research. However, independent of the details of this migration, recent detections of extrasolar planets are telling us more about where Earths are not, than about where Earths are.

The aims of this paper are to use the most recent observational data to quantify the metallicity range compatible with the presence of Earths and estimate the age distribution of Earth-like planets in the Universe. The outline of the analysis is as follows:

1. Compare the metallicity distribution of stars hosting hot Jupiters with the metallicity distribution of stars in the solar neighborhood to obtain the probability of hosting hot Jupiters (and therefore the probability of destroying Earths).
2. Assume that starting in extremely low metallicity stars, the probability to produce Earths increases linearly with metallicity (this assumption is discussed in Section 2.2).
3. Combine items 1 and 2 above to estimate the probability of harboring Earths as a function of metallicity (Fig. 1).

0019-1035/01 $35.00

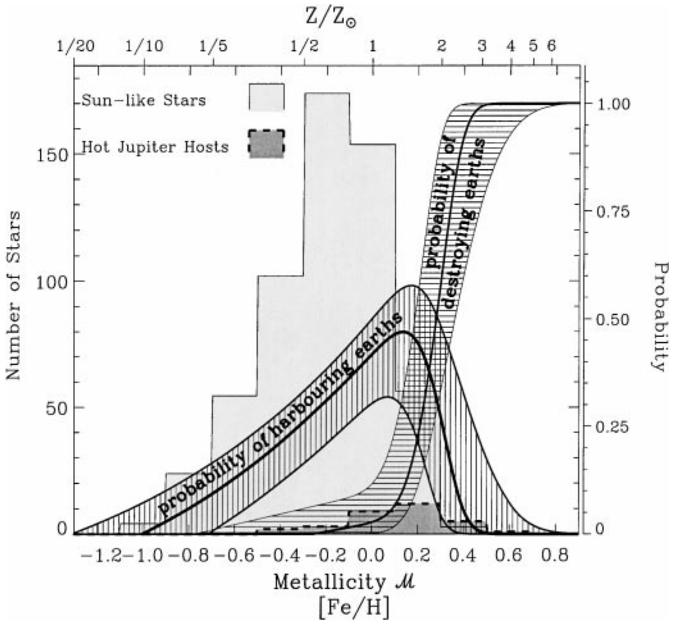

FIG. 1. If metallicity had no effect on planet formation we would expect the metallicity distribution of stars hosting hot Jupiters (giant, close-orbiting extrasolar planets, dark gray) to be an unbiased subsample of the distribution of Sun-like stars in the solar neighborhood (light gray). However, hot Jupiter hosts are more metal-rich. Hot Jupiters have the virtue of being Doppler-detectable but they destroy or preclude the existence of Earths in the same stellar system. For a given metallicity, the probability of destroying Earths is the ratio of the number of hot Jupiter hosts to the number of stars surveyed (Eq. (1)). The probability of harboring Earths (Eq. 2) is based on the assumption that the production of Earths is linearly proportional to metallicity but is cut off at high metallicity by the increasing probability to destroy Earths. The upper x-axis shows the linear metal abundance.

4. Use current estimates of the star formation rate in the Universe (Fig. 2A) and observations of high redshift metallicities to estimate the metallicity distribution of star-forming regions as a function of time (Fig. 2B).

5. Combine items 3 and 4 above to estimate the age distribution of Earth-like planets in the Universe (Fig. 2C).

2. HARBORING AND DESTROYING EARTHS

Figure 1 shows the metallicity distribution of 32 stars hosting hot Jupiters whose metallicities have been published (Gonzalez 2000, Table 1, Butler *et al.* 2000, Table 4, and references therein). The fact that these hosts are significantly more metal-rich than Sun-like stars in the solar neighborhood has been reported and discussed in several papers, including Gonzalez (1997, 1998, 2000), Ford *et al.* (1999), Queloz *et al.* (2000), and Butler *et al.* (2000). The metallicity distribution of Sun-like stars in Fig. 1 is a linear combination of similar histograms in Sommer-Larsen (1991) and Rocha-Pinto and Maciel (1996). These two references were chosen because their G dwarf samples are taken from the solar neighborhood and, although they are not identical to the metallicity distribution of the target stars that have been searched for planets using the Doppler technique, they are good representatives of these stars.

Let the observed metallicity distribution of the Sun-like stars hosting giant planets be $N_H(\mathcal{M})$, where $\mathcal{M} = [\mathrm{Fe/H}] \equiv \log(\mathrm{Fe/H}) - \log(\mathrm{Fe/H})_\odot \approx \log(Z/Z_\odot)$, and $Z_\odot = 0.016$ is the mass fraction of metals in the Sun. In Fig. 1, the distribution of Sun-like stars, $N(\mathcal{M})$, has been normalized so that the 32 host stars represent 5.6% (the average planet-finding efficiency given in Marcy and Butler (2000)), of the total. That is, each bin of $N(\mathcal{M})$ has been rescaled such that $0.056 \sum_i N(\mathcal{M}_i) = 32$. Target stars have not been selected for metallicity. Although Doppler shifts can be measured with slightly more precision in metal-rich stars, and metal-rich stars are slightly brighter for a given spectral type (leading to a Malmquist bias), these two selection effects are estimated to be minor compared to the difference between the distributions in Fig. 1 (Butler *et al.* 2000).

2.1. *Probability of Destroying Earths*

For a given metallicity, an estimate of the relative probability that a star will host a hot Jupiter is the ratio of the number of stars hosting hot Jupiters to the number of stars targeted,

$$P_{DE}(\mathcal{M}) = \frac{N_H(\mathcal{M})}{N(\mathcal{M})}. \tag{1}$$

This is plotted in Fig. 1 and labeled "probability of destroying Earths." At low metallicity, $P_{DE}(\mathcal{M})$ is low and remains low until solar metallicity, where it rises steeply. This probability predicts that more than 95% of Sun-like stars with $\mathcal{M} > 0.4$ will have a Doppler-detectable hot Jupiter, ~20% of $\mathcal{M} \sim 0.2$ stars will have one, and ~5% of solar metallicity stars ($\mathcal{M} \sim \mathcal{M}_\odot \equiv 0$) will have one. These predictions are also supported by independent observations:

- A star with extremely high metallicity was included in the target list because of its high metallicity ($\mathcal{M} = 0.5$). A planet, BD-10 3166, was found around it (Butler *et al.* 2000). This star was not included in Fig. 1 because of selection bias, but this result does support the probability calculated here: $P_{DE}(\mathcal{M} = 0.5) \sim 1$.
- Thirty-four thousand stars in the globular cluster Tucanae 47($\mathcal{M} = -0.7$) were monitored with HST for planets transiting the disks of the hosts. Fifteen or 20 such transits were predicted based on an ~5% planet-finding efficiency (assumed to be independent of metallicity and stellar environment). None has been found (Gilliland *et al.* 2000). This result is consistent with the probability calculated here, $P_{DE}(\mathcal{M} = -0.7) \sim 0$, but Gilliland *et al.* (2000) also suggest that the lack of planets could be due to high stellar densities disrupting planetary stability.

The width of the "probability of destroying Earths" region has been set by the errors on the terms in Eq. (1). The region is broad enough to contain $P_{DE}(\mathcal{M})$'s calculated when alternative estimates of $N(\mathcal{M})$ are used singly or in combination (e.g., Sommer-Larsen 1991, Rocha-Pinto and Maciel 1996, Favata *et al.* 1997) and when a range of planet-finding efficiencies are assumed (3 to 10%). Thus, the curve is fairly robust to variations in both the estimates of the metallicity distribution of the target stars and to varying estimates of the efficiency of finding hot Jupiters. When larger numbers of hot Jupiters are found and the metallicity distribution of the target stars is better known, the new $P_{DE}(\mathcal{M})$ should remain in (or very close to) the region labeled "probability of destroying Earths" in Fig. 1.

2.2. *The Probability of Producing Earths*

The probability of producing Earths is zero at zero metallicity and increases as metals build up in the Universe. The qualitative validity of this idea is broadly agreed upon (Trimble 1997, Whittet 1997), but it is difficult to quantify. During star formation, varying degrees of fractionation transform a stellar metallicity disk into rocky and gaseous planets. Simulations of terrestrial planet formation by Wetherill (1996) suggest that the mass of rocky planets within 3 AU is approximately proportional to the surface density of solid bodies in the protoplanetary disk. In the low surface density regime ($\sim$3 g/cm^2), where finding enough material to make an Earth is a problem, the number of planets in the mass range $0.5 < m/m_{Earth} < 2$ increases roughly in proportion to the surface density, i.e., to the metallicity. This increase is not because the overall number of planets increases but because the masses (of a constant number of planets) increase, bringing them into the Earth-like mass range. These simulations may be the best evidence we currently have to support the idea that in the low metallicity regime, the probability of forming Earths is linearly proportional to metallicity. This also suggests that the earliest forming Earths orbit minimal metallicity stars and are at the low mass end of whatever definition of "Earth-like" is being used.

Similar considerations apply to Jupiter formation but at a slightly higher surface density threshold. Weidenschilling (1998) finds that a 10 g/cm^2 disk surface density is not quite enough to initiate runaway Jupiter formation but that a modest increase in surface density will. These simulations support the standard core accretion models of planet formation and suggest that planet formation (both rocky and gaseous) is enhanced when more metals are available.

In this analysis I make the simple assumption that the ability to produce Earths is zero at low metallicity and increases linearly with metallicity of the host star. Specifically, let $P_{PE}(\mathcal{M})$ be the relative ability to produce Earths as a function of metallicity. I assume the following:

- $P_{PE}(\mathcal{M}) \propto Z$ (Earth production is proportional to the abundance of metals).
- $P_{PE}(\mathcal{M} = -1.0) = 0$. That is, at very low metal abundance ($Z/Z_\odot \sim 1/10$), the probability of producing Earths is 0. To represent the uncertainty in this zero probability boundary condition, the range $1/20 < Z/Z_\odot < 1/5$ is shown in Fig. 1. This assumption is discussed later.
- The most metallic bin, $\mathcal{M} = 0.6$, is assigned the probability of 1: $P_{PE}(\mathcal{M} = 0.6) = 1$.

2.3. *Probability of Harboring Earths*

The probability of a stellar system harboring Earths, $P_{HE}(\mathcal{M})$, is the probability of producing Earths times the probability of not destroying them,

$$P_{HE}(\mathcal{M}) = P_{PE}(\mathcal{M}) \times [1 - P_{DE}(\mathcal{M})]. \tag{2}$$

This probability of harboring Earths is plotted in Fig. 1. Starting at low metallicity, it rises linearly and then gets cut off sharply at $\mathcal{M} \gtrsim 0.3$. It peaks at $\mathcal{M} = 0.135$, has a mean of -0.063, and a median of -0.036. The 68% confidence range is $[-0.38 < \mathcal{M} < 0.21]$. $P_{HE}(\mathcal{M})$ can be used to focus terrestrial planet search strategies. For example, to maximize the chances of finding Earths, NASA's terrestrial planet finder (TPF) should look at stars with metallicities within the 68% confidence range and in particular near the peak of $P_{HE}(\mathcal{M})$. Also, since there is a radial metallicity gradient in our Galaxy, $P_{HE}(\mathcal{M})$ can be used to define a galactic metallicity-dependent habitable zone analogous to the water-dependent habitable zones around stars. This can be done by replacing "t" in Eqs. (3), (4), and (6) with galactic radius "R" and replacing the $SFR(t)$ with the density of Sun-like stars $\rho(R)$.

The Sun ($\mathcal{M}_\odot \equiv$ [Fe/H] $\equiv 0$) is more metal-rich than $\sim 2/3$ of local Sun-like stars and less metal-rich than $\sim 2/3$ of the stars hosting close-orbiting extrasolar planets. The high value of $\mathcal{M}_\odot$ (compared to neighboring stars) and the low value compared to hot Jupiter hosts may be a natural consequence of the Goldilocks metallicity selection effect discussed here (see also Gonzalez 1999).

Models need to simultaneously explain the presence of hot Jupiters close to the host star, the high metallicity of the host stars (specifically the steepness of the rise in P_{DE} seen in Fig. 1) and the small eccentricities of the closest-orbiting planets and the large eccentricities of the planets further out. Planet–planet gravitational scattering may provide a natural way to explain these features (Weidenschillling and Marzari 1996, Rasio and Ford 1996, Lin and Ida 1997). Higher metallicity of the protoplanetary disk enhances the mass and/or number of giant planets, thereby enhancing the frequency of gravitational encounters among them. Simulations with up to nine planets have been done (Lin and Ida 1997) and, apparently, "the more the merrier." That is, the more planets there are, the more likely one is to get scattered into a sub-AU orbit. The least massive planets suffer the largest orbital changes. Thus the least massive are more likely to be ejected, but they also are more likely to be gravitationally scattered into orbits with small periastrons which can become partially circularized either by tidal circularization or by the influence of a disk (provided the disk has not dissipated before the scattering).

3. STAR FORMATION RATE OF THE UNIVERSE

The observational determination of the star formation rate (*SFR*) of the Universe has been the focus of much current work, which we summarize in Fig. 2A. Various sources indicate a *SFR* at high redshift an order of magnitude larger than the current *SFR*. Initial estimates in which a peak of star formation was found at redshift $1 \lesssim z \lesssim 2$ are being revised as new evidence indicates that there may be no peak in the star formation rate out to the maximum redshifts available ($z \sim 5$).

Let us restrict our attention to the set of Sun-like stars (spectral types F7–K1, in the mass range $0.8 \lesssim m/m_{\odot} \lesssim 1.2$) that have ever been born in the Universe. Since ∼5% of the mass that forms stars forms Sun-like stars, the star formation rate as a function of time, $SFR(t)$, can be multiplied by $A \sim 0.05$ to yield the age distribution of Sun-like stars in the Universe. Here, the standard simplification is made that the stellar initial mass function is constant. If low mass star formation is suppressed in low metallicity molecular clouds (Nishi and Tashiro 2000) then the 1.5 Gyr delay between *SFR* and *PFR* (Section 5) is even longer.

If all Sun-like stars formed planets irrespective of their metallicity, then the planet formation rate in the Universe would equal $A \times SFR(t)$, shown in Fig. 2A. However, Fig. 1 indicates that metallicity is a factor which should be taken into account. Thus, we estimate the Earth-like planet formation rate, $PFR(t)$, orbiting Sun-like stars as

$$PFR(t) = A \times SFR(t) \times f(t), \tag{3}$$

where $f(t)$ is the fraction of stars being formed at time t which are able to harbor Earths. If all Sun-like stars formed planets and metallicity had no effect on terrestrial planet formation, we would have $f(t) = 1$. If we knew that on average one out of every thousand Sun-like stars had an Earth-like planet (and this number did not depend on the metallicity of the star), then the planet formation rate would be $PFR(t) = A \times SFR(t) \times 0.001$, which is just a rescaling of the *SFR* in Fig. 2A. A plausible first approximation could have $f(t) \propto \overline{\mathcal{M}}(t)$. That is, the higher the average metallicity of the Universe, the higher the efficiency with which star formation produces Earths. In this analysis, however, this guess is improved on by taking into account the dispersion of metallicity of star-forming regions around the mean at any given time, as well as by including the metallicity-dependent selection effect for harboring Earths. When these are taken into consideration, $f(t)$ becomes an integral over metallicity,

$$f(t) \approx \int P(\mathcal{M}, \overline{\mathcal{M}}(t))\, P_{HE}(\mathcal{M})\, d\mathcal{M}, \tag{4}$$

where P_{HE} was derived above and $P(\mathcal{M}, \overline{\mathcal{M}}(t))$ is a Gaussian parametrization of the metallicity distribution of star-forming regions in the Universe (Eq. (6)).

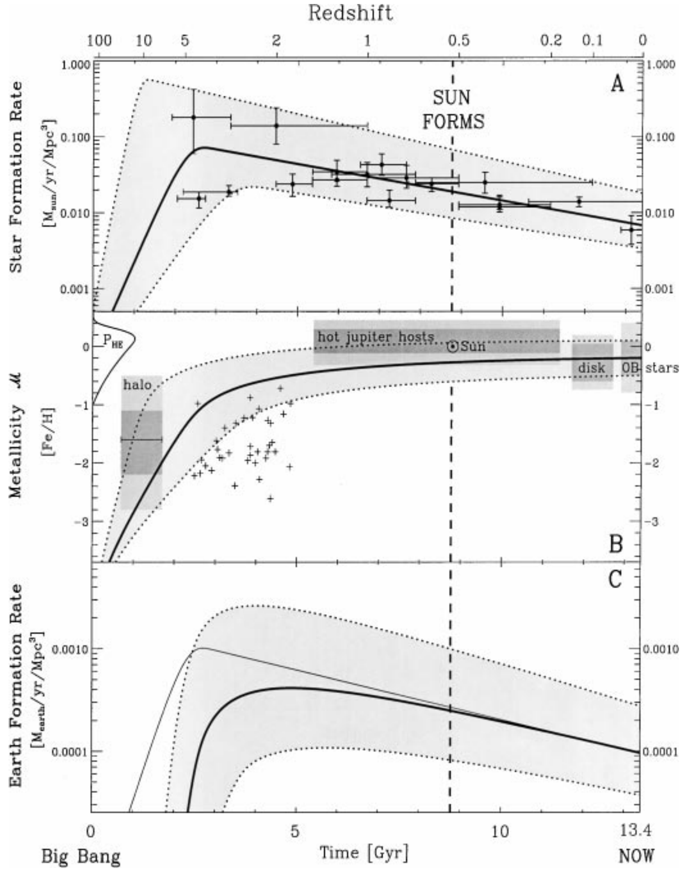

FIG. 2. These three panels show (A) current estimates for the evolution of the star formation rate in the Universe, (B) current estimates of the buildup of metallicity in the Universe, and (C) the age distribution of Earths in the Universe. The cumulative effect of star formation is to gradually increase the metallicity of the Universe. The cumulative integral of the star formation rate in A (Eq. (5)) is plotted in B. A combination (Eq. (4)) of the probability of harboring Earths (Eq. (2)) with the metallicity of the Universe as a function of time (Eq. (6)) yields an estimate (Eq. (3)) of the age distribution of Earths in the Universe (C). The star formation rates in A are from a compilation in Barger *et al.* (2000). The gray band represents the uncertainty in the star formation rate and controls the width of the gray bands in B and C. In B, the metallicity distributions of various stellar populations are plotted and are consistent with this universal metallicity plot. The metallicity distribution of the stars in the Milky Way halo (Laird *et al.* 1988) is represented by the dark gray (68% confidence level) and light gray (95% confidence level) and is plotted at its time of formation (Lineweaver 1999). The metallicity distributions of stars in the Milky Way disk (Favata *et al.* 1997), of massive OB stars (Gummersbach *et al.* 1998), and of stars hosting hot Jupiters are similarly represented. The probability of harboring Earths, P_{HE} from Fig. 1, is plotted in the top left of B. The "+" signs in B are the metallicity of damped Lyman-α systems from a compilation by Wasserburg and Qian (2000). The age range of the disk metallicity has been reduced to aid comparison with the OB stars and the hot Jupiter hosts. The thin solid line in C is the star formation rate from A, rescaled to the current Earth formation rate. If the formation of Earths had no metallicity dependence (or any other dependence on a time-dependent quantity) it would be identical to such a rescaling of the star formation rate. The ∼1.5 Gyr delay between the onset of star formation and the onset of Earth formation is due to the metallicity requirements for Earth formation.

4. THE BUILDUP OF METALLICITY IN THE UNIVERSE

The Universe started off with zero metallicity and a complete inability to form Earths. The metallicity of the Universe gradually increased as a result of star formation and its by products: various types of stellar novae and stellar winds. Various observations form a consistent picture of the gradual increasing metallicity of the Universe (Fig. 2B).

The star formation rate plays a dual role in this analysis since stars make planets ($PFR \propto SFR$, Eq. (3)) and stars make metals, $\frac{d\mathcal{M}}{dt}(t) \propto SFR(t)$. Integration of this last proportionality yields the increasing mean metallicity, $\overline{\mathcal{M}}(t)$, of star-forming regions in the Universe:

$$\int_0^t SFR(t')\,dt' \sim \overline{\mathcal{M}}(t). \tag{5}$$

The resulting $\overline{\mathcal{M}}(t)$ is plotted in Fig. 2B (thick line). The gray area around $\overline{\mathcal{M}}(t)$ reflects the spread in the estimates of the *SFR* (gray area in A). Metallicity observations in our Galaxy and at large redshifts are available to check the plausibility of this integral and are shown in Fig. 2B.

At any given time t, some star-forming regions have low metallicity while some have high metallicity. We parametrize this spatial dispersion around the mean by a time-dependent Gaussian centered on $\overline{\mathcal{M}}(t)$:

$$P(\mathcal{M}, \overline{\mathcal{M}}(t)) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{(\mathcal{M} - \overline{\mathcal{M}}(t))^2}{2\sigma^2}\right]. \tag{6}$$

The current metallicity distribution of OB stars in the thin disk (Gummersbach *et al.* 1998), which may be our best estimate of the current mean metallicity of star-forming regions in the Universe, is used to normalize this function, $\overline{\mathcal{M}}(t_o) = 0.63$, and provide the dispersion, $\sigma = 0.3$.

5. THE AGE DISTRIBUTION OF EARTHS IN THE UNIVERSE

Performing the integral in Eq. (4) and inserting the result into Eq. (3) yields an estimate of the terrestrial planet formation rate in the Universe, which is also the age distribution of Earths orbiting Sun-like stars in the Universe. This distribution is plotted in Fig. 2C and indicates that the average age of Earths around Sun-like stars is 6.4 ± 0.9 billion years. The error bar represents the uncertainty in the *SFR* (shown in Fig. 2A) as well as the range of assumptions about the low metallicity tail of P_{FE}, discussed below. Thus, the average Earth in the Universe is 1.8 ± 0.9 billion years older than our Earth. And, if life exists on some of these Earths, it will have evolved, on average, 1.8 billion years longer than we have on Earth. Among these Earths, $74 \pm 9\%$ are older than our Earth while $26 \pm 9\%$ are younger; 68% of Earths in the Universe are between 3.3 and 9.3 Gyr old while 95% are between 0.6 and 10.5 Gyr old.

The time delay between the onset of star formation and the onset of terrestrial planet formation is the difference between the x-intercept of the thin and thick solid lines in Fig. 2C. This delay is $\sim 1.5 \pm 0.3$ Gyr and has an important dependence on the low metallicity tail of P_{HE}, specifically, on the metallicity for which $P_{FE}(\mathcal{M}) = 0$ has been assumed. To estimate the dependence of the main result on this assumption, both a high and a low metallicity case ($Z/Z_\odot = 1/5$ and $1/20$) have been considered. That is, I have used the two boundary conditions, $P_{FE}(\mathcal{M} = -0.7) = 0$ and $P_{FE}(\mathcal{M} = -1.3) = 0$, and the variation they produce in the result to compute representative error bars. The resulting variation is about one-half of the variation due to the uncertainty in the *SFR*. If rocky planets can easily form around stars with extremely low metallicity because of high levels of fractionation during planet formation, then the lower limit used here, $Z/Z_\odot = 1/20$, may not be low enough.

These linear metallicity variations yield error estimates but other possibilities exist. The masses of Earth-like planets and the ability of a stellar system to produce them may not be linear functions of metallicity. For example, there may be a strongly nonlinear dependence on metallicity such as a metallicity threshold below which Earths do not form and above which they always do. If that were the case then the *PFR* plotted in Fig. 2C would shift to the right or left depending on where the threshold is.

In this analysis I have assumed that the moons of hot Jupiters do not accrete into Earth-like planets. This speculation has not been explored in any detail. If true, hot Jupiters would destroy Earths but would also help create alternative sites for life. However, the delayed onset of planet formation compared to star formation derived here would be largely unchanged.

The cratering history of the Moon tells us that the Earth underwent an early intense bombardment by planetesimals and comets from its formation 4.55 Gyr ago until ~3.8 Gyr ago. For the first 0.5 Gyr, the bombardment was so intense (temperatures so high) that the formation of early life may have been frustrated (Maher and Stevensen 1988). The earliest isotopic evidence for life dates from the end of this heavy bombardment ~3.9 billion years ago (Mojzsis *et al.* 1996). Thus, life on Earth seems to have arisen as soon as temperatures permitted (Lazcano and Miller 1994).

To interpret Fig. 2C as the age distribution for life in the Universe several assumptions need to be made. Among them are:

1. Life is based on molecular chemistry and cannot be based on just hydrogen and helium.
2. The dominant harbors for life in the Universe are on the surfaces of Earths in classical habitable zones.
3. Other time-dependent selection effects which promote or hamper the formation of life (supernovae rate?, gamma ray bursts?, cluster environments?) are not as important as the metallicity selection effect discussed here (Norris 2000).

4. Life is long-lived. If life goes extinct on planets then the *PFR* needs to have its oldest tail chopped off to represent only existing life.

6. DISCUSSION

This paper is an attempt to piece together a consistent scenario from the most recent observations of extrasolar planets, the star formation rate of the Universe, and the metallicity evolution of the star-forming regions of the Universe. The precision of all of these data sets is improving rapidly. With more than 2000 stars now being surveyed, we expect more than $\sim$100 giant planets to be detected in the next few years. The metallicities of target lists are also under investigation. Thus, the uncertainties in the metallicities of target stars and stars hosting planets will be reduced (reducing the error bars in both the numerator and denominator of Eq. (1)).

Planet–planet interactions may explain the hot Jupiter–high metallicity correlation but at least two other (nonmutually exclusive) explanations exist: (1) metallicity-enhanced migration of giants in protoplanetary disks (e.g., Murray *et al.* 1998) and (2) infall of metal-rich accretion disks onto the host stars, precipitated by the in-spiraling of large planets (e.g., Gonzalez 1998, Quillen and Holman 2000). The infall of metallicity-enhanced material probably occurs in all migration or interaction scenarios. However, if the outer convective zones of G dwarfs are thick enough to mix and dilute this material (Laughlin and Adams 1997) then the analysis done here requires no significant modification for metallicity enhancement. If the dilution is not effective then the observed metallicity of a star will not be a faithful indicator of the star's true metallicity and therefore will not be a good indicator of the probability to produce Earths as assumed here.

The results obtained here for the metallicity and age distributions of Earth-like planets in the Universe are easily testable. Over the next decade or two, intensive efforts will be focused on finding Earths in the solar neighborhood. Microsecond interferometry (SIM) and even higher angular resolution infrared interferometry (TPF and IRSI-DARWIN) as well as micro-lensing planet searches (PLANET) and high sensitivity transit photometry (COROT) all have the potential to detect Earth-like planets. These efforts will eventually yield metalllicity and age distributions for the host stars of Earth-like planets that can be compared to Figs. 1 and 2C. In addition, Figs. 1 and 2C can be used to focus these efforts.

ACKNOWLEDGMENTS

I acknowledge G. Gonzalez, F. Rasio, J. Lissauer, A. Fernandez-Soto, D. Whittet, G. Wetherill, P. Butler, K. Ragan, and R. dePropris for helpful comments and discussion. This work has been supported by an Australian Research Council Fellowship.

REFERENCES

Barger, A. J., L. L. Cowie, and E. A. Richards 2000. Mapping the evolution of high-redshift dusty galaxies with submillimeter observations of a radio-selected sample. *Astrophys. J.* **119**, 2092–2109.

Beckwith, S. V. W., T. Henning, and Y. Nakagawa 2000. Dust properties and assembly of large particles in protoplanetary disks. In *Protostars and Planets IV* (V. Mannings, A. P. Boss, and S. S. Russell, Eds.), pp. 533–558. Univ. of Arizona Press, Tucson.

Bodenheimer, P., O. Hubickyj, and J. J. Lissauer 2000. Models of in situ formation of detected extrasolar giant planets. *Icarus* **143**, 2–14.

Boss, A. P. 1995. Proximity of Jupiter-like planets to low-mass stars. *Science* **267**, 360–362.

Butler, R. P., S. S. Vogt, G. W. Marcy, D. A. Fischer, G. W. Henry, and K. Apps 2000. Planetary companions to the metal-rich stars BD-10 3166 and HD 52265. *Astrophys. J.* **545**, 504-511.

Favata, F., G. Micela, and S. Sciortino, 1997. The [Fe/H] distribution of a volume limited sample of solar-type stars and its implications for galactic chemical evolution. *Astron. Astrophys.* **323**, 809–818, Fig. 3 histogram of [Fe/H].

Ford, E. B., F. A. Rasio, and A. Sills 1999. Structure and evolution of nearby stars with planets I. Short-period systems. *Astrophys. J.* **514**, 411–429.

Gilliland, R. L., and 23 colleagues 2000. A lack of planets in 47 Tucanae from a Hubble Space Telescope search. *Astrophys. J.* **545**, L47–L51.

Gonzalez, G. 1997. The stellar metallicity–giant planet connection. *Mon. Not. R. Astron. Soc.* **285**, 403–412.

Gonzalez, G. 1998. Spectroscopic analysis of the parent stars of extrasolar planetary system candidates. *Astron. Astrophys.* **334**, 221–238.

Gonzalez, G. 1999. Is the Sun anomalous? *Astron. Geophys.* **40**(5), 25–29.

Gonzalez, G. 2000. Chemical abundance trends among stars with planets. In *Disks, Planetesimals and Planets* (F. Garzon, C. Eiroa, D. de Winter, and T. J. Mahoney, Eds.), ASP Conference Series, Vol. 219. Astron. Soc. Pac., San Francisco, pp. 523–533.

Gummersbach, C. A., A. Kaufer, D. R. Schaefer, T. Szeifert, and B. Wolf 1998. B stars and the chemical evolution of the galactic disk. *Astron. Astrophys.* **338**, 881–896.

Habing, H. J., C. Dominik, M. Jourdain de Muizon, M. F. Kessler, R. J. Laureijs, K. Leech, L. Metcalfe, A. Salama, R. Siebenmorgen, and N. Trams 1999. Disappearance of stellar debris disks around main-sequence stars after 400 million years. *Nature* **401**, 456–458.

Laird, J. B., B. W. Carney, M. P. Rupen, and D. W. Latham 1988. A survey of proper-motion stars. VII. The halo metallicity distribution function. *Astron. J.* **96**, 1908–1917.

Laughlin, G., and F. C. Adams 1997. Possible stellar metallicity enhancements from the accretion of planets. *Astrophy. J.* **491**, L51–L55.

Lazcano, A., and S. L. Miller 1994. How long did it take for life to begin and evolve to cyanobacteria? *J. Mol. Evol.* **39**, 549–554.

Lin, D. N. C., and S. Ida 1997. On the origin of massive eccentric planets. *Astrophys. J.* **477**, 781–791.

Lin, D. N. C., P. Bodenheimer, and D. C. Richardson 1996. Orbital migration of the planetary companion of 51 Pegasi to its present location. *Nature* **380**, 606–607.

Lineweaver, C. H. 1999. A younger age for the Universe. *Science* **284**, 1503–1507.

Lissauer, J. J. 1995. Urey prize lecture: On the diversity of plausible planetary systems. *Icarus* **114**, 217–236.

Maher, K. A., and D. J. Stevenson 1988. Impact frustration of the origin of life. *Nature* **331**, 612–614.

Marcy, G. W., and R. P. Butler 2000. Millennium essay: Planets orbiting other suns. *Publ. Astron. Soc. Pac.* **112**, 137–140.

Mayor, M., and D. Queloz 1995. A Jupiter-mass companion to a solar-type star. *Nature* **378**, 355–359.

Mojzsis, S. J., G. Arrhenius, K. D. McKeegan, T. M. Harrison, A. P. Nutman, and C. R. L. Friend 1996. Evidence for life on Earth by 3800 million years ago. *Nature* **384**, 55–59.

Murray, N., B. Hansen, M. Holman, and S. Tremaine 1998. Migrating Planets. *Science* **279**, 69–72.

Nishi, R., and M. Tashiro 2000. Self regulation of star formation in low metallicity clouds. *Astrophys. J.* **537**, 50–54.

Norris, R. 2000. How old is ET? In *When SETI Succeeds: The Impact of High-Information Contact* (A. Tough, Ed.). Foundation of the Future, Washington, DC, pp. 103–105.

Papaloizou, J. C. B., and C. Terquem 1999. Critical protoplanetary core masses in protoplanetary disks and the formation of short period giant planets. *Astrophys. J.* **521**, 823–828.

Queloz, D., M. Mayor, L. Weber, A. Blecha, M. Burnet, B. Confino, D. Naef, F. Pepe, N. Santos, and S. Udry 2000. The CORALIE survey for southern extra-solar planets I. A planet orbiting the star Gleise 86*. *Astron. Astrophys.* **354**, 99–102.

Quillen, A. C., and M. Holman 2000. Production of star-grazing and star-impacting planetesimals via orbital migration of extrasolar planets. *Astron. J.* **119**, 397-402.

Rasio, F. A., and E. B. Ford 1996. Dynamical instabilities and the formation of extrasolar planetary systems. *Science* **274**, 954–956.

Rocha-Pinto, H. J., and W. J. Maciel 1996. The metallicity distribution of G dwarfs in the solar neighborhood. *Mon. Not. R. Astron. Soc.* **279**, 447–458.

Schneider, J. 2000. Extra-solar planets catalog. http://www.obspm.fr/encycl/catalog.html.

Sommer-Larsen, J. 1991. On the G-dwarf abundance distribution in the solar cylinder. *Mon. Not. R. Astron. Soc.* **249**, 368–373.

Trimble, V. 1997. Origin of the biologically important elements. *Origins of Life Evol. Biosphere* **27**, 3–21.

Wasserburg, G. J., and Y.-Z. Qian 2000. A model of metallicity evolution in the early Universe. *Astrophys. J.* **538**, L99–L102.

Weidenschilling, S. J. 1998. Growing Jupiter the hard way. American Astronomical Society, DPS meeting 30, 21.03.

Weidenschilling, S. J., and F. Marzari 1996. Gravitational scattering as a possible origin for giant planets at small stellar distances. *Nature* **384**, 619–621.

Wetherill, G. W. 1996. The formation and habitability of extra-solar planets. *Icarus* **119**, 219–238.

Whittet, D. 1997. Galactic metallicity and the origin of planets (and life). *Astron. Geophys.* **38**(5), 8.