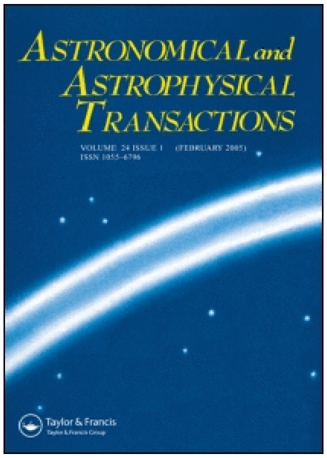

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A tertiary component in close binary systems

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A tertiary component in close binary systems

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In this short review, the existence of third bodies in close binary systems is presented. Starting with the observational methods used to detect the tertiary component, we continue with the theoretical studies concerning the stability and evolution of triple systems and also of multiple systems in general. We next consider the type of tertiary component and give a list of catalogues for these systems; we end with a general discussion.

Keywords: Star; Close binary systems; Light–time effect; Stability; Evolution; Catalogues

1. Introduction

Current observational estimates suggest that about 30% (or even more) of all binary stars are in triple systems. For example, in a sphere of radius 5 pc around our Sun, 46 stars are known; of these, 27 are apparently single systems, 14 are double systems and five are triple systems [1]. Recently, from a comparison of the results, from a 2.2 μm speckle imaging survey of 167 bright Hyades members, with previous radial velocity, optical speckle and direct-imaging Hyades surveys, it was found that 98 were single systems, 59 were binary systems and ten were triple systems [2].

Moreover, the abundance of a third body in W UMa-type systems must be greater than the abundance of triple and higher multiples among star systems in general [3]. So, during the last few years the following question has been increasingly asked: do all close binaries have a third companion? This question is especially pertitnent as, out of 12 binaries, five were found to have tertiary candidates [4]. According to current star formation theories and simulations of dynamic processes occurring in small-N clusters, an enhanced fraction of binaries among the primaries of systems with a brown dwarf or a very-low-mass star in a wide orbit was required [5, 6].

So, the aim of this short review is to present and comment on the tertiary component in close binaries, from both the observational and the theoretical point of view.

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2. Methods of detection of triple and/or multiple systems

Triple and multiple systems have been discovered either after a systematic research or accidentally. To study multiplicity, all kinds of observational material are used. First, *visual*, *photoelectric* and *spectroscopic* observations were used since, in a triple system, very often one member is a spectroscopic binary (or a close eclipsing pair) and the third body is a visual companion. In such a case, the spectrum of a triple star will contain one slowly and two rapidly changing components, and in this way many binaries were found to be triple systems. So, a triple or a multiple system is very often the result of spectroscopic data analysis, as in the case of the young double-line spectroscopic binary HD 34700 discovered recently [7]. Spectroscopy was and still is a very efficient way of detection, especially now as methods and techniques are being continuously developed. Thus, besides the simple methods used long ago to obtain the radial velocities of the component stars of a triple or a multiple system, more complicated and elegant techniques are now used.

The formalism developed recently, for example, make it possible to determine radial velocities from the complex spectra of multiple-component systems with component stars showing very different degrees of rotational line broadening [8]. This technique was applied to a large number of close binaries and the results appeared in a series of papers. Most of the examined binaries are of the contact W UMa type, some of which are new systems discovered by Hipparcos. Thus, the elements of some systems were improved [9], the third component was separated (from the close pair) [10], spectroscopic companions were detected [11] or, finally, some multiple (or suspected multiple) systems were found [12, 13].

Moreover, a highly sensitive technique of spectroscopic observations is that at wavelengths centred around the NaD and Hα lines for the detection of tertiary components in short-period binaries [3]. According to this, the NaD lines are ideal for the detection of late-type unresolved companions, because of their great strength and because they increase with later spectral types. Application of this method to a sample of five W UMa-type binary stars yields positive results in two cases: for SW Lac and V502 Oph.

Speckle interferometry is another technique used to detect triple systems. It not only enables us to determine the orbits of binary stars but also, in combination with light-curve solutions (or spectroscopic observations) has helped to determine the masses, radii and luminosities of at least some of the triple stars (*e.g.* for the HR 6469 case [14]). Regarding its contribution to the multiplicity of binaries, examples have been given in many studies (see, [15–18]).

Concerning photometric observations, and their subsequent analysis to obtain the binary's elements, the following should be considered:

(i) A variation in the inclination angle of a binary may indicate the presence of a third body in it, too. Two such cases are known so far: IU Aur [19–21] and AH Cep [22, 23].

(ii) There are some cases where the 'third light' is necessary for interpretation of the light curves of a system (see, for example, the LY Aur and AH Cep cases given in [23]). (Although it is also possible that another explanation exists, the idea proposed so far is the existence of an extra component.)

In eclipsing binaries, in particular, the presence of a third body in a system can be detected from the behaviour of the times of its minimum light (*light–time effect*). Among others, in the early work [24] and in recent publications [25, 26], many systems have been studied, and a catalogue of such systems has also been presented [27]. Many other studies based on the $O - C$ diagram analyses of individual binaries can be found in the literature concerning the presence of one or more components in them, *e.g.* for ZZ Cas [28], for AM Leo [29], for V505 Sgr [30] and for RT Lac [31] and many others, although not all of these have been properly analysed, as is the AK Her case [32]. For a proper analysis, new methods of analysing an $O-C$ diagram exist today. A review of the traditional and new methods can be found in [33], while the eclipsing binary BX And has been analysed by a classical method and by a new method for comparison [34].

In some cases the presence of the third body in a close eclipsing binary is really obvious from the shape of its $O-C$ diagram, which is sinusoidal and strictly periodic. However, there are cases where even an $O-C$ diagram can be changed when many more data are added; see, for example, the $O-C$ diagram of the short-period eclipsing binary AB And [35].

Moreover, the observed changes in the $O-C$ diagram of an eclipsing binary may arise when more than one mechanism is active. An example of this could be RU Mon, where both the apsidal motion and the light–time effect were considered [36].

3. Stability

Concerning the stability of multiple systems, it was found that triple systems are generally stable [37–39]. This problem has attracted the attention of many investigators. So, very important investigations have been made in the past [40–45] as well as during the last decade [46, 47]. To be more specific, a lower limit for the stability of the ratio P_L/P_S was determined in the study of the dynamic stability of triple systems, with initially circular orbits. This limit varies from 6.3, through 4.3, to 2.4, as the ratio $P = M_3/(M_1 + M_2)$ of the mass of the distant companion to the mass of the inner pair varies from 100, through 1, to 0.01 [44].

The effect of eccentricity was examined and it was found that, for systems with binaries moving on circular orbits, the stability regions are slightly expanded or contracted in size for large or small mass ratios respectively, as the eccentricity of the outer mass is increased [45]. It was also found that retrograde systems are more stable. The effect of the stellar wind on the stability of triple systems was studied [47].

Also, great progress has been made during the last 3 to 4 years. It was thus found that, as a rule, stable triple systems display pronounced hierarchy [48]. Investigations in the last few years have concerned special cases of multiple systems, too. Thus:

(i) Of 16 multiple systems studied, 11 were found to be stable, while the rest (five) may be unstable on timescales of about 10^6 years or less; all six stability criteria were found to be in qualitative agreement with the numerical computation [49].
(ii) The dynamic stabilities of the quadruple systems HD 68255/6/7 and HD 76644 were studied via numerical integration of the equations of motion of the four-body problem, with chain-like regularization of close stellar interactions. It was found that the first system is probably stable, while HD 76644 is unstable [50].

Moreover, it was found that triple systems are unstable if the ratio of the orbital period P_S of the enclosed binary to the period P_L of the third component exceeds a critical value. From a $\log P_L - \log P_S$ diagram, it was shown that the stability criteria are satisfied for the majority of multiple systems with $P_L > 10P_S$ [51]. From a similar diagram for triple systems, a bimodal distribution of P_S with a gap at $P_S \approx 100$ days was noted, which can hardly be explained by the discovery biases [52].

4. Evolution

Very little was known about the evolution of multiple systems. Our knowledge until recently was limited to triple stars only. Observations show that components of triple stars are usually so far apart that the included binary and the third star can be studied separately, as if they were isolated stars.

4.1 *Chemical evolution*

If the included binary loses its mass slowly, on a timescale that is long compared with the orbital period of the distant companion, the triple system remains gravitationally bound, but the companion moves away from the included binary with an ever-increasing orbital period. If, on the other hand, mass loss takes place on a timescale that is short compared with the orbital period of the distant component, and if more than half of the total mass of the system is lost, the triple system will become unbound [53].

Moreover, some fraction of SNe Ia (and also other explosions involving the collapse of an ONe white dwarf to a neutron star) can be attributed to close triple systems. Some triple systems evolve into an unstable configuration and eject, at a high velocity, simple helium white dwarfs, or subdwarfs that evolve into helium white dwarfs.

4.2 *Dynamic evolution*

As regards the dynamic evolution, the following studies have been carried out:

(i) The dynamic evolution of small groups ($N = 3 - 18$) of stars in the framework of the gravitational N-body problem, taking into account the possible coalescences of stars and the ejection of single and binary stars from the system, has been studied [48].
(ii) The dynamic evolution of 15 000 equal-mass triple systems with zero initial velocities (the free-fall three-body problem) has been studied, too [54]. The results of this was 170 triple systems, which reach a state where the motions take place within a limited region of phase space during a long time. These regions are concentrated in the zones of regular motions in the vicinities of stable periodic orbits.
(iii) The dynamic evolution of plane non-rotating triple systems for which the initial conditions were specified in such a way that one of the bodies is located at the centre of mass of the triple system has also been investigated [55].
(iv) The dynamic evolution of 120 000 equal-mass rotating triple systems has been examined, too. The initial coordinates and velocities of the components were chosen randomly. The initial data were chosen assuming that either there was an initial hierarchical structure or there was not [56].

5. Types of third body

Another very interesting topic is the types of third body discovered. Thus, the third body can be an ordinary main-sequence star or a highly evolved star. It can also be a binary star itself (*e.g.* FZ CMa [57], HR 226 = ADS 784 [58], IU Aur [59] and SZ Cam [60]). The eclipsing and spectroscopic binary TY CrA, which is a Herbig Be star and the brighter member of a young embedded cluster in the Corona Australis dark cloud complex, is interesting. TY CrA was found to contain a third component at a distance of about 1 AU from the close pair [61, 62]. So, usually, the third body is either a single star, or it can be a binary, as has already been mentioned. Some cases have also been reported in which the third body is a substellar mass object; see, for example, the V471 Tau case, in which the eclipsing binary consists of a white dwarf and a red dwarf. From a light–time effect study, it was found that for inclinations greater than 30° the mass of the third component is substellar [63]. Recent studies have given the same result, although different values for the period and other elements of the third companion were derived. It was thus found that for i_3 greater than 35° its mass would be below the limit of $0.7M_{\odot}$, and thus this star would be a brown dwarf [64, 65]. This fact and the recent discoveries of a continuously increasing number of planets orbiting either single or binary stars have attracted increasing interest. A good example of this could be a new component E in the nearby multiple system Gliese 225.2, making it a quadruple system [66]. A preliminary 24 year astrometric orbit of this new system was derived, while the new component E, which is 3 magnitudes below the main sequence, has an anomalously blue colour index. From these, the mass of the E component was estimated as approximately $0.2M_{\odot}$.

6. Lists and catalogues of triple and multiple systems

A large number of catalogues of triple and multiple systems can be found in the literature. Over the 20–25 last years, the following catalogues have been published:

(i) a list of triple systems with periods $P < 100$ years [67];
(ii) a catalogue of visual triple stars, where all three components were resolved [68], which was later extended to include 700 visual triple systems within 200 pc from the Sun [69], but not all of these were physically related;
(iii) a list of eclipsing binaries with visual companions [70];
(iv) a catalogue of triple and quadruple systems, in which short-period systems are not included [71];
(v) a catalogue of 612 multiple stars, known as the multiple star catalogue (MSC), of multiplicity 3–7, is the latest to appear in the literature [72] (all the multiple stars included in it are hierarchical with a few exceptions, while half of them are within 100 pc from the Sun; elements such as P, a and q are estimated for each subsystem, and orbital elements are given when available).

7. Discussion

Soon after the first catalogues of binary stars appeared, it was realized that a considerable percentage of binary stars had a third component or more and were in fact simply triple or even multiple systems. It was thus found that about 10% of all binary systems are close binaries (i.e. with $P < 1000$ days) and, among those with $P < 10$ days, over 40% are known to belong to higher-multiplicity systems [4]. To answer the question of whether all close systems have tertiary companions, 12 nearby and apparently ‘single’ close binaries with solar-mass dwarf primary components were selected (from the eighth catalogue of spectroscopic binary orbits) and images in the B and R filters were taken. Of these 12 single binaries, four were found to have tertiary candidates (HD 67084, HD 120734, HD 93486 and VV Mon), while observations using adaptive optics reveal a companion to HD 148704 also, making five the binaries with tertiary candidates [4].

Moreover, a large sample of visual multiples of spectral types F5-M was surveyed for the presence of spectroscopic subsystems. So, some 4200 radial velocities of 574 components were measured between 1994 and 2000 with a correlation radial velocity meter [73]. The results of this latter work, which have been given in [73], are very interesting and are as follows:

(i) In triple systems with both outer (visual) and inner (spectroscopic) orbits known, an anticorrelation between the periods of inner subsystems and the eccentricities of outer orbits exists, which must be related to dynamic stability constraints.
(ii) The period distribution of subsystems has a maximum at periods from 2 to 7 days, which can probably be explained by a combination of tidal dissipation with triple-star dynamics.

The statistics of stellar systems of multiplicity three and higher have been reviewed recently [74]. So, some 700 multiples are expected among the 3383 stars of spectral types F, G and K within 50 pc, while only 76 of these are actually known.

This large percentage has caused investigators, especially those who analyse photometric data only, such as the $O-C$ diagrams of eclipsing binaries to 'discover' third bodies even where there is none. Many such examples can be found in the literature. All these lead to the following question: how sure can we be, if the presence of the third body has not been confirmed by spectroscopy or observations of any other kind? (In particular, as the 'detected' periodic terms are not constant, as expected, in most cases they are the result of Fourier transformation applied to the $O-C$ diagram, which is highly dependent on the ephemeris used.) The answer to this question is not easy at all and cannot be simple. It should not be forgotten that the detected periodicities, at least in some cases, could be contributed for other reasons, too. In most cases, for example, they are explained as being the result of magnetic activity in one or both components of the binary star [75, 76]. This is the reason why most investigators in their analyses take into account both hypotheses: a third body and magnetic activity cycles. However, for the first mechanism a constant periodicity is required, which does not happen, as has resulted from some examined systems [77]. For this reason, and as in many cases the observed variations in the $O-C$ values do not have a constant periodicity (as there should be in the case of a third body), a new approach has been suggested [78].

In cases where the existence of the third body is certain, its influence has to be removed from the $O-C$ diagram before any further analysis. This also has to be done if there is apsidal motion, as in the case of RW Lac [79].

The occurrence of multiple systems is of special interest, since a high frequency may denote a mechanism according to which three or even more stars can be produced from a collapsed cloud. Thus, the distribution of such systems may give information about the physical conditions inside an interstellar cloud, and the processes that are dominant during contraction. According to current star formation theories and simulations of dynamic processes occurring in low-N clusters, an enhanced fraction of binary stars among the primaries of systems with a brown dwarf or very-low-mass comparison in a wide orbit is expected, as already mentioned [5]. To test this theoretical result, high-resolution adaptive optics imaging data of six systems were obtained to investigate the duplicity of the primaries [6].

So, apart from the problems and difficulties, many binary systems were recognized, and still are, to consist of more than two stars, *e.g.* the new component E in the nearby multiple system Gliese 225.2 and already referred to [66], or the triple or quadruple systems discovered during some recent spectroscopic studies [11, 12, 80, 81].

From the above, it is clear that many contributions, both theoretical and observational, have demonstrated the existence of a tertiary component in close binaries. From the theoretical point of view the birth, formation, evolution and statistics have been examined. As regards observations, although most contributions have been from spectroscopy, photometry has offered much, too.

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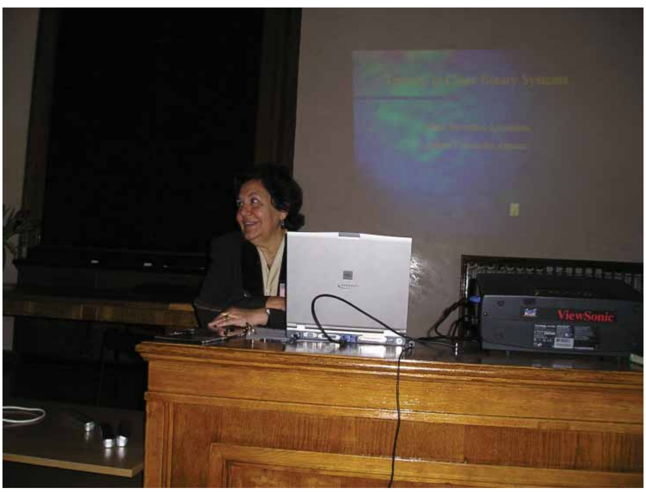

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