THE PROTOPLANETARY SYSTEM FORMATION AS A RESULT OF THE MERGING OF CLOSE BINARY STAR CONSISTING OF THE LOW MASS PRE–MS STARS

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ABSTRACT. The mechanism of protoplanetary system formation as a result of a merge of binary star consisting of the low mass $(0.5 - 1M_\odot)$ preMS stars is considered. During the merging the more massive component is destroyed. The substance of the destroyed component forms spiral gaseous arm and circumstellar disk. The protoplanetary embryos (clouds) with masses about 2-5 M_j are forming as the result of division of the spiral arm. The rotation of the circumstelar disk, clouds and star are in plane. The formed clouds are on the eccentric $(e > 0.3)$ orbits.

Key words: computational fluid dynamics, binary star, protoplanetary system

1. Introduction

The degree of the stars multiplicity (number of systems divided by a number of stars) in the solar neighborhood is more than 57 % (Duquennoy 1991) and probably is underestimated. The probability of discovery of not found yet component always exists. Such components are discovered gradually with an increase of an accuracy of observations and use of other methods of observation and data processing. Thus, *it is possible to consider that the multiplicity of observed star is the lower limit of real star multiplicity.* The multiplicity of preMS stars twice exceeds the multiplicity of solar type MS stars (Köhler 1998).

The basic parameter determining properties of binaries is the specific angular moment of the protostellar cloud. The angular moment distribution of binaries of various types is continuous. The lower limit of the specific angular moments range of observable binaries is $\sim 2 \cdot 10^{18}$ cm^2c^{-1} (Masevich, Tutukov 1988). It extends to the specific angular moments range of the planetary systems $10^{17} - 10^{21}$ cm^2c^{-1} (Goodman and all 1993). Thus, the range of the angular moment of binaries overlaps the range of the angular moment of protostellar systems. The angular moment of binaries with brown dwarfs extends to the specific angular moment range of the planetary systems (Tutukov 2002). Thus, the distribution of the binaries and planetary systems on the angular moment is continuous. It allows assuming, that the *binaries with the extreme small (transitive between binary and planetary systems) angular moment can exist.*

Binary stars with semiaxis A that satisfy equation:

$$A/R_\odot < 6(M/M_\odot)^{1/3} \qquad (1)$$

where $M = M_1 + M_2$ is mass of system, nearly are not observed (Popova 1982) (see fig. 1). During contraction to the main sequence the binaries with semiaxis which are satisfying equation (1), will have common envelopes, because the components will have radii about $3 - 5R_\odot$ (Stahler 1993).

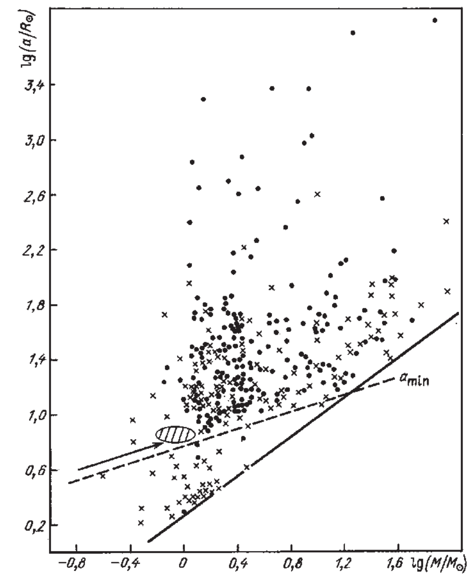

Figure 1: The semiaxes - primary component mass distribution (Masevich, Tutukov 1988) for spectroscopic binaries. A shaped line corresponds to equation 1. The shaded oval corresponds to considered binaries.

The considered stars have deep convective envelopes (Palla, Stahler 1993). And binaries can lose the angular momentum by stellar wind with rather small loss of system mass (Krajcheva 1978). As the result of a loss of the angular moment the orbital separation can decrease and mass transfer in such systems can occur. If the mass transfer ratio is high, then system can merge. This mechanisms of angular moment loss is actual for stars with low ($< 1.5M_\odot$) mass. For more massive stars, the time interval on which they are convective, is much shorter (Palla, Stahler 1993)

During last years hundreds planetary systems are discovered. The comparison of extrasolar planets and planets of solar system shows, that the extrasolar planets can have masses about $0.1 - 10M_J$ and can have orbits with higher eccentricity (0.69 for HD 89744) and semiaxis in the range 0.2 - 10 a. u. *The presence of wide range of parameters of observable extrasolar planets allows to assume that mechanisms of formation of planetary systems another than for solar system can exist.*

The standard mechanism of planetary systems formation is its formation from systems with circumstellar disks. The probability of detection of the disk practically linearly grows with age of stars. The observation of stars in young clusters shows that the quantity of stars with disks decreases from 80-90 % in clusters with age $0.3 - 1 \cdot 10^6$ years is up to 3 % in clusters with age $\sim 3 \cdot 10^7$years (Haisch etc. 2001). Thus, *the presence of disks around young stars is the same widespread phenomenon as their multiplicity.*

The noted observation facts allows to assume, that disks around some protoplanet systems could be produced in the merging binaries. This merging possible as a result of angular moment loss by stellar wind, interaction of system with the common envelope and other processes.

We suppose that the planetary system forms step by step in the following processes:

1. The close binary star formation. $M_{1,2} < 1.5M_\odot$, $M_2/M_1 \sim 1$
2. The loss of angular moment by stellar wind or interaction with common envelope.
3. Merging of binary star. The formation of the circumstellar disk
4. The mass transfer and angular moment transfer along the circumstellar disk and between star and circumstellar disk under the viscous friction.
5. The formation of protoplanetary embryos

2. Method

In the case of polytropic state equation:

$$P = K\rho^\gamma, \tag{2}$$

where γ is the ratio of specific heats (in present calculations $\gamma = 5/3$), K is the entropy function, the equation of motion of a compressible fluid can be written in the form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\vec{v}) = 0 \ , \tag{3}$$

$$\rho\frac{\partial K}{\partial t} + \rho(\vec{v} \cdot \nabla)K = -\frac{\gamma - 1}{\rho^\gamma}\Im \ . \tag{4}$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\frac{1}{\rho}\nabla P - \vec{F}, \tag{5}$$

where ρ is the density, $\vec{v}$ the velocity, P pressure, and the $\Im$ the energy loss function which comprises all nonadiabatic sources and sinks of energy.

In SPH (Lucy 1977, Gingold & Monaghan 1977), these equations of motion are solved using Lagrangian formulation in which the gas is partitioned into fluid elements. A subset of these fluid elements are selected and represented by particles. In SPH these subset is chosen so that the particle mass density is proportional to the fluid density, ρ. This means that ρ can be estimated from the local density of particles at later times if the system is updated according to the equations of hydrodynamics.

Since the number of particles is finite, it is necessary to include a "smoothing"procedure to interpolate between them to represent the fields as continuous quantities. If each particle has a mass m_j then the smoothed density is given by

$$\rho(\vec{r}) = \sum_{i=1}^{N} m_i W(|\vec{r} - \vec{r}_i|, h), \tag{6}$$

where h_i is the smoothing length, and $W(r, h)$ is the smoothing kernel which satisfies the following conditions:

$$\int W(r - r', h)dr' = 1, \tag{7}$$

$$\lim_{h \to 0} W(r - r', h) = \delta(r - r'). \tag{8}$$

The calculations presented here were performed using the Gaussian kernel

$$W(r, h) = \frac{\exp(-r^2/h^2)}{\pi^{3/2}h^3}, \tag{9}$$

In the implementation used here the components of a binary system have their own fixed smoothing length. The primary component is described by N_p particles with smoothing length h_p and mass $m_p = M_1/N_p$. The secondary component is described by N_s particles with smoothing length h_s and mass $m_s = M_2/N_s$, $N_s = N - N_p$, where N is the total number of particles. For this case the SPH form of the equation (6) is

$$\rho_i = \sum_{j=1}^{N} m_j W_{ij}, \tag{10}$$

$$W_{ij} = W(r_{ij}, h_i)/2 + W(r_{ij}, h_j)/2 \tag{11}$$

where ρ_i is the smoothing density at the point $\vec{r}_i$, and $r_{ij} = |\vec{r}_i - \vec{r}_j|$.

SPH form of the equation (3) is the following

$$\frac{d\vec{v}_i}{dt} = -\sum_{j=1}^{N} m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2}\right) \cdot \nabla_i W_{ij} -$$

$$-G \sum_{j=1}^{N} \frac{M(r_{ij})}{r_{ij}^2} \frac{\vec{r}_{ij}}{r_{ij}} + \vec{a}_i^{visc} \qquad (12)$$

$$M(r_{ij}) = 4\pi m_i \int_0^{r_{ij}} r^2 W(r,h) dr,$$

where G is the Newtonian gravitation constant. The second term in equation (12) is the gravitational forces, $\vec{a}_i^{visc}$ is the viscous forces. The standard artificial viscosity is employed (Monaghan 1992):

$$\vec{a}_i^{visc} = \sum_{j=1}^{N} m_j \Pi_{ij} \nabla_i W_{ij}, \qquad (13)$$

where

$$\Pi_{ij} = \frac{-\alpha \mu_{ij} c_{ij} - \beta \mu_{ij}^2}{\rho_{ij}} \qquad (14)$$

$$\mu_{ij} = \begin{cases} \dfrac{\vec{v}_{ij} \cdot \vec{r}_{ij}}{h(r_{ij}^2/h^2 + \eta^2)}, & \vec{v}_{ij} \cdot \vec{r}_{ij} < 0 \\ 0, & \vec{v}_{ij} \cdot \vec{r}_{ij} \geq 0 \end{cases} \qquad (15)$$

and $\vec{v}_{ij} = \vec{v}_i - \vec{v}_j$, $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$, $c_{ij} = c_i - c_j$ is the average sound speed of particles i and j, $h_{ij} = (h_i + h_j)/2$, $\rho_{ij} = (\rho_i + \rho_j)/2$. The numerical simulation is performed with constant $\alpha = 0.5$, $\beta = 1$, $\eta = 0.001$.

Ignoring any sources of entropy other than artificial viscosity, the smoothed equation(4) for the entropy function K is

$$\frac{dK_i}{dt} = \frac{\gamma - 1}{2\rho_i^{\gamma-1}} \sum_{j=1}^{N} \Pi_{ij} m_j \vec{v}_{ij} \cdot \nabla_i W_{ij} \qquad (16)$$

The solution of the equations (10),(12),(16) is determined by a choice of the initial conditions. The construction of initial conditions can be divided into three steps:

- The first step is the construction of internal structure of each component as a star in the state of hydrostatic equilibrium.
- The second step is to take into account the rotation of each component and tidal forces operating between them.
- The last step is the coordinate transformation and establishing of the initial velocities of particles.

At the first step the models were constructed by placing particles down randomly and then solving equation (12) in the presence of frictional dumping to achieve a stationary equilibrium (Gingold and Monaghan 1977).

At the second stage we take into account rotation and tidal forces. For each binary component the tidal forces were estimated considering another companion as a point mass.

At the last step we make transformation of coordinates. For the primary component this transformation of coordinates can be written as follows':

$$\vec{r}_i = \vec{r}_i + \vec{r}_{cm_1}\ ,\ \vec{v}_i = \vec{\Omega} \times \vec{r}_i\ ,\ i = 1...N_p, \qquad (17)$$

and for the secondary one:

$$\vec{r}_i = \vec{r}_i + \vec{r}_{cm_2}\ ,\ \vec{v}_i = \vec{\Omega} \times \vec{r}_i\ ,\ i = N_p + 1...N, \qquad (18)$$

where $\vec{r}_{cm_1}$ is the primary component's center of mass, $\vec{r}_{cm_2}$ is the secondary component's center of mass. The initial angular velocity $\vec{\Omega}$ was set in units of the Keplerian angular velocity $\vec{\Omega}_K$:

$$\vec{\Omega} = k_\Omega \vec{\Omega}_K, \quad |\vec{\Omega}_K| = \sqrt{\frac{GM}{(2A)^3}} \qquad (19)$$

where $M = M_1 + M_2$. In close binaries, the tidal distortion of a star by its companion gives rise to a perturbation of the external gravitational field which in turn causes a secular motion of the line of the apses (Stern 1939):

$$\frac{d\omega}{dt} = \left(\frac{R_1}{A}\right)^5 \Omega_K q k_2 15 (1 - e^2)^{-5} \left(1 + \frac{3e^2}{2} + \frac{e^4}{8}\right) \qquad (20)$$

where $q = M_2/M_1$ is the ratio of component masses, e is the orbital eccentricity, ω is the longitude of the periastron. The apsidal-motion constant k_2 depends on the internal structure of the star and measures the extent to which mass is concentrated towards the stellar center. For the preMS stars along their vertical part of the evolutionary track the apsidal-motion constant is typically of the order of $10^{-1} - 10^{-2}$. For systems with circular orbits this means that the angular velocity higher than the Keplerian angular velocity (i.e. $k_\Omega > 1$). To estimate parameter k_Ω one can use the following formula

$$k_\Omega = 1 + \frac{0.22q^{7.71}}{32.13q^{7.46} + \ln(1 + q^{6.48})}. \qquad (21)$$

This formula is correct in case if the orbital eccetntriciry is zero, the primary component fill its Roche lobe, the secondary component is point mass and the ratio of specific heats γ equals to 5/3.

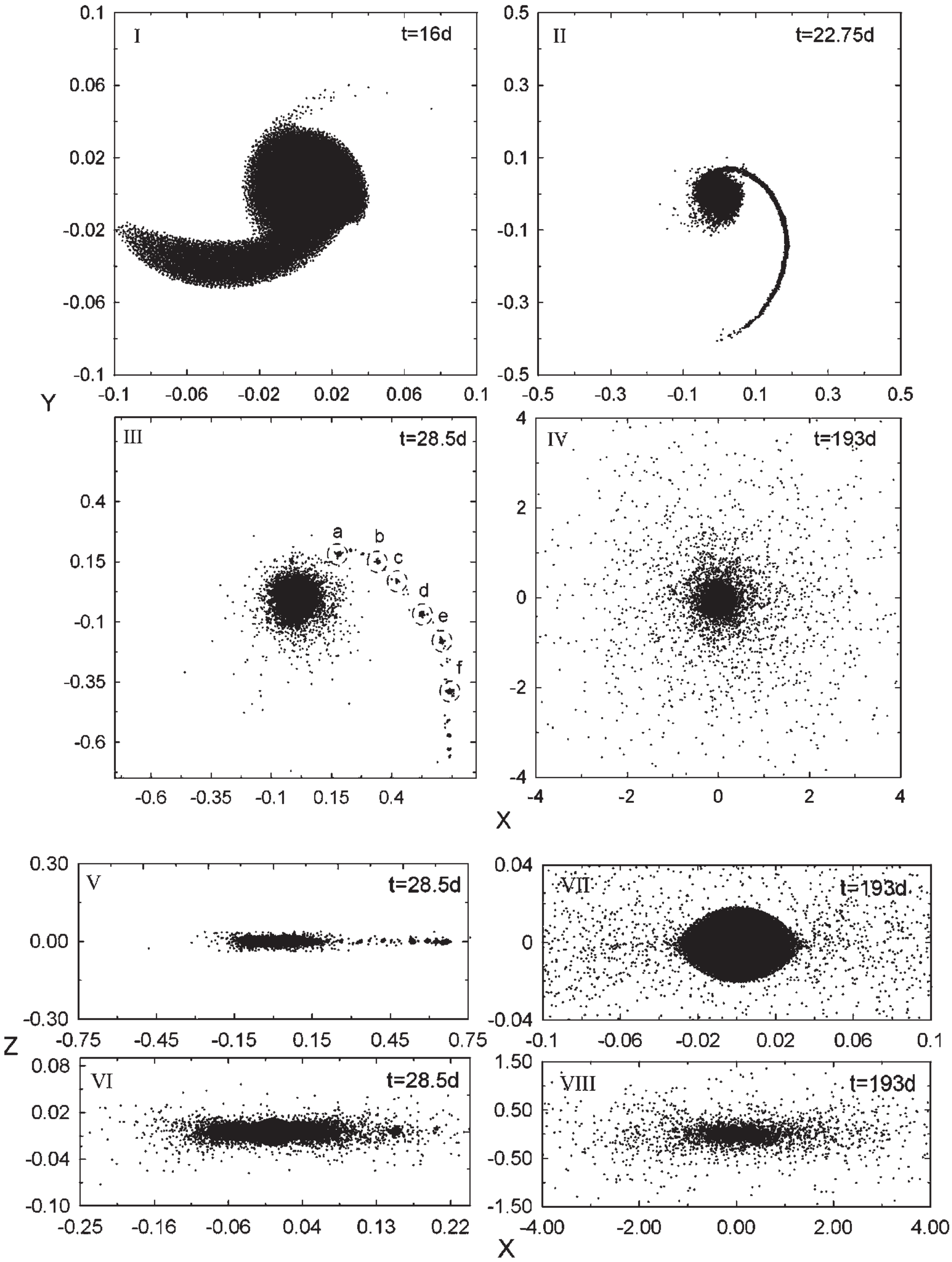

Figure 2: There are particle positions at the various moments of time in the orbital plane (I-IV), and in the XOZ plane(V-VIII). The dotted line on the figure (III) border the formed clouds. The moment of time is marked on each figure. Distances are in units of a.u.

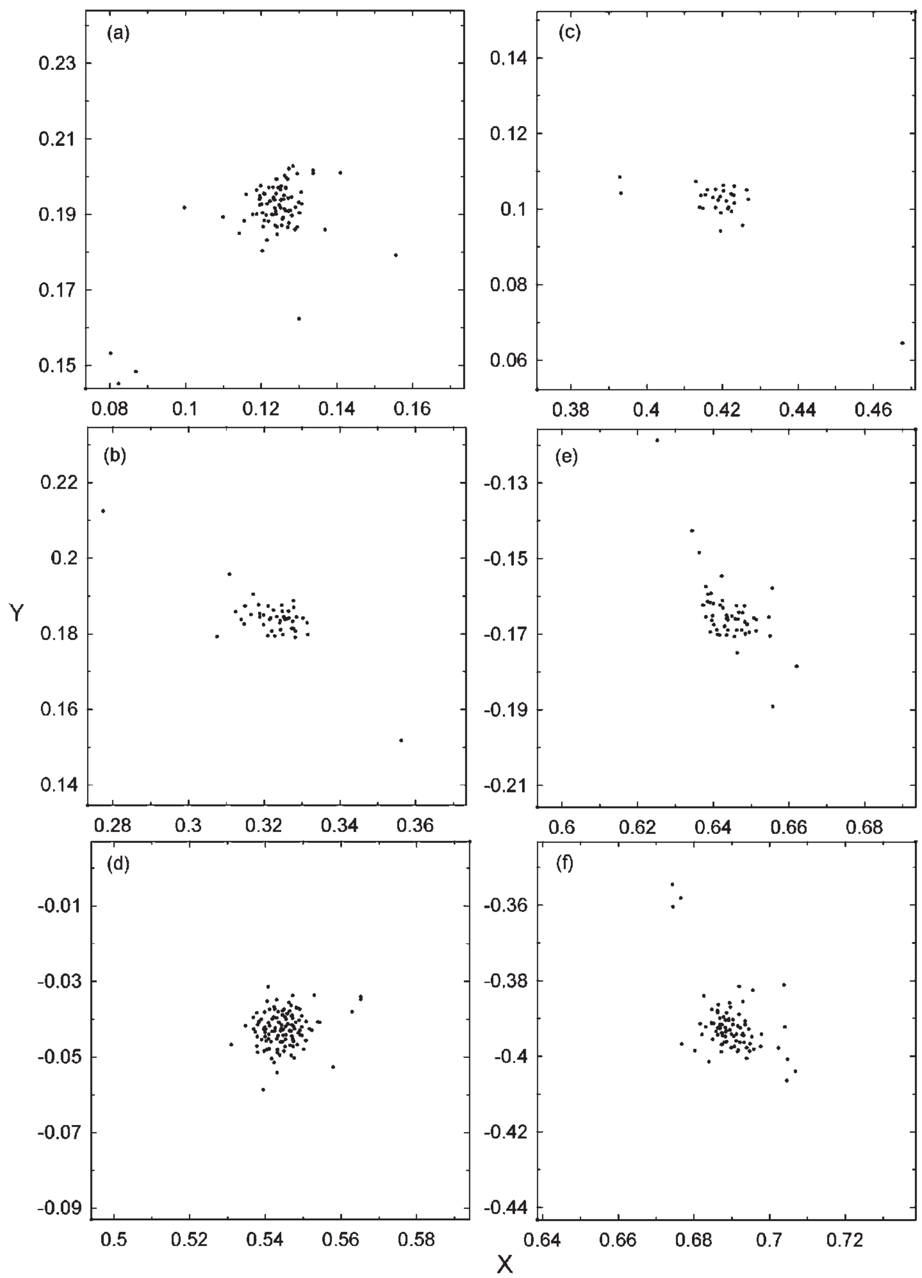

Figure 3: The particle positions which correspond to formed clouds. The marking of pictures corresponds to the marking of clouds on fig. 2.III.

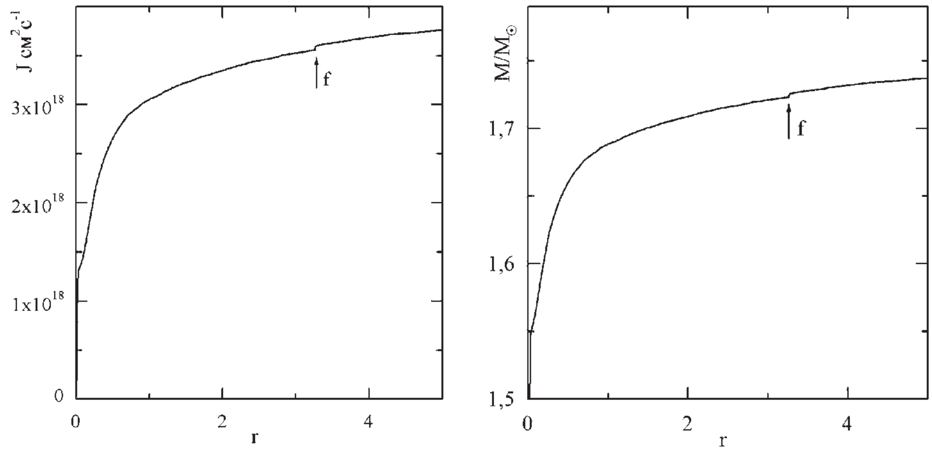

Figure 4: Left figure is angular moment - radius distribution in the orbital plane. Right figure is mass - radius distribution in the orbital plane. Radius is in units of a.u.

3. Results

We choose the following limits of binaries parameters which satisfy the observation data and at which the merging of binary star are probably:

1. The age of binary star should be less, or is comparable with the age of such Tauri stars.
2. The binary's mass is $M_{1,2} < 1.5M_\odot$
3. The ratio of component masses is in the range of $0.5 < q < 1$.
4. The specific angular moment is about $10^{18} - 10^{19}$ cm^2c^{-1}
5. The semiaxis is $A < 7.3R_\odot$
6. The binaries components should be close to filling its Roche lobe.

Cloud marking	Mass (M_J)	semiaxis	eccen.
a	3.16	...	...
b	1.69	...	...
c	1.14	...	...
d	4.26	0.3	0.5
e	2.02	~ 0.5	0.6
f	2.98	~ 3	0.6-0.7

Table 1: Some clouds parametrs. See fig 2.II

The calculation with the following parameters of binary star was performed: $M_1 = 0.9M_\odot$, $M_2 = 0.85M_\odot$, $R_1 = 4.6R_\odot$, $R_2 = 4.4R_\odot$, $A = 6R_\odot$. The primary component was approximated using $Np = 27000$ particles and secondary component $Ns = 3000$ particles. Size of the smoothed length for a primary component is $h_p = 0.045R_1$ and for secondary component is $h_s = 0.045R_2$

The integration was performed up to the moment of time $t = 220d$ with an average time step $\Delta t = 3d$. The mass transfer will begin at the time moment $t = 3d$, when components are in the periastron. Through 4-5 periods the rate of mass transfer grows so, that the primary component begins to overflow its Roche cavity. The matter of the primary component begins to flow out of the Roche cavity through an external La-grange point, forming the spiral arm (fig. 2,I-VI).

The most part of primary component matter accrete by the secondary component. The rest of the matter forms the circumstellar disk, which is $\sim$ 12% of the system mass.

The spiral arm divides on clouds of planetary ($< 5M_J$) masses. The masses of these clouds depend on distance up to the central star (see tab. 1, fig. 2.II).They are on the orbits with high eccentricity $e > 0.3$. The most of these clouds accrete on the star or become a part of circumstellar disk. The direction of clouds rotation coincides with a direction of star rotation. The disk has radius is approx 4 a.u. The inner layers of the disk matter (closer to the star) are on circular orbits, and the external layers are on the eccentric orbits. As a result of circumferential pressure, which arises at friction of adjacent cylindrical layers rotating with different angular velocities, the transfer of mass and angular moment in a radial direction exists. Destruction and accretion to the disk of the formed clouds results an increase of velocity of radial expansion of the disk. The direction of the disk rotation coincides with a direction of teh star rotation. Disk and clouds contain 12 % of the system mass and 64 % of the angular moment of the system (see fig. 4). Mass of the formed star is $1.54M_\odot$, equatorial radius is $6.5R_\odot$. The relation of polar radius to equatorial radius is approx 1/2.

The specific angular moment of system is $3.86 \cdot 10^{18}$ and was invariable during integration. The full system

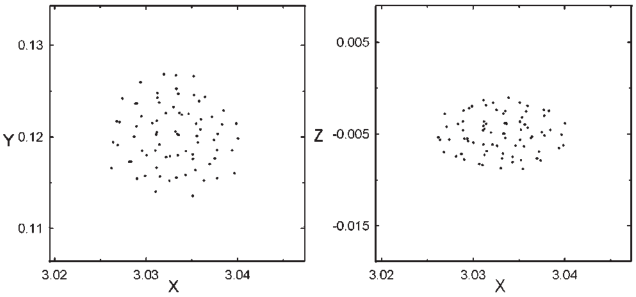

Figure 5: There is particle positions for the cloud "f"on the orbital plane $t = 220d$.

energy has changed less than 1% from its initial value.

4. Conclusion

1. As a result of a merge of the binary star, consisting from low mass preMS of stars, the basic structures of planetary systems can be formed: the central star, the circumstellar disk and compact cloud of the planetary masses.

2. Clouds are formed occurs in time about hundreds orbital periods of initial binaries from the spiral arm, formed during merging.

3. The clouds are on the orbits with semiaxis < 5 a.u. and high eccentricity. Masses of clouds are 2 - 5 M_J, that is in the good agreement with masses of observed planets.

4. For an explanation of the observable super planets eccentricity is not required of additional mechanisms. It is possible to explain this eccentricity as residual from received at the moment of clouds formation. The initial eccentricity can be reduced by dissipation of kinetic energy in the tides and interaction of clouds with disk.

5. A star devours embryos that form in the spiral arm, resulting in bursts of luminosity. This explains the variations of luminosity of a class of young stars known as the FUOrs.

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