The spin-orbit alignment of the Fomalhaut debris disk

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Exoplanets galore

- 600+ exoplanets discovered so far
  - Many more unconfirmed Kepler candidates
- « Hot Jupiters » are most emblematic
- Planetary transits
  - Radius
  - Composition
  - Spin-orbit orientation

![Graph: "Planet Semi-Major Axis" vs "Planet Mass" (638)](exoplanet.eu (30/09/11))
The Rossiter-McLaughlin effect

- Takes place during (planetary) transit
- Planet hides small fraction of one velocity component on photosphere
- Small bump moves through spectral line
- Creates RV anomaly

Gaudi & Winn 2007
The Rossiter-McLaughlin effect

- Access to projected star/orbit inclination
RM detected for hot Jupiters

- First detection by Queloz et al. (2000)
  - HD 209458b aligned
- 40+ systems observed
  - 18 significantly misaligned
  - 9 on retrograde orbits
- Detection not easy
  - Significant error bars (~10°) on relative inclination

Example: HAT-P-6b (Hébrard et al. 2011)
Misalignments more frequent for hot stars (>6250K)
- Due to tidal dissipation in stellar convective zone?
- Exceptions: light planets and long periods

Most hot Jupiters may have « arrived » misaligned
Possible explanations

- Disk-driven migration not possible
- Kozai mechanism
  - Requires distant 3\textsuperscript{rd} body on inclined orbit (40° < i < 140°)
  - Secular oscillations of eccentricity and inclination for inner planet
  - Circularisation by tidal friction
- Planet-planet scattering
  - Instabilities in multiple (packed) planetary systems
  - Orbit crossing → high eccentricities / inclinations
  - Circularisation by tidal friction
Kozai or scattering?

- Strongly debated issue (Morton & Johnson 2011)
  - Need 2× more observed systems to conclude
Misalignment may date back to formation (disk)

- Early stellar encounter (Bate et al. 2010)
  - Stellar cluster → chaotic environment
  - Interactions → misalignment + truncation

- Magnetosphere-disk interactions (Lai et al. 2011)
  - Magnetic protostar exerts warping/precessional torque on inner disk before disruption
  - Disk resists warping → back-reaction torque

- Interaction with gas-rich birth cluster (Thies et al. 2011)
  - Passage of young star through gas reservoir → capture of gas onto existing disk
  - Disk can be tilted up to retrograde
How to discriminate?

- Use debris disks
  - ~25 have been resolved
  - More with Herschel
- Resolved image
  - Inclination / position angle
  - Materialises the plane of planetary formation
- Need stellar orientation
How to get stellar orientation?

- Inclination from $P_{\text{rot}} \times v \sin i / 2\pi R_\star$ (Watson et al. 2011)
  - $P_{\text{rot}}$ from photometry or Ca II lines (low precision)
  - $v \sin i$ from high resolution spectroscopy
  - $R_\star$ from spectra, interferometry, ...
  - Result: no misalignment in 8 systems (FGK stars)
    - BUT: final error bars generally $\geq 10^\circ$
    - New Herschel resolved disks $\rightarrow$ 1st misaligned case?

- Position angle from spectro-interferometry
  - Only for rapidly rotating stars (A / early F)
  - Subject of this talk
Requirements
- Rapidly rotating star
- Deep absorption line
- Partly resolved photosphere (≥ 1 mas)

Displacement of photocenter across the Br-γ line
- Signature in fringe phase versus wavelength
- 2D phase → position angle
The Fomalhaut planetary system

- Fomalhaut: A4V, 7.7 pc
- Debris disk resolved at various wavelengths
  - Ring at 140 AU
  - Brightness asymmetry
  - Sharp inner edge
  - Off-centered by 15 AU
- Candidate planet at 115 AU
  - Orbital movement
Fomalhaut with VLTI/AMBER

- **Fomalhaut**
  - $v \sin i = 93$ km/s
  - Angular diam: $\theta = 2.2$ mas

- **AMBER**
  - $3 \times$ Auxiliary Telescopes
  - Baselines: ~100m
  - Medium spectral resolution ($R=1500$) in K band

- **Measure wavelength-differential phase**
  - Deduce 2D differential astrometry

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Le Bouquin et al. 2009
2D differential astrometry

- Clear signature inside Br-γ line
  - Precision: $\sim 3 \mu \text{as}$

Le Bouquin et al. 2009
Spin-orbit alignment

- Photosphere position angle: $155^\circ \pm 3^\circ$
  - But inclination not constrained (needs advanced model)
- Disk position angle: $156.0^\circ \pm 0.3^\circ$
- By-product: discriminate front side / back side
  - Assuming planet prograde and stellar spin not flipped
Backward scattering dominant?

- Possible only with big grains
  - Similar to lunar phases
- Small grains ejected?
  - What about further collisions?

Min et al. 2010
Future work: mini survey

- 6 more potential targets for VLTI/AMBER
  - + a few more to the North
- Zeta Leporis
  - Position angle retrieved while $\theta = 0.75$ mas only
- Beta Pictoris
  - Star aligned with inner or outer disk?
Fomalhaut with VLTI/PIONIER

- Detection limits based on closure phases
  - 7 OBs in total (~3h)
  - 7 spectral channels within K band