BOLETÍN DE LOS OBSERVATORIOS DE TONANTZINTLA Y TACUBAYA, VOL. 4, N°28, 1967.

RUN-AWAY STARS AS THE RESULT OF THE GRAVITATIONAL COLLAPSE OF PROTO-STELLAR CLUSTERS.

A. Poveda, J. Ruiz and C. Allen

Abstract

Some of the difficulties in our present understanding of the origin of run-away stars and expanding clusters are briefly discussed; an alternative explanation for these phenomena is proposed here as the result of dynamical interactions during the collapse of small clusters of massive stars. The initial conditions of the collapse are discussed and justified in terms of current ideas on star formation, and the dynamical evolution of 54 cases of collapsing clusters (containing 5 and 6 stars) is followed numerically. Out of these 54 cases a total of 38 run-away stars were formed with velocities larger than 35 km/sec and up to 185 km/sec with percentages of production that go as high as 15% of the stars involved in different clusters. Approximately one half of the run-away stars are produced together with a second star having positive energy and running in opposite direction. Twelve clusters ejected at least one half of their stars with positive energy.

Sumario

Se discuten brevemente algunas de las dificultades que actualmente se tienen para explicar el origen de las estrellas desbocadas y de los cúmulos en expansión. Se propone una explicación alternativa para estos fenómenos, como resultado de las interacciones dinámicas durante el colapso de cúmulos pequeños de estrellas masivas. Las condiciones iniciales para el colapso se discuten y se justifican con base en las ideas actuales acerca de la formación de las estrellas. Se ha calculado numéricamente la evolución dinámica de 54 cúmulos en colapso. De estos 54 cúmulos se formaron un total de 38 estrellas desbocadas con velocidades mayores de 35 km/seg. y hasta de 185 km/seg. El porcentaje de desbocadas respecto al número total de estrellas en los diversos cúmulos llega al 15%. Aproximadamente la mitad de las desbocadas se produjeron acompañadas por otra estrella con energía positiva escapándose en dirección opuesta. En doce cúmulos la mitad (o más) de las estrellas se fugaron con energía positiva.

It is known for many years that clusters of young massive stars are frequently in expansion and that occasionally some of their motions are rather violent, as it is the case of the OB stars that "run away" from young clusters and associations with speeds which range from 30 – 40 km/sec up to 190 km/sec. A very impressive example of a cluster expanding with a small time scale is the Trapezium in the Orion nebula (θ^1 Orionis) for which Parenago (1953) found an age of expansion of 10,000 years. Also from Orion we have a fine example of 3 run-away stars: AE Aurigae, μ Columbae and 53 Arietis of which the first two "run away" in almost opposite directions from a point very close to the Orion nebula (Blaauw and Morgan, 1954) while 53 Arietis seems to have been produced again in Orion but in a different event.

The explanations that have been proposed for these phenomena rest basically on some explosive event. Thus, for instance Ambartzumian (1955) has suggested that prestellar matter at nuclear densities may become unstable leading to the formation of expanding clusters; run-away stars would be related also to the instability of prestellar matter. On a different vein, Blaauw (1961) and Zwicky think that the rapid ejection of matter by the primary component of a massive double star can release the secondary with velocities in the range needed to explain the run aways. In Blaauw's model the explosive event is identified with a supernova of type II, which would have to eject more than 100 $M_\odot$.

As Blaauw has pointed out, if young stars and nebulae are the result of the instabilities of dense prestellar bodies, the former should not show a concentration towards the galactic plane. Such a concentration is the result of gas dynamics, which does not hold for dense prestellar bodies. In fact young stars and nebulae should, then, be distributed more like population II. On the other hand the supernova theory, clearly, cannot explain the expanding motions of the θ^1 Orionis stars, for there is no evidence of such a young SN remnant inside the Orion nebula. Furthermore the spectroscopic and photometric behavior of supernovae of type II at maximum light —and the energy content of their remnants— do not support such large mass ejections (Poveda, 1964).

In view of the above difficulties we have attempted to give an alternative explanation to the run away stars and the expanding clusters by showing that they may originate as the result of dynamical interactions during the collapse of small clusters of massive stars. In this note we want to report some preliminary results of our computations, leaving for a forthcoming paper a more extensive and detailed discussion on the whole problem.

The point of departure, in our model, corresponds to Pottasch's most pointed bright rims (class 4) and Bok's densest G-globules for which Pottasch (1962) has estimated the number density in the non-ionized part as $n = 1.8 \times 10^6$ atoms/cm^3; for a radius of curvature of 2.5×10^4 A.U. their masses are about 400 $M_\odot$. At a temperature of 100 °K it can readily be verified that $2T + \Omega \ll 0$ (T: kinetic energy, Ω: potential energy) and hence such structures, as Pottasch himself has remarked, must be in rapid gravitational contraction. The dense G-globules should be contracting at constant temperature since their cooling rates, that go as n^2, are capable of removing all the heat that is released by the gravitational contraction (Cameron, 1965); in fact, what might have started as a gentle contraction will accelerate to the point of nearly free fall collapse. This situation will proceed until the globule becomes opaque to its own radiation. At this moment the energy released by the contraction is not lost so readily to the interstellar space but rather it is stored as heat; this builds up a pressure which in turn halts the collapse. From Hayashi's (1965) results one can estimate that the radius at which such a G-cloud becomes opaque to it own radiation is 2,000 A.U. At this radius the G-cloud will probably be again in gentle contraction in view of the increased contribution of the magnetic pressure and the angular momentum which also oppose the collapse.

In the second stage, at which this cloud has become opaque to its own radiation and is characterized by a radius of 2,000 A.U., the density ($n \simeq 3.6 \times 10^9/\text{cm}^3$) is so high that conditions are most favorable for fragmentation into individual proto-stars. The first proto-stars to be formed are the most massive ones; in fact, fragments with a radius of 1,000 A.U. and a mass of 50 $M_\odot$ give $2T + \Omega \leq 0$ (taking for the total kinetic and magnetic energies twice the thermal energy corresponding to 100 °K). One can fit approximately up to 6 such proto-stars inside a G-globule with $r = 2{,}000$ A.U. and if no further fragmentation takes place these pieces will evolve into O-type stars.

The second stage suggests that, if the fragmentation results only in a few massive proto-stars, these, upon further collapse, will disconnect themselves from the rest of the cloud and will begin to move like independent bodies following orbits in the cluster's field of force. For the purpose of describing the further dynamical evolution of such a star cluster we have performed the numerical integration of several idealized n-body problems ($n = 5{,}6$) with initial conditions as suggested by the last stage previously described. The initial conditions have been taken as follows:

i) As suggested by the geometry of the fragmentation mentioned above, we take the centers of mass of the proto-stars in symmetric configurations; for instance, if we have 4 proto-stars we take their centers of mass at the vertices of a regular tetrahedron and so that their distances to the center of mass of the cluster are 1,000 A.U. If we have 6 proto-stars we put them by pairs on each one of the axes of a cartesian system placing them symetrically with respect to the origin and again at a distance of 1,000 A.U. from the center of the configuration.

ii) The initial velocities are taken at random, with each one of the components having the same probability within $\pm\, v$; cases were considered with $\sqrt{3}\, v = 1$ km/sec, 0.5 km/sec and 0.1 km/sec.
iii) The masses of the particles are all the same and equal to 50 $M_\odot$; cases of 5 and 6 particles have been treated.

The hypothesis that small clusters of massive stars may begin within volumes of 2,000 A.U. radius is supported by the system θ^1 Orionis, which at the present time has 6 stars ($M \approx 100\ M_\odot$) within a sphere with a radius of 5,000 A.U.; it is quite easy to extrapolate backward and to imagine that some 6,000 years ago this expanding cluster was within a radius of 2,000 A.U. Furthermore the magnitudes of the initial velocities are consistent with a) the speed of sound at 100 °K, b) the velocity dispersion in HI regions and c) the velocity dispersion of stars in galactic clusters. In the Pleiades for instance $\sigma_v = 0.8$ km/sec (Limber, 1962).

The problem of numerical integration of the equations of motion follows von Hoerner's (1960) pioneer discussion, with the following changes relevant to the present problem: von Hoerner's time step τ is taken here equal to $\frac{1}{8}\left(\frac{v_i}{a_i}\right)_{\min}$ where v_i and a_i are respectively the velocity and the acceleration of the i[th] star; the index min means that we take the smallest ratio among the n stars; for the micro interval $\Delta t = \tau/\mu$ we take $\mu = 7$. In order to check the accuracy and the stability of the computations, some cases have been repeated with $\tau = \frac{1}{16}\left(\frac{v_i}{a_i}\right)_{\min}$ and $\mu = 14$. Experience has shown that the total energy E is the most sensitive parameter to the growth of the errors; most of our cases had errors $\frac{\Delta E}{E} < 2 \times 10^{-3}$. All the computations were performed at the computing center of the National University of Mexico with a Bendix G-20.

The initial conditions described before lead to a collapse of the proto cluster yielding close encounters and strong dynamical interactions; on occasions the encounters are closer than 4 A.U. and frequently the time steps Δt of integration are shorter than a day. Every 500 years and sometimes more frequently, we printed the results for each star, i.e. the position, the velocity and the energy.

When a star acquired positive energy with a velocity larger than 35 km/sec and at a distance –from the center of mass– larger than 8,000 A. U., we stopped the computation of the case and called the star a "run-away"; such a star will continue to move outwards practically undisturbed by the rest of the cluster, making useless any further numerical integration.

Table 1

Initial Coordinates (A.U.)

	x	y	z	*Distance to Center of Mass*
1:	–333.15	577.35	–225.17	695.00
2:	–333.15	–577.35	–225.17	695.00
3:	667.50	000.00	–225.17	705.00
4:	– 0.60	000.00	000.00	0.60
5:	– 0.60	000.00	675.50	676.00

Initial Velocities (km/sec)

	v_x	v_y	v_z	v
1:	–0.0367	–0.0506	–0.0619	0.088
2:	–0.2755	0.1739	–0.1978	0.381
3:	0.0090	–0.0139	0.1769	0.178
4:	0.0884	–0.1710	0.2715	0.324
5:	0.2148	0.0607	0.1651	0.278

Initial Energies

1: -1.8045×10^{47} ergs
2: -1.8038×10^{47} ,,
3: -1.8022×10^{47} ,,
4: -2.5605×10^{47} ergs
5: –1:8536 $\times 10^{47}$,,

Total initial energy of the cluster: -4.9115×10^{47} *ergs.*

Final Coordinates (A.U.)

	x	y	z	*Distance to Center of Mass*
1:	1975.71	700.55	–804.28	2245.22
2:	1977.10	687.08	–804.44	2242.36
3:	–7153.98	–2412.30	2661.94	8005.30
4:	1879.24	634.12	–753.22	2121.56
5:	1321.91	390.54	–300.02	1410.67

Final Velocities (km/sec)

	v_x	v_y	v_z	v
1:	5.9651	20.3611	–2.2456	21.3355
2:	26.0747	–12.9262	9.0864	30.4884
3:	–61.9877	–20.8940	23.1072	69.3755
4:	9.3144	6.2195	–23.0817	25.6555
5:	20.6335	7.2395	–6.8662	22.9194

Final Energies

1: -34.704×10^{47} ergs
2: -32.483×10^{47} ,,
3: 23.910×10^{47} ,,
4: -4.46941×10^{47} ergs
5: 0.98023×10^{47} ,,

Total final energy of the cluster: -4.9122×10^{47} ergs.

We have computed some 18 cases of 5 stars and 36 cases of 6 stars. From the results of the computations it appears rather easy to produce run-away stars through the collapse of a small cluster. Certainly the behavior of these collapsing clusters should be quite different from that of quasi-sta-

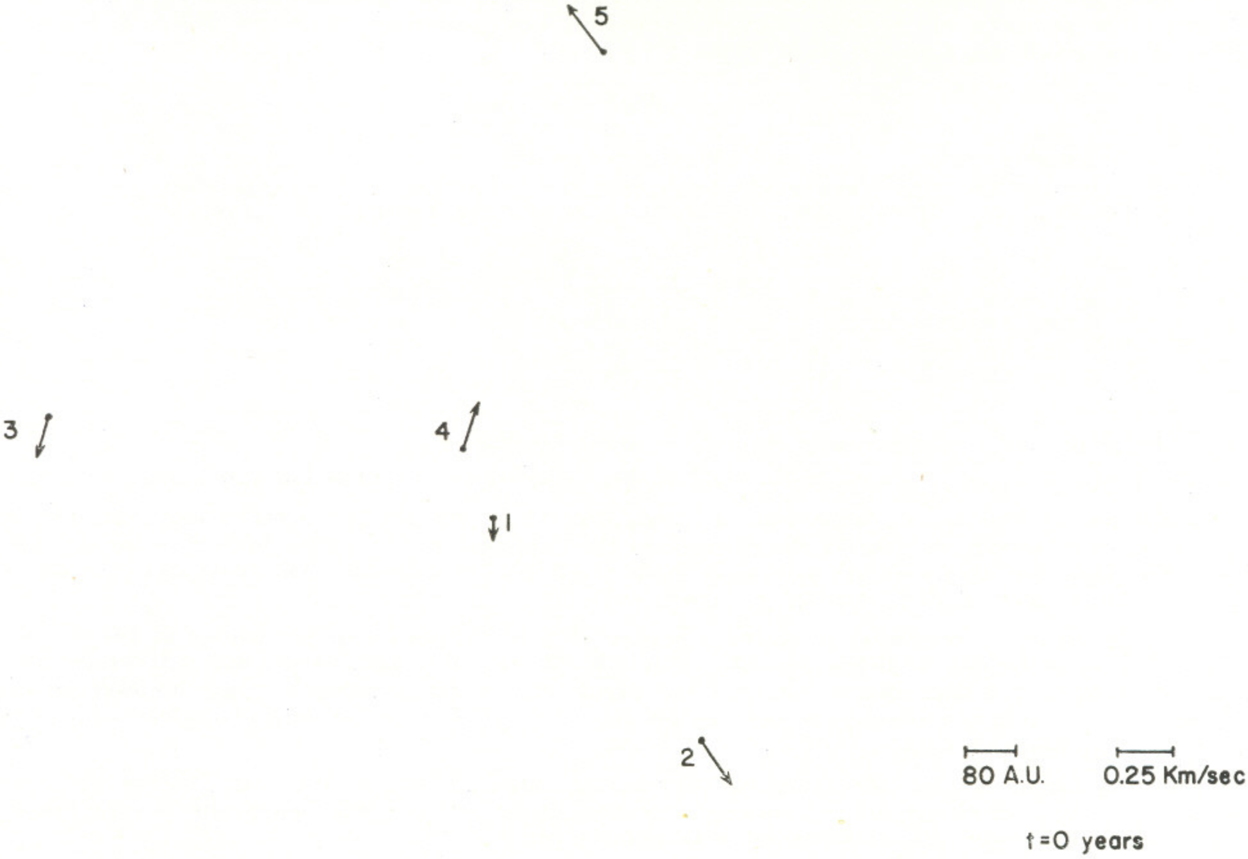

Fig. 1.—*Initial positions and velocities of the stars from Table 1, projected on the plane defined by the velocity vectors of the run-away star and its opposite. Star 4 is at the center of mass of the cluster.*

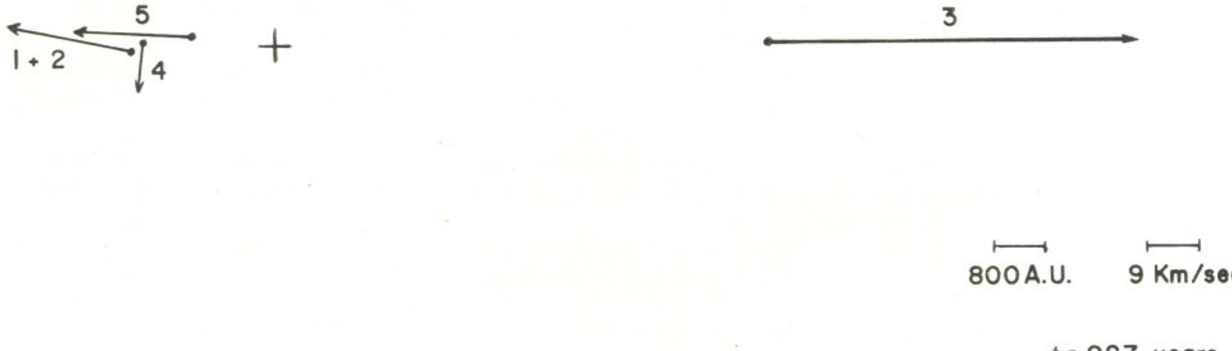

Fig. 2.—*Positions and velocities of the same stars projected on the same plane after 927 years. Stars number 1 and 2 form a close pair for which only the position and velocity of the center of mass is shown. The cross shows the position of the center of mass of the cluster. The system formed by stars 1, 2, and 4 is bound and escapes with a velocity of 15.5 km/sec.*

tionary clusters and, in fact, the frequency of high velocity ejections compared to the classical "evaporation" clearly confirms the expectation. Out of these 54 cases we have found 38 run away stars, of which one was expelled with a velocity as high as 185 km/sec.

A typical case of 5 stars is shown in Table 1 where the initial positions and velocities are listed, as well as the positions and velocities after 927 years; this case is shown in projection in figures 1 and 2. The general results are summarized in Table 2.

Table 2

Number of stars per cluster and initial velocities	*Number of clusters*	*Number of run away stars and their percentages*	*Number of stars running opposite*	*Number of expanding clusters*
5 (0.5 km/sec)	9	7 (15.3%)	3	1
5 (1.0 km/sec)	9	1 (2.0%)	0	1
6 (0.1 km/sec)	1	1 (17.0%)	0	0
6 (0.5 km/sec)	21	18 (13.0%)	9	6
6 (1.0 km/sec)	14	11 (13.1%)	6	4

From the study of the results the following can be stated:

a) Low initial velocities —as expected— yield higher percentages of run-aways, and higher velocities.

b) About one half of the run-away stars are accompanied by another star ejected approximately in the opposite direction; in general the velocity of the "opposite star" is large, but below the 35 km/sec limit. However, there are several cases where the 2 stars that are ejected in opposite directions have velocities larger than 35 km/sec.

c) The percentage of run-aways produced is up to 15% of the stars that participate in the various clusters. This percentage is below the 20% found by Blaauw for the O stars and still lower than the 25% found by Vitrichenko, Gershberg, and Metik (1965); our percentage could however be increased by taking larger masses, for instance 70 $M_{\odot}$, which is the average mass of the run-away stars of type O in Blaauw's list.

d) We have found 12 cases of expanding clusters, i.e. clusters where at least one half of the stars acquire positive and escape. Several clusters were found where, after the collapse, only a close binary was left and the remaining stars escaped with positive energy.

e) The time scale of the event is very brief; since the run aways are produced around the minimum radius of the cluster, the important events occur around 500 years after the beginning. The qualitative behavior of the cluster is stabilized after 2,000 - 3,000 years.

f) Most of the run aways produced are single stars, which is also consistent with Blaauw's findings.

g) It is interesting to realize that we start with a cluster having a total negative energy and that this energy is conserved (within $2-3 \times 10^{-3}$); however, the energies of the individual stars which also start being negative vary enormously. Obviously the positive energies of the ejected stars are compensated by the negative energies of the close pairs that are formed.

The results presented here suggest that a single mechanism inspired by current ideas on stellar formation may explain most of the run away stars, expanding clusters, as well as a sizable fraction of the close pairs with separations in the range of a few astronomical units.

We are very pleased to acknowledge the unusual facilities granted to us by Mr. S. F. Beltrán, director of the Computing Center, as well as by various members of its personnel, particularly Messrs. R. Castañeda, A. Carrillo and U. Beltrán.

REFERENCES

Ambartzumian, V. A., 1955. The Observatory **75**, 72.
Blaauw, A., 1961. B. A. N. **15**, 265.
Blaauw, A., and Morgan, W. W. 1964. Ap. J. **119**, 625.
Cameron, A. G. W., 1965. in W. Hess Introduction to Space, Science p. 553. Gordon and Breach.
Hayashi, C., 1966. In Annual Review of Astronomy and Astrophysics, **4**, 171.
Limber, N., 1962. Ap. J. **135**, 16.
Parenago, P. P., 1953. Astr. J. USSR, **30**, 249.
Pottasch, S. R. 1962 in L. Woltjer Interstellar Matter in Galaxies p. 205. Benjamin.
Poveda, A., 1964. Ann. d' Astro. **27**, 522.
Vitrichenko, E. A., Gershberg, R. E. and Metik, C. P., 1965. Izv. Krymsk., Astrofiz. Obs., **34**, 193.
von Hoerner, S. 1960. Zeit. fur Astro., **50**, 184.