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RUNAWAY STARS AS TRACERS OF STAR FORMATION AND EARLY DYNAMICAL EVOLUTION

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RESUMEN

La reciente y muy precisa determinación de los movimientos propios en el sistema BN-KL-n en Orión nos ha motivado a construir un modelo dinámico capaz de producir las estrellas desbocadas presentes en el sistema por medio de encuentros cercanos entre sus miembros. Hemos realizado integraciones de N-cuerpos y presentamos un modelo congruente para el sistema BN-KL-n.

ABSTRACT

The newly determined, very accurate, proper motions for the BN-KL-n system in Orion motivated us to construct a dynamical model capable of producing the runaway stars of this extremely young system by close interactions among its members. We perform N-body integrations and present a consistent model for the BN-KL-n system.

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

1. INTRODUCTION

A study of the proper motions of the BN-KL-n objects, deeply embedded in the Orion I molecular cloud and about 1 arcmin distant from the Trapezium (Rodríguez et al. 2005; Gómez et al. 2005) has revealed the existence of a system of runaway stars (similar to AE Aurigae and μ Columbae) whose expansion began about 500 years ago (see Figure 1). This extremely young system can provide important information about the conditions of star formation and early dynamical evolution.

To accelerate young protostars from the typical thermal velocities to several tens of km s^{-1} we proposed long ago (Poveda et al. 1967) very close encounters among the stars of a gravitationally collapsing protomultiple system. The very precise kinematical data for the BN-KL-n system obtained by radioastrometric techniques allow us to model initial conditions so as to reproduce the observed motions. We have numerically integrated several hundred cases of 5, 6 and 7 bodies densely packed within a sphere of 400 AU radius and with a velocity dispersion corresponding to the thermal velocity expected for a cold molecular cloud. We show that several of our cases closely reproduce the observed kinematical configuration of the BN-KL-n system. In particular, within the uncertainties of the observed proper motions of BN and I and of the estimates of their masses, we may adopt M(BN)= 18 $M_\odot$, while source I would be a binary with component masses $M(1) = 20\ M_\odot$, $M(2) = 16\ M_\odot$ and with a major semiaxis $a = 13$ AU. (compare especially with Case 1, illustrated in Figure 2). The numerical results that best model the BN-KL-n system imply that several massive stars can form in volumes as small as 400 AU in radius.

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2. A DYNAMICAL SCENARIO FOR THE REGION

The kinetic energy involved in the three kinematically peculiar objects, BN, I and n, is about 2×10^{47} ergs (Gómez et al. 2005). To accelerate these objects to their observed velocities from the typical random motions of recently formed stars we postulate very close encounters in a multiple star system, as first proposed by Poveda, Ruiz, & Allen (1967). We have recently updated these computations, using the chain-regularization N-body code of Mikkola & Aarseth (1993). The results illustrated in the 1967 paper were exactly reproduced by the new computations. From the observed proper motions of BN and I (Rodríguez et al. 2005; Gómez et al. 2005; Gómez et al. 2008) and within the uncertainties listed in these papers, we may adopt $\mu(BN)/\mu(I) = 2$. Moreover, since the directions of the proper motions are practically antiparallel, conservation of momentum allows us to estimate that $M(BN)/M(I) = 2$. The mass of BN is very uncertain; perhaps the best determination is that of Scoville et al. (1983), which was

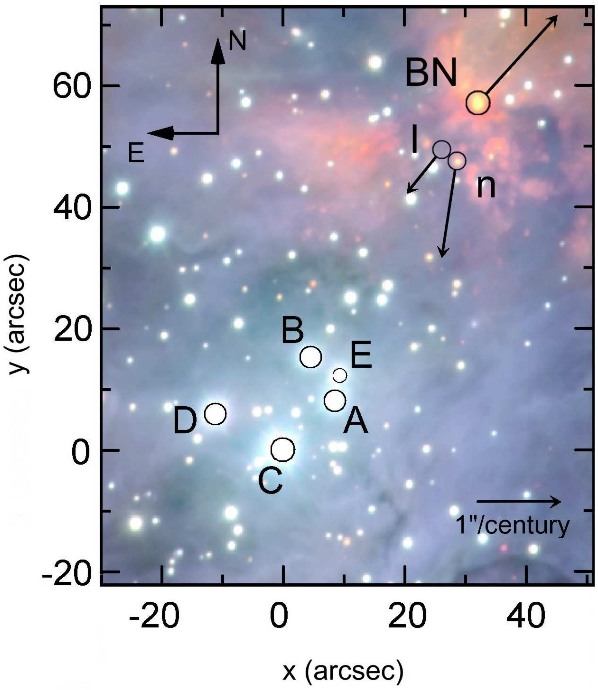

Fig. 1. Proper motion vectors of the system BN-I-n superposed on an infrared image of the center of the Orion Nebula Cluster. (Image adapted from McCraughrean 2001).

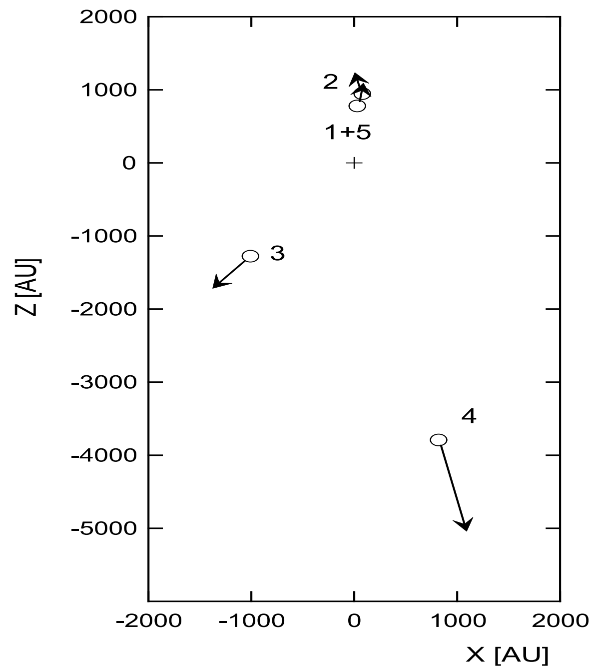

Fig. 2. Example 1. Positions and velocities on the plane XZ for 5 stars after 2.2 crossing times (650 years). The Y component of the velocity vector of the runaway star (star 4) is small compared to the XZ components. The space velocities of the BN-I system lie mostly on the plane of the sky and are observed as transverse velocities. Thus this figure is directly comparable to Figure 1 of the BN system. In this example $Vxz(4) = 40$ km s^{-1}, $Vxz(1+5) = 8.4$ km s^{-1}, the major semiaxis of binary $a(1+5) = 13.6$ AU, the binding energy of this binary $E(1+5) = -2.1 \times 10^{47}$ 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 $(1+5)$, 704 AU.

adopted by Plambeck et al. (1995) and is based on the observed compact HII region around BN. According to Scoville's model, to maintain such a compact HII region one needs the UV flux corresponding to a B 0.5 star, with a mass of 18 $M_\odot$. Therefore, the mass of I should be about 36 $M_\odot$. If we tentatively identify I with a close binary (of $20 + 20\ M_\odot$) formed by dynamical interactions, we can estimate the binding energy necessary to compensate the positive energy of its own motion as well as that of BN and possibly Orion-n. The resulting major semiaxis turns out to be $a = 13.6$ AU. It is relevant to point out that the average binary formed in the computed examples that gave runaway stars had a major semiaxis $a = 13$ AU.

For the new examples, we adopted initial conditions inspired by recent observational results on regions of massive star formation; we simulated compact multiples composed of 5 stars of different masses ($M(1) = M(2) = 16\ M_\odot$, $M(3) = M(4) = 8\ M_\odot$, $M(5) = 20\ M_\odot$) densely packed within radii of 400 AU and with a velocity dispersion (0.4 km s^{-1}) corresponding to the thermal velocity of a 10 K region. The stellar density required is thus 1.6×10^8 stars per cubic parsec, which appears to be very large. However, there are several examples of very young stellar systems with such large number densities. In the surroundings of the protostar Cep A HW2 the results of Curiel et al. (2002) and Martin-Pintado et al. (2005) imply the presence of at least four embedded young stellar objects within a projected area of $0''.8 \times 0''.8$ (600×600 AU). If the physical depth of the region is similar to its projected size, the stellar density is 1.6×10^8 stars per cubic pc. Another example of high stellar densities can be found in the θ^1 B Ori component of the Trapezium. This more evolved group is composed of five stars within about $1''$ of each other (Close et al. 2003), which at the distance of Orion corresponds to about

TABLE 1

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	8.0	344.0	303.2	458.4
4	−7.6	−328.0	293.6	440.0
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})	$V_{\rm TOT}$ (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

400 AU. Thus, the stellar density in this group is similar to that of the Cep A HW2 region. Therefore, the initial conditions of our simulations, several massive stars in a region with dimensions of a few hundred AU, are consistent with the observations of both the Cep A HW2 and the θ^1 B Ori groups.

Preliminary results of the the first 100 five-body cases fully confirm our earlier findings. We find that a sizable fraction of such compact configurations produces one or more escapers with large velocities (greater than about 30 km s^{-1}), ie., runaway stars, after only about 2 crossing times. The positive energy carried away by the high velocity escapers is compensated by the formation of a tight binary or multiple. In over 70% of the cases the binary was composed of the two most massive stars. To illustrate the dynamical evolution of such compact multiple systems we plot in Figures 2 and 3 final positions and velocities (after 2.2 crossing times, corresponding to about 650 years) for two five-body examples. The similarity of these examples to the observed configuration of the BN system (Figure 1; see also Figure 3 in Gómez et al. 2005) is evident, provided the uncertainties in the proper motions and in the estimated masses are taken into account. Tables 1 and 2 list the initial conditions for both cases.

Of course, these simulations are just an illustration of the physical process, and explore a very small range of the possible parameters. A forthcoming paper will present results of many more N-body realizations of several variants of the initial configurations. We emphasize that the initial conditions we chose were not the result of "integrating backwards in time" the observed positions and velocities of BN,

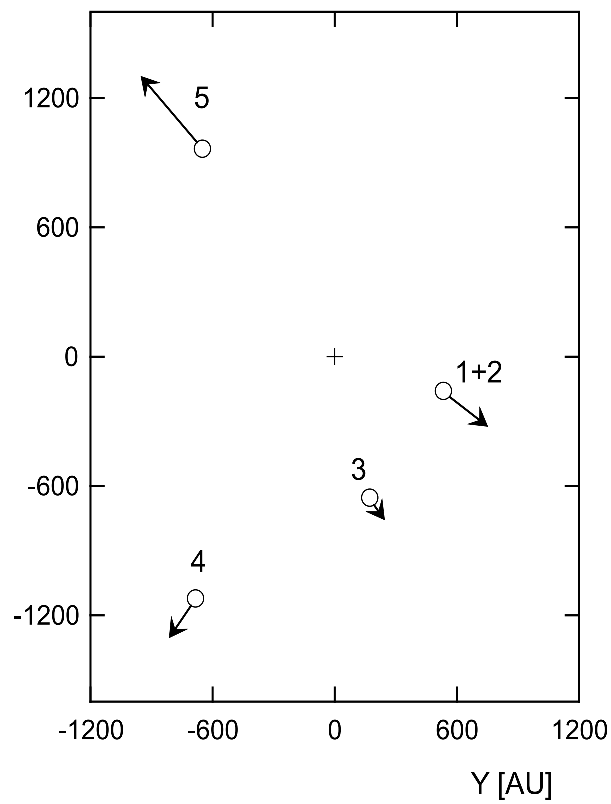

Fig. 3. Example 99. Similar to Figure 2, but on the plane YZ. In this example, $Vyz(5) = 28.4$ km s^{-1}, $Vyz(1+2) = 18.7$km s^{-1}, $a(1+2) = 7.6$ AU, $E(1+2) = -3 \times 10^{47}$ ergs, and the total kinetic energy of stars 3, 4 and 5 plus that of the center of mass of the binary $(1+2)$ is 2.6×10^{47} ergs. The runaway star (star 5) has reached a projected distance of 1163 AU from the center of mass, and the binary $(1+2)$, 563 AU.

TABLE 2

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})	$V_{\rm TOT}$ (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

I and n, but were taken to simulate very dense stellar systems, such as those observed in some small regions of massive star formation.

3. CONCLUSIONS

We confirm that close encounters among protostars in a non-virialized compact system can produce energy exchanges sufficiently large to eject stars with large velocities (runaway stars). The positive energy of the runaway stars is compensated by the binding energy of a binary or multiple. The system BN-I-n is an example of an initially very compact multiple ($R \leq 400$ AU) with a large number density ($n = 1 \times 10^8$ stars pc^{-3}), that is now observed to be in the process of dynamical disintegration.

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