Formation of the Widest Binaries from Dynamical ‘Unfolding’ of Triple Systems

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The formation of very wide binaries\textsuperscript{1−3}, such as the α Cen system with Proxima separated from the A/B stars by 15000 AU\textsuperscript{4}, challenges current theories of star formation, as their separation can exceed the typical size of a collapsing cloud core. Various hypotheses have been proposed to overcome this problem, including the suggestion that ultra-wide binaries result from the dissolution of a cluster, when a star gravitationally captures another distant star\textsuperscript{5−7}. Recent observations have shown that very wide binaries are frequently members of triple systems\textsuperscript{8,9} and that close binaries often have a distant third companion\textsuperscript{10−12}. Here we report Nbody simulations of the dynamical evolution of newborn triple systems still embedded in their nascent cloud cores that match observations of very wide systems\textsuperscript{13−15}. We find that although the triple systems are born very compact – and therefore initially are more protected against disruption by passing stars\textsuperscript{16,17} – they can develop extreme hierarchical architectures on timescales of millions of years as one component is dynamically scattered into a very distant orbit. The energy of ejection comes from shrinking the orbits of the other two stars, often making them look like a single star. Such loosely bound triple systems will therefore appear as very wide binaries.

Evidence is building that stars often, and possibly always, are formed in small multiple systems\textsuperscript{18,19}. Dynamical interactions between members of such systems lead to close triple encounters in which energy and momentum is exchanged, typically causing the disintegration of the triple system, with the escape of a single component (most frequently the lowest mass member) and the formation of a stable binary\textsuperscript{20−22}. A bound triple with a hierarchical architecture may also result, but only if it forms in the presence of a gravitational potential can such a triple system achieve long-term stability\textsuperscript{23}. However, this is frequently fulfilled for newborn triple systems, since break-up typically occurs in the protostellar phase, when the newborn stars are still deeply embedded in their nascent cloud cores\textsuperscript{24}.

We have used an advanced Nbody code to run 180218 simulations of a newborn triple system placed in a gravitational potential\textsuperscript{23} (for technical details see Supplementary Information). Figure 1a shows results for the 13727 stable hierarchical systems that are formed in the 180218 simulations. The blue dots mark the semimajor axes of the inner binaries, while the red dots indicate the semimajor axes of the outer components relative to the center-of-mass of the inner binary. The distant components have semimajor axes that span from hundreds
of AU to several thousands of AU, with a small but not negligible number of cases reaching several tens of thousands of AU and beyond.

We run the simulations for 100 million years, and classify the outcome at 1, 10 and 100 Myr into stable triples, unstable triples, and disrupted systems. If the outer orbit is hyperbolic, then the system is disrupted. If not, then the system is (at least temporarily) bound, and a stability criterion is applied\(^\text{25}\). If the system passes this test, it is classified as stable. If not, it is still bound but internally unstable, and will sooner or later disrupt. Figure 1b shows the semimajor axis distribution for 56957 bound but unstable triple systems. The number of systems in each category is merely an estimate, since a rigorous theory of stability is not mathematically possible, because the three-body problem is non-integrable. Hence we do see that the number of stable triples at 1, 10, and 100 Myr is not completely constant, but declines a few percent with time. The number of unstable triples, on the other hand, dramatically declines with age, by a factor of 3 or more from 1 to 100 Myr (Fig. 2a). At 1 Myr, 39\% of systems are bound (stable and unstable), at 10 Myr this number has decreased to 18\%, and at 100 Myr it is 12\%. This number will continue to decrease until only the stable triple systems remain, which is $\sim$7\%. This last number compares well with the 8\% of triple systems (mean of all spectral types) observed in the field\(^\text{26}\), suggesting that most star forming events must start as triple systems.

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The reason for the difference in distribution of semimajor axes between stable and unstable triple systems (Figs. 1a,b) lies in their orbital parameters. Figure 2b shows the separation distribution function of stable outer (red) and inner (blue) and unstable outer (green) and inner (aqua) systems at an age of 1 Myr. Figure 2c shows the distribution of eccentricities among the bound triple systems. The primary reason that some systems are stable and others unstable is that the stable systems are well separated even at periastron, when the three bodies have their closest approach. In contrast, the unstable systems are much more likely to suffer perturbations at closest approach, ultimately leading to their disruption. This is reflected in the eccentricity of the systems, see the figure caption for details.

There are mainly three parameters that control the stability of a triple system: the semimajor axis, the eccentricity, and the ratio of periastron distance of the outer binary to apastron distance of the inner binary. If the outer periastron distance becomes smaller than roughly 5–10 times the inner apastron distance, then the system will eventually break up. Systems with close inner binaries thus have a larger chance of achieving stability. For the outer binary, the relation between eccentricity and semimajor axis is shown in Figure 2d. Wide binaries (1000 – 10000 AU) are found with all eccentricities except the very smallest, although with a clear preference for larger eccentricities. For the very wide binaries (>10000 AU), in contrast, the eccentricities $e$ tend to be extreme (red dots in Figure 2d). The reason they can survive is that their periastron distance $a(1−e)$ is also large, thanks to their semimajor axes $a$ also being extremely large, although a few are stable even with moderate eccentricity, presumably because they have unusually small inner binaries.

Wide stable and unstable triple systems differ in one important respect. Figure 3a,b show how total binary mass relates to mass of the distant third body for systems wider than 1000 AU at ages of 1 Myr and 100 Myr. A large population exists at 1 Myr with members that are either all three approximately of the same mass, or with the distant third member being of very low mass. This population, however, is largely unstable (green), and so has mostly disappeared by 100 Myr, except for the very low-mass systems. The reason
that systems with a dominant binary and a light single are more unstable than the opposite configuration is likely that massive binaries more easily can alter the orbit of the third body near periastron, eventually leading to disruption. Stable triple systems (red) are much more uniformly distributed across Figure 3, although with a preference for members of very low-mass systems to be approximately of the same mass, and a slight preference for systems with dominant singles rather than dominant binaries. Such time-dependent properties of wide triple systems may be a dynamic signature of the triple decay mechanism.

Our simulations do not take into account that there may be further orbital evolution of the inner binary when the decay from non-hierarchical to hierarchical configuration occurs during the protostellar phase (as it does for more than 50% of simulations). In that case, viscous evolution will cause further inspiraling, leading to the formation of spectroscopic binaries. Gas induced orbital decay can ultimately lead to the merger of the binary components in a non-negligible number of cases. It follows that although wide binaries formed through triple decay initially consist of three stars, they may during the pre-main sequence phase evolve into a true wide binary containing only two stars.

The results presented here refer to the birth population of binaries, at an age of 1 Myr. The orbital parameters of a triple system are established at the moment when a stable hierarchical triple is formed. But since the birth configuration of a triple system is compact, it will take half an orbital period of the outer component before the triple system reaches its first apastron passage and attains its maximum extent \(a(1 + e)\). We call this the initial unfolding time of the newborn triple system. Many wide systems have not unfolded fully at 1 Myr, and the most extreme wide systems will take tens to hundreds of million years to unfold, and they are thus more protected against disruption by passing stars than if triple systems were born with such enormous separations in their crowded natal environments (Figure 3c). See Supplementary Information for more details.

Non-hierarchical systems that have broken up shortly after birth lead to a close binary and a detached single star that is moving away from the binary. Those with small velocity differences, or with motions mainly along the line of sight, will be observed to linger for a while in the vicinity of each other, mimicking a bound binary. It is of interest to determine what is the fraction of stable bound, unstable bound, and unbound triple systems that exist at different projected separations at different ages. Figure 4 shows the number and fraction of systems in each category for 1, 10, and 100 Myr. As a specific example, the recently discovered very wide (\(\sim 12–40\) kAU) triple systems found in 7-10 Myr old associations have only a \(\sim 20\%\) chance of being long-lived systems, a \(\sim 20\%\) chance of already being disrupted systems, but a \(\sim 60\%\) chance that they are unstable still bound systems.

At 100 Myr, 8.5\% of the 180218 simulations have led to bound (stable and unstable) systems with semimajor axes \(a\) between 1000 and 10000 AU, and 2.1\% are bound with \(a > 10000\) AU. That is, more than 10\% of the birth population of triple systems end up as wide or very wide, in excellent agreement with observations. The simulations also broadly reproduce the observed distribution of projected separations, see Supplementary Information for details. The present N-body simulations have thus demonstrated that the widest binaries known can arise naturally as a consequence of three-body dynamics shortly after birth. The subsequent, lengthy unfolding of the widest systems offers increased protection against external disruption by other young stars, and allows such wide systems to be born in both stellar associations as well as the outskirts of dense clusters.


Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgments We thank two anonymous referees and C.J. Clarke, M.B.N. Kouwenhoven, and A. Tokovinin for comments. BR thanks ESO and Tuorla Observatory for hospitality during the period when this paper was written, and Hsin-Fang Chiang and Colin Aspin for providing additional computer facilities. This work was supported by the National Aeronautics and Space Administration through the NASA Astrobiology Institute under Cooperative Agreement No. NNA09DA77A issued through the Office of Space Science. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of NASA’s Astrophysics Data System Bibliographic Services.

Author Contributions BR conceived the idea, carried out the simulations and data analysis, and wrote the paper. SM developed the code and wrote the software tools for analysis.

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The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to reipurth@ifa.hawaii.edu
Figure 1 | Semimajor axes of stable and unstable bound triple systems. (a): The semimajor axes of the outer and inner pairs in bound stable triple systems. Filled blue circles are the inner binaries in stable hierarchical triple systems, filled red circles are the more distant singles in stable hierarchical triple systems. (b) The semimajor axes of the outer and inner pairs in bound unstable triple systems. Turquoise circles are binaries in bound unstable triple systems, and green circles are singles in bound unstable triple systems. For both figures the semimajor axes refer to orbital parameters for systems that still remain bound at 1 Myr; at later times many of the unstable systems will have disrupted. For the widest systems, the distant bodies have not yet reached their extreme apastron distances.
Figure 2. | Statistical properties of stable, unstable, and disrupted triple systems. (a): Histogram with number of stable hierarchical, unstable hierarchical, and disrupted triple systems at 1, 10 and 100 Myr. The stable systems are essentially constant, while many of the unstable systems disrupt. (b): The distribution of semimajor axes for both inner and outer binaries that are bound at 1 Myr. The color scheme is the same as in Figure 1. The grey dashed line shows the sum of all (inner and outer) binaries. (c): The distribution of eccentricities for bound inner and outer binaries at 1 Myr. The color scheme is the same as in Figure 1. It is evident that highly eccentric systems are common, and the number of triple systems is a growing function of eccentricity for all but the stable outer systems, which peak around $e \sim 0.7$. Systems with very high eccentricity tend to have smaller periastron distances $a(1 - e)$, leading to the possibility of perturbations which after one or more close periastron passages eventually lead to breakup. Hence, the decline seen at high eccentricities for bound stable systems (red) is compensated by an increase among the unstable outer systems (green). The eccentricity distribution for the inner binaries will evolve significantly if circumstellar material is still present at birth or due to Kozai cycles. (d): The distribution of semimajor axes of the outer components in triple systems show a very strong dependence on the eccentricity. Wide binaries ($1000 < a < 10000$ AU) get in the mean increasingly wide as the eccentricity increases. For very wide binaries ($a > 10000$ AU, marked in red) this correlation becomes even more pronounced. While very wide binaries can be found with modest eccentricities ($e \sim 0.3-0.4$), the majority have eccentricities exceeding 0.9.
Figure 3. | Stable and unstable hierarchical triple systems at 1 Myr and 100 Myr, and the maximum extent $a(1+e)$ of a triple system as a function of time. (a) The total mass of the close binary is plotted against the mass of the distant third body at an age of 1 Myr for all wide systems with outer semimajor axes exceeding 1000 AU. Systems that are classified as unstable are marked green, and systems that are stable over long timespans are marked red. The figure is divided into two areas, in one half most of the system mass resides in the binary, whereas in the other half the single dominates the system. A line indicates where systems with three identical bodies lie. (b) The same figure for wide systems at an age of 100 Myr. The figures show that stable and unstable systems can be found all over the diagram, but with a strong preference for unstable systems to have a dominant binary, while stable unequal systems have a slight preference for a dominant single. At young ages hierarchical triple systems therefore frequently have dominant binaries if they are not having three comparable masses. (c) A system with outer period of 2 Myr will for the first time reach apastron after 1 Myr. In the figure all systems in the grey shaded area have reached apastron at least once within 1 Myr. During that time, no system has reached a separation of more than 50000 AU. The dotted blue line shows how far the center-of-mass of a triple system has moved in a given amount of time assuming a velocity of 1 km/sec. Values are shown for 1 Myr and 10 Myr. The widest systems, which take tens or hundreds of millions of years to unfold, will have moved away from the denser and more perilous environment in which they were born before being fully unfolded.
Figure 4. Frequency of stable, unstable, and disrupted triple systems as function of projected separation. *Left column:* The number of bound stable (red), bound unstable (green) and unbound (blue) triple systems as a function of projected separation for three different ages. The black dotted line indicates the sum of all three. This is an actual snapshot at 1, 10, and 100 Myr of the random locations in their orbits of the distant third stars relative to the center-of-mass of the binaries projected onto the sky for all 180218 simulations. *Right column:* The fraction of bound stable (red), bound unstable (green), and unbound (blue) triple systems relative to the total number of triple systems as a function of projected separation for three different ages. These diagrams allow a statistical determination of the state of an observed triple system. At 1 Myr the bound systems dominate but only out to separations of 0.1 pc, after which the disrupted pairs strongly dominate. At these early ages, the unstable triples are more common than stable triples by factors of three or more. As time passes, the unstable triples break up and for systems with observed separations of less than 4000 AU the stable triples slightly outnumber the unstable ones at 10 Myr. At the same time, the disrupted systems (which will appear as common proper motion pairs) are moving apart and become dominant only at separations exceeding 4 pc. Finally, at 100 Myr, the stable triples dominate out to separations of about 8000 AU, but for larger separations the very widest binaries are mostly bound but unstable systems, while the disrupted triples play only a minor role at these more advanced ages. The two vertical dashed lines mark separations of 1000 AU and 10000 AU.
Fraction of all systems

Logarithm of time [yr]

DISRUPTED
UNSTABLE
STABLE

Number of cases

logarithm of semimajor axes

Outer semimajor axis [AU]

Very wide binaries
Wide binaries

Number of cases

Outer eccentricity

1e-07
1e-06
1e-05
1e-04
1e-03
1e-02
1
Mc + Ma

DOMINANT SINGLE

DOMINANT BINARY

THREE IDENTICAL STARS

1 Myr

100 Myr

Maximum Extent a(1+e) [AU]

Time of first apastron passage \( t = P/2 \) [yr]

1 pc

10 pc

13000 AU

50000 AU

3
1. Code and Assumptions

Stellar Masses: We use an initial mass function\textsuperscript{21,22} with minimum and maximum mass values of 0.02 to 2.0 $M_\odot$, between which the masses were selected according to the Chabrier probability density function. Initially the selected three bodies have identical masses, but they are allowed to accrete from surrounding gas (see below), usually altering at least one or two of the masses. The three bodies were positioned randomly in non-hierarchical configurations, not exceeding a ratio of 5:1, and scaled so their mean initial separations matched a number randomly picked between 40 and 400 AU, values guided by observations. Subsequently the center of mass of the three-body system was moved to the origin which also was the center of the gas cloud. Finally, the initial three-dimensional velocity vectors were randomly chosen for each body and re-scaled so that the virial ratio was 0.5 at the beginning of the simulations.

Gas Cloud and Accretion: The three bodies initially move within a cloud core described as a Plummer sphere with the potential $\Phi = -M_\odot \sqrt{r^2 + R^2}$. The core radius $R$ is set to 7500 AU, as suggested by observations\textsuperscript{33}. For each simulation a core mass $M$ is picked randomly between 1 and 10 $M_\odot$. The stellar bodies are allowed to accrete according to the Bondi-Hoyle prescription. Twice the accreted mass is subtracted from the cloud core in order to mimic the effect of outflow activity from young stars. Finally, to simulate the effect of the diffuse interstellar radiation field, the remaining gas disappears linearly with time over a period of 440,000 yr, which is the duration of the Class I phase determined from Spitzer data\textsuperscript{34}. We do not consider any angular momentum of the accreting material, which could affect the orbits of the closer pairs of binaries\textsuperscript{35,36}, but our main focus here is the behavior of the third body. This simplified treatment of the gas dynamics is less realistic than a full-scale hydrodynamic simulation, but is necessary in order to perform the hundreds of thousands of simulations required to study statistically the complex dynamical evolution of triple systems. Consequently, the present numerical simulations do not properly represent the Class 0 phase of the star formation process, when the bulk of the stellar masses is rapidly built up. Rather, these calculations represent the Class I phase, when the newly formed stars have reached almost their final masses.

Integration: The motions of the three-body system were integrated using the chain regularization method\textsuperscript{37} that provides good accuracy in dealing with the $1/r^2$ character of the gravitational force as required for a precise treatment of frequent close encounters. Accretion effects were taken into account after every integration step according to the Bondi-Hoyle prescription. We assumed the gas speed to be zero and thus the accretion causes friction in addition to increasing the star masses. After the gas cloud has vanished entirely, the slowdown method\textsuperscript{38} was used to speed up the computation.

2. Dynamical Evolution of Newborn Triple Systems

It has been known for a long time that systems of three bodies are unstable if they are in a non-hierarchical configuration. Such systems will always evolve dynamically into either a stable hierarchical system, or one member will escape and leave behind a bound binary system\textsuperscript{20,22}. This highly chaotic behavior of multiple systems has been extensively explored numerically in the context of young stars\textsuperscript{21,39–42}. The breakup of a young multiple system will most often occur during the protostellar stage\textsuperscript{24}, and as a consequence some of the ejected members may not have gained enough mass to burn hydrogen, thus providing one of the key pathways for the formation of brown dwarfs\textsuperscript{43}. Detailed N-body simulations of newborn triple systems still embedded in their placental cloud cores show that protostellar objects are often ejected with insufficient momentum to climb out of the potential well of the cloud core and associated binary. These loosely bound companions can travel out of their dense cloud cores to distances of many thousands of AU before falling back and eventually being ejected into escapes as the cloud cores gradually disappear and the gravitational bonds weaken. Protostellar objects that are dynamically ejected from their placental cloud cores, either escaping or for a time being tenuously bound at large separations, are dubbed orphaned protostars and offer an intriguing glimpse of newborn stars that are normally hidden from view\textsuperscript{23}. A number of such orphans have been identified in nearby star forming regions in the vicinity of deeply embedded protostars, for the first time allowing detailed studies of protostars at near-infrared and even at optical wavelengths.

The role of the cloud core is important. It is a rarely appreciated fact that without an additional gravitational potential, non-hierarchical triple systems will virtually always break apart into a stable binary and a third member that escapes the system\textsuperscript{22,44}. In order to form a hierarchical system where all three members are bound, an additional potential is needed. This can be provided either by the nascent cloud core, or by additional stellar bodies, such as in quadruple or higher-order multiple systems.

For comparison with observations, it is important to re-
call that the higher the eccentricity is, the longer will the third body stay at distances larger than the semimajor axis of the orbit.

In recent years much discussion has centered on the ejection of planets from forming planetary systems. We note that such processes are dynamically very different from those discussed here. In a stellar triple system the masses of the bodies are generally large and within one or two orders of magnitude comparable. This generates strong and very fast interactions, resulting in a rapid dissolution of the system. In contrast, for a forming planetary system the planets have minuscule masses compared to the central star and thus are in orbit around the star. Their orbital evolution is secular, only gradually changing until the planets approach orbital resonances, at which time an ejection under the right circumstances may become possible.

3. Classification of Binaries

There is a rather well established classification of binaries depending on observable or physical characteristics (e.g., visual binaries, eclipsing binaries, spectroscopic binaries, low-mass X-ray binaries, W UMa binaries, etc.). In contrast there is very little agreement on the classification of binaries as a function of their separation, even though this is perhaps the most important parameter for determining the physical properties of a binary. We here list two attempts of a classification based on separation:

Zinnecker proposed this nomenclature

\[ P > 1000 \]

Wide binaries: 10 < \( P < 1000 \)

Intermediate binaries: 50 < \( a < 1000 \)

Close binaries: 10 < \( a < 100 \)

Very close binaries: \( a < 10 \)

With steadily improving observational techniques it is now possible to determine the (projected) separation of most binaries, and hence a more practical classification scheme has been proposed by Goodwin (\( a \) is the semimajor axis in AU):

\[ P > 10^3 \]

Extremely wide binaries: \( a > 10000 \)

Wide binaries: \( 1000 < a < 10000 \)

Intermediate binaries: \( 50 < a < 1000 \)

Close binaries: \( a < 50 \)

This classification is particularly relevant for binaries formed in dense clusters, where the stellar density is high and leads to dynamical processing of the initial binary population. In the present paper we have adopted this nomenclature.

We note that observationally the very wide binaries correspond to common proper motion pairs, and so it is extremely difficult to determine if a given very wide binary is bound or disrupted, which could raise a semantic question about what constitutes a true binary.

The lack of a widely accepted nomenclature has led to a rather arbitrary use of the prefix “wide” in the literature.

4. Are all Wide Binaries Triple Systems?

This question can be addressed from an observational and a theoretical perspective. Observationally, wide binaries are often found to be triple systems\(^8, 9, 48\). However, most wide binaries are not known to be triple systems\(^49\). This might reflect an intrinsic property of wide binaries, but also reflects the fact that only for nearby wide binaries (up to \( \sim 30 \) pc) does the combination of present-day direct imaging and radial velocity studies cover the full separation range for companions. In other words, the detection of triple systems is severely incomplete\(^26\). The question is not likely to be answered empirically in the foreseeable future.

Theoretically, there are two aspects. First, while wide binaries can naturally form via dynamical evolution of triple systems, this does not imply that other formation mechanisms do not operate (see the following section), and other mechanisms can form wide binaries that are not triple systems. Second, as pointed out earlier, the close binary will during the protostellar and pre-main sequence phases be surrounded by significant gas in the cloud core and by circumstellar gas, and the dynamical friction will lead to gas induced orbital decay\(^27, 50\). If the binary becomes bound shortly after birth of the triple system then a merger of the binary components is possible. These events will not affect the third body that has been ejected into a distant orbit, and so the final result is a wide binary with only two stars.

The answer to the question is therefore “no”.

5. Formation of Wide Binaries in Dissolving Clusters

Many binaries are likely formed through disk fragmentation, which readily explains the existence of some close and intermediate binaries. It is also generally accepted that core fragmentation plays a critical role in the formation of stars and binaries, but with typical core sizes of several \( 10^3 \) AU, fragmentation fails to explain systems larger than this. Independent star forming events in cores with larger separations might conceivably lead to bound systems, but even if this were to occur, the pair would likely not remain bound as the gas disperses. Additionally, most stars form in clusters, where stellar separations typically are less than a few thousand AU, and so binaries approaching such sizes would promptly be destroyed through dynamical interactions. In short, the existence of binaries with very wide separations poses a challenge to models of star formation.

Recently an interesting theory for the formation of very wide binaries has been proposed\(^5\). As gas is dispersed in a newborn cluster of stars, the cluster will rapidly expand, leading to loss of stars. Two initially unbound stars (or, for that matter, a star and a binary) may find themselves closely associated in phase space and thus form a binary. The upper
separation limit is set by the size of the cluster, which is of the order of 0.1 pc. As the cluster potential becomes less important, the pair may remain bound as it drifts away. The resulting wide binary fraction is very sensitive to the initial conditions. In a similar study, the long-term survival of the wide binaries was examined. At any given time, a cluster will contain a transient population of weakly bound pairs, which are perturbed into and out of formally bound states. To evaporate intact from the cluster, a pair must form in the outskirts of the cluster. The total number of such wide binaries is not sensitive to the cluster population, and is about 1 pair per cluster. The dissolution of many small clusters of typically a few hundred stars is therefore likely to contribute more very wide binaries than larger but more rare clusters.

It is likely that the cluster evaporation mechanism is contributing to the field population of very wide binaries. We note that the wide binaries formed this way may or may not be triple systems, that they are not primordial, in the sense that the stars are born in separate collapse events, and that the binaries are formed, i.e. become bound, with their wide separations.

In marked contrast, for the triple mechanism espoused here, (a) the very wide systems are primordial, i.e. all members are formed in the same collapse event, and (b) the systems are formed in a compact configuration and expand as they are drifting away, and for the widest binaries may unfold to their largest dimensions only after they have escaped from their dense and perilous nascent environment.

6. Unfolding of Wide Binaries

A key aspect of the triple decay mechanism is that all three bodies in a wide or very wide system were born from the same collapse event, in close proximity despite their current enormous separations. Once the dynamical interactions transforming the three bodies from a chaotic non-hierarchical configuration to a stable hierarchical system have taken place, then the orbital parameters are set, and the bodies will follow well determined orbits. While the inner binary in most cases will have a rather short period, the outer body can take very long (more precisely half an orbital period) before the system for the first time has fully unfolded.

Figure 3c shows the maximum extent \(a(1 + e)\) of the simulated triple systems as a function of half the orbital period of the systems. It will take any system half the orbital period to reach its full extent for the first time. As an example, the vertical dashed line marks an age of 1 million years. All systems in the grey area to the left of the line will have reached their apastron at least once, and, for the shorter period systems, many times. But none of the systems to the right of the vertical line will have reached their first apastron passage and are thus not fully unfolded at 1 Myr. Because stellar masses are factors in Kepler’s 3. law, and because the maximum extent also depends on the orbital eccentricity, the relation between maximum extent and time has a non-negligible width. As the figure shows, all systems with full extent of less than 13000 AU have fully unfolded after 1 Myr, while no systems with full extent larger than 50000 AU have fully unfolded.

During the time that the system is unfolding for the first time, it also drifts gently away from its birth site. Typical turbulent velocities in star forming clouds are around 1 km/sec, and hence this is the velocity dispersion of the stars and multiples born from the cloud. The blue dashed line in Figure 3c indicates how far the center-of-mass of a triple system has moved in a given amount of time assuming a velocity of 1 km/sec. In 1 Myr a system will have drifted 1 pc and in 10 Myr it has drifted 10 pc. This is important, because the space density of stars is higher at the birth sites of the triple systems than in the general field. So by the time the very widest systems have finally unfolded, they have drifted away from the more perilous environment of their birth, diminishing their risk of premature disruption.

7. The Destruction of Very Wide Binaries

Wide binaries are ‘soft’, i.e. they have binding energies that are much smaller than the mean of the local stellar velocity distribution. While ‘hard’ binaries are resilient to encounters with other stars, the soft binaries are sensitive to breakup partly from (rare) close encounters with stars, but also from the cumulative effects of distant but much more numerous weak encounters. Additionally, very wide binaries that pass near or through giant molecular clouds are subject to immediate disruption. Finally, for very wide binaries the Galactic tidal field will also lead to eventual dissolution of the binary. Such perturbations primarily have an impact on very wide binaries with separations larger than 0.1 pc and on timescales of Gyr, so the distributions shown in Figure 4 for much younger ages would not be significantly influenced by this dynamic erosion.

The above assumes that the wide binaries have survived encounters at their birth sites. Most stars are formed in clusters, where the stellar density is much higher than in the comparatively empty space exemplified by the solar neighborhood. Many binary systems are therefore expected to be disrupted shortly after birth, as is indeed observed in the binary separation distribution function in the Orion Nebula Cluster.

8. The Separation Distribution Function

Binaries have separations that span more than a factor 1 million, from close, short-period spectroscopic binaries to systems more than 0.1 pc wide. The separation distribution function describes the frequency with which binaries populate the various separations. Ōpik proposed that this distribution follows \(f(a) \propto 1/a\), in other words it is flat in \(\log(a)\), whereas Kuiper found a log-normal distribution, which was later supported by the work of Duquennoy & Mayor, who found a peak around 30 AU. For wider binaries however, several studies offer evidence that the separation distribution more looks like...
opik’s law\textsuperscript{60,61}, at least out to separations where the destruction of the widest systems becomes significant. For the inner binaries in triple systems it has been shown that the application of the statistical theory of the three-body breakup leads to opik’s law of binary separations\textsuperscript{62}.

Our simulations are, for practical reasons, stopped after 100 Myr. We are thus following a population of triple systems that were all formed in a single “burst”. Observationally, this is well matched at 1 Myr when one observes a star forming region, or at 10 Myr when one observes a moving group. However, at 100 Myr the triple systems presumably will have mixed with the general Galactic field population. If the widest of these field systems have been gradually destroyed, then in principle a more correct comparison would be with a population of triple systems that have been continuously created, destroyed, and mixed\textsuperscript{17}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Comparison between simulations and observations. The red dots represent the most recent observations of wide binaries\textsuperscript{15}, the grey curve is a power-law $f(s)ds \sim s^{-1.6}ds$ fit to another data set of observations\textsuperscript{14}, and the blue dots are the triple simulations at 100 Myr sampled in the same bins as the red dots. The error bars on the observations represent sqrt(N) without including subtle systematic biases that are difficult to quantify. The errors on the simulations are smaller than the blue circles. The simulations include stable and unstable hierarchical systems as well as disrupted triple systems with projected separations in the selected separation ranges.}
\end{figure}

Lépine & Bongiorno studied wide common proper motion pairs from the \textit{Hipparcos} catalog\textsuperscript{14}, and found that the projected separations $s$ follow Opik’s law $f(s)ds \sim s^{-1.6}ds$ only up to 3000–4000 AU, beyond which it falls more steeply, like $f(s)ds \sim s^{-l}ds$ with $l = 1.6\pm0.1$ out to $s \sim 100000$ AU. Chanamé & Gould fit the distribution of wide binaries in the disk and in the halo\textsuperscript{13}, and found a power law with $l \sim 1.67 \pm 0.07$ for the disk and $l \sim 1.55 \pm 0.10$ for the halo, in excellent agreement with the results of Lépine & Bongiorno\textsuperscript{14}.

In a recent study Tokovinin & Lepine have determined the number of wide binaries in five bins between 2000 and 64000 AU\textsuperscript{15}. We have counted all triple systems with projected separations in these bins and plotted them in Figure S1 together with the data of Tokovinin & Lepine\textsuperscript{15} and the power law $f(s)ds \sim s^{-l}ds$ with $l = 1.6$ found by Lepine & Bongiorno\textsuperscript{14}. The overall correspondence is good, especially when considering that the observational data are still incomplete for low-mass companions (which the simulations find are abundant) and that the data may still be affected by systematic biases.

9. Compact Triple Systems

Triple systems are found with a huge range in separations between the inner binary and the outer third body. Our simulations have demonstrated that the very widest binaries observed can be understood as extremely hierarchical triple systems. But the question naturally arises how very compact triple systems are formed. Examples of compact triple systems abound, one case is LHS 1070, where three mid-to late-M dwarfs have separations of 3–9 AU\textsuperscript{63}. The smallest mean separations in our simulations are of the order of 40 AU, and so do not naturally account for such compact systems. The simulations, however, do not take into account that newly formed binaries in dense cloud cores are surrounded by massive disks and envelopes, so viscous interactions will sometimes shrink newly formed binaries\textsuperscript{64}. This effect is sensitively dependent on how early the close binary is formed; the later the two components become bound, the less circumstellar material will be present, and the less will be the effect of viscous interactions (see also Section 4).

Additionally, a triple system can be the decay product of a quadruple or higher-order system. Each time a body is ejected from a non-hierarchical system the mean separation of the remaining bodies grows smaller. This effect can be particularly important in a cluster of stars, where small N-body systems initially are common. The end-product of such higher-order decay can therefore be a very hard triple system. The ejected stars may have been stripped of much of their circumstellar material in the dynamical interactions\textsuperscript{65}, and this could naturally account for the existence of diskless stars\textsuperscript{66}.

10. Examples of Wide and Very Wide Binaries

10.1 Proxima Centauri

The nearest known star to Earth is Proxima Centauri, discovered by Innes\textsuperscript{67}, who noted the similarity of its high proper motion with that of α Centauri, located at an angular distance of 2.2°. α Cen is a G2V star, and has a close companion with an orbital period of 80 yr, while Proxima Cen has a spectral type of M5.5V. The similarity of the distance to α Cen A/B (1.33 pc) and to Proxima Cen (1.30 pc) and their similar motions have long suggested that they may form a gravitationally bound system\textsuperscript{68,69}. Using the best available data, including from \textit{Hipparcos}, it has been concluded that the triple system is indeed likely to be
physically bound, with a physical separation currently of 15000±700 AU. In our model, despite their current very large separation, the three α Cen components were born together in the same collapse event, initially forming an unstable non-hierarchical configuration. Shortly after birth, Proxima was ejected into its current distant orbit. At an age of -5.4 Gyr, evidently the α Cen triple system has achieved a highly stable orbit. Even if the eccentricity of Proxima were as high as 0.9, this would imply a periastron distance of ~1500 AU, much higher than the semimajor axis of the AB pair of about 22 AU, thus ensuring that the system has remained stable.

10.2 Wide Binaries in Star Forming Regions
Wide binaries have been known in star forming regions for a long time, examples include Haro 1-14 (projected separation 1700 AU, with the companion being a spectroscopic binary), the non-hierarchical triple systems Sz 41 (320+1840 AU) and LkHα336 (2320+4320 AU), and the hierarchical triple system SR 12 (1100 AU, where the distant component is a brown dwarf). Detailed studies of embedded protostars have revealed a population of distant (<4500 AU) companions that become less and less frequent as the protostars age. That is, many of these components are lost already during the protostellar stage. As detailed imaging studies become more common, it is expected that more such wide triple systems will continue to be found.

10.3 Wide Binaries in Young Moving Groups
If a star forming region is not very massive, all its stars will disperse after the original molecular cloud has disappeared, without leaving a cluster behind. For a while, these young stars can be identified as a moving group, where the members share kinematical and physical properties, and all have the same age, typically 10-20 Myr. Because members of young moving groups have not been part of a massive cluster with violent dynamical interactions, binaries have a better chance of surviving the time immediately after birth. In recent years, careful analysis has led to the discovery of an increasing number of wide and very wide binaries in moving groups, including 51 Eri, TW Hya, V4046 Sgr, T Cha, and RX J0942.

This is consistent with the results presented here: after 10 Myr all but the most extreme wide binaries have unfolded and the members of the moving group have spread apart, typically having traveled ~10 pc from their sites of birth, and so it is much easier to identify those stars that belong together in physical systems. Since highly eccentric systems, once unfolded, spend most of their time near apastron, and since many of the bound but unstable systems have not yet disintegrated, there should consequently be a larger number of wide and very wide systems at an age of 10-20 Myr than at any other time. We therefore expect that many more wide binaries will be discovered in moving groups in the coming years. For a given projected separation, Figure 4 allows to determine the probability that a given wide system is bound and stable, or bound and unstable, or disrupted.

10.4 Wide Binaries in the Field
The simulations presented here show that a non-negligible fraction of the initial triple systems remain stable at an age of 100 Myr, when the simulations are stopped. Most of the bound but unstable triples have decayed by then, so the majority of triple systems that remain are stable, and if they have not already broken up, the main threat to their existence is likely to come from external perturbations rather than internal instability. An example is the triple system HD 212168 where the third component is at a projected distance of 6090 AU. Another example is the α Cen/Proxima Cen system discussed in Section 10.1.

11. Summarizing the Observational Predictions
We here summarize the observational consequences of the triple decay mechanism discussed in this paper:

[1] Although all very wide binaries formed through the triple decay mechanism have originated as triple systems, they are not necessarily all triples after completing their pre-main sequence evolution, because dynamical friction in a gas reservoir will cause orbital decay that in some cases can lead to mergers.

[2] Most very wide binaries are likely to be found in young moving groups because in star forming regions they have not all had time to fully unfold, and in the field they are eventually destroyed, so the peak is likely to be somewhere between 10 and 100 Myr.

[3] Many distant companions will be very low-mass objects, since they are preferentially ejected in three-body dynamics. However, the companions can also be binaries because a frequent outcome of dynamical triple interactions with accretion is the formation of a single more massive star and a lower-mass binary.

[4] The components of very low mass wide triple systems tend to have comparable masses (Figure 3a,b). Wide unstable triple systems often have either components with comparable masses or a more massive binary and a distant low-mass single star. Since unstable systems are more common than stable systems at ages of 1-10 Myr (see Figure 4), it follows that - especially in star forming regions - we should often find triple systems with a more massive binary and a distant single low-mass star. Wide stable triple systems, in contrast, are much more uniformly distributed across Figure 3, perhaps with a slight preference for systems with unequal components to have one higher mass component associated with a distant lower-mass binary. As the unstable triple systems eventually break part, we expect that the population of triple systems at young ages differ markedly from the old field population of triple systems.
REFERENCES


