The role of star-planet interactions and binarity in stellar evolution

S. Mathis

CEA/DSM/IRFU/SAp; Laboratoire AIM Paris-Saclay, CEA/DSM - CNRS - Université Paris Diderot

Laboratory Dynamics of Stars and their Environment

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Binarties in stellar systems

Star-planet systems

PLATO, SPIRou (J.-F. Donati)

Binary stars

Star-compact object systems

Laboratory to study interactions and their impact on the evolution of stellar systems
Interactions and related torques

- Tides (& irradiation)
- Circumstellar disk
- Magnetospheric interactions & winds
- Mass transfer

→ Need to understand each of these interactions, their couplings and their impact
Rotational & orbital evolution of stellar systems

In studies of star-planet and multiple stars systems, bodies are often treated as point-mass objects or solids with ad-hoc prescriptions for angular momentum exchanges and torques.

However the stellar internal structure impacts rotation, magnetic field and tides.

→ Need of an ab-initio physical modeling

**Star-planets:**

![Image of Mercury orbit around a star and a planet with labels](image)

Huber et al. 2013; Chaplin et al. 2013; Gizon et al. 2013

**Binary stars:**

![Diagram showing evolutionary stages with age and initial orbital period](image)

De Mink et al. 2013 (Siess et al. 2013; Song et al. 2013)
A first “engine” for the dynamical evolution of binary systems: the tidal energy dissipation

Tidal evolution of a binary system (e.g. Zahn 1977):

Initial state:
- elliptic keplerian orbits of the two components
- non-synchronized rotations with the orbital motion
- non-aligned orbital and components’ spins

Final state: minimum energy state
- circularised orbits
- components synchronised with the orbital motion
- aligned spins
  or spiraling (Hut 1980, 1981; Levrard et al. 2009)

Necessity to identify the dissipative processes that convert the kinetic energy of tidal flows into thermic one ( time-scales for circularisation, synchronisation ($\Omega \to B$) and alignment or of tidal migration)
The tidal fluid velocity fields in stars

- **Equilibrium tide**: large-scale circulation induced by the hydrostatic adjustment to the tidal potential perturbation

- **Dynamical tide**: waves excited by the tidal potential (and their elliptical instabilities)

\[
\begin{align*}
\text{Excitation by each Fourier component of the potential} \\
2\Omega & \quad \text{N} & \quad f_L \\
\text{Gravito (-inertial) waves (R.Z.)} & \quad \text{Inertial waves (C.Z.)} \\
\text{Acoustic waves} & \quad \sigma_0 \\
\end{align*}
\]

Mathis & Remus 2013 (Zahn 1975; Rieutord & Valdetarro 2010; Mathis & de Brye 2012; Baruteau & Rieutord 2013; Jouve & Ogilvie 2013; etc.)
Dissipative processes

C. E.: turbulent friction
- equilibrium tide
- dynamical tide: inertial waves

R. C.: radiative damping
dynamical tide: gravito-inertial waves

R. E.: radiative damping
dynamical tide:
gravito-inertial waves

Solar-type stars

R. C.: radiative damping
dynamical tide: gravito-inertial waves

Massive stars

C. C.: turbulent friction
dynamical tide: inertial waves

Elliptic instabilities: both in convective and radiative regions

→ Challenge: coupling tides - turbulence (Lesur & Ogilvie 2012)
Impact on global rotation & orbit

Equilibrium tide

Slow tide

Fast tide

Dynamical tide

Ogilvie & Lin 2007; Rieutord & Valdettaro 2010

Remus, Mathis, Zahn 2012

→ Complex orbital & spin evolution

Witte & Savonije 1999-2002;
Auclair-Desrotour, Le Poncin-Lafitte & Mathis 2014
Angular momentum transport in stars with a companion

Transport mechanisms

- Meridional circulation: stresses; applied torques
- Turbulence
- Fossil field
- Gravitational waves: convection & tides
- Thermohaline: accretion (Theado & Vauclair 2012)

Talon & Charbonnel 2005; Mathis et al. 2013
Barker & Ogilvie 2010
Stellar magnetism and binarities

- What is the impact of magnetic fields during stellar formation, and vice-versa?
- How do tidally-induced internal flows impact fossil and dynamo fields?
- How do magnetospheric Star-Star Interactions modify stellar activity?
- What is the magnetic impact on angular momentum exchanges and mass transfers?

LPs TBL (C. Neiner) & CFHT (E. Alecian)
Magnetic fields: convection vs. radiation

Cool stars:
C.E.: Dynamo field (correlations with M, age, Ω)
R.C.: Fossil field

Hot stars:
C.C.: Dynamo field
R.E.: Fossil field (not correlated)

Subsurface convection

Kippenhahn & Weigert 1997
Magnetic field and stellar formation: the case of fossil fields

Interstellar medium

PMS

Stable zone relaxation

Braithwaite & Nordlund 2006; Duez & Mathis 2010

Impact of magnetic field on stellar formation
(fragmentation; Commerçon, Hennebelle & Henning 2011)

→ Magnetic dichotomy in hot stars?
Impact of tidal velocity fields on internal dynamics and magnetism

Equilibrium tide  Dynamical tide  Elliptical instabilities

Transport angular momentum $\Rightarrow$ modify $\Delta \Omega$ and $\Omega$ – effect

Helical flows $\Rightarrow \alpha$ - effect
Modification of stellar magnetism

- Tides (& precession, libration) \(\rightarrow\) modification of dynamo mechanisms and of the topology and stability of fossil fields?
- Comparison external mechanical forcings v.s. internal convective driving and instabilities (mass ratio threshold?) \(\rightarrow\) SPI
- Magnetic fields \(\rightarrow\) modification of tidal flows and related torques?
Magnetospheric interactions

- Applied torques (added to tides and winds)
- Helicity exchanges $\rightarrow$ modification of the magnetic activity (Lanza 2012)

Dunstone & Holzwarth, et al. 2008

Cohen et al. 2009; Strugarek, Brun, Matt 2012
Interaction with MHD stellar environment: winds & accretion disks

Winds: pressure-driven, line-driven (and colliding winds)

Pinto et al. 2011
Matt et al. 2012

Ud-Doula et al. 2008, Petit et al. 2013 MiMeS

Accretion disks (J. Bouvier)

Matt & Pudritz 2005, Romanova et al. 2010

MaPP, MaTYSSE
Whole system evolution

Barker & Ogilvie 2009

Need to simultaneously treat gravitational and MHD interactions and determine their relative orders of magnitudes.
The study of habitability

Stars are the core of planetary systems

PLATO

K2, CHEOPS, TESS

Tidally locked

Rauer et al. 2013

Orosz et al. 2012 (Kepler 47)
Towards a complete picture

Dynamical evolution of stars interacting with companions

- How do tidal dissipation and torque vary as a function of stellar mass and evolutionary stage?
- What is the relative importance of the different applied torques along their evolution?
- For a given evolutionary stage, which physical processes dominate the transport?
- How do this rotational evolution and binarity impact stellar chemical properties (mixing) and magnetism?

Dynamical evolution of multiple systems

- What are the respective impact of tides and magnetic interactions on multiple system evolution?
- In multi-body systems, how do tidal and MHD interactions couple with resonances?
- How do the orbital architecture (and the habitable zone) change along the host star’s evolution?
- …

Dynamical vision of the evolution of stars and their environment: transverse to PNPS/PNP/(PNST/GRAM)