The warped young stellar disc in the Galactic Centre

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\begin{abstract}
Within the central parsec of the Galaxy, several tens of young stars orbiting a central supermassive black hole are observed. A subset of these stars forms a coherently rotating disc. Other observations reveal a massive molecular torus which lies at a radius \(r \approx 1.5\) pc from the centre. In this paper we consider the gravitational influence of the molecular torus upon the stars of the stellar disc.

\textbf{Methods.} We derive an analytical formula for the rate of precession of individual stellar orbits and we show that it is highly sensitive upon the orbital semi-major axis and inclination with respect to the plane of the torus as well as on the mass of the torus.

\textbf{Results.} Assuming that both the stellar disc and the molecular torus are stable on the time-scale \(\geq 6\) Myr, we constrain the mass of the torus and its inclination with respect to the young stellar disc. We further suggest that all young stars observed in the Galactic Centre may have a common origin in a single coherently rotating structure with an opening angle \(\lesssim 5^\circ\), which was partially destroyed (warped) during its lifetime by the gravitational influence of the molecular torus.

\textbf{Key words.} stellar dynamics — Galaxy: nucleus
\end{abstract}

1. Introduction

Near infrared observations of the central parsec of the Galaxy that were made over the past decade have brought new views of the environment in the vicinity of a supermassive black hole. They revealed a numerous population of young massive stars which may be distinguished into at least two different groups: within a distance \(\lesssim 0.03\) pc from the centre there are found more than ten so called S-stars orbiting the supermassive black hole on apparently randomly oriented and highly eccentric \((e \gtrsim 0.8)\) orbits. They appear to be standard OB main sequence stars (Ghez et al. 2003, Eisenhauer et al. 2005) which is in contradiction with strong tidal forces that prevent stellar formation at the place. Unless these stars mimic their age, it is likely that they have migrated to the centre from larger distances.

Further away, at \(0.03\) pc \(\lesssim r \lesssim 0.5\) pc, nearly up to one hundred young stars were detected (see Paumard et al. 2006 for one of the most recent reviews). These stars are classified mainly as post main sequence OB supergiants and Wolf-Rayet stars. According to the evolutionary phase, their age is estimated to be \(6 \pm 2\) Myr. Levin & Beloborodov (2003) pointed out that a substantial fraction of these stars form a coherently rotating disc (usually referred to as a ‘clockwise’ stellar disc or CWS). It is a flaring disc with an opening angle \(\approx 15^\circ\) with a rather sharp inner edge at \(0.03\) pc and it extends up to radius of \(\approx 0.3\) pc. The radial column density profile of the CWS decreases approximately as \(r^{-2}\), i.e. most of the stars are concentrated at the inner edge. The mean plane of the disc can be determined by two angles: inclination \(i' \approx 127^\circ\) with respect to the plane of the sky and longitude of the ascending node \(\Omega' \approx 99^\circ\) (measured from the North direction; see Paumard et al. 2006 for a detailed description of the convention). Levin & Beloborodov (2003) suggested that this disc-like pattern is a consequence of a stellar formation in a self-gravitating accretion disc.

Further analyses (Genzel et al. 2003, Paumard et al. 2006) indicate the presence of another coherent stellar system which is usually referred to as the ‘counter-clockwise’ stellar disc (CCWS). This structure is assumed to be formed by fewer \((\lesssim 15)\) stars, it is narrower in the radial extent being concentrated around \(r \gtrsim 0.15\) pc and has a larger opening angle \(\approx 20^\circ\). The existence of the CCWS disc is a matter of an ongoing debate (e.g. Lu et al. 2007), nevertheless, even if it is accepted as an explanation of the origin of another subset of young stars in the Galactic Centre, there would still remain more than twenty stars not belonging to any of the two stellar discs and, therefore, without a satisfactory explanation of their origin.

The gravitational potential in the considered region is dominated by the supermassive black hole of mass \(M_\bullet \approx 3.5 \times 10^6 M_\odot\) (Ghez et al. 2003). It is surrounded by a roughly spherical cluster of late-type stars. The radial density profile is well fitted with a broken power-law \(\rho(r) \propto r^{\beta} \) with index \(\beta = 1.19\) below \(r = 0.22\) pc and \(\beta = 1.75\) above the break radius (Schödel et al. 2007). Its mass, \(M_\bullet\) within \(1\) pc is comparable to the mass of the black hole.

The central region is surrounded by a molecular torus (circum-nuclear disc; CND) which lies at the outer edge of the black hole’s sphere of influence \((R_{\text{CND}} \approx 1.5\) pc). Its mass estimated from the radio observations of ionised molecular gas is \(M_{\text{CND}} \approx 10^6 M_\odot\) (Christopher et al. 2005). This massive structure defines a non-spherical component of the gravitational field in the central parsec.

In this paper we investigate the influence of the CND upon the dynamical evolution of the disc-like stellar structures. In the subsequent section we briefly review the dynamics in the perturbed Keplerian potential. In Sec. 2 we apply the results on the motion of the stellar discs — we present constraints on some parameters of the CND and the CWS determined from their gravitational interaction and we also give suggestions on the
dynamics of the whole system of young stars over its lifetime. Conclusions and discussion of our results are given in Sec. 4.

2. Dynamics in the perturbed Keplerian potential

For the purpose of the study presented in this paper we introduce a simple model of the Galactic Centre which consists of three main constituents determining the gravitational field: (i) the central supermassive black hole of mass $M_\bullet = 3.5 \times 10^6 M_\odot$ which is treated as a source of the Keplerian potential, (ii) the massive molecular torus modelled as an infinitesimally thin ring of radius $R_{\text{CND}}$ and mass $M_{\text{CND}}$ and (iii) a spherical stellar cusp with a power-law density profile $\beta$ and mass $M_c$ within the radius $R_{\text{CND}}$. Both the ring and the cusp are centred on the black hole.

The stars are treated as test particles whose motion is determined by the composed smooth external potential. Their orbits can be represented by five orbital elements: the semi-major axis, $a$, eccentricity, $e$, inclination, $i$, argument of pericentre, $\omega$, and longitude of the ascending node, $\Omega$. Here we assume the angles to be measured in the frame in which the ring lies in the $x$-$y$ plane. For convenience, the results presented in the subsequent section will be transformed into coordinates with $x'$-$y'$ representing the plane of the sky and $z'$ pointing from the observer. The inclination and longitude of the ascending node in this observer’s coordinate system will be denoted $i'$ and $\Omega'$, respectively.

If the gravity of the spherical cusp were ignored, the dynamics in the field of the central body and the ring would be equivalent to the reduced hierarchical three body problem. In this case, the orbital elements $e$, $i$, $\omega$ and $\Omega$ would undergo secular evolution (Kozai 1962, Lidov 1962) on a time-scale of

$$T_K \equiv \frac{M_\bullet}{M_{\text{CND}}} \frac{R_{\text{CND}}^3}{a \sqrt{G M_\bullet a}}.$$ (1)

The equations of motion for mean orbital elements read:

$$T_K \sqrt{1 - e^2} \frac{de}{dt} = \frac{15}{8} e (1 - e^2) \sin 2\omega \sin^2 i,$$ (2)

$$T_K \sqrt{1 - e^2} \frac{di}{dt} = -\frac{15}{8} \cos 2\omega \sin i \cos i,$$ (3)

$$T_K \sqrt{1 - e^2} \frac{d\omega}{dt} = \frac{3}{4} [2 - 2e^2 + 5 \sin^2 \omega (e^2 - \sin^2 i)],$$ (4)

$$T_K \sqrt{1 - e^2} \frac{d\Omega}{dt} = \frac{3}{4} \cos i [1 + 4e^2 - 5e^2 \cos^2 \omega].$$ (5)

The temporal evolution does not depend on the angle $\Omega$ which is merely a consequence of the axial symmetry; furthermore, energy conservation implies a constant $\omega$ in this order of approximation.

Including the gravity of the spherical cusp leads to an additional shift of the pericentre which can be incorporated by an extra term in equation (4), dependent upon the global parameters of the cusp and the semi-major axis and eccentricity of the orbit (Ivanov et al. 2005). The overall influence of the cusp can be characterised by a decrease of the amplitude of the oscillations of eccentricity and inclination and shortening of their period (Karas & ˇSubr 2007). This is clearly seen also in Fig. 1 which shows the evolution of an example orbit both in the case with and without the potential of the spherical cusp. On the other hand, a generic influence of the cusp upon the evolution of $\Omega$ lies in diminishing the variations of its first time derivative; the characteristic timescale of the change of $\Omega$ becomes in general much longer than that of the mutually coupled elements $e$, $i$ and $\omega$.

![Fig. 1. Evolution of orbital elements of two example orbits. The solid line represents a trajectory in the gravitational field of the central mass $M_\bullet = 3.5 \times 10^6 M_\odot$ and a ring of radius $R_{\text{CND}} = 1.5 \text{pc}$ and mass $M_{\text{CND}} = M_\bullet$. The dotted line shows an orbit integrated in the field including in addition a spherical cusp of mass $M_c = 0.1 M_\bullet$. In both cases the initial values of the orbital elements are: $a = 0.1 R_{\text{CND}}$, $e = 0.1$, $i = 80^\circ$ and $\Omega = 0$.](image)

Within the context of this paper we are interested in a system where $M_c \gtrsim 0.1 M_{\text{CND}}$. In this case the amplitude of the oscillations of eccentricity and inclination can be considered negligible and $\omega$ rotates with frequency much higher than that of $\Omega$. This configuration allows us to simplify eq. (5) by averaging over one revolution of $\omega$:

$$\frac{d\Omega}{dt} \approx -\frac{3}{4} \frac{\cos i}{T_K} \frac{1 + \frac{5}{2} e^2}{\sqrt{1 - e^2}} \approx \text{const}.$$ (6)

The change of $\Omega$ over an interval $\Delta t$ can then be written as:

$$\Delta \Omega = -\frac{3}{4} \cos i a^{3/2} \frac{\sqrt{GM_\bullet M_{\text{CND}}}}{R_{\text{CND}}^3} \frac{M_\bullet}{\sqrt{1 - e^2}} \Delta t$$

$$\times \cos i \left[ 1 + \frac{5}{2} e^2 \right] \frac{R_{\text{CND}}^{-3/2}}{1 \text{pc}} \frac{M_\bullet}{M_c} \frac{\Delta t}{1 \text{Myr}}.$$ (7)

According to the underlying perturbation theory, eqs. (1) – (7) refer to the elements averaged over one orbital period, which cannot be trivially mapped to the osculating elements defined by
3. Consequences of differential precession

3.1. Constraints on the CND

Let us now consider an ensemble of stars forming a thin disc, i.e. with inclinations and longitudes of ascending nodes lying in a narrow interval. Let us further assume that the stellar orbits evolve solely due to the external gravitational potential determined by fixed parameters \( M_\star, M_\odot = M_\star, M_{\text{CND}} \lesssim M_\star \) and \( R_{\text{CND}} \gg a \). The key feature of the orbital evolution will be precession around the symmetry axis of the ring-like component of the gravitational field.

If the semi-major axes of stars at the inner edge of the disc are smaller than those at the outer edge by a factor of \( \gtrsim 5 \), the two edges of the disc will precess at a rate different by a factor \( \gtrsim 10 \). After a certain period of time, their angular momenta will point to completely different directions, i.e. the disc-like structure will be destroyed. Hence, the requirement of the stability of the disc over a given period of time transforms into the requirement of a sufficiently slow precession at its outer edge.

Let us consider the subset of the young stars in the Galactic Centre which form the ‘clockwise’ stellar disc (CWS). Inserting values \( R_{\text{CND}} = 1.5\,\text{pc}, a = 0.1R_{\text{CND}}, \Delta t = 6\,\text{Myr} \) and \( e = 0 \) into eq. (7), we obtain

\[
\Delta \Omega = -560^\circ \cos i \frac{M_{\text{CND}}}{M_\star} \cdot \frac{M_\star}{M_\odot}. 
\]

In order to be compatible with observations, \( \Delta \Omega \) has to be smaller than \( \lesssim 10^\circ \), which is the opening angle of the inner part of the CWS (Beloborodov et al. 2006). Hence, eq. (8) poses a constraint upon the inclination of the disc with respect to the molecular torus, depending on its mass. Considering e.g. \( M_{\text{CND}} \approx 0.3M_\star \) (Christopher et al. 2005) requires \( \cos i < 0.06 \), i.e. \( i \gtrsim (86^\circ, 90^\circ) \). Simultaneously, this poses an upper limit \( \theta_0 \lesssim 5^\circ \) on the initial opening angle of the stellar disc. For the sake of simplicity, we have considered a common sense of precession of all disc stars, i.e. \( i < 90^\circ \). Identical results would be obtained for \( i > 90^\circ \) due to the symmetry of the problem. The constraint would be tighter by a factor of \( \approx 1.5 \) if we consider nonzero \( \lesssim 0.5 \) eccentricities of the stellar orbits.

To conclude this analysis, we remark that \( \cos i = n_{\text{CWS}} \cdot n_{\text{CND}} < 0.06 \) is in accord with estimates of the normal vector of the plane of the disc and torus \( \left( n'_{\text{CWS}}, \Omega', i' \right) = (\sin i' \cos \Omega', -\sin i' \sin \Omega', -\cos i') \).

1 We follow the convention of Paumard et al. (2006) according to which angles \( \Omega' \) and \( \Omega' \) are related to the normal vector of the orbital plane as: \( \left( n'_{\text{CWS}}, \Omega', i' \right) = (\sin i' \cos \Omega', -\sin i' \sin \Omega', -\cos i') \).

3.2. A common origin of young stars in the Galactic Centre?

Formula (8) indicates that orbits of stars at radii 
\( \gtrsim 0.1\,\text{pc} \) and/or inclinations \( i < 85^\circ \) or \( i > 95^\circ \) were considerably affected by precession within the past 6 Myr, i.e. their current orbital parameters are different from their values at the time of the birth. We suggest a possibility that stars which are not considered to be members of the CWS nowadays have been its members at the time of its formation. During the \( \sim 6\,\text{Myr} \) of the dynamical evolution their orbits were subject to precession due to the gravity of the CND and were detached from their parent stellar system. This model could represent a possible solution of the problem of the origin of all young stars in the Galactic Centre.

The mapping between the initial and the current orientation of the stellar orbit is formally rather straightforward within our simple model. Unfortunately, the observational data do not provide us with sufficiently accurate values of the parameters \( R_{\text{CND}} \) and \( M_{\text{CND}} \). Furthermore, the high sensitivity of the precession rate upon the inclination and semi-major axis together with a lack of robust determination of these orbital elements from the observational data also stand as a severe obstacle in an attempt to track the orbits of the observed stars back in time, which could prove or discard the hypothesis of a common origin. In the rest of this section we describe a test shows that our model is compatible with the publicly available observational data.

We have taken data from Table 2 of Paumard et al. (2006) from which we have considered all stars with determined 3D velocity and index \( \gtrsim 15 \) (i.e. excluding the S-stars) which gives in total \( N_\star = 72 \) stars. Five free parameters of the model consist of the two angles, \( (\Omega'_0, i'_0) \), determining the initial orientation, \( n'_0 \), of the stellar disc; another two angles, \( (\Omega'_{\text{CND}}, i'_{\text{CND}}) \), determine the orientation of the CND, and \( M_{\text{CND}} \) represents its mass. (The last parameter can be considered as a degenerate combination of \( M_{\text{CND}}, R_{\text{CND}} \) and \( \Delta t \); in the following, we will implicitly assume \( R_{\text{CND}} = 1.5\,\text{pc} \) and \( \Delta t = 6\,\text{Myr} \).) For a given set of parameters we scan the 1\( \sigma \) neighbourhood of each star’s velocity with sampling \( d_\theta \). The \( x' \) and \( y' \) coordinates of the stars’ positions are assumed to be determined exactly. On the other hand, the \( z' \) coordinate (along the line of sight) is unknown. Therefore, we scan it with sampling \( d_\delta \) in a whole range allowed by the condition that the star is gravitationally bound to the black hole. In total, we consider \( V_{1\sigma} = d_\delta d_\theta \) pairs of position and velocity vectors which represent states compatible with the observational data of a particular star. For each state we perform a rotation of the normal vector of the orbit around the axis of the CND according to formula (7), which gives its direction, \( n_{0,0} \), at \( t = 0 \), i.e. 6 Myr ago. We further calculate its angular distance to \( n_{0,0} \), \( \cos \theta_0 = n_{0,0} \cdot n_{0,0} \) and count the number of states, \( N_{j,5} \), with \( \theta_0 < 5^\circ \). We consider the measured star’s position and velocity to be compatible with the hypothesis that it was born in the disc with normal vector \( n'_0 \) and thickness \( 5^\circ \), provided \( N_{j,5} > 0 \). Finally, we denote \( N_j(\Omega'_0, i'_0, \Omega_{\text{CND}}, i_{\text{CND}}, M_{\text{CND}}) \) the number of stars with \( N_{j,5} > 0 \) for a given set of values of the parameters of the model.

As we have discussed in Section 3.1 the inner part of the CWS must have undergone only negligible precession due to the gravity of the CND. Therefore, we assume that it conserves orientation of the putative single parent disc and we consider \( (\Omega'_0, i'_0) = (99^\circ, 120^\circ) \) which is the normal vector of the inner part of the CWS according to Beloborodov et al. (2006). We further set \( M_{\text{CND}} = M_\star \) which enables us to plot \( N_j \) as a func-

\[\text{value} = \text{value of Paumard et al. (2006)}\]
tion of $\Omega'_{\text{CND}}$ and $i'_{\text{CND}}$ as it is shown in Figure 2. We see that there exists an extended region where the observational data of nearly all stars are compatible with the hypothesis of their origin in a parent disc of thickness $\sim 5^\circ$. This region of large values of $N_5$ extends along the set of $(\Omega''_{\text{CND}}, i''_{\text{CND}})$ perpendicular to the normal vector $\mathbf{n}_5$. This is a natural consequence of the assumption that $\sim 35$ stars, identified as CWS nowadays, haven’t undergone large precession. The region of good compatibility also includes an approximate orientation of the CND as determined from observations, $(\Omega''_{\text{CND}}, i''_{\text{CND}}) = (25^\circ, 70^\circ)$, e.g. by Jackson et al. (1993).

We have performed analogical test of compatibility also for $M_{\text{CND}} = 0.3 M_\star$ and $3 M_\star$ and $10^\circ$ neighbourhood of $(\Omega''_{\text{CND}}, i''_{\text{CND}}) = (99^\circ, 120^\circ)$. In all cases we have obtained a picture similar in that there exists an extended region with $N_5 \gtrsim 68$. Enlarging the inspected neighbourhood of the observed velocities to $3 \sigma$ leads to larger values of $N_5$ with its maximum reaching 72. This means that the observational data are compatible with the hypothesis of the common origin of the young stars in a single thin disc, nevertheless, they do not pose strong constraints on the parameters of the model. We introduce three supplementary tests that may be applied to the observational data to verify validity of our hypothesis. First, the model of star formation is assumed to prefer low eccentricities of the stellar orbits. Hence, we introduce $N_{e,5}$ in the same way as $N_5$, but now with an additional condition $e < 0.5$ for all tested orbits. Middle panel of Fig. 2 shows that region with large $N_{e,5}$ coincides with the region of large $N_5$. Maximum value of $N_{e,5}$ is $\sim 55$, i.e. the model requires about one third of the stellar orbits to have moderate to large eccentricities. Again, considering $3 \sigma$ neighbourhood of the measured velocity vectors weakens this constraint, giving $N_{e,5} \gtrsim 70$ for a wide range of the model parameters. Additional analysis reveals that most of the eccentric orbits does not belong to the CWS subset of stars.

A ratio $N_{e,5}/V_{1\sigma}$ can be considered as a measure of the probability that the orbit of star $j$ originated in a disc with opening angle $5^\circ$ and normal vector $\approx \mathbf{n}_0$. Consequently, we introduce

$$P_3 \equiv \left[ \prod_{j=1}^{N} \frac{N_{e,5} + 1}{V_{1\sigma}} \right]^{1/N},$$

as a measure of the probability that all stars originated in a thin disc (Adding a unity to $N_{e,5}$ in (9) prevents $P_3$ from being zero everywhere while it does not strongly affect its meaning.) . Bottom panel of Fig. 2 shows that $P_3$ accentuates orientations of the CND nearly perpendicular to the normal vector $(\Omega''_{\text{CND}}, i''_{\text{CND}})$, but it does not strongly discriminate among the models that fall into this region. Maximum of this function is at $(\Omega''_{\text{CND}}, i''_{\text{CND}}) \approx (55^\circ, 40^\circ)$.

Following Beloborodov et al. (2006), the configurations compatible with the hypothesis of a single warped disc are expected to have equally distributed value of the mean anomaly, $M$, of the individual orbits. Full test of the distribution of the
mean anomaly of all configurations that have fulfilled other criteria of compatibility is not possible as it would require analysis of $\approx P \sqrt{N_0}$ combinations of orbits. (Note, that other tests presented here require analysis of only $N_0 V_1$ individual orbits.) In the bottom panel of Fig. 2 we present a restricted test showing the mean value of the mean anomaly, $\langle M_5 \rangle$, for all tested orbits with $\delta \theta < 5^\circ$. This quantity is close to $\pi$ which corresponds to the expected uniform distribution in the major part of the $(\Omega_{\text{CND}}, i_{\text{CND}})$ space. Analogical plot would show that $\langle M_5^2 \rangle$ is close to the expected value $\pi^2/2$ in the regions of large value of $N_5$ and $P_5$. This indicates that our hypothesis does not require some preferred value of $M$ and, therefore, some of the configurations with large $N_5$ are also compatible with the assumption of random distribution of the orbital phases.

4. Conclusions

The massive molecular torus (CND) surrounding the central parsec of the Galactic Centre causes precession of the orbits of young stars which move at distances $0.03 \text{pc} \leq r \leq 0.3 \text{pc}$ around the supermassive black hole. The rate of the precession depends on the orbital parameters as well as on the orientation and mass of the CND. This rate is comparable to the lifetime of the young stars for a wide range of parameters and, therefore, this process should be taken into consideration in attempts to determine the relation between initial and current values of their orbital parameters. We have shown that $M_{\text{CND}} \gtrsim 0.3 M_\odot$ would destroy any coherently rotating disc-like stellar structure within 6Myr, provided the inclination of most of the orbits with respect to the CND deviates by more than $5^\circ$ from $90^\circ$. In other words, the stability of the stellar disc within its lifetime poses constraints on its inclination with respect to the CND and on the mass of the CND.

We further suggest that most if not all young stars observed in the Galactic Centre may have been formed in a single, initially coherently rotating structure, presumably via fragmentation of a thin self-gravitating gaseous disc. Within this hypothesis, the orientation of the stellar disc was nearly exactly perpendicular with respect to the CND. Its “core”, represented by the CWS nowadays, remained nearly untouched by the precession. On the other hand, stars that were formed at the outer parts of the disc and/or slightly off its mean plane, or that were scattered out of it via two-body encounters, have undergone a more rapid precession of their orbits, i.e. they apparently don’t belong to the stellar disc any longer. We have shown that within the $1\sigma$ uncertainty of their current velocities there exist such parameters of the stellar orbits that would have had their angular momenta collinear about $6 \text{Myr}$ ago. Due to the high sensitivity of the precession upon the orbit inclination with respect to the CND and the uncertainty in the observed parameters of the stellar orbits, the procedure described in the previous Section cannot provide robust constraints on the parameters of the model. Therefore, the concept of a single warped disc of young stars in the Galactic Centre may be considered as being viable, but not proven yet. Our hypothesis, however, gives an explicit prediction on a specific pattern of the normal vectors of the stellar orbits which may be determined from future, more accurate observations: all of them are assumed to be found close to the circumference perpendicular to the normal vector of the CND.

Let us emphasise that the gravitational influence of the CND leaves stronger imprints on the dynamics of stars more distant from the centre. Hence, we suggest that these stars deserve further attention from the observational point of view. Improved measurements of their kinematical state may bring a new light into the question of the formation and dynamical evolution of the population of the young stars in the Galactic Centre. Beside a generic demand on better constraints on orbital parameters from the observational side, there is also a room for improvements of the model itself. Its most important (and computationally rather expensive) modification will probably lie in an improved treatment of the evolution of the individual orbits, which would take into account gravity of the stellar disc itself.

As a final remark let us note that the strict constraints on the mutual (perpendicular) orientation of the stellar disc and the CND raises a question about the dynamics of gas from which the young stars were formed. It is likely that the parent gaseous disc had to be nearly perpendicular to the CND, so that it would not be destroyed via differential precession before it gave birth to the numerous stellar population. Such an initial orientation is statistically not very probable, opening the question whether it can be a generic result of dissipative (hydro)dynamics in the resonant external potential.

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