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ORIGINAL ARTICLE

Planets in the early Universe

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Abstract Several planets have recently been discovered around stars that are old and metal-poor, implying that these planets are also old, formed in the early Universe together with their hosts. The canonical theory suggests that the conditions for their formation could not have existed at such early epochs. In this paper we argue that the required conditions, such as sufficiently high dust-to-gas ratio, could in fact have existed in the early Universe immediately following the first episode of metal production in Pop. III stars, both in metal-enhanced and metal-deficient environments. Metal-rich regions may have existed in multiple isolated pockets of enriched and weakly-mixed gas close to the massive Pop. III stars. Observations of quasars at redshifts $z \sim 5$, and gamma-ray bursts at $z \sim 6$, show a very wide spread of metals in absorption from $[\mathrm{X/H}] \simeq -3$ to $\simeq -0.5$. This suggests that physical conditions in the metal-abundant clumps could have been similar to where protoplanets form today. However, planets could have formed even in low-metallicity environments, where formation of stars is expected to proceed due to lower opacity at higher densities. In such cases, the circumstellar accretion disks are expected to rotate faster than their high-metallicity analogues. This in turn can result in the enhancement of dust particles at the disk periphery, where they can coagulate and start forming planetesimals. In conditions with the low initial specific angular momentum of the cloud, radiation from the central protostar can act as a trigger to drive small-scale instabilities with typical masses in the Earth to Jupiter mass range. Discoveries of planets around old metal-poor stars (e.g. HIP 11952, $[\mathrm{Fe/H}] \sim -1.95$, $\sim$13 Gyr) show that planets did indeed form in the early Universe and this may require modification of our understanding of the physical processes that produce them. This work is an attempt to provide one such heuristic scenario for the physical basis for their existence.

Keywords Planetary systems: formation · Quasars: abundances · Cosmology: early Universe

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1 Introduction

A two-year gravitational lensing survey by the Microlensing Observations in Astrophysics (MOA) and Optical Gravitational Lensing Experiment (OGLE) groups towards the Galactic bulge (Sumi et al. 2011) has found ten events which can be attributed to Jupiter-mass planets. These microlensing planets are free-floating, in the sense that no host stars have been detected within about 10 AU. Recent estimates show that there can be up to 10^5 as many such planets as stars in the Galaxy (Sumi et al. 2011; Strigari et al. 2012); a more conservative estimate has been found by Tutukov and Fedorova (2012). Three out of the 10 microlensing events from planets have galactic latitudes of $b \simeq -3°$, and one has $b \simeq -6°$, corresponding to the heights from 0.4 to 0.8 kpc. Therefore these planets are likely to belong to the thick disk population, where a considerable fraction (up to 30 % to 50 %) of stars is occupied by the oldest (Pop. II) Milky Way stars with mean metallicity[1]

[1] $[\mathrm{X/H}] = \log_{10}(N_\mathrm{X}/N_\mathrm{H})_{star} - \log_{10}(N_\mathrm{X}/N_\mathrm{H})_\odot$.