The Correlation between Stellar Metallicity and Planet Formation: A Short Review of Recent Studies

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Stellar Stoichiometry Workshop at Arizona State University, April 11-12, 2013

Following the formation of the first stars and galaxies, which transformed the Universe by bringing an end to the cosmic dark ages [1, 2], the formation of the first planets marked another important transition in cosmic history. Assembled from the heavy elements produced in the cores and supernovae of the first generations of stars, the first planets represent a milestone in the increasing complexity of the early Universe and set the stage for the emergence of the first life [3]. In Astronomy, the metallicity (also called Z [4]) of an object is the proportion of its matter made up of chemical elements other than hydrogen and helium [5]. The present short review is a compilation of most recent studies on the correlation between stellar metallicity and planet formation.

Planet-Metallicity Correlation for M Dwarfs

Nevas et al. (2013) [6] aimed their work to find out planet-metallicity and the planet-stellar mass correlations for M dwarfs from the HARPS GTO M dwarf subsample. They used a new method that takes advantage of the HARPS high-resolution spectra to increase the precision of metallicity, using previous photometric calibrations of [Fe/H] and effective temperature as starting values. The result showed that the well-known correlation for giant planet FGKM hosts with metallicity is present. Regarding Neptunians and smaller hosts no correlation is found but there is a hint that an anti-correlation with [Fe/H] may exist. They combined their sample with the California Planet Survey late-K and M-type dwarf sample to increase their statistics but no new trends were found [6].

Critical Metallicity and Planet Formation

Citing the core accretion model of planet formation, Jerret Jhonson and Hui Li stress that heavier elements are necessary to form the dust grains and planetesimals which build planetary cores. As well, there is observational evidence that the lifetimes of circumstellar disks are shorter at lower metallicities, likely due to greater susceptibility to Photoevaporation [3]. In their paper Jhonson and Li (2012) [3] estimate the minimum metallicity for planet formation, by comparing the timescale for dust grain growth and settling to that for disk photoevaporation. For a wide range of circumstellar disk models and dust grain properties, they find that the critical metallicity above which planets can form is a function of the distance r at which the planet orbits its host star. With the iron abundance relative to that of the Sun [Fe/H] as a proxy for the metallicity, they estimate a lower limit for the critical abundance for planet formation of $[Fe/H]_{crit} \simeq -1.5 + \log(r/1\ AU)$, where an astronomical unit (AU) is the distance between the Earth and the Sun.

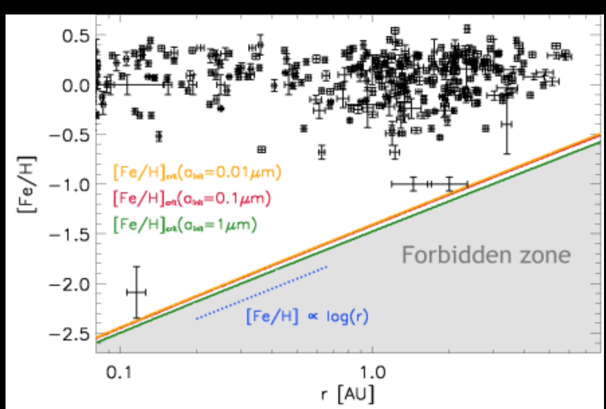

Figure: 1. This image shows the critical metallicity for Earth-like planet formation, expressed as iron abundance relative to that of the Sun, as a function of distance (r) from the host star. If systems with planets are discovered in the "forbidden zone", it may pose a challenge to the "core accretion" model of planetary formation [3].

This prediction carries implications for the properties of the first planets and for the emergence of life in the early Universe. In particular, it implies that the first Earth-like planets likely formed from circumstellar disks with metallicities Z & 0.1 $Z_\odot$. If planets are found to orbit stars with metallicities below the critical metallicity, this may be a strong challenge to the core accretion model [3].

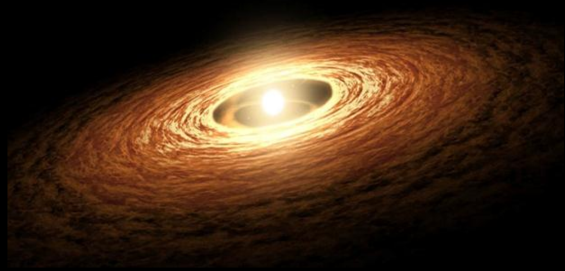

Figure: 2. Artist's concept showing a young Sun-like star surrounded by a planet-forming disk of gas and dust [7].

Planet Formation-Metallicity Correlation and Comparison to other Galaxies

In a study, Falguni Suthar and Christopher P. McKay (2012) [8] argued that the defining feature of the Galactic Habitable zone is the probability of planet formation which has been assumed to depend on the metallicity. They compared the metallicity distribution of nearby stars with the metallicity of stars with planets to document the correlation between metallicity and planet formation and to provide a comparison to other galaxies. Metallicity distribution, based on the [Fe/H] ratio to solar, of nearby stars peaks at [Fe/H] &−0.2 dex, whereas the metallicity distribution of extrasolar planet host stars peaks at [Fe/H] &+0.4 dex. They compare the metallicity distribution of extrasolar planet host stars with the metallicity distribution of the outer star clusters of M87 and M32. The metallicity distribution of stars in the outer regions of M87 peaks at [Fe/H] &−0.2 dex and extends to [Fe/H] &+0.4 dex, which seems favourable for planet formation. The metallicity distribution of stars in the outer regions of M32 peaks at [Fe/H] &−0.2 dex and extends to a much lower [Fe/H]. Both elliptical galaxies met the criteria of a GHZ. They concluded that many galaxies should support habitable zones, and in considering GHZs for microbial life, only the presence of planets, and thus indirectly, stellar metallicity, is essential [8].

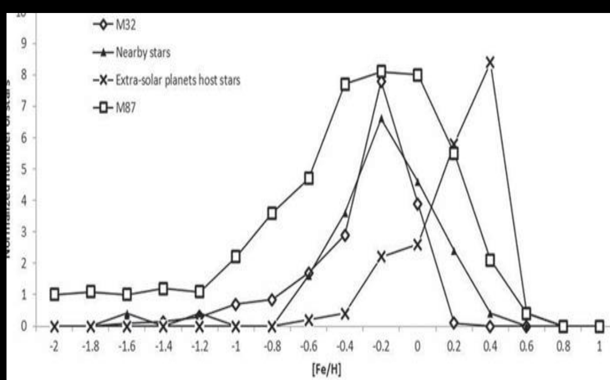

Figure: 3. The metallicity distribution of stars is shown. The triangles represent themetallicity distribution of nearby stars, x's represent the metallicity distribution of extrasolar planets hosts stars, squares represent metallicity distribution of M87, and diamonds represent metallicity distribution of M32 [8].

Extrasolar Planet Population Synthesis and Metallicity Correlation

Another study proposed by Mordasini et al. (2012) [9] discusses about extrasolar planet population synthesis and correlation with disk metallicity, mass and lifetime. For a large number of protoplanetary disks they calculated a population of planets with core accretion formation model including planet migration and disk evolution. They found large number of correlations: For high [Fe/H], giant planets are more frequent. For high [Fe/H], giant planets are more frequent. For high disk masses, giant planets are more massive. For long disk lifetimes, giant planets are both more frequent and massive. At low metallicities, very massive giant planets cannot form, but otherwise giant planet mass and metallicity are uncorrelated. In contrast, planet masses and disk gas masses are correlated. Low metallicities can be compensated by high disk masses, and vice versa, but not ad infinitum. At low metallicities, giant planets only form outside the ice line, while at high metallicities, giant planet formation occurs throughout the disk. No clear correlation of metallicity and the semimajor axis of giant planets exists because in low [Fe/H] disks, planets start further out, but migrate more, whereas for high [Fe/H] they start further in, but migrate less. Close-in low mass planets have a lower mean metallicity than Hot Jupiters. They concluded that properties of protoplanetary disks are decisive for the properties of planets, and leave many imprints [9].

High Metallicity and Gas Giant formation around Low Mass Stars

Guillem et al. (2011) [10] have obtained precision astrometry of the planet hosting M dwarf GJ 317 in the framework of the Carnegie Astrometric Planet Search project. The new astrometric measurements give a distance determination of 15.3 pc, 65% further than previous estimates. The resulting absolute magnitudes suggest it is metal rich and more massive than previously assumed. This result strengthens the correlation between high metallicity and the presence of gas giants around low mass stars. At 15.3 pc, the minimal astrometric amplitude for planet candidate GJ 317b is 0.3 milliarcseconds (edge-on orbit), just below our astrometric sensitivity. However, given the relatively large number of observations and good astrometric precision, a Bayesian Monte Carlo Markov Chain analysis indicates that the mass of planet b has to be smaller than twice the minimum mass with a 99% confidence level, with a most likely value of 2.5 MJup. Additional RV measurements obtained with Keck by the Lick-Carnegie Planet search program confirm the presence of an additional very long period planet candidate, with a period of 20 years or more. Even though such an object will imprint a large astrometric wobble on the star, its curvature is yet not evident in the astrometry. Given high metallicity, and the trend indicating that multiple systems are rich in low mass companions, this system is likely to host additional low mass planets in its habitable zone that can be readily detected with state-of-the-art optical and near infrared RV measurements [10].

Finally, the present short review clearly indicates that a strong correlation may exist between stellar metallicity and the formation of gas giants and rocky planets. Moreover, the properties of protoplanatry disks are likely to contribute to the properties of planets.

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