Rossby waves in astrophysics

ISSI proposal for an international team in space sciences (2016)

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Abstract

The proposal aims to set up an International Team with a wide range of expertise in order to summarize current studies of Rossby-type waves in different astrophysical applications and to set up collaboration between the different areas. The expertise of the Team members combines skills in the theory of Rossby waves, numerical simulations, ground- and space- based observations applied to different astrophysical objects (Sun, solar-like stars, astrophysical discs, exoplanets, neutron stars etc). The proposal intends to discuss three main points. 1) Besides the well-known 11-yr cycle, solar activity undergoes variations over shorter (155-160 days, 1-2 yrs) and longer (100-1000 yrs) time scales, which can be explained in terms of Rossby waves (Lou 2000, Zaqarashvili et al. 2010, 2015). Similar "Rossby range" periodicity was detected on solar-like stars by Kepler and CoRoT missions (Lanza et al. 2009, Bonomo and Lanza 2012). Therefore, it is of invaluable importance to discuss the relation between periodicities in activity of Sun and Sun-like stars in terms of Rossby wave theory. 2) Spatial variations of rotation and background plasma parameters (entropy, magnetic field) trigger Rossby-type wave instabilities in astrophysical discs (Lovelace et al. 1999, Umurhan 2010, Lovelace and Romanova 2014) and solar tachocline (Dikpati and Gilman 1999, Zaqarashvili et al. 2010), which are important for angular momentum transport in discs and for magnetic dynamo on the Sun. The proposal will stimulate the exchange of knowledge in both areas. 3) Nonlinear Rossby waves have important influence on large-scale dynamics of planetary atmospheres. The proposal aims to discuss the effect of large-scale magnetic field on nonlinear behavior of Rossby waves in general and on Rossby soliton solution in particular. The main expected outcome of the proposal is to share knowledge and to establish collaboration between the different communities working on Rossby waves in different astrophysical applications.

Scientific rationale

Rossby (or planetary) waves determine the large-scale dynamics of the Earth's atmosphere and oceans (Rossby, 1939). The waves arise due to the conservation of total vorticity in rotating fluids and they are well studied in the geophysical context (Gill, 1982). Latitudinal variation of Coriolis parameter is responsible for the waves on rotating spheres, while the radial differential rotation is the main reason for the waves in discs. Rossby waves have been discussed to have important influence on the large scale dynamics of different astrophysical objects: the solar atmosphere/interior (Lou 2000, Zaqarashvili et al. 2010), in galactic (Lovelace and Hohlfeld 1978) and accretion (Lovelace et al. 1999, Umurhan 2010, Lovelace and Romanova 2014) discs, in rapidly rotating solar-like stars (Zaqarashvili et al. 2011), in neutron stars (Andersson et al. 1999, Lou 2001, Heng and Spitkovsky 2009, Lou and Lian 2012), in the atmosphere of Jupiter (Petviashvili 1980) and in exoplanetary atmospheres (Heng and Workman 2014). While Rossby waves appear with very different spatial and temporal scales in different astrophysical environments, the common physical properties of these waves probably lead to similarities across many astrophysical systems, which, consequently, may simplify aspects of scientific approach to each of the above mentioned objects. Moreover, theoretical and observational knowledge gathered in a particular astrophysical area of research generally triggers further developments in others.

Besides the well-known 11-yr cycle, the Sun's activity undergoes other temporal variations of shorter and longer time scales. Short-term variations (Rieger-type periodicity, quasi biennial oscillations) occur over several months to 1-2 years in many indices of solar activity (Rieger et al. 1984, Carbonell and Ballester 1990, Oliver et al. 1998, McIntosh et al. 2015), while long-term variations occur over hundreds of years as found in the concentrations of cosmogenic radionuclides on the Earth (Solanki et al. 2004). Lou (2000) suggested that the Rieger periodicity can be explained in terms of hydrodynamic Rossby waves in the solar photosphere. On the other hand, large-scale toroidal magnetic field leads to the splitting of hydrodynamic Rossby waves into fast and slow magnetic Rossby modes (Zaqarashvili 2007, Heifetz et al. 2015). It was shown that the fast and slow magnetic Rossby modes in the solar tachocline lead to the shorter (Zaqarashvili et al. 2010) and longer (Zaqarashvili et al. 2015) periodicity in solar activity.

Main-sequence stars generally follow an activity-rotation relationship in which faster rotating stars are more active. Mathioudakis et al. (1995) showed that in a sample of stars with different effective temperatures the Rossby number (the ratio of inertial to Coriolis forces in the momentum equation) is a better parameter for describing the levels of EUV emission as compared to the rotational period. The stellar activity also displays cyclic variations like solar cycles, but time scales are rather dispersed. Saar and Brandenburg (1999) showed that the ratio of cyclic and rotational frequencies, which is generally proportional to Rossby number, for most stars with age $t>0.1$ Gyr has two different scales: one corresponds to that of solar cycles and the other to longer periodicity. On the other hand, radio and optical observations of UX Arietis, one of most active RS CVn systems, showed the periodicity of 294 days (Massi et al. 2005), which is similar to that found on the Sun. Recent observations by CoRoT and Kepler space missions have also discovered shorter periodicities in several solar-like stars, which are in the range of Rossby wave time scales (Lanza et al. 2009, Bonomo and Lanza, 2012). The shorter and longer periodicities observed on main sequence stars may correspond to fast and slow magnetic Rossby modes as in the case of the Sun. The indication that Rossby wave dynamics is relevant across these sub-disciplines necessitates close discussion between solar and stellar communities about observed similarities as well as theoretical understanding of Rossby wave as a source for periodicity in main sequence stars.

Spatial inhomogeneity in background plasma parameters (rotation, entropy, magnetic field) generally leads to the instability of Rossby waves in different situations. It was shown that local maximum in entropy profile along the radial direction of the accretion disc traps the unstable Rossby waves in its vicinity if the height-to-width ratio of the disc is larger than the threshold value (Lovelace et al. 1999). A similar result was obtained by (Umurhan 2010), who showed that the Rossby wave instability occurs near the localized peaks of the mean enthalpy profile. The Rossby wave instability (RWI) in astrophysical discs is a potentially important mechanism for driving angular momentum transport and for the formation of macroscopic planetesimals (Lovelace and Romanova 2014). Large-scale toroidal magnetic field and differential rotation triggers the magnetohydrodynamic (MHD) instabilities in the solar tachocline (Dikpati and Gilman 1999, 2001), which can be related with magnetic RWIs when a rotating frame is considered (Zaqarashvili et al. 2010, Heifetz et al. 2015). The instability may have important influence on solar magnetic dynamo and hence on magnetic activity, which eventually has huge impact on scientific-technological development of our civilization. The instability may trigger short term variation in solar activity (Zaqarashvili et al. 2010), which is a potentially important mechanism to improve the space weather forecast (McIntosh et al. 2015). Understanding the roles played by RWIs in both; astrophysical discs and in the solar interior will stimulate significant progress in the research of both sub-disciplines.

Nonlinear equations of hydrodynamic Rossby waves often lead to a Korteweg-de-Vries equation, which has soliton solution when weak nonlinearity is balanced with wave dispersion (Petviashvili 1980). The Rossby wave soliton may explain the Red Spot on Jupiter. But, the inclusion of magnetic field influences the character and dynamics of Rossby waves (Lou 2001, Zaqarashvili et al. 2007, Heng and Spitkovsky 2009, Heng and Workman 2014, Heifetz et al. 2015), which probably will affect the nonlinear dynamics of Rossby waves and hence the soliton solution. Modification of Rossby soliton by magnetic field may have interesting consequences in the solar interior and exoplanetary atmospheres.

Goals

The main goal of the proposal is to set up an international team with wide expertise in Rossby wave theory and observations/data analysis in order to discuss already achieved results in different astrophysical applications and to stimulate future collaboration between different branches where possible. The following main scientific questions (or tasks) will be discussed during the meetings (and beyond):

a. Rossby waves and solar-stellar magnetic activity;
b. RWI in astrophysical discs and in the solar tachocline;

c. Nonlinear magnetic Rossby waves in exoplanetary atmospheres and in the solar interior.

Rossby waves and solar-stellar activity. It becomes increasingly clear that the mid-range periodicities in solar activity are caused by Rossby waves. Rieger periodicity (150-160 days) and quasi biennial oscillations (1-2 years) are explained in terms of Rossby wave spherical harmonics (Lou 2000, Zaqarashvili et al. 2010). On the other hand, recent observations by Kepler and CoRoT showed similar time scales (as compared to stellar rotation period) in the activity of solar-like stars (Lanza et al. 2009, Bonomo and Lanza, 2012). The goal of this task is to discuss current observational and theoretical knowledge in the solar and stellar activity and push forward a connection between these two fields. The proposal brings together well known experts (observers and theorists) in both fields. The first meeting will center on discussing the current status of solar-stellar activity and establish working plans for collaborations amongst the team members. The second meeting will summarize the first results of the collaboration and promote future closer cooperation.

RWI in astrophysical discs and in the solar tachocline. RWI has been studied in astrophysical discs and in the solar tachocline, but until now no clear attempt to discuss similarities and differences has been made. The instability is usually triggered by differential rotation and entropy gradients in astrophysical nonmagnetic discs (Lovelace and Hohlfeld 1998, Lovelace et al. 1999, Umurhan 2008, 2010, Lovelace and Romanova 2014, Yellin-Bergovoy et al. 2016). However, toroidal large-scale magnetic field and differential rotation are necessary ingredients for the instability in the solar tachocline (Dikpati and Gilman 1999, 2001, Zaqarashvili et al. 2010). The goal of this task is to discuss the influence of magnetic field on RWI in astrophysical discs and the influence of entropy gradients on the instability in the solar tachocline. Project team includes well known experts in both fields, which will stimulate the exchange of knowledge in both areas and will lead to interesting discussions for cooperation in analytical solutions and numerical simulations. RWI driven by gravitational radiation from rotating neutron stars (Andersson et al. 1999, Lou and Lian 2012) will be also discussed during meetings. Prof. Nils Andersson (University of Southampton, UK) will be invited as an external expert to discuss this issue.

Nonlinear magnetic Rossby waves in exoplanetary atmospheres and in the solar interior. The nonlinear dynamics of Rossby waves is important for planetary atmospheres and for solar/stellar interiors/atmospheres. Moreover, the nonlinearity and the dispersion may lead to the formation of Rossby soliton, which may persist during long time like the Red Spot on Jupiter. However, influence of magnetic field on the nonlinear dynamics of Rossby waves and/or on soliton solution is not well studied. The goal of this task is to discuss the nonlinear dynamics of Rossby waves in magnetized plasma and the possible magnetic Rossby soliton solution.

Timeliness

In this regards, the proposal is very timely as it will discuss possible points of intersections between the Sun and Sun-like stars. Another important point is that observations of solar surface phenomena inevitably lead to invoke instabilities in the solar tachocline. Knowledge of RWI gained in astrophysical discs will be very helpful to simulate large-scale instabilities in the solar tachocline. The observed structure of protoplanetary disc systems, recently imaged with high resolution by the ALMA mm-array, increases the importance of theoretical inquiries towards the understanding of the nature of Rossby waves in disks. Large-scale and long-term dynamics of solar activity over Rossby time scales (from several months to few years) may improve space weather predictions, which is a hot topic in heliospheric science.

Expected output

The main expected output of this proposal is to share knowledge between the different communities working on Rossby waves in different astrophysical objects and to establish links between these different communities. Planned meetings will stimulate intensive collaboration between team members leading to a number of papers in refereed journals. Final achievements collected during both meetings will be summarized in a Space Science Reviews paper.

Value of ISSI

ISSI gives a great opportunity to scientists from different countries and institutions to meet in comfortable and lovely place in order to discuss achieved results, to exchange the ideas and to plan the future collaborations. The relaxed atmosphere at ISSI meetings, which is free from political discussions and questions typical for larger conferences, will help team members to concentrate on scientific aspects of research. Ideal geographical location of Bern (central location between Europe, USA and China/Japan) is also significant advantage of ISSI. Convenient location of hotels and reimbursement of local expenses are also important.

Confirmed members

José Luis Ballester, Universitat de les Illes Balears, Spain (brings expertise in Rieger periodicity of solar activity)
Mausumi Dikpati, High Altitude Observatory, USA (brings expertise in solar tachocline instabilities and solar dynamo)
Kevin Heng, University of Bern, Switzerland (brings expertise in atmospheric dynamics of exoplanets)
Eyal Heifetz, Tel Aviv University, Israel (brings expertise in atmospheric dynamics and shear flow instabilities)
Antonino Lanza, Osservatorio Astrofisico di Catania, Italy (brings expertise in stellar activity)
Yu-Qing Lou, Tsinghua University, China (brings expertise in Rossby wave theory in different astrophysical applications)
Richard Lovelace, Cornell University, USA (brings expertise in Rossby wave instabilities in astrophysical discs)
Mihalis Mathioudakis, Queen's University Belfast, UK (brings expertise in solar and stellar activity)
Scott McIntosh, High Altitude Observatory, USA (brings expertise in solar atmospheric dynamics and magnetic activity)
Ramon Oliver, Universitat de les Illes Balears, Spain (brings expertise in Rieger periodicity of solar activity and numerical simulations)
Orkan Umurhan, NASA Ames Research Center, USA (brings expertise in Rossby wave instabilities in astrophysical discs)
Teimuraz Zaqarashvili, University of Graz, Austria (team leader, brings expertise in Rossby wave theory in different astrophysical applications)

Besides the core team members, few external experts will be invited to attend the meetings and to discuss particular subjects. Prof. Nils Andersson (University of Southampton, UK) will be invited to discuss the Rossby wave instability driven by gravitational radiation from rotating neutron stars. Prof. Michael Rudermann (University of Sheffield, UK) will be invited to discuss nonlinear dynamics of magnetic Rossby waves.

Schedule

Two meetings each with duration of 5 days are planned. The first meeting will take place at the end of 2016 or at the beginning of 2017. The second meeting will take place in the second half of 2017. The exact days will be coordinated later according to availabilities of team members.

Facilities and financial support

The proposed workshops will need one meeting room with projection facilities, whiteboards, and internet access. Financial support for standard living expenses (hotel and per diem) for all meeting participants and for travel expenses of team leader is requested from ISSI.

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Annex_1

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