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THE ORIGIN OF MULTIPLE STARS BY CONDENSATION IN DENSE NEBULAE

(Invited Paper)

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RESUMEN

Se hace una breve reseña de las teorías clásicas para explicar el origen de las estrellas dobles, y de su relación con el origen de los sistemas múltiples. Se discuten las observaciones que recientemente se han hecho en el infrarrojo, enfatizado su importancia para el entendimiento del proceso de formación de las estrellas múltiples. Estas observaciones, junto con consideraciones dinámicas y datos estadísticos sobre trapecios y sistemas múltiples jerárquicos, apoyan la idea de que las estrellas múltiples, en general, se originan como trapecios, es decir, como condensaciones independientes.

ABSTRACT

The classical theories of double star formation are briefly reviewed in relation to the origin of multiple stars. Modern observations in the infrared are discussed and their relevance as clues to the process of multiple star formation is stressed. These observations, together with dynamical considerations and data on the statistics of trapezia and hierarchical multiple systems, support the view that multiple stars, in general, are born as trapezia, that is, as independent condensations.

I. INTRODUCTION

The problem of the origin of multiple stars cannot be studied separately from the general problem of star formation. The significant question seems to be whether the mechanism of condensation that produces single stars can also produce double and multiple stars. Since the origin of stars is not yet fully understood, even less so is the origin of groups of stars. However, a number of data related to this problem have been accumulating in recent years, and a general pattern is beginning to emerge. A new look at the problem of the origin of double and multiple stars seems to be in order.

We will begin by quickly reviewing the three traditional —and basic— mechanisms of formation of double and multiple stars: the capture theory, the fission theory and the theory of independent condensations.

The capture theory envisages double star formation by encounters involving three field stars; a binary is left and the third star carries off the excess energy. For triple-star formation, an encounter of four stars is needed, and so on. In an important paper, Ambartsumian (1937) showed convincingly that the capture theory cannot account for the observed frequency of double stars: the predicted equilibrium value comes out a factor of 10^8 to 10^9 smaller than the observed value. Also, the predicted eccentricities are in strong disagreement with the observed ones. It is even more difficult for the classical capture theory to account for the observed properties of multiple stars. In order for the capture theory to yield values for the frequency of binaries comparable to the observed ones, extremely artificial conditions are necessary, which are not likely to occur, or to have occurred in the past, in our Galaxy (Allen 1968). For these reasons, the classical capture theory has received very little attention in recent times.

The fission theory, although it is as old as the capture theory and beset by many problems, is still advocated by a number of workers. It is commonly accepted nowadays that the fission theory can account —at most— only for the close pairs (major semiaxes smaller than about 5 AU), because of the too large angular momentum of wider pairs. Some very recent work by Abt and Levy (1975) has provided strong observational evidence that close, and wide binaries are two distinct classes of objects, having different origins. The implication is that fission is responsible for the close pairs, the wide ones having formed by another process.

The classical fission theory was thought to apply to stars that were already formed, that already had, so to say, a well-defined identity. Recent work (Ostriker 1975) has dealt with the possibility of fission applying to very early stages of star formation, before the onset of the Hayashi phase. This is important for the understanding of Abt and Levy's subgroup of short period binaries.

The theory of independent condensations within a cloud, to which I will devote the remainder of this paper, also goes back a long way. Perhaps one of the earliest references to this theory is found in Laplace's *"Système du Monde"*. Laplace argued as follows:

"Such groups as the Pleiades are a necessary result of the condensation of nebulae with several nuclei, for it is plain that the nebulous matter being constantly attracted by these different nuclei must finally form a group of stars like the Pleiades. The condensation of nebulae with two nuclei will form stars in very close proximity, which will turn one around the other, similar to those double stars whose relative motions have already been determined".

This theory was, of course, not universally accepted; some very important objections were raised against it. This is well illustrated in the following quote of H. N. Russell (1910): "The alternative theory —that multiple stars have developed from nebulae which originally had well defined nuclei, corresponding to members of the system— must in any case be invoked to account for those wide and irregular groups (such as the Trapezium in Orion) for which the fission theory gives no explanation. But the arrangement in close and wide pairs, so characteristic of the large majority of multiple stars, is in this theory a positive difficulty. Not only is there no apparent reason for it, but if we try to retrace in imagination the history of such a system, through stages of greater and greater diffusion, as we penetrate farther into the past (keeping in mind that the moment of momentum of the whole system must remain constant) it is hard to form any idea of the history of the nuclei which finally form a close and rapidly revolving pair, attended by a distant companion".

The gist of Russell's argument continues to be valid today, and any theory of multiple star formation by independent condensations must answer this objection.

II. THE PROCESS OF STAR FORMATION

It has been generally accepted for many years that stars form out of the interstellar medium by a process of contraction. As predecessors of stars, dark dense globules have been proposed. Such globules have been observed by Bok *et al.* (1970) and Thackeray (1950). The smallest and densest of these globules have radii of about 1000 to 6000 AU. The densities of some globules with radii of about 2×10^4 AU have been estimated by Pottash (1962) to be about 1.8×10^6 cm^{-3}. This implies globule masses of 300 $\mathcal{M}_\odot$. Assuming their temperatures to be about 100°K, the virial theorem shows that these globules will be in rapid contraction; moreover, the contraction will proceed without greatly changing the temperature, since the opacity is low enough to enable radiation to freely escape (Poveda *et al.* 1967).

Taking Bok's globules as a starting point, one can envisage the following evolutionary sequence: the dense globule continues in rapid contraction until it becomes opaque to its own radiation. This happens when the radius reaches values around 2000 AU. At this moment, the globule may again be in quasi-equibrium but conditions are most favorable for fragmentation to occur; indeed, the virial theorem is satisfied for individual fragments of about 50 $\mathcal{M}_\odot$ each. If no further fragmentation occurs, these fragments will become O stars. Successive fragmentation will yield less masive stars.

This evolutionary sequence would imply that stars originate in groups, and that at early stages these groups are either trapezium-like systems —if composed of massive stars— or very compact clusters of less massive stars.

Whether the above sketch correctly represents the process by which stars originate, or whether some other mechanism is at work, one would expect, in any case, a recently formed star (or stellar group) to be still surrounded by its cocoon nebula. This cocoon nebula may obscure the star, either partially or totally, re-emitting the star's radiation at infrared wavelengths (Poveda 1965).

Several examples of young objects still associated with their cocoon nebulae (or with remainders thereof) are known. The best known case is a complex region of infrared sources near the Orion Trapezium, which has been recently studied by Becklin *et al.* (1974). It has been known for some years that the region is very rich in infrared and molecular sources. However, the above authors have succeeded in producing a high-resolution map of the region, at 20 microns (see Wynn-Williams *et al.* 1974, Figure 6). The most conspicuous features of their map are the folowing:

i) A source centered around component D of the Orion Trapezium (Ney-Allen or NA-source).

ii) Several other point sources situated north of θ^1 Orionis, less than 1′ away from it.

iii) Several OH and H_2O sources.

iv) A strong, point-like, infrared source (Becklin-Neugebauer or BN-object), with a luminosity of 10^4 $L_\odot$ and radius of about 7 AU; it has not been possible to identify this source with any star.

v) An infrared nebula (Kleinmann-Low or KL-nebula) located close to the BN-object and partially engulfing it, of a size comparable with that of the Orion Trapezium. Its luminosity is about 2×10^5 $L_\odot$, and its radius about 5000 AU.

We would like to suggest that an object like the KL-nebula is a very young trapezium —similar to θ^1 Orionis— still embedded in its cocoon nebula; with the passage of time the cocoon nebula will clear away and the trapezium will become visible. Note that one of the components of θ^1 Orionis, namely, component D, seems to have still some remains of a cocoon.

The spectral distribution of the infrared sources in Orion (Wynn-Williams and Becklin 1974) seems to confirm the above interpretation. The temperature turns out to be about 530°K for the BN point source and about 200°K for the KL-nebula. Absorption dips in the BN-object have been identified as ice and silicate features. Analogous features have been detected in the NA source, but in emission; this is hardly surprising since the NA is a more diluted object.

Low (1970) has estimated the mass of the KL-nebula as 200 $\mathcal{M}_\odot$, including dust and gas. This mass is similar to that of the Orion trapezium.

The above studies lend credibility to the evolutionary sequence previously proposed: a dark cloud, after several intermediate stages (Bok globule, KL-nebula, NA-nebula) will give as an end product a multiple star system of trapezium-type (Orion Trapezium). Incidentally, we note that if the KL-nebula were situated in front of the Orion Nebula, it would look like a compact Bok globule, since its visual extinction is estimated to be 350 magnitudes (Gillett and Forest 1973).

III. SUBSEQUENT EVOLUTION THROUGH DYNAMICAL INTERACTION

The next question that arises is: how does the further evolution of a trapezium-like system proceed? Note that, according to the above picture, all multiple systems originate as trapezia. But if this is the case, then Russell's objection must be answered, that is, we have to account for the existence of hierarchical multiples.

An important clue to this end is provided by the distribution of magnitudes of the components of hierarchical multiples. It was found by Wallenquist (1944) that in hierarchical triple systems the distant companion tends to be the faintest star. This result has been attributed to the presence of many optical companions among multiple systems (Heintz 1969). However, a recent study, which attempts to exclude optical companions, shows that the effect is still present (Allen *et al.* 1977). The same effect is very noticeable in the multiple stars contained in Finsen and Worley's (1970) catalogue of orbits. This implies that in a triple system the lightest star tends to be the most distant companion, which in turn suggests that stellar-dynamical effects have been at work.

With these points in mind, the dynamical evolution of trapezium systems was simulated numerically (Allen and Poveda 1974). Starting from initial conditions representative for the Orion Trapezium (total mass, $170\,\mathfrak{M}_\odot$, initial radius 5000 AU; distances of the same order of magnitude among components, and virialized velocities) a sample of 35 trapezium clusters was integrated numerically for 10^6 years (corresponding to about 30 crossing times).

As an example, Figure 1 shows the initial positions of the components of a trapezium, projected on the *xy* and *xz* planes. Figure 2 shows the final positions. Note the change of scale. In this example, the original trapezium evolved into a hierarchical quadruple system; a stable triple system was formed, in which the two massive stars form a tight binary, accompanied by a distant *light* star. A fourth star at a much greater distance is still bound to the system. This fourth star, whose distance from the others corresponds to more than 1 pc in the units we have used, would not be recognizable observationally as still belonging to the system. For all practical purposes, then, the original trapezium evolved into a stable, hierarchical triple system.

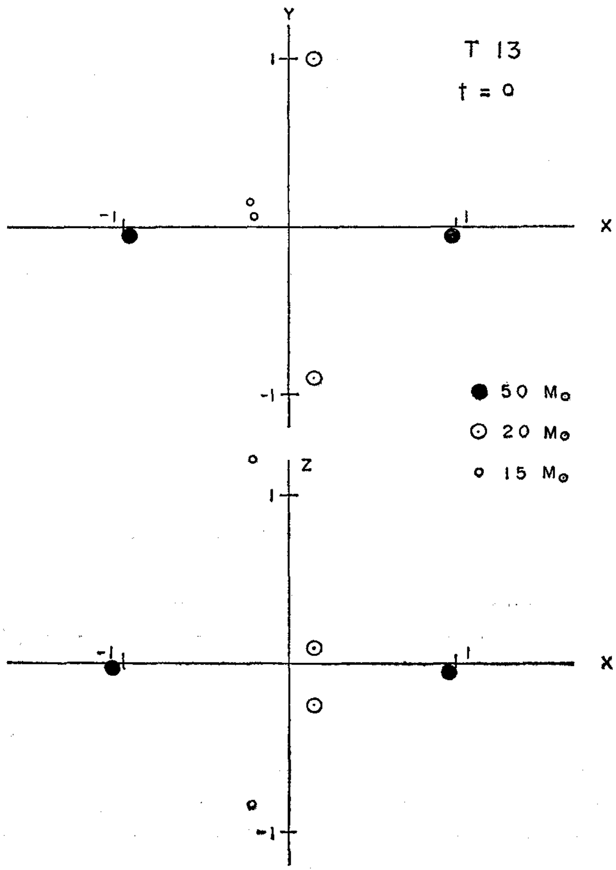

Fig. 1. Initial positions of the member stars of a trapezium, projected on the *xy*-plane and on the *xz*-plane. One distance unit corresponds to 5000 AU.

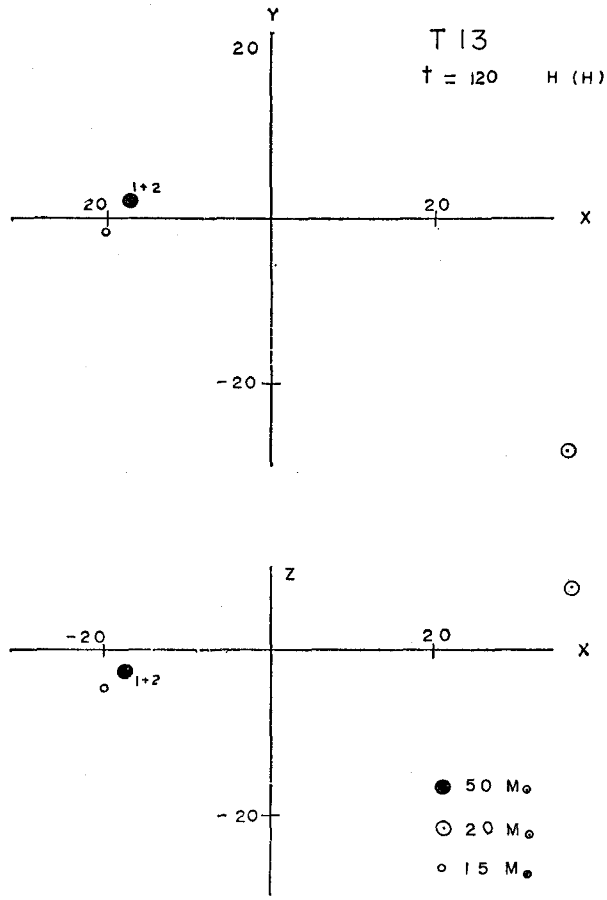

Fig. 2. Final positions of the member stars of the trapezium of Figure 1, after 10^6 years of dynamical evolution. One distance unit corresponds to 5000 AU.

Another example is shown in Figures 3 and 4. In this case, the trapezium transformed into a stable double-double system after 10^6 years of dynamical evolution.

Finally, Figures 5 and 6 show yet another case; this time the trapezium continued being a trapezium

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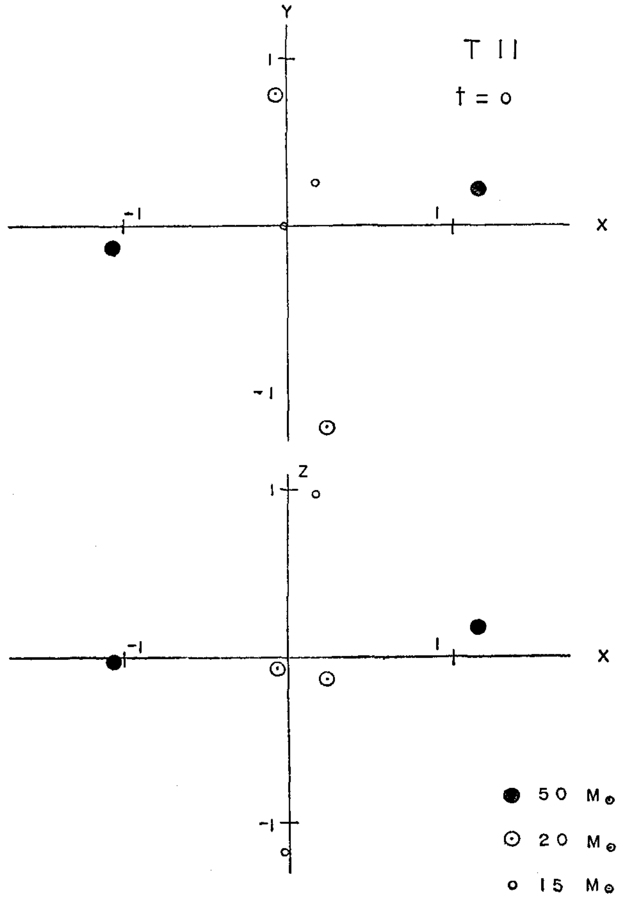

FIG. 3. Initial positions of the member stars of a trapezium, projected on the xy-plane and on the xz-plane. One distance unit corresponds to 5000 AU.

throughout the 10^6 years covered by the computations. In the 35 examples that were integrated, a strong tendency for the two most massive stars to join into a tight binary was found. From the results of this study it was possible to obtain a half-life for trapezia, that is, a time after which a population of trapezia reduces to $1/e$ of its initial value. For massive trapezia (composed of 2 stars of 50 $\mathfrak{M}_\odot$, 2 of 20 $\mathfrak{M}_\odot$ and 2 of 15 $\mathfrak{M}_\odot$ each, some with 10 stars of 1 $\mathfrak{M}_\odot$ each added) the half-lives are 8×10^5 years. Note that the half-lives scale as $\mathfrak{M}^{-1/2}$, so that the half-lives of trapezia composed of, say, two stars each of 2, 0.8 and 0.6 $\mathfrak{M}_\odot$, would be of the order of 4×10^6 years, everything else being equal. Thus, for massive trapezia the dynamical lifetimes are of the order of the nuclear lifetimes of their member stars. If a steady-state situation exists, this means that very few massive trapezia will be able to evolve into hierarchical multiples. On the other hand, *for less massive systems, the nuclear ages are much larger than the dynamical lifetimes*. This means that in a nuclear lifetime quite a few trapezia will become hierarchical systems, or will dissolve.

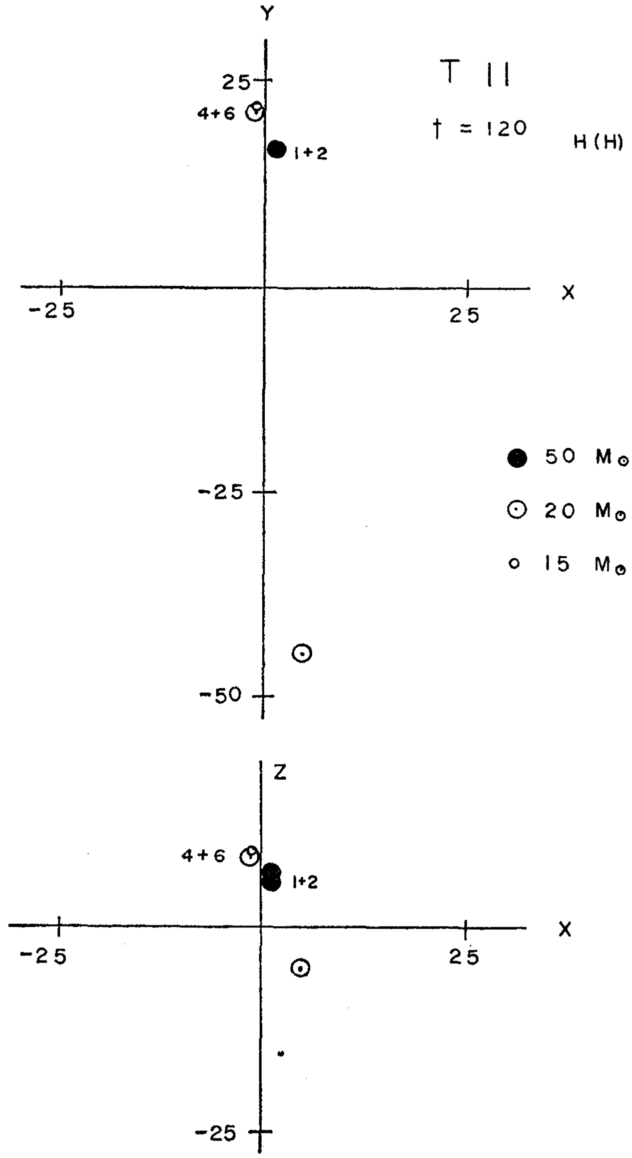

FIG. 4. Final positions of the member stars of the trapezium of Figure 3, after 10^6 years of dynamical evolution. One distance unit corresponds to 5000 AU.

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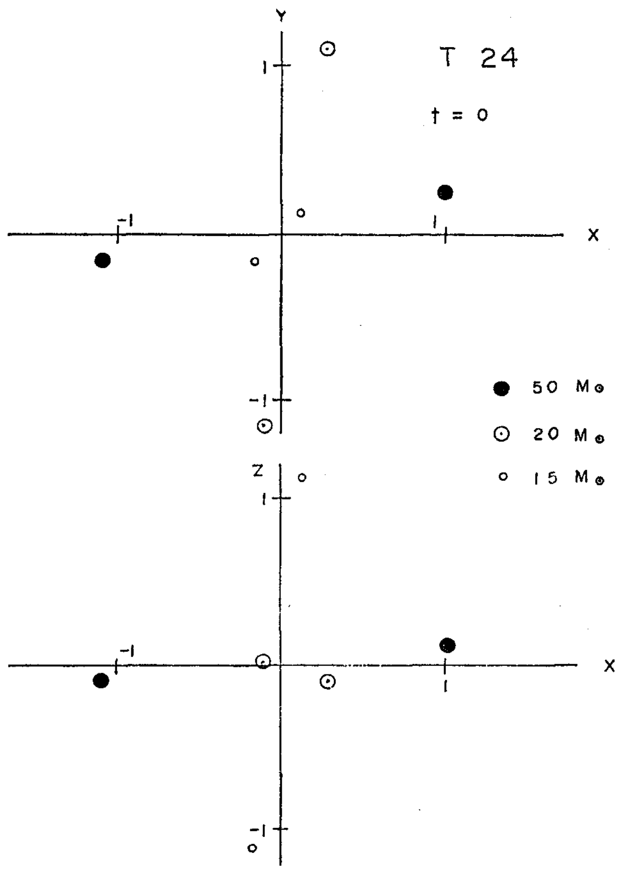

Fig. 5. Initial positions of the member stars of a trapezium, projected on the *xy*-plane and on the *xz*-plane. One distance unit corresponds to 5000 AU.

A simple model, based on the above ideas and on the results of the computations, can be used to predict the relative frequencies of trapezia and hierarchical systems as a function of spectral type; this model supposes that all visual multiple stars are born as trapezia. The results of this calculation agree very well with the observed relative numbers of trapezia —and hierarchical multiples— for the early spectral types (O and B systems). For systems of later spectral types, (F and later) the agreement is not so good, in the sense that there seems to exist a smaller proportion of hierarchical systems per trapezium than expected from the model. This apparent inconsistency may be due to two causes: *a*) the observed proportion of hierarchical systems to trapezia may be smaller than the "true" proportion because of selection effects. In fact the "filtering" procedure used to reject optical companions will also tend to reject hierarchical systems with faint distant companions. *b*) The expected proportion of hierarchical systems to trapezia is the result of scaling the half-lives of massive trapezia with $M = 170\,\mathcal{M}_\odot$, to trapezia of a few solar masses; this scaling down by a factor of nearly 50 in the masses may not be quite correct without also scaling the linear dimension of the systems; this was not done in the model.

We may conclude that most of the visual multiple stars of intermediate or large masses ($\geq 2\,\mathcal{M}_\odot$) are born as trapezia which by dynamical interaction evolve into hierarchical systems; in a steady-state, where trapezia are continuously formed, the observed

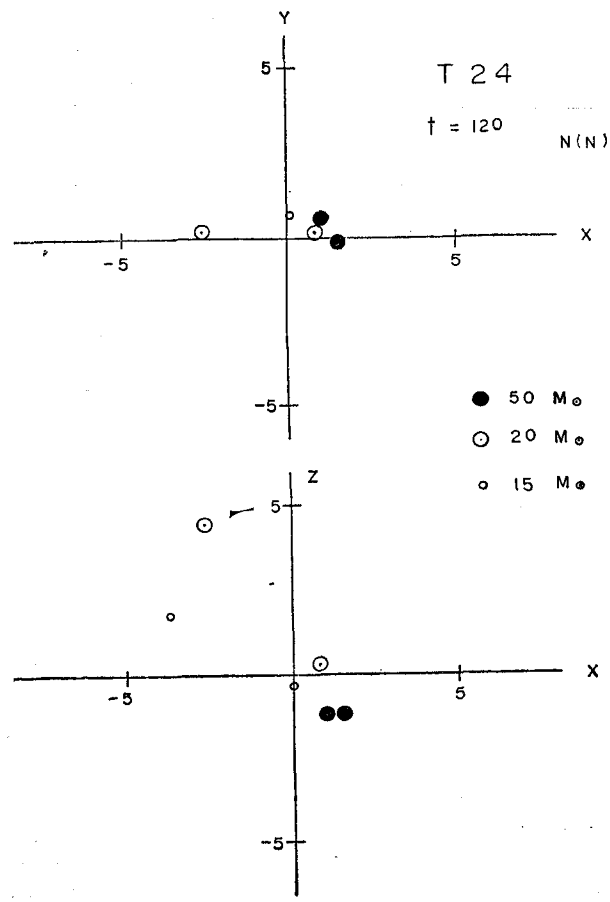

Fig. 6. Final positions of the member stars of the trapezium of Figure 5, after 10^6 years of dynamical evolution. One distance unit corresponds to 5000 AU.

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proportion of hierarchical systems to trapezia will rapidly increase with decreasing mass of the system; this agrees in general with the observations. We may also conclude that multiple stars (visual multiples) are formed as independent condensations.

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DISCUSSION

Hayli: What is the smallest separation of the binaries you form?
Poveda: The minimum semi-major axis is about 300 AU.
Harrington: Of the dissolved and hierarchical systems, did you determine the members of binaries versus triples versus quadruples, etc.?
Poveda: We have determined that out of 30 trapezia, 33 binaries were formed. In 21 of these cases the two most massive stars formed the closest pair. We have not made statistics of the proportion of triples and quadruples.

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