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Planets in orbit around *β* Pictoris formed the orbital architecture of planetesimal belts?

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We report near-infrared imaging observations of the β Pic dust disk, from which we infer the orbital architecture of planetesimal belts that remain near mean motion resonances (MMRs) with a planet at 62 AU. Our results reveal that one of the previously identified planetesimal belts lies in the 2/3 MMR with the planet, similar to the resonant relation between Plutinos and Neptune. We suggest that all the previously reported planetesimal belts are located near the 2/3 MMRs of four planets whose spatial arrangements make a similar figure of Jupiter, Saturn, Uranus, and Neptune. This implies that the Solar System is a prototype of planetary systems around main-sequence stars in terms of planets' configuration, as expected from planet formation theories.

Key words: Stars: individual (β Pictoris), stars: planetary systems, planetary systems: formation, Kuiper Belt, meteors, meteoroids.

1. Introduction

Imaging observations of the A5 V star β Pictoris have revealed its circumstellar dust disk viewed almost edge-on from the Earth (Smith and Terrile, 1984; Paresce and Burrows, 1987; Golimowski *et al.*, 1993, 2006; Kalas and Jewitt, 1995; Tamura *et al.*, 2006). The disk is not primordial, but a dynamical consequence of debris that are continuously replenished by mutual collisions between planetesimals (Weissman, 1984; Backman *et al.*, 1992; Backman and Paresce, 1993; Krivova *et al.*, 2000). The location of the debris or dust is most likely confined near its parent-body planetesimals in nearly coplanar orbits (Krivov *et al.*, 2000; Freistetter *et al.*, 2007). This indicates that the spatial distribution of planetesimals can be traced through observed brightness profiles of the dust disk. A warp and rings in the inner disk suggest that the structures are formed by gravitational influences of planets on the planetesimals (Heap *et al.*, 2000; Wahhaj *et al.*, 2003; Okamoto *et al.*, 2004; Freistetter *et al.*, 2007). Surface brightness along the mid-plane of the β Pic disk shows a kink in its radial profile around 100 AU from the star (Golimowski *et al.*, 1993, 2006; Kalas and Jewitt, 1995; Krivova *et al.*, 2000). Such a brightness profile is consistent with the radial dust distribution that peaks around 100 AU, analogous to the dust in the Kuiper Belt (Backman *et al.*, 1992; Backman and Paresce, 1993). These observations are well modeled under the assumption that planetesimals are concentrated in the range of 80–120 AU (Augereau *et al.*, 2001; Thébault and Augereau, 2005). It is worth noting that, in the solar system, a number of trans-neptunian objects in the Kuiper Belt are trapped in mean motion resonances (MMRs) with Neptune (Luu and Jewitt, 2002). Analogous to the outer edge of the Kuiper Belt at the 1/2 MMR with Neptune, the sharp drop in the surface density of β Pic planetesimals may be linked to the outer edge of a planetesimal belt at the 1/2 MMR with a yet unseen planet, which is hereafter referred to as Planet N. Near-infrared observations of linear polarization revealed a dip at 5.3±0.1 arcsec (i.e., 102–104 AU) in the north-east and south-west directions of the β Pic disk (Tamura *et al.*, 2006). We can interpret this dip as a paucity of planetesimals in the region from 1/2 MMR to 4/9 MMR with Planet N. Placing the dip in the middle of the 1/2 and 4/9 MMRs, we would find Planet N at 62 AU from the central star.

Spatially localized enhancements in the K-band brightness of the disk manifested a sign of multiple planetesimal rings (Tamura *et al.*, 2006). If planetesimals in the β Pic

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system reside in MMRs with a planet, the observed clumps in the surface brightness profile of the disk can be simply resonant structures of planetesimal belts. Therefore, we seek evidence for the presence of Planet N by investigating whether its MMRs match the locations of observed humps in the brightness distribution of the disk.

2. Observation and Data Analysis

Using the Subaru 8.2-m telescope and the CIAO infrared coronagraph imager with adaptive optics, we imaged the circumstellar dust disk of β Pic in H (1.65 μm) and K (2.2 μm) bands on January 4, 2003. A detailed description of the observations and the data reduction as well as a preliminary analysis of the K-band data can be found in Tamura *et al.* (2006). Hereafter, we focus on our data analyses to find observational evidence of multiple planetesimal rings in our data set. Signals of planetesimal rings would appear as brightness peaks in both northeast and southwest directions as well as both H- and K-bands. We compare the excess emission in both bands after subtracting their continuum levels (see Section 3). A weak correlation with a correlation coefficient (r) of 0.3 is indeed found between the clumps in H- and K-bands. We assess the statistical significance of brightness peaks by testing the null hypothesis that the observed brightness distribution is merely random noise superimposed on a smooth curve of radiation scattered by circumstellar dust. Therefore, the random noise is smoothed out by averaging over both wavelengths and offset directions, resulting in a smooth declining curve of the average surface intensity. On the one hand, we admit that fake features might appear in the average brightness, if the random noise was not completely smoothed out by the averaging procedure. On the other hand, even real enhancements in the K-band brightness might be diluted with the H-band brightness, because the latter had a lower signal-to-noise ratio than the former. In such an analysis, only strong peaks, which we attribute to nearly circular, coplanar rings, will remain in the residuals after subtraction of a smooth brightness component. Therefore, we derive the residuals from the mean of the surface intensities to trace possible resonant structures of multiple planetesimal rings associated with Planet N.

We use a dip at 5.3 arcsec in the polarimetric data of Tamura *et al.* (2006) to infer the location of Planet N as analogous to the outer edge of the Kuiper Belt in the solar system, while the evolutionary history of the β Pic system is likely different from that of the solar system. However, a different evolutional history does not necessarily mean that there is no paucity of planetesimals between the 1/2 and 4/9 MMRs of a planet in the β Pic system. Therefore, we do not argue the presence of the planet at 62 AU from an evolutional point of view, but we hereafter examine it with our observational data. Note that the dip at 5.3 arcsec in our polarimetric data is simply our motivation to seek a planet around 62 AU.

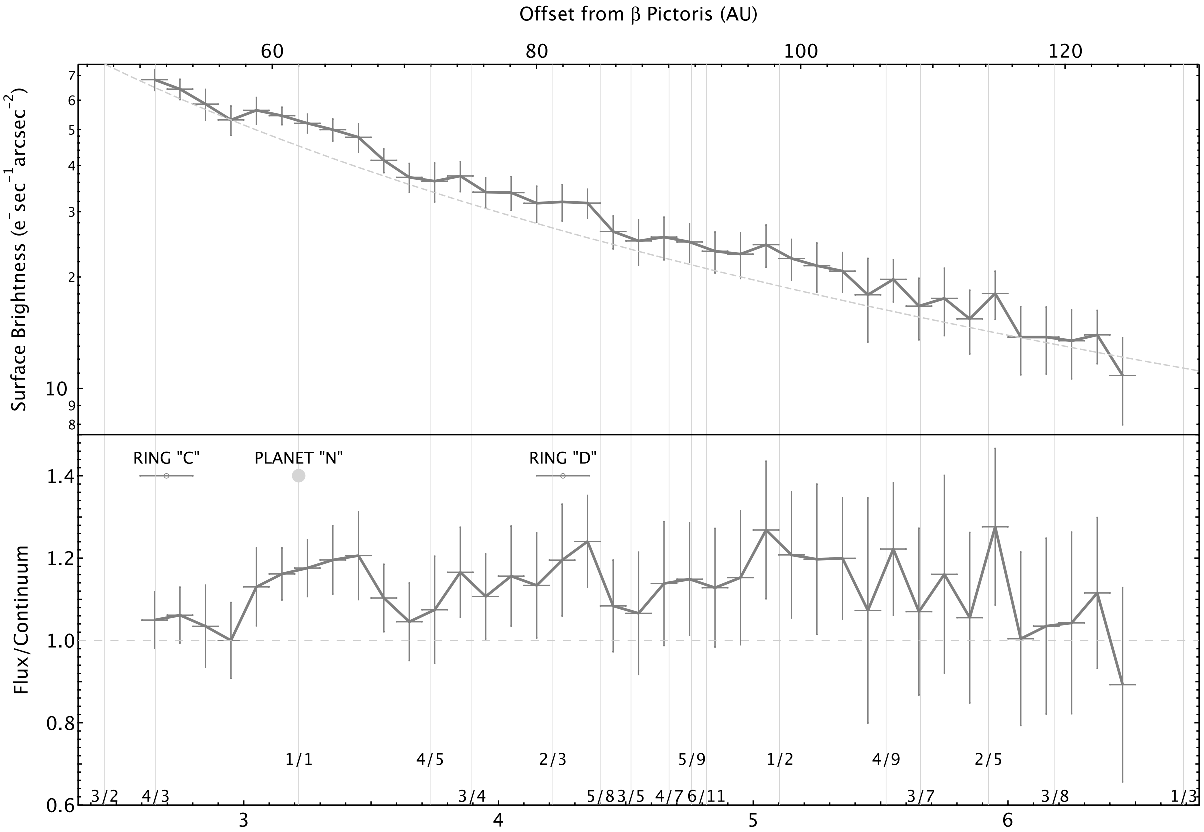

Fig. 1. Resonance structures in the composite near-infrared intensity of the dust disk around β Pictoris. Also indicated are the locations of possible planetesimal belts, Ring C and Ring D found by Wahhaj *et al.* (2003), and the outermost planet, called Planet N.

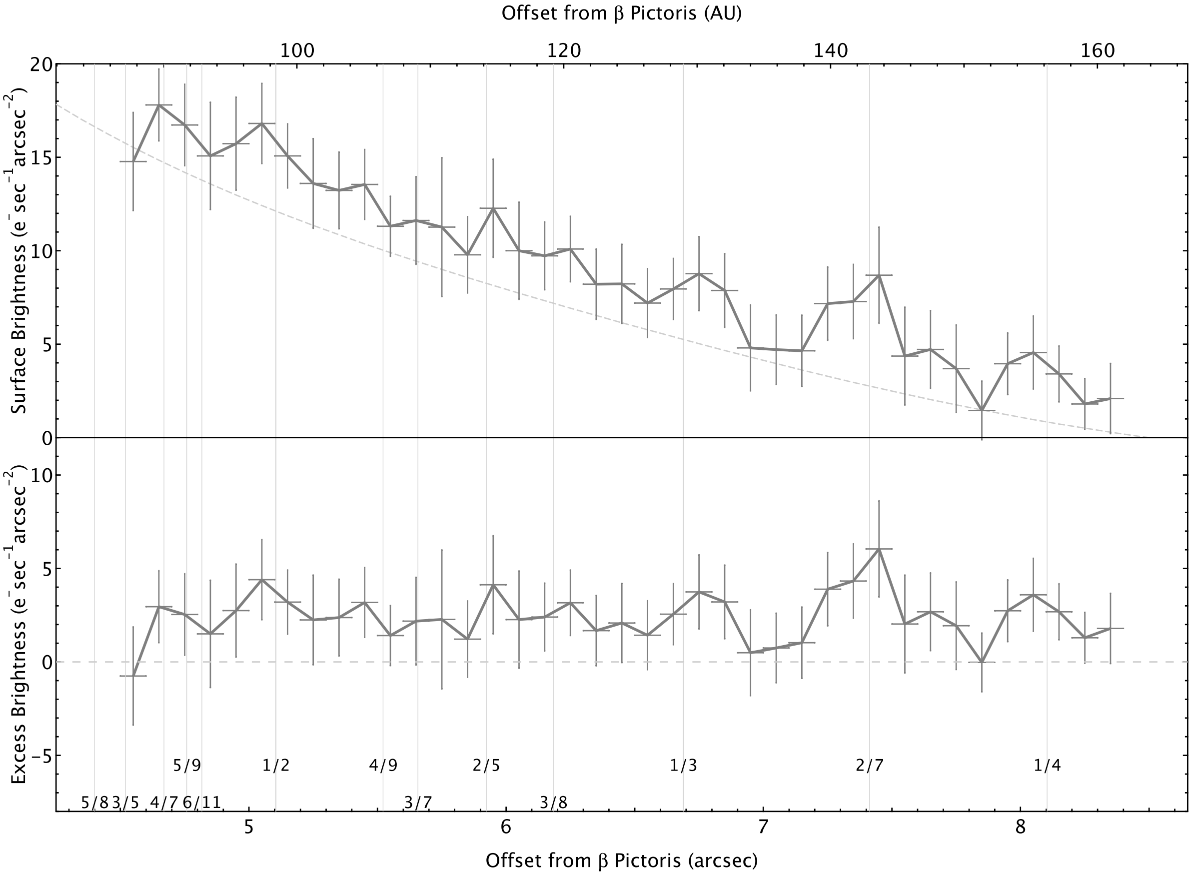

Fig. 2. Resonance structures in the K-band intensity of the dust disk around β Pictoris.

3. Results

Figure 1 shows the geometric mean of the four surface intensities and a smooth declining curve, "continuum", as a function of radial distance from the central star. Here we take a smooth declining curve at the lowest envelope of the data as being the continuum, which is the sum of real smooth brightness and true random noise, since the random noise has an additive effect. Also plotted is the ratio of the geometric mean flux to the continuum, which gives a measure of excess intensities (clumps). If the null hypothesis is true, we would expect that any peculiar features cancel out by the averaging over two directions and two wavelengths. The vertical lines indicate the locations of the MMRs associated with Planet N in orbit around β Pic at 62 AU. We find 2σ excess above the continuum brightness around the 1/1 and 2/3 MMRs with Planet N at 62 AU. Given this result, we would be inclined to reject the null hypothesis and to accept the alternative hypothesis that the 2σ excess indicates real features of planetesimal rings. If we regard 1σ excess over three bins to be a real feature, an additional feature appears in the 1/2 MMR. We realize the presence of similar enhancements around 1/2 and 2/3 MMRs in the K-band brightness measured by Mouillet *et al.* (1997). It is worth noting that the D ring identified by Wahhaj *et al.* (2003) in their mid-infrared images lies in the 2/3 MMR with Planet N. Taking into account the occurrence of the 2/3 MMR peak in three independent infrared observations, it is unlikely that the null hypothesis is true. The correlation between the MMR and the clump locations is also inferred by $r = 0.3$, which supports our assessment.

Identification of MMRs at larger distances is easier because of a wider interval between two neighboring MMRs beyond the 1/2 MMR (i.e., 5 arcsec). Unfortunately the H-band beyond 6 arcsec intensity suffers from low signal-to-noise ratios and its radial slope departs from that of the K-band intensity. Therefore, we use only the K-band data to identify further clumps of planetesimals in the surface brightness beyond 5 arcsec. Figure 2 shows the structures of clumps in the K-band surface brightness derived from the arithmetic mean of the north-east and south-west intensities. The positions of brightness humps appear to coincide with the locations of MMRs, in particular, 1/2, 1/3, 2/7 and 1/4. We find that the correlation of locations between these MMRs and the observed clumps is stronger ($r = 0.4$) than in the inner region. In this distance range, the intervals of MMRs are greater than the FWHM of approximately 0.19 arcsec in the K-band. Accordingly, it is unlikely that the locations of the residual clumps and the MMRs overlap by chance. Contrary to the null hypothesis, this gives indirect evidence for the presence of Planet N at 62 AU.

4. Discussion

4.1 Large dust particles

The radial distribution of edge-on-disk brightness traces the radial distribution of the dust that dominates the total cross section of light scattering by dust particles in the disk. If the size distribution of the dust in the β Pic disk is similar to that of interplanetary dust in the solar system or that of cometary dust, the scattering cross section is determined by large dust particles (Grün *et al.*, 1985; McDonnell *et al.*, 1987; Kolokolova *et al.*, 2007). Indeed, the infrared spectra of cometary dust and β Pic dust are very much alike (Knacke *et al.*, 1993). Although this does not guarantee the similarity in the size distribution between cometary dust and β Pic dust, we do not find a reason that small dust particles dominate the scattering cross section. Large dust particles tend to scatter stellar radiation in forward directions and to stay near the orbit of their parent bodies (e.g., Kresák,1976; Bohren and Huffman, 1983). Polarimetric observations of the β Pic debris disk have revealed an effect of strong forward scattering that decreases the degree of linear polarization with decreasing radial distance from the star (Krivova *et al.*, 2000; Tamura *et al.*, 2006). The strong forward scattering is also manifested in the pronounced dip around 5.3 arcsec in the radial profile of linear polarization, in contrast to its insignificant correspondence in the radial profile of our K-band intensity (Tamura *et al.*, 2006). Since large dust particles are less affected by stellar radiation pressure, they accumulate along the orbit of their parent body as seen in dust trails of comets (e.g., Ishiguro *et al.*, 2002). In addition, collisional models of debris disks predict that the peak of thermal radiation from dust particles appears at a planetesimal belt in a typical debris disk (Krivov *et al.*, 2008). Even though the location of parent-body planetesimals may not exactly coincide with associated dust rings, the difference is not necessarily notified with our spacial resolution of approximately 4 AU. Therefore, the location of a planetesimal belt can be identified by observations of its associated dust ring, unless the β Pic dust is very different from the dust in the solar system and in typical debris disks. We conclude that observations of stellar radiation scattered by dust particles in a typical debris disk would provide an opportunity of detecting extrasolar planets in the disk if the orbital architecture of planetesimal belts are shaped by the gravitational field of the planets.

4.2 The outermost planet

Even though the radial distribution of planetesimals steeply drops near the $1/2$ MMR with Planet N, the β Pic system appears to consist of planetesimal rings on the outskirts of the planetesimal disk beyond the $1/2$ MMR. We note that we certainly have to wait for future observations to confirm our identification with these high-order resonances, which could be criticized to be premature at this stage. Hahn and Malhotra (1999) have shown that planetary migration results in concentration of planetesimals at the outermost planet's exterior MMRs and allows the planetesimals beyond $1/2$ MMR to remain in orbits with low eccentricities and low inclinations. The resonant planetesimals beyond Planet N's $1/2$ MMR seem to reside in nearly circular, low-inclination orbits, because they are identified at the same distance from the star along northeast and southwest directions. This may indicate that these outer planetesimal rings around β Pic are relatively undisturbed remnants of the natal planetesimal disk. Although the numerical results by Hahn and Malhotra (1999) might depend on various input parameters, we may expect that Planet N is the outermost planet in the β Pic system.

Owing to its spatially resolved edge-on viewing, the width of the β Pic disk has been measured over a wide range of distances. The disk width increases with distance in the outer disk (>100 AU), but it is almost constant in the inner disk (<100 AU) (Kalas and Jewitt, 1995; Krivova *et al.*, 2000; Golimowski *et al.*, 2006; Tamura *et al.*, 2006). The flared structure of the outer disk is akin to the structure of the outer Kuiper Belt where the planetesimal disk is flared up from the ecliptic plane. Lecavelier des Etangs (1998) pointed out that the vertical structure of the β Pic disk might have resulted from the outward migration of multiple giant planets. In terms of Planet N, planetary migration is consistent with a planet formation scenario that precludes in-situ formation of a planet at 62 AU around β Pic (Nakano, 1988). To place a planet at 62 AU around β Pic, however, the planet formation scenario might require rapid planet migration that is at odds with nearly circular, coplanar planetesimal rings. Consequently, the presence of Planet N at 62 AU would give new insights into formation of a planetary system, in particular, planetary migration.

4.3 Planetary system

Mid-infrared images of the inner β Pic disk revealed four inner rings at 14 ± 1 (A ring), 28 ± 3 (B ring), 52 ± 2 (C ring), and 82 ± 2 AU (D ring) with the greatest optical depth in the D ring (Wahhaj *et al.*, 2003). We notice that the location of the D ring corresponds to the $2/3$ MMR of planetesimals with Planet N at 81.2 AU. Note that Pluto and Plutinos in the $2/3$ MMR with the outermost planet Neptune are known to have stable orbits (Luu and Jewitt, 2002). Therefore, the greatest optical depth of the D ring is reasonably a consequence of the strong $2/3$ MMR with Planet N, the outermost planet of the β Pic system. In addition to the A and B rings, mid-infrared spectral features of silicates revealed the presence of a planetesimal belt (O ring) around 6 AU (Okamoto *et al.*, 2004). If the O ring were a main asteroid belt in relation to a yet undetected planet having the A ring in its $2/3$ MMR, the hypothetical planet, which is hereafter referred to as Planet J, would exist at 11 AU. In fact, Jupiter-mass Planet J around 10–12 AU in a slightly eccentric orbit is an appropriate solution to generate the warp of the disk and a number of star-grazing comets observed in the β Pic system (Lecavelier des Etangs, 1998; Heap *et al.*, 2000; Freistetter *et al.*, 2007). Located slightly inside Planet J is the ice boundary around 9 AU from the central star. A model of planet formation indicates that gas giants can form slightly outside the ice boundary (Ida and Lin, 2004). Therefore, we expect Planet J, if exists, to be a gas giant[1].

The slightly eccentric orbit of Planet J may indicate the presence of another external giant planet, which is hereafter termed Planet S (Thébault and Beust, 2001). If the near $5/2$ resonant relation between Jupiter and Saturn in the Solar System holds in the β Pic system, one may find Planet S orbiting β Pic at 20 AU. Interestingly, the $2/3$ MMR with Planet S is located at 26.2 AU where the B ring was identified by infrared observations. Furthermore, we realize

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[1] When revising the manuscript, Lagrange *et al.* (2009a, b) reported a probable detection of a giant planet around 8 AU, which is in accord with the location of Planets J within the accuracy of the observational data used in our discussion.

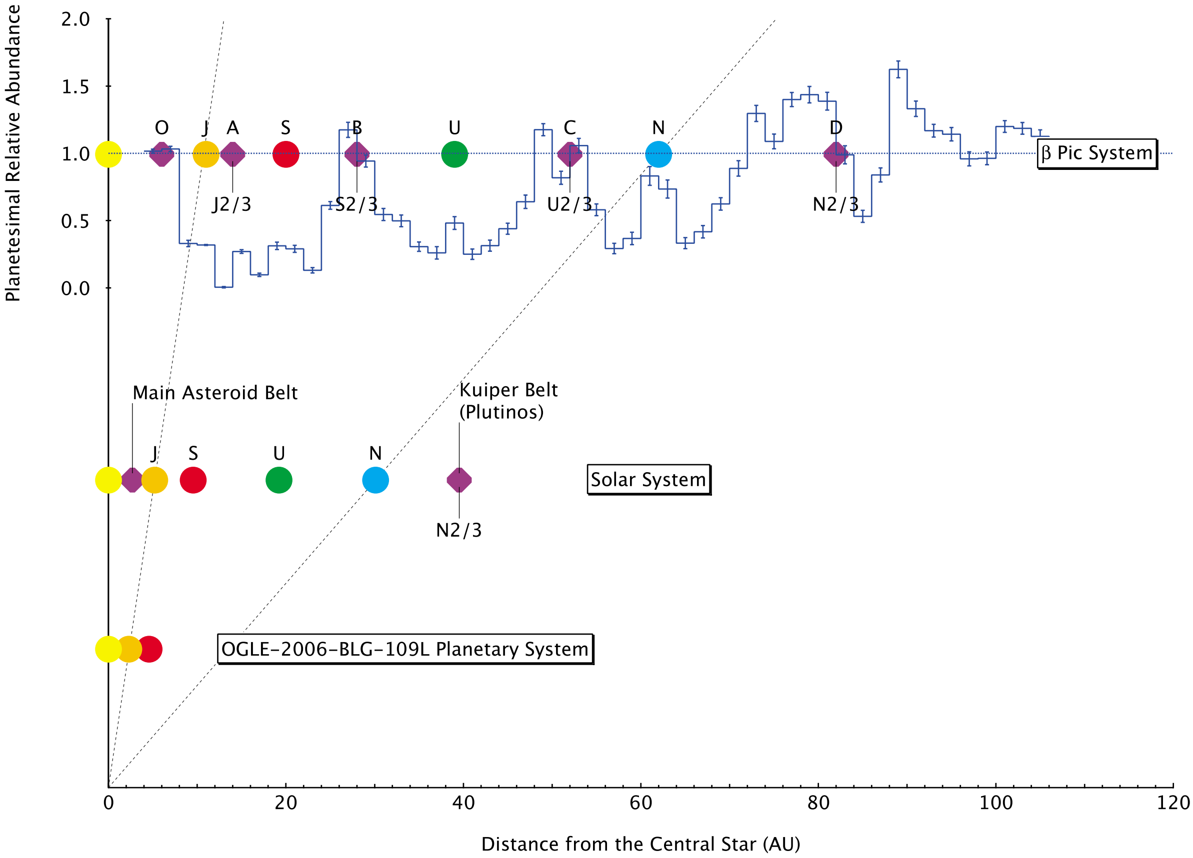

Fig. 3. Illustration of planetary systems around β Pic, the Sun, and OGLE-2006-BLG-109L. The extent of the β Pic system is twice as large as that of the Solar System. In the β Pic system, the A, B, C, and D rings are associated with the 2/3 mean-motion resonance of Planets J, S, U, and N, while the O ring corresponds to the main asteroid belt inside the ice boundary.

that the semimajor axis ratio of Planets J and N is similar to that of Jupiter and Neptune. This leads us to speculate the presence of a planetary system in the β Pic disk that is akin to our own planetary system. If the near 2/1 resonant relation between Neptune and Uranus also holds in the β Pic system, a planet, which we call Planet U, would orbit β Pic at 39 AU with the C ring in the 2/3 MMR at 51.1 AU. In Fig. 3, we provide our perspective picture of the planetary system around β Pic together with the Solar System and the OGLE-2006-BLG-109L planetary system (see Gaudi *et al.*, 2008). One could find that Planets J, S, U and N are all accompanied with a planetesimal ring in their 2/3 MMRs. A very recent numerical study on the dynamical evolution of planetesimals in the β Pic system with three planets suggests the presence of a Saturn-mass planet around 25 AU and a Uranus-mass planet around 44 AU in addition to a Jupiter-mass planet around 12 AU (Freistetter *et al.*, 2007). We have also performed a similar dynamical simulation of planetesimals with our four planets J, S, U and N in coplanar circular orbits at their expected locations.[2] The fourth-order predictor-corrector method is used for the numerical simulation on the dynamical evolution of planetesimals over 12 Myrs (see for the method Kokubo and Makino, 2004). Our results of numerical simulation indicate that planetesimals tend to stay in orbit near 1/1 and 2/1 MMRs of the planets. The masses of the planets would be constrained by further simulations, if we take into account the fact that our observational data do not show the secular resonance around 90 AU, which depends on the planets' masses. The numerical results appended in Fig. 3 are consistent not only with our perspective but also with observational results given in Fig. 1. By taking account of the observational uncertainties in the locations of the planetesimal rings, these numerical results support our perspective given in Fig. 3.

5. Concluding Remarks

The presence of a planetary system around β Pic is consistent with available observations of the β Pic dust disk from near- to mid-infrared wavelengths. The detection of planetesimal rings in the visible wavelength range is more difficult, because a number of clumps in the foreground more easily obscure a planetesimal ring that is tangential to the line of sight. In fact, optical observations with Hubble Space Telescope have not succeeded in imaging the clumps of planetesimals up to date (Golimowski *et al.*, 2006). On the one hand, higher resolution infrared observations are able to reveal the resonant structures of planets and to identify their precise locations. On the other hand, numerical

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[2] We place 2, 0.5, 0.1, 0.1 Jovian-mass planets to simulate their gravitational influences on planetesimals initially distributed from 5 to 110 AU in a disk according to a power-law radial distribution with the power of −0.5. Our results on the relative abundance of planetesimals do not depend on the assumed distribution of planetesimals, because each test particle in our simulation has no gravitational force on the other particles.

dynamical simulations of planetesimals in the stellar and planetary gravitational fields allow us to constrain the mass and orbital parameters of the planets. If the presence of Planets J, S, U and N were confirmed by future observations, then the coming question would be: Are there Earth-like planets in the β Pic system? A radial velocity survey excludes the presence of an inner giant planet in the immediate vicinity of the star ($\leq$1 AU) (Galland *et al.*, 2006). However, the result does not contradict the presence of Earth-like planets in orbit around β Pic within a few AU from the star.

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