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RUNAWAY STARS. THEN AND NOW

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RESUMEN

En este trabajo haré una breve revisión de la clase de objetos conocidos como estrellas desbocadas (runaway stars), desde su descubrimiento por Blaauw y Morgan hasta el más reciente caso de los objetos BN–I–n en la región Becklin-Neugebauer/Kleinman-Low, en el cúmulo de la Nebulosa de Orión. Presentaré simulaciones numéricas basadas en el modelo de interacciones dinámicas fuertes entre protoestrellas, que reproducen la configuración cinemática del sistema BN–I–n

ABSTRACT

I will briefly review the history and evolution of the concept of runaway stars, from the discovery of this class of objects in Orion by Blaauw and Morgan up to the recent discovery of three very young runaway stars: BN–I–n in the Becklin-Neugebauer/Kleinman-Low region again in Orion. I will show numerical simulations based in the model of strong dynamical interactions among protostars that reproduce the observed kinematical configuration on the BN–I–n systems.

Key Words: stars: formation — stars: kinematics — stars: pre-main sequence

1. INTRODUCTION

When I received the invitation to participate in this homage to our friend Luis Carrasco, on the occasion of his 60th anniversary, my first reaction was to say "of course", I have to be with Luis to wish him many more years of a fruitful astronomical activity. As I looked back to his long and productive walk through astronomy, *flash after flash* reminded me of the many interesting and original papers he wrote, but one topic caught my attention because of our common interest in runaway stars. Luis' contribution to the subject is still valid and thus I decided to talk about runaway stars.

As everybody remembers, the class of young massive high velocity stars was discovered and characterized by Blaauw & Morgan in 1954. Two OB stars, AE-*Auriga* and μ-*Columba*, "run away" from the Orion nebulae region in practically opposite directions; tracing back the motions of these stars they seem to reach their minimum separation some two million years ago, as if some "special event" accelerated each one of them to space velocities larger than 100 km s^{-1}, (see Figure 1).

In a classical paper, Blaauw (1961) published the first list of runaway stars (RAS): 19 OB stars characterized by peculiar velocities larger than 40 km s^{-1}. Blaauw found in this paper that neither an exponential nor a Gaussian fit to the peculiar velocities of OB stars with velocities smaller than 40 km s^{-1} could reproduce the observed number of runaway stars. Furthermore, he noted that none of the runaways was a member of a visual binary or was a known spectroscopic binary. In this investigation Blaauw advanced an explanation for the peculiar kinematic behaviour of the RAS: their high velocities were the result of the rupture of a massive binary, when the primary exploded as a supernova ejecting more than half of its mass (tens of solar masses) and therefore releasing the secondary, the RAS, with a velocity comparable to its orbital one ($30 - 100$ km s^{-1}). This mechanism had already been forseen a few years before by Zwicky.

After Blaauw's classical work, many more RAS have been identified and listed in various catalogues (see Gies & Bolton 1986, and references therein for the early observations; Hoogerwerf et al. 2001 for more recent lists of RAS). Also, Allen & Kinman (2004) have identified more than 30 RAS in the galactic halo.

My interest in the subject arose after an investigation I did on the masses ejected by Type II Supernova; I found that in these explosions the mass ejected was much smaller than the tens of solar masses required by Blaauw's mechanism, and thus these events could not eject RAS with masses as large as those observed. To solve this problem we proposed an alternative model to explain the acceleration of RAS (Poveda et al. 1967). In this model a multiple stellar system composed of a few massive protostars begin their gravitational contraction in a

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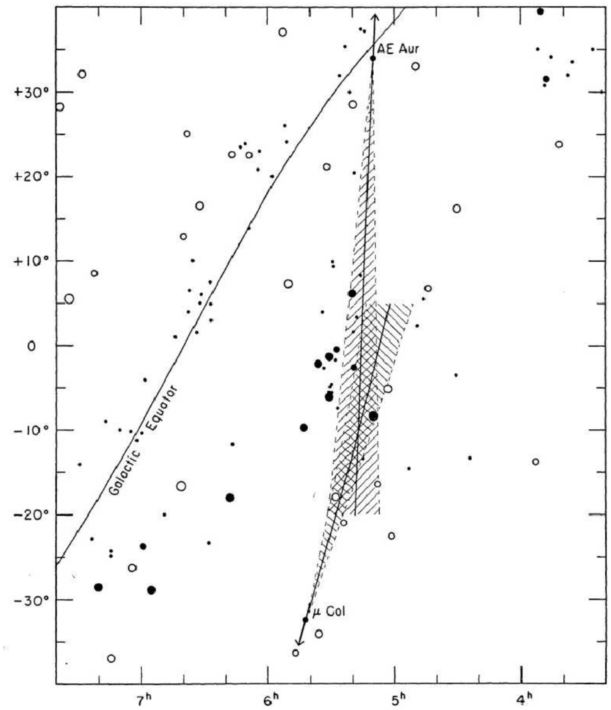

Fig. 1. The positions of AE Aurigae and μ Columbae with respect to the Orion association. Arrows show the directions of their proper motions when corrected for the standard solar motion. The paths of the two stars with respect to the standard of rest thus defined are shown by the great circles traced backward from the proper motions. The shaded areas indicate the uncertainty in their directions. The sizes of the arrows correspond to the displacements in 4×10^5 years. Stars brighter than apparent magnitude 3.5 are presented by large dots (OB supergiants) and open circles. Small dots represent the fainter OB supergiants (Blaauw & Morgan 1954).

cold and very dense cloud (Bok globule?); as each one of the protostars begin their gravitational contraction, they break apart from the parental cloud, and in so doing they loose the pressure support they enjoyed when they were in pressure equilibrium in the cloud. Thus, the protostars begin a free fall towards the center of mass of the system; a number of n-body simulation in which the initial conditions were not virialized, i.e. $2T + \Omega \ll 0$, led to very close encounters near the center of mass of the system. These encounters produced strong gravitational accelerations, ejecting stars with large velocities, as we showed in our 1967 paper.

A third interpretation of the RAS phenomenon was advanced in a series of papers by Carrasco and collaborators (Carrasco et al. 1978; Carrasco et al. 1980), where they claimed that in many cases the RAS phenomenon was not real but rather the result of a spectroscopic misclassification of old thick disk population stars.

In the last 40 years these three interpretations have been debated in the literature: Gies & Bolton (1986), in a very exhaustive investigation, and more recently Hoogerwerf et al. (2001) in a rather detailed discussion, arrived at the conclusion that the RAS phenomenon is real and that the two main mechanisms were at work in the galaxy.

In the present contribution we will try to gain some further insight into the initial conditions that are part of our strong interaction model.

The very young Beckling-Neugebauer (BN) object in Orion (one arc minute to the northwest of the Trapezium), seems to be the most interesting case of a RAS "caught in the act" of getting accelerated together with the close radio sources I and n (Figure 2). Around 500 years ago a multiple star system disintegrated dynamically (Rodríguez et al. 2005; Gómez et al. 2005, 2008). The short time elapsed since these three stars were accelerated allows us to advance in the understanding of the massive star formation process and its dynamics; in five hundred years there has not been much time for the star formation scenario to have changed significantly. There is no other site known in the galaxy where one could have such a close look to the moment of RAS formation. This process liberated some energy (comparable to the kinetic energy of the RAS) in the form of a gas explosion visible in the H_2 emission lines as the spectacular "fingers" whose expansion seems to have started at about the same time and from the same area where the RAS got accelerated (Zapata et al. 2009).

2. THE SYSTEM BN, I, n, IN ORION

Very accurate and absolute (referred to distant quasars) radioastrometry of the objects BN, I and n in the Becklin-Neugebauer/Kleinman-Low region in Orion (Rodríguez et al. 2005; Gómez et al. 2005, 2008) has revealed and confirmed that the object BN is moving in the plane of the sky with a velocity of 21.6 ± 2 km s^{-1}. Moreover, the very bright radio source I (GMRI) has also a large transverse velocity of 14.6 ± 2.4 km s^{-1} (assuming a distance of 414 pc to Orion, Menten et al. 2007). The position angle of the proper motion of the I source is almost antiparallel to the motion of the BN object. Object n is also moving with a large transverse velocity: 26 ± 2.4 km s^{-1}. Table 1, taken from Gómez et al. 2008, lists the proper motions of these three objects. Tracing back in time their proper motions, Gómez et al. find that

TABLE 1

ABSOLUTE PROPER MOTIONS OF THE BN–I–n SYSTEM

Source	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	$\mu_{\rm total}$ (mas yr^{-1})	P. A. (°)
BN object	-5.3 ± 0.9	9.4 ± 1.1	10.8 ± 1.0	-29 ± 5
Orion-n	0.0 ± 0.9	-13.0 ± 1.2	13.0 ± 1.2	180 ± 4
GMR I	4.5 ± 1.2	-5.7 ± 1.3	7.3 ± 1.2	142 ± 10

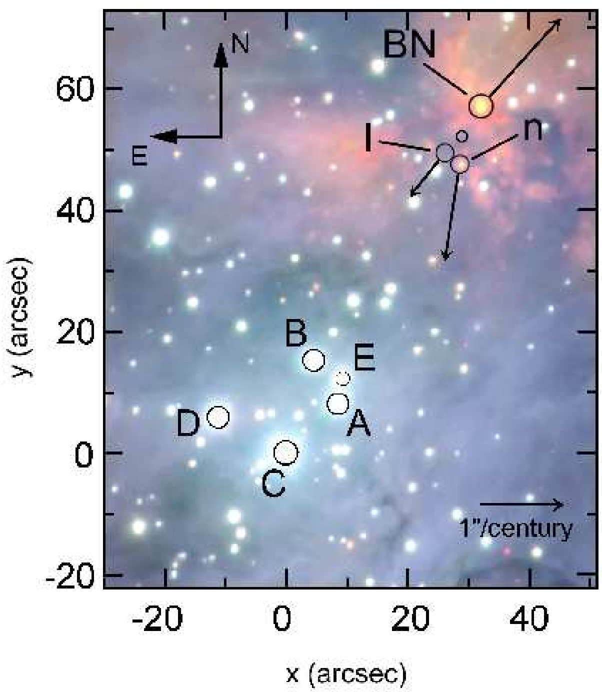

Fig. 2. Proper motion vectors of the system BN–I–n superposed on an infrared image of the center of the Orion Nebula Cluster. [Note the proximity of the older trapezium system (A B C D E)] (Image adapted from McCraughrean 2001).

their minimum separations was about 230 AU some 500 years ago.

The proper motions of BN and I are reminiscent of the first runaway stars identified by Blaauw & Morgan (1954), see Figures 1 and 2. The very precise measurements of the proper motions of BN and I, as well as the youth of this system, motivated us (Allen et al. 2007; Poveda et al. 2008) to apply our model of strongly interacting few bodies to reproduce the kinematics of the BN–I–n system. We have numerically integrated several hundred cases of 5 and 7 bodies using the chain regularization N-body code of Aarseth & Heggie (1993).

From the observed proper motions of BN and I and within the errors listed (Gómez et al. 2008) we may adopt $\mu(\mathrm{BN})/\mu(\mathrm{I}) = 2$. Since the direction of the corresponding proper motion vectors are antiparallel, conservation of momentum allows us to adopt $M(I)/M(BN) = 2$. The mass of BN is very uncertain. We adopt with Plambeck et al. (1995), the determination by Scoville et al. (1983) $M(BN) = 18\ M_\odot$, which is based on the argument that to maintain the observed dense H II region around BN, an UV flux corresponding to a B0.5 star, of some 18 $M_\odot$, is necessary. Thus the mass of the infrared object I becomes $M(I) = 36\ M_\odot$. In our model the kinetic energy of the RAS is compensated by the binding energy of a close binary, usually formed by the two more massive bodies; taking I to be composed of two stars of masses 20 and 16 $M_\odot$, we find that a semimajor axis $a = 13.6$ AU will have a binding energy sufficient to compensate the positive energy of BN + I + n.

For the first one hundred cases that we have computed, we adopted initial conditions similar to those observed in regions of massive star formation. We took initial random position and velocities of 5 stars with masses: $M(1) = M(2) = 16\ M_\odot$; $M(3)$, $M(4) = 8\ M_\odot$ and $M(5) = 20\ M_\odot$; we set these 5 protostars closely packed at random within a radius $R = 400$ AU with initial (non virialized) random velocities $\sigma_v \sim 0.4$ km s^{-1} corresponding to the thermal velocities in a molecular cloud at $T = 10°$ K. The number density of protostars implied by our initial conditions: $n = 10^8$ pc^{-3}, looks at first too large. However, close to protostar cep AHW2, Curiel et al. (2002) and Martin-Pintado et al. (2005) have identified the existence of at least four embedded young stellar objects within an area of some 600×600 AU; the corresponding stellar density $n = 1.6 \times 10^8$ pc^{-3} is similar to the one implied by our initial conditions. Also, note that the component θ^1B in the Orion Trapezium is composed of five stars within about 400 AU (Close et al. 1990), giving a stellar density just similar to our initial conditions. Note

TABLE 2

CASE 1, INITIAL CONDITIONS

Star	X (AU)	Y (AU)	Z (AU)	R (AU)
1	−345.2	−5.2	−188.8	393.6
2	340.4	−5.6	−185.2	387.6
3	8	344	303.2	458.4
4	−7.6	−328	293.6	440
5	3.6	2.0	60.8	60.8
Star	V_x(km s^{-1})	V_y (km s^{-1})	V_z(km s^{-1})	V_t(km s^{-1})
1	0.0267	−0.0267	0.1937	0.2004
2	0.2138	−0.4142	−0.2071	0.5077
3	−0.0334	−0.0200	−0.3474	0.3474
4	−0.0802	0.0000	0.1202	0.1403
5	0.0534	−0.0468	−0.0334	0.0735

TABLE 3

CASE 99, INITIAL CONDITIONS

Star	X (AU)	Y (AU)	Z (AU)	R (AU)
1	−330	10.4	−190.8	381.6
2	319.2	−10.4	−162	358
3	24.8	345.6	303.6	460.4
4	4	−348.8	302	461.2
5	−2.8	1.6	40	40.4
Star	V_x (km s^{-1})	V_y (km s^{-1})	V_z (km s^{-1})	V_t (km s^{-1})
1	0.08684	0.11356	−0.32064	0.35404
2	−0.25384	−0.12024	−0.08684	0.29392
3	0.1336	0.18704	−0.3674	0.4342
4	−0.22044	−0.14028	−0.05344	0.2672
5	−0.0334	0.24716	0.32064	0.40748

that these would correspond to an average number density of molecular hydrogen $n(H_2) \simeq 10^{16}$ cm^{-3}.

The non-virialized initial conditions in our simulations produced very close multiple encounters near the center of mass; the energy exchanges correspond to a process of violent relaxation such that in a few crossing times several stars are ejected with positive energy, frequently some of them with velocities typical of RAS. Tables 2 and 3 list the initial conditions of two of our simulations (No. 1 and 99) which, after 2.2 crossing times produced a kinematical configuration similar to that of the BN–I–n system. Figures 3 and 4 show the 5 stars of each case, with their space velocities projected on the plane of the sky.

The kinetic energy of the three objects BN, I, n, about 2×10^{47} ergs, (Gómez et al. 2005) is compensated by the binding energy of a close binary; in over 70% of the cases, the binary is formed by the two most massive bodies in each simulation. From the adopted initial conditions we find that 2.2 crossing times correspond to about 650 years. In Example 1, shown in Figure 3, stars 1 and 5 formed a binary with a semimajor axis $a = 13.6$ AU; the binding energy of this binary is -2.1×10^{47} ergs. The total kinetic energy of stars 4, 2 and 3 plus that of the center of mass of the binary $(1+5)$ is 1.9×10^{47} ergs. Example 99 is shown in Figure 4, after 2.2 crosing times. In this case the binary is formed by stars $(1 + 2)$ with a semimajor axis $a = 7.6$ AU and an energy $E(1 + 2) = -3 \times 10^{47}$ ergs. The total kinetic energy of stars 3, 4 and 5 plus that of the center of mass of the binary is 2.6×10^{47} ergs. Note that the

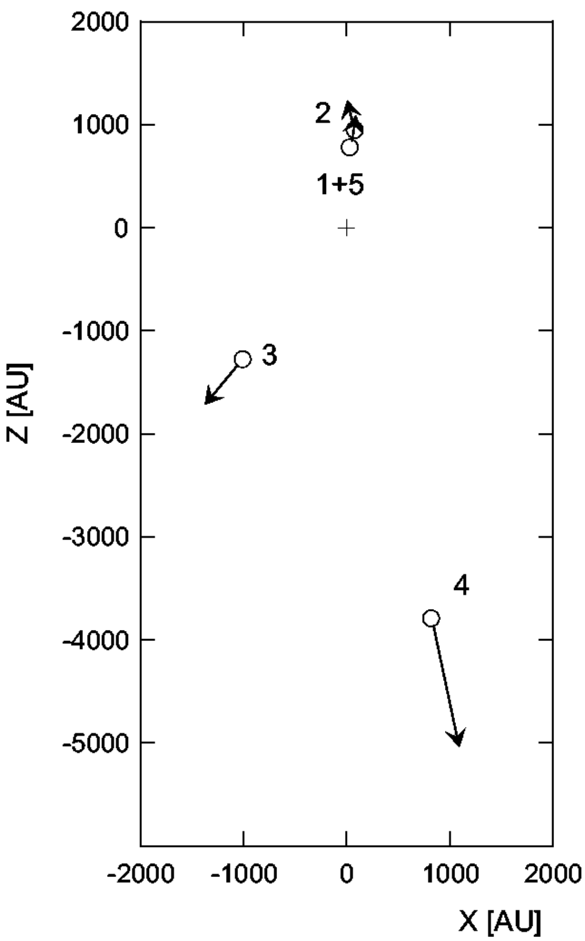

Fig. 3. Example 1. Positions and velocities on the $X-Z$ plane for 5 stars after 2.2 crossing times (650 yr). The center of mass is marked by a cross. The Y component of the velocity vector of the runaway star (star 4) is small compared to the $X-Z$ components. The space velocities of the BN–I system lie mostly on the plane of the sky and are observed as transverse velocities. Thus, this figure is directly comparable to Figure 2 of the BN system in the present paper. In this example $V_{xz}(4) = 40$ km s^{-1}, $V_{xz}(1+5) = 8.4$ km s^{-1}, the major semiaxis of binary $a(1+5) = 13.6$ AU, and the binding energy of this binary is $E(1+5) = -2 \times 10^{47}$ ergs. The individual masses are $M(1) = M(2) = 16\ M_\odot$, $M(3) = M(4) = 8\ M_\odot$, $M(5) = 20\ M_\odot$. The total kinetic energy of stars 4, 2, and 3 plus that of the center of mass of the binary $(1+5)$ is 1.9×10^{47} ergs. The runaway star (star 4) has reached a projected distance of 3879 AU from the center of mass, and the binary $(1+5)$ a projected distance of 704 AU.

sum of the binding energy of the binaries plus the kinetic energy of the stars is negative because the initial conditions are such that $T + \Omega = E < 0$.

The RAS produced in our simulations are ejected in a very short time. In fact, despite of the youth of the system BN–I–n, it is unreasonable to think that these stars are only 650 years old; so we analized many more cases where we examined the evolution of systems of seven bodies for a longer period of time, i.e., 10 and 100 crossing times with initial conditions similar to those used for the five body cases. We find from these simulations that the seven body systems keep ejecting RAS up to 100 crossing times. (Allen & Poveda, in preparation). This multigeneration process of violent relaxation may take more than 10,000 years to eject some delayed runaways. This suggests that BN–I–n are not first generation RAS, in fact, they may be some 10,000 years old, which is a more realistic age for these stars and consistent with the time scale for the delayed ejection of RAS in the violent interaction model.

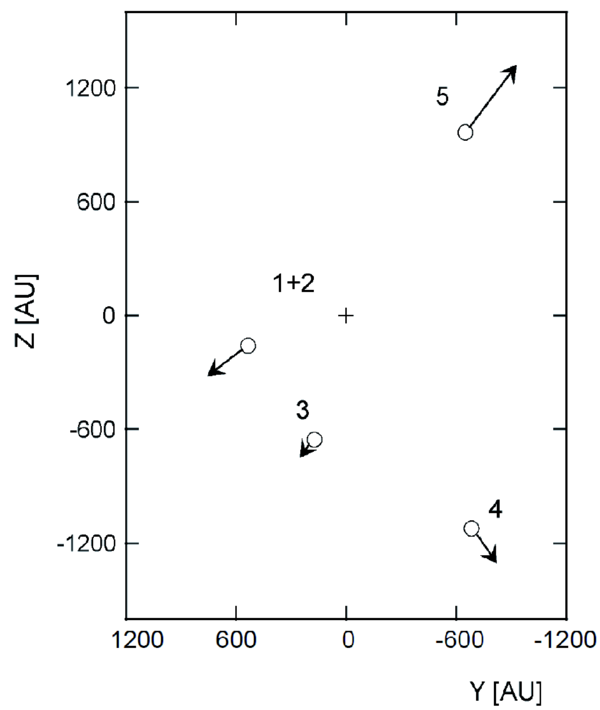

Fig. 4. Example 99. Similar to Figure 3, but on the plane $Y-Z$. In this example, $V_{yz}(5) = 30$ km s^{-1}, $V_{yz}(1+2) = 18.7$ km s^{-1}, $a(1+2) = 7.6$ AU, $E(1+2) = -3 \times 10^{47}$ ergs, and the total kinetic energy of stars 3, 4, and 5 plus that of the center of mass of the binary $(1+2)$ is 2.6×10^{47} ergs. The runaway star (star 5) has reached a projected distance of 1163 U from the center of mass, and the binary $(1+2)$ a projected distance of 557 AU.

3. CONCLUSIONS

About $10-30\%$ of the OB stars have large peculiar velocities and frequently are found in the disk or in the halo far from the sites of star formation. The prototype of this class of objects are the stars AE

Auriga and μ-*Columba* which appear to be "running away from some point in the Orion nebula Cluster. To accelerate the very young stars from the typical peculiar velocities of $1-2$ km s^{-1} relative to their sites of formation, up to velocities larger than 30 km s^{-1} in the lifetime of an OB star demands a mechanism that is not part of the dynamical history of most stars. When studying the dynamical history of a suspected RAS we first have to be sure that they are indeed bright young OB star and not a misclassified low mass evolved object, i.e. an old disk population.

We owe to Luis Carrasco this call of alert when studying a high velocity OB star. However, in spite of Carrasco warnings, a large number of well studied high velocity OB stars, are indeed RAS.

To explain the kinematics of RAS, two mechanisms are still valid: the supernova explosion in a binary and the strong dynamical interaction in a compact, infant multiple star; in a very exhaustive investigation on the subject, Hoogerwerf and collaborators concluded that both mechanisms are present in the formation of RAS.

The very young BN–I–n system in the Becklin-Neugebauer/Kleinman-Low region in Orion, is a perfect example of a RAS accelerated as the result of the mechanism of strong delayed dynamical interactions. A number of n-body simulations produced several cases with kinematics similar to the BN–I–n objects.

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