On the history and future of cosmic planet formation

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比較惑星学コロキウム

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ABSTRACT

We combine constraints on galaxy formation histories with planet formation models, yielding the Earth-like and giant planet formation histories of the Milky Way and the Universe as a whole. In the Hubble volume (10^{13} Mpc^3), we expect there to be $\sim 10^{20}$ Earth-like and $\sim 10^{20}$ giant planets; our own galaxy is expected to host $\sim 10^9$ and $\sim 10^{10}$ Earth-like and giant planets, respectively. Proposed metallicity thresholds for planet formation do not significantly affect these numbers. However, the metallicity dependence for giant planets results in later typical formation times and larger host galaxies than for Earth-like planets. The Solar system formed at the median age for existing giant planets in the Milky Way, and consistent with past estimates, formed after 80 per cent of Earth-like planets. However, if existing gas within virialized dark matter haloes continues to collapse and form stars and planets, the Universe will form over 10 times more planets than currently exist. We show that this would imply at least a 92 per cent chance that we are not the only civilization the Universe will ever have, independent of arguments involving the Drake equation.

Key words: planets and satellites: gaseous planets – planets and satellites: terrestrial planets – galaxies: formation.

背景

- Livio(1999), Lineweaver(2001)による，宇宙史における惑星形成の研究．

「75-80%の地球類似惑星が形成されたのちに地球形成」

- Kepler Missionでの大量の系外惑星の発見
- host星の質量とmetallicityが及ぼす惑星形成への影響の理解が進歩．
- 銀河の星形成率やmetallicityの時間発展も制約されてきた．

→近年の惑星頻度モデルと銀河形成史を統合して惑星の種類 (地球類似，ガス) ごとに銀河や宇宙の全惑星形成史に制約を与えたい．

仮定と手法

- WMAP9の観測で制約された宇宙論パラメータを使用．平坦な宇宙と冷たいダークマターのモデルを使用．
- 初期質量関数 (IMF) はChabrier (2003)の0.1-100太陽質量におけるものを仮定．
- 惑星形成率 (PFR) は，惑星形成率がmetallicityのべき乗則に従うとすると，

$$\mathrm{PFR}(M_*, t) = n\left(\frac{Z(M_*, t)}{Z_\odot}\right)^\alpha \frac{\mathrm{SFR}(M_*, t)}{\langle m_* \rangle}.$$

n : 恒星系あたりの惑星数，α : べき乗則のパラメータ，$Z(M_*, t)$: 銀河ガス相の平均metallicity，
$\langle m_* \rangle = 0.67 M_\odot$: 原始星の平均質量，SFR : 太陽質量で規格化した銀河の星形成率．

- 地球類似惑星については，$\alpha = 0,\ n = 0.15$とした．ガス惑星では$n \sim 0.22,\ \alpha \sim 3.0$ という値を採用．

ただし，Johnson & Li (2012)で地球型惑星を作るためのmetallicityの最小値が求められているので，metallicityの限界値を-1.5と置いた．

- SFR はBehroozi et al. (2013e)のものを使った．13億年前までの星形成を求めている．

同じ恒星質量を持つ二つの銀河の間の星形成率の傾向性を得るためのモデル．

- metallicityを得るために，Maiolino et al. (2008)の公式を使う．酸素存在度から鉄存在度を求める公式．

$$[\mathrm{Fe}]/[\mathrm{H}] = -0.1 + 1.182\,[\mathrm{O}]/[\mathrm{H}]\,.$$

結果と考察

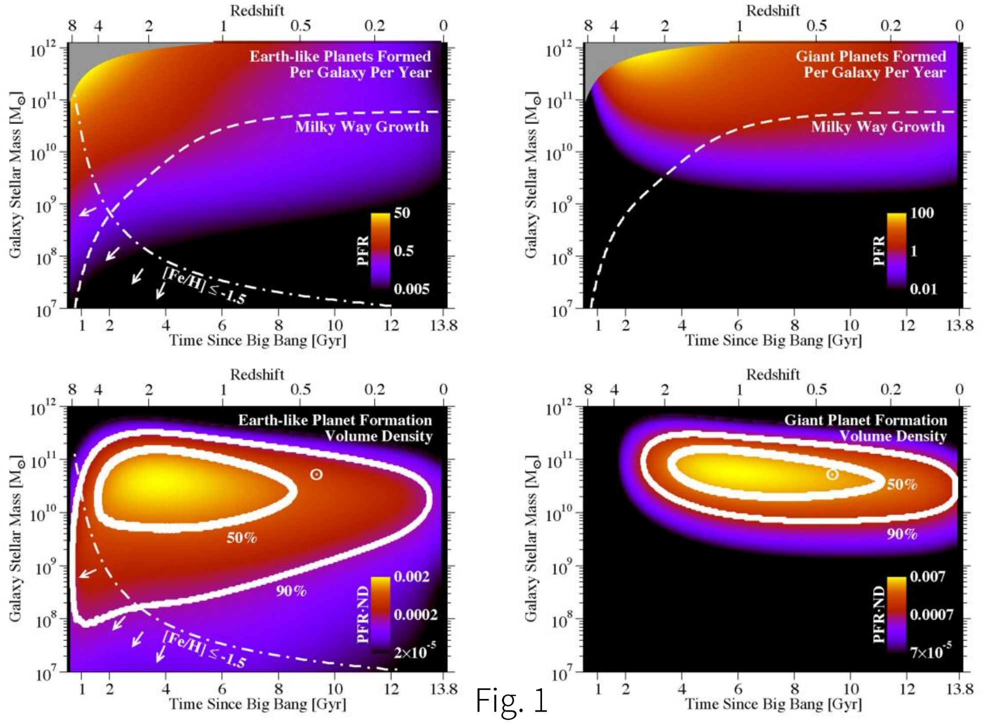


Fig. 1

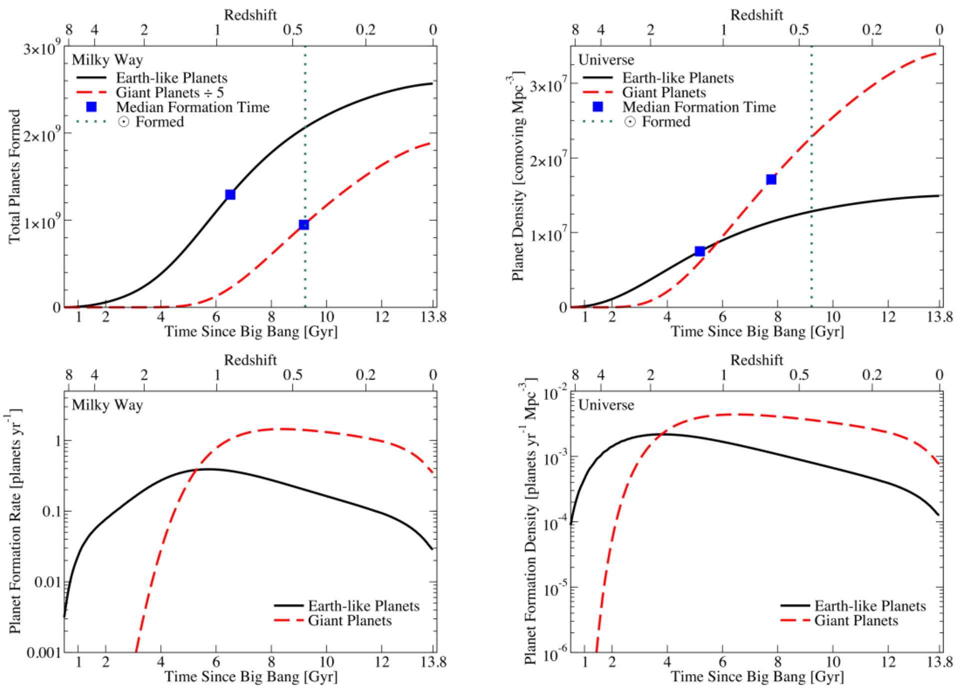
上 地球類似惑星 (左) とガス惑星 (右) の銀河PFR

下 各種惑星の銀河PFR密度

→太陽系は局部銀河群全史で形成される地球類似惑星の61%よりも早く形成された．
全宇宙で見れば，92%もの地球類似惑星よりも早期に形成．

結果と考察 (つづき)

Figure 1. Top-left panel: formation rate (in planets/yr) for Earth-like planets as a function of galaxy stellar mass and cosmic time. The dashed line indicates the median expected growth history of the Milky Way (Behroozi et al. 2013e). The dot–dashed line indicates [Fe/H] = −1.5, which has been suggested (Johnson & Li 2012) as the threshold metallicity for planet formation. Grey shaded areas indicate where galaxies are not expected to exist in the observable Universe. Top-right panel: same, for giant planets. Bottom-left panel: Earth-like PFR multiplied by galaxy number density as a function of stellar mass and cosmic time, i.e. the volume density of planet formation (in planets/yr/comoving Mpc^3 dex^{-1}). Contours indicate where 50 and 90 per cent of all planet formation has taken place. The ⊙ symbol indicates the Milky Way's stellar mass and age at the formation of the Solar system. Bottom-right panel: same, for giant planets.



上左 銀河系の総惑星数の時間発展

上右 宇宙の惑星密度の時間発展

下左 銀河系のPFRの時間発展

下右 宇宙のPFR密度の時間発展

地球類似惑星は $z = 2$，ガス惑星は $z = 1$ でPFRが減少に転じる．
→多くの惑星は遠い未来 (1000億~10兆年) まで形成される (銀河系からは観測できない) .

Figure 2. Top-left panel: total Earth-like and giant planets formed in the Milky Way as a function of cosmic time. Giant planet counts have been shifted by a factor of 5 to allow better comparison with the Earth-like planet formation history. Top-right panel: average planet density in the Universe as a function of cosmic time. Earth-like planet formation tracks the galaxy/cosmic star formation rates, whereas giant planet formation times are greater at late times due to their metallicity dependence. Blue squares mark the median formation times of each population. The vertical dotted line indicates the formation time of the Solar system, which occurred after 80 per cent of present-day Earth-like planets and 50 per cent of present-day giant planets were formed in the Milky Way. Bottom panels: PFRs and densities, respectively, for the Milky Way and the Universe as a whole. Uncertainties in all estimates are ∼1 dex, arising from uncertainties in planet detection rates with *Kepler*.

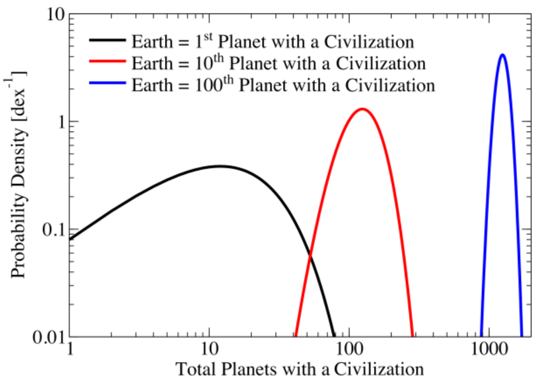


Figure 4. Probability for the total number of planets with civilizations in the Universe, given that the Earth formed before 92 per cent of similar planets expected to exist. If Earth is the *n*th planet since the big bang to have formed a civilization, then the average (expected) total number of planets with civilizations scales as 12.5*n*. Even for the most conservative possible assumption (i.e. that Earth was the first planet formed that evolved an intelligent civilization), it is unlikely that we will be the only civilization that the Universe will ever have (black line). As the number of earlier planets with civilizations increases (red and blue lines), it becomes more and more likely that the Universe will have many more civilizations than currently exist. For comparison, if the Milky Way today contained another civilization, it is likely that Earth would be at least the ten billionth planet to host a civilization in the observable universe, which would eventually contain at least a hundred billion civilizations.

- 銀河系は10^9の地球類似惑星を含む．
- 宇宙は10^{20}の地球類似惑星を含む．
- 太陽系は宇宙 (もしくは銀河系) に存在できる惑星数の8割ができたころに形成された．
- 星形成が続くことを考えると，宇宙でこれから形成されるものも含めた全地球類似惑星数の92%が作られていない時期に地球はできた．
- 統計学的に，「地球は全宇宙史で唯一の文明惑星である」というステートメントは宇宙原理と調和しないということがこの結果から言える．
- 地球の文明惑星形成順位から全宇宙史の文明惑星数を求める確率分布を得ることができる．