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Orbit Orientations and Eccentricities in Triples: Implications on their Formation and Evolution

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Abstract. Observations of the relative alignment of inner and outer orbits in visual multiple stars suggest a moderate, but significant, correlation. The distribution of the relative angle Φ between the orbital planes of triple stars that are formed by dynamical decay from realistic initial conditions agrees quantitatively with the latest observational data, as recently shown by Sterzik & Tokovinin (2002). The eccentricity distribution $f(e)$ of outer orbits for a sub-sample of long-term stable triple systems is also consistent with the observed distribution. The statistics of Φ and e are important fossil records of star formation that allow to sensitively constrain physical processes and properties of initial clusters.

1. Introduction

Observable properties of triple and higher order multiple systems can give important information about their formation and evolution. For example, the relative alignment of orbits can, in principle, constrain their formation mechanisms. Binary formation in rotating, highly flattened, clouds should produce coplanar configurations (planetary configurations), whereas chaotic dynamical processes, expected in environments with high stellar densities should lead to uncorrelated orbital momenta in the resulting multiples.

Measurements of the relative orientation angles of orbits in real multiple stellar systems are difficult, as they require solutions of the inner and outer orbits, spanning vastly different timescales up to thousands of years. As already pointed out by Fekel (1981), at least 1/3 of all triple stars should have non-coplanar orbits, based on a sample of 23 stellar systems. Tokovinin (1993) analysed visual orbits of 14 stellar systems contained in the Multiple Star Catalog (MSC, Tokovinin 1997). He found that neither coplanarity nor complete random orientation prevailed. Instead, a modest degree of orbital momenta alignment was required to explain the data. Recently, Sterzik & Tokovinin (2002, in the following ST) enhanced this study by increasing the statistical basis of the observed data-set to 22 multiple systems with known orbits. They confirmed the earlier studies, and found an average angle between the momentum vectors of inner and outer orbits, $\langle\Phi\rangle$, to be between 67° and 79°. For the first time, they tried to explain the measured Φ distribution by analysing triple systems that form as (meta-)stable remnants in numerical simulations of dynamical decaying stellar clusters. These clusters, initially containing a few stellar embryos in a non-hierarchical configuration, might represent an important evolutionary phase during star formation.

In this contribution we continue to statistically compare the properties of triple stars resulting from dynamical decay simulations with data from the MSC. First, we compare the relative orbit orientations. Then, we compare the eccentricity distributions of outer orbits of the simulated data with those found in MSC, following a recent study by Shatsky (2001). We show that the general trends in the distribution functions are matched by the assumed, simplistic model prescription (pure gravitational interactions among point-masses). Finally, we discuss that additional physical processes, such as dissipation during close encounters, are probably required to explain specific features in the observed distribution functions $f(\Phi)$ and $f(e)$.

2. Orbital Plane Correlations

ST analyzed the statistics of the angle Φ between the angular momentum vectors of inner and outer orbits in triple systems produced in direct dynamical decay simulations of few-body clusters with $3 \leq N \leq 10$. The decay calculations use precise numerical orbit integrators to evolve few-body point-mass systems under their mutual newtonian gravity until (meta-) stable sub-systems are formed (for a detailed description of the methodology see Sterzik & Durisen, 1998). Assuming a realistic stellar mass function, the Φ correlation is sensitive to the geometry and rotation of the progenitor cluster. Models which involve a moderate oblateness of 10:1 and relative rotational energy characterized by $\beta = 0.1$ yield a mean $\langle\Phi\rangle = 63° \pm 5°$. For the 22 real multiple systems from MSC with both inner and outer visual orbits known, there is an ambiguity in the determination of the angle, so 44 angles Φ^* can be computed, of which only 22 are true angles; the average is $\langle\Phi^*\rangle = 79° \pm 6°$. When this ambiguity is incorporated in the simulations, we obtain $\langle\Phi^*\rangle = 73° \pm 5°$.

For quantitative comparison, we plot the cumulative distribution function of Φ^* in Fig.1. Completely uncorrelated orbit orientations would follow the thin line. Instead, the MSC data appear slightly, but significantly, correlated. The orientation distribution for the model triples resulting from dynamical decay matches the observations well for $\Phi \leq 90°$. Note that the depletion of perpendicular orbit orientations $\Phi \approx 90°$ apparent in the data *cannot* be reproduced by the decay models described above.

3. Eccentricity Distribution

It is well known that the eccentricity distribution of binary orbits resulting from pure stellar dynamical interactions is $f(e) = 2 \cdot e$. This is in fact observed for

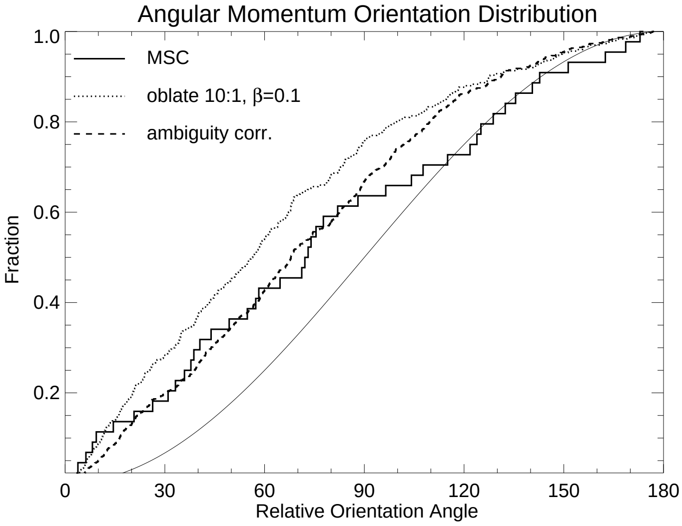

Figure 1. Cumulative distribution of the relative orbit orientation Φ^*.

visual binaries in the solar neighborhood (Duquennoy & Mayor 1991). For the *outer orbits* in visual triple systems the linear distribution of $f(e)$ does not hold, as has been recently demonstrated by Shatsky (2001) based on the analysis of 174 multiple systems from the MSC. In the following we discuss the $f(e)$ of outer orbits in triple systems generated by dynamical decay calculations. A priori it is not clear how this distribution looks like. The situation is complicated by the fact that triple systems are intrinsically meta-stable and decay chaotically on long orbital time scales.

In Fig.2 we plot the distribution of outer eccentricities for all (3636) simulated triple systems investigated by ST. We note that the distribution does not follow a simple $f(e) = 2 \cdot e$ law. Most significantly, the high eccentricity bin $e \approx 1$ is over-represented. But these systems are not long-term stable. The systems shown were integrated for 300 cluster crossing times, obviously not long enough to decay meta-stable triples. Carrying the orbit integrations up to 10000 crossing times we can show that the systems having high eccentricity orbits decay preferentially. These calculations are very (computing) time expensive, though. Therefore we employ a semi-analytic stability criterion developed by Mardling & Aarseth (2001) that describes the survival rate in hierarchical triples having coplanar, prograde, orbits. The critical period ratio that defines the stability boundary is a function of the mass ratio and the outer eccentricity, implying that high eccentricity systems have to be dynamically unstable. We apply their criterion to our sample, and show the distribution of *stable* triple systems in Fig.2 (hatched histogram). The $f(e)$ distribution becomes bell-shaped.

We compare this synthetic distribution with observed data following the analysis of Shatsky (2001). Outer eccentricities in real triples are not directly observable. Therefore Shatsky introduced a variable γ which relates observable orbital motion to the orbital eccentricity. From a given $f(e)$, $f(\gamma)$ can be generated. Figure 3 shows the results. The thick line depicts the distribution of $f(\gamma)$ from MSC, the dashed dotted curve assumes the synthetic $f(e)$ distribution of *stable* triple systems from Fig.2. The general appearance of both

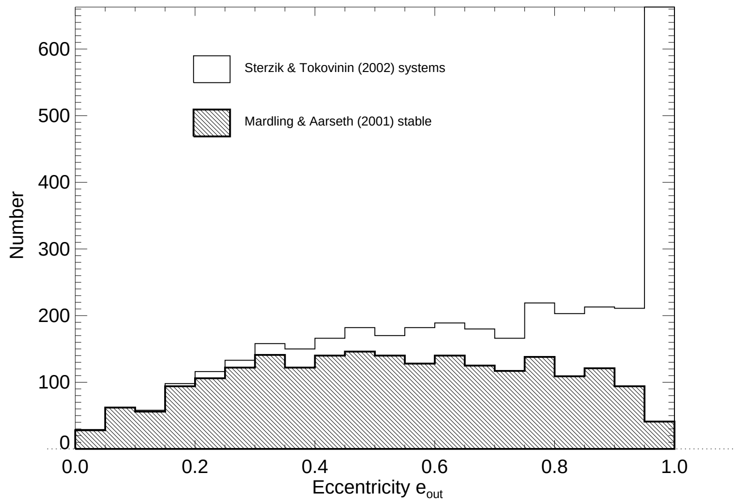

Figure 2. Distribution of outer eccentricities of 3636 triple systems from ST before and after stability correction.

distributions is similar, with a higher abundance of $\gamma \approx 90$ systems, and a lower abundance of low- and high-γ systems. A formal comparison yields $\chi^2 = 14$. An even better match can be achieved once the MSC sample is further sub-divided. Considering only triples in MSC that have a high degree of stability, χ^2 reduces formally to 6 (dashed line). Shatsky (2001) argued that the dynamical stability constraint in triple systems is not sufficient to explain the "rounded-off" outer orbits. But he assumed $f(e) = 2 \cdot e$ as underlying outer eccentricity distribution for triple systems. Here, we have shown that numerical simulations of decaying few-body systems *do not* produce a linear distribution, but instead a bell-shaped one (once unstable systems are excluded). This distribution is more consistent with current data.

4. Conclusions

The statistical comparison of properties in wide (visual) triple systems originating from dynamical decay calculations with observable data shows

1. The distribution of relative angular momentum vectors between inner and outer orbit exhibits slight, but significant, orbital alignment in observed triples.

2. The distribution can be quantitatively matched by synthetical triples originating from dynamical decay calculations. The progenitor clusters are constraint to have a modest degree of geometrical oblateness and rotation.

3. Observationally, perpendicular orbit orientations appear depleted with respect to a pure random distribution. This cannot be explained by gravitational point-mass dynamics alone.

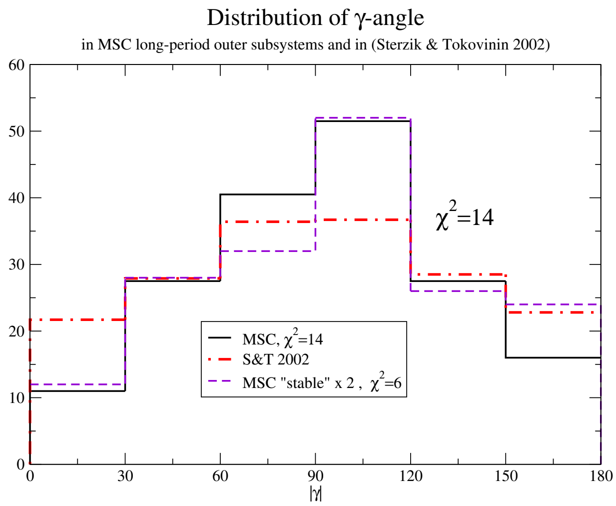

Figure 3. Comparison of observed and model $f(\gamma)$ distributions.

4. The outer eccentricity distribution in the synthetic triple sample does not follow a $f(e) = 2 \cdot e$ law, as for binary systems. Once cleaned by unstable or meta-stable systems, the eccentricity distribution is bell-shaped, and appears to be consistent with current observations.

The depletion of $\Phi \approx 90°$ (perpendicular orbits) - if observationally confirmed - might point towards an interesting additional physical effect that has not yet been incorporated in the numerical modelling. Perpendicular orbits are especially sensitive to dynamical Kozai cycles, which pump the *inner eccentricities* in triples. Then, under the action of tidal friction and other dissipative effects, inner orbits shrink, outer eccentricities diminish, and orbit orientations are modulated (see e.g. Kiseleva et al. 1998). The statistical effects have to be explored, and it is planned to include this process in future numerical decay models.

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