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Investigating star-planet interactions with CoRoT

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1. Introduction

The method of transits allows to detect a planet by the periodic light dips it induces on its host star when it passes in front of it once per orbital period. Since the probability of having a suitably oriented orbital plane is R/a, where R is the radius of the star and a the orbital semimajor axis in the case of a circular orbit, this technique strongly favours the discovery of close-in planets. CoRoT (Auvergne et al. 2009) opened a new era in extrasolar planetary studies by allowing for the first time a systematic space-borne search yielding planets with sizes approximately between that of the Earth and Jupiter (Léger et al. 2009; Moutou et al. 2013).

The proximity of those planets to their hosts makes the study of the mutual interactions particularly important. Stars interact with planets through their radiation, magnetic, and gravitation fields. Here, I focus on magnetic interactions considering also the role of tides because they can affect rotation and magnetic activity of the host stars. CoRoT light curves contain a wealth of information to pursue these studies and allow us to address important questions about the way massive close-in planets affect the rotation and hydromagnetic dynamos of their hosts. This is relevant for the measurement of the stellar age through gyrochronology (Barnes 2007; Meibom et al. 2015) and the determination of the planet mass because magnetic activity induces a jitter that limits the accuracy of the radial velocity measurements for planets orbiting active stars.

2. Tidal interaction

Stars are fluid bodies and the gravitational field of a nearby planet induces a deformation of their isopotential equilibrium surfaces that adds to the effect of stellar rotation producing deviations of their shape from spherical symmetry. In addition to this equilibrium tide, the time-varying gravitational potential of the orbiting planet can excite different kinds of oscillations inside the star (dynamic tide). The tidal bulge of the equilibrium tide is carried by stellar rotation away from the line joining the barycentres of the two orbiting bodies. This produces a dissipation of the kinetic energy of the tidal flow, particularly in stars with outer convective envelopes. Similarly, the kinetic energy of the waves excited by the dynamic tide is dissipated in stellar convection zones and radiative interiors. Eventually, the dissipation ceases when the stellar spin becomes aligned with the orbital angular momentum, the orbit is circularized, and the rotation periods of the two bodies become equal to the orbital period (e.g., Zahn 2008; Souchay et al. 2013).

Our current understanding of tides is hampered by a lack of knowledge about the processes that dissipate their kinetic energy leading to the establishment of the above equilibrium state (or the fall of the planet onto its host, in the case its orbital angular momentum is not large enough to reach the equilibrium state). Estimates of the time scale to attain the equilibrium state often span 2−3 orders of magnitudes. The discovery of close-in planets allows to investigate tidal dissipation in an hitherto unexplored regime characterized by orbital periods from a few to tens of days and a mass ratio of the two bodies $\leq 10^{-3}$. Statistical studies of the distribution of the orbital periods of hot Jupiters provided some constraints on tidal dissipation (e.g., Jackson et al. 2008; Hansen 2010, 2012), but there is still considerable uncertainty because of our ignorance of the initial state and the ages of the considered systems.

Tides affect magnetic activity by modifying the evolution of stellar rotation that plays a fundamental role in controlling the stellar hydromagnetic dynamo (cf. Fig. III.9-1.1). Equilibrium tides might perturb the shape and affect the stability of magnetic flux tubes at the bottom of the convection zone, thus producing preferential longitudes for magnetic activity (Holzwarth & Schüssler 2003a,b), while waves excited by the dynamic tides may affect stellar turbulence, modifying dynamo parameters, notably the magnetic diffusivity. In extreme cases, the dynamo might be quenched by tidal effects (Pillitteri et al. 2014b). On the other hand, the continuum loss of angular momentum produced by a magnetized stellar wind affects tidal evolution on timescales of hundreds of Myrs or Gyrs, possibly preventing the reaching of a final equilibrium state, i.e., leading to the infall of the planet into the star during its main-sequence lifetime (e.g., Damiani & Lanza 2015).

The modification of stellar rotational evolution produced by tides affects the possibility of estimating stellar age by means of gyrochronology with a strong impact on our understanding of planetary systems.

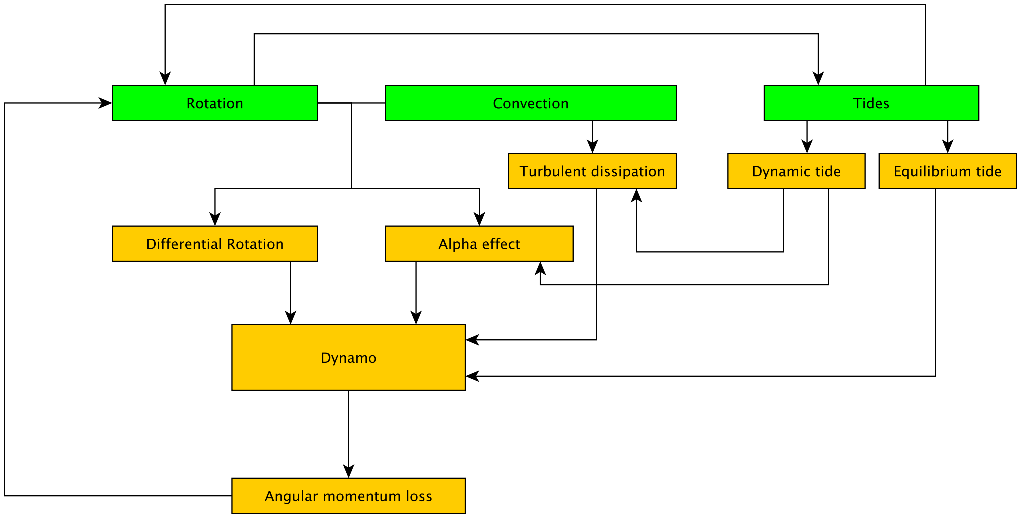

Fig. III.9-1.1. Main connections between stellar rotation, convection, and tides. Rotation and tides directly interact with each other. On the other hand, the interaction of rotation and convection produces differential rotation and the α effect – associated with the helicity of the turbulent flows – that, together with turbulent dissipation, are the basic ingredients of solar-like hydromagnetic dynamos operating in late-type stars. The dynamo affects rotation by producing a steady loss of angular momentum in a magnetized stellar wind. In turn, this modifies the tidal evolution of a planetary system. Equilibrium tides interact with the dynamo by perturbing the shape of large-scale magnetic flux tubes at the base of the stellar convection zone, thus affecting their stability (see the text), while the dynamic tide (by exciting various types of waves) can affect the turbulent dissipation and possibly the α effect.

2.1. Some CoRoT results

CoRoT provided precise measurements of rotation periods in late-type stars with transiting hot Jupiters thanks to the detection of the flux modulation produced by starspots. It measured stars with an activity level too low to reach the same precision from the ground, such as in the case of CoRoT-4 (Aigrain et al. 2008). Since most of the main-sequence lifetime of planetary hosts of F, G, or K-type is characterized by rather low levels of activity, CoRoT allowed to study their rotation without the limitation of spectroscopy that is rather inaccurate for slowly rotating stars. Moreover, CoRoT allowed us to measure a lower limit for the amplitude of surface differential rotation by tracing the longitude migration of starspots vs. time (cf. Lanza et al. 2009a,b, 2011a). Differential rotation affects the age determination by gyrochronology because the rotation period of starspots depends on their latitude. Its measurement is important also for a better understanding of tidal interaction in planetary systems (Guenel et al. 2014).

CoRoT allowed a precise timing of planetary transits with typical errors ranging from a few to tens of seconds on bright stars. This opens the possibility of directly measuring tidal dissipation in some transiting systems. Assuming a tidal dissipation comparable to that observed in close binary stars, precisely a modified stellar tidal quality factor $Q'_{\rm s} = 10^6$, we expect a variation of the epoch of mid transit of 5−10 s in one or two decades in the most strongly interacting systems with respect to a constant-period ephemeris. This is within our reach by combining CoRoT measurements with future measurements by CHEOPS or PLATO 2.0. Systems with a star rotating slower than the orbit should display a shortening of the orbital period, while systems with a star rotating more rapidly, such as CoRoT-11, show an increase of the period (Lanza et al. 2011b). These observations have the potential to put strong constrains on the intensity of tidal interaction allowing to discriminate among different models of tidal dissipation (e.g., Ogilvie & Lin 2007; Ogilvie 2014).

The duration of transits is another parameter that is worth of being measured because it can be changed by the precession of the orbital plane when the stellar spin is oblique to the orbital angular momentum. Rapidly rotating stars, such as CoRoT-11 or WASP-33, have a remarkable quadrupole moment inducing a relatively fast nodal precession (e.g., Damiani & Lanza 2011; Johnson et al. 2015). For both the determination of the orbital evolution and the nodal precession, a sample consisting of several systems is recommended in order to avoid spurious detections due to the perturbations produced by third bodies in the systems. CoRoT-11 is particularly suitable for this kind of measurements because the light curve shows no signs of magnetic activity that could distort the transit profile and affect their timing (cf. Lanza et al. 2011b).

Another important contribution of CoRoT is the measurement of the projected obliquity in the CoRoT-2 system by means of spot occultations during transits (Nutzman et al. 2011). The obliquity between the stellar spin and the orbital angular momentum depends on the mechanism that produced the inward migration of the hot Jupiter after its formation: a loss of angular momentum by planet-disc interaction would produce small obliquity, while planet-planet scattering or Kozai-type mechanisms would induce higher obliquity (for a recent review see Winn & Fabrycky 2015, also discussing other mechanisms). The Rossiter-McLaughlin effect can be used to measure the projected obliquity, but it requires high-precision radial velocity measurements and a sufficiently rapidly rotating star (say, at least $v \sin i \sim 3$ km s^{-1}). On the other hand, the method introduced by Nutzman et al. exploits only high-precision photometry to constrain the projected obliquity. In a nearly aligned system, the same spots are repeatedly occulted during successive transits when the stellar rotation bring them again along the transit chord. Combining out-of-transit precise rotation measurements with the observations of spot features during transits, this method has been extensively applied to Kepler systems (e.g., Sanchis-Ojeda & Winn 2011; Sanchis-Ojeda et al. 2012, just to cite two interesting cases). In the case of oblique systems, it allows to find the latitude of spot formation in a solar-like star and its migration along the activity cycle (Sanchis-Ojeda & Winn 2011; Llama et al. 2012). The correction for nodal precession in the case of rapidly rotating hosts can be derived from the variation of the duration of the transits or estimated from theory.

From a wider perspective, CoRoT provided some of the best characterized transiting planetary systems. Here we focus on the importance of a precise measurement of stellar rotation and the estimate of the amplitude of differential rotation using the light modulation produced by starspots. For a comparison of gyrochronological ages to those derived by isochrone fitting, Maxted et al. (2015) selected a sample of 28 stars with transiting exoplanets whose rotation periods are accurately known, including five CoRoT systems with estimates of the amplitude of the differential rotation that is relevant to controlling one fundamental source of error in the gyro age determination. The discovery of CoRoT-4, with a host star that appears to rotate synchronously in spite of the weak tidal interaction predicted by the theory (Aigrain et al. 2008; Lanza 2010), and of CoRoT-6 and CoRoT-11, whose hosts are rotating more rapidly than the orbital period (Fridlund et al. 2010; Gandolfi et al. 2010) are other valuable results that will certainly allow long-term studies of the tidal effects in systems with close-by planets. CoRoT-6 is also particularly relevant for the study of magnetic star-planet interactions because CoRoT clearly detected its spot activity (Lanza et al. 2011a).

3. Magnetic interactions

Chromospheric hot spots rotating in phase with the orbit of their close-in massive planets have been reported in υ And and HD 179949 by Shkolnik et al. (2005), although the phenomenon is certainly not a steady one (Shkolnik et al. 2008). Pillitteri et al. (2011, 2014a, 2015) found evidence of flaring activity occurring after the occultation egress of the hot Jupiter in HD 189733 in a restricted range of orbital phases ($\phi \simeq 0.52-0.65$) and suggested that, as an alternative to magnetic interaction, the energy could be released by the infall of material evaporated or stripped from the planet onto the star (see the numerical models of Matsakos et al. 2015). In HD 17156, hosting a massive planet on an eccentric orbit with a period of 21 days, there is some preliminary indication of flaring activity preferentially occurring close to periastron (Maggio et al. 2015). In the case of photospheric activity, Béky et al. (2014) reported the case of starspots that rotate in close commensurability with the orbital period in HAT-P-11 and possibly Kepler-17, while Hernán-Obispo et al. (2015) suggested the presence of a close-in planet with a related light curve modulation at the synodic period in BD+20°1790. Details on the theoretical models proposed to account for such observations can be found in, e.g., Lanza (2008, 2012, 2013), while general reviews are presented in Lanza (2011, 2015).

Statistical studies revealed apparent correlations between chromospheric or coronal emissions and close-in massive planets that were successively attributed to biases in the sample selection or to the rather limited number of stars considered (see Poppenhaeger et al. 2010; Poppenhaeger & Schmitt 2011; Canto Martins et al. 2011; Miller et al. 2015, and references therein). The only correlation that gained support by extending the sample and refining the selection criteria was that between the chromospheric $\log R'_{\rm HK}$ index and the surface gravity of transiting planets (Hartman 2010; Figueira et al. 2014; Fossati et al. 2015).

3.1. The role of CoRoT

CoRoT played a fundamental role in the study of stellar magnetic activity and of star-planet magnetic interactions by demonstrating the possibility of mapping the surface of active stars using suitable spot modelling techniques applied to high-precision light curves. CoRoT-2 became a benchmark in the field because it has been mapped with different approaches, including spot occultations during transits, thus providing a reliable account of the potentials and the limitations of spot modelling (cf. Lanza et al. 2009a; Huber et al. 2010; Silva-Valio & Lanza 2011, see Fig. III.9-1.2). Spot occultations allowed to derive the distributions of size, contrast and longitude of the spots along the transit chord (Silva-Valio et al. 2010; Silva-Valio & Lanza 2011). Previous comparisons between spot models and maps obtained with Doppler Imaging techniques provided much less definite conclusions on the potentiality of spot modelling (cf. Lanza et al. 2006).

CoRoT-2 is an extremely interesting system in itself. The planet is strongly inflated (Guillot & Havel 2011) and it is possible that stellar activity plays a role in this phenomenon. A crucial parameter to understand this system is its age. From the activity level of the host star and its short rotation period, CoRoT-2 appears younger than ∼0.5 Gyr. However, Poppenhaeger & Wolk (2014), on the basis of the lack of any detectable X-ray emission from its K-type visual companion, proposed an age of at least ∼5 Gyr for the system (cf. Schröter et al. 2011). A similar discrepancy, although not so extreme, was found in HD 189733 that hosts another massive close-in planet. Recently, Maxted et al. (2015) found other planet hosts with ages derived by isochrone fitting significantly older than gyrochronological ages. A tidal spin-up of those stars or a decrease of the magnetic wind braking due to the close-in planet could be possible explanations (see Lanza 2010). To make the case even more intriguing, the Lithium abundance favors a young age in the case of CoRoT-2 (Schröter et al. 2011). The impact of starspots on these measurements is usually regarded as minimal (Pallavicini et al. 1993), but a recent work by Somers & Pinsonneault (2015) suggests that possible effects of activity on Lithium abundance should be investigated.

CoRoT-2 displayed a short-term spot cycle whose period is close to ten times the synodic period of the planet (Lanza et al. 2009a). A similar phenomenon was found in Kepler-17, although no commensurability with the planet orbit was apparent there (Bonomo & Lanza 2012). These short-term cycles have been observed in the Sun close to the maxima of some eleven-year cycles (Rieger et al. 1984; Oliver et al. 1998) and have been suggested in the active close binary system UX Ari (Massi et al. 2005), but their discovery in CoRoT-2 is the first case in another solar-like star. As in the case of the Sun, they are expected to be transient phenomena.

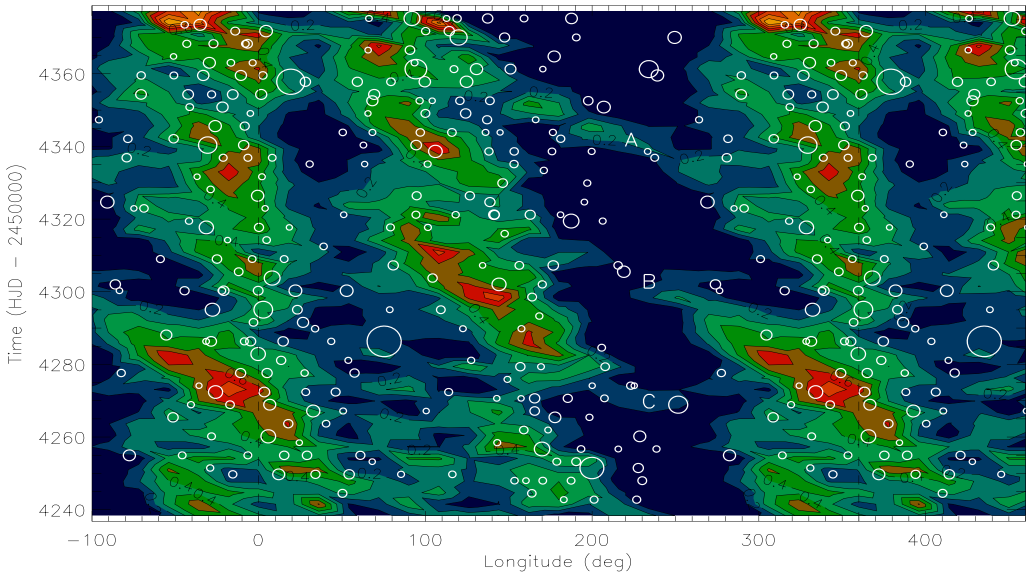

Fig. III.9-1.2. A comparison of the maximum entropy map of the starspot filling factor in CoRoT-2 vs. longitude and time, and the position of the spots occulted during transits (white open circles, the symbol size is proportional to the effective area of the spot). The maximum filling factor corresponds to orange-yellow and red areas, while the minimum is dark blue. Three bridges of spots connecting the two main active longitudes are labelled A, B, and C. Spots detected through their occultation during transits are preferentially located at the active longitudes found in the maximum entropy map of the out-of-transit light curve. This gives strong support to the possibility of mapping spot longitudes using CoRoT out-of-transit light curves (see Silva-Valio & Lanza 2011, for details) (Credit: Silva-Valio & Lanza (2011), reproduced with permission, © ESO).

Another interesting system is CoRoT-1 (Barge et al. 2008) whose chromospheric emission level was found to be remarkably lower than in similar systems (cf. Fig. 2 in Fossati et al. 2013). A possible interpretation is a torus of circumstellar plasma filled by the evaporation of the planet and absorbing in the cores of the Ca II H&K resonance lines. The relatively low surface gravity of the planet may enhance the evaporation thus making this star more absorbed (Lanza 2014).

Finally, CoRoT played a fundamental role in the investigation of the radial velocity jitter associated with stellar magnetic activity, thanks to the discovery of CoRoT-7, the first transiting super-Earth that prompted two campaigns of simultaneous high-precision radial velocity measurements with HARPS. They allowed to discover a second and possibly a third planet in the system. CoRoT-7 fostered the development of several techniques to reduce the impact of the activity-induced jitter on the measurement of the mass of its planets (e.g., Queloz et al. 2009; Hatzes et al. 2011; Ferraz-Mello et al. 2011; Aigrain et al. 2012; Haywood et al. 2014) as well as the treatment of the activity-induced distortions of its transits (Barros et al. 2014). The activity and rotation of this host could be studied in detail thanks to the high-precision CoRoT light curve (Lanza et al. 2010).

4. Conclusions and future prospect

CoRoT achieved very important results in the field of star-planet interactions because it provided very accurate rotation periods and differential rotation amplitudes for several stars with close-in transiting planets, allowing to study their magnetic activity at the photospheric level. Activity features directly associated with the orbiting planet have possibly been found in the case of CoRoT-6 (Lanza et al. 2011a) and CoRoT-4 (Lanza et al. 2009b), but the latter host is rotating synchronously, so any evidence is much less sound. Chromospheric or photospheric features associated with a close-in planet, if real, are characterized by a remarkable time variability with long time intervals without any detectable effect (cf. Santos et al. 2003; Shkolnik et al. 2008). Therefore, a long-term investigation of selected systems is required to confirm and study this kind of interaction; alternatively, a large statistical sample could be monitored for shorter time intervals. This will become possible first with TESS (Ricker et al. 2015) and then with PLATO 2.0 (Rauer et al. 2014) that will target bright stars ($V \leq 12-13$), the only ones for which such subtle effects can be detected. Moreover, those telescopes will allow the detection of short-term Rieger-like spot cycles in other late-type stars and a confirmation of those reported in CoRoT-2 and Kepler-17.

The high precision rotation periods determined by CoRoT (and Kepler) are unrivalled in the case of G and K hosts with period longer than 15−20 days because the amplitude of their rotational modulation is at the limit of ground-based photometry. This has contributed to show that in a substantial fraction of host stars with massive close-in planets the age derived from the rotation period through gyrochronology is at variance with the age estimated by isochrone fitting (Maxted et al. 2015). In the case of CoRoT-2, the discrepancy is confirmed by the X-ray observations of its visual companion (Poppenhaeger & Wolk 2014). Again, bright hosts are the best for this kind of investigation because they allow a much better characterization of the parameters of the systems which is difficult in the case of the rather faint targets of Kepler. TESS and PLATO 2.0 will certainly provide very interesting data for a better understanding of the discrepancy, thanks to the observations of planets in wide binaries and in clusters, for which alternative age estimates will be possible. Furthermore, age estimates by asteroseismology

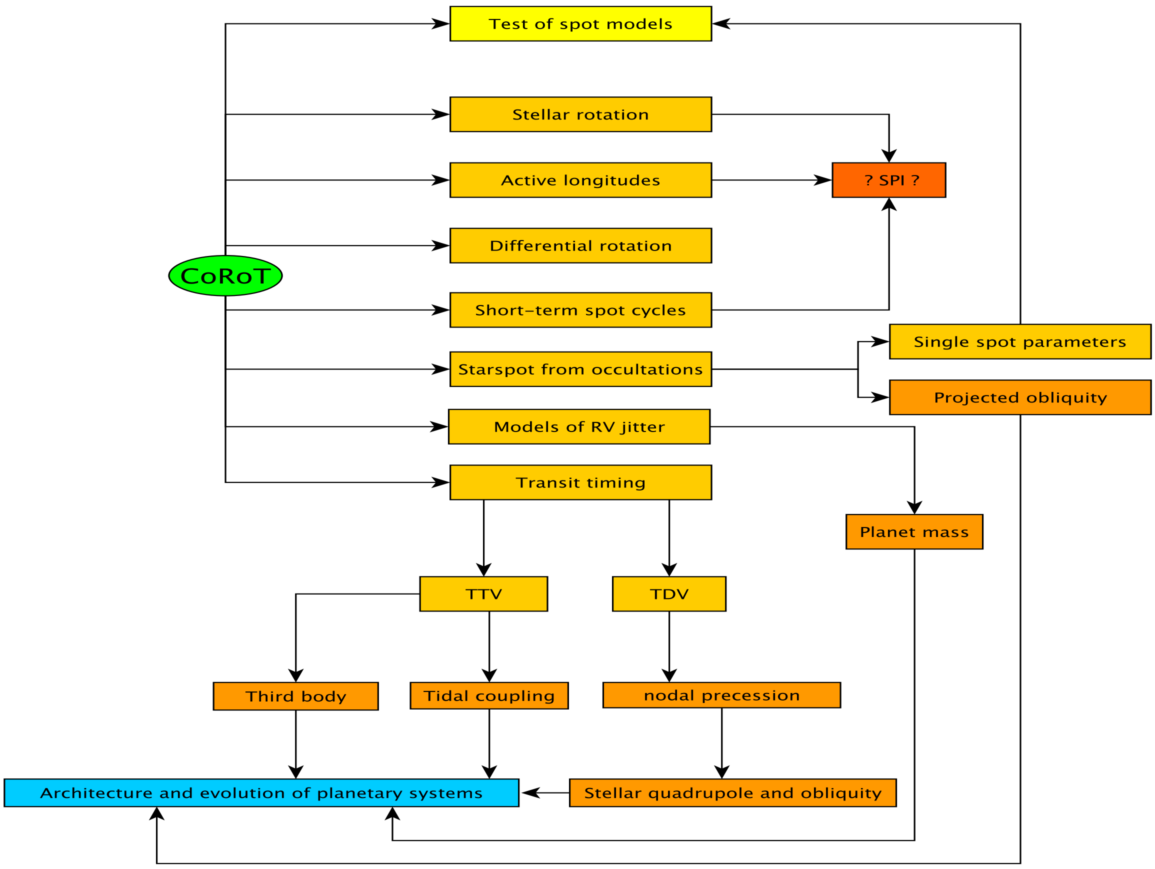

Fig. III.9-1.3. CoRoT main results that are relevant for the study of star-planet interactions. Stellar rotation, active longitudes, and short-term spot cycles might be affected by some direct effect of a close-in massive planet on the stellar dynamo, indicated with SPI. Spot occultations during transits allow us to derive accurate parameters for individual spots to test out-of-transit spot modelling, while providing information on the projected stellar obliquity. Simultaneous high-precision photometry can be used to model and reduce the radial velocity jitter due to stellar activity, thus improving the measurement of a planet's mass. The accurate long-term transit timing possible by combining CoRoT data with those coming from forthcoming space-borne telescopes will allow us to measure transit mid-time variations (TTV) and transit duration variations (TDV) that can be related to the presence of a third body or to angular momentum transfer by tides, and to orbital nodal precession, respectively.

will be provided by PLATO 2.0 with an accuracy of ∼10 percent.

Finally, the re-observation of the bright CoRoT systems with hot Jupiters will provide an estimate of the stellar tidal quality factor $Q'_{\rm s}$, i.e., a measurement of tidal dissipation in solar-like stars. A direct measure of a $Q'_{\rm s} \sim 10^6$ is possible with a time baseline of 15−20 yr in the best cases. Even a non-detection of the expected timing effect will put a lower limit on $Q'_{\rm s}$ ruling out models that predict a strong interaction (cf. Ogilvie & Lin 2007).

A summary of the main results obtained by CoRoT that are relevant for the study of star-planet interactions is provided on Fig. III.9-1.3.

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