A primordial origin for misalignments between stellar spin axes and planetary orbits

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The existence of gaseous giant planets whose orbits lie close to their host stars ('hot Jupiters') can largely be accounted for by planetary migration associated with viscous evolution of proto-planetary nebulae\textsuperscript{1}. Recently, observations of the Rossiter–McLaughlin effect\textsuperscript{2} during planetary transits have revealed that a considerable fraction of hot Jupiters are on orbits that are misaligned with respect to the spin axes of their host stars\textsuperscript{3}. This observation has cast doubt on the importance of disk-driven migration as a mechanism for producing hot Jupiters. Here I show that misaligned orbits can be a natural consequence of disk migration in binary systems whose orbital plane is uncorrelated with the spin axes of the individual stars\textsuperscript{4–5}. The gravitational torques arising from the dynamical evolution of idealized proto-planetary disks under perturbations from massive distant bodies act to misalign the orbital planes of the disks relative to the spin poles of their host stars. As a result, I suggest that in the absence of strong coupling between the angular momentum of the disk and that of the host star, or of sufficient dissipation that acts to realign the stellar spin axis and the planetary orbits, the fraction of planetary systems (including systems of 'hot Neptunes' and 'super-Earths') whose angular momentum vectors are misaligned with respect to their host stars will be commensurate with the rate of primordial stellar multiplicity.

The obliquities (angles between the planetary orbits and the stellar spins) of detected planetary orbits range from almost perfectly aligned prograde to almost perfectly aligned retrograde systems\textsuperscript{6}. Previously, the misalignment between planetary orbits and stellar spin axes had been attributed to post-nebular multi-body interactions. Most notably, Kozai cycles with tidal friction\textsuperscript{7–8}, planet–planet scattering\textsuperscript{9–10}, and chaotic secular excursions\textsuperscript{11} have been invoked as a means of producing misaligned planets. These mechanisms are probably responsible for a few specific examples (for example, the extreme eccentricity of HD80606b is almost certainly due to Kozai resonance with the stellar companion HD80607). However, it is unlikely that they can explain misaligned hot Jupiters as a population. For instance, the Kozai mechanism can be stifled by forced apsidal precession in multi-planet systems\textsuperscript{12}. Likewise, within the context of planet–planet scattering and secular chaos, the allowed parameter range is limited, because the production of close-in orbits requires the timescale for tidal capture to be considerably shorter than that for eccentricity growth\textsuperscript{13}, while demanding the associated tidal heating to be small enough not to over-inflate the planet beyond its Roche lobe\textsuperscript{14}. Additionally, the observed presence of mean-motion resonances among giant planets on wide orbits (which rely on smooth, convergent migration to congregate\textsuperscript{15}) provides further motivation for the development of a unified model for disk migration that is capable of producing misaligned orbits.

The dynamics of self-gravitating proto-planetary disks under external perturbations can be extremely complex, making precise quantitative modelling computationally infeasible. Consequently, here I shall concentrate on characterization of the qualitative physical behaviour of the system and use classical perturbation methods to obtain a solution. In the spirit of secular theory\textsuperscript{16}, I model the proto-planetary disk as a series of initially planar, circular, concentric, massive wires that interact gravitationally. Our model is based on the Gaussian averaging method\textsuperscript{17,18} and the gravitational potential is softened to partially account for the discrete representation of the disk. The effects of dissipative fluid forces within the disk are neglected. The perturbing body is also modelled as a massive ring, but is eccentric ($e' = 0.5$) and inclined with respect to the disk by an inclination $i'$. A description of the model and its inherent assumptions is presented in ref. 19, and the details of our implementation are stated in the Supplementary Information.

A self-gravitating disk will preserve an untwisted structure and act as a rigid body, provided that the characteristic timescale of the external perturbation greatly exceeds that of the disk's self-interaction\textsuperscript{20}. Mathematically, this amounts to a statement of adiabatic invariance of the phase-space area occupied by a single secular cycle within the disk\textsuperscript{21}. If this condition is satisfied, the external perturber's sole effect is to induce a recession (that is, a retrograde drift) of the ascending node of the disk, as defined by the plane of the stellar orbit. The embedded planetary orbit will also adiabatically follow the disk.

In the reference frame of the host star, the nodal recession of the disk will appear as a cyclic excitation of inclination between the disk and the stellar spin axis (see Fig. 1), provided that the host star’s angular momentum vector does not adiabatically trail the disk. For this to hold true, the characteristic interaction timescale between the disk and the

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stellar spin-axis, $\mathcal{T}_{\text{star}}$, must exceed the disk’s nodal recession time-scale, $\mathcal{T}_{\text{disk}}$, by a considerable amount (that is, angular momentum coupling between the disk and the host star must be non-adiabatic)\(^9\). The former can be estimated by modelling the stellar rotational bulge as an inertially equivalent orbiting ring, effectively reducing the characteristic interaction timescale to the forced nodal recession period of the ring.

Observations suggest that rotational periods of T Tauri pre-main sequence stars, whose masses exceed $M > 0.25M_\odot$, where $M_\odot$ is the mass of the Sun, form a bimodal distribution where fast and slow rotators are centred around 2 days and 8 days respectively, with a preference for slow rotation at higher masses\(^22\). Thus, for typical pre-main-sequence stars, we obtain $\mathcal{T}_{\text{star}} \approx 10$ Myr and $\mathcal{T}_{\text{star}} \approx 0.3$ Myr for slow and fast rotators, respectively (see Supplementary Information for details). As will be shown below, this suggests that the adiabatic trailing of the stellar spin axes will only prevent excitation of mutual misalignment for fast rotators. Furthermore, the transfer of angular momentum from the disk to the star will probably be unimportant in mature disks because of low accretion rates\(^23\). In addition to avoiding the adiabatic trailing of the host stars, the prominence of the mechanism described here is determined by the abundance and longevity of wide stellar binary systems in star-formation environments, because the misalignment angle, $\psi$, becomes fixed when the binary companion is stripped away or when the proto-planetary disk dissipates (although a long-lived binary companion can act to misalign a mature planetary system with its host star\(^21\)). It is tempting to estimate the frequency with which significant misalignments are attained by this mechanism via population synthesis, but the enormous range and vast observational uncertainties in the input parameters would render such a calculation of little practical use. In particular, although observations of the Taurus–Auriga star-forming region\(^25\) suggest that the orbital distribution of young solar-type binaries is roughly log-flat with an overall binary fraction of around 40%, it is noteworthy that the process of wide binary formation also appears to exhibit environmental dependence\(^\ast\). Simultaneously, the rate at which wide binaries get disrupted in birth clusters depends sensitively on the local densities within the clusters\(^\ast\), which remain observationally elusive, because the majority of stars are born in aggregates that disolve quickly (on timescales of a few tens of millions of years or less)\(^26\). Nevertheless, the above conditions probably imply that the timescale for excitation of significant misalignment should be considerably less than 10 Myr or so.

In systems where self-gravity is strong enough to maintain the effective rigidity of the disk, fast circulation of the disk’s argument of perihelion also ensures adiabatic eccentricity dynamics. Specifically, this means that the disk will not develop significant eccentricity, and the Kozai resonance within the individual annuli will be suppressed\(^20\) (see Supplementary Information). Additionally, recall that here I am ignoring dissipative effects that would generally act to circularize the disk and maintain its rigidity. Assuming that the angular momentum of the stellar binary greatly exceeds that of the proto-planetary disk, the maximal inclination that can be excited between the stellar rotation axis and the disk’s orbital plane is approximately equal to twice the inclination of the proto-planetary disk with respect to the binary orbit: $\psi_{\text{max}} = 2\iota'$. As a result, retrograde planetary orbits can be naturally achieved, provided that the inclination of the stellar companion exceeds 45°. Figure 2 shows the time evolution of two such examples.

Although the Gaussian averaging model used above yields a rigorous representation of the secular evolution of the system, it is also computationally expensive. Fortunately, similar results can be obtained with a modified (arbitrary $\iota'$, $\epsilon'$) Laplace–Lagrange analytical theory\(^18\) (see Supplementary Information), providing an avenue for efficient mapping of parameter space. We have quantified the precession timescale for a range of stellar companion masses as well as binary separations. The results are summarized in Fig. 3. This calculation highlights an effective equivalence between distant massive perturbers and lower-mass perturbers with smaller semi-major axes, because the recession period of the disk scales approximately as $\mathcal{T}_{\text{disk}} \propto a'^{3/2}/M'$, where $a'$ is the binary star’s semi-major axis and $M'$ is its mass. Thus, the precessional effect of a $M' = 1M_\odot$ star orbiting at $a' = 10^3\text{AU}$ is equivalent to the precessional effect that arises from the protoplanetary disk and its host star orbiting an approximately $10^3M_\odot$ star cluster at $a' = 0.25$ pc.

I note that bound companions are not necessarily required for production of oblate disks, given that impulsive perturbations from passing stars in the birth cluster will cause the inclination of the disk to execute a random walk and in some cases can excite significant misalignment\(^27\). Collectively, this explanation places the approximately 7° misalignment between the Sun’s spin axis and the Solar System’s invariable plane into a more general, extrasolar context. However, the process of planet formation in perturbed, possibly warped, disks certainly deserves further study.

Given the diverse nature of the environments in which planetary systems may form, one would expect a wide range of characteristic precession timescales for proto-planetary disks. Although this does not necessarily imply an isotropic distribution of spin-orbit angles, it is quite possible that hot Jupiters that emerged from protoplanetary disks in multi-stellar systems already resided on misaligned orbits at the time of nebular dispersion. If this is true, small spin-orbit angles must be in large part either a result of adiabatic trailing of the host stars or dissipative re-alignment of the system. Such a scenario appears to be supported by observations: hot Jupiters orbiting hot, massive stars tend to be misaligned while hot Jupiters orbiting less-massive cooler stars.
undergone disk-driven migration. Theoretically, disk-driven migration of hot Jupiters. This model can be tested as follows. Although multiple studies have shown that disk-driven migration in binary systems is a favourable origin of misaligned planets, our model.

Figure 3 | Timescales for excitation of spin-orbit misalignment. The characteristic nodal recession period of a disk with $m_{\text{disk}} = 10^{-3} M_\odot$ is shown as a function of binary mass and orbital properties. The disk considered has an outer edge at $a_{\text{out}} = 50$ AU. Increasing $a_{\text{out}}$ will result in an approximately linear increase of the precession frequency. The period is expressed as a scaling law in the mass of the host star. In the region of parameter space where the precession period greatly exceeds the disk lifetime, only small misalignment angles between the disk and the host star can be excited. In principle, however, if the stellar companion does not get stripped away, the ascending node of the invariant plane of the formed planetary system can also reorient. However, the degree to which this can affect a planet on a close-in orbit is sensitive to the particular architecture of the system. In the region of the parameter space where dynamics ceases to be adiabatic, misalignment is certain to appear, but more precisely quantified (magnetohydrodynamical) modelling is required for its characterization. Finally, at the extreme high-mass/small-orbit-separation end of parameter space, one could envision a scenario where a newly formed disk becomes severely twisted and eventually gets disrupted as a result of strong external perturbations. Driven by viscous dissipation, however, such a structure would probably collapse into a new protoplanetary disk, whose orbital plane will be close to the Laplace plane of the stellar binary orbit.

tend to have small spin-orbit angles. This transition has been attributed to tidal re-alignment of cooler stars owing to the increased size of their convective zones and thus appears to be in good agreement with our model.

The consistency arguments presented above indicate that disk-driven migration in binary systems is a favourable origin of misaligned hot Jupiters. This model can be tested as follows. Although multiple studies have shown that disk-driven migration in binary systems is a favourable origin of misaligned planets, our model.

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