Origin of the Break and Mass-Dependence in the Wide-Binary Projected-Separation Distribution

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ABSTRACT

The distribution of Galactic-disk wide binaries shows a clear break in slope at projected separations of about $r_\perp \sim 2500$ AU in two basically independent surveys by Chanamé & Gould and Lépine & Bongiorno. The latter also showed that the frequency of wide-binary companions to G-star primaries declines monotonically as a function of companion mass. We show that both effects can be explained by the operation of Heggie’s law in the typical open-cluster environments where binaries form. One immediate conclusion is that most Galactic-disk stars formed in open clusters with internal dispersions of a few hundred meters per second and disruption times of a few hundred million years.

Subject headings: stars: fundamental parameters

Two separate studies demonstrate that there is break in the distribution of Galactic-disk wide-binary separations at about $r_\perp \sim 2500$ AU. For large separations, $\Delta \theta \gtrsim 30''$, Chanamé & Gould (2004) find a power-law distribution $dN/d\Delta \theta \sim \Delta \theta^{-\alpha}$, with $\alpha = 1.67 \pm 0.07$, while for $10'' \lesssim \Delta \theta \lesssim 30''$, they find a flat “Opik’s (1924) Law” distribution, i.e., $\alpha \sim 1$. Because the characteristic distance of the Chanamé & Gould (2004) sample is about $d \sim 60$ pc, this angular-scale break point corresponds to a physical scale of $r_\perp \sim d\Delta \theta \sim 1800$ AU. Lépine & Bongiorno (2006) studied wide-binaries with Hipparcos (ESA 1997) primaries. Because their targets have parallaxes, they present their results directly in terms of $r_\perp$ (rather than $\Delta \theta$). They find a break at about $r_\perp \sim 3000$ AU. Each estimate is uncertain at about the 20% level. Lépine & Bongiorno (2006) are hampered by small number statistics near the break because their bright-primary sample does not permit them to probe inward of $\Delta \theta < 20''$. On the other hand, while Chanamé & Gould (2004) probe to smaller angular separations and have much better statistics, it is difficult to make precise the interpretation of their angular break in terms of physical scales because of the substantial uncertainties in the individual distances of their sample. Thus, the two studies are broadly consistent. Moreover, as we will
show below, one actually expects the Chanamé & Gould (2004) sample to have a somewhat smaller break point.

Neither of these two surveys can probe inward of about $r = 1000 \text{ AU}$. However, it is known from the work of Duquennoy & Mayor (1991) that the G-star binary distribution roughly obeys Opik’s Law over about 4.5 decades of separation, from $10^{-1.5} \text{ AU}$ to $10^3 \text{ AU}$. (The Duquennoy & Mayor 1991 distribution is often expressed as a Gaussian, but it should be remembered that the abscissa of this “Gaussian” is in log while the ordinate is linear.)

For binaries observed at random orientations, their semi-major axis $a$ is related to their projected separation by $\langle a^{-1} \rangle = (\pi/4) \langle r^{-1} \rangle$, so the observed break at $r \sim 2500 \text{ AU}$ corresponds to $a \sim 3000 \text{ AU}$, i.e., to orbital velocities $v_{\text{orb}} \sim 0.5 \text{ km s}^{-1}$ (assuming a typical total mass $M \sim 1 \text{ M}_\odot$).

Lépine & Bongiorno (2006) suggested that the observed break could be due to dynamical effects in the clusters in which the binaries were born. Indeed, the orbital velocity at $a_{\text{break}} \sim 3000 \text{ AU}$ is very similar to the 1-dimensional dispersion observed in open clusters, which typically ranges from $\sigma \sim 0.3 \text{ km s}^{-1}$ to $\sigma \sim 1 \text{ km s}^{-1}$. Hence, it immediately argues that the break is an effect of “Heggie’s (1975) Law”, which states that “hard binaries get harder, soft binaries get softer”. The boundary point of this law is defined by the internal binding energy of the binary being equal to the mean kinetic energy of the ambient perturbers. Since, the binary components and the perturbers have roughly the same mass, the break point occurs when $v_{\text{orb}} \sim \sigma$.

Consider a “soft binary” population whose members are being injected with energy at a rate that is a function of their binding energy $E_b$: $dE_b/dt \sim E_b^{\beta}$. If the population is subjected to this process for a sufficiently long time, it will reach a steady state with $dN/dE_b \sim E_b^{\beta}$, corresponding to a separation distribution $dN/da \sim a^{-2-\beta}$. That is, $\alpha = 2 + \beta$. To a good approximation, the injection of energy into the binary is independent of separation, i.e., $\beta = 0$. This would predict $\alpha = 2$, somewhat larger than the value $\alpha = 1.67 \pm 0.07$ observed by Chanamé & Gould (2004). To next order, the energy injection actually grows logarithmically with separation, so $\beta \gtrsim 0$, which goes in the wrong direction but only by a small amount. Hence, if the argument we are giving is correct, the explanation for the discrepancy in slopes must be that the cluster dissolves before it has time to reach its “asymptotic state”.

The timescale for binary evolution is $T \sim (n\Sigma v)^{-1}$, where $n = \rho/m$ is the ambient perturber number density, $\rho$ is the mass density, $m$ is the mass of a typical perturber, $\Sigma = \pi a_{\text{break}}^2$ is the cross section for a major perturbation at the break point $a_{\text{break}} \sim 3000 \text{ AU}$, and $v = \sigma$ is the ambient velocity. Using the virial theorem, $4\pi G\rho \sim (\sigma/R)^2$, one finds
\(T \sim R^2/(a_{\text{break}}\sigma) \sim 100 \text{ Myr}\), where we have assumed \(M \sim 2m\), adopted a cluster radius of \(R \sim 1 \text{ pc}\), imposed Heggie’s Law \((v_{\text{orb}} \sim \sigma)\), and dropped factors of order unity. Since open clusters generally dissolve on timescales that are one or several times this binary-disruption timescale, it is plausible that the binary distribution does not have time to fully reach its asymptotic state.

The explanation just given makes an important prediction. The binding energy of a binary scales \(E_b \sim M_1 M_2/a\), where \(M_1\) and \(M_2\) are the component masses. The Hipparcos primaries in the Lépine & Bongiorno (2006) study are virtually all solar-type stars, i.e., \(M_1 \sim M_\odot\). This means that for secondaries of different masses, the break point scales as \(a_{\text{break}} \sim M_2\). It is plausible to assume that the secondaries with \(a \sim a_{\text{break}}\) are initially drawn randomly from the field population. Then we would predict that after the binaries diffuse to larger \(a\), the ratio of secondaries to field stars of the same mass would fall by a factor \(M_2^\alpha\), or in other words as \(M_2^\alpha\). Figure 9 of Lépine & Bongiorno (2006) shows the frequency of observed secondaries compared to what would be expected based on a distribution normalized at \(4 < M_V < 8\), i.e., stars of mass \(M_2 = 0.8 M_\odot\). The foregoing argument would predict that at \(M_V = 12\) (\(M_2 \sim 0.25 M_\odot\)), the observed secondaries should be deficient by a factor \(\sim (0.25/0.8)^{1.67} \sim 0.15\). The actual deficiency is about 0.5, which is significantly less dramatic. Nevertheless, this figure does show the expected overall trend. One possible explanation for the discrepancy is that the timescale for disruption of the binaries with smaller secondaries at their break point is considerably longer simply because their orbits present smaller cross sections. Since the binary disruption timescales at “typical” masses are already of order the cluster-disruption timescale, this increase in binary-disruption timescale could substantially mitigate the accelerated disruption relative to the naive scaling we have given.

The same argument predicts that the Chanamé & Gould (2004) sample should have a smaller \(a_{\text{break}}\) than the Lépine & Bongiorno (2006) sample because each of the latter is guaranteed to have a Hipparcos (i.e., roughly solar mass) component, and so to have a systematically higher binding energy.

We attempt a first test of our hypothesis by dividing the sample shown in Lépine & Bongiorno (2006) into three subsamples, with \(M_V < 8\), \(8 \leq M_V < 12\), and \(M_V \geq 12\). See Figure 1. Our prediction would be that the fainter stars should plateau at smaller \(r_\perp\). If there is any trend it would appear to go in the opposite direction, although these subdivided data are quite noisy and could still be subject to selection effects if the faintest stars are more difficult to detect at \(\sim 20''\) separations that Lépine & Bongiorno (2006) believe.

An important implication of this argument is that the break in the binary separation function tells us about the typical conditions in which disk stars form, namely that over
the lifetime of the Galactic disk, most stars formed in clusters with velocity dispersions of order a few hundred meters per second and that these clusters disrupt on timescales of order a few hundred million years. Figure 10 of Chanamé & Gould (2004) hints that the halo binary breakpoint occurs at at least a somewhat smaller semi-major axis than that of the disk. If this is confirmed by future observations, it would imply that halo stars were born in environments that were kinematically at least slightly hotter than disk stars. (Note that it is also possible, in principle, to produce a smaller \( a_{\text{break}} \) by selecting a sample of halo binaries with systematically smaller companion masses. However, the Chanamé & Gould 2004 sample actually has the opposite bias: since the halo stars are a factor \( \sim 4 \) farther away, they are actually biased toward being more luminous – and so more massive – stars.)

Detailed verification of the scenario presented here will require simulations that simultaneously model the disruption of the binary and of the cluster in which it initially resides. If verified, the same simulations will permit more precise characterization of the typical clusters in which today's field binaries were born.

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Fig. 1.— Frequency of binary companions as a function of projected separation in three luminosity bins for the secondaries: $M_V < 8$ (triangles), $8 \leq M_V < 12$ (squares), and $M_V \geq 12$ (stars). These correspond roughly to secondary mass intervals $M_2 > 0.65 M_\odot$, $0.25 M_\odot < M_2 < 0.65 M_\odot$, and $M_2 < 0.25 M_\odot$. For clarity, the 3 sets of points are slightly offset in the horizontal direction. The data are taken from Lépine & Bongiorno (2006) and correspond to their Figure 10. According to the argument presented here, the lower-mass bins should plateau at smaller projected separations. The data do not show this trend but they are noisy and may still be affected by selection.