RevMexAA (Serie de Conferencias), **39**, 21–25 (2011)

OVERVIEW AND CURRENT RELEVANCE OF "RUN-AWAY STARS AS THE RESULT OF THE GRAVITATIONAL COLLAPSE OF PROTO-STELLAR CLUSTERS" BY POVEDA, RUIZ, & ALLEN (1967)

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RESUMEN

Se describe brevemente el mecanismo para producir estrellas desbocadas masivas propuesto por A. Poveda, J. Ruiz y C. Allen, 1967, BOTT, 4, 28, 86. Se reseña su impacto a través de los años desde su publicación, y su gradual aceptación como una manera viable de generar desbocadas. Se evalúa su relevancia a la luz del conocimiento moderno sobre dichas estrellas.

ABSTRACT

The mechanism for producing massive runaway stars proposed by A. Poveda, J. Ruiz and C. Allen, 1967, BOTT, 4, 28, 86, is briefly described. Its impact over the years and its gradual acceptance as a viable way to account for such stars are traced. Its current relevance for the understanding of runaway stars is assessed.

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

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Ed. S. Torres-Peimbert & O. López-Cruz

1. INTRODUCTION

It is only on rare occasions that one is able to cast a retrospective view on research that was conducted more than 40 years ago. It is valuable to be able to assess old results in view of more recent developments. I am grateful to the organizers of this Meeting for providing such an opportunity. I shall review the paper "Run-away stars as the result of the gravitational collapse of proto-stellar clusters", by A. Poveda, J. Ruiz and C. Allen, published in 1967, but on which we started to work around 1965.

The class of young massive high velocity stars was first characterized by Blaauw & Morgan in 1954. The best known runaway stars, AE Aurigae and μ Columbae, "run away" from the Orion Nebula region in opposite directions, with space velocities of about 100 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 a result of the rupture of a massive close binary, when 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).

As was pointed out by several authors (Poveda et al. 1967; Gies & Bolton 1986) there are some problems with the supernova mechanism. One is that the masses ejected by Type II supernovae are much smaller than those required by Blaauw's mechanism, and thus these events could not eject massive RAS. Another is that supernova remnants are not frequent among clusters known to have generated runaway stars. The three best known runaway stars, AE Aurigae, μ Columbae and 63 Arietis, are associated to the Orion Cluster, where no supernova remnant is found.

Poveda et al. (1967) proposed an alternative model to explain the acceleration of RAS. 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. We performed a number of N-body simulation with initial conditions ensuring the collapse of the configuration ($2T + \Omega \ll 0$), and found that very close encounters among three or more stars occurred. These encounters produced strong accelerations, and resulted in the ejection of stars with large velocities. We obtained a fraction of about 20% of runaway stars, with velocities of up to 180 km s^{-1}.

For a few years after publication our paper was practically ignored. Then, slowly, dynamical ejection from clusters began to be considered a viable alter-

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native to supernova ejection. In more recent times, it has become clear that, indeed, both mechanisms are at work. Two fortunate circumstances have made possible the persistence of our old results: the initial conditions (symmetric positions, non-virialized velocities, both of which propitiate very close encounters) and the fact that the dynamical disintegration occurs very rapidly, before numerical errors (prevalent in the early N-body computations) had time to render our results unreliable.

2. EARLY WORK ON RUNAWAY STARS

Cruz-González et al. (1974), as a by-product of their work on the ionization of HII regions, provided the next list of runaway candidates, comprising 72 O stars. Among them, they found that only 2% were binaries (spectroscopic or visual), whereas among their total sample of galactic O stars, 12% showed signs of multiplicity. They pointed out that even a few double or multiple runaway stars would pose a serious problem to the then known mechanisms of formation (supernovae or cluster ejection).

A very interesting paper on high velocity pulsars was published in 1975 by Harrison & Tademaru. They investigated high velocity pulsars and runaway stars. They pointed out several deficiencies of Blaauw's mechanism and proposed that the cluster ejection mechanism was the more likely alternative, except for the highest velocity pulsars and runaway stars. This paper was thus the first to refer to our mechanism as a viable alternative to produce runaway stars.

A few years later, Carrasco et al. (1980) proposed that many runaways –if not all– are in reality misclassified evolved old disk stars with absolute magnitudes about 2.7 mag fainter than OB stars, and hence smaller distances and velocities. Carrasco et al.'s paper served as a useful reminder of the need to be cautious when interpreting stellar spectra, but upon closer study most of the original runaway stars –and many new ones– proved to be *bona fide* high velocity, early-type, stars.

Then, in 1981, Isserstedt & Feitzinger studied the radial velocity distribution of the single O stars of the Cruz-González et al. catalog. Although the radial velocity data were compatible with both the cluster and the supernova ejection mechanisms, they found, from age considerations, that the available data favored the cluster ejection model. Regarding Carrasco et al.'s idea, they pointed out that it did not explain the most salient characteristics of runaways, namely their single status and their provenance from known OB associations, which are confined to the galactic plane. This was another instance of our work being recognized as a plausible mechanism to produce runaway stars.

Some years later, in 1986, Gies & Bolton studied the radial velocities of bright northern OB stars. They found very few evolved stars among them. Also, they detected among them neither chemical peculiarities nor collapsed companions. Thus, they could reject both the supernova and the evolved star hypotheses to explain runaway stars. They adopted dynamical ejection as the most plausible alternative and found that it could produce velocities of up to 200 km s^{-1}. (the highest velocity we found among our RAS was 180 km s^{-1}.).

In 1988, Leonard & Duncan studied and rejected both the supernova ejection and the evolved star hypotheses to explain runaway stars. They adopted the dynamical ejection model and performed N-body simulations (with clusters of 30 to 480 stars in dynamical equilibrium), but considering an initial binary fraction of 50%. They showed that runaways can be produced in low density OB clusters of about 1 pc radius, but only when a relatively large fraction of initial binaries is present. In their simulations, runaway stars are produced mostly by binary-binary interactions. However, since such interactions are rare, the fraction of runaway stars they found was low. Another interesting result of their paper was that in order to avoid physical collisions a maximum ejection velocity of about 200 km s^{-1} was obtained.

The origin of runaway stars was re-examined by Stone (1991) who, based on the observed (but very uncertain) frequency of O runaways, concluded that a supernova ejection was the most probable mechanism. He also found that most O-type RAS are not under-luminous. From observations for the B-type RAS he found, however, that both dynamical ejection and ejection by a supernova were feasible. He found an observed space frequency of 46% for the O runaways, and 4% for the B runaways. The dynamical ejection model produces a frequency of about 15%. It is interesting to point out that very 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).

Throughout the years, both the supernova and the cluster ejection mechanisms for producing RAS have been hotly debated in the literature. The possibility that most runaways are misclassified hot stars is no longer considered to be supported by observations. Already Gies & Bolton (1986), in their exhaustive investigation, and more recently Hoogerwerf, de Bruijne, & de Zeeuw (2001) in a rather de-

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tailed discussion, arrived at the conclusion that the runaway star phenomenon is real, and that the two main mechanisms are at work in the galaxy.

From about 1990 on, research on runaway stars has focused mainly on three topics: OB stars in the galactic halo, hypervelocity stars (hyper-runaways), and "classical" runaways. In the next sections I will discuss these topics in turn.

3. OB STARS IN THE GALACTIC HALO

Many authors (Conlon et al. 1989, 1990, 1992; Ringwald et al. 1998; Martin 2006; Silva & Napiwovski 2011, etc.) have found young, apparently normal, OB stars at large distances from the galactic plane, far from any region of star formation. Subsequent determinations of accurate surface gravities and colors, detailed chemical abundances (not only of the CNO group, but also of heavier elements, notably Al and Fe) and of rotational velocities have shown that the majority of such stars are indeed normal, young, OB stars. The problem thus arises: how do these stars reach such large distances from their formation places within their short lifetimes?

In a detailed study, Tobin (1991) reviewed 11 possible explanations for normal OB stars found far from the galactic plane. He concluded that most of them formed in the plane and were dynamically ejected. However, he found a few that could not be explained in this way, thus raising the intriguing possibility of star formation at large distances from the galactic plane.

A few years later, Leonard (1993) studied mechanisms for ejecting stars from the galactic plane. After evaluating once again the supernova versus the cluster ejection mechanisms (studying the velocities of the ejected objects, the properties and frequency of binaries among them, etc.) he concluded that the cluster ejection mechanism was the most likely to account for runaway stars, including those in the halo.

The problem was taken up again by Allen & Kinman (2004). We discussed two possible explanations for normal OB stars far from the galactic plane: ejection from the plane as the result of dynamical evolution of small clusters (Poveda et al. 1967) and cluster formation above the plane, via induced shocks created by spiral density waves (Martos et al. 1999) followed by dynamical ejection. Instead of supposing vertical trajectories, as had until then been done, we computed backward galactic orbits for 32 such stars, and identified those that could be explained by one or the other mechanism. We found that about 90 percent of the stars could be accounted for by the cluster ejection mechanism, that is, they can be regarded as runaway stars in the galactic halo.

4. HYPERVELOCITY STARS (HYPER-RUNAWAYS) AND HIGH VELOCITY RUNAWAYS

Interest in runaway stars has experienced a vigorous revival since the recent discovery of the hypervelocity stars. The definition of hypervelocity stars varies, but in the current literature they are usually considered to be stars with radial velocities larger than the local escape velocity (but less than about 800 km s^{-1}). This is a topic of lively research, so any numbers here given will be quickly obsolete, but about 17 unbound stars are now known in our Galaxy (Brown et al. 2005, 2007, 2009; Hirsch et al. 2005; Edelmann et al. 2005; Heber et al. 2008, etc.). Most of these are B stars. Only two, HD 271791, and J0136+2425 have measured proper motions, and in both cases these motions imply an origin far from the galactic center, thus contradicting the currently accepted model for their origin (see below). Another star, HE 04375439 is found to be unlikely to originate in the galactic center because it is too young, and has a discrepant chemical composition.

Other (usually early-type) stars are known to have velocities larger than about 200–300 km s^{-1}. They are the so-called high-velocity runaway stars.

4.1. *Proposed mechanisms to generate hypervelocity stars*

Hills (1988) predicted that hypervelocity stars should be an inevitable consequence of the central black hole of the Galaxy. He proposed interactions with the massive black hole in the galactic center, in which the tidal breakup of a tight binary would accelerate one component beyond the galactic escape velocity. Since then, many mechanisms and variants of the Hills model have been proposed (Yu & Tremaine 2003; Bromley et al. 2006; Gualandris et al. 2005; Gvaramadze et al. 2009, among others). These mechanisms can satisfactorily account for some of the hypervelocity stars. But: as mentioned before, at least HD 271791, J0136+2425, and possibly HE 04375439 did not originate in the galactic center, so this means that several mechanisms must be at work to produce hypervelocity stars.

As an example of an alternative formation mechanism, Gvaramadze et al. (2009) studied gravitational interactions in young clusters, some with very massive ($m > 200\ M_\odot$) binaries. This mechanism can eject B stars with velocities of 200–400 km s^{-1}, and thus can account for the high velocity RAS. They also found that 3–4 $M_\odot$ stars could attain velocities of up to 400 km s^{-1} and occasionally a few can even exceed the local escape velocity.

5. RECENT WORK ON "CLASSICAL" RUNAWAY STARS

Work on "classical" runaway stars has continued in recent years. For instance, Kiseleva et al. (1998) performed many numerical integrations of clusters of 3 to 10 stars, without initial binaries, taking random initial positions and initial velocities from 0.0 to 0.4 km s^{-1}. They find a very low rate of formation of runaway stars, only about 1%. This is a result of the initial conditions they assume for their clusters.

On the other hand, Vanbeveren et al. (2009) combined an N-body code with a massive stellar evolution code. They followed in detail the formation of very massive star by "runaway mergers" in the cores of dense clusters. They found that black holes with masses of up to 70–100 $M_{\odot}$ could be formed, depending on the metallicity. In this context, both supernova ejection and cluster ejection are relevant for the production of runaways.

A different approach has been taken by Hoogerwerf et al. (2001), who obtained an updated sample of RAS using *Hipparcos* data; they 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 enabled them to specifically determine the formation scenario for two cases: ζ Ophiuchi and the pulsar PSR J1932-1059 originated about 1 million years ago in a supernova explosion occurring in a binary star, whereas AE Aurigae, μ Columbae and the binary ι Orionis occupied a very small volume about 2.5 million years ago, and were ejected from the nascent Trapezium cluster. At least 21 additional runaway stars could be linked to nearby associations and young clusters, among them 53 Arietis, ξ Persei and λ Cephei. This study convincingly showed that both the binary ejection and the cluster ejection mechanisms are at work to produce RAS.

Our group has also been active in the study of extremely young RAS. From archival VLA data of the BN/KL region going back to 1991, Rodríguez et al. (2005) found that the objects designated as BN and I have anti-parallel proper motions, with corresponding velocities of 27 and 12 km s^{-1} respectively. We interpreted these motions as due to the dynamical decay of an extremely young multiple system, that is, by the dynamical ejection mechanism proposed by us long ago (Poveda et al. 1967).

Somewhat later, Gómez et al. (2005) were able to measure proper motions of 35 sources in the Orion Trapezium region and in the BN/KL region, and found that the radio counterpart of infrared source n also has a large proper motion, corresponding to a velocity of $v = 24$ km s^{-1} (see Figure 3 in their paper). All three objects appear to be moving away from a common point where they were situated some 500 years ago. This suggests that these objects were located within a few arcsec from each other about 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. To verify this interpretation we performed numerical simulations of 100 cases of 5 bodies, using the code developed by Mikkola & 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 $r \approx 400$ AU, assigning to them random velocities with a $\sigma(v) \approx 0.4$ km s^{-1}, which corresponds to the thermal velocity in a molecular cloud at $T = 10$ K. The integrations were stopped after only about 2.2 crossing times, corresponding to 650 years. The observed configuration and velocities of the system BN-I-n were well reproduced.

We confirmed that close encounters ($r < 1$ AU) among proto-stars in a non-virialized compact system can produce energy exchanges sufficiently large to eject stars with large velocities. The positive energy of the RAS is compensated by the binding energy of a binary or multiple star (with a typical major semiaxis of 17 AU). The system BN-I-n is thus an example of an initially very compact multiple ($r \leq 400$ AU) with a large density ($n \approx 1 \times 10^8$ 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 which now has a comparable stellar density.

However, a problem soon became apparent: the ages of stars BN-I-n, although 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 of 400 AU radius and with masses $M(1) = M(2) = 16\ M_{\odot}$, $M(3) = M(4) = M(5) = M(6) = 8\ M_{\odot}$, $M(7) = 20\ M_{\odot}$ assigning to them random velocities with a $\sigma(v) \approx 1.0$ km s^{-1}, and 100 additional cases of 7 bodies, but now situated in a filamentary configuration of similar dimensions. We carried out the integrations for 2, 10, and 100 crossing times.

The new integrations imply that the Orion region has been in the past a veritable "factory" of runaway

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stars, and that the system BN-I-n is only the most recent example. The sub-trapezium Θ^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 seven body systems keep ejecting runaway stars for up to 100 crossing times (Allen & Poveda, in preparation). This multi-generation process of violent relaxation may take more than 10,000 years. This suggests that BN-I-n are not necessarily first-generation runaway stars. In fact, they may be about 10 000 years old, which is a more realistic age for these stars. 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).

6. CONCLUDING REMARKS

The dynamical origin for runaway stars proposed more than 40 years ago by Poveda et al. has proved to be a remarkably durable model whose usefulness persists until the present day. Variants of the model have been proposed, and successfully account for, phenomena like hypervelocity stars and young stars in the galactic halo, which were unkown back in 1966, when the original model was published.

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