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ORPHANED PROTOSTARS

BO REIPURTH[1], SEPPO MIKKOLA[2], MICHAEL CONNELLEY[1], AND MAURI VALTONEN[3]
[1] Institute for Astronomy, University of Hawaii at Manoa, 640 N. Aohoku Place, HI 96720, USA; reipurth@ifa.hawaii.edu
[2] Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland
[3] Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Väisäläntie 20, Piikkiö, Finland
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ABSTRACT

We explore the origin of a population of distant companions (∼1000–5000 AU) to Class I protostellar sources recently found by Connelley and coworkers, who noted that the companion fraction diminished as the sources evolved. Here, we present *N*-body simulations of unstable triple systems embedded in dense cloud cores. Many companions are ejected into unbound orbits and quickly escape, but others are ejected with insufficient momentum to climb out of the potential well of the cloud core and associated binary. These loosely bound companions reach distances of many thousands of AU before falling back and eventually being ejected into escapes as the cloud cores gradually disappear. We use the term orphans to denote protostellar objects that are dynamically ejected from their placental cloud cores, either escaping or for a time being tenuously bound at large separations. Half of all triple systems are found to disintegrate during the protostellar stage, so if multiple systems are a frequent outcome of the collapse of a cloud core, then orphans should be common. Bound orphans are associated with embedded close protostellar binaries, but escaping orphans can travel as far as ∼0.2 pc during the protostellar phase. The steep climb out of a potential well ensures that orphans are not kinematically distinct from young stars born with a less violent pre-history. The identification of orphans outside their heavily extincted cloud cores will allow the detailed study of protostars high up on their Hayashi tracks at near-infrared and in some cases even at optical wavelengths.

Key words: binaries: general – brown dwarfs – stars: formation – stars: low-mass – stars: pre-main sequence – stars: protostars

1. INTRODUCTION

Stars are commonly formed in binary or small multiple systems. This has been long known from observations (Herbig 1962; Reipurth & Zinnecker 1993; Köhler & Leinert 1998), but is also the frequent outcome of numerical and theoretical work (Goodwin et al. 2007). In fact, a strong case can be made that the normal outcome of the collapse of a rotating cloud core is the formation of a binary or multiple system (Larson 1972, 2002). It is well known that a system of three bodies is unstable if they are in a non-hierarchical configuration, and dynamically always will evolve into either a stable hierarchical system, or one member will escape and leave behind a bound binary system (Anosova 1986; Valtonen & Mikkola 1991). The dynamical and highly chaotic behavior of multiple systems of young stars has been extensively explored numerically (Sterzik & Durisen 1995, 1998; Armitage & Clarke 1997; Bate et al. 2002; Delgado-Donate et al. 2004). It has been noted that the breakup of a young multiple system will most often occur during the protostellar stage (Reipurth 2000), and a consequence of this is that 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 (Reipurth & Clarke 2001; Whitworth et al. 2007).

The most detailed numerical studies so far of a collapsing filamentary and turbulent cloud leading to a small cluster demonstrate the enormous dynamical complexity of the many subsystems of stars, with continuous formation and destruction of multiple stellar systems (Bate 2009). Although most stars are formed in clusters, in the present study we focus on the simpler, more tractable problem of the dynamical behavior of triple systems formed in relative isolation, without interference from other cluster members, such as found in the more tranquil environments of stellar associations. We focus in particular on the ejection of one of the triple members and the resulting observable consequences.

In recent years, surveys of the binarity of embedded protostars have begun to appear (Reipurth et al. 2004; Haisch et al. 2004; Duchêne at al. 2004, 2007; Maury et al. 2010). Connelley et al. (2008a, 2008b) observed a large number of isolated Class I sources and found to their surprise that these embedded sources have numerous distant companions. In the projected interval from 963 AU to 4469 AU, they found a clear decrease in the number of companions as function of spectral index (used as a proxy for age). In this Letter, we attempt to understand the origin and fate of this population of loosely bound companions.

2. CODE AND CALCULATIONS

We employ a numerical code for few-body calculations with a regularization method 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 triple encounters (Mikkola & Aarseth 1993). Furthermore, we include the presence of a cloud core surrounding the young triple system. This gravitational potential has profound effects on the dynamical behavior of the stars. We allow the stars to grow in mass using the prescription of Bondi–Hoyle accretion; this typically increases the body masses by about 5%. Further, we subtract twice the accreted mass from the core to crudely simulate the destruction of cloud cores from outflow activity. Finally, we let the remainder of the gas gradually disappear over a period of 300,000 yr, mimicking the effect of the diffuse interstellar radiation field.

These calculations do not properly represent the dynamical collapse of the star formation process, during which the bulk of the stellar masses is rapidly built up in the Class 0 phase when the protostellar embryos are deeply embedded; this would require a full hydrodynamical treatment. Our calculations instead start at the beginning of the Class I phase, when the newly formed stars have reached almost their final masses. However, we emphasize that the processes discussed here are also effective during the Class 0 phase, making the disintegration of newborn multiple systems occur even earlier than we demonstrate here. Evans et al. (2009) suggest that, on average, the Class 0 phase lasts 100,000 yr, and the Class I phase as long as 440,000 yr. McClure et al. (2010) find a shorter embedded lifetime of about 200,000 yr. The figures presented here span an intermediate range of 300,000 yr.

We have performed 12,800 numerical experiments, each spanning 10 Myr. Three parameters were varied, and 200 simulations run for each parameter set. Stellar masses were set to 0.08, 0.2, 0.5, and 1.25 $M_{\odot}$, representing the most common stellar mass range above the brown dwarf limit. Bodies are treated as point masses. Mean initial separations were chosen as 50, 100, 200, and 400 AU; for much smaller separations breakup occurs instantaneously, and for much larger separations the stars would represent independent star-forming events. The stellar velocities were set so they are approximately virialized, and the relative initial separations were all non-hierarchical, not exceeding a ratio of 5:1. Remnant core masses were set to 0, 1, 3, and 6 $M_{\odot}$ with Plummer mass distributions (Plummer 1911) and radii that remain fixed at 7500 AU, a size suggested by observations (Kirk et al. 2006). The three bodies initially have identical masses, as the breakup of a system is sped up if one or two of the bodies are smaller, and we want to take a conservative approach that, if anything, underestimates the number of escaping bodies. However, two of the bodies soon sink toward the center of the core and gain more mass than the third body (Bonnell et al. 2001), which in most cases is the body that eventually will escape the system. We do not consider the angular momentum, if any, of the accreting material onto the stars, which could have the effect of changing the orbits of the remaining binaries (Bate 2000; Umbreit et al. 2005), and consequently we ignore the binaries. The escaping third bodies, which are the focus of the present study, are, however, frequently evicted from the interior of the cloud core, and thus spend much of their time in the tenuous outskirts of the core, less affected by direct accretion from the core.

3. RESULTS

3.1. Dynamical Interactions

Our 12,800 simulations illustrate the well-known chaotic character of three-body motion. Figure 1 shows four examples of our simulations, with orbits projected onto the *XY*-plane. Extinction through the cloud is indicated by color, black representing an A_V of 50 or higher, and yellow–white indicating negligible extinction. Local circumstellar gas is ignored, so the extinction is a lower limit. However, at least part of an infalling envelope would be truncated in an ejection event.

Almost immediately, two of the three stars join together in a (temporary) binary and begin to bounce the third star around. In the process, it is common that the third star exchanges position with one of the binary components. Figure 2 contains eight panels showing the separation of the third body from the binary center of mass as a function of time, illustrating the rich dynamical behavior of such systems. Panel (A) shows a relatively stable triple system. These are not common, they are frequently fragile and prone to sudden disintegration. In

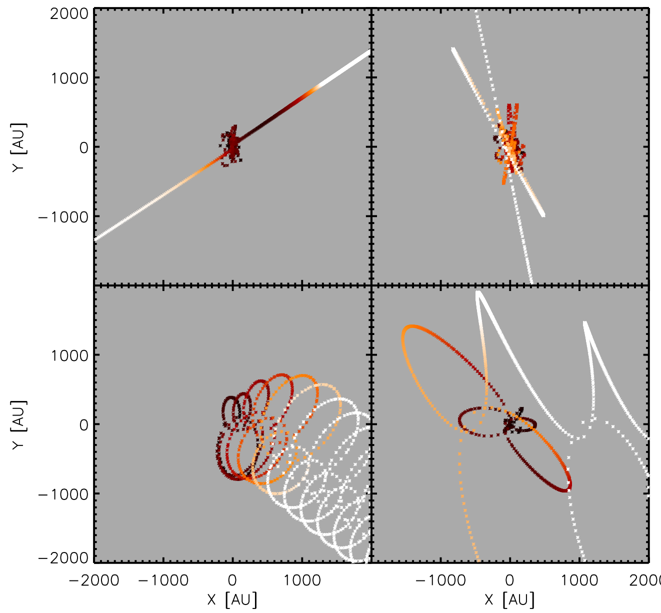

Figure 1. Four examples of physical orbits projected on the *XY*-plane. Color indicates extinction from the cloud core, from black representing $A_V = 50$ or higher down to light yellow/white representing little or no extinction. The core dissipates after 300,000 yr, so the stars become visible with time or as they are ejected or drift out of the core.

contrast, panel (B) shows a very common behavior, where the triple system almost instantaneously breaks up and the third body escapes. In this case the recoil of the binary is so powerful that it, too, escapes from the core. However, more frequently the recoil of the binary is too weak to overcome the gravity of the cloud core, and the binary oscillates around the center of the core until the core has dispersed enough to let the binary drift away (Figure 2(C)). In yet other cases, both single and binary are immediately ejected, but with insufficient speed for any of them to escape, so they rejoin for a period of further close interactions until the system eventually breaks up (Figure 2(D)). It is common that a triple system must undergo numerous weaker ejections before an ejection is finally strong enough to overcome the gradually weakening potential of the core (Figures 2(E) and (F)). Ejections that almost, but not quite, reach escape speed can lead to giant long-lived excursions spanning many thousands of AU and lasting 100,000 yr or more before an encounter leads to disintegration (Figures 2(G) and (H)). Figure 3 shows 100 simulations with color-coded ejections (escapes are red and bound excursions are blue), providing a sense of the chaotic nature of early triple evolution.

3.2. Companion Fraction as Function of Parameters

The companion fraction of a population of young stars is a fairly easily observed parameter, and we here show that it is influenced by fundamental properties of the triple systems in the population.

A measurement of a companion fraction must be related to a chosen range in separation. Figure 4(a) shows the companion fraction for four intervals between 100 AU and 5 pc. Due to the highly dynamic nature of newborn triple systems, the companion fraction undergoes significant changes, especially during the protostellar phase. For the interval 100–1000 AU, almost 100% of the simulations start with the most distant component being within this interval. With the rapid decay of the

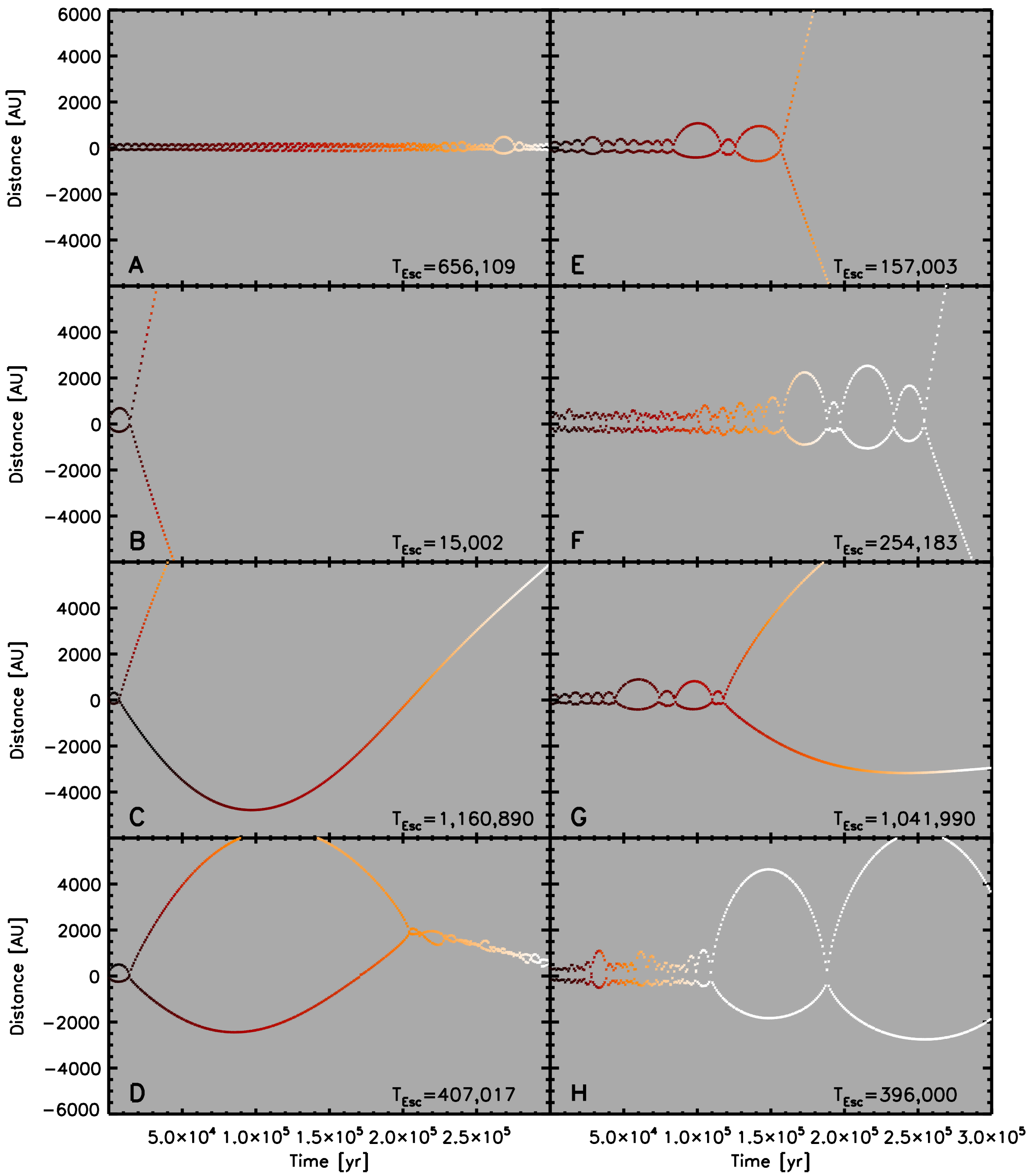

Figure 2. Samples of characteristic dynamical behavior of single and binary components of an unstable triple system. The single is always toward the top, and the binary toward the bottom. Color indicates the extinction, from black representing $A_V = 50$ or higher down to light yellow/white representing little or no extinction. The line of sight is along the *Z*-axis of the simulations. Numerous ejections are occurring, but only three cases (B, E, and F) lead to an escape during the time interval shown. Eventually all the cases shown lead to an escape (that is, single and binary meet again, even in case C), and the time of escape is listed for each.

triple systems, however, the companion fraction in this interval drops steeply and after 300,000 yr has fallen to about 10%. For the interval 1000–10,000 AU, very few simulations start out with a component in this range, but ejections soon send components out beyond 1000 AU. As the escapers move to ever larger distances, the companion fraction peaks and then diminishes, and is increasingly accounted for by bound components. For larger separation intervals, a similar behavior is seen but due to the time required for escapers to travel to these larger distances, the peak appears at later times and becomes increasingly broad.

In Figures 4(b)–(d), we examine the companion fraction in the interval 1000–10,000 AU as a function of selected parameters.

In Figure 4(b), we see the effect of varying the mass of the cloud core from 0 to 6 $M_\odot$. The large number of early ejections initially boosts the companion fraction, but as the escapers move away, the companion fraction is increasingly defined by bound systems. The main effect of the cloud core is to limit the number of ejected stars that succeed to escape. As a result, the companion fraction increases with increasing core mass, and for higher core masses almost stabilizes with time.

The companion fraction turns out, not surprisingly, to be very sensitive to the mean initial separation of the three bodies (Figure 4(c)). At 50 AU, the three stars almost instantaneously develop configurations that decay, leading to a flurry of escapes so the companion fraction soon drops dramatically. For increasing mean initial separation, the ejections become weaker

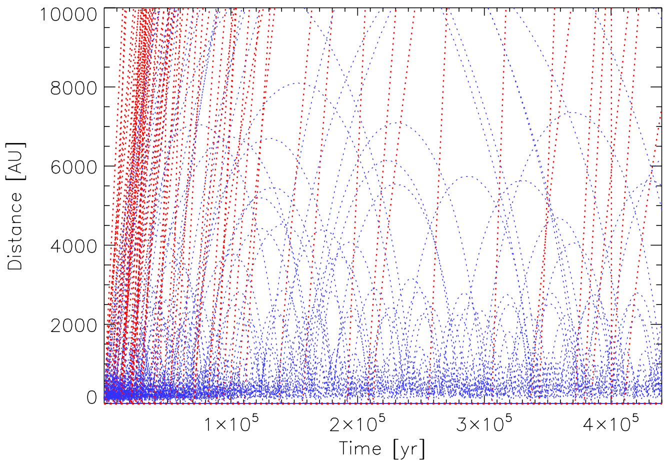

Figure 3. One hundred simulations showing the dynamical evolution of a triple system of three 0.5 $M_\odot$ stars with initial mean separations of 100 AU embedded in a 3 $M_\odot$ cloud core. Among the numerous ejections seen in the plot, those leading to an escape are plotted in red, while bound systems are blue.

leading to fewer escapes, so the companion fraction increases significantly and only slowly falls with time as bound systems eventually become dislodged. After 10 Myr, 10% of the original 12,800 triple systems are still bound, albeit often tenuously. The fraction of bound systems primarily depends on the separation: mean initial separations of 50 AU lead to far fewer bound systems than do 400 AU.

The mass of the stars also affects the companion fraction, as seen in Figure 4(d). Perhaps less intuitively, the more massive triple systems break up more easily, producing an initial peak as escapers pass through the 1000–10,000 AU interval. For lower masses, the ejected stars are more readily bound to the core, thus increasing the companion fraction.

3.3. Ejection Velocity and Terminal Velocity

Of the 12,800 simulations performed here, 90.1% lead to an escape within the first 10 Myr. The majority of those escapes, however, occur very early: within the first 200,000 yr already 52% of the triple systems have decayed.

The mean ejection velocity of the third body for all ejection events leading to an escape is 2.8 km s^{-1}, with a tail stretching out to almost 100 km s^{-1} (Figure 5). We sample the velocities approximately every 1000 yr, and since the peak velocity of the ejection occurs on a much shorter timescale, these numbers underestimate the highest velocities. The peak velocity is attained only very briefly, because the potential well of the core and binary is steep, and velocities consequently decline rapidly.

We define the terminal velocity of a population of escapers as the velocity measured at an age of 10 Myr, independent of the time of ejection. The mean terminal velocity of all escapers is 1.13 km s^{-1}. This is well within the turbulent velocity range of molecular clouds, and escapers are thus kinematically indistinguishable from single stars born in the same star-forming region (see also Bate et al. 2003).

4. DISCUSSION

The original motivation for this study was to explore the origin of the population of distant (~1000–5000 AU) companions found around isolated embedded Class I sources by Connelley et al. (2008a, 2008b). Our simulations indeed reveal that the

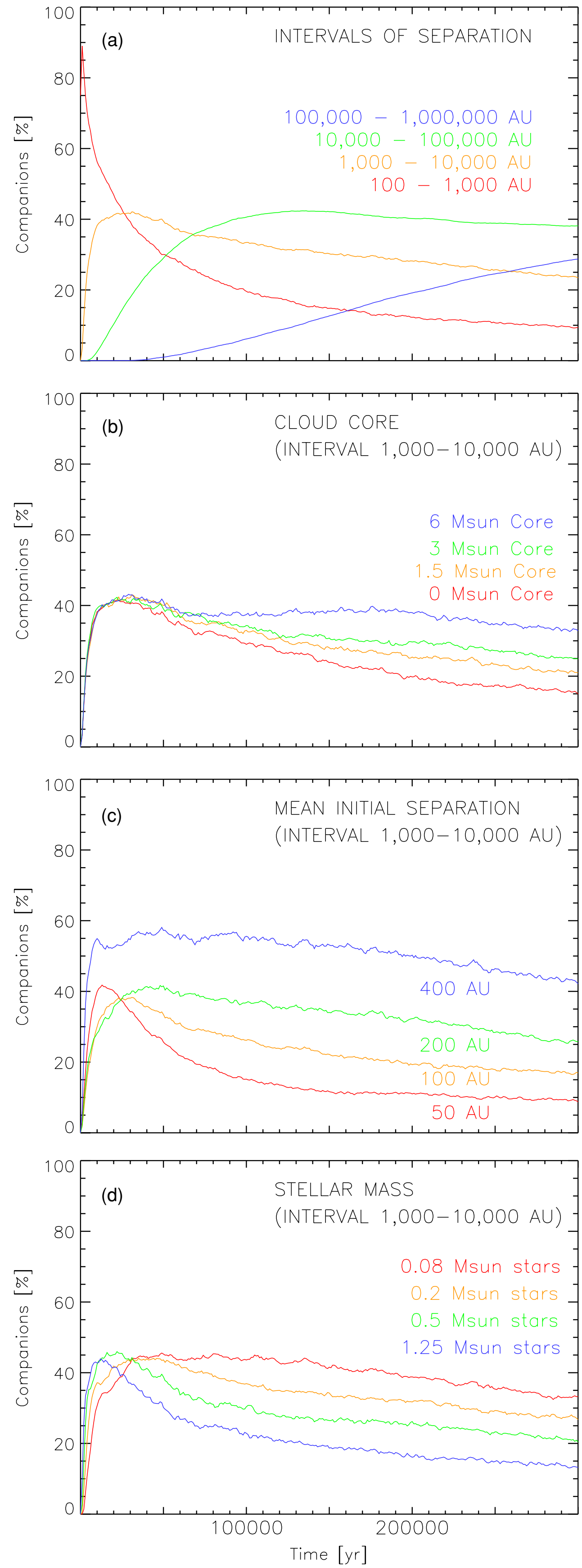

Figure 4. Companion fraction as function of various parameters. In panel (a), the companion fraction is plotted as function of time in four different intervals of separation. In panels (b)–(d), the effect of varying core mass, mean initial separation, and stellar mass is shown for the interval 1000–10,000 AU. Mean of all 12,800 simulations.

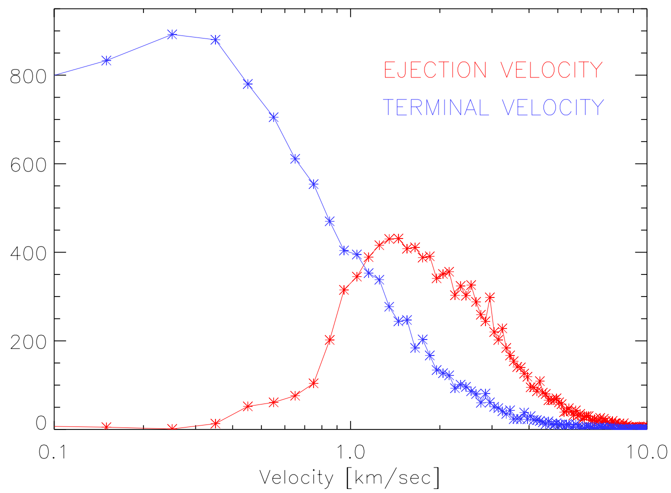

Figure 5. Distribution of ejection and terminal velocities plotted in 0.1 km s^{-1} intervals. For the terminal velocity, the large majority of cases are found below 2 km s^{-1}.

dynamical evolution of triple systems naturally lead to ejection of components into distant, long-lived excursions, or into escapes. Components that remain bound are only weakly so and ultimately most will escape, as indeed observed. We conclude that the observations are well explained if a significant fraction of embedded protostars are triple (or higher-order) systems. We note that these results pertain to isolated star formation, since stellar interactions in a cluster will break up wide loosely bound systems (Kroupa 1995; Reipurth et al. 2007; Bate 2009; Parker et al. 2009).

The nature of the escaping components is of considerable interest, and we here introduce the term *orphan* to describe *a protostellar object which has been dynamically ejected from a newborn multiple system*, either into a tenuously bound orbit or into an escape, thus depriving it from gaining much additional mass.[4] We emphasize that the term orphan refers only to protostellar objects, and thus describes a dynamical condition occasionally experienced by a newborn star. It is not easy to say when an orphan no longer is a protostellar object, thus ceasing to be an orphan, just as the boundary between Class I and Class II objects in general is diffuse, but in practical terms an object retains its label as an orphan as long as its coeval siblings are Class I objects. We note a semantic issue here: protostars are usually empirically defined by the presence of significant circumstellar disks and envelopes. Due to their dynamical history, many orphans are likely to have reduced circumstellar reservoirs, and thus may sooner lose their protostellar characteristics. We use the term protostar here in a chronological sense, for objects of an age less than the typical duration of the embedded phase (a few hundred thousand years).

We here summarize the expected properties of orphans.

1. Disintegration of triple systems preferentially leads to the ejection of the lowest-mass member, so orphans are mostly very low mass objects, including many brown dwarfs, as discussed by Reipurth & Clarke (2001).
2. Orphans are often found in distant orbits tenuously bound to embedded close protostellar binaries, although many are also escaping shortly after birth.
3. Due to their violent dynamical history, orphans are likely to be surrounded by circumstellar material for a shorter period than if they had remained in the center of their parental cores (e.g., Clarke & Pringle 1993; Bate & Bonnell 2005), but the youngest will still display evidence of accretion activity (e.g., emission lines, veiling, outflows, and/or variability) and all unveiled orphans should display lithium.
4. The amount of circumstellar material that remains bound to an orphan may vary depending on the specific circumstances of the ejection process, and this may be a contributing element in explaining how classical and weak-line T Tauri stars can have comparable ages but very different circumstellar environments, as already suggested by Armitage & Clarke (1997).
5. Orphans which carry limited circumstellar material, and which have been ejected out of their nascent cores, may offer a unique opportunity to study protostellar objects at near-infrared and in some cases even at visible wavelengths.
6. Due to the steep climb out of the potential well formed by the cloud core and the remaining binary, even escaping orphans will not have unusually high velocities; a consequence of this is that orphans will not form a diaspora of far-flung stars surrounding a star-forming region (see also Goodwin et al. 2005).
7. It is likely that distant third components in hierarchical triple systems have been ejected in dynamical interactions (Tokovinin 1997; Valtonen 1997, 1998), and those ejected as protostars will have a pre-history as orphans.
8. Orphans will often be found in close association with embedded Class 0 and Class I objects, although early escapers may have moved as much as 0.2 pc (corresponding to ∼5 arcmin at the distance of Taurus) from their site of origin within a few hundred thousand years.
9. Orphans are a common result of the breakup of newborn triple systems; of the 12,800 simulations performed here 52% of the triple systems disintegrate within 200,000 yr, which is a recent estimate of the duration of the embedded phase (McClure et al. 2010).
10. Most orphans produced in our simulations are single, but it is not unusual for the remaining binary to temporarily recoil out of the core center, and in some cases it recoils sufficiently forcefully to even escape; orphans (including substellar objects) can therefore also be binaries, and we note that this may be an important source of brown dwarf binaries.
11. Although we expect some orphans to display weaker signatures of circumstellar material than other protostars, they will—especially the younger ones—reside high up on their Hayashi tracks, generally making them more luminous than their more evolved T Tauri counterparts (discounting accretion luminosity) that have emerged from their placental clouds at a more leisurely pace.
12. Examples of well-known, probable orphans include T Tauri (Köhler et al. 2008), HH 111 B (Reipurth et al. 1999), TMR-1C (Riaz & Martin 2010), and HBC 515 C/D (Reipurth et al. 2010).

5. CONCLUSIONS

We have performed *N*-body calculations of newborn triple systems embedded in a placental cloud core. While the members of a triple system interact in the center of a cloud core they feel only a fraction of the potential of the core. But as soon as one of the members is ejected to the outskirts of the core it must climb out of the full potential well of the core before it can escape. As

[4] *orphan*: one deprived of some protection or advantage [Merriam-Webster].

a result many fall back, leading to a series of ejection events, and thus a yo-yo-like motion of the star takes place. To escape, the star must await either a particularly forceful close triple encounter or wait until the core has lost enough mass to lower its potential barrier. We conclude that the loosely bound distant companions to embedded protostars found by Connelley et al. (2008a, 2008b) are well explained as orphans. The identification and observational study of orphans may offer important insights into the very earliest stellar evolutionary stages.

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