In this section, we quantitively show how different the distributions of the orbital properties and planet masses for the extrasolar gaseous objects orbiting the metal-rich and -poor regions are, minimizing the impact of the selection effect on their distributions. We also explore how many components exit in the extrasolar gaseous objects through classifying the selected samples with the Gaussian Mixture Model (GMM).

We first determined the boundary of metallicity that divides the original samples into two such that the distributions of planet mass and semi-major axis in the two metal-rich and -poor regions are most different, respectively, using the method that considers the selection effects of the radial velocity measurements, as explained in Section 2.1. Figure 2 shows the P-values derived by the two-sample AD test for the distributions of the semi-major axes and lower mass limits of the selected samples, changing the boundary of metallicity from -0.7 to 0.4 (dex). Note that the selected samples, which were applied to the AD test, were constructed such that the impacts of the selection effects in the metal-rich and -poor regions on the selected sub-samples are equalized; the comparison between the two distributions of the selected sub-samples is not affected by the selection effects of the radial velocity measurements. We iterated the calculation 1,000 times and averaged the calculated P-values for each divided point to derive the mean and standard deviation of the P-values. The minimum p-values of the AD tests for the distributions of the semi-major axis and the planet mass were 2.4x10-3 and 3.5x10-5/ 4.2x10-5 at the metallicity of -0.04 and -0.29/-0.06 (dex), respectively; thus, the planetary distributions in the metal-rich and -poor regions do not arise from the selection effect of the radial velocity measurements but from the planet formation and evolution. In this study, we used applied -0.05 (dex) as the boundary of metallicity through considering that the two minimum p-values are around -0.05 (dex).

Next, we compared the distributions of the lower mass limit and semi-major axis for the selected sub-samples in the metal-rich and -poor regions that are divided by the boundary of metallicity. Figure 3 shows two scatter plots of the selected sub-samples in the metal-rich and -poor regions on the semi-major axis and lower-mass limit and compared the cumulative fractions of the selected sub-samples in terms of the semi-major axis and lower-mass limit, respectively. The gas giants with semi-major axis less than 0.1 AU and the planets more massive than about 5 MJ in the metal-poor region are relatively lack and excess compared to those in the metal-rich region, respectively. We discuss where the difference between the planetary distributions in the metal-rich and -poor regions comes from in Section 4.

Three Mass-Regimes of Gaseous Objects

We classified the \*個数を明記\* selected sample into multiple sub-samples on the host-star metallicity and planet-mass plane with the GMM to explore how many sub-samples exist in the extrasolar gas giants discovered to data, given that each sub-sample follow a normal distribution (e.g., Santos et al. 2017 ; Schlaufman 2018 ). Changing the number of the sub-samples, we evaluated each model with the Bayesian Information Criterion (BIC) and found that the three-component model is suitable as the best Gaussian Mixture Model for the \*個数を明記\* selected samples. Figure 4 shows the best suited model for the selected samples. The selected samples are divided into three almost along two boundary masses of 4 and 20 MJ. The three-component model results from relative paucity of the selected samples in two specific regions in the diagram of host-star metallicity versus companion mass; the two regions indicate gaseous objects with masses ranging from 20 to 30MJ around both the metal-rich and -poor stars and those with masses ranging from 0.1 to 4 MJ around the metal-poor stars. The mean metallicity of the stars hosting the gaseous objects more with masses from 4 to 20 MJ is lower than that of the lighter samples and the mean metallicity of the samples more massive than 20 MJ is much lower than those of the other two sub-samples. Thus, the three-mass regimes exist in the extrasolar gaseous objects discovered so far instead of the two-mass regimes proposed by the previous studies (Ribas & Miralda-Escude 2007; Santos et al. 2017; Schlaufman 2018). Based on the theoretical studies on the maximum mass of the core-accreted planet (e.g., Mordasini et al. 2012; Tanigawa & Tanaka 2016), we redefined the samples lighter than 20 MJ as planetary-mass objects and labeled the two sub-samples with masses from 0.1 to 4 MJ and from 4 to 20 MJ as ‘intermediate-mass planets’ and ‘massive planets.’ In addition, the samples more massive than 20 MJ are labeled as ‘brown dwarfs.’ Note that the boundary between planetary mass and brown dwarf objects established by the deuterium-burning minimum mass of ~ 10 MJ mentioned in a previous study is semantic (Chabrier et al. 2014); this boundary has no physical meaning from the perspective object evolution.

We next investigated the eccentricity distributions of the brown dwarfs, massive planets, and intermediate-mass planets in both the metal-rich and -poor regions, respectively. The upper panels of Figure 5 are scatter plots of the selected samples in the diagram of eccentricity versus companion mass in the metal-rich and -poor regions. The bottom panels are the cumulative fractions of the eccentricities for the three populations orbiting the metal-rich and -poor stars, respectively. The observational result common to the selected samples orbiting the metal-rich and -poor stars is that, while the eccentricities of the brown dwarfs uniformly distribute from 0 to 1, about 80% of the intermediate-mass planets have eccentricities smaller than 0.3. In contrast, the eccentricity distributions of the massive planets in the metal-rich and -poor regions are largely different; while the cumulative fraction of the eccentricities for the massive planets orbiting the metal-rich stars is close to that of the brown dwarf, that of the metal-poor massive planets is consistent with that of the intermediate-mass planets. In fact, as shown in Figure 6, the mean eccentricity of the massive planets decreases as the metallicity of the host star decreases. Thus, the eccentricity distributions also support the three-mass regimes of the extrasolar gaseous objects.

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Note that the cumulative fraction of the eccentricities for the intermediate-mass planets orbiting the metal-rich stars is largely affected by the inner planets with circular orbits that arise from tidal circularization with the host star.

Note that the eccentricity distributions of the intermediate-mass and massive planets orbiting the metal-rich stars are consistent with the previous studies (e.g., Adibekyan et al. 2013 ; Dawson & Murray-Clay 2013 ).