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Recipes for making short-period binaries

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Abstract.
Three possible mechanisms of close binary formation are discussed: accretion during infall, disk braking and tidal dissipation. Evidence exists that all these processes actually occur but it is not clear which one is dominating and how it can be modeled to explain the observed statistics of short-period binaries. Available data related to close binary formation are reviewed and new observing programs are suggested.

1. Introduction

Close binaries are formed at early evolutionary stages, they are already present in 1 Myr-old stellar populations. For example, the Orion Trapezium contains a 6-day enigmatic eclipsing binary BM Ori. A 3-day eclipsing classical T Tau binary RXJ 0529.4+0041 was studied by Covino et al. (2000), while numerous other spectroscopic binaries among pre-main sequence (PMS) stars were catalogued by Mathieu (1994) and others. The most striking example is provided by García & Mermilliod (2001): in a very young open cluster NGC 6231, 79% of O-type stars are spectroscopic binaries with periods from 3 to 7 days, most of them double-lined.

Binaries are a natural outcome of star-formation. However, rapid formation of *close* systems is difficult to explain. The usual channels of binary formation, fragmentation and cluster decay, produce wide systems with high angular momentum. Even assuming extremely dense initial clusters, Kroupa & Burkert (2001) were unable to obtain short orbital periods by pure dynamical interactions. Hence, additional loss of orbital energy and angular momentum is needed to produce short-period ($P < 30$ y) binary systems. This contribution reviews such orbit-degradation mechanisms and the observational data in favor or against them.

Fig. 1 resumes the major stages of star formation as a diagram of binary periods vs. age. The resulting distribution of binary periods is depicted on the right as logarithmically-uniform, spreading from 1 d to 10^6 y. The lowest possible periods of contact binaries of one solar mass are defined by the stellar radii during PMS evolution, as taken from D'Antona & Mazzitelli (1994) models. Similarly, longest binary periods can not exceed their age, as shown by the upper line.

The earliest epoch of close-binary formation is at infall stage when the masses of components are still being assembled. Later, PMS stars become observable as T Tau variables. Their circumstellar disks are not massive, but they

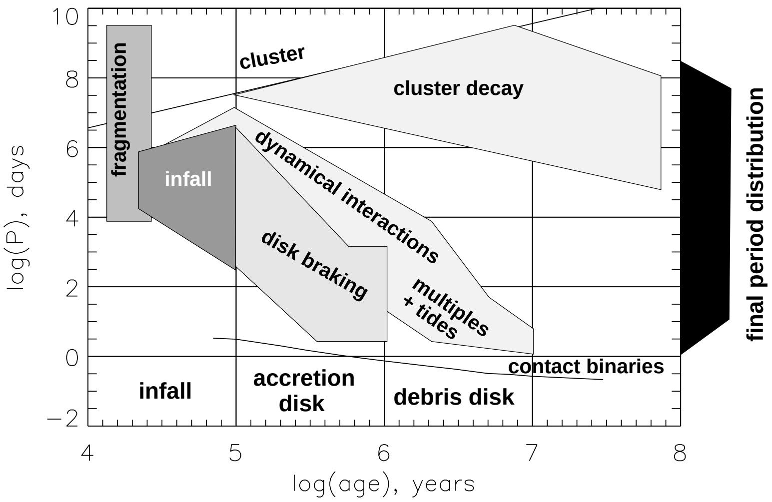

Figure 1. Scheme of early stellar evolution and binary formation.

can still sink considerable amounts of angular momentum and shorten binary periods. The third possibility consists in the dissipative action of tides.

Fission was a popular theory for close binary formation but it is now definitely out of fashion because simulations consistently show that rotating stars get rid of the angular momentum without fission (Tohline & Durisen 2001). Moreover, contact systems of convective protostars are unstable with respect to mass transfer: even if such a system were formed by fission, most of the mass will go into the primary (Whelan 1970), while real close binaries often have similar-mass components.

2. Close binaries at infall stage

PMS objects during infall (class 0) are heavily obscured and difficult to observe. Nothing is actually known about the existence of close binary systems at this stage, whereas the evidences for wide binaries and multiples are abundant. Our information about close binaries is indirect: if they exist at the epoch of mass build-up, this must be reflected in the statistics of the component's masses. Bate (2000) have demonstrated that accretion of material with high specific angular momentum onto a binary drives the mass ratio $q = M_2/M_1$ towards unity. It is hence expected that mass ratios of close (low-angular-momentum) systems will be higher than those of wide binaries.

Indeed, the available statistics shows that low mass ratios are frequent in wide systems, but in closer (spectroscopic) binaries the distribution of q is almost uniform (Mazeh et al. 1992). However, other processes like dynamical capture lead to similar signatures in the mass ratio distribution. More direct evidence is related to the peak in mass ratio distribution at $q = 1$ (Lucy & Ricco, 1979; Tokovinin, 2000). Wider (visual) systems also have an excess of equal-mass (twin) components (Söderhjelm 2000). Independent support for the $q = 1$ peak comes from the color-magnitude diagrams of open clusters that often contain a prominent "binary sequence". Explanation of this peak by accretion as offered by Bate (2000) is the only one viable to date.

Recently Reipurth (2000) has drawn attention to the fact that most of the PMS stars with outflows and jets are multiple. He relates jets to accretion episodes stimulated by companions that either come close to the inner binary periodically or experience close encounters in unstable disintegrating triples. The shortest obserbed periods of jet modulation are of the order of 100 y. It is not yet clear whether still closer binaries can be formed in this way, but the likelihood of such a scenario is supported by the fact that many close twin binaries are indeed found in higher-order multiple systems.

3. Disk braking

Several close PMS binaries are known to be surrounded by circumbinary disks. The most prominent example is a 15.8-day twin binary DQ Tau which shows signs of accretion modulated with orbital period (Mathieu et al. 1997). The outer (circumbinary) disk interacts dynamically with components through spiral waves excited in the disk. These waves remove angular momentum from binary and make its orbit more eccentric. At the same time some matter is accreted by the binary and settles in the circumstellar disks around components. At periastron the interaction of circumstellar disks with binary components is the strongest, it leads to increased accretion onto the stars and, probably, to the dissipation of some orbital energy. Dissipation is essential to reduce period and semi-major axis. Combined action of outer and inner disks should lead to orbit degradation. The process outlined above has not yet been modeled quantitatively.

Apart from direct observations of close PMS binaries with disks, the evidence of important role of disks in orbital evolution is circumstantial. The eccentricity-period diagram (e.g. Udry et al. 1998) shows that spectroscopic binaries almost never have circular orbits when born. This indicates that orbit degradation process produces ecccentric orbits, as would be the case with disk braking. The joint eccentricity-period statistics of giant planets around nearby stars is indistinguishable from the same statistics of spectroscopic binaries (e.g. Stepinski & Black 2001), while disk braking is the most popular theory explaining period distribution of those planets. A correlation of close binaries with IRAS sources (Friedmann et al. 1996) suggests that many binaries are surrounded by circumstellar material.

4. Multiples and tides

Direct comparison of the catalogues of spectroscopic binaries and multiple stars has revealed a striking fact: at least 40% of solar-type binaries with periods less than 10 days are members of higher-multiplicity systems, whereas at longer periods the fraction of known multiples is only 8% (Tokovinin 1997). The period distribution of close sub-systems within multiple stars is quite remarkable: it has a maximum at periods from 2 to 7 days (Tokovinin & Smekhov 2002). Similar maximum exists for spectroscopic binaries in Hyades.

Kiseleva et al. (1998) and Eggleton & Kiseleva (2001) modeled the combined effect of stellar dynamics and tidal dissipation leading to the formation of close sub-systems. In a triple star with large relative inclination between inner and outer orbits, the eccentricity of the inner orbit is modulated by the Kozai cycles (Kozai 1962) and may reach high values. Kozai cycles are extremely sensitive to apsidal rotation of inner sub-systems: if its period is comparable to the period of Kozai cycles $P_{cycle} \sim P_{out}^2/P_{in}$, the cycles break. This happens in triple stellar systems like Algol: as soon as the inner orbit acquires high eccentricity and the components begin to interact tidally, apsidal rotation prevents further interaction with outer sub-system. Tides progressively dissipate the orbital energy of the inner pair, and in the end a close sub-system with a period of few days and nearly circular orbit is formed. This mechanism explains the origin of the PMS triple system TY CrA with orbital periods of 2.9 and 268 days (Beust et al. 1997). The drop in the number of sub-systems at periods longer than 7 days corresponds roughly to the cutoff period for tidal orbit circularization.

An alternative mechanism involving tidal dissipation consists in chaotic interactions between stars in very dense clusters. High density may be reached either during the initial collapse of a "cold" cluster followed by violent relaxation or by a process of competitive accretion in an embedded cluster, when most massive stars sink to the center of the cluster and experience strong dynamical friction from the surrounding gas (Bonnell et al. 1998). In both cases close encounters may lead to stellar mergers and to formation of very massive stars. High percentage of close binaries in rich clusters with massive members (García & Mermilliod 2001) is indeed suggestive of this scenario.

5. Observational tests

The mechanisms outlined above are not mutually exclusive: available data suggest that all are encountered in reality, sometimes in combination with each other. Still, there is no theory of close binary formation capable to explain quantitatively the period distribution, the eccentricity and mass ratio statistics, and the dependence of binary properties on their environment. Given the complexity of the physical processes involved, it is very important to constrain the theories as much as possible by observations.

An outstanding challenge is to search for very young close binaries formed already at the infall stage. It seems that such binaries will be exception rather than a rule, but this assertion needs to be checked. If true, it would point to disk braking as a major factor of early binary orbit evolution.

Do *all* close binaries have additional components? This statement will be extremely difficult but not impossible to prove. A combination of precise radial velocities with high-resolution, high dynamic range imaging of nearby close binaries can constrain the detection of tertiary companions to such an extent that we shall be able to prove that some binaries are indeed *not* triple. This would mean that disk braking can shrink binary orbits efficiently even without the aid of tertiaries or tides. An easier but less direct way is to characterize the incidence of spectroscopic sub-systems among the components of visual multiples on the Main Sequence (Tokovinin & Smekhov 2002) or at PMS stage.

The statistics of the orbital elements of close binaries of different mass and age in different environments provides valuable data for testing the formation theories. One of the unexplained facts is the apparent difference of the frequency of spectroscopic binaries among open clusters. Spectroscopic surveys of nearby clusters (Hyades, Praesepe, Pleyades) are complete or almost so. It means that this work must be extended to fainter and more distant clusters, which is now feasible with multi-object spectrometers at large telescopes.

Interaction of a close binary with its disk occurs at a spatial scale of 10 $R_{\odot}$, or 0.7 mas at a distance of 140 pc. Long-baseline interferometry gives a promise to observe this interaction directly in the near future.

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