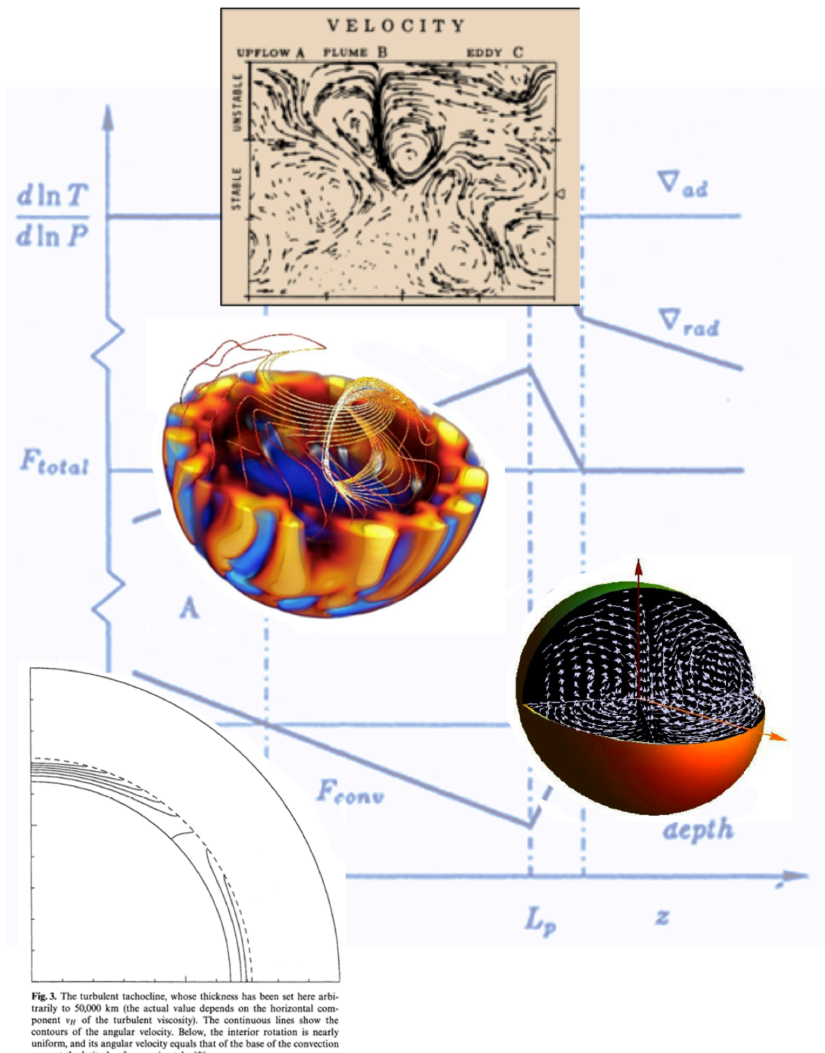
Astrofluid 2016

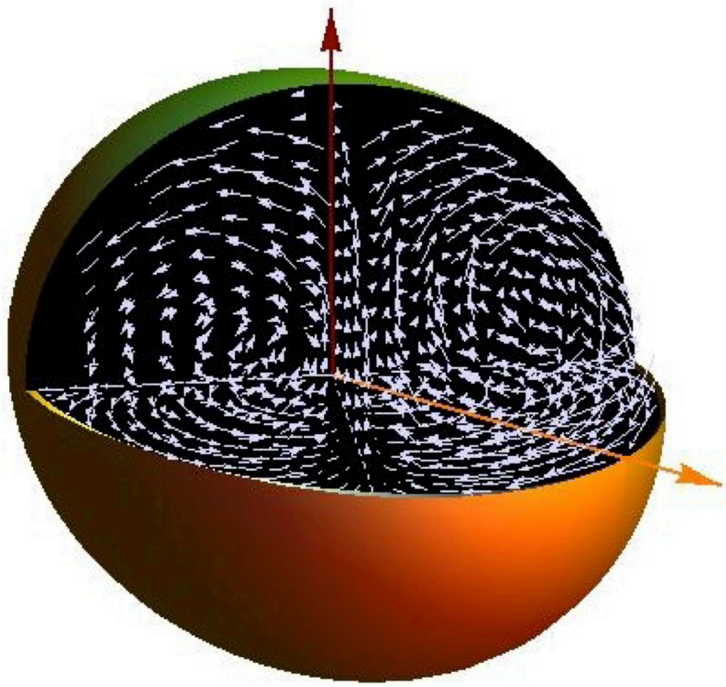
an international conference
in honor of Prof. Jean-Paul Zahn



Institut d'Astrophysique de Paris
June 27-30, 2016

With the support of

Tides in stars and planets



Dr Stéphane MATHIS and Pr Sébastien CHARNOZ

Interactions from stellar to giant planet systems

Tidal and disc-planet/moon interactions are key physical mechanisms that drive the evolution of planetary systems from the solar to exoplanetary systems. In this context, Jean-Paul Zahn was the first to establish a coherent physical description of hydrodynamical tidal waves in stellar interiors, of their dissipation and of the resulting rotational and orbital dynamics. André Brahic, his friend, funded the theory of the formation and the structure of planetary rings. In this keynote lecture, we will review the key contributions of Jean-Paul and André on tides, rings and discs in stellar and planetary systems and show the large number of new fields of research they opened.

Pr Gordon OGILVIE

On the frequency-dependent effective viscosity of laminar and turbulent flows
(in collaboration with G. Lesur and H. Braviner)

In his classic work on tidal dissipation in stars, Jean-Paul Zahn pointed out that the effective viscosity of a stellar convective zone in response to oscillatory tidal forcing should be significantly reduced, relative to the value predicted by mixing-length theory, when the tidal oscillation period is short compared to the convective timescale. The reduction factor is important for understanding the efficiency of tidal dissipation in stars and giant planets, and has proven to be controversial. We use analytical methods to discuss the viscoelastic response of a fluid flow in the asymptotic limit of high frequency. We also use numerical simulations of laminar and turbulent flows to measure the effective viscosity as a function of frequency, and compare with theoretical predictions.

Pr Adrian BARKER

Nonlinear tidal flows in short-period planets

Tidal interactions between short-period planets and their host stars are thought to play an important role in the evolution of the planetary orbit as well as the stellar and planetary spins. However, the mechanisms responsible for tidal dissipation are not well understood theoretically. I will present new results from a set of global hydrodynamical simulations that study nonlinear tidal flows in short-period gaseous planets from first principles. I will discuss the outcome of the elliptical instability, and the resulting implications for the circularisation, spin-orbit synchronisation and planetary spin-orbit alignment for short-period planets. I will also present results from a set of local ("small-patch") magnetohydrodynamical simulations designed to study the turbulent damping of spin precession in gaseous planets. This mechanism could be important in driving tidal evolution of the planetary spin-orbit angle.

Dr Benjamin FAVIER

The turbulent response of planetary fluid interiors to tidal and librational forcing

(in collaboration with A. M. Grannan, M. Le Bars and J. M. Aurnou)

The turbulence generated in the electrically conductive liquid metal cores and subsurface oceans of planetary bodies may be due, in part, to the role of boundary forcing through such geophysically relevant mechanisms of precession/nutation, libration, tidal forcing, and collisions. Here, we combine laboratory equatorial velocity measurements with selected high-resolution numerical simulations to show, for the first time, the generation of bulk filling turbulence driven by tidal forcing. The transition to saturated turbulence is characterized by an elliptical instability that first excites primary inertial modes of the system, then secondary inertial modes forced by the primary inertial modes, and finally small-scale turbulence.

The results of the current work are compared with recent studies of the libration-driven turbulent flows. These separate analog models correspond, in geophysical terms, to two end-member types of mechanical forcing. In tidal forcing, non-synchronous satellites possess elastically deformable boundaries such that shape of the distortion has a non-zero mean motion. For librational forcing, the core-mantle boundary possesses an inherently rigid or tidally frozen-in ellipsoidal shape in a synchronous orbit such that the mean motion of the elliptically deformed boundary is zero. We find striking similarities in both the transition to bulk turbulence and the enhanced zonal flow hinting at a generic fluid response independent of the forcing mechanism.

Dr Florian GALLET

From stellar evolution to tidal interaction: impact on planetary habitability

With the ever-growing number of detected and confirmed exoplanets, the probability to find a planet that looks like the Earth increases every year. While it is clear that being in the habitable zone does not imply being habitable, a systematic study of the evolution of the habitable zone as well as the evolution of the planetary orbital motion is required to account for their dependence upon stellar parameters.

While stellar rotation plays a crucial role in stellar structure evolution, stellar activity, and star-planet interaction through tidal perturbation, it is usually not included in such analysis.

In this presentation, I will present, for the first time, the results of the impact of rotating stellar models (using the STAREVOL code) on both habitable zone and tidal dissipation evolution around and inside low-mass stars.

Dr Jérémy LECONTE

Powering planets with tides: coupling thermal and orbital evolution in exoplanetary systems

Just like stars, planets feel the gravitational distortion caused by a nearby companion. And just like inside stars, these tides are also dissipated in planetary interiors, where they deposit energy. However, contrary to stars, planets are much less massive, and thus, much less luminous. As a result, the energy deposited by tides can be a major component of the whole energy budget of a planet, and drastically influence the thermal evolution of the latter. But the efficiency of the tidal dissipation, and the resulting orbital evolution, also depend on the internal structure of the distorted body. This creates a strong feedback.

In this review, I will thus explain how the thermal evolution of the planet and its orbital evolution are coupled and show dramatic examples of this coupling. I will especially focus on exoplanetary systems for which the huge diversity of orbital configurations can lead to very intense tidal interactions.

Dr Emeline BOLMONT

Effect of the rotation and tidal dissipation history of stars on the evolution of close-in planets

Since twenty years, a large population of close-in planets orbiting various classes of low-mass stars (from M-type to A-type stars) has been discovered.
In such systems, the dissipation of the kinetic energy of tidal flows in the host star may modify its rotational evolution and shape the orbital architecture of the surrounding planetary system.
In this context, recent observational and theoretical works demonstrated that the amplitude of this dissipation can vary over several orders of magnitude as a function of stellar mass, age and rotation.
In addition, stellar spin-up occurring during the Pre-Main-Sequence (PMS) phase because of the contraction of stars and their spin-down because of the torque applied by magnetized stellar winds strongly impact angular momentum exchanges within star-planet systems.
Therefore, it is now necessary to take into account the structural and rotational evolution of stars when studying the orbital evolution of close-in planets.
At the same time, the presence of planets may modify the rotational dynamics of the host stars and as a consequence their evolution, magnetic activity and mixing.

In this work, we present the first study of the dynamics of close-in planets of various masses orbiting low-mass stars (from 0.6 Msun to 1.2 Msun) where we compute the simultaneous evolution of the star's structure, rotation and tidal dissipation in its external convective envelope.
We demonstrate that tidal friction due to the stellar dynamical tide, i.e. tidal inertial waves excited in the convection zone, can be larger by several orders of magnitude than the one of the equilibrium tide currently used in celestial mechanics, especially during the PMS phase.
Moreover, because of this stronger tidal friction in the star, the orbital migration of the planet is now more pronounced and depends more on the stellar mass, rotation and age. This would very weakly affect the planets in the habitable zone because they are located at orbital distances such that stellar tide-induced migration happens on very long timescales.
We also demonstrate that the rotational evolution of host stars is only weakly affected by the presence of planets except for massive companions.

Pierre AUCLAIR-DESROTOUR

Atmospheric tides: modelling and consequences on the rotational dynamics of super-Earths in the habitable zone

Tides can strongly affect the evolution of the spin of planets. Super-Earths presenting a solid core and an atmosphere are submitted to both gravitational tides caused by bodies' mutual gravitational interactions and thermal tides resulting from stellar insolation. Thermal tides are particularly important for planets in the habitable zone where they drive the tidal response of the atmosphere (Correia et Laskar 2008). They play a key role for the equilibrium states of the spin, as in the case of Venus (Correia et Laskar 2004) and of exoplanets (e.g. the numerical simulations by Leconte et al. 2015), and therefore affect the climate of such planets. Given the complex mechanisms involved in thermal tides, analytic models are essential to understand the dependence of the perturbation on the physics of the atmosphere and the tidal frequency. The one proposed in the 60's by Lindzen and Chapman explains well thermal tides in the asymptotic regime of fast rotators but presents a singularity near synchronization. We will present a new analytic approach that generalizes this early work to all regimes of tidal perturbations. This model describes tidal waves generated in the atmosphere by both gravitational and thermal tides. The tidal torque is computed as a function of the frequency of the forcing and agrees very well with results obtained by direct numerical simulations using General Circulation Models. We then use it to determine and characterize analytically the possible states of equilibrium of the spin rotation of Venus-like planets and telluric exoplanets in the habitable zone of low-mass stars.

Pr. Gwenaël BOUÉ

3D evolution of the spin of close-in bodies made of Maxwell viscoelastic material

In this talk, we outline a new formalism designed to model the 3D rotation of viscoelastic bodies made of Maxwellian material. This formalism remains regular for any spin rate and orientation and for any orbital configuration including high eccentricities and close encounters. Applying this model to close-in exoplanets without permanent multipole shows that their rotation can be trapped in spin-orbit resonances not only if their orbit is eccentric but also in the case of circular orbit if their spin axis is tilted. This behaviour is of great importance for close-in super-Earths which are mainly found in multiplanet systems with non-zero mutual inclinations.

Dr Valéry LAINEY

The ENCELADE team: A new vision of the Saturn system

Composed mainly of researchers from the Paris Observatory at the beginning, the ENCELADE team was initiated in 2007. Our main objective was to quantify the possible orbital acceleration of Enceladus, one of the main moons of Saturn, and associated to the strong tides raised by its primary. This work led us to a much broader issue, requiring scientific expertise in astrometry, physics of gaseous planets and icy satellites. As an expert in the field of tidal dissipation of gaseous bodies, Jean-Paul Zahn was an active member of our team. In this talk we will summarize the major results we obtained concerning the Saturn system with consequences for Jupiter and the gaseous exoplanets.

Pr Tamas BORKOVITS

Third-body perturbed apsidal motion in eclipsing binaries in the primordial Kepler-field

(in collaboration with Saul A. Rappaport and Emese Forgacs-Dajka)

Tidally forced apsidal motion in eccentric eclipsing binaries is a key-observable of inner stellar structure studies, and may serve as important probe for different tidal dissipation theories. There are, however, alternative physical processes which result in additional contribution to the observed apsidal motion. Here we mainly concentrate on the perturbing effect of a third, distant stellar companion, which forms hierarchical triple system with the eclipsing pair.

First we discuss shortly the mathematical form of the combined 3-rd body and tidally forced apsidal motions, and its observational aspects, then an eclipse timing variation study (based on the above mentioned analytical formulae) of 26 Kepler spacecraft-discovered 3-rd body perturbation-dominated compact hierarchical triple will be presented.

Dr Lionel SIESS

A scenario for the formation of long-period eccentric binaries with a helium white dwarf

The recent discovery of long-period eccentric binaries hosting a He-white dwarf or a subdwarf star has been challenging binary-star modeling. Based on accurate determinations of the stellar and orbital parameters for IP Eri, a K0 + He-WD system, we propose an evolutionary path that is able to explain the observational properties of this system and, in particular, to account for its high eccentricity (0.25). Our scenario invokes an enhanced-wind mass loss on the first red giant branch (RGB) in order to avoid mass transfer by Roche-lobe overflow, where tides systematically circularize the orbit.

POSTERS

Mathieu GUENEL (P1)

Tidal dissipation by inertial waves in differentially rotating convective envelopes of low-mass stars

Tidal interactions in close star-planet or binary star systems may excite purely inertial waves, whose restoring force is the Coriolis effect, in the convective region of stars. The dissipation of these waves plays a prominent role in the long-term orbital and rotational evolution of the bodies involved. If the primary star is assumed to be rotating as a solid-body, the inertial waves have a Doppler-shifted frequency restricted to the range [-2Ω, 2Ω] (Ω being the angular velocity of the star), and they can propagate in the entire convective region. However, turbulent convection can sustain differential rotation with an equatorial acceleration (as in the Sun) or deceleration that modifies the waves' frequency range and propagation domain, and permits the possibility of corotation resonances for non-axisymmetric oscillations. We perform numerical simulations of tidally excited inertial waves for two parameterized rotation laws within a convective envelope, namely conical (or latitudinal) and cylindrical profiles. The tidal forcing we adopt contains spherical harmonics that correspond to the case of both eccentric and/or inclined orbits. We also study the energy dissipation induced by these waves as a function of tidal frequency for various stellar masses and differential rotation parameters, as well as its dependence on the turbulent viscosity coefficient (Ekman number). We compare our results with previous studies assuming solid-body rotation and point out the key role of corotation resonances in the dynamical evolution of close-in star-planet or binary systems.

Dr János SZTAKOVICS (P2)

Statistical analysis of period-eccentricity distribution for large samples of Kepler, K2 and CoRoT eclipsing binaries

(in collaboration with Borkovits, T., Forgács--Dajka, E., Hajdu, T.)

Period – eccentricity distribution of eccentric eclipsing binaries (eEB) has inevitable importance in the study of the different kind of tidal circularization (and synchronization) processes. Recent time space missions provides a large amount of continuous and precise light curves, which enable us to determine several accurate stellar and dynamical parameters for thousands of freshly discovered eEBs. For compiling statistics we developed a fast, automated, though approximating method for determining eccentricity and argument of periastron from the displacement of the secondary minima and the difference of primary and secondary eclipse durations for large samples of eclipsing lightcurves.

Applying this method for several hundreds of recently discovered eEBs in the fields of the primordial and secondary Kepler and also the CoRoT missions, we present a comprehensive statistical analysis of the period--eccentricity relation for different subgroups of these double star systems. Finally we compare our findings with the results of similar previous studies on different samples of eccentric binaries.

Seismology and Stellar Structure, Evolution and Rotation

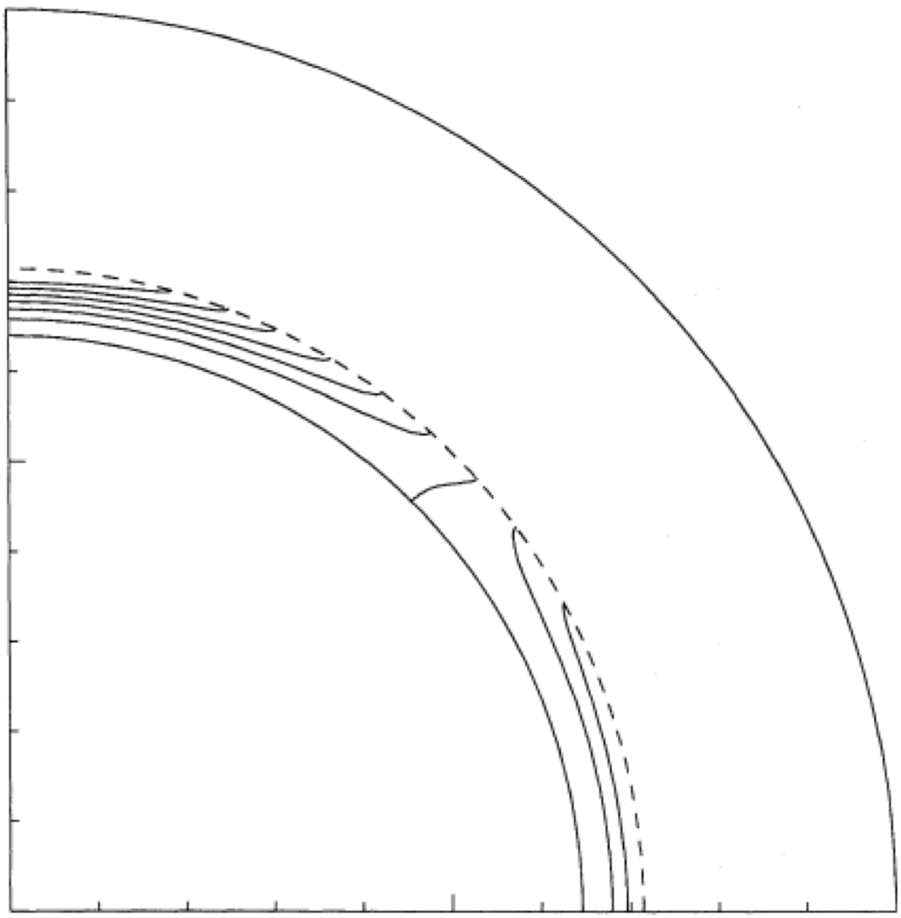


Fig. 3. The turbulent tachocline, whose thickness has been set here arbitrarily to 50,000 km (the actual value depends on the horizontal component ν_H of the turbulent viscosity). The continuous lines show the contours of the angular velocity. Below, the interior rotation is nearly uniform, and its angular velocity equals that of the base of the convection zone at the latitude of approximately 42°.

Pr André MAEDER

Stellar rotation and evolution

E pur si muove! said Galileo Galilei for the Earth. This famous sentence also applies to the Sun and stars as emphasized by Jean-Paul Zahn, who explored in master pioneer works, which will always stay as major references, the many effects of axial rotation on stellar structure and evolution. These are in particular the meridional circulation, shear instabilities and mixing, shellular rotation, horizontal turbulence, solar tachocline, possible dynamo effect, surface oblatness, etc.

These effects deeply impact the course of stellar evolution and influence all outputs of stellar models: lifetimes, core masses, surface composition, oscillations and pulsations, mass of the remnants, formation of GRB, types of supernovae and chemical yields, as well as binary interactions. We shall examine several of these effects, with a particular emphasis on the observational evidences of mixing, on the interaction of rotation with tidal mixing, on problems set by the rotation of pulsars as well as the properties of the first stars in the Universe.

Pr Pascale GARAUD

Double-diffusive instabilities in stars

In this talk I will review recent progress in understanding double-diffusive mixing in stars, both in the fingering regime ("thermohaline" convection) and in the oscillatory regime ("semiconvection").

With the help of 3D numerical simulations, we propose and calibrate new models for mixing that can, with reasonable ease, be implemented in stellar evolution codes such as MESA. I will discuss the implications of these new mixing models for stellar evolution.

Louis AMARD & Dr Stéphane MATHIS

Anisotropic transport in stellar radiation zones: coming back on horizontal turbulence

(in collaboration with V. Prat, A. Palacios & C. Charbonnel)

In his seminal work on transport of angular momentum and chemicals in stellar radiation zones (Zahn 1992), Jean-Paul Zahn proposed a coherent and complete formalism based on the hypothesis of an anisotropic transport stronger in the horizontal direction because of the stable stratification of these regions. This allowed him to derive equations in a formalism assuming the so-called « shellular » rotation which has been broadly and successfully implemented in stellar evolution codes and applied to many types of stars.

On the other hand, very few prescriptions (at least three) have been proposed in the literature for the eddy-transport coefficients in the horizontal direction. While based on the hypothesis of an anisotropy of turbulent transport induced by stable stratification in rotating radiation zones, none of them have an explicit dependence on the buoyancy frequency neither rotation. Actually, understanding the properties of turbulent transport in such a rotating stratified fluid is at the forefront of fundamental fluid dynamics research using theory, numerical simulations and laboratory experiments. In this work, based on the last advances in the field, we derive a new prescription for the anisotropy of transport and related horizontal eddy diffusion coefficient that now has an explicit dependence on stratification, rotation and related dimensionless characteristic numbers as the Rossby number.

This new prescription is implemented in the dynamical stellar evolution code STAREVOL and applications to solar-type stars evolution from their PMS to advanced stages of evolution are computed. The results we obtain evidence a strong impact on the rotational and chemical evolution of these stars showing why characterizing turbulent transport in stably stratified stellar radiation zones remains a key field of research, that should be pursued following the path initiated by Jean-Paul Zahn.

Pr Michel RIEUTORD

Convective overshooting: state of the art and perspectives

In this talk I shall present ongoing work on core overshooting with a focus on the way laboratory experiments, numerical simulations and general theoretical constraints, including the role of turbulent plumes, can contribute to our understanding of this important phenomenon in stellar physics. I will recall the perceptive contribution of Jean-Paul Zahn (1991) to this subject and then present the concept of a new laboratory experiment designed to explore the problem of convective overshooting when it is combined with a stable chemical stratification. I shall conclude with some ideas on the most promising perspectives on this subject.

Dr Vincent PRAT

Vertical shear mixing in stellar radiative zones

Jean-Paul's formalism for vertical shear mixing in stellar radiative zones is still used in stellar evolution codes nowadays, in various forms. I will discuss the constraints on this transport process that can be obtained thanks to numerical simulations.

Pr Sylvie VAUCLAIR

The mic-mac connection inside stars

The interdependence of microscopic (atomic) and macroscopic (hydrodynamic) processes inside stars and their consequences for stellar structure and evolution were recognized by Jean Paul several decades ago. He was a pioneer in that respect, discussing the importance of the macroscopic motions related to stellar rotation, in competition with the chemical stratification induced by gravitational settling and radiative accelerations. This has been much developed in recent years, in connection with the improvements of observational data, including asteroseismology. I will remind Jean Paul's work and some specific discussions we had on these subjects, and discuss the recent improvements.

Dr Jérôme BOUVIER

The connection between lithium and rotation during early stellar evolution

The evolution of lithium abundance in solar-type stars, from the early pre-main sequence to the evolved giant stage, has long been a conundrum, with observations failing most models. Indeed, it remains very much of a challenge today. As in many other fields, Jean-Paul's intuitions regarding the necessary connection between angular momentum evolution and lithium depletion have been incredibly useful to tackle this issue. I will attempt to give a brief account of the status of the field today, and discuss how current angular momentum evolution models and recent observational results on the lithium-rotation connection can be reconciled. Or not.

Dr Gérard VAUCLAIR

Fingering convection in accreting hydrogen-rich white dwarfs

F.C. Wachlin (1), S. Vauclair (2,3), G. Vauclair (2,3) and L.G. Althaus (1)
1-Instituto de Astrofisica de La Plata (UNLP-CONICET), Universidad National de La Plata, Argentina
2- Université de Toulouse, UPS-OMP, IRAP, France
3-CNRS, IRAP, 14 avenue Edouard Belin, 31400 Toulouse, France

The accretion of heavy material from debris disk on the surface of hydrogen-rich white dwarfs induces a double diffusivity instability known as the fingering convection. It leads to an efficient extra mixing which brings the accreted material deeper in the star than by considering only mixing in the surface dynamical convection zone, in a time scale much shorter than that of gravitational settling. We performed numerical simulations of a continuous accretion of heavy material having a bulk Earth composition on the two well studied DAZ and ZZ Ceti pulsators GD 133 and G 29-38. We find that the existence of fingering convection implies much larger accretion rates to explain the observed abundances than previous estimates based on the standard mixing length theory and gravitational settling only.

Dr Thomas CONSTANTINO

Modeling stellar interiors with the new time-implicit 3D hydrodynamic code MUSIC

We present recent scientific results from the new multi-dimensional, fully compressible, hydrodynamical, time-implicit, large eddy simulation code MUSIC. MUSIC uses realistic opacity and equations of state and is suited to flows characterized by low- (M ~ 1e-6) to moderate-Mach number (M ~ 1). This makes it a valuable tool for investigating a wide range of multi-dimensional phenomena in stellar astrophysics that will contribute to the effort to improve prescriptions used in 1D calculations. Our study of the accretion of material onto a young stellar object shows that there is a critical entropy above which the accreted material forms a stable layer that suppresses convection throughout the envelope. This result for "hot" accretion contradicts the assumption previously adopted in stellar evolution calculations that the accretion energy is redistributed throughout the stellar interior. It therefore suggests that earlier calculations may have significantly overestimated the resulting effect on the stellar structure, particularly expansion. A second study, into the influence of the size of the simulation domain on the properties of convection, demonstrates the importance of non-local aspects of convection to the convective velocity and overshooting layer width. Moreover, these effects could be quantified because the numerical scheme in MUSIC allows us to analyse statistics computed from hundreds of convective turn-over times. Finally, we add that we are currently using MUSIC to tackle other problems in stellar evolution such as shear mixing, angular momentum transport, convective overshoot, and the thermohaline instability.

Dr Kevin BELKACEM

Energetic aspects of solar-like oscillations in low-mass stars: from the main-sequence to the red giant stars

Solar-like oscillations are ubiquitous to low-mass stars from the main-sequence to the red-giant branch as demonstrated by the space-borne missions CoRoT and Kepler. Understanding the physical mechanisms governing their amplitudes (and more precisely mode driving and mode damping) as well as their behavior along with the star evolution. This is a prerequisite for interpreting the wealth of seismic data and for inferring stellar internal structure.

In this talk, I will discuss our current knowledge of both mode driving and damping as well as how these physical processes evolve from the main-sequence to the red-giant branch. Then, I will show how these modes permitted to unveil the rotation of the inner-most layers of low-mass stars and how they put stringent constraints on the redistribution of angular momentum.

Dr Rafael A. GARCIA

Stellar dynamics from the surface to the interior measured by CoRoT & Kepler

Continuous high-precision photometry of stars —provided by space missions such as CoRoT and Kepler represents a unique way to study stellar rotation and magnetism, which coupled to asteroseismology is changing our view to surface and internal dynamics. In this talk I will describe the evolution of surface and internal rotation and magnetic fields. I will describe in details the recent discovery of the presence of strong internal magnetic fields in the convective cores of stars above 1.2-1.4 solar masses. I will finish by providing constraints on gyrochronology laws for low-mass stars and put the Sun into context of its magnetism when compared to other solar-analogues.

Dr Francois LIGNIERES

Oscillations of rapidly rotating stars

Interpreting the frequency spectrum of rapidly rotating stars is a long standing problem of stellar seismology. I shall present recent progresses in modelling the effects of rotation on acoustic and gravito-inertial oscillation modes with emphasis on the interplay between results coming from the numerical exploration of the mode properties and the physical understanding provided by the asymptotic theory based on ray dynamics.

Charlotte GEHAN

Toward a better understanding of red giants rotation

Red giant stars have proved to be asteroseismic targets of choice: conditions in their interior are met to couple pressure waves propagating in the envelope and gravity waves propagating in the core, so that we have a direct view on their core through mixed modes, which is not the case for main-sequence stars. In particular, asteroseismology of red giants gives us the opportunity to study their internal rotation, especially their core rotation.
Rotation is known to deeply impact the evolution of stars, but including rotation in stellar evolution models is still challenging. Models predict central rotation rates at least ten times too large compared to asteroseismic measurements. This implies that angular momentum transport is at work in stellar interiors, whose physical mechanisms are not yet fully understood.
It is thus of prime importance to know how internal rotation evolves in time. This is particularly true for red giants, in order to better characterize the physical processes operating in the deepest region of these stars. Such a study requires core rotation measurements for a maximum number of red giants. In this context, I have developed an automatic method to determine the mean core rotation of red giant stars presenting different evolutionary stages with Kepler data. In the future, obtaining mean core rotation rates for thousands of red giants will improve the characterization of the physical mechanisms causing angular momentum transport in these stars, and therefore our understanding of stellar evolution. I will present preliminary results that I obtained with a new and promising method to determine automatically core rotation rates of red giants. Such an automated measurement of the core rotation of red giants will moreover be required to analyse the hundreds of thousands of oscillation spectra that PLATO should provide in a few years. Hence this automated method is paving the way for the future PLATO data.

Victor RÉVILLE

Evolution of stellar winds properties with age, constrained by spectropolarimetric maps and activity measurements

Magnetic activity is proven to decrease with age and stellar rotation rate. X-ray emission studies indicate that the X-ray fluxes originating from the magnetically heated coronae, decrease as the square of the rotation frequencies. Zeeman Doppler Imaging of Young stars that are rapidly rotating have proven that at least part of the enhanced coronal activity is due to a high amplitude large scale magnetic field. We investigate the properties of stellar winds with 3D MHD simulations of a sample of six stars of increasing age, whose magnetic field is constrained by spectropolarimetric maps. The coronal density and temperature are modeled to follow the change in rotation rate. We find global trends for the evolution of mass and angular momentum loss that are compatible with the Skumanich law. We analyse the velocity distribution shaped by the coronal magnetic field and find slow and fast components that interact in their rotating motion.

POSTERS

Dr Paul BECK (P3)

Multi-technique analysis of oscillating red giant stars in binary systems

(in collaboration with P. Gaulme, T. Kallinger, R. A. Garcia, K. Pavlovski, A. Palacios, S. Mathis, A. Tkachenko, J. Jackiewicz, E. Corsaro, B. Mosser, S. Mathur, et C. Johnston)

In the Kepler sample, the number of binary stars with oscillating components is growing. Besides the classical eclipsing binaries, we also find various types of binaries through Kepler photometry as well as ground-based spectroscopic surveys. A large arsenal of state-of-the art seismic, spectroscopic, and light curve analyses techniques is at our disposal, which allows us to constrain the system and stellar fundamental parameters independently in numerous ways.

In this talk we present results of joint analysis of the ensemble of binary systems, hosting oscillating stellar components, as well as detailed case studies. By combing numerous techniques like spectroscopy, light curve modeling and asteroseismology, we can draw comprehensive pictures of the studied binary systems and constrain the systems properties. Especially seismology provides us with a wealth of information about the oscillating component, such as its mass, radius but even the evolutionary state and internal rotational gradient. Very interesting cases are double-line spectroscopic and seismic binary systems for which we have good constraints on the masses of both components from seismology as well as the light curve and spectroscopic analysis. Therefore, ensemble as well as detailed case-by-case study allow an improved characterization of the system and to derive inferences on the interaction between two components, the stellar structure and its evolution.

Gaël BULDGEN (P4)

Analysis of the linear relations of seismic inversions for various structural pairs

Thanks to the space-based photometry missions CoRoT and Kepler, we now benefit from a wealth of seismic data for stars other than the sun. In the future, K2, Tess and Plato will complement this data and provide observations in addition to those already at hand. The availability of this data leads to questions on how feasible it is to extend kernel-based, linear structural inversion techniques to stars other than the sun. Linked to the inversion problem is the question of the validity of the linear assumption. In this study, we analyse the limitations of this assumption with respect to changes of structural variables.

We thus point towards limitations in inversion techniques in the asteroseismic and helioseismic cases. We explain how kernels for new structural variables can be derived using two methods. For this second method, we present a new structural couple, namely the A,Y structural kernels. The kernels are then tested in various numerical experiments that enable us to evaluate the weaknesses of different structural pairs and th limitations of their respective linear regime.

Dr Enrico CORSARO (P5)

Formation history of open clusters constrained by detailed asteroseismic analysis of red giant stars observed by Kepler

(in collaboration with Y.-N. Lee, R. A. García, P. Hennebelle, S. Mathur, P. G. Beck, S. Mathis, D. Stello, J. Bouvier)

Stars originate by the gravitational collapse of a turbulent molecular cloud of a diffuse medium, and are often observed to form clusters. Stellar clusters therefore play an important role in our understanding of star formation and of the dynamical processes at play. However, investigating the cluster formation is difficult because the density of the molecular cloud undergoes a change of many orders of magnitude. Hierarchical-step approaches to decompose the problem into different stages are therefore required, as well as reliable assumptions on the initial conditions in the clouds.
In this talk we report for the first time the use of the full potential of NASA Kepler asteroseismic observations coupled with 3D numerical simulations, to put strong constraints on the early formation stages of open clusters. Thanks to a Bayesian peak bagging analysis of about 50 red giant members of NGC 6791 and NGC 6819, the two most populated open clusters observed in the nominal Kepler mission, we derive a complete set of detailed oscillation mode properties for each star, with thousands of oscillation modes characterized. We therefore show how these asteroseismic properties lead us to a discovery about the rotation history of stellar clusters. Finally, our observational findings will be compared with hydrodynamical simulations for stellar cluster formation to constrain the physical processes of turbulence, rotation, and magnetic fields that are in action during the collapse of the progenitor cloud into a proto-cluster.

Dr Delphine HYPOLITE (P6)

The 2D dynamics of stellar radiation zones

(in collaboration with S. Mathis and M. Rieutord)

The internal rotation of low-mass stars all along their evolution is of primary interest when studying their rotational dynamics, internal mixing and magnetic fields generation. In this context, helio- and asterosismology probe angular velocity gradients deep within Solar-type stars. Still the rotation of the close center of such stars on the main-sequence is hardly detectable and the dynamical interactions of the radiative core with the surface convective envelope is not well understood. Among them, the influence of the differential rotation profile sustained by convection and applied as a boundary condition to the radiation zone may be very important leading to the formation of tachoclines. Indeed, in the Solar convective region, the equator is rotating faster than the pole while anti-solar rotation can also be expected in other low-mass stars envelopes since numerical simulations predict a bistable state.

In this work, we therefore build for the first time 2D hydrodynamical models of solar-type stars radiation zone providing a full 2D description of their dynamics and studying the influence of a general shear boundary condition accounting for a solar or anti-solar differential rotation in the convective envelope. We compute coherently differential rotation and the associated meridional circulation using the anelastic approximation which is compared to the simplest Boussinesq one. Analytically, we demonstrate that the imposed shear implies a cylindrical differential rotation. Moreover, flux of angular momentum both in the radial and latitudinal directions are proportional to the shear and the radial flux is concentrated near the surface to counterbalance its action. The core to the surface rotation ratio decreases as the shear increases. These results will be discussed in the framework of seismic observables while perspectives to improve our modeling by including magnetic field or transport by waves will be presented.

Dr Nadège LAGARDE (P7)

Star quakes : a new tool to test the properties of red giant stars

(in collaboration with D. Bossini, A. Miglio, M. Vrard and B. Mosser)

In the context of the determination of stellar properties using asteroseismology, we study the influence of rotation and convective-core overshooting on the properties of red giant stars. We used stellar evolution models computed with the codes STAREVOL and MESA to investigate effects of these both mechanisms on the asymptotic period spacing of redgiant stars that ignite He burning in degenerate conditions ($M \leq 2.0$ Msun). We also compare the theoretical predictions with recent Kepler observations (Vrard et al 2016). We find that mixing processes have an impact on $\Delta\prod(l=1)$, hence on the determination of the stellar mass when $\Delta\prod(l=1)$ is used as a constraint. In the case of more evolved red-giant-branch stars and regardless of the transport processes occurring in their interiors, the observed $\Delta\Pi1$ can provide information as to their stellar luminosity, within ~ 10-20 per cent. In general, the trends of $\Delta\Pi1$ with respect to mass and metallicity that are observed in Kepler red-giant stars are well reproduced by the models.

Dr Nadège LAGARDE (P8)

Models of red giants in the CoRoT asteroseismology fields combining asteroseismic and spectroscopic constraints - The open cluster NGC 6633 and field stars

(in collaboration with A. Miglio, P. Eggenberger, T. Morel, J. Montalbán and B. Mosser)

The availability of asteroseismic constraints for a large sample of red giant stars from the CoRoT and Kepler missions paves the way for various statistical studies of the seismic properties of stellar populations. We use the first detailed spectroscopic study of CoRoT red-giant stars (Morel et al 2014) to compare theoretical stellar evolution models to observations of the open cluster NGC 6633 and field stars. In order to explore the effects of rotation-induced mixing and thermohaline instability, we compare surface abundances of carbon isotopic ratio and lithium with stellar evolution predictions. These chemicals are sensitive to extra-mixing on the red-giant branch. We estimate mass, radius, and distance for each star using the seismic constraints. We note that the Hipparcos and seismic distances are different. However, the uncertainties are such that this may not be significant. Although the seismic distances for the cluster members are self consistent they are somewhat larger than the Hipparcos distance. This is an issue that should be considered elsewhere. Models including thermohaline instability and rotation-induced mixing, together with the seismically determined masses can explain the chemical properties of red-giants targets. Tighter constraints on the physics of the models would be possible if there were detailed knowledge of the core rotation rate and the asymptotic period spacing.

Dr Michael LEBARS (P9)

Internal wave excitation by turbulent convection

D. Lecoanet (1), M. Le Bars (2,3), K. J. Burns (4), E. Quataert (1), G. M. Vasil (5), B. P. Brown (6) & J. S. Oishi (7)

(1) University of California, Berkeley, USA. (2) IRPHE, Marseille, France. (3) University of California, Los Angeles, USA. (4) MIT, Cambridge, USA. (5) University of Sydney, Sydney, Australia. (6) University of Colorado, Boulder, USA. (7) Farmingdale State College, Farmingdale, USA.

Convection near a stably stratified region can excite internal gravity waves. This occurs in a wide range of geophysical settings, including the Earth's atmosphere and core, as well as in astrophysical systems like some gas giants, and most stars including the Sun. The remote observation of these internal waves can be used to probe the interior of stars via asteroseismology. In addition, internal waves transport energy and momentum, and may play an important role in the dynamics of natural systems.

Water's density maximum at 4oC makes it well suited to study this problem: an increasing temperature profile is unstable to convection below 4oC, but stably stratified above 4oC. We present laboratory experiments and two dimensional numerical simulations of this system [1, 2]. The simulation is run using the flexible, open-source pseudo-spectral code Dedalus [3]. We describe the main features of the excited wavefield. To isolate the physical mechanism exciting internal waves, we use data from the full simulation as source terms in two simplified models of internal-wave excitation by convection: bulk excitation by convective Reynolds stresses, and interface forcing via the mechanical oscillator effect. We find excellent agreement between the waves generated in the full simulation and the simplified simulation implementing the bulk excitation mechanism.

References

[1] D. Lecoanet et al. Phys. Rev. E 91, 063016 (2015)
[2] M. Le Bars et al. Fluid Dyn. Res. 47, 045502 (2015)
[3] The code is available at dedalus-project.org.

Charly PINCON (P10)

Generation of internal gravity waves by penetrative convection

The space-borne missions CoRoT and Kepler provide seismic data of thousands of stars from the main sequence to the red giants branch. The detection of mixed-modes in subgiants and red giants enabled us to show that their core rotate much more slowly than expected. In this context, internal gravity waves (hereafter, IGW) can play a role since they are known to be able to transport angular momentum in the radiative zone of the stars.

The efficiency of the transport of angular momentum by IGW depends on their driving mechanism. Two different kinds of mechanism of excitation are usually invoked. The first one, due to the turbulent pressure through the convective bulk, has already been theoretically investigated. The second one, due to the penetration of convective plumes into the stably stratified region at the edge of the base of the convective zone, has already been observed in numerical simulations and studied in geophysics, but a theoretical estimate was still missing.

We will present a semi-analytical model in order to estimate the energy of the plumes transferred into waves at the base of the convective zone. The importance of the steepness of the Brunt-Väisälä frequency at the base of the convective zone on the transmission of the waves into the propagative region will be stressed. The plume-induced wave energy flux will be compared to the turbulence-induced one in the solar case. Possible extension to evolved stars will be discussed.

Dr Takafumi SONOI (P11)

Analysis of surface effects on solar-like oscillation frequencies using 3D hydrodynamical models

The recent observation by spacecrafts such as CoRoT and Kepler allows us for seismic inferences of stellar interiors. However, the poor modeling of the suface layers in the standard stellar models has prevented us from making the maximum use of the high precision by such observation (the surface effects). In many cases, an empirical correction based on the solar case (Kjeldsen et al. 2008, ApJ, 683, L175) has been adopted to correct the model frequencies for keeping the quality of the seismic inferences, while we have not yet obtained the physical justification for this treatment. The aim of our study is therefore to constrain the surface-effect corrections across the HR diagram using a set of 3D hydrodynamical simulations by the CO5BOLD code. We constructed ``patched models'', replacing upper layers of the standard 1D models. They play roles as observed stars. The frequency difference between the patched models and the corresponding 1D models allows us to constrain the surface-effect correction. Our analyses suggest that we should no longer use the solar-calibrated coefficients in the Kjeldsen et al.'s correction. In particular, the additional support by the turbulent pressure in the upper layers makes substantial discrepancy from the standard models.

Veronika WITZKE (P12)

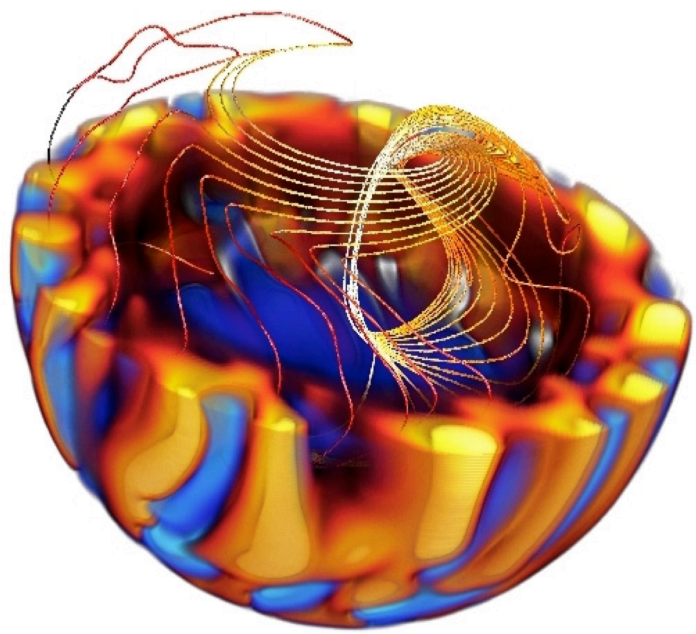
Evolution of forced shear flows in polytropic atmospheres

(in collaboration with Pr. L. J. Silvers)

Shear flows are ubiquitous in astrophysical objects including planetary and stellar interiors, where their dynamics can have significant impact on thermal transport and chemical processes. Here three-dimensional direct numerical calculations of unstable shear flows are performed to study the long-time evolution of the resulting turbulent motions in a compressible polytropic fluid. At present, there exist several different forcing methods to sustain large-scale shear flows in local models.

Here we examine and compare various methods used in the literature. These techniques are compared during the exponential growth of a shear flow instability, such as the Kelvin-Helmholtz (KH) instability, and the subsequent non-linear evolution. For this we used the concept of available potential energy to analyse the energy budget of the system. The forced shear flows that we consider here can be used to model flows in stellar interiors. Hence, we examine the effect of varying the Prandtl number and thermal diffusivity on the non-linear evolution of an unstable shear flow. Finally, preliminary calculations of a low Péclet number instability with large Richardson number are briefly discussed.

Convection & Magnetism



Pr Juri TOOMRE

Some travels in the land of nonlinear convection and magnetism

Rotating stars with convection zones are the great builders of magnetism in our universe. Seeking to understand how turbulent convection actually operates, and so too the dynamo action that it can achieve, has advanced through distinctive stages in which Jean-Paul was often a central player, or joined by his former students. Some of the opening steps in dealing with the basic nonlinearity in such dynamics involved modal equations (with specified horizontal structure) to study convective amplitudes and heat transports achieved as solutions equilibrated by feeding back on the mean stratification. These dealt in turn with laboratory convection, with penetrative convection in Boussinesq settings, then with compressible penetration via anelastic equations in simple settings, and finally with stellar penetrative convection in A-type stars that coupled two convection zones. Advances in computation power allowed 2-D fully compressible simulations, and then 3-D modeling including rotation, to revisit some of these convection and penetration settings within planar layers. With externally imposed magnetic fields threading the 2-D layers, magnetoconvection could then be studied to see how the flows concentrated the fields into complex sheets, or how new classes of traveling waves could result.

The advent of helioseismology was a major stimulus to refocus on our nearest star whose convection zone dynamics could now be actually probed, and whose cycling magnetism continued to be somewhat a mystery. The internal differential rotation was now clearly visible, including the striking shear layer at the convection zone base called the solar tachocline. This needed explaining, and the first so offered involved Ed Spiegel and Jean-Paul invoking anisotropic turbulence, and then a number of studies examining the role of magnetic fields in possibly maintaining the thinness of that layer. The era of studying turbulent convection in rotating spherical shells had also arrived, using 3-D MHD codes such as ASH to consider how the solar differential rotation is achieved. Similarly the manner in which global magnetic fields could be built by dynamo action within the convection zone took center stage, finding that coherent wreaths of strong magnetism could be built, and also cycling solutions with field reversals. The coupling of convection and magnetism continues as a vibrant research subject. It is also clear that stars like the Sun do not give up their dynamical mysteries readily when highly turbulent systems are at play.

Pr Alan TITLE

Organized flaring behaviors

(in collaboration with M. de Rosa)

The continuous full disk observations provided by the Atmospheric Imaging Assembly (AIA) can give an observer the impression that many flare eruptions are causally related to one another. However, both detailed analyses of a number of events as well as several statistical studies have provided only rare examples or weak evidence of causal behavior. For this study we detected groups of flares (flare clusters) in which successive flares occurred within a fixed time - the linking window. The data set used for the investigation is the flare waiting times provided by the X-ray flare detectors on the Geostationary Operational Environmental Satellites (GOES). We limited the study to flares of magnitude C5 and greater obtained during cycles 21, 22, 23, and 24. The GOES field of view includes the entire visible surface. While clusters may come from the same active region because of the durations of the longer clusters, which often last longer than a solar rotation, sum must have origins in multiple regions.. We show that that X class flares cluster and that a superpose epoch analyses shows that there is a pronounced enhancement of C5 and and above flares centered on the X flare clusters. The full width at half maximum of the peaks associated with the X flares is 10 days and and the flare rate is enhanced for about 20 days. We suggest that this behavior implies that a component of the observed coordinated behavior originates from the MHD processes driven by the solar dynamo. The relationship between flare clusters and magnetic centers of activity is explored.

Pr Matthew BROWNING

Buoyancy, dissipation, and magnetism in convective stars

Observations have suggested that some low-mass stars may have larger radii than predicted by 1D structure models. Some theoretical models have invoked extraordinarily strong interior magnetic fields (of order 1 MG or more) as a possible cause of such large radii. Here, we examine whether such fields could in principle remain in the interior of a low-mass object for a significant time, and whether they would have any other obvious signatures (apart from the claimed radius inflation). First, we estimate timescales for the loss of strong fields by magnetic buoyancy instabilities in the presence of magnetic pumping. We consider a range of field strengths and simple morphologies, including both idealized flux tubes and smooth layers of field. Separately, we consider the Ohmic dissipation of such fields. We find that dissipation provides a complementary constraint to buoyancy: while small-scale, fibril fields might be regenerated faster than they rise, for example, the dissipative heating associated with such fields would in some cases greatly exceed the luminosity of the star. We show how these constraints combine to yield limits on the internal field strength and morphology in low-mass stars. These limits rule out some of the extreme fields proposed to account for the "inflation" of these objects. More generally, we argue that the combined constraints of buoyancy, dissipation, and magnetic pumping provide some insight into the frequency and properties of rare magnetic events. We also briefly note some possible consequences of extraordinarily dissipative convection for the structure of low-mass stars.

Dr Lucia DUARTE

Helicity inversion mechanism

We discuss here a purely hydrodynamical mechanism to invert the sign of the kinetic helicity, which plays a key role in determining the direction of propagation of cyclical magnetism in most models of dynamo action by rotating convection. Such propagation provides a prominent, and puzzling constraint on dynamo models. In the Sun, active regions emerge first at mid-latitudes, then appear nearer the equator over the course of a cycle, but most previous global-scale dynamo simulations have exhibited poleward propagation (if they were cyclical at all). Here, we highlight some simulations in which the direction of propagation of dynamo waves is altered primarily by an inversion of the kinetic helicity throughout much of the interior, rather than by changes in the differential rotation. This tends to occur in cases with a low Prandtl number and internal heating, in regions where the local density gradient is relatively small. We analyse how this inversion arises, and contrast it to the case of convection that is either highly columnar (i.e., rapidly rotating) or locally very stratified; in both of those situations, the typical profile of kinetic helicity (negative throughout most of the northern hemisphere) instead prevails.

Pr Steven TOBIAS

Direct Statistical Simulation of Astrophysical Flows and Dynamos

The solar cycle, the jets on Jupiter and the flows in planets, stars and disks are all examples of systematic large-scale flows co-existing with turbulence on a vast range of spatial and temporal scales. Even with the advent of peta and exascale computers direct numerical simulations of these astrophysical flows will remain beyond our reach. Here I will describe a program of calculations, which we term Direct Statistical Simulation, where the statistics of such astrophysical flows are solved for directly. I will explain how this program relates both to mean-field theory and statistical models such as EDQNM and demonstrate the effectiveness of the procedure for problems such as the driving of zonal flows and joint instability in the solar tachocline.

Pr Douglas GOUGH

The Solar Tachocline

Jean-Paul and Ed Spiegel were the first to address the structure of the tachocline in a dynamically cogent way. They demonstrated that if the convection zone presented a rotationally sheared boundary to an implicitly assumed magnetic-field-free quiescent radiative interior, an imprint of that shear would propagate throughout the interior in a time less that the age of the Sun. They concluded that therefore the tachocline must annul the shear. Right or wrong, that work laid the foundations upon which all further discussion had to be built. The principal matters that needed clarification were whether the tachocline really does insulate the radiative interior from the differential rotation of the convection zone, and, if not, whether there is actually some mechanism, neglected in Ed's and Jean-Paul's simple pioneering study, that holds the interior rigid. Mike McIntyre and I, arguing from our knowledge of the dynamics of the Earth's atmosphere, concluded that a primordial large-scale magnetic field pervading the radiative zone is the only possibility that remains. Jean-Paul and his colleagues rejected the meteorological evidence, and argued for gravity-wave dissipation. Is there any distinguishing direct observational evidence? Precious little at present. However, I am optimistic that more soon will come.

Dr Antoine STRUGAREK

The solar tachocline and the solar magnetic activity cycle

(in collaboration with R. Barnabé, A.S. Brun and P. Charbonneau)

More than twenty years after the seminal paper of Spiegel et Zahn (1992) (SZ92), the thinness of the solar tachocline continues to puzzle the solar physics community today. In their pioneering paper, Spiegel et Zahn laid out the basic foundations of the understanding of the long-term evolution of the tachocline by unveiling a theoretical radiative spreading of the solar differential rotation downwards, inside the radiative interior of the Sun. In order to explain the thinness of the tachocline (constrained by helioseimology to be less than 4% of the solar radius), physical mechanism(s) counter-balancing or suppressing this radiative spreading need to be identified. The tachocline is also invoked by numerous dynamo models of the solar magnetism to provide an efficient storage location of energetic magnetic wreaths thanks to the turbulent downward pumping of magnetic flux in the solar convection zone. As a result, understanding the dynamics and evolution of the solar tachocline is mandatory for our physical understanding of the solar differential rotation profile as well as the solar magnetic activity cycle.

We will first give a tour of the several attempts made since SZ92 to explain the thinness of the tachocline. We will focus in particular on the potential contributions of a confined fossil field in the radiative zone of the Sun on one hand, and of the dynamo field sustained in the turbulent convection zone on the other hand (the so-called slow and fast tachocline scenarios). We will then explore the possibility to counter-balance the radiative spreading with an oscillatory dynamo field using a simple reduced (1D) model legated by Jean-Paul Zahn. Finally, we will turn to recent advances with 3D global numerical simulations coupling the convective and radiative zones of the Sun, and explore the potential role of the tachocline in participating in setting the solar dynamo cycle period thanks to the development of magneto-rotational instabilities in the large-scale azimutal magnetic structure stored in its upper part. We will conclude by laying out the remaining unknowns about the solar tachocline, and what progress we can expect to achieve in the coming years regarding our understanding of this intriguing internal region of our Sun.

Dr Evelyne ALECIAN

Fossil magnetic fields in intermediate-mass and massives stars: a global observational picture

A small fraction of the intermediate and massive stars host strong and stable magnetic fields organised on large scales. These fields are believed to be fossil, i.e. not continuously maintained against ohmic decay, and to be remnants of star formation. It is however not clear how such fossil fields have been shaped during the star formation. I will report recent work on the determination of magnetic properties in PMS stars and MS binaries, allowing us to make progress in that field.

Pr Nicholas BRUMMELL

Fully nonlinear Spiegel & Zahn "burrowing"

Jean-Paul was deeply interested in elucidating an understanding of the dynamics of the solar interior and, in particular, the interface between the solar convection zone and the radiative zone at the tachocline. The Spiegel et Zahn (1992) paper was a seminal work that investigated the role of meridional circulation in a differentially-rotating system in transporting angular momentum, and formalised the concepts of radiative spreading or "burrowing" in this context. Such transport has significant consequences for stellar evolution, but is very difficult to capture in global simulations due to numerical constraints on the vast range of timescales required. Here, we use three-dimensional local Cartesian simulations of penetrative compressible convection to study the efficiency of transport by meridional flows below a convection zone in several turbulent parameter regimes of relevance to the Sun and solar-type stars. We find that, even though the generation of internal waves by convective overshoot produces a high degree of time dependence in the meridional flow field, the mean flow has the qualitative behavior predicted by the laminar models, including burrowing, if the local Eddington–Sweet timescale is shorter than the viscous diffusion timescale. Magnetic versions of these models can then be used to test balanced theories of the tachocline.

Dr Allan-Sacha BRUN

Turbulence and magnetism in stars: from dynamo effect to stellar winds

There is a complex feed back loop between convection, rotation, magnetism and stellar wind in solar-like stars. Intense sometimes cyclic magnetic fields are generated by the rotating conducting convective envelope via dynamo action. This magnetized surface further heats the corona and drives a wind. This wind on the main sequence brakes down the star by extracting angular momentum and hence changes the stellar rotation and dynamo properties.

In this talk I will summarize the angular momentum history and transport inside and outside solar-like stars thanks to advanced 3-D MHD simulations, in keeping with the spirit of Jean-Paul's key contributions to convection, magnetism and rotation in stars.

Pr Yokoi NOBUMITSU

Inhomogeneous flow effects on turbulent dynamo, with special reference to stellar activity cycle

Global flow inhomogeneity is one of the main factors that determines the statistical properties of turbulence. However, this effect has not engaged much attention in the current studies of turbulent electromotive force (EMF). This is in marked contrast with the differential-rotation ($Omega$) effect in the global magnetic-field induction. If we retain the large-scale flow inhomogeneity in the treatment of turbulence, it serves itself as the cross-helicity (velocity--magnetic-field correlation) effect coupling with the global absolute vorticity in the expression of the EMF. We propose a simple dynamo model for the stellar activity evolution. In the model, the cross-helicity effect is included in the EMF, and the spatiotemporal evolution of the turbulent cross helicity is solved as well as the mean magnetic field. First we shows the results of the eigenvalue analysis of the simplest possible form of the present model. Basic scenario of the field reversal is as follows: (i) The turbulent cross helicity induces the toroidal magnetic fields; (ii) The poloidal magnetic field is induced from the toroidal one by the usual $alpha$ effect; (iii) The poloidal field generated by the $alpha$ effect produces a cross helicity whose sign is opposite to the original cross helicity; (iv) Then, the reversed field configuration starts to be generated. The resultant butterfly diagram reveals that the reversal of the cross helicity is not the result of the magnetic field reversal, but the cause of it. Due to the coupling of the magnetic fields and the turbulent cross helicity, the present dynamo equations constitute a nonlinear system of equations. A possibility of nonlinear chaotic behavior in the present system of equations is also discussed.

Pr David HUGHES

Magnetic Layering

(in collaboration with N.H. Brummell)

One of the most striking aspects of double-diffusive convection is the formation of layered density profiles (or "staircases"), with enhanced transport properties. Here we exploit the formal analogy between the equations describing magnetic buoyancy instability and those describing thermohaline convection, in order to investigate the possibility of magnetic layering. We discuss where such a phenomenon might occur in stellar interiors, together with the possible implications for transport.

Dr Ludovic PETITDEMANGE

Dipole collapse in spherical rotating dynamos

Observations of low mass stars reveal a variety of magnetic field topologies ranging from large-scale, axial dipoles to more complex magnetic fields. At the same time, three-dimensional spherical simulations of convectively driven dynamos reproduce a similar diversity, which is commonly obtained either with Boussineq models, or with more realistic models based on the anelastic approximation, which take into account the variation of the density with depth throughout the convection zone. Nevertheless, a conclusion from different anelastic studies is that dipolar solutions seem more difficult to obtain as soon as substantial stratifications are considered. In this paper, we aim at clarifying this point by investigating in more details the influence of the density stratification on dipolar dynamos. To that end, we rely on a systematic parameter study that allows us to clearly follow the evolution of the stability domain of the dipolar branch as the density stratification is increased. The impact of the density stratification both on the dynamo onset and the dipole collapse is discussed and compared to previous Boussinesq results. Furthermore, our study indicates that the loss of the dipolar branch does not ensue from a specific modification of the dynamo mechanisms related to the background stratification, but instead results from a bias as our observations naturally favour a certain domain in the parameter space, owing to current computational limitations.

POSTERS

Dr Kyle AUGUSTSON (P13)

Generalized Tayler instabilities in stellar radiation zones

(in collaboration with S. Mathis and A. Strugarek)

The radiative core of main-sequence low-mass stars and the radiative envelope of main-sequence massive stars likely host a fossil magnetic field, namely a remnant of the field built during the star's birth. Massive stars with an observed magnetic field typically possess a non-axisymmetric oblique magnetic dipole. If a comparison is drawn between the stably-stratified regions of massive and low mass stars, given their hydrodynamical similarity, such non-axisymmetric magnetic fields may also exist within these regions for low-mass stars. Moreover, fossil magnetic fields have been proposed as an important source of angular momentum transport and mixing across the Hertzsprung-Russel diagram. In this context, the stability of axisymmetric magnetic field configurations within a quiescent, stably-stratified medium have been understood for quite some time (e.g., Tayler 1973). Such analyses indicate that only certain mixed (poloidal and toroidal) configurations of axisymmetric magnetic fields are permitted within the radiative regions of stars. We have generalized this class of global stability analysis, extending it for the first time to regions with both non-axisymmetric magnetic fields and a differential rotation. Here, we present the resulting stability criteria. Such criteria help to restrict the number of magnetic field configurations that are possible within the stable regions of low-mass stars, thereby limiting the choices of interior magnetic fields that transport angular momentum in the radiative interior and that may interact with the dynamo-generated magnetic fields established in their overlying convective layers.

Roxane BARNABE (P14)

Magnetic confinement of the solar tachocline

(in collaboration with A. Strugarek, A.-S. Brun and P. Charbonneau)

The solar tachocline is a thin region between the radiation and convection zones where the transition from uniform to differential rotation occurs. Spiegel et Zahn (1992) showed that the tachocline should have extended deep in the Sun due to radiative spreading, which is in contradiction with helioseismology's observations. One of the hypothesis proposed to explain the thinness of the tachocline is the penetration into the radiative zone of an oscillatory dynamo field maintained in the convection zone. In this fast tachocline model, the magnetic stresses redistribute angular momentum horizontally, and in doing so prevent the propagation of the differential rotation deeper in the Sun's interior.

The results presented here are a continuation of Jean-Paul Zahn's work using a simplified 1D model of this fast tachocline hypothesis, capturing the competition between viscous spreading and magnetic stresses. We show that if we consider a more realistic tachocline subjected to radiative spreading, as in the original work of Spiegel et Zahn (1992), the presence of this magnetic field can still lead to the confinement of the tachocline.

Laura CURRIE (P15)

Scaling laws in rotating turbulent convection

(in collaboration with A. Barker, M. Browning and Y. Lithwick)

Rotating convection occurs in many stars and planets and is a fundamental phenomenon that governs the behaviour of such objects. Despite decades of research, a comprehensive theory of rotating convection has remained elusive. Here we consider a simple Cartesian model of rotating convection and present physical arguments of a rotating mixing-length theory (MLT) first proposed by Stevenson (1979) and more recently by Barker et al. (2014). The theory predicts properties of the bulk convection (e.g., the mean temperature gradient and the size of the convection rolls that dominate the heat transport) as a function of the imposed heat flux and rotation rate, and independently of the diffusivities. We discuss an extension of this theory to consider cases where rotation is oblique to gravity, representative of mid-latitudes on a spherical body. We test the predictions of the rotating MLT with numerical simulations using two models: (i) rotating Rayleigh-Benard convection and (ii) a setup where convection is driven by heating and cooling layers which sandwich a convection zone (to eliminate thin boundary layers). In particular, we show that the horizontal lengthscale that dominates the heat transport agrees with the rotating MLT but differs from the lengthscale at which convection onsets, in contrast to what was previously believed. Some differences between the two models will be discussed, but both setups provide support for the rotating MLT.

Constance EMERIAU-VIARD (P16)

Evolution of internal magnetic field in solar-like stars during the PMS

Internal structure and rotation rate of solar-like stars change drastically during the pre main sequence (PMS). At the very beginning of this evolution, during the first stage of the PMS, young stars are fully convective objects. During the PMS, after a phase of disk-locking, the stellar rotation rate increases as the star contracts. Temperature and density in the core of these stars are not sufficient enough to sustain thermonuclear reactions, except for a short deuterium-burning phase, and luminosity is supported by release of gravitational potential through stellar contraction. As the core temperature grows, and the internal structure of the star adapts accordingly, the convective envelope starts retracting towards the surface. Therefore a stably stratified radiative core appears and grows until the star reaches the ZAMS and hydrogen burning becomes the dominant source of energy. The question we want to answer in our study is how the initial magnetic field in a young, and thus fully convective, solar-type star evolves as its radiative zone and rotation rate change during the PMS phase.

To answer this question, we develop 3D MHD simulations, with the ASH code, that represent specific stages of the evolution of a solar-like star along the PMS. We want to compute different models : a fully convective star and four with a radiative core with a varying radiative core size of respectively 20%, 40%, 60% and 70% of the stellar radius corresponding to an age of 141.7 Myr, 277 Myr, 612 Myr, 1978 Myr and 4295 Myr respectively. Each model is started in hydrodynamical model to develop the convection and coupling to the radiative interior when present and a seed magnetic field is then introduced in the fully convective model. This model develops an intense dynamo with ME/KE reaching superequipartition state. This strong magnetic field back reacts on the internal differential rotation of the progenitor hydrodynamical model, resulting on an almost solid-body rotation. The magnetic field possess a mixed poloidal-toroidal topology. This 3-D magnetic field once the dynamo simulation as reached a saturated
state and evolved for several Ohmic diffusion time scales is introduced in the next model (e.g the one with a core size of 0.2 R_*, and likewise for the other cases). Moving to the simulations of more evolved PMS stars possessing a radiative interior, we can see changes in magnetic topology and amplitude during the growth of the radiative core. We study the consequences of the evolution of stellar rotation rate and geometry of the convective zone on the dynamo field that exists in the convective envelope. As the radius of the core grows from 0% to 20% and then 40% of the stellar radius, the dynamo field in the convective zone remains in an superequirepartition state where ME/KE is 1.16, 1.55 and 206 respectively. Moreover we also analyze the relaxation of the vestige dynamo magnetic field within the growing radiative core and found that it retains its mixed poloidal-toroidal topology.

Pr Laurène JOUVE (P17)

Investigating the magnetic dichotomy of A-type stars

(in collaboration with F. Lignières, T. Gastine and M. Gaurat)

Some A stars (Ap stars) possess strong large-scale magnetic fields which seem to remain rather stable in time. Some recent observations now tend to show that another class of A stars exists, which exhibit a more complex and weak magnetic field, organized at smaller scales at their surfaces. We would like to understand this magnetic dichotomy by investigating the stability of magnetic fields created by differential rotation in the stellar radiative envelope.

We numerically compute the joint evolution of the magnetic and velocity fields in a 3D spherical shell where the initial poloidal magnetic field and initial profile of the differential rotation are varied. In agreement with previously suggested scenarios, we find that after an Alfven time, a maximum for the ratio of toroidal to poloidal fields is reached. This ratio is closely related to the initial dipole strength and the stellar rotation rate. Depending on this value, we will show that such magnetic configurations may or may not be subject to a magneto-rotational instability, which could explain the dichotomy between strong and weak observed magnetic fields in A-type stars.

Lydia KORRE (P18)

The hidden parameter in Boussinesq convection

A problem that Jean-Paul Zahn was very interested in, in the context of solar interior, is penetrative convection. Convective overshooting and penetrative processes can occur between a convection zone (CZ) and a stable radiative zone (RZ). A model of such dynamics in a spherical shell could consist of a two layered system where the stability of the layers is determined by a Rayleigh number that is a function of radius, r, such that the Ra number is above the critical Rac for the onset of convection in the CZ and below Rac in the RZ. However, there are many different ways of making Ra a function of r. One could, for instance, impose either a) the background temperature gradient, b) the thermal expansion coefficient, or c) the thermal diffusivity, as a function of r. All of these implementations have been used in previous modeling efforts but it is not obvious that they are all equivalent in terms of the overshooting and penetrating dynamics they engender. We investigate this conundrum by implementing the different methodologies outlined above in the PARODY code (Dormy et al. (1998)), which solves the Navier-Stokes equations under the Boussinesq approximation in a spherical shell. Whilst it is straightforward to set up Rayleigh functions as described above, we find that it is difficult to make directly comparable simulations, since the Prandtl number cannot always be completely controlled, and surprisingly another parameter must be introduced. The latter is only necessary if direct comparisons are to be made among models and therefore has not been previously considered, and unfortunately creates further restrictions. We conclude that perhaps the most physically realistic model is actually a combination of models. Having chosen our preferred setup, we intend to study overshooting and penetrative convection varying the relative stability of the CZ and RZ and the Ra number, which will lead to more quantitative results related to these physical processes.

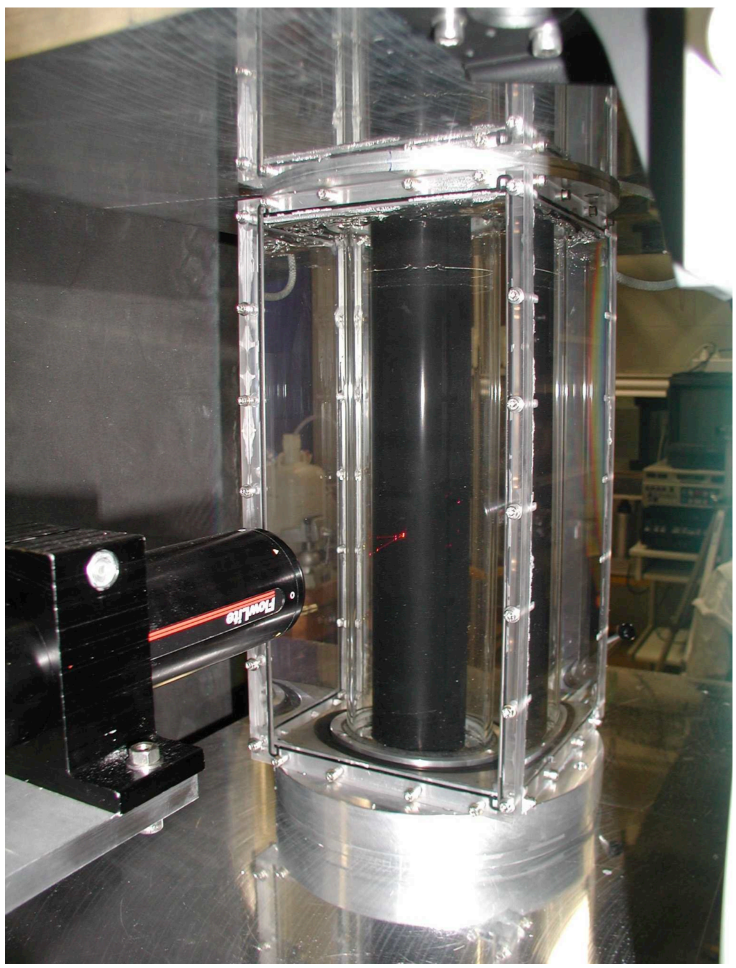
Dr Jacobo VARELA (P19)

Characterizing the feedback of magnetic field on the differential rotation of solar-like stars

(in collaboration with A. Strugarek and A.-S. Brun)

The differential rotation of solar-like stars is influenced by rotation rate and mass in presence of magnetic fields generated by a convective dynamo. We use the ASH code to model the convective dynamo of solar-like stars at various rotation rates and masses, hence different effective Rossby numbers. We obtained models with either prograde (solar-like) or retrograde (anti-solar-like) differential rotation. We study the trends of differential rotation versus stellar rotation rate obtained for simulations including the effect of the magnetic field compared with the hydro cases, showing a better agreement with the observations in the magnetic models. Analysis of angular momentum transport revealed that the simulations with retrograde and prograde differential rotation have opposite distribution of the viscous, turbulent Reynolds stresses and meridional circulation contributions. The thermal wind balance is achieved in the prograde cases. However, in retrograde cases Reynolds stresses are dominant for high latitudes and near the top of the convective layer. Baroclinic effects are stronger for faster rotating models. In most cases we observe temporal fluctuations of angular velocity that could be interpreted as torsional oscillations.

Instabilities, Turbulence and Disks



Dr Sébastien FROMANG

Angular momentum transport in accretion disks: a hydrodynamic perspective

In the last forty years, understanding the processes leading to angular momentum tranport in accretion disks has been a central issue in astrophysics. While a magnetohydrodynamical origin for this transport, mediated by the magnetorotational instability, is clearly favored, pure hydrodynamical processes are still being actively investigated, and particularly so in the context of protoplanetary disks. In the late 90's, Jean-Paul Zahn pioneered this research by stimulating a lab experiment specially designed for the purpose of accretion disk, an initiative that subsequently enabled progress to be made in our understanding of this difficult question. Today, if signatures of a dynamical transition to turbulence in hydrodynamic disk remain elusive, the effect of coupling even simple thermodynamics to these dynamical processes has produced spectacular and unexpected results. In this talk, I will review the current status of our understanding of hydrodynamical processes in accretion disks, highlight the recent discoveries of the baroclinic and vertical shear instabilies, and discuss along the way the many questions that remain.

Dr. Bérengère DUBRULLE

Turbulence in disks and laboratory experiments: the contribution of Jean Paul Zahn

Jean-paul Zahn was, among all other things, a visionary. 30 years in advances, he foresaw that focused laboratory experiments can contribute to our understanding of disk turbulence. In this talk, I review the contribution of Jean Paul Zahn to this question.

Pr Georges CHAGELISHVILI

Subcritical MHD turbulence in Keplerian disks - bypass concept via interplay of linear transient growth and nonlinear transverse cascade

(in collaboration with D. Gogichaishvili, G. Mamatsashvili, W. Horton)

We study the mechanism of the self-sustenance of subcritical MHD turbulence in spectrally stable stratified Keplerian disk system with toroidal magnetic field configuration and kinematic, magnetic and thermal Reynolds numbers equal to 5000. For this purpose, we performed direct numerical simulations of (homogeneous, subcritical) shear turbulence using: the grid resolution of 256 x 256 x 128; the local shearing-box approximation for domains Lx x Ly x Lz = 2 x 2 x 1; 2 x 2π x 1. Further, we analyzed the turbulence dynamics in Fourier/wavenumber/spectral space based on the simulation data to gain deeper insight into the dynamics/sustenance of such subcritical MHD turbulence.

Specifically, we examined the interplay of linear transient growth of Fourier harmonics and nonlinear processes. At toroidal magnetic field configuration, the linear growth of harmonics has transient nature and is strongly anisotropic in spectral space. This, in turn, leads to anisotropy of nonlinear processes in spectral space and, as a result, the main nonlinear process appears to be not a direct/inverse, but rather a transverse/angular redistribution of harmonics in Fourier space referred to as the nonlinear transverse cascade. It is demonstrated that the turbulence is sustained by the interplay of the linear transient growth (LTG) and the nonlinear transverse cascade (NTC). The essence of this interplay in Keplerian disks has been first proposed in G. Chagelishvili, J.-P. Zahn, A. Tevzadze and J. Lominadze, Astron. And Astrophys., 402, 401, 2003. The scheme proposed in this paper exemplifies the bypass concept of subcritical turbulence in spectrally stable shear flows.

LTG and NTC mainly operate at large length scales, comparable to the box size. Consequently, the central, small wavenumber area of Fourier space is crucial in the self-sustenance and is labeled the vital area. Outside the vital area, LTG and NTC are of secondary importance - Fourier harmonics are transferred to dissipative scales by the nonlinear direct cascade.

Giulio FACCHINI

Zombie vortex instability in protoplanetary disk: can we find it in the lab?

In stratified-rotating shear flows, Marcus et al. (2013) show the existence of a new hydrodynamic instability called the Zombie Vortex Instability (ZVI), where successive generations of self replicating vortices (zombie vortices) may fill the disk with turbulence and destabilize it. The instability is triggered by finite amplitude perturbations, including weak Kolmogorov noise, in stratified (with Brunt-Vaisala frequency N) flows, rotating with angular velocity W and shear S.
So far there are no observational evidences of the Zombie Vortex Instability and there are very few laboratory experiments of stratified plane Couette flow with background rotation in the literature. We perform systematic simulations exploring existence of Zombie Vortex Instability in terms of control parameters (Reynolds number Re, S/f and N/f). We present a parameter map show

Dr Jean TEYSSANDIER

Growth of eccentricity in planet-disc interactions

The origin and wide distribution of eccentricities in planetary systems remains to be explained, in particular in the context of planet-disc interactions. I will present a set of linear equations that describe the behaviour of small eccentricities in a protoplanetary system consisting of a gaseous disc and a planet. Eccentricity propagates through the disc by means of pressure and self-gravity, and is exchanged with the planet via secular interactions. Excitation and damping of eccentricity can occur through Lindblad and corotation resonances, as well as viscosity. In this talk I will present a study of the eccentric modes of the coupled disc-planet system in the case of short-period giant planets orbiting inside an inner cavity, possibly carved by the stellar magnetosphere. Three-dimensional effects allow for a mode to be trapped in the inner parts of the disc. This eccentric mode can easily grow within the disc's lifetime. An eccentric mode dominated by the planet can also grow, although less rapidly. I will present the structure and growth rates of these modes and their dependence on the assumed properties of the disc. An extension of the theory to gap-opening planets will also be presented. Finally, the linear theory will be compared with hydrodynamical simulations, and I will discuss the implication of these results for the eccentricity distribution of planetary systems.

POSTERS

Dr Saber NASRAOUI (P20)

Secondary instability in magnetogravity shear waves

Magnetogravity waves are ubiquitous in various astrophysical systems i.e. galactic disks and solar corona. By means of a time-periodic excitation (i.e., a time-periodic shear) of magnetogravity waves, for an inviscid and nondiffusive unbounded conducting fluid, we report the existence of a parametric instability. Under a primary vertical velocity perturbation and a radial density perturbation consisting of a one-dimensional standing wave with frequency N and amplitude proportional to Ã   ÂµN x, where x denotes the radial coordinate and Âµ a small parameter, and due to the fact that the magnetic potential induction is a Lagrangian invariant for magnetohydrodynamic Euler-Boussinesq equations, we show that plane-wave disturbances are governed by a four-dimensional Floquet system. For axisymmetric disturbance we show that stability of the Floquet system can be characterized by the Hill equation and we perform an asymptotic analysis of this equation following the perturbation theory.

Dr Antoine RIOLS-FONCLARE (P21)

Gravito-turbulence in magnetised protostellar discs

Gravitational instability (GI) features in several aspects of protostellar disk evolution, most notably in angular momentum transport, fragmentation, and the outbursts exemplified by FU Ori and EX Lupi systems. The outer regions of protostellar discs are not magnetically inert, and so magnetic fields could modify the development of GI. To understand the basic elements of this interaction, I will present results on local 2D ideal and resistive MHD simulations with an imposed toroidal field. In the regime of moderate plasma beta, I will show that the system supports a hot gravito-turbulent state, characterised by considerable magnetic energy and stress and a surprisingly large Toomre parameter Q ~ 10. This result suggests that the onset of GI in a magnetised disk significantly heats the gas and thus enhances ionisation fractions, as required by certain outburst models. Simulations also reveal the existence of long-lived and dense `magnetic islands' or plasmoids. Lastly, I will discuss about the impact of magnetic fields on the fragmentation criterion of the disk.