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PLANETARY SYSTEMS AND STELLAR MULTIPLICITY

(Invited Paper)

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RESUMEN

En este trabajo hemos discutido, por un lado, el origen del sistema planetario y por el otro, el de estrellas binarias y múltiples. Primero, se muestra que las diferencias fenomenológicas entre estas dos clases de objetos celestes se debe a sus diferencias genéticas. El punto básico es que la formación de un sistema planetario alrededor de una estrella es un evento menor en la vida de la estrella, mientras que la formación de un sistema binario o múltiple tiene que ser un evento igualmente importante para todas las componentes del sistema. Por lo tanto, el sistema planetario evoluciona de un disco en rotación de partículas de polvo y gas que se forma después de que la estrella ya está formada. Es entonces razonable sugerir que el disco giratorio resulta de la transferencia de momento angular entre la estrella central y el medio circundante, el cual es posiblemente el residuo del proceso de la formación de la estrella central.

Sistemas binarios y múltiples no se pueden originar de esta manera, puesto que no muestran las características de que provienen de un disco en rotación. El mecanismo dominante de su origen es que se formaron naturalmente tal como son, cada una tal vez de una condensación única del medio interestelar. Sin embargo, tal mecanismo único de formación no puede explicar satisfactoriamente la dispersión de la separación media entre las componentes observada de las binarias (o bien, en forma equivalente, de sus periodos orbitales). Pero este desacuerdo puede ser eliminado incluyendo un número pequeño de binarias formadas por otros procesos y considerando el cambio de los elementos orbitales de las binarias después de su formación. Los trapecios posiblemente se formaron mediante más de un mecanismo.

El que varias estrellas puedan formarse en una sola condensación requiere la existencia de núcleos pre-estelares, lo cual se discute brevemente al final de este trabajo.

ABSTRACT

In this paper we have discussed the origin of planetary systems on one hand and binary and multiple stars on the other. First we show that phenomenological differences between these two kinds of celestial objects are due to their genetic difference. The basic point is that formation of a planetary system around a star has to be a minor event in the life history of the star while formation of a binary or multiple system has to be an event that is important equally to all components of the system. Thus the planetary system evolves from a rotating disk of gaseous and dust particles that comes into being after the star has already been there. It is therefore reasonable to suggest that the rotating disk results from transfer of angular momentum from the central star to the surrounding medium which is likely a residue left over in the process of formation of the central star.

Binary and multiple systems cannot be formed in this way because they do not show the characteristics of having come out of a rotating disk. The dominant mechanism of their formation is that they were formed naturally as they are, each from perhaps a single condensation in the interstellar medium. However such a single mechanism of formation cannot satisfactorily explain the observed spread of binaries in mean separations between two components (or equivalently orbital periods). But the disagreement may be removed by including a small number of binaries formed by other processes and by considering the change of orbital elements of binaries after their formation. Trapezia were likely formed also by more than one mechanism.

That several stars could be formed from a single condensation requires the existence of pre-stellar nuclei which are briefly discussed at the end of the paper.

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I. INTRODUCTION

The origins of both multiple systems of stars and the planetary system to which our own earth belongs had been separately studied for hundreds of years but to my knowledge it was Kuiper (1935) who first made a systematic statistical study that was meant to probe the pertinent question of whether our planetary system and, for that matter, other planetary systems in the cosmos belong genetically to the same group as do binary and multiple systems. Kuiper's study of 465 systems included not only all three usual kinds of binaries but also common-proper motion pairs of wide separations and served well as a statistical means for inferring their origin. In his study K and M giants are excluded from the statistics because they do not follow the mass-luminosity relation which was used by him to derive the mean separation. Systems composed of more than two stars were counted as two or more binaries as the case may be, if the binaries thus obtained should satisfy the two conditions on the magnitudes of the components, namely the combined magnitude of both components < 6.45 mag and the difference in magnitude of two componentes, < 4.0 mag. Replotted as broken lines in Figure 1 is Kuiper's histogram for the frequency distribution of log a, where a denotes the semi-major axis of the relative orbit of binaries in AU in a volume of space near the sun. Marked respectively on the diagram by J, S, U, and N are the mean separations of the four major planets, Jupiter, Saturn, Uranus and Neptune in our system from the Sun. Kuiper has pointed out that the mean distances of these four planets from the Sun all fall in the peak range of the distribution histogram he derived as can be seen in Figure 1. He therefore went on to suggest an intrinsic closeness between binaries and the planetary system.

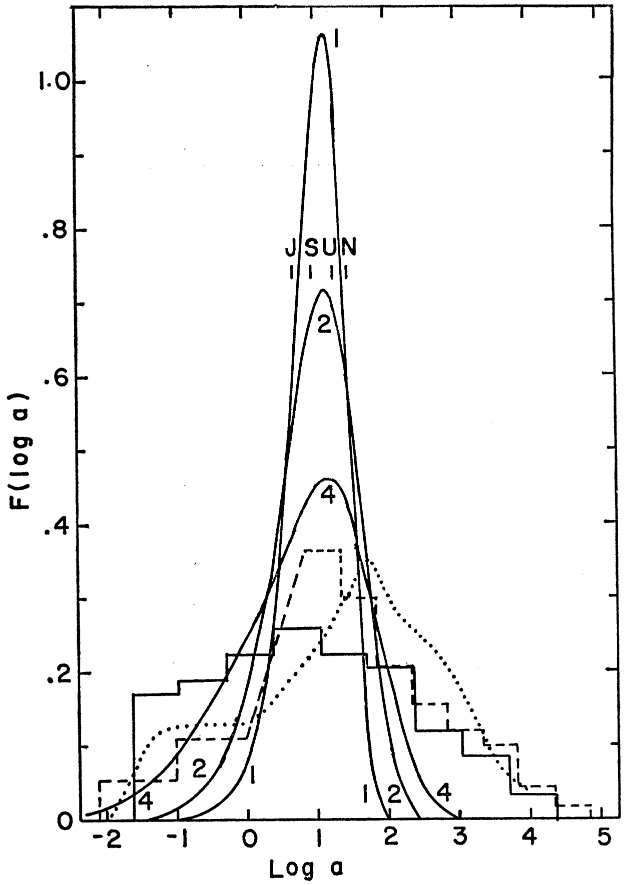

Fig. 1. Histograms and computed curves of the distribution of binaries in the solar neighborhood with respect to the common logarithm of the mean separation, *a*, (in AU) between two components. The histogram represented by the solid line is due to Abt and Levy, that represented by the broken line due to Kuiper and the dotted curve due to Heintz; all were derived from observational data. Three solid curves have been calculated from the assumption that every binary was formed from one single condensation of the matter in the interstellar medium. Three curves represent respectively three ways of treating the problem as is described in the text. All histograms and curves are normalized such that the area under each is unity.

Kuiper has also studied the distribution of mass ratios of two components in the binary. If M_1 and M_2 denote respectively the masses of the more and the less massive component in the binary, $\mu = M_2/(M_1 + M_2)$ is distributed evenly, making the small value of the planetary system a possible extrapolation of his statistical result.

Statistical study of binaries has been further carried out by several other investigators (for references see Abt and Levy 1975) within some special sections of the main sequence, even though Heintz (1967) has sketched from his own histogram a distribution curve which is reproduced in Figure 1 by the dotted line. But the most recent and significant study has been one given by Abt (1977, Abt and Levy 1976) who has presented the result in this colloquium. By observing many spectroscopic binaries

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themselves and confining their study to stars of the spectral range F3-G2 V and IV, Abt and Levy have derived results which are believed to be not unduly distorted by selection effects, and which are more significant than others because they have limited their study to a narrow spectral range for primary components. They have derived the distribution function with respect to orbital periods, P, of binaries. Consequently it cannot be compared directly with Kuiper's distribution which is with respect to the mean separations. The conversion from one to the other and vice versa is computationally tedious because the distribution with respect to log a, hereafter denoted by F(log a) is related to that with respect to log P, denoted by $\Phi(\log P)$, by an integral equation in which the distributions of M_1 and M_2 enter. Since the latter distributions are limited to small range in Abt and Levy's study, we may neglect their effect. Then by adopting an average value $M_1 + M_2 = 2M_\odot$ we can transform $\Phi(\log P)$ to F(log a) by simply changing the scales. F(log a) thus transformed from $\Phi(\log P)$ of Abt and Levy is shown in Figure 1 as the histogram plotted in the solid line. All three empirical distributions have been normalized such that the total area covered by the histogram or under the curve is unity for the purpose of easy comparison. It appears that Kuiper's result and Abt and Levy's result agree in their general trend.

However the mass distributions derived by Kuiper and by Abt and Levy do not agree too well. Kuiper found the distribution with respect to μ to be constant, which would correspond to a distribution that is proportional to $(M_1 + M_2)^{-2}$ if M_1 were constant, while Abt and Levy found a distribution of M_2 to be proportional to $M_2^{1/3}$. This discrepancy might have arisen from the condition imposed by Kuiper that the distribution is a function of μ alone, while actually it is a function of both M_1 and M_2, (or equivalently μ and M_1).

In general Abt and Levy's more recent study does not invalidate Kuiper's conclusion that the distances of major planets from the sun fall at and near the peak of distribution of binary separations. Also, small masses of planets could be interpreted as possible in binaries if we extrapolate Abt and Levy's mass distribution to small values.

Thus Kuiper concluded that the planetary system and binary systems form an homogeneous group. He had never changed his view on this point. I know because I talked with him about it less than one year before he died. In general most stellar astronomers seem to agree with Kuiper's conclusion. I myself took this view when I first became interested in the origin of stars and planetary systems (Huang 1957). However gradually I changed my view after I was convinced that our planetary system and planetary systems in general were formed by a unique process that could not produce binary and multiple systems of stars as we shall see presently. So now I consider the planetary system or planetary systems in general, to belong to a different category from the binary systems. In fact I went even a step further because I consider binary systems themselves to be heterogeneous genetically, as we will see in Section V.

II. PHENOMENOLOGICAL DISTINCTION BETWEEN PLANETARY SYSTEMS AND MULTIPLE STELLAR SYSTEMS

Let us first consider why I regard planetary systems and multiple stellar systems as completely different objects. There are two reasons, one dynamical and the other physical. Dynamically, all important members in our planetary system are moving in nearly circular and coplanar orbits. If there should be other planetary systems in the universe, we would expect that they also would follow this general rule (Huang 1973). For otherwise the system would be unstable and would not last long in terms of the nuclear time-scale of the star. Consequently it could not be an abode of life (Huang 1959). Such systems, even if they did exist at all, would not be the object of our concern because the importance of the planetary systems is their life-supporting feature. With respect to the orbital eccentricity and orientation, stars in binaries and multiple systems other than what has been termed the trapezium systems where no permanent orbits can be defined, behave differently from planets in the planetary system. In the binary and multiple stellar systems the eccentricity of the orbits can vary from 0 to 1. As regards the orbital orientation in the binary and multiple

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systems, there is no definitive result at present, because it is difficult to determine. Some degrees of alignment have been detected (Gabovits 1938, 1940; Worley 1967) but others like Grigorieff (1950) concluded random orientation of planes inside each multiple system. In this colloquium Worley (1977) once more stressed that orbital orientation in a multiple system is not a settled problem. In any case there appears at present no conclusive proof that orbital planes in each multiple system are always nearly coplanar. Here again we have found a clear distinction between planetary systems and multiple systems.

Finally we may also comment on the significance of extrapolation of the mass ratios from the observed values in binary system varying from 1 to 0.1 to the order of 10^{-3} found in the planetary system. Structurally a mass ratio differing by a factor of 100 makes a great difference. This leads me to think that such a structural difference must be a result of genetic difference. Here I may illustrate it by a non-scientific example which nevertheless will show my line of thinking.

Consider the difference between the twin cities like Minneapolis and St. Paul in Minnesota and Kansas City in Kansas and Kansas City in Missouri on one hand and the huge megalopolis like Chicago with many satellite towns surrounding it on the other. If you examine these two kinds of cities, you see their structural differences most clearly. There is simply no ambiguity to blur their difference. People from the satellite towns will not hesitate to identify themselves with the metropolitan city their towns attach to. For example I live in Evanston which is a satellite town of Chicago. I always tell my friends in the east coast or the west coast or abroad that I come from Chicago. But people from a twin city do not want to be mixed up with the sister city. This is because each city is big enough to have its own identification. I look at the distinction between multiple systems of stars and the planetary systems in the same way. Multiple systems are equivalent to twin cities, each component having its own identity and planetary systems are equivalent to satellite cities that are attached to the huge metropolis and have little individual identity.

This comparison so far is only superficial. However I can now come to the more fundamental analogy between the two cases. I may ask why sometimes a city develops into a huge metropolis with a large number of satellite towns while others become twin cities. You can immediately see that this is not due to pure chance. Big twin cities come into being initially as little twin cities. Each component then grows in its separate way because of external necessity. In the case of the Minnesota twin cities, it is their functions that maintain their separate identity. In the case of Kansas City, the two parts belong to two states that prevent them from becoming one city politically. Here I come to my point. The twin cities and the simple metropolis are phenomenologically and structurally different due to the fact that they were intrinsically different in the very beginning. To put it briefly and forcefully we may say that phenomenological differences are due to the genetical difference. In my opinion binary stars and planetary systems behave the same way. Their phenomenological difference, such as mass ratio eccentricity, coplanarity, are all due to the difference that comes from their origin. If we have purely dynamical differences between binary stars and planetary systems, such an idea is no more than a conjecture. Actually these two kinds of objects have also their physical differences which must have been the result of the divergent ways through which they were formed. This is because it is very difficult to envisage the physical difference to change with time, while it is possible to consider the orbital elements to change with time as a result of the gravitational interaction, even though I personally do not consider it likely that the coplanar and circular nature of orbits of planets in our system could be anything other than formed in this way. Thus we must consider the genetical difference between the two kinds of objects in the background of their physical differences.

III. GENETIC DIFFERENCE BETWEEN MULTIPLE STELLAR SYSTEMS AND PLANETARY SYSTEMS

We know that the cosmic abundance of chemical species is dominated by hydrogen and helium. So whether we look at stars or at interstellar media, we find these two chemical elements to be the major

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constituents. However, there is the exceptional case of terrestrial-like planets where heavier elements are present in a large proportion. This unusual chemical composition obviously resulted from some unusual processes. At one time it was thought that the terrestrial-like planets were also composed of hydrogen and helium in the beginning. Kuiper (1951) took this point of view. Being closer to the Sun these planets are hotter than major planets. As a result, rapid thermal motion in these inner planets gradually dissipated hydrogen and helium, leaving only heavier elements behind while the major planets have practically kept their original chemical composition dominated by hydrogen and helium. However a close examination (Shklovskii 1952) indicates that such a process is untenable. Because elements heavier than hydrogen and helium occupy only a small fraction of the cosmic matter, the planets had to dissipate more than 90 percent of their mass in order to reach their present composition. That would make the original masses of the terrestrial planets more than ten times more massive than their present values. If so, the original planets would be too massive and its surface gravity too large to permit most hydrogen and helium to escape.

A more reasonable explanation of the differentiation of chemical composition in the planetary system occurred in the solar nebula before planets came into being. Only non-volatile matter in the gas and dust medium in the hot region close to the Sun could condense with lighter elements being driven away to the outer region. In this way we have a differentiation of chemical species due to the temperature difference in the solar nebula. When the matter condensed into planets, the inner ones would be terrestrial-like, composed of heavy elements while the outer ones would contain a large amount of hydrogen and helium.

Thus we see that whatever is the theory for the existence of two kinds of planets in our planetary system, one must invoke the presence of the Sun first as an agent that made the differentiation possible. This is exactly parallel to the fact that small cities cluster in a megalopolis because the central metropolis was there before small cities were built. This parallelism goes beyond that if we consider the differentiation of small towns around a metropolis according to financial, educational and other social statuses. Such a differentiation is rendered possible by the presence of the big central city and is unlikely to happen elsewhere. Therefore it is my own feeling that the emergence of the small clustering ones as a consequence of the existence of the central big one is true for both megalopolis and the solar system. On the other hand components of binary and multiple systems of stars are of equal rank. Formation of one does not depend upon the existence of the other. That is why stars in these systems behave quite like single stars. In other words, they maintain their individual identity each burning hydrogen just as twin cities do each with their own city governments.

One may ask whether every planetary system would have two kinds of planets like our own. I am inclined to think that the natural phenomenon always repeats itself when the condition is satisfied. Therefore if our system has two kinds of planets, it is highly likely that other planetary systems formed in the same way also possess the same two kinds of planets. Also, the planetary systems that we are interested in are those which contain terrestrial-like planets on which life may emerge. We may even define planetary systems to be those where terrestrial-like planets exist (Huang 1973). This definition would put them definitely in a different class from multiple star systems where main-sequence stars behave like single main-sequence stars indicating the same hydrogen abundance.

What then is the genetic process that shapes our planetary system or planetary systems in general and differs from that which shapes multiple systems of stars? In order to answer this question let us examine the dynamical properties of the planetary system. The circular and coplanar properties of the movement of planets around the Sun all indicate that they must have emerged from a rotating disk of gases and dust. In the first place the rotating disk of gaseous and dust particles is one of the most prevalent shapes that we have found in the universe because of its easy formation (e.g., Huang 1972). Any gaseous and dust medium around a gravitational center will collapse into a rotating disk, as soon as it has acquired a certain amount of angular momentum. On the other hand, several large bodies

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moving around do not easily collapse into a rotating disk like that of our planetary system even if they possess on the whole a net angular momentum. This is so because there is no easy way to dissipate energy of large bodies short of direct collisions in which case large bodies would be fragmented instead of channeling their orbits into a common plane.

At the same time, because the present mass ratio of the planetary system to the Sun is small, the total mass of the rotating disk must be small compared to the Sun even if we take into account the loss of hydrogen and helium in the course of evolution of this rotating solar nebula. Therefore the formation of the solar nebula must be a minor event, as far as the Sun was concerned. This is just like the formation of a satellite city in the suburb is only a minor event with respect to the central metropolis. It follows from this reasoning that the formation of the solar nebula is an offshoot of evolution of the Sun and cannot be a competing event in the process of formation of the Sun itself while whatever the process of formation of multiple systems of stars is, it has to treat all component stars on an equal footing.

IV. FORMATION OF THE ROTATING DISK OF GAS AND DUST

If there is no doubt of the presence of a rotating disk of gas and dust before the appearance of a planetary system, there are many theories as to how the rotating disk comes into being. Most theories are based upon pure reasoning but lack observational support. I regard such a practice not objetive enough.

I started my approach to the problem from Struve's result of stellar rotation instead of Kuiper's result of binaries. Struve (1930) has found that the observed rotational velocity of stars, namely V sin*i* (where V is the equatorial velocity and *i* the angle of inclination of the equator), varies greatly with their spectral types. For single main-sequence stars of spectral type earlier than F5 or so, the Vsin*i* value can be as large as 400-500 km s^{-1} in some stars, even though it can be small in other stars. However the Vsin*i* value of single main-sequence stars of spectral type later than F5 has never been found greater than the limit of observational accurac of Vsin*i* for stars except the Sun. We also know that the Sun which rotates with a small speed o a mere 2 km s^{-1} at its equator has a planetary system which possesses a large amount of angular momentum. But if we should put all the angular momentum of the planetary system into the Sun, the Sun would rotate with an equatorial velocity of the order of 100 km s^{-1}. So it occurred to Struve that the lack of stellar rotation of main-sequence stars later than F5 might have something to do with the existence of planetary systems in general. This idea obviously occupied Struve's thought for a long time. However at that time there was simply no conceivable mechanism that could create such a bifurcation of th rotational behavior of stars at F5. So Struve could not pursue this line of thought further. Then h became interested in binaries especially W Ursa Majoris stars. Remember that at that time Kuipe was a colleague of Struve, and they had frequen discussions on binary stars. Obviously Kuiper's statistical result of binaries mentioned previously convinced Struve that binaries had something to do with planetary systems because Struve (1949) suggeste that W Ursae Majoris stars must be predecessors o planetary systems. Struve has spent many years developing this idea. In his book. "Stellar evolution" published in 1950, he has developed a scheme indicating that rapidly rotating stars evolve to become W Ursae Majoris binaries which in turn evolve to becom planetary systems. I have regarded Struve's schem as not satisfactory because it evaded the crucia question of why there exists a bifurcation point a F5 for rotation of single main-sequence stars an have always considered this critical point of bifurcation of stellar rotation at F5 as an importan empirical fact that might help us understand th origin of planetary systems, even though I had n idea how this bifurcation could happen, unti Schatzman's (1962) theory of magnetic braking o stellar rotation was advanced. Schatzman's theor has convinced me that the bifurcation at F5 is du to pre-main-sequence evolution of stars of differen masses. I have therefore proposed (Huang 1965 1967) that as a result of magnetic braking, rotatin disks are formed around stars that are to become F and later when they reach the main sequence. Sinc

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magnetic braking is a result of convection in the star, it varies with stellar mass. Massive stars which bypass the convection stage suffer little braking, retain their angular momenta and consequently rotate rapidly, while less massive stars suffer a great deal of braking. The latter thereby lose practically all of their angular momentum to the surrounding medium, which in turn collapses into a rotating disk first and becomes a planetary system afterwards. In this way the frequency of occurrence of planetary systems in the cosmos and even their sizes may be estimated from data on stellar rotation. However that is not the point of emphasis on this occasion. What is to be stressed here is that the process of formation of planetary systems belongs to a class of its own because such a process is not expected, from a consideration of both the mass and the angular momentum, to produce binary and multiple systems whose components have masses that are comparable.

In this way we have decoupled binary stars and planetary systems into two distinct and non-transferable groups of stellar objects while we put rotating stars and planetary systems closer together genetically. That, however, does not mean that rotation and duplicity of stars are two stellar events that are completely unrelated. As we know, some clusters, like Pleiades, rich in stars of large Vsin*i* values, are often deficient in spectroscopic binaries (Struve 1950). Other clusters, like IC 4665 rich in spectroscopic binaries (Abt and Snowden 1964; Abt *et al.* 1972) contain stars with low Vsin*i* values for their spectral type (Deutsch 1955). (For frequencies of spectroscopic binaries and the rotational behavior of stars in other clusters see Batten's (1973) compilation). Duplicity also varies in different kinds of stars. For example among high-velocity dwarfs, short period binaries are rare (Abt and Levy 1969). On the other hand metallic line stars (Am) have been found to be mostly spectroscopic binaries (Abt 1961) but their Vsin*i* values are usually low (Slettebak 1955). Recently Drobyshevski (1975) suggested that peculiarities found in Am and Ap stars may be due to the existence of planetary systems. In any case synchronization of rotation with orbital motion in binaries brings down Vsin*i* values in many cases (Abt 1961). But it is also likely that formation of rapidly rotating stars and that of spectroscopic binaries in a cluster are two competing mechanisms—one dominates at the expense of the other. I will come to this point later. If so, planetary systems and binaries are also competing events according to this view of formation of planetary systems directly from rotating stars.

The observational base of our theory of formation of planetary systems is not limited to the property of stellar rotation. As Poveda (1965) has pointed out, it can be further tested by the side effects of the envelope that can be actually observed around the stars in their pre-main-sequence stage, such as the existence of infrared objects and the clearing effect of obscuration in certain directions during the collapse phase of the spherical envelope into a disk. All these have been briefly reviewed by Huang (1973) in connection with the formation of planetary systems. The most significant observational finding was the detection of infrared excess in some T Tauri stars by Mendoza (1966, 1968). Since this pioneer discovery, infrared excess has been found in many young stars by several investigators. Indeed, the infrared study of T Tauri stars has ince become one of the most active branches of stellar astronomy. It would be out place here to review the numerous papers that have been published in this field in recent years.

V. MULTI-ORIGIN OF BINARIES

After we have separated planetary systems from the multiple systems of stars, we can now examine whether the binary systems themselves form a uniform group that has a unique cause for their origin. That the binary systems were not formed by a unique process has been suggested by many authors. The most convincing observational fact to bring about this suggestion is the statistical result given in Figure 1. There is simply no single process that can account for such a wide distribution of separations, or equivalently a wide range of angular momenta per unit mass. Kuiper, after having derived his histogram shown in Figure 1, realized this difficulty, but he attributed the wide spread in separations to various mechanisms that change the separation after the formation of binaries by a single process. We

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shall discuss these mechanisms later on. I myself am inclined to think that binaries were actually formed by several processes although Kuiper's idea of spreading of binaries to a large range of separations after their formation is also important, as we will see later.

In order to show quantitatively why a single mechanism of formation cannot account for the distribution given by the histograms in Figure 1, we must consider the distribution of stellar angular momenta. The natural distribution of the amplitude of a vector is of course the Maxwellian distribution (i.e., each component is given by the Gaussian distribution). If Ω denotes the angular momentum of one of the binaries, and if Ω_p is the most probable value of Ω, we may write,

$$\Omega = \xi\Omega_p \quad (1)$$

and the distribution function can be written in a dimensionless variable ξ as follows:

$$\phi(\xi)\, d\xi = \frac{4}{\sqrt{\pi}} \xi^2 e^{-\xi^2} d\xi \quad (2)$$

The distribution function of ξ given by equation (2) corresponds to a distribution function of log a, denoted by F_1 (log a) and shown as the curve 1 in Figure 1, if the spin of component stars as well as the effect of variations in M_1, M_2 and eccentricity e of orbits are neglected. F_1(log a) was first derived by Kuiper (1955). But it is interesting to note that Kuiper never plotted this function to compare with his own statistical result. My guess is that Kuiper found the discrepancy too great to be believable as we can now see in Figure 1, where F_1(log a) is represented by the curve labelled by 1. On the other hand the four major planets in our planetary system appear to fit all in the peak distribution of F_1(log a), a result that is interesting to note.

We have generalized Kuiper's calculation by inquiring whether the binary distribution could be a result of a single random process taking place in different physical circumstances which themselves are distributed at random (Huang 1968*a*). For example we may argue that angular momenta of binaries in each cluster or association are randomly distributed, as is given by equations (1) and (2), but Ω_p in different clusters is itself distributed randomly. If we write $\eta = \Omega_p/\Omega_0$ where Ω_0 is constant, the distribution of η is also given by equation (2). The resulting distribution of ξ would produce another distribution of binaries with respect to log a, denoted by F_2 (log a) and shown in Figure 1 as curve 2, if again the spin of stars as well as the effect of variation of M_1, M_2, and e are neglected. While F_2(log a) is closer to the empirical histograms of Kuiper and of Abt and Levy than F_1(log a), it cannot be said to agree with them.

It may be further argued that since the relation of Ω and a is given by

$$\Omega = M_1 M_2 \left[\frac{Ga(1 - e^2)}{M_1 + M_2}\right]^{1/2} \quad (3)$$

the distribution of a depends upon not only on that of Ω but also that of M_1, M_2 and e, even if we neglect the spin angular momentum. If we assume that distributions of ξ and η are both given by equation (2), that $M_1 + M_2$ is distributed according to that given by Salpeter (1955) for single stars and that the distribution of $M_2/(M_1 + M_2)$ is constant according to Kuiper, the distribution function of log a, denoted by F_4(log a) is given by curve 4 in Figure 1. F_3(log a) takes into account the variation in $M_1 + M_2$ but neglects the variation of $M_2/(M_1 + M_2)$ is very similar to F_4(log a), and is not given here. Introduction of the variation of e also produces a distribution of log a not significantly different from F_4(log a) (Huang 1968a).

I have not had time to calculate the distribution of log a according to Abt and Levy's result of mass distribution. However I do not think it will produce any large change in the resulting distribution of log a (or log P). Consequently we may conclude by comparing curve 4 with histograms in Figure 1 that there is no agreement between observed data and calculated results. It shows that the binary systems could not have all been formed by a single process of direct condensation from interstellar media. They must be formed by several mechanisms. It goes without saying that multiple systems of stars, like binaries, were also formed by several mechanisms because any multiple system with the exception of the trapezium type, is nothing but a superimposition of several binaries.

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VI. INDIVIDUAL MECHANISMS OF BINARY FORMATION AND DYNAMICAL EVOLUTION

Evolution of binaries has a double meaning. In the first place the component stars evolve just as any single star will evolve because of energy dissipation. This we may call physical evolution. In addition, even if component stars do not evolve appreciably in a certain time period such as in the main-sequence stage, the nature of their relative orbit could change for one reason or another. This we may call dynamical evolution. Needless to say, physical evolution is often, even though not necessarily, accompanied by dynamical evolution. Therefore wa cannot neglect the physical processes even in dealing with the simple problems of relative orbits of binaries.

With this understanding we can now come back to examine the distribution function F(log a) of binaries. How is this function shaped? The first question we would like to ask is : whether it is also a function of time and space, namely F(log a; l,b; t) where l,b denote galactic coordinates and t time. The answer is that it is likely to be a function of space and time, because we know that some clusters are full of spectroscopic binaries (Abt and Snowden 1964), while others are poor in spectroscopic binaries (Struve 1950). However at present we are not concerned with those binaries in any particular cluster, but will limit our discussion to field stars that result from disintegration of many clusters and associations. In other words we consider what is a space average, although the region of space being averaged is more or less limited only to a certain region of space in which the statistical data, as given by histograms in Figure 1, were obtained.

There are several mechanisms that determine this distribution: (1) the formation of binaries by different processes, (2) dynamical evolution of binaries taking place for one reason or another, (3) the different dissociation processes. The first mechanism creates binaries and therefore increases the number of binaries in different ranges of separations a (or log a). The last mechanism destroys binaries and therefore reduces the number of binaries in different ranges of separations a (or log *a*). The middle mechanism reshuffles the distribution from one region of separations to another without changing the total number of binaries in space. The actually observed distribution is the result of all these mechanisms. At least this is the most general view of how the histogram may be looked at theoretically. If a steady state has been established, we may derive the distribution by setting the time derivative equal to zero. In any case a mathematical theory can be formulated only if we know all the three mechanisms in detail.

A binary or a multiple system is obtained when two or more stars are formed together in the interstellar medium such that their dynamical energy happens to be negative. Kuiper (1955) took this as the sole mechanism of formation of binary and multiple systems and considered each system the final product of a single condensation in the interstellar medium. I myself think this process to be the dominant, but not the sole, mechanism. The distribution of binaries formed in this way should be given by F_4(log a). But it is modified by other processes.

One such process is the three-body collision which traps two encountering stars into their mutual gravitational field to form binaries, perhaps distant ones in most cases. The three-body collisions have been studied extensively in recent times, thanks to the fast electronic computers. Several papers have been devoted to this topic in this colloquium alone. All have treated it as a problem in celestial mechanics. However the computed results have yet to show their significance to the actual cases of triple stars in the sky. To bridge the gap that now exists between computed and observed results of three-star encounters, I think, is one of the most serious tasks facing both the observer and the theoretician.

The physical picture is also complicated by the fact that while three-body collisions can trap binaries, they can also disrupt binaries. In the general galactic field of stars, the interstellar distances are so vast that the chance of three-body encounters resulting in any significant interchange of energy is likely to be insignificant. Consequently we may state that formation of binaries through three-body collisions in the general galactic field is very small. Perhaps the process has some bearing only on the common-proper motion pairs. But the situation is different in a cluster where the star density is high and gravitational encounters frequent.

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The motions of stars in a cluster have been simulated by numerical experiments by many investigators. Binaries may be formed easily through encounters of three or more bodies. This is especially so when the cluster is disintegrating (van Albada 1968; Aarseth 1972; Aarseth and Lecar 1975; Allen and Poveda 1972). This is because the dynamical energy of the cluster is continually removed from it as a result of disintegration. Physically this is a very disturbing situation because a galactic cluster cannot be treated as an isolated system, even though a globular cluster and the galaxy as a whole may be treated as such. For this reason alone we do not expect that a kind of thermodynamics can be formulated for gravitationally interacting particles in a galactic cluster as we have done for an enclosure of gaseous particles. Actually as we see later there is another difficulty introduced by the computational approximation that prevents us to consider any equilibrium state of gravitationally interacting particles. In practice the escape of stars from a cluster makes formation of binary and multiple systems, statistically speaking, a one-way street, namely more binary and multiple systems are formed than destroyed by gravitational encounters of three or more bodies. On the other hand the number of binaries and multiple systems formed in the course of disintegration of a cluster, depends critically upon the initial conditions of stars in the cluster. It cannot be predicted.

The final residue of a cluster after disintegration is perhaps a trapeziun type system. Allen and Poveda (1972) (also Allen *et al.* 1974) have shown that trapezia are reasonably stable and are not expanding. Consequently they are no more and no less than little clusters after other members have escaped from them. They may be seen as degenerated clusters. On the other hand trapezia could also be formed as they are (tiny clusters). That is why I said earlier that trapezia were formed through more than one simple mechanism. But whatever their origin, trapezia will eventually disintegrate and populate the galactic field as single stars, binaries and multiple sytems. Therefore the existence of trapezia indicates clearly that binaries are not always formed as they are from single condensations. The name trapezia I used here refers, for the sake of simplicity, to three-dimensional space and may be contrary to its usual sense defined by the projection on the celestial sphere (e.g., Allen *et al.* 1977), Hence these objects form, according to my view, a subgroup of multiple systems where no orbital elements can be defined for the component stars, while those multiple systems where orbital elements are definable have often been called hierarchical systems (e.g., Allen and Poveda 1974).

Formation of binary and multiple systems in a cluster has often been compared with chemical reactions. Actually I should say exothermic reactions. Hence it is a natural tendency for stars to form binaries. For after all, particles, whether atoms or gravitational bodies, have the tendency to seek a minimum potential level. So atoms form molecules and stars form binaries. In the case of stars the energy minimum occurs when two stars are in physical contact. As a result we do expect the formation of close binaries in a cluster. In actual computation of dynamical evolution of the cluster, all investigators have used the point mass approximation for the star. This approximation introduces some serious complication because the energy curve between two mass-points has no finite minimum. It creates an infinite energy reservoir, even though mathematicians prefer to call it a singularity. This infinite energy reservoir, introduced by investigators themselves as a result of their mass-point approximation, in turn messes up the physical problem of dynamical evolution of star clusters. Most of all, under this point-mass approximation we cannot expect a statistical equilibrium for the gravitationally interacting mass points, even if we should be able to impose some fictitious boundary conditions. This is the second difficulty I find in the computational approach to dynamical evolution of the cluster, in addition to the first one mentioned earlier, that the cluster has no boundary. After all if there should exist a state of equilibrium for a system of particles, then we could always approach that state if we wait long enough (in the numerical simulation that means a long time of calculation). But when a system has no equilibrium state, the result of computation never converges. It will depend greatly upon the initial conditions no matter how long we compute. Different initial conditions will give different results. This conclusion is fully vindicated by the outcome of many numerical experiments by various

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authors. However that does not mean that dynamical evolution through actual computations based on the assumption of gravitationally interacting mass points has no significance in practice, because the singularity will cause most of its trouble in the case where the star density is very high, while actual cases are far from having reached this state. Thus, a cluster could completely disintegrate without encountering this difficulty, thanks to the small value of the gravitational constant, G. It follows that evolution of a particular cluster could indeed be followed quite faithfully by N-body calculation in celestial mechanics if initial conditions of all particles were known in the very beginning. However a change of the initial conditions of a single mass point could lead to a very different result of disintegration.

In addition to formation of binaries through gravitational encounters of three or more bodies at the large-separation end, there is the fission process which creates binaries at the short-separation end. However I personally do not consider the fission as a likely process for forming binaries (Huang 1966) even though it has been quite popular recently since its revival by Roxburgh (1966). In any case both fission and gravitational encounters of three of more bodies, whether inside a cluster or not, do not populate binaries in great numbers as compared with their natural formation because the histograms in Figure 1 do not show any secondary peak at least for the solar type primaries.

As regards the mechanisms that destroy binaries we may mention gravitational perturbations of a third body or bodies. Again this process is only effective for binaries of large separations in a cluster. Binaries may also be dissociated by the fluctuation force of the general galactic field and interstellar clouds (Chandrasekhar 1944, Takase 1953). If one component of a binary loses suddenly a large amount of mass, which may occur for example in a supernova explosion, the other component can run away. This idea was first proposed by Blaauw (1961). However recent investigations show that the loss mass during a supernova explosion, especially that of supernova type II, is not large enough to disrupt the binary (Poveda 1964). Poveda *et al.* (1967) also Allen and Poveda (1971) have since considered the runaway stars as escapees from collapsing clusters. In addition to these processes of destruction of binaries, we must add one of fusion which would bring two components in a binary together to be a single star, if magnetic braking of binary motion should be very strong (Huang 1966, Mestel 1967).

Finally there are processes that change the binary's separation. When the component stars lose their masses, their orbit changes correspondingly. This problem has been studied extensively by the past generation since Kuiper's (1941) classical investigation. Consequently the distribution of binaries is continually shuffled by this change. Also magnetic braking mentioned a moment ago will make the orbit of a binary shrink. These two processes occur at the small separation end. At the long separation end there is the perturbation by the stars, interstellar clouds and general fluctuations of galactic potential fields. The orbit of a binary also changes when it moves in a resisting medium (Kiang 1962).

From all these considerations and from a comparison of histograms with $F_4(\log a)$ in Figure 1, I venture to propose that the dominant portion of binaries in the peak range ($a = 1$ to 100 AU say) of the histograms are formed as binaries. However a small fraction might be formed also at both short and long separation ends by the processes mentioned before. At the same time mechanisms that change orbits spread the distribution in both directions to make the distribution flat and extended in the log a range, as is shown in the histogram. We have not explained the histograms in their details, but their general trend can be understood from the present discussion.

VII. FORMATION OF BINARIES AND MULTIPLE SYSTEMS

We know that a large proportion of stars in the solar neighborhood are members of binary and multiple systems. In order to see the formation of these systems, we have proposed a theory (Huang 1957) of pre-stellar nuclei whose existence was first suggested by Urey (1956) and Krat (1952). A condensation of gas and dust having a large angular momentum per unit mass will rotate faster and faster as it contracts, until rotational instability sets in at the equator. Thereafter, the condensation loses mass from its surface instead of continuously contracting. Consequently this condensation cannot lead

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to a binary system. However, if nuclei were formed first, the entire gas and dust in the condensation can fall into two or more resolving nuclei. Consequently the process of contraction (to two or more stars) can proceed without interruption. If double and multiple stars should be formed from pre-stellar nuclei, there is no reason why single stars should be formed otherwise.

We believe that the nature of stars that will be formed depends upon the angular momentum per unit mass, h, in the medium populated with gas, dust and pre-stellar nuclei, upon the total mass, M, that is available and most of all on the turbulent spectrum of the medium. Consider the character of stars that would be formed in media of increasing h. For small h single stars of different masses will be formed, depending upon the total available mass in the media. Single stars thus formed will rotate in different degrees. When h further increases, particles in the medium can no longer be captured by a single central nucleus because of their angular momenta. These particles together with other nuclei have to fall into two or more revolving nuclei in order to satisfy the law of conservation of momentum. Therefore a binary, triple or multiple system will be formed. From this consideration, formation of rotating stars and of binaries are indeed competing processes, as has been observationally concluded. The difference in the duplicity nature of dM and dMe stars discused in this colloquium by Lippincott (1977) may be caused by this same difference in the pre-stellar medium that produces the difference in their space motion (Delhaye 1953). At least the trend appears to be consistent because a low dispersion of space velocity, indicating a low state of turbulent motion of the pre-stellar medium, does favor the formation of binaries.

Here we see that my idea of binary formation resembles the growth of a city that I have already described earlier in the paper. Twin cities can be formed only when originally they were two little cities close together. A single little city would never grow to become big twin cities. Thus formation of stars according to my view follows the same pattern as the growth of cities. However the similarity is not perfect because in the pre-stellar medium we assume that there are many nuclei floating around. According to this scenario of star formation there should be a wide spread of mass ratios between two components. However even if some components are of small masses, they come out in the process in the way as components of large masses. Thus component stars in binaries may be comparable in the mass to planets in our system but the way they come into being is independent of other more massive components. It is this independent process of formation that I regard as the basic characteristic of planet-like objects in binaries. They are not to be put into the same class as the *bona fide* planets whose formation as we have seen depends upon the presence of the central star. Phenomenologically this leaves some ambiguity when objects of masses comparable to those of planets are found. Are they planets in a planetary system or planet-like objects in a binary? Thus in terms of the masses alone stellar astronomers have the tendency not to distinguish these two physically distinct groups. However such an ambiguity can be in principle at least removed by the genetical consideration. Phenomenologically a detailed study of all aspects of each particular system may also clarify this ambiguity. In our analogy of binaries with twin cities, a very small secondary mass in a binary may be compared to Vatican City in Rome but not to Evanston near Chicago. No matter how big is the disparity in population between Rome and Vatican City, the latter is always able to maintain its own identity independent of the existence of the former.

What are the pre-stellar nuclei made of? I am inclined to identify the earliest pre-stellar nuclei with what we know as comet nuclei, which come into being mainly through collisions. If we take the view that the dust particles in the prestellar medium are needle-like (Donn and Sears 1963), the accumulation of particles will take place quite rapidly. Even so, the further agglomeration beyond the size of comet-nuclei has to be gravitational. Both in the collisional and gravitational stages of accumulation of forming pre-stellar nuclei, it is highly likely that the accumulation process may be aided by the state of hydrodynamic flow. If the turbulent velocity field is composed of a large number of vortices, as has been recently developed by Chou and his associates (see Chou and Huang 1975 for reference) the gaseous matter in each vortex will stay together for a longer time than otherwise will

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be and the staying-together of dust grains for a while certainly facilitates the accumulation process. Also it is my conjecture that the angular momentum of stellar objects may have something to do with that of vortices in the pre-stellar medium, because stellar angular momenta have been found to be oriented in space at random instead of being parallel to the angular momentum of galactic rotation. (For a detailed review of stellar angular momenta see Huang 1968*b*.)

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We regret to inform that Professor Su-Shu Huang passed away on September 15, 1977 as these Proceedings were in press.

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