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# "EARLY" AND "LATE" RUNAWAY STARS IN THE ORION BN/KL REGION

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RESUMEN

Revisamos el origen dinámico de las fuentes de radio con grandes movimientos propios BN–I–n observadas en la región BN/KL de Orión. Hacemos hincapié en la aparente contradicción entre las edades de las radiofuentes y el tiempo de colapso dinámico. Mostramos que pueden producirse generaciones subsecuentes de estrellas desbocadas después del colapso inicial, y hasta la disolución final del protocúmulo.

ABSTRACT

We review the dynamical origin of the high proper motion BN–I–n radio sources in the Orion BN/KL region, emphasizing the apparent contradiction between the ages of the sources and the dynamical collapse time. We show that further generations of runaway stars can be produced after the initial collapse, and right until the final dissolution of the protocluster.

*Key Words:* stars: early-type- — stars: kinematics and dynamics — stars: protostars



## 1. INTRODUCTION

The class of young massive high velocity stars (runaway stars) was first characterized by Blaauw and Morgan in 1954. The best known runaway stars, AE Aurigae and $\mu$ Columbae, "run away" from the Orion Nebula region in opposite directions, with space velocities of more than 70 km s$^{-1}$.

In a classical paper, Blaauw (1961) published the first list of 19 OB runaway stars (RAS) with peculiar velocities larger than 40 km s$^{-1}$. Blaauw noted that among the runaways there were no known visual or spectroscopic binaries. He proposed that the large velocities were the result of the rupture of a massive close binary, where the primary exploded as a supernova releasing the secondary with a velocity almost as large as the orbital velocity (30 - 100 km s$^{-1}$). Blaauw's suggestion was similar to the one advanced a few years before by Zwicky (1957)

Poveda et al. (1967) proposed an alternative model to explain the acceleration of runaway stars. In this model, a multiple star system composed of a few massive protostars begins its evolution in a cold, dense cloud. As each one of the protostars gravitationally contracts, they break apart from the natal cloud, and cease to be supported by pressure as they were when they were part of the cloud. Thus, the protostars begin an almost-free fall towards the center of mass of the system. A number of N-body simulations were carried out, with initial conditions ensuring the collapse of the configuration ($2T+\Omega \ll 0$). Very close encounters among three or more stars occurred, resulting in the ejection of stars with large velocities. A fraction of about 20% of runaway stars was obtained, with velocities of up to 180 km s$^{-1}$, values similar to the then known observations.

More recently, Hoogerwerf et al. (2001), from an updated sample of runaways using Hipparcos data, were able to trace back the trajectories of 56 runaway stars and 9 compact objects in order to identify their parent stellar groups. This study convincingly showed that both the binary supernova ejection and the cluster ejection mechanisms are at work to produce runaway stars.

It is interesting to point out that recently an indication of a surprisingly high incidence of runaway stars (27% among young stars of all masses) has been found (Tetzlaff et al. 2010). Such a large fraction of runaways poses problems for both the binary supernova ejection and the cluster ejection mechanism.

## 2. THE HIGH PROPER MOTION RADIO SOURCES IN THE BN/KL REGION IN ORION

Recent studies of the extremely young BN/KL region (Rodríguez et al. 2005; Gómez et al. 2005; Gómez et al. 2008) found that the objects designated as BN and I have large anti-parallel proper motions, with corresponding velocities of 27 and 12 km s$^{-1}$ respectively. Source n was also found to have a large proper motion, corresponding to a $v$ = 24 km s$^{-1}$, and emanating from the same region, where all three

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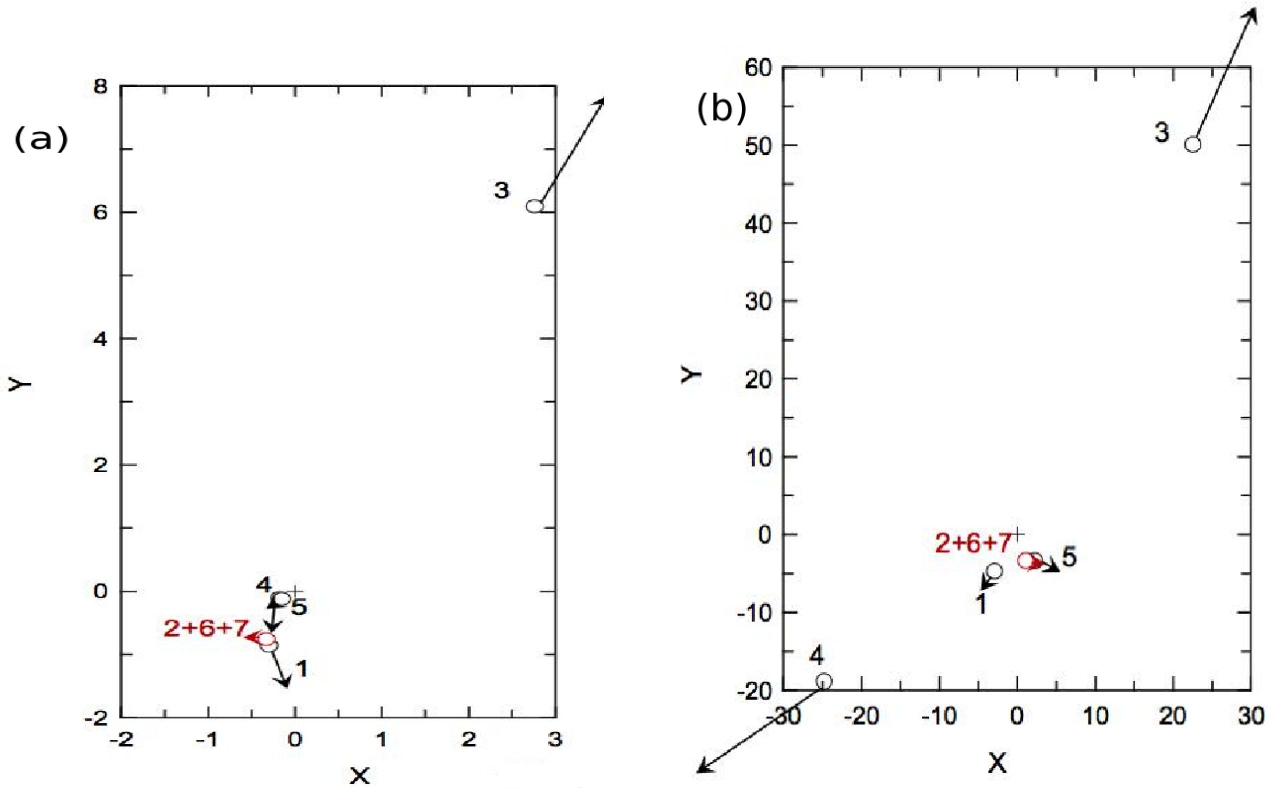


Fig. 1. (a) An example of the evolution of a 7-body case, with the stars placed initially in a spherical configuration. Panel (a) shows the system after 2 crossing times (about 600 years). An "early" runaway star (star 3) has been produced. An unstable sextuple system remains. Panel (b) shows the same example after 10 crossing times (about 3000 years). A second, "late" runaway star (Star 4) is now present. The remaining five stars form an unstable system. After 100 crossing times of evolution, successive ejections occur, until the complete dissolution of the system, Stars 2 and 7 form a close binary, whose negative energy compensates the positive energy of all the escapers.



objects were located within a few arcsec from each other some 500 years ago. We interpreted the BN–I–n object as a massive multiple system that disintegrated by dynamical interactions as recently as 500 years ago, as in the dynamical ejection mechanism proposed by us long ago (Poveda et al. 1967).

To verify this interpretation we performed numerical simulations of 100 cases of 5 bodies, using the code developed by Mikkola and Aarseth (1993) which includes chain regularization and is thus able to accurately follow very close encounters. We assumed masses $M(1) = M(2) = 16$ M$_\odot$, $M(3) = M(4) = 8$ M$_\odot$, $M(5) = 20$ M$_\odot$ and placed the five protostars within a radius $r \sim 400$ AU, assigning to them random velocities with a $\sigma(v) \sim 0.4$ km s$^{-1}$, which corresponds to the thermal velocity in a molecular cloud at $T = 10$K. We confirmed that close encounters ($r < 1$ AU) among proto-stars in such a non-virialized compact system can produce energy exchanges sufficiently large to eject stars with large velocities. The positive energy of the runaway star is compensated by the binding energy of a binary or multiple star (with a typical major semiaxis of 17 AU). The integrations were stopped after only 2.2 crossing times, corresponding to 650 years. The observed configuration and velocities of the system BN–I–n were well reproduced.

## 3. SUCCESSIVE GENERATIONS OF RUNAWAY STARS

Although our model successfully reproduced the observed geometry and velocities of the BN/KL system, a problem soon became apparent: the ages of stars BN–I–n, although very uncertain, are probably greater than 650 years, the time it takes for the initial dynamical collapse to produce the first runaways. This difficulty, and the need to explore other initial configurations, motivated us to carry out further N-body simulations. For this purpose we computed 100 cases of 7 bodies, located within spheres

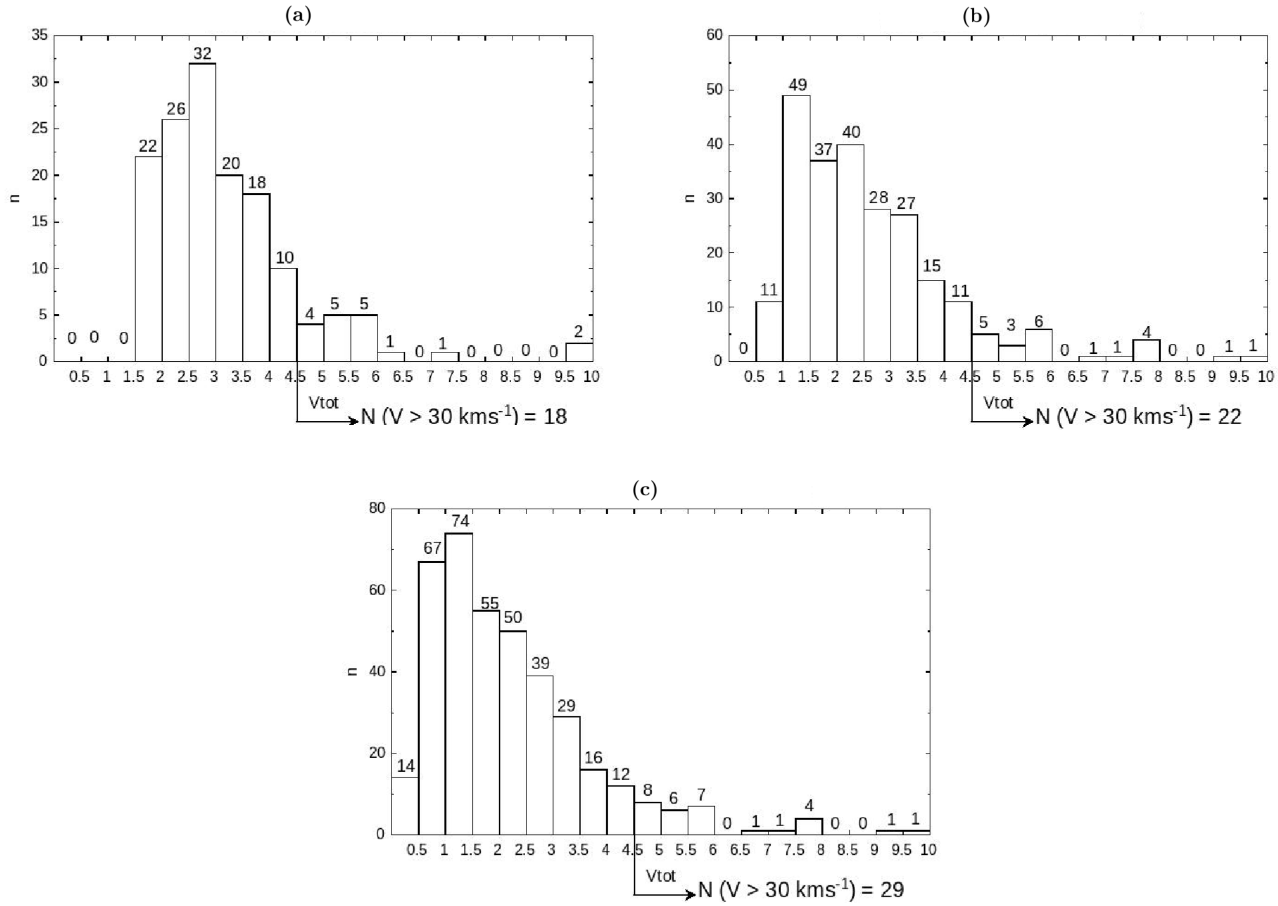


Fig. 2. The distribution of velocities of the escaping stars, for 100 examples of 7 bodies, initially placed in a spherical configuration. Panel (a) shows that after 2 crossing times (about 600 years) a total of 18 runaway stars were produced. These would correspond to runaway stars formed during the initial collapse of the clusters, thus "early" runaways. Panels (b) and (c) show the same examples after 10 and 100 crossing times )3000 and 30,000 years, respectively). The number of runaway stars increases to 22 and 29, respectively. These runaways were formed well after the initial collapse of the cluster, hence they are "late" runaways.

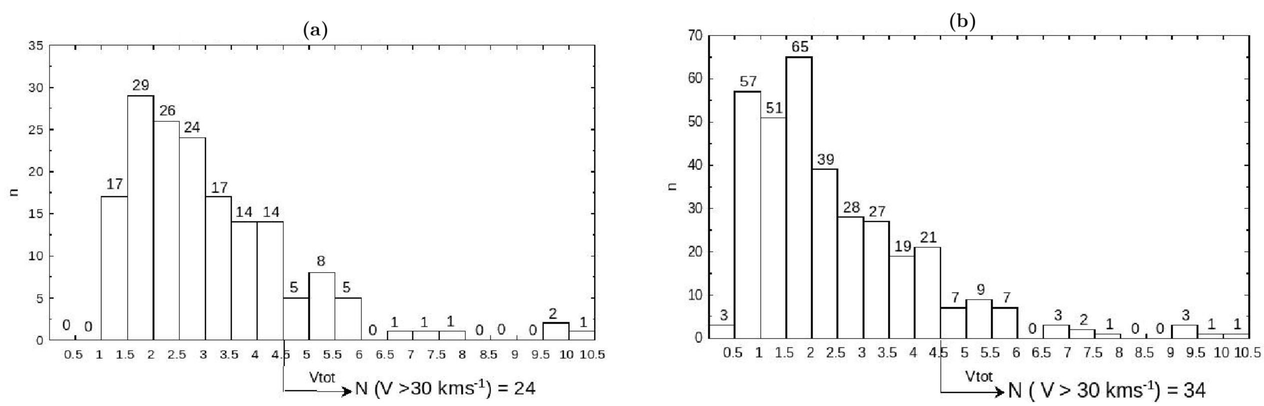


Fig. 3. The distribution of velocities of the escaping stars, for 100 examples of 7 bodies, initially placed in a filamentary configuration. Panel (a) shows that after 10 crossing times (3000 years) the number of runaway stars is 24. Panel (b) shows that after 100 crossing times (30,000 years) the number of runaways has increased to 34. This is another example of "late" runaways, formed well after the initial collapse of the cluster.

of 400 AU radius and with masses $M(1) = M(2) = 16\ \mathrm{M}_\odot$, $M(3) = M(4) = M(5) = M(6) = 8\ \mathrm{M}_\odot$, $M(7) = 20\ \mathrm{M}_\odot$, assigning to them random velocities with a $\sigma(v) \sim 0.4$ km s$^{-1}$, and 100 additional cases of 7 bodies, but now situated in filamentary configurations of similar dimensions. Instead of stopping the integrations after the first runaways were produced (2.2 crossing times), we carried them out for 2, 10, and 100 crossing times.

Figures 1a and 1b show an example of our results. In Figure 1a, we illustrate the evolution of a 7-body case. We see that after only 2 crossing times a runaway star is produced (Star 3). The remaining stars form an unstable, more tightly bound 6-body system. Figure 1b shows the system after 10 crossing times. A second runaway star has been produced (star 4) and there still remains an unstable 5-body system. After 100 crossing times this remaining system completely dissolves ejecting three additional stars; only a tight binary is left (stars 2, 7).

Figures 2a,b and c show the distribution of velocities for escaping stars obtained for a sample of 100 clusters of 7 stars, initially placed in spherical configurations, after dynamically evolving for 2, 10 and 100 crossing times. The number of runaway stars is seen to increase from 18 to 29, thus showing that successive generations of runaway stars ("late" runaways) are indeed formed after the initial collapse of the cluster produces the first, "early" runaways. Finally Figures 3a, b show that a similar situation obtains for 100 clusters of 7 stars initially placed in filamentary configurations. Here, too, the numbers of runaway stars increase from 24 to 34, after 10 and 100 crossing times, respectively. Here, too, several generations of runaway stars were produced after the initial collapse.

## 4. DISCUSSION AND CONCLUSIONS

The system BN - I - n is an example of an initially very compact multiple ($r \leq 400$ AU) with a large density ($n \sim 1 \times 10^8$ stars per pc$^3$), that is now observed to be in the process of dynamical disintegration. Component B of the Orion Trapezium (5 stars within a radius of 2 arcsec) is a sub-trapezium with a comparable stellar density. We may conclude that the Orion region has produced in the past many "early" runaway stars, and that the system BN–I–n is only the most recent example. The sub-trapezium $\theta^1$ Ori B (a dynamically unstable quintuple system) will probably decay dynamically and produce in the future one or more runaway stars. Furthermore, the discrepancy between the (uncertain) ages of the stars BN–I–n and the time of dynamical collapse can be resolved taking into account that the further dynamical evolution produces additional, "late", runaway stars. We find from these simulations that the 7-body systems keep ejecting runaway stars for up to 100 crossing times. This multi-generation process of violent relaxation may take more than 30,000 years. This suggests that BN–I–n are not necessarily first generation, "early" runaway stars. In fact, they may be $10,000 - 30,000$ years old, which is a more realistic age for these stars. Interestingly, the BN-I-n system appears to be an example of a runaway star "caught in the act" of getting accelerated. Other possible examples are discussed by Costero et al. (2008).

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