Evidence for Early Stellar Encounters in the Orbital Distribution of Edgeworth–Kuiper Belt Objects

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ABSTRACT

We show that early stellar encounters can explain the high eccentricities and inclinations observed in the outer part (>42 AU) of the Edgeworth–Kuiper Belt (EKB). We consider the proto-Sun as a member of a stellar aggregation that undergoes dissolution on a timescale of ~106 yr, such that the solar nebula experiences a flyby encounter at pericenter distance \( q \) on the order of 100 AU. Using numerical simulations we show that a stellar encounter pumps up the velocity dispersion in the young solar nebula in the outer parts. In the case of a nearly parabolic encounter with a solar mass companion, the velocity dispersion at \( a > 0.25q \) is pumped up to such an extent that collisions between planetesimals would be expected to become highly disruptive, halting further growth of planetesimals. This has the consequence that planet formation is forestalled in that region. We also find that a stellar encounter with pericenter distance \( q \sim 100–200 \) AU could have pumped up the velocity dispersion of EKB objects outside 42 AU to the observed magnitude while preserving the velocity dispersion magnitude inside Neptune's 3:2 mean motion resonance (located at 39.5 AU). This allows for the efficient capture of objects by the resonance during a phase of orbital migration by proto-Neptune, which we also test with simulations. We point out that such a stellar encounter generally affects the dynamical and material structure of a protoplanetary disk, and the planetesimal distribution can remain imprinted with this signature over much of the main-sequence lifetime of the star. In particular, our results support the notion that an analogous process has operated in some recently observed extrasolar dust disks.

Subject headings: celestial mechanics, stellar dynamics — Kuiper Belt, Oort Cloud — open clusters and associations: general — solar system: formation

1. INTRODUCTION

Stars commonly form in groups or clusters within turbulent molecular clouds on timescales that are of about a million years (Hillenbrand 1997). Typical young stellar aggregates have sizes of roughly 1 pc and consist of a few hundred stars. Recent observations have also shown that most stars form in eccentric binary systems and that the binary frequency of young stars is about two times higher than that of main-sequence stars in the solar neighborhood (Ghez et al. 1997; Köhler & Leinert 1998). This reflects the fact that secular dynamical processes within newly formed stellar groups tend to reduce their binary fraction over time. Recent numerical modeling (Kroupa 1995, 1998) demonstrates that encounters between binaries can lead to the dissolution of aggregates on timescales of several hundred million years and that stochastic close stellar encounters—which are in general very energetic—can lead to the dissolution of the widest binaries. Binary dissociation occurs at binary orbital periods greater than about 3000 yr, corresponding to separations on the order of a few 100 AU. It is therefore reasonable to expect that most single main-sequence stars actually formed as part of a wider binary system that was disrupted through interactions within a young stellar cluster. Even after a protostar becomes detached from its companion, or if it is born as a single star, encounters by passing stars would occur before the dissolution of the stellar cluster. The timescale for encounters with pericenter distance \( q \sim 200 \) AU may be comparable to the dissolution timescale of the stellar cluster (Laughlin & Adams 1998). Thus, if the Sun formed in such a clustered environment, it most likely experienced a few close encounters with a transient binary companion or with passing stars at pericenter distances on the order of 100 AU, before the breakup of the stellar cluster.

Laughlin & Adams (1998) have suggested that the large eccentricities of extrasolar planets associated with Cyg B and 14 Her could have been pumped up by interactions with passing binary systems in an open cluster. Here, we will consider interactions of a star (the proto-Sun) having a protoplanetary system (a planetesimal disk) that encounters a passing single star. In general, interactions with a binary system are more disruptive to the protoplanetary system than interactions with a single star. Since we seek to model the solar system, the interactions we consider are necessarily much less disruptive to the planetary system than those considered by Laughlin & Adams. (More distant encounters with passing binary systems may lead to similar results.)

Such an encounter will generally affect the dynamical and material structure of the solar protoplanetary disk, and, provided internal conditions allow, the planetesimal disk will remain imprinted with this signature over much of the main-sequence lifetime of the star. In this paper we study the dynamical effects of the stellar encounters on protoplanetary disks and point out that the orbital distribution of Edgeworth–Kuiper Belt (EKB) objects may indicate that the solar system has experienced close stellar encounters. We demonstrate that puzzling kinematical features in the orbital distribution of the EKB objects can be explained naturally if the Sun formed as a member of a stellar cluster and experienced a stellar encounter (or series of encounters) with \( q \sim 100–200 \) AU.
2. DYNAMICAL STRUCTURE OF THE EDGEWORTH–KUIPER BELT

The EKB objects observed at multiple oppositions or during relatively long duration are shown in Figure 1. The increasing numbers of EKB objects being revealed by observations presently fall into three distinct groups. First, many objects have semimajor axes close to the 3:2 resonance with Neptune’s orbit (located at 39.5 AU), and these display a wide range of eccentricities and inclinations (each up to ~0.35). Second, outside 42 AU, the objects have slightly lower average eccentricity (~0.1) and inclination (~0.1 radian). At $a \leq 39$ AU and $40 \leq a \leq 42$ AU, there are unpopulated regions (hereafter “gaps”). The cutoff outside ~50 AU may imply depletion of objects, but it could also be due to the present observational sensitivity limit (Jewitt, Luu, & Trujillo 1998; Gladman et al. 1998). The third group is comprised of the “scattered disk” objects (Duncan & Levison 1997), which have experienced close approach with Neptune. Pericenter for the scattered disk objects is located near Neptune’s orbit. An example is TL66, with $e \sim 0.6$ and $a \sim 85$ AU, which is outside the range of Figure 1.

Secular perturbations by the giant planets can account for the gap between 40 and 42 AU (Duncan, Levison, & Budd 1995). They cannot account for the other features (Duncan, Levison, & Budd 1995). The model of sweeping mean motion resonances due to Neptune’s outward migration successfully accounts for the concentrated distribution at the 3:2 resonance as well as for the gap inside 39 AU (Malhotra 1995). This model also predicts that a large accumulation ought to occur at Neptune’s 2:1 resonance (located at 47.8 AU) with a cleared gap interior to the present resonant location. If the number of objects captured by the 2:1 sweeping resonance is similar to that captured by the 3:2 resonance, it may be expected that more objects should now be detected near the 2:1 resonance (Jewitt et al. 1998). However, the current population near the 2:1 resonance is still poorly constrained, owing to the observational sensitivity limit. The migration speed of Neptune also affects the relative population between the 3:2 and 2:1 resonances (Ida et al. 1999). In summary, the good agreement of the theoretical predictions by Malhotra (1995) with the observations for the objects near the 3:2 resonance supports the sweeping of mean motion resonances.

The relatively high eccentricities and inclinations found outside 42 AU cannot be accounted for by long-range secular perturbations of the planets. The velocity dispersion of most of these observed objects exceeds their surface-escape velocity, and this cannot be explained by internal gravitational scattering (Safronov 1969).

The capture probability of the sweeping 3:2 resonance becomes small—and the gap inside 39 AU cannot be created—when the initial eccentricity exceeds ~0.05 (Malhotra 1995). The objects with $e \geq 0.05$ would not be swept, and they remain inside 39 AU, although a clear gap is presently observed inside 39 AU. Thus, the mechanism to pump up velocity dispersion outside 42 AU should satisfy the condition of having occurred in a highly localized manner to keep $e$ and $i$ small enough inside 39 AU, although we note that objects with $e \geq 0.1$, inside 39 AU, can be destabilized by planetary perturbations in the age of the solar system (Duncan et al. 1995).

Some models have been proposed to account for the high $e$ and $i$ outside 42 AU. The Earth-sized bodies that are thought to have existed at one time in the formation stage and were subsequently ejected might have been able to pump up the velocity dispersion (Stern 1991; Morbidelli & Valsecchi 1997; Petit, Morbidelli, & Valsecchi 1999). Partial trapping by sweeping of the 2:1 resonance might have also pumped up the eccentricities outside 42 AU (Hahn & Malhotra 1999).

Here we propose that another mechanism, stellar encounters, dynamically heats the planetesimal disk outside 42 AU. While the two former mechanisms are associated

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*See, e.g., B. Marsden’s Web site, http://cfa-www.harvard.edu/~graft/lists/TNOs.html.*
with processes occurring after the formation of Neptune, the stellar-encounter model can operate before Neptune’s formation as well. Although all these mechanisms may be able to account for the dynamical heating of the velocity dispersion between the 3:2 and 2:1 resonances, the predicted velocity dispersion beyond the 2:1 resonance (which has not been observed up to now) is expected to be quite different in our model, as discussed below.

3. MODELING

We have investigated the possibility that stellar encounters with the solar protoplanetary disk could have increased the eccentricity \( e \) and inclination \( i \) of EKB objects presently located outside 42 AU. In our modeling we assume the following:

1. A single star passes by the proto-Sun on a nearly parabolic orbit and perturbs the planetesimal system. The passing star may be weakly bound to the proto-Sun, in which case we can consider a series of encounters.
2. The pericenter distance \( q \) of the encounter(s) is on the order of 100 AU.
3. Planetesimals with the present EKB object mass \((\sim 10^{12}–10^{13} \text{ g})\) are formed on low-\( e \) and low-\( i \) orbits prior to the first encounter that pumps up \( e \) and \( i \) significantly.

As discussed in the introduction, the assumptions 1 and 2 are consistent with recent observations and numerical modeling. If we are concerned only with the effects of stellar encounters on the protoplanetary system, assumption 3 is not necessary. However, in order to apply our results to the EKB, assumption 3 is needed in our model because the induced velocity dispersion is larger than the surface-escape velocity, which we would expect to halt planetesimal agglomeration (see below). According to conventional models (e.g., Safronov 1969; Goldreich & Ward 1973; Hayashi, Nakazawa, & Nakagawa 1985), dust grains settle to the equatorial plane of the nebula and subsequent gravitational instability of the dust layer results in planetesimal formation. The dust grain sedimentation timescale may be only \( 10^3–10^5 \text{ yr} \) (e.g., Hayashi et al. 1985), and the gravitational instability operates over a timescale that is comparable to the orbital period (reviewed by Papaloizou & Lin 1995). Firstborn planetesimals have masses of a few times \( 10^{22} (a/40 \text{ AU})^{3/2} \text{ g} \) (e.g., Hayashi et al. 1985), which is already comparable to the masses of the present EKB objects. However, nebula turbulence may prevent dust grains from settling onto the equatorial plane, so the gravitational instability does not occur (e.g., Weidenschilling & Cuzzi 1993). If this is the case, planetesimal accretion up to the present size of the EKB objects would require \( 10^8–10^9 \text{ yr} \) (e.g., Stern & Colwell 1997), so assumption 3 may be too restrictive for our model of repeated encounters in an eccentric binary and only the model of flyby stellar encounters (before dissolution of a stellar aggregate) would be allowed.

A series of numerical simulations to test the effect of stellar companion encounters in protoplanetary disks has been performed. We consider collisionless particles (corresponding to planetesimals), orbiting initially on coplanar circles around a primary star (the proto-Sun). This particle disk encounters a hypothetical companion star. The orbital changes of the test particles are integrated taking into account the gravitational forces of the primary and the companion star by using a fourth-order predictor-corrector scheme. Many different encounter geometries and companion masses have been examined. If the scale length is defined by the pericenter distance \( q \) of the encounter, each encounter is characterized by (1) the companion mass \( (M_c) \), (2) the inclination angle of the companion orbit relative to the initial disk \( (\theta_c) \), and (3) the orbital energy or eccentricity of the perturber \( (e_c = 1) \) (Ostrouh 1994).

In the models, typically \( 10^4 \) test particles were initially distributed in the region \( a/q = 0.05–0.8 \), where \( a \) denotes semimajor axis. The initial surface number density \( n_{\infty} \) is proportional to \( a^{-1.5} \). Since we consider test particles that do not interact with one another, the particular choice of disk mass or surface number density profile does not affect the generality of the results. The initial eccentricity and inclination \( (e_0 \text{ and } i_0) \) of the particles are taken to be \( \leq 0.01 \). Figure 2 shows the eccentricity and inclination of the particles after the encounter as a function of \( a/q \), in the case with \( e_0 = i_0 = 0 \text{ and } M_c = M_p \). Inclination angle \( i_c \) is shown at \( 5^\circ \) (Fig. 2a), \( 30^\circ \) (Fig. 2b), and \( 150^\circ \) (Fig. 2c) with the line of nodes along the \( x \)-axis. The spatial distribution in the case of \( \theta_c = 30^\circ \) is shown in Figure 3.

As shown in Figure 2, the encounter leads to a strong increase in \( e \) and \( i \) in the outer parts of the disk. In the case of \( \theta_c = 30^\circ \), \( e \) and \( i \) are pumped up only slightly \((\leq 0.01)\) at

![Figure 2](image_url)
growth at $a \sim 0.2\cdot0.3q$: outside this region planetesimal growth is greatly inhibited, while it is not affected at all inside.

For different encounter parameters, the distribution of the pumped-up $e$ and $i$ is generally very similar to Figure 2, except for the length scale $q$. In other words, for different encounters, the distribution of particles in Figure 2 shifts toward larger or smaller values of $a/q$, except that $i$ is not pumped in the special case of a coplanar encounter. In general, more massive companions and lower inclination encounters yield stronger interactions. For example, the distribution shifts as $a/q \propto (M_s/M_p)^{-0.2-0.25}$. Encounters with $\theta_e$ closer to $90^\circ$ result in higher $i$ relative to $e$. The $\theta_e = 150^\circ$ encounter has the same amplitude of inclined angle as that with $\theta_e = 30^\circ$. Hence, the pumped-up $i$ is similar, but $e$ is smaller (see Fig. 2), because the parameter $\theta_e = 150^\circ$ gives a retrograde encounter and the relative velocity between disk particles and the passing star is therefore significantly larger, resulting in only very weak coupling.

As mentioned above, if the proto-Sun had a transient binary companion, the proto-Sun may have experienced a few close encounters with the companion before the binary system broke up. In this case, the individual encounters would have similar parameters and $e$ and $i$ would be pumped up cumulatively with each encounter, so that the perturbed forms of $e$ and $i$ would be preserved except for shifts toward smaller values of $a/q$.

We shall now consider an encounter that gives the required $e$ and $i$ distributions for the inner EKB. As stated above, such encounters with $q$ on the order of 100 AU may be reasonable for the proto-solar system. We performed a simulation similar to that presented in Figure 2b ($\theta_e = 30^\circ$) except $\langle e^2 \rangle^{1/2} = \langle i^2 \rangle^{1/2} = 0.01$. Overall features of the pumped-up $e$ and $i$ are quite similar to those in Figure 2b (see Fig. 4a). With $q = 160$ AU, we randomly selected 500 particles in the range 30 AU $< a < 65$ AU from the results, to compare them with the observed numbers of EKB objects. The selected distribution is shown in Figure 4a. For $a \geq 42$ AU, $e$ and $i$ are as large as those of the observed EKB objects. Some objects that originally had larger $a$ are scattered to this region with very high $e$ and $i$. However, at $a \lesssim 39$ AU, $e$ is still small enough ($\lesssim 0.05$) to allow the formation of a gap inside 39 AU via resonance sweeping, without the need for any other processes, e.g., long-term orbital destabilization.

In order to study the sweeping mean motion resonances we also performed simulations similar to other authors’ (Malhotra 1995; Ida et al. 1999), starting from the resultant distribution of particles after the stellar encounter (Fig. 4a). The proto-Neptune with a mass of $10^{24}$ g (comparable to the present Neptunian mass) was artificially moved from 23 to 30 AU (therefore, the 3:2 resonance moved from 30 to 39.5 AU), on a circular zero-inclination orbit. We assumed a time dependence for the semimajor axis evolution given by $\dot{a}/a = 2 \times 10^6$ yr. If we choose a longer migration time, more particles are captured by the 2:1 resonance and a gap is created interior to the resonance, while the capture probability of the 3:2 resonance would remain much as before (Ida et al. 1999).

The result after the sweeping is shown in Figure 4b. The objects between 40 and 42 AU would be destabilized by a long-term secular resonance (Duncan et al. 1995). The

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**Figure 3.**—Spatial distribution of particles after a companion encounter, projected into the initial orbital plane ($x$-$y$ plane) and projections perpendicular to the $x$- and $y$-axes, 20 rotation times ($a/q = 1$) after the encounter. The results of the encounter in Fig. 2b ($\theta_e = 30^\circ$) are shown. The $x$, $y$, and $z$-axes are scaled by the pericenter distance $q$ of the companion encounter. The companion enters from the lower right, passes through pericenter ($x/q, y/q, z/q = 0, 1, 0$), and exits to lower left.
objects that have high eccentricity and are not trapped by mean motion resonances may experience close encounters with Neptune and go to the “scattered disk.” Sweeping secular resonances, which we do not include in our simulations, may alter the inclination distribution both near the 3:2 resonance and beyond 42 AU (Malhotra, Duncan, & Levison 1999). Thus, our result is consistent with the observed distribution in Figure 1. In particular, the puzzling high values of $e$ at $a \gtrsim 42$ AU are explained without diminishing the capture probability of the sweeping 3:2 resonance. Different geometry of a stellar encounter, multiple encounters, or an encounter with a passing binary system might result in a better match.

The time for damping of $e$ and $i$ due to hydrodynamic gas drag at 40 AU is $10^6 (m/10^{22} \text{ g})^{1/3} (e/0.1)^{-1} \text{ yr}$ (Adachi, Hayashi, & Nakazawa 1976) for a typical minimum-mass solar nebula model (Hayashi 1981). This is much longer than the lifetime of disk gas, which is inferred from observations to be on the order of $10^6$–$10^7$ yr (e.g., Zuckerman, Forveille, & Kastner 1995). Also, the two-body relaxation time and collision time for the presently estimated surface density at 40 AU are longer than the solar system age (Stern 1995, 1996; Davis & Farinella 1996). Hence, the orbital elements of the present EKB objects should not have changed significantly after the orbital perturbation. It is expected that the orbital distribution in $e$, $i$, and $a$ after the encounter reflects that observed today.

4. DISCUSSION

Our simulations show that early stellar encounters would lead to interesting features in the solar protoplanetary disk that might explain the structure of the outer part of the EKB. The stellar encounters would occur on timescales of dissolution of stellar aggregates, which is of the order of $\sim 10^6$ yr. This may allow the EKB objects to grow to their observed sizes before the encounters. The objects initially inside 30 AU would be strongly scattered to form the “scattered disk” during Neptune’s migration (Duncan & Levison 1997). The objects with initial $a$ from 30 to 40 AU would be captured by the sweeping of the 3:2 resonance with resultant high $e$ and $i$. Outside 40 AU, the stellar perturbations are strong enough to pump up $e$ and $i$ to $\gtrsim 0.1$. Once their velocity dispersion is pumped up to more than the surface-escape velocity, collisions between the EKB objects would produce copious amounts of dust particles which would be removed by gas drag, Poynting-Robertson drag, and radiation pressure–driven ejection (Stern 1995; Backman et al. 1995). The initial surface density is therefore eroded by virtue of its dynamical state, the present EKB objects being remnants that have avoided significant erosion (Stern 1996; Davis & Farinella 1996). This result could explain the fact that the observationally inferred surface density in the EKB is much lower than that extrapolated from a minimum-mass solar nebula model (e.g., Stern 1995). Detailed numerical modeling of the subsequent collisional evolution of the perturbed EKB is required in order to test this hypothesis.

Our model predicts that there should be a steep increase in $e$ and $i$ with semimajor axes. In contrast, the model of stirring by Earth-sized bodies would predict decrease in $e$ and $i$ and that by partial trapping by the Neptunian-sweeping 2:1 resonance predicts a “cold” disk beyond 50 AU. Future observations can validate these models by the trend of radial dependences in $e$ and $i$. If $e$ and $i$ systematically increase beyond 50 AU, our model is supported.

The high eccentricities and inclinations that follow immediately from such an encounter also have a number of consequences for extrasolar planetary systems. First, as stated previously, the augmented velocity dispersion among planetesimals promotes the production of dust particles. This can significantly increase the dust replenishment rates and lead to more prominent circumstellar disks around some main-sequence stars (Stern 1995; Kalas & Jewitt 1996; Holland et al. 1998). The existence of the dust disks may reflect stellar encounters in the formation epoch. Second, as stated above, planetesimal growth could be forestalled in the outer region of the disk by a stellar encounter. This situation could be reflected in the fact that Neptune marks the outer boundary of our planetary system, at 30 AU. Thus, the existence of substantial planetary bodies outside 50 AU would be inconsistent with our model. Finally, we comment that recent advances in star formation theory and observation suggest that such stellar encounters with disks as those considered here should be viewed not as unique catastrophic events but as an integral part of the star- and planetary-system formation process.

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