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 (> 42AU) of the Edgeworth-Kuiper Belt (EKB). We consider the proto-sun as a member of a stellar aggregation that undergoes dissolution on a timescale \( \sim 10^8 \) yrs, such that the solar nebula experiences a flyby encounter at pericenter distance \( q \) on the order of 100AU. Using numerical simulations we show that a stellar encounter pumps 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 \( a \gtrsim 0.25q \) 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 42AU to the observed magnitude while preserving that inside Neptune’s 3:2 mean-motion resonance (located at 39.5AU). 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: open clusters and associations: general – solar system: formation – Kuiper belt – celestial mechanics – extrasolar planets
1. Introduction

Stars commonly form in groups or clusters within turbulent molecular clouds on timescales which 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 neighbourhood (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 dissociation of the widest binaries. Binary dissociation occurs at binary orbital periods greater than about 3000 yrs, corresponding to separations of order 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 which was disrupted through interactions within a young stellar cluster. Even after a proto-star 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 \( q \sim 200\text{AU} \) 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 of order 100 AU, before the break up 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 which encounters a passing single star. In general interactions with a binary system are more disruptive to the protoplanetary system than those 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 Letter 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 observed EKB objects observed at multiple oppositions or during relatively long duration are shown in Fig.1 (e.g. see Marsden’s web site, http://cfa-www.harvard.edu/~graff/lists/TNOs.html). The increasing numbers of EKB objects being revealed by observations presently fall into three distinct groups. Firstly, many objects have semimajor axes close to the 3:2 resonance with Neptune’s orbit (located at 39.5AU), and these display a wide range of eccentricities and inclinations (each up to $\sim 0.35$). Secondly, outside 42 AU, the objects have slightly lower average eccentricity ($\sim 0.1$)
and inclination (∼ 0.1 radian). At semimajor axes inside 39AU, and between 40AU and 42AU, there are unpopulated regions (hereinafter “gaps”). The cut-off outside ∼ 50AU may imply depletion of objects but it could also be due to the present observational sensitivity limit (Jewitt, Luu, and Trujillo 1998; Gladman et al. 1998). The third group is comprised of the ’scattered disk’ objects (Duncan and 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 Fig.1.

Secular perturbations by the giant planets can account for the gap between 40AU and 42AU (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 39AU (Malhotra 1995). This model also predicts that a large accumulation ought to occur at Neptune’s 2:1 resonance (located at 47.8AU) 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 by the 3:2 resonance, it may be expected that more objects should now be detected near the 2:1 resonance (Jewitt, Luu, and Trujillo 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 42AU cannot be accounted for by long-range secular perturbations of the planets. The velocity dispersion of these observed objects exceeds their surface escape velocity for most objects, which cannot
be explained by internal gravitational scattering (Safronov 1969).

The capture probability of the sweeping 3:2 resonance becomes small, and the gap inside 39AU cannot be created, when the initial eccentricity exceeds $\sim 0.05$ (Malhotra 1995). The objects with $e \gtrsim 0.05$ would not be swept and remain inside 39AU, although a clear gap is presently observed inside 39AU. 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 39AU, although we note that objects with $e \gtrsim 0.1$, inside 39AU, can be destabilized by planetary perturbations in the age of the Solar System (Duncan, Levison, & Budd 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 once existed in the formation stage and were subsequently ejected might have been able to pump up the velocity dispersion (Stern 1991; Morbidelli and Valsecchi 1997; Petit, Morbidelli, and Valsecchi 1999). Partial trapping by sweeping of the 2:1 resonance might have also pumped up the eccentricities outside 42AU (Hahn and Malhotra 1999).

Here we propose another mechanism, stellar encounters, to dynamically heat the planetesimal disk outside 42AU. While the two former mechanisms are associated 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 young solar nebula could have increased the eccentricity $e$ and inclination $i$ of EKB objects presently located outside 42AU. In our modeling we assume:

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 100AU.

3. Planetesimals with the present EKB object mass ($\sim 10^{22} – 10^{23}$ 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 only concerned with the effects of stellar encounters on the protoplanetary system, the assumption 3 is not necessary. However, to apply our results to the EKB the 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 $10^3–10^5$ yrs (e.g., Hayashi, Nakazawa, & Nakagawa 1985) and the gravitational instability operates over a timescale that is comparable to the orbital period (reviewed by Papaloizou & Lin 1995). First-born planetesimals have masses of a few $\times 10^{22}(a/40\text{AU})^{3/2}$ g (e.g. Hayashi, Nakazawa, & Nakagawa 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 that 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 $10^8$–$10^9$ yrs (e.g. Stern & Colwell 1997), so that 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 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: the companion mass ($M_c$), the inclination angle of the companion orbit relative to the initial disk ($\theta_c$), and the orbital energy or eccentricity of the perturber ($e_c = 1$) (Ostriker 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 $n_{s0}$ is proportional to $a^{-1.5}$. Since we consider test particles which 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 ($e_0$ and $i_0$) of the particles are taken to be $\lesssim 0.01$. Figure 2 shows the eccentricity and inclination of the particles after the encounter as a function of $a/q$, in the case with $e_0 = i_0 = 0$ and $M_c = M_p$. Inclination angle $\theta_c$ is (a) 5 degrees, (b) 30 degrees, and (c) 150 degrees with the line of nodes along the $x$-axis. The spatial distribution in the case of $\theta_c = 30$ degrees is
shown in Fig. 3.

As shown in Fig. 2 the encounter leads to a strong increase in $e$ and $i$ in the outer parts of the disk. In the case of $\theta_c = 30$ degrees, $e$ and $i$ are pumped up only slightly ($\lesssim 0.01$) at $a/q \lesssim 0.2$, while they are pumped up highly ($\gtrsim 0.1$) at $a/q \gtrsim 0.25$. Note that the former condition is similar to the orbital stability condition of bounded three-body systems (e.g. Black 1982). At $a/q \gtrsim 0.3$ a large fraction of particles are ejected: respectively 70% and 95% of objects with initial $a/q \sim 0.5$ and 0.7. The remaining particles at $a/q \gtrsim 0.3$ have large eccentricities. The other $\theta_c$ cases show similar features. The spike in $i$ at $a/q \sim 0.3$ coincides with the 3:1 commensurability of the unperturbed disk orbital frequency and the companion’s orbital frequency at pericenter. Since the companion’s angular velocity at pericenter is $[2G(M_p + M_c)q^{-3}]^{1/2}$, the 3:1 commensurability is located at $a/q = [2(1 + M_p/M_c) \times 3^2]^{-1/3} \approx 0.30$, for prograde encounters. Thus the highly localized character of the disk response in this region appears to be associated with a corotation resonance occurring near pericenter (Korycansky & Papaloizou 1995).

As shown in Fig. 3, long-lived features in the spatial distribution are the inclined bar-like envelope and prominent one-armed spiral, both due to close correlations in the longitudes of perihelion and ascending node. Precession of the longitudes due to, for example, the nebula potential would gradually destroy the features.

If the velocity dispersion is greater than the surface escape velocity of a planetesimal, collisions between planetesimals is too destructive (Backman, Dasgupta, & Stencel, 1995) and growth of planetesimals is halted. The surface escape velocity of a planetesimal with mass $m$ and density $\rho$ is $0.5 \times 10^5(m/10^{24}g)^{1/3}(\rho/1gcm^{-3})^{1/6}cm/s$. The velocity dispersion is $\sim (e^2 + i^2)^{1/2}v_{\text{Kep}} \approx 0.5 \times 10^6(e^2 + i^2)^{1/2}(a/40AU)^{-1/2}(M_p/M_\odot)^{1/2}cm/s$, where $v_{\text{Kep}}$ is Keplerian velocity. As a result, in the region where pumped-up $e$ or $i \gtrsim 0.1$, planetesimal growth would be inhibited. The steep radial gradient of $e$ and $i$ seen in Fig. 2 indicates that
there exists a well-defined boundary for planetesimal growth at $a \sim 0.2-0.3q$: 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 Fig. 2, except for the length scale $q$. In other words, for different encounters the distribution of particles in Fig. 2 shifts towards 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 $a/q \propto (M_c/M_p)^{-(0.2-0.25)}$. Higher energy (i.e. more eccentric) encounters result in stronger effects further into the disk owing to the improved coupling there. Encounters with $\theta_c$ closer to 90 degrees result in higher $i$ relative to $e$. The $\theta_c = 150$ degree encounter has the same amplitude of inclined angle as that with $\theta_c = 30$ degrees. Hence, the pumped-up $i$ is similar, but $e$ is smaller (see Fig. 2), because the parameter $\theta_c = 150$ degrees 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 towards 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 protosolar system. We performed a similar simulation to that presented in Fig. 2b ($\theta_c = 30$ degrees) except $\langle e_0^2 \rangle^{1/2} = \langle i_0^2 \rangle^{1/2} = 0.01$. Overall features of the pumped-up $e$ and $i$ are quite similar to Fig. 2b (see Fig. 4a). With $q = 160$AU, we
randomly selected 500 particles in the range $30 \text{AU} < a < 65 \text{AU}$ from the results, to compare them with the observed numbers of EKB objects. The selected distribution is shown in Fig. 4a. For $a \gtrsim 42 \text{AU}$, $e$ 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 $a \lesssim 39 \text{AU}$, $e$ is still small enough ($\lesssim 0.05$) to allow the formation of a gap inside 39AU 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 $10^{29}$g (comparable to the present Neptunian mass) was artificially moved from 23AU to 30AU (therefore the 3:2 resonance moved from 30AU to 39.5AU), on a circular zero inclination orbit. We assumed a time dependence for the semimajor axis evolution given by: $30 \times [1 - (7/30) \exp(-t/5 \times 10^5 \text{yrs})] \text{AU}$, and a migration timescale $a/\dot{a} = 2 \times 10^6 \text{yrs}$. If we chose 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 Fig.4b. The objects between 40AU and 42AU would be destabilized by a long-term secular resonance (Duncan, Levison, & Budd 1995). The 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 Fig.1. In particular, the puzzling high values of $e$ at $a \gtrsim 42 \text{AU}$ 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 typical damping time of $e$ and $i$ due to hydrodynamic gas drag at 40AU is $10^9 (m/10^{22}g)^{1/3} (e/0.1)^{-1}$ yrs (Adachi, Hayashi, & Nakazawa 1976), for a typical minimum mass solar nebular model (Hayashi 1981). This is much longer than the lifetime of disk gas, inferred from observations, being of order $10^6$–$10^7$ yrs (e.g. Zuckerman, Forveille, & Kastner 1995). Also the two-body relaxation time and collision time for the presently estimated surface density at 40AU is 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 young solar nebula 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 $\sim 10^8$ yrs. This may allow the EKB objects to grow to their observed sizes before the encounters. The objects initially inside 30AU would be strongly scattered to form the ‘scattered disk’ during Neptune’s migration (Duncan & Levison 1997). The objects with initial $a$ from 30AU to 40AU would be captured by the sweeping of the 3:2 resonance with resultant high $e$ and $i$. Outside 40AU, 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, Dasgupta, & Stencel 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; Weissman and Levison 1997). Detailed numerical modeling of the subsequent collisional evolution of the perturbed EKB is required to test this hypothesis.

Our model predicts that there should be a steep increase in $e$ and $i$ with semimajor axis. In contrast, stirring by 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 50AU. Future observations can validate these models by the trend of radial dependences in $e$ and $i$. If $e$ and $i$ systematically increase beyond 50AU, 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. Firstly, as stated previously, the augmented velocity dispersion amongst 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. Secondly, 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 30AU. Thus the existence of substantial planetary bodies outside 50AU 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 not be viewed as unique catastrophic events but as an integral part of the star- and planetary-system formation process.

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Fig. 1.— Orbital distribution (eccentricity, inclination, and semimajor axis $a$) of the observed EKB objects (from Marsden’s web site, http://cfa-www.harvard.edu/~graff/lists/TNOs.html). The objects observed at multiple oppositions or during a relatively long period are plotted. Inclination is plotted in radians $[0, 2\pi]$. The unit of $a$, AU, is the mean distance between the sun and Earth. The present locations of Neptune and its 3:2 and 2:1 resonances are 30AU, 39.5AU, and 47.8 AU, respectively.

Fig. 2.— Orbital eccentricity $e$ and inclination $i$ of the particles pumped up by a companion encounter, as a function of semimajor axis $a$. (Initial $e$ and $i$ are zero.) Semimajor axis is scaled by the pericenter distance $q$. Inclination is given in radians $[0, 2\pi]$. $M_c = M_p$ and parabolic encounter are assumed for the companion: (a) the case with $\theta_c = 5$ degrees, (b) the case with $\theta_c = 30$ degrees, (c) the case with $\theta_c = 150$ degrees.

Fig. 3.— The spatial distribution of particles after a companion encounter, projected into the initial orbital plane ($xy$-plane) and projections perpendicular to the $x$ and $y$-axis, 20 rotation times (at $a/q = 1$) after the encounter. The results of the encounter in Fig.2b ($\theta_c = 30$ degrees) is 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.

Fig. 4.— Orbital distribution of the predicted EKB objects: (a) predicted distribution after the stellar companion encounter (before the sweeping resonances), (b) prediction by combined simulations of the stellar companion encounters and the sweeping mean motion resonances associated with Neptune migration. For parameters of the companion encounters and Neptune’s migration, see text.