Structure of the Edgeworth-Kuiper Belt (EKB) dust disk and implications for extrasolar planet(s) in ε Eridani

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Numerical simulations of the orbital evolution of dust particles from Edgeworth-Kuiper Belt (EKB) objects show that the three giant planets, Neptune, Jupiter, and Saturn impose distinct and dramatic signatures on the overall distribution of EKB dust particles. The features are very similar to those observed in the dust disk around the nearby star ε Eridani. Numerical simulations of dust particles in the ε Eridani system show that planetary perturbations may be responsible for the observed features.

1. INTRODUCTION

Over the past 10 years infrared surveys have discovered many stellar systems with dust rings or disks around the central stars. Small dust particles (micrometer to millimeter sized), once created from their large parent objects, spiral slowly toward the central star via Poynting-Robertson (PR) and stellar wind drag [1]. On their way toward the star, dust particles would interact with planets if planets exist in the system. The three major planetary perturbations on dust particles are resonance trapping, gravitational ejection, and secular perturbation. These perturbations may cause large-scale features on a dust disk. A good example is our Solar System's zodiacal cloud. Resonance trapping with the Earth triggers the formation of an enhanced dust ring around the Earth's orbit [2, 3] while secular perturbation causes the plane of symmetry of the cloud to be different from the invariable plane [4]. Similar features should exist in the EKB dust disk in the outer Solar System and, in fact, have been observed in several circumstellar dust disks. By analyzing the long-term evolution of dust particles under interactions with the planets in our Solar System, we may be able to decode some of the structures in other circumstellar dust disks and use the information to identify the existence of extrasolar planets.

2. STRUCTURE OF THE EKB DUST DISK

Since the discovery of the first EKB object in 1992, more than 280 trans-Neptunian objects have been discovered as the end of July 2000. The dust production rate in the EKB region should be at least comparable to that in the main asteroid belt. Numerical simulations of dust particles between 1 and 100 μm from the EKB region show that giant planets induce large-scale structures on the EKB dust disk [5, 6]. Trapping into exterior mean motion resonances (MMRs) with Neptune dominates the orbital evolution of dust particles 5 μm and greater from the EKB region. The main resonances are the 2:1 and 3:2 exterior MMRs. Trapping into MMRs with Uranus is rare because gravitational perturbations from Neptune usually make the resonance trap highly unstable. Once particles escape MMRs with Neptune, they continue to spiral toward the Sun. About 80% of the particles are eventually ejected from the Solar System by Jupiter and Saturn. The signatures of giant planets imprinted on the EKB dust disk, due to these effects, include: (1) the deviation of radial spatial density distribution from that determined by PR drag alone; (2) an enhanced ring-like structure along the orbit of Neptune; (3) a brightness variation along the ring with an opening (a dark spot) located where Neptune is and with two bright arcs about 70° apart on either side of Neptune; (4) a seasonal variation of features in the ring that moves along with Neptune's orbital motion; and (5) a relative lack of particles inside about 10 AU.

3. EPSILON ERIDANI DUST DISK

Epsilon Eridani is a bright (V=3.7) K2V star at a distance of only 3.22 pc from the Sun. Its mass and luminosity are 0.8 M_{sun} and 0.33 L_{sun}, respectively. The age of the star is estimated to be less than 1 billion years. The dust disk around ε Eridani was revealed and imaged using the Submillimeter Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea Hawaii in 1997 [7]. At 850 μm wavelength, the observations clearly show a dust disk around the star with an azimuthal brightness variation along the disk. The disk has a 25° inclination with respect to the plane of sky. The inner and outer edges of the disk are approximately 30 and 90 AU, respectively, from the star with a peak brightness occurring around 60 AU. The brightness variation along the ring is about a factor of 2.5. The brightest spot/arc in the ring is a real feature. Other features (secondary bright spots and a dark gap) along the ring are less certain since they were identified in only half of the observational maps.

What makes the ε Eridani disk differ from other circumstellar dust disks is the azimuthal brightness variation along the ring and its almost face-on orientation. If one compares the pattern of the variation with the modeled structures of the EKB dust disk [6, 7], one finds global similarities between the two. Therefore, a simple explanation for the observed structures in ε Eridani is that they are caused by perturbations from objects (planets) orbiting the star.

To identify whether or not planets exist in ε Eridani we have performed 15 numerical simulations (with perturbations from planets) to see if we could produce dust disk patterns that match the observed features. The numerically produced dust disk patterns depend on several factors: (1) number of planets, (2) masses and orbital locations of the planets, (3) size distribution of the dust particles, and (4) the source region of the dust particles. As a first step, we have assumed there is only one planet in ε Eridani in our numerical simulations. In addition, we have placed the planet at either 30 or 40 AU from the star. It is based on (1) previous radial profiles of dust particles from the EKB dust simulations and the orbital location of the major perturber, i.e., Neptune [6], and (2) the radial profile of ε Eridani that shows a brightness peak at 60 AU [7].

Five different planetary masses are used in the simulations: (1) 5 Jupiter masses (the mass ratio between the planet and the star is five times that between Jupiter and the Sun), (2) 1 Jupiter mass, (3) 1 Neptune mass, (4) 5 Earth masses, and (5) 1 Earth mass. The eccentricity of the planet's orbit is assumed to be 0.01. Dust particles are assumed to be released from parent objects between 50 and 80 AU with eccentricities of 0.1 and inclinations of 10°. The effect of radiation pressure and PR drag are also included in the simulations. We simulate the orbital evolution of dust particles of 4 different sizes: 5, 10, 50, and 100 μm in diameter. In most cases (12 out of 15), there are 100 dust particles in each simulation. The remaining simulations include 50 dust particles. Since the age of ε Eridani is estimated to be between 500 million and 1 billion years, all simulations are carried out for at least 700 million years, unless all dust particles are ejected from the system or spiral into the star prior to that.

Results from each simulation are analyzed and the major MMRs that dominate the orbital evolution of dust particles are identified. To visualize a simulated dust disk (as viewed from a given direction) to compare with the actual observations, output positions of dust particles from each simulation are accumulated together and analyzed. For a massive planet, such as Jupiter, dust particles are trapped in various MMRs that are far away from the planet. However, as the mass of the perturbing planet decreases, those distant MMRs become weaker and are less likely to trap dust particles. Dust particles continue to spiral toward the star and get trapped in MMRs that are closer to the planet. The following examples are from 50 μm particles simulations. The major MMRs that trap particles in the four simulations are: (1) 1 Jupiter-mass planet: 5/2 (at 73.4 AU), 2/1 (63.3 AU), and 3/2 (52.2 AU), (2) 1 Neptune-mass planet: 5/2, 2/1, 5/3 (56.0 AU), and 3/2, (3) 5 Earth-mass planet: 2/1, 5/3, 3/2, and 4/3 (48.3 AU), (4) 1 Earth-mass planet: 3/2, 4/3, 5/4 (46.3 AU). The most dominant MMR in each simulation is: (1) 2/1, (2) 2/1, (3) 3/2, and (4) 3/2, respectively.

While trapped in an exterior MMR with a planet, a dust particle's trajectory, when viewed from a coordinate system co-rotating with the perturbing planet, forms simple ring-like geometric patterns around the star that consist of "loops" [2]. Different MMRs result in different numbers of loops. For example, 3:2 (2 loops), 2/1 (1), 5/3 (3), 4/3 (3). The loops are evenly spaced along the ring and in general are more stable when all loops remain far away from approaching the planet. The only exception is the 2/1 MMR where only one loop is formed and is kept about 90° from the planet in a stable trap. The 2/1 MMRs are also unusual in that there are two types of 2/1 MMRs. One is the more typical MMR where a dust particle gains orbital energy directly from the perturbing planet, by having the loop trailing behind the planet, to counterbalance the energy loss due to PR drag [2]. In the other 2/1 MMR, the loop leads the planet, and the dust particle gains orbital energy via the "indirect" perturbation that arises because the star is moving around the barycenter of the star and planet. An accumulation of dust particles trapped into an MMR for a long period of time will form a ring-like structure with an azimuthal brightness variation. The bright regions are associated with the loops while the region closest to the planet always appears as a brightness minimum in the ring since dust particles in stable MMRs tend not to pass near the perturbing planet.

When all simulations are analyzed, the following conclusions are obtained: (1) to have a ring-like structure with a strongly depleted inner region, a giant planet (≥ Jupiter) is needed to eject dust particles from the system, (2) to have an azimuthal variation along the ring, a planet (Earth-like to Jupiter-like) is needed to trap particles in MMRs, and (3) to have a single bright spot/arc in the ring, the 2:1 MMR with a giant planet has to be the dominant resonance. Figure 1 show a simulated image of the ε Eridani dust disk with a Jupiter-like planet at 40 AU from the star. Figure 2 is the observed image published in 1998 [7]. The parts that match the key observation features include a ring-like structure around the star, the location of the bright peak in the ring and the adjacent bright arc-like structure. However, the faintest part of the ring as well as the width of part the ring are not well matched. Since the bright peak is the only reliable feature identified from the observations [7], it is somewhat premature to compare other features in the ring. Additional and improved observations will be needed to further characterize the ring features and, then, the property of the perturbing planet.

4. CONCLUSIONS

Large-scale dust structures should exist in the outer Solar System due to perturbations from Neptune. Similar interactions between dust disks and unseen planets should also exist in many extrasolar planetary systems. Using structures on a dust disk to detect and characterize planets provides a different way for extrasolar planet detection. In some cases, for example if a system has a close-to-face on orientation and/or the planet is very far away from the central star, this method may be more powerful than any other.

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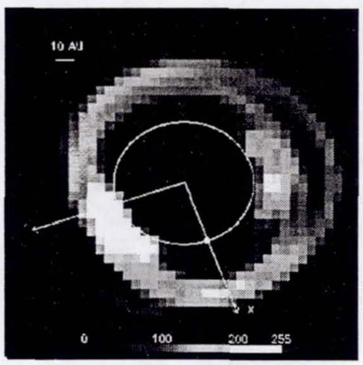

Figure 1. A simulated image of the ε Eridani disk with a Jupiter-like planet in the system.

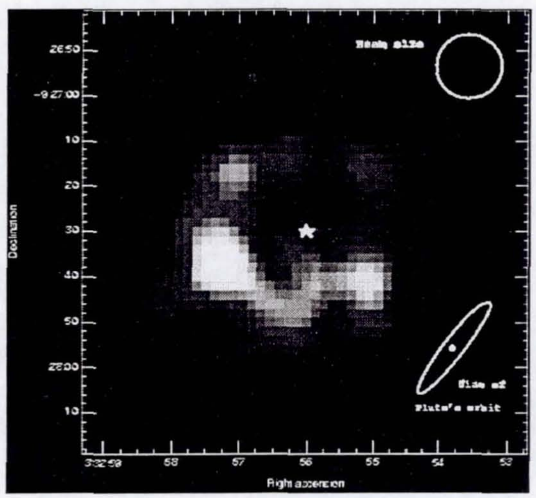

Figure 2. The observed ε Eridani disk, adapted from [7].