Circumbinary Planets and Assembly of Protoplanetary Disks

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Transiting Circumbinary Planets from Kepler

Welsh’s talk

Planetary and stellar orbits are aligned to within a few degrees.
Are there circumbinary planetary systems with misaligned (say >10 degrees) orbits?
Simplistic Answer:

All circumbinary planets have aligned (<a few degrees) orbits wrt stellar binary, since all rotations trace back to the angular momentum of same MC core/clump.
Evidence for Misalignments

-- Solar system: 7 degree
-- Stellar spin axes in (wide & close) binaries: Misaligned
-- Hot Jupiters
Evidence for Misalignments

-- Solar system: 7 degree
-- Stellar spin axes in (wide & close) binaries: Misaligned
-- Hot Jupiters
-- PMS/YSO binaries: Misaligned protostellar disks measured from jets or disks

Haro 6-10:
Two disks: one edge-on, one face-on
(Roccatagliata et al. 2011)

-- Misaligned circumbinary disks:
e.g., KH 15D (Winn et al 2004; Chiang & Murray-Clay 2004)
Reasons for misalignments in circumbinary planet systems

• Dynamics after formation (“perturber”)
• “Primordial” misalignment
“Primordial” Misalignments:
Star Formation in Turbulent Molecular Clouds

-- Supersonic turbulence --> clumps --> stars
-- Clumps can accrete gas with different rotation axes at different times

Bate et al. 2003
Tsukamoto & Machida 2013
Formation of Circumbinary Planetary Systems

1. A clump forms, collapses, and fragments ==> Compact Stellar Binary

2. Binary is embedded in a disk, and continues to accrete from the parent MC (The infalling material may not rotate in the same direction as the binary)

3. Planet forms in the circumbinary disk
Formation of Circumbinary Planetary Systems

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→ Expect misalignment between stellar binary and planet orbit
Consider Stage #2:
Binary + Disk (with misaligned gas supply)

Questions: What is the shape of the disk? How does the system mutual inclination evolve?
Dynamics of Warped Disks

Torque from binary on disk $\Rightarrow$ disk (ring) precession

$$\Omega_p(r) \approx \frac{3\mu}{4M_t} \left(\frac{a}{r}\right)^2 \Omega(r)$$

Differential precession + internal fluid stress $\Rightarrow$ warped/twisted disk

For protoplanetary disks, warp/twist spread as bending waves (efficient)
Dynamics of Warped Disks

\[ \sum r^2 \Omega \frac{\partial \hat{l}}{\partial t} = \frac{1}{r} \frac{\partial G}{\partial r} + T_b, \]

\[ \frac{\partial G}{\partial t} = \left( \frac{\Omega^2 - \Omega_r^2}{2\Omega} \right) \hat{l} \times G - \alpha \Omega G + \frac{\Sigma H^2 \Omega_z^2 r^3 \Omega}{4} \frac{\partial \hat{l}}{\partial r} \]
Steady-State Disk Warp/Twist

\[ \beta(r) \sim \beta_{\text{out}} \]

Appreciable twist \( \Rightarrow \) (if planets form at this stage, they will have some mutual inclination)
Long-Term Evolution of Binary -- Disk Inclination

Back-reaction of warped/twisted disk on the binary
===> reduce the binary-disk inclination on long timescale

\[ t_{\text{align}} \sim \frac{\mu}{\dot{M} f} \quad f \sim 200 \left( \frac{0.1a}{H_{\text{in}}} \right)^4 \]

\[ \mu = \text{reduced mass of binary} \]

\[ \sim 1 \text{ Myr} \quad \text{for} \quad \dot{M} \sim 10^{-8} M_\odot \text{yr}^{-1} \]

After accreting mass \( \Delta M \), the inclination angle reduces to

\[ \beta(t) \sim \beta(0) \exp \left[ -f \frac{\Delta M}{\mu} \right] \]

e-fold reduction requires

\[ \Delta M \sim 0.05\mu \left( \frac{H/r}{0.1} \right)^4 \left( \frac{r_{\text{in}}}{2a} \right)^{3.5} \]
Implications/Summary

Inclination between stellar orbit and circumbinary planet orbit reflects the condition of protostellar disk and how it is assembled ⇔ Star/binary formation

Details:
-- It is plausible (likely?) that gas falling onto the protostar/binary has misaligned rotation direction relative to the binary
   ==> Possibility of misaligned circumbinary planets
-- Nontrivial interaction between binary and warped/twisted disks
  (a) If planets form early in twisted, inclined circumbinary disk:
      ==> misaligned wrt stellar binary; mutual inclinations
  (b) If planets form late (after some mass accretion)
      ==> (maybe) realigned disk-binary system ==> aligned planets

Finding misaligned circumbinary planets (via eclipse timing) would be interesting…
Thanks
Possible Reasons for Misalignments:
Star Formation in Turbulent Molecular Clouds

-- Supersonic turbulence --> clumps from shock compression --> stars
-- In crowded SF region, clumps can accrete gas with different rotation directions at different times

Bate et al. 2003