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A natural formation scenario for misaligned and short-period eccentric extrasolar planets

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ABSTRACT

Recent discoveries of strongly misaligned transiting exoplanets pose a challenge to the established planet formation theory which assumes planetary systems to form and evolve in isolation. However, the fact that the majority of stars actually do form in star clusters raises the question how isolated forming planetary systems really are. Besides radiative and tidal forces, dense gas aggregates in star-forming regions are potential sources for perturbations to protoplanetary discs or systems. Here we show that subsequent capture of gas from large extended accretion envelopes on to a passing star with a typical circumstellar disc can tilt the disc plane to retrograde orientation, naturally explaining the formation of strongly inclined planetary systems. Furthermore, the inner disc regions may become denser, and thus more prone to speedy coagulation and planet formation. Pre-existing planetary systems are compressed by gas inflows leading to a natural occurrence of close-in misaligned hot Jupiters and short-period eccentric planets. The likelihood of such events mainly depends on the gas content of the cluster and is thus expected to be highest in the youngest star clusters.

Key words: hydrodynamics – planets and satellites: formation – planet–disc interactions – planet–star interactions – protoplanetary discs – open clusters and associations: general.

1 INTRODUCTION

The discoveries of retrograde or strongly misaligned transiting exoplanets like WASP-17b and others (Hébrard et al. 2008; Gillon 2009; Johnson et al. 2009; Narita et al. 2009; Pont et al. 2009, 2010; Winn et al. 2009a,b; Anderson et al. 2010; Triaud et al. 2010) pose a challenge for established planet formation theories. These classically assume the birth of planetary systems out of collapsing protostellar cloud fragments. While contracting from subparsec to milliparsec (or hundreds of au) scale the conservation of its initial angular momentum causes the cloud to spin and flatten, while part of its mass settles towards the centre, eventually igniting the hydrogen burning in the stellar core. Given such a protostar with a circumstellar disc that contains a certain amount of dust, solid particles collide and stick together, forming larger particles. This coagulation leads to bodies (cores) of sufficient mass to accrete surrounding material (dust and even gas) by gravity until no more disc material is available. This mechanism is probably the dominant process of the formation of the Solar system, including the Earth (Mordasini et al. 2008). As an alternative, gravitational instability as a forming mechanism for giant planets and brown dwarfs is being discussed (Boss 2004), and at least for brown dwarfs it has actually been shown to work (Stamatellos, Hubber & Whitworth 2007a; Thies et al. 2010). More recent variations of these models assume gravitational instability of the solid phase only or dust trapping in vortices as a speed-up for coagulation.

Being isolated from any external perturbation, everything inside this protostar–disc system spins in the same direction, thus the forming planets orbit their host star the same way. This simple model has been severely questioned by the findings mentioned above. The transiting exoplanet WASP-17b (Anderson et al. 2010), for example, has been found to have a sky-projected inclination of the orbital plane normal against the stellar spin axis of $148^\circ\!.5^{+5^\circ\!.1}_{-4^\circ\!.2}$. A number of other misaligned transiting exoplanets have been discovered (Hébrard et al. 2008; Gillon 2009; Johnson et al. 2009; Narita et al. 2009; Pont et al. 2009, 2010; Winn et al. 2009a,b; Anderson et al. 2010). These discoveries suggest that misalignment between planetary orbits and the spin of their host star (hereafter called spin–orbit misalignment) is quite common, at least among close-in transiting planets for which the spin–orbit alignment can be measured by using the Rossiter–McLaughlin effect (McLaughlin 1924; Rossiter 1924). The nearby υ And planetary system exhibits even mutually inclined planetary orbits (McArthur et al. 2010).

Such planetary orbits cannot be explained by the standard planet formation model according to which the conservation of angular

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★E-mail: ithies@astro.uni-bonn.de (IT); pavel@astro.uni-bonn.de (PK) momentum forces any coplanar system to remain coplanar forever. There have been recent suggestions that may shed some light into the possible mechanism. Fabrycky & Tremaine (2007) and Naoz et al. (2011) deduce a formation scenario for misaligned 'hot Jupiters' through long-term mutual perturbations of two planets (or an inner planet and an outer brown dwarf; for simplicity, we use the term 'planet' for all substellar companions in this paper) orbiting the same star. Given an initial mutual inclination between 40° and 140°, the Kozai–Lidov mechanism leads to secular oscillations of eccentricity versus inclination. Tidal friction circularizes the orbit of the inner planet if its periastron falls below a few stellar radii, eventually leaving the planet on a close-in orbit with near-random inclination with respect to the stellar spin. This scenario, however, requires a sufficient initial mutual inclination of both planets.

Another possible mechanism is tilting the spin axis of the star. Direct stellar encounters within a stellar radius (about 0.01 au) can be effectively ruled out, because they are improbable, even within stellar clusters (Thies, Kroupa & Theis 2005; Thies & Kroupa 2007), and would destroy the disc. Secular transfer of angular momentum between the protostellar spin and the protoplanetary disc (PPD) via magnetic fields has been investigated by Lai, Foucart & Lin (2011).

Multistage or episodic accretion of circumstellar material may provide another viable mechanism for misaligned planetary systems. The underlying idea is that accretion from different sources (i.e. gas filaments, accretion envelopes) from different directions may sever the classically assumed spin–orbit correlation. The star itself may get its angular momentum from a different accretion event than the bulk of circumstellar material. Bate, Lodato & Pringle (2010) have analysed turbulent accretion events using data from Bate, Bonnell & Bromm (2003). They deduce a high frequency of misaligned planets as a consequence of multidirectional accretion. However, due to the limited simulation data available, they were forced to make simplified assumptions to what happens within the close vicinity of a star. Our work aims to take a deeper insight into such scenarios by self-consistent calculations of close interactions of a circumstellar disc with encountered new material, and by also treating the effects on pre-existing planets.

As Pfalzner, Tackenberg & Steinhausen (2008) and Olczak, Pfalzner & Eckart (2010) have shown, encounters between stars and pre-stellar/protostellar objects do occur frequently in dense stellar environments and may lead to significant accretion bursts. Although the precise mechanisms proposed (Pfalzner et al. 2008) differ from ours, their calculations emphasize the importance of encounter events to accretion processes.

In this paper the effects of gas capture on to a pre-existing circumstellar disc are studied. In Section 2 we depict the physical scenario, while Section 3 briefly describes the numerical methods used in our computations. The results are presented in Section 4.

2 MODEL

In our model, both the initial mutual inclination as well as the inclination with respect to the stellar equator can be naturally explained by multistage accretion during the formation process of the planetary system. The scenario can be described as follows. First, a star with a PPD is forming the classical way, i.e. out of a collapsing spinning cloud fragment. Soon after this, the protostar passes another region in the star cluster that contains dense gas, e.g. the protostellar cloud fragment or accretion envelope of another star, hereafter called the target. Accordingly, the star which encounters the target and its disc are referred to as the bullet star and the bullet disc, respectively. In our calculations, a massive circumstellar disc around another star is used as the target. While grazing the outer regions of this target, the star captures material from it at an angle that depends on the encounter orbit and the arbitrarily chosen orientation of the target and the bullet disc. Since there is no correlation between the orientations of the bullet disc, the target and the encounter orbit, this configuration reflects an uncorrelated or random inflow of material. The subsequent evolution mainly depends on the amount and infall angle of this additional material, and also on the protoplanetary evolution stage during the capture.

In our calculations, we focus on the case of an encounter before any planet has formed in the passing star's disc. It is thus a purely gaseous interaction computed via smoothed particle hydrodynamics (SPH). In our model, the star is a Sun-type star with a low-mass PPD ($M_\mathrm{d} \leq 0.1\,\mathrm{M}_\odot$, radius $<$100 au), passing through the target disc ($0.5\,\mathrm{M}_\odot$).

The initial conditions for the PPD are taken from Stamatellos & Whitworth (2008, 2009). The disc model has power-law profiles for temperature, T, and surface density, Σ, from Stamatellos & Whitworth (2008), both as a function of the distance, R, from the central star:

$$\Sigma(R) = \Sigma_0 \left(\frac{R}{\mathrm{au}}\right)^{-q_\Sigma}, \tag{1}$$

$$T(R) = \left[T_0^2 \left(\frac{R}{\mathrm{au}}\right)^{-2q_T} + T_\infty^2\right]^{1/2}, \tag{2}$$

where $1.5 \leq q_\Sigma \leq 1.75$ and $0.5 \leq q_T \leq 1.0$. $T_\infty = 10\,\mathrm{K}$ is a background temperature to account for background radiation from other stars within the host cluster. The radiation temperatures of the stars are estimated assuming a mass-to-luminosity relation of $L \propto M^4$ for low-mass stars.

The disc is initially populated between 4 and 40 au. Preceding the actual encounter, the disc is allowed to 'settle' during the approach time of about 5000 years (equivalent to 20 orbits at the outer rim), erasing artefacts from the initial distribution function. During this settling the disc smears out at the inner and the outer border extending its radial range from a few au up to $\gtrsim$60 au. The actual surface density after the settling and thus the mass content within a given radius is therefore slightly smaller than in the initial set-up.

Similarly, the target is set up as a massive extended disc with mass of $0.48\,\mathrm{M}_\odot$ and a radius of $\approx$400 au, as well as a $0.75\,\mathrm{M}_\odot$ star to keep the gas gravitationally bound. The set-up is therefore equivalent to those used in Thies et al. (2010), where triggered fragmentation inside this envelope upon tidal perturbations has been studied, and is indeed realistic as long as encounters with large circumstellar discs are considered. However, future models will also use different set-ups (protostellar cores, dense gas filaments, etc.) as the target.

Both systems are initially set on a hyperbolic orbit around their centre of mass with the discs being inclined mutually as well as with respect to the orbital plane. The periapsis is set to 500 au initially. The eccentricity is set to 1.1, corresponding to a pre-encounter relative velocity of about $0.7\,\mathrm{km}^{-1}$. The periapsis relative velocity is $2.9\,\mathrm{km}^{-1}$. The hyperbolic orbit is inclined 15° against the target disc plane using Eulerian *z*–*x*–*z* rotation angles 0°, 15°, 0°, while the plane of the bullet disc (initially in the *x*–*y* plane) is tilted by 0°, 135°, 60°.

The eccentricity value is in agreement with the likelihood estimation of encounter parameters by Olczak et al. (2010). In addition, encounters at distances of the order of a few hundred au are likely to happen in clusters comparable to the Orion nebula cluster (Thies et al. 2005; Olczak et al. 2010); thus, our scenario is rather likely than exceptional. The actual periapsis and eccentricity may differ slightly due to tidal angular momentum transfer, but these effects on the orbit are negligible at that time. After the passage, when both stars have reached a sufficient distance (∼1000 au) again, the gas particles around the bullet star (i.e. the remains of its own disc and any captured gas) are separated from the system and analysed in the centre-of-mass system of the bullet star.

3 NUMERICAL METHOD

All computations were performed by using the well-tested SPH code DRAGON by Goodwin, Whitworth & Ward-Thompson (2004) including the radiative heat transfer extension by Stamatellos et al. (2007b). Most of the numerical parameter settings have been adopted from Stamatellos et al. (2007a) and Stamatellos & Whitworth (2009). The radiative-transfer algorithm is not strictly required in our model, but due to its high numerical efficiency it does not significantly slow down the calculations, so we left it in to keep it consistent with previous calculations by Thies et al. (2010). All gas particles have the same mass and equation of state. The artificial viscosity parameters are $\alpha = 0.1$ and $\beta = 0.2$, i.e. lower than the usually used values (1 and 2, respectively; Monaghan 1992), to keep the disc dispersion low. Stars and planets are treated by sink particles which are set in the initial conditions, but may also form if the local volume density exceeds $10^{-9}\,\mathrm{g\,cm^{-3}}$ (not expected in the current model, however). The sink radius is chosen as 0.5 au, while the sink masses are the masses of the stars involved, i.e. $1.0\,\mathrm{M}_{\odot}$ for the bullet star and $0.75\,\mathrm{M}_{\odot}$ for the host star of the target disc. Any gas particle that becomes gravitationally bound to a sink within less than the sink radius is treated as being accreted by the sink. The code currently does not treat magnetic field nor dust.

The numerical model used here is the same as used in Thies et al. (2010), using 250 000 SPH particles for the target, while the PPD of the passing star has been set up by 25 000–50 000 particles, for disc masses between 0.05 and $0.1\,\mathrm{M}_{\odot}$, respectively.

4 RESULTS

4.1 General effects

Fig. 1 shows six snapshots of the encounter and subsequent gas capture. The view is centred on the passing star (the ‘bullet star’) at face-on direction towards the unperturbed disc. The time stamp refers to the moment of the periastron passage. Frame (a) shows the unperturbed disc. Its core has a radius of about 40 au, while the low-density outer regions extend to about 100 au. Shortly after the encounter, as shown in frames (b–d), the captured material starts to form an annulus around the star, while, at the same time, the original bullet disc is partly truncated, with the inner region being condensed. The persistent quadrupole forces continue to alter the disc’s orientation and eventually tilt it into edge-on orientation (frames e and f). At the same time, the orientation of the annulus is only slightly changed due to its larger radius and thus higher moment of inertia. As clearly visible, both the captured annulus and the disc are progressively aligning each other, eventually forming a combined disc. The dynamical evolution of the mutual orientation and the total tilt of the original bullet disc is depicted in Figs 2 and 3. Here, the SPH particles have been separated into groups sharing a similar angular momentum unit vector and thus belonging to the same rotational structure. Particles which deviate more than 15° from the bulk angular momentum as well as unbound or loosely bound particles beyond 100 au from the bullet star are neglected. The mutual inclination of both structures is declining from initially 130° to near 0° within 35 kyr. On the other hand, the original disc is tilted by nearly 100°, i.e. *if being initially aligned to the stellar equator, it is now retrograde*.

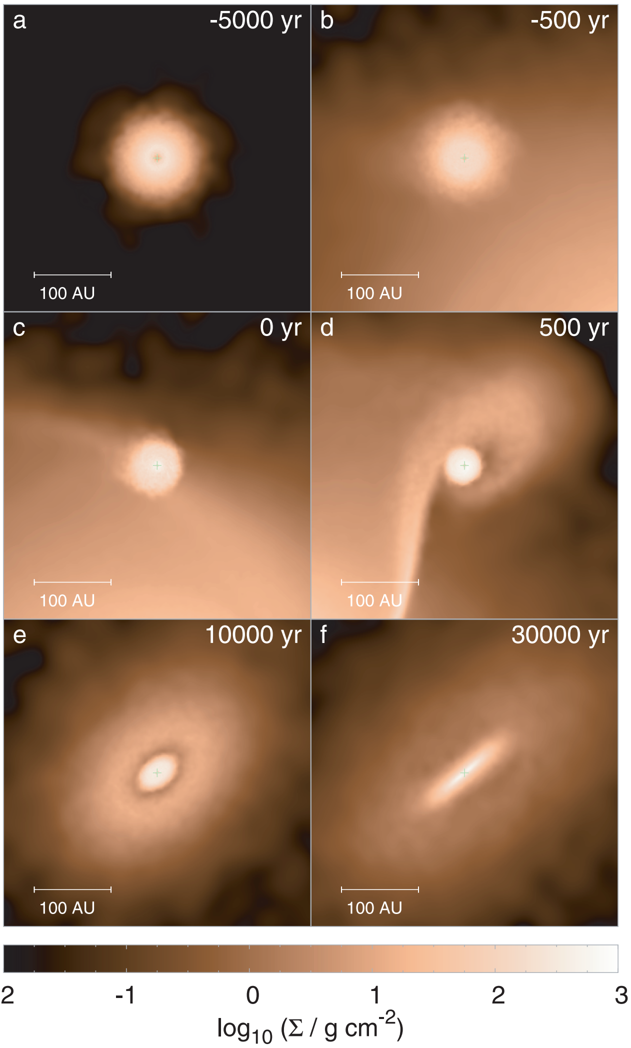

Figure 1. Snapshot of a bullet star with a $0.1\,\mathrm{M}_{\odot}$ circumstellar disc passing through a massive extended ($0.5\,\mathrm{M}_{\odot}$, 400 au) target disc on an inclined orbit. While the original disc is partially truncated, partially condensed to the centre, and somewhat tilted, the bullet star accretes additional material from the target disc, forming an inclined annulus of gas around it (frames b to d). The initially strongly inclined structures progressively align each other within 30 000 years after the encounter (frames e, f). The time stamp in each frame refers to the time of the encounter.

During the encounter, typically around 10–30 M_{J} of gas is captured by the bullet star (Fig. 1, frames b–d; Section 4.2). In the cases where a PPD (hereafter called the original disc) is already present, two general effects can be distinguished: (i) during the capture process, the original disc is compressed to about one-half or one-third of the initial radius, accordingly increasing the surface density, and (ii) the captured material settles in an outer annulus, the inclination of which depends on the orbital orientation and the orientation of the target disc relative to the encounter orbit.

The orientation of this annulus, shown in Fig. 2 in spherical coordinates, is not constant, but changes over time. Within about a few thousand years after formation the annulus and the bullet disc

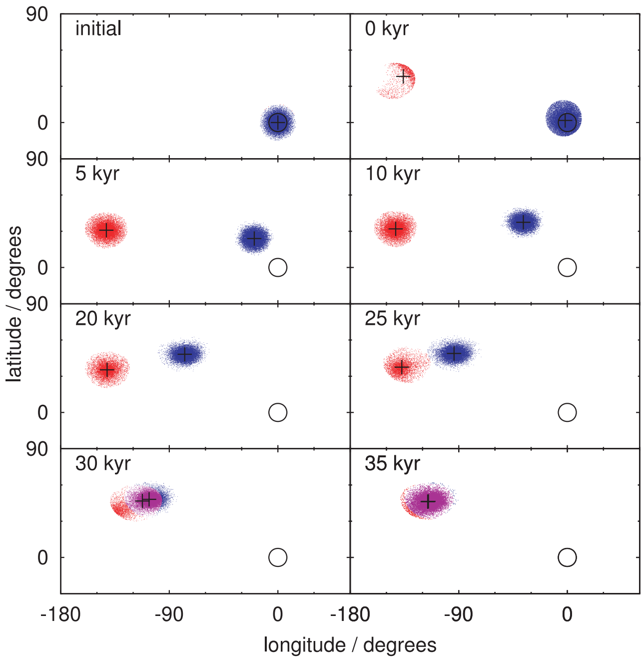

Figure 2. The angular momentum unit vectors of the particles of the material around the bullet star in spherical coordinate angles, ϑ (latitude) and φ (longitude), i.e. projected on the unit sphere. The reference frame is adjusted so that the normal vector of the bullet disc points at $(\varphi, \vartheta) = (0, 0)$. The topmost two frames show the angular momenta initially and at the time of the closest approach. While the original bullet star disc is altered only slightly, there is clearly another population of particles settling in an annulus which is tilted against the initial disc plane. After formation, both structures progressively align to each other, and the angular difference between both degrades (subsequent frames). The total angular momentum vector of each disc is marked by a cross, while the open circle indicates the initial angular momentum vector of the bullet star disc before the encounter (being in fact nearly identical to that at the moment of the encounter, $t = 0$). This also denotes the direction of the bullet's star spin vector. The time stamp in each frame refers to the time of the encounter.

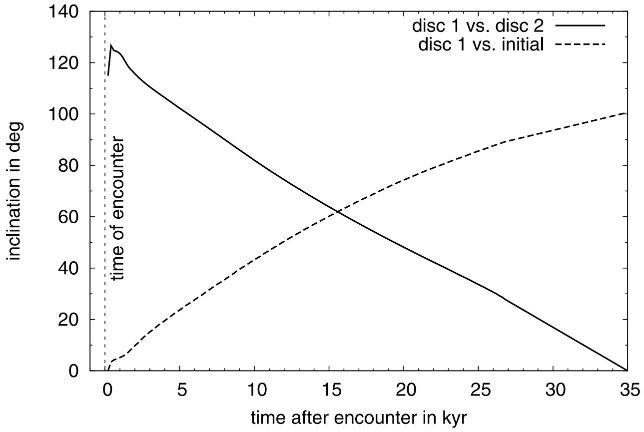

Figure 3. The mutual angular tilt between the pre-existing disc of the bullet star and the annulus of captured gas, as well as the net angular tilt of the pre-existing disc as a function of time. While being almost retrograde wrt each other before the encounter, the two structures progressively align with each other over time. 25 kyr after the encounter the mutual tilt has degraded to about 35°. At the same time, the pre-existing disc has been tilted wrt its initial orientation by about 90°. It has become retrograde wrt the bullet star's spin after about 27 000 yr.

have considerably lowered their mutual inclination (third and fourth frame), as shown in Fig. 3. A few ten thousand years after the encounter, they have almost aligned to each other, eventually forming a single circumstellar disc. Consequently, the orientation of this disc differs considerably from its initial orientation and therefore from the stellar equatorial plane. It should be noted that this tilt may be much lower if a steady and homogeneous gas flow is assumed (Moeckel & Throop 2009).

4.2 Captured mass

The amount of captured mass is an important quantity to judge its impact on planet formation. In our calculations, typically between 0.01 and 0.02 $\mathrm{M}_\odot$ is captured from the target disc, i.e. about one-third of the initial bullet star disc mass. Fig. 4 depicts the time evolution of the masses of the bullet star disc and the captured annulus. As shown here, the capture of material from the target disc begins quickly about the closest encounter, and is almost finished within about 3000 yr. At the same time, the pre-existing disc suffers a radial compression (see frames b–d in Fig. 1). The distinction of these two structures has been done by the angular momentum grouping method described in Section 4.1. It has to be noted that the curves in Fig. 4 show a representative fraction of each gas body defined by this method. Since part of the gas particles are also subject to scattering into large separations (>100 au) and/or inclinations (>15°), these are omitted by this selection process, thus leading to a decreasing mass of each disc. These losses are in part due to dynamical scattering and frictional heating of the gas, in part due to accretion by the bullet star. To a certain degree, they are also due to numerical diffusion, which is unavoidable in SPH, especially for relatively low resolution, and may thus be reduced by using larger particle numbers in future calculations. However, the mass loss does not affect the central conclusion of this paper in any way.

4.3 Pre-existing planets

We also studied the effects of such a gas capture event on a pre-existing planetary system. Here, the circumstellar disc of the bullet

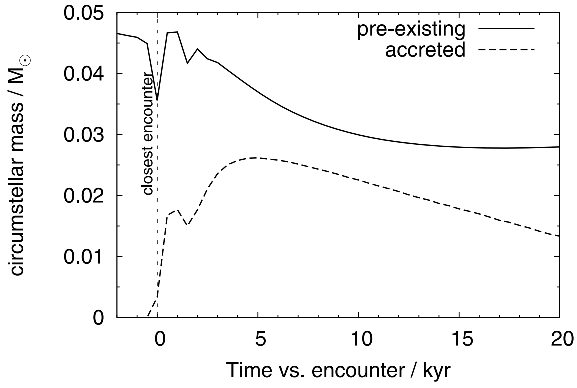

Figure 4. The mass of the pre-existing bullet star disc (solid curve) and of the captured annulus (dashed curve; see Section 4.1) as a function of time. The peaks in the solid curve at about the moment of the closest encounter are due to the perturbations of the pre-existing disc caused by the impact of inflowing gas and tidal forces by the target mass. The capture process starts shortly before the encounter and continues to drag material from the tidal arm (Fig. 1) even several kyr later. The slight decrease of mass of both structures is mainly caused by dynamical scattering and, in particular for the inner disc, accretion on to the star, but also by a small amount due to the numerical diffusion that is unavoidable in SPH calculations. In a real disc, the final masses would thus be somewhat larger.

Table 1. Masses and orbital elements of four model planets before and after a flyby and capture event equivalent to the scenario in Fig. 1. The planets, which replace the bullet star disc of the first scenario, are initially equivalent to Jupiter, Saturn, Uranus and Neptune. 20 kyr after the flyby, when the capture and accretion process is essentially over, the orbits are shrunk to a fraction of their initial values, while being highly eccentric now. Furthermore, the orbital positions of planets 2–4 have been altered. The system has apparently become unstable.

	Initial			20 kyr after flyby		
Object	$m_{\mathrm{ini}}/M_{\mathrm{J}}$	a_{ini}/au	e_{ini}	$m_{\mathrm{fin}}/M_{\mathrm{J}}$	a_{fin}/au	e_{fin}
1	1.0	5.2	0.05	2.8	1.6	0.67
2	0.30	9.5	0.05	3.1	5.1	0.20
3	0.046	19.2	0.05	3.2	6.5	0.70
4	0.054	30.1	0.01	2.2	2.2	0.89

star has been replaced by a model planetary system equivalent to Jupiter, Saturn, Uranus and Neptune. Like the stars, the planets are represented by sink particles with a sink radius of 0.5 au. This value is a compromise between spatial resolution and mass resolution. Gas particles passing through the sphere defined by the sink radius are considered as captured if they are gravitationally bound to the sink, otherwise they simply pass through it. The current results, summarized in Table 1, show that a planetary system equivalent to the Sun orbited by Jupiter, Saturn, Uranus and Neptune (with initial orbital radii of 5, 10, 20 and 30 au, respectively) is severely affected by gas–planet interaction. During the capture, some 0.01 $\mathrm{M}_{\odot}$ of gas flow towards the bullet star, crossing the planetary orbits. In response, the planets migrate inwards to semimajor axes of about one-tenth their initial separations, i.e. between about 0.5 and 4 au. In addition, some orbits get strongly eccentric (up to $e = 0.8$, where $e = 0$ means a circular orbit and $e \geq 1.0$ means ejection). Such a system is dynamically unstable, i.e. some planets are probably ejected over time, typically leaving one to three planets, with the most massive planet on a close-in orbit. Systems like these are expected to undergo significant subsequent evolution. Even after ejection of the most unstable planets, the remaining ones may still be subject to Kozai resonance, altering their eccentricities and inclinations over many orbital times. But it is clear that these results suggest that misaligned planets and hot Jupiters as well as short-period planets on eccentric orbits may both be an outcome of gas flow on to a forming or existing system.

4.4 Stellar spin

The current work assumes that the stellar spin is not largely changed since the assembly of its circumstellar disc, and thus its angular momentum vector points into approximately the same direction as the angular momentum vector of the disc before the encounter. This assumption, however, may not be true in general. As Lai et al. (2011) have found, the stellar spin may, in some cases, be tilted through magnetic interaction with the disc. Furthermore, during the early phases, when the protostar has still a considerable diameter (tenths of an au), it may still realign to the disc after an encounter event of the kind proposed in our paper. However, a large fraction of stars will already be compact enough to be effectively decoupled from angular momentum transfer with their disc, given the absence of strong magnetic torque. Since encounter events and gas capture are a natural consequence of star formation in dense environments, we conclude that they indeed do play an important role in forming misaligned planetary systems.

4.5 Resolution issues

The required resolution strongly depends on the kind of scenario to be modelled. For example, for studying fragmentation the local Jeans mass has to be sufficiently resolved, meaning by at least about 50 SPH particles. The study of the global behaviour of gas masses without focus on fragmentation, on the other hand, requires much less resolution. In our model, the mass of each gas particle is $1.92 \times 10^{-6}\ \mathrm{M}_{\odot}$ or $0.64\,\mathrm{M}_{\oplus}$. The well-resolved mass therefore is about $32\,\mathrm{M}_{\oplus}$ or twice the mass of Neptune. The transferred mass in both models (encounter of disc with target and planetary system versus target, respectively) is of the order of $0.01\ \mathrm{M}_{\odot}$ or 5000 SPH particles, so mass resolution is not an issue here. For calculating the impact on dust components or to study vortex formation (Barge & Sommeria 1995; Klahr & Bodenheimer 2004), this resolution is likely to be insufficient. These issues will be addressed in future work.

One could argue that the masses of Uranus and Neptune equivalents (planets 3 and 4, see Section 4.3), which are roughly equal to the interacting mass required for efficient momentum transfer, are less optimally resolved by only 20–25 SPH particles. The statistical scatter in terms of the number of gas particles interacting with these minor giant planets is about $\sqrt{1/25} = 20$ per cent and therefore does not significantly influence the outcome of drag-induced migration. Furthermore, this behaviour is fully consistent with the migration of the Jupiter and Saturn equivalents (planets 1 and 2). A word of caution has, however, to be stated at this point: apart from mere resolution issues, the proper treatment of accretion on to sinks shows a number of pitfalls. For example, the void of material in the sink may lead to artificial suction effects and thus speed-up accretion. The time evolution of the planetary orbits has therefore to be treated with great caution. The long-term outcome, however, largely depends on basic physical principles like conservation of angular momentum and can therefore be expected to reflect the real consequences on a pre-existing planetary system.

5 DISCUSSION AND CONCLUSIONS

We have analysed the general effects of inclined gas capture on to a pre-existing circumstellar disc upon passage through a dense gaseous reservoir. The secondary gas capture does not destroy a pre-existing disc even if the new material inflows at a highly inclined angle. Rather, the inner regions of the disc (inside about 30 au) become denser, while some of the outer disc material is scattered away. The major result is the formation of an inclined combined circumstellar disc from captured material and the pre-existing disc. After capturing a few $0.01\,\mathrm{M}_{\odot}$ into an initially inclined annulus, both structures tend to align with each other within a few 10 000 years after the encounter. An annulus with an initial inclination of 135° aligns to about 35° within 20 000 years. Due to conservation of angular momentum, this results in a net shift of more than 90° in our model, and even more for lower mass pre-existing discs or discless stars. If planets form from the resulting inclined disc, one naturally arrives at misaligned planets.

The resulting disc may have two chemically distinct radial regions, the inner region which is associated with the star, and the outer region composed from the captured material.

In addition, the basic effect of capture on to a pre-existing planetary system has been estimated. Orbits typically shrink and become strongly eccentric in response to the contact with captured gas and subsequent planet–planet interaction, while their orbital planes can be dramatically altered, thus naturally leading to (even mutually) misaligned short-period planets with eccentric orbits.

Important constraints are given by recent observations of apparent inclinations between circumstellar discs and their host stars. In a most recent analysis, Watson et al. (2011) have found no significant misalignment between the normal vectors of debris discs and the spin axis of low-mass to solar-type stars. In particular, the projected inclinations between the star and its disc typically differ by 5°–10°, and 15°–45° in a few cases. Their results do not necessarily contradict our scenario since even moderate disc tilts and warps may lead to a Kozai resonance in a planetary system born out of such a disc. Following the mechanism described by Fabrycky & Tremaine (2007) and Naoz et al. (2011), near-random misalignment of a close-in planet and the spin of its host star may result.

Future studies will also consider PPDs with embedded planets and systems with a brown dwarf on a wide orbit (about 100–200 au). In addition, the consequences for dust content and mixing of differently composed material will be analysed.

The mechanism described in this paper provides a natural scenario for the formation of misaligned planetary systems in gas-rich dense star-forming regions. While other models have been proposed, our scenario requires rather simple assumptions, and may even provide the initially misaligned planetary orbits required by the recent model of Naoz et al. (2011).

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