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MODEL OF BINARY SYSTEM FORMATION

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Abstract. A simplified model for the formation of binary star systems is presented and used to classify possible binary systems. The classification and other analytical predictions are found to be in good agreement with observations. Within the confines of the model a connection is established between the formation of binary and multiple star systems and of planetary systems.

1. INTRODUCTION

We begin by giving a brief 'physics perspective' on the basic properties of binary stars. At the outset of star formation we are faced with a problem: simple order of magnitude calculations show that protostars have 100 to 1000 times more angular momentum than the stars they beget. Nature solves this problem by having planetary systems, circumstellar disks, or companion stars circling the primary, carry off the access angular momentum. Planets are hardest to detect, still we have already seen more than 150 of them around other stars (see e.g. Perryman, 2000). Important new information is being gathered about size and composition of circumstellar disks (Vicente and Alves, 2005) particularly with the help of the Spitzer and Hubble space telescopes. Of the three mechanisms for getting rid of angular momentum, by far the easiest to see are binaries. Indeed binary and multiple star systems are common, making up around 60% of all stars (see e.g. Duquennoy and Mayor, 1991). These phenomena are interrelated. For examples, there exist planetary systems and disk remnants, planets in binary systems, etc. They serve the same purpose, they're interrelated – it is natural to attempt to describe them in a unified setting in which disks accrete thus spawning binaries, planets and/or disk remnants.

The outcome of this process depends on: the angular momentum of the protostar; details of accretion (particularly accretion time scales – the usual slow gravitational accretion $t \sim 10^8$ years, but also fast accretion $t \sim 10^3$ years that is inferred from IR observations on the Spitzer telescope of gaps in disks about young stars); details of the depletion of the material in the disk (particularly depletion time scales and depletion length scales for processes such as photo-evaporation); efficiency of accretion which is essentially driven by the dimensionless parameter $K = M_{disk}/M_{star}$ (see e.g. Balaž et al., 1999) i.e. for $K \sim 1$ all available material accretes into a single body, while smaller K leads to more condensates.

Let us now focus on binary systems, and in particular on three key properties of these systems: (1) most stars are in binary systems (roughly 60% of them); (2) the two stars in a binary system are strong correlated with respect to age and composition; (3) in most binary systems the masses of the two stars are strongly correlated, i.e. the distribution of mass ratios $q = M_1/M_2$ is strongly peaked near $q = 1$ (some authors believe, however, that this could be a result of observation biases and not inherent properties of binary systems).

Several different scenarios have been proposed for the formation of binary systems. They fall into three major classes: capture, cloud fragmentation, and fission of protostar through centrifugal instability. In the capture scenario all of the three properties given above are poorly explained. The capture scenario can't explain the observed frequency of binaries, it leads to no correlation in age, composition or mass. The cloud fragmentation scenario is possible if the initial mass distribution of the cloud is inhomogenous enough. Although it is hard to give a quantitative assessment, it is possible that this scenario could explain the first property. The second property follows directly, however, the third is poorly explained in this scenario, i.e. there seems to be no mechanism that would lead to a correlation of masses of primary and secondary star. The third scenario, as we shall show, very easily explains all three observed properties. In addition the scenario itself is crucially linked to angular momentum decrease – from the theoretical viewpoint we have been espousing that this is the vary reason for the existence of disks and objects that accrete from disks.

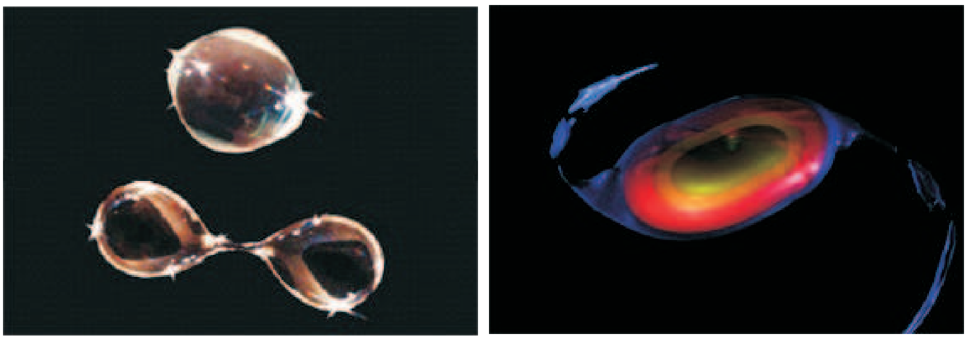

Figure 1: Light: Micro-gravity experiment in orbit – fission of a spinning water drop into two pieces of roughly the same mass (1992 space shuttle mission STS-50, Drop Dynamics Experiment). Right: Numerical simulation of the centrifugal instability of a protostar – growth of spiral arms that form disk.

The fission scenario is often illustrated by a simple analogy – the fission of a spinning drop of water. Fig. 1a shows a micro-gravity experiment of a spinning water droplet. The experiment agrees with theory – as a result of centrifugal instability a spinning drop of water divides into two pieces of roughly the same mass. Essentially all of the initial angular momentum goes into the orbital angular momentum of the two pieces. This could give a nice explanation for why binary star mass ratios are peaked around $q = 1$, however, unlike water, protostars are compressible fluids and are held together not by surface tension but by gravitation. Numerical investigations have shown that, because of this, protostars display a different kind of centrifugal instability: growth of spiral arms that form a disk (Cazes and Tohline, 2000). This disk forming instability is shown in Fig. 1b, a frame of a simulation done by Cazes and Tohline (see `http://www.phys.lsu.edu/astro/movie_captions/fission.html`).

In the following section we present a simplified model of circumstellar disks within this kind of fission scenario and analyze its consequences for binary formation.

2. SIMPLIFIED MODEL OF BINARY FORMATION

We look at a protostar of mass M_{PS} and angular momentum J_{PS}. Conservation of angular momentum implies that as it contracts the protostar spins faster and faster giving rise to centrifugal forces that deform it into an elipsoidal shape. At a certain point in the contraction the centrifugal force at the equator balances out gravitational attraction leading to the start of the formation of a disk about the protostar. This centrifugal instability occurs at a r_c and a disk starts to form. We assume that all of the protostars angular momentum goes into orbital angular momentum of the disk, that the disk is planar, and that all the material in the disk moves on circular Keplerian orbits. We further assume that the mass is distributed according to a scale free distribution

$$\rho(r) = \begin{cases} 0 & r < r_* \\ (p-1) M_D r_*^{-1} \left(\frac{r}{r_*}\right)^{-p} & r \geq r_* \end{cases} . \tag{1}$$

The only scale dependence above is in the cut-off $r_* = \lambda r_c$. The proportionality factor λ is essentially the ratio of semi-major axis of the protostar ellipsoid at the centrifugal instability. M_D is the mass of the disk. The gas giants in the Solar system satisfy $m \propto r^{-2}$ which is consistent with the above distribution for $p = 2.5$. Our binary formation scenario is completed by assuming that depletion can be neglected, i.e. no mass is lost and disk and star have the same chemical compositions.

At the point of instability the protostar's moment of inertia is $I = \alpha M_{PS} r_c^2$, where α is the usual geometrical factor of order one. We find

$$J_{PS} = \alpha G^{1/2} M_{PS}^{3/2} r_c^{1/2} , \tag{2}$$

G being Newton's gravitational constant. The above formula, therefore, determines the centrifugal radius of a protostar in terms of its mass and angular momentum.

The formation of the disk continues until practically all of the protostar's angular momentum is transformed into the disk's orbital angular momentum. The decoupling of disk and the spherically shaped central mass allows the remaining protostar to continue with its gravitational collapse. In the simplified model we consider here we will in fact assume that all the angular momentum has been transferred to the disk. Let us note that this agrees well with observation, i.e. if we plot the angular velocity of stars as a function of their mass we find that for $M \lesssim 2.5 M_\odot$ the angular velocities are hundreds of times smaller than what we would expect. Historically this was the first evidence that the majority of such stars have about them circumstellar disks that carry most of the original protostar's angular momentum. Today we directly see these circumstellar disks.

Note that $M_{PS} = M + M_D$, where M is the mass of the star. From the assumptions of our model it follows that the disk carries angular momentum

$$J_D = \frac{p-1}{p-3/2} \sqrt{GM}\, M_D \lambda^{1/2} r_c^{1/2} \ . \tag{3}$$

The fact that $J_D = J_{PS}$ now gives us a simple equation for the mass ratio $q \equiv M_D/M$. We find

$$\left(\frac{p-1}{p-3/2} \right)^2 q^2 = \frac{\alpha^2}{\lambda} (1+q)^3 \ . \tag{4}$$

All reasonable choices of parameters lead to $q \sim 1$. If the accretion time scale is shorter than the depletion time scale (fast accretion) or r_c is larger than the characteristic length scale for depletion then accretion is efficient, i.e. $K \sim 1$, and the fission of a protostar leads to the formation of a binary system with $q \sim 1$. It is easy to show analytically that the two stars are separated by a distance $d = \frac{p}{p-1} \lambda\, r_c$. The simplified model outlined determines the initial conditions for accretion for the general case. Formation of planetary systems is a bit more complicated to analyze because of the competition between depletion and accretion, and because smaller K leads to a larger number of condensates.

To conclude, let us note that protostars react to centrifugal instabilities by throwing off circumstellar disks. These disks start of with a mass roughly equal to that of the star. If depletion is bypassed (essentially if r_c is larger than the characteristic depletion length scale) the the result is a binary system. On the other hand, if depletion does acts then the disk's mass can decreases substantially with time. Both depletion and accretion decrease that mass. This has been seen in recent observations of circumstellar disks about Sol like stars. 10^7 year old disks have been shown to have a 1/10 of the mass of the star (IR measurements using Spitzer), while $4\,10^9$ year old disks have 1/1000 the mass of the star or less. The ultimate goal of this line of research is to determining a two dimensional phase diagram (in M_{PS} and J_{PS}) classifying different products of accretion: binary systems, (various types of) planetary systems, depleted disks, etc.

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