Here are sketches of several projects which are suitable as masters thesis. If they look interesting to you I suggest that you contact me. Whether we can work on a particular project on a particular year depends on my workload and your abilities. The projects are mere sketches, not set in stone. The following ones are available for the year 2016. I can advise at most one masters student in this year.

- *On the formation of condrules*
- *Surface signatures of solar dynamo*
- *Forecasts in models of Self Organized Criticality.*

Each of the topics are described in further details below.

On the formation of chondrules

Chondrules are round grains found in certain meteorites which are called chondrites. The chondrites are presumed to be one of the earliest solid objects that has formed in the Solar system. Chondrules are drops of molten metal trapped inside the chondrites. How did the chondrules form is one of the central puzzles in the theories of formation of planetary systems. Recently, in a remarkable paper McNally et al. (2013) is has been suggested that a mechanism of formation of chondrules could be a kind of run-away effect as we describe now. The accretion disk around a central star is excepted to be a turbulent magnetohydrodynamic (MHD) flow. Such flows generally for thin current sheets which are sites of magnetic reconnection and regions of very high magnetic energy dissipation. This could heat precursor grains for chondrules and other high-temperature minerals in current sheets. Once the grains are heated above a certain temperature the local resistivity could decrease, consequently the local current would increase heating the grains to even higher temperatures and possibly melting them. The same short-circuit mechanism may perform other high-temperature mineral processing in protoplanetary disks such as the production of crystalline silicates and CAIs. But for such a process to work a dust grain need to remain for a significant time within a region of high dissipation. Can that happen ? Testing this is the object of this project.

The motion of dust and gas in an accretion disk is often modeled by solving equations of MHD turbulence together with a set of equations for the dust grains, given by

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{v} \\ \dot{\boldsymbol{v}} &= \frac{1}{\tau}\left[\boldsymbol{u}(\boldsymbol{x}) - \boldsymbol{v}\right] \end{aligned} \tag{1}$$

where $\boldsymbol{u}(\boldsymbol{x})$ is the velocity of the flow at the position of the dust particle, $\boldsymbol{x}$. The velocity of the particle is $\boldsymbol{v}$ and the characteristic time scale τ. Such particles, by virtue of their inertia, behave quite differently from fluid particles. They can be ejected from vortices and have been shown to cluster in hyperbolic regions of the flow. To test whether it is possible for MHD turbulence to melt dust grains, we shall monitor the rate of dissipation of magnetic energy (which is converted to heat) at the position of a dust grain. We shall then ask what is the distribution of times over which the rate of energy dissipation changes by a significant amount. This will be calculated by direct numerical simulations of MHD turbulence with dust particles using the pencil-code.

Magnetic flux emergence at the solar surface

One of the most striking and at the same time most observed magnetic features of the sun is the phenomenon of formation of active regions and sunspots. At present, we all agree that the

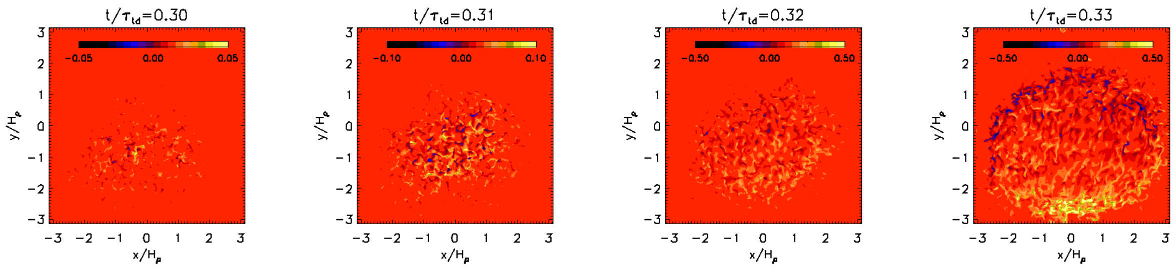

Figure 1: Formation of bipolar regions from DNS of stratified forced magnetohydrodynamic turbulence. This is a contour plot of the vertical component of the magnetic field on the top surface; blue is negative and yellow positive. The two horizontal boundaries have periodic boundary conditions. Figure adapted from Mitra et al. (2014).

magnetic behaviour of the sun is determined by the solar dynamo which operates in the convection zone of the sun. This brings us to the question, how is the magnetic field generated by the solar dynamo related to the magnetic field observed on the surface of the sun ?

The traditional picture is that at the bottom of the convection zone (the tachocline) the solar dynamo generates a strong toroidal magnetic field, which becomes buoyant and eventually penetrate through the surface layers of the sun to create bipolar active regions on the surface. In recent times, several observational (Stenflo & Kosovichev, 2012) and theoretical works (Brandenburg, 2005) have critised various aspects of the traditional picture. Furthermore, direct numerical simulations (DNS) have found that solar-like dynamo can operate even in the absence of a tachocline (Ghizaru et al., 2010; Käpylä et al., 2012; Augustson et al., 2013);

In the last decade, an alternative scenario (Brandenburg, 2005) which assumes that active regions form by concentrating a background magnetic field near the solar surface, has emerged. There has been recent realistic numerical simulations that provides evidence in support of this picture (Stein & Nordlund, 2012). Semi-analytical and numerical studies (Brandenburg et al., 2011; Kemel et al., 2012; Brandenburg et al., 2013) in a very idealized setup, which ignores radiative transport and ionization but takes into account the gravitational stratification, have shown that the effective mean-field equations of this system has an additional (negative) contribution to the magnetic pressure that comes from averaging the small scale turbulence. This terms is nonzero only when there is gravity and is negative only when the magnetic field is weak, otherwise it may be positive. When it is negative the flux-concentration can happen. This instability is often called the Negative Effective Magnetic Pressure Instability (NEMPI). This aim of this project is to study this instability and its possible ramifications; in particular, the following questions shall be investigated.

- How would NEMPI be affected by inclusion of radiative transfer and ionization effects ?
- What would be the signatures of NEMPI that can be detected by local helioseismology ?

- How does the solar dynamo operating beneath the surface interact with the NEMPI ? Preliminary results show, see Fig 1, that it is possible to have concentration of magnetic flux in a way the bipolar magnetic regions emerge.

Forecast in models of Self Organized Criticality

The sun shows activity over a large range of length and time scales. The total number of sunspots seen in the sun varies with an eleven year cycle. This cycle itself is not a regular one, its amplitude varies (with no particular regularity) with time. There are instances where almost no sunspots were seen for several decades – called the Maunder minima. On short time scales the sun shows far more violent events, e.g., solar flares and coronal mass ejections (CMEs). Remarkable examples of such ejections can be seen in the movies produced by the SOHO and SDO missions[1], an example of which is reproduced in the left panel of Fig. 2. These short and long time variations are weakly related to each other – during the peak of the solar magnetic activity (as measured by the sunspot numbers) more CMEs are observed – although the correlation is not very strong. There is also a turbulent, highly fluctuating solar wind blowing from the sun.

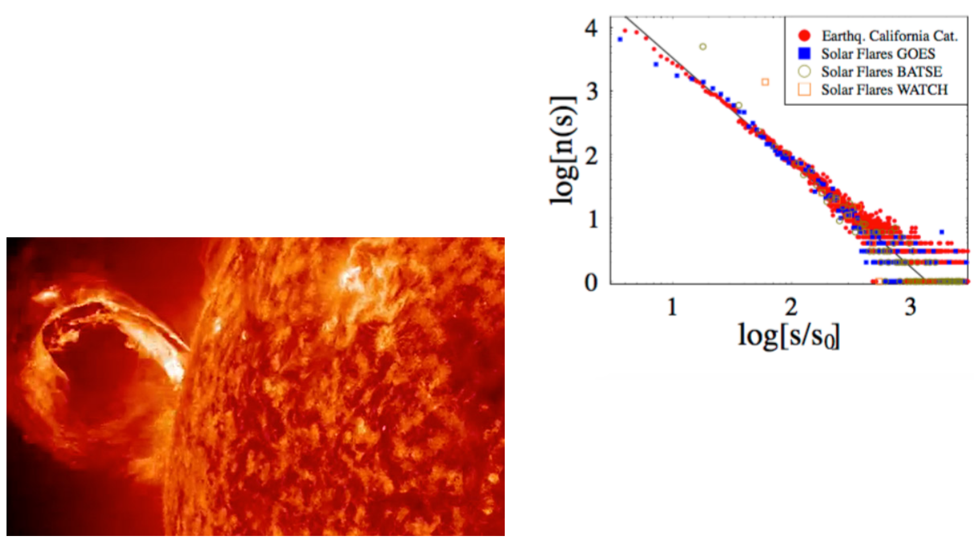

Figure 2: (left panel) An example of an image of coronal mass ejection captured by the NASA's SDO mission in ultraviolet light on 1st May 2013. The CME originated on the suns's limb and was not heading towards the Earth. (right panel) Same power-laws emerge from statistics of solar flares and earthquakes !

[1]To see movies visit the location, `http://sohowww.nascom.nasa.gov/bestofsoho/Movies/10th/transcut_sm.mpg`

The magnetic (in)activities of the sun play an important role in our present day society. The effects of CMEs on earth can be devastating magnetic storms which can disrupt power grids, sever telecommunication networks and stop global positioning systems from working. As a matter of fact, events far less violent than CME-driven geomagnetic storms, e.g., energetic electronic storms which are triggered by high-speed solar wind that emanates from coronal holes have been known to disrupt satellite communication. The economic costs of a severe magnetic storm, of the magnitude of the great magnetic storm of 1859 – the Carrington event – are estimated to be greater then the economic cost of Hurricane Katrina (Committee on the Societal and Economic Impacts of Severe Space Weather Events:A Workshop, 2008). Hence it is very important to study and to eventually be able to forecast both short-term and long-term magnetic activities of the sun.

Let us here make a clear distinction between the words "prediction" and "forecasting". Prediction will be used in the sense that "Dirac's theory of electron predicted the existence of positron". There is no element of chance involved in such a process. Whereas the word "forecasting" will be used in the sense that "We forecast that tomorrow there is 80% possibility of raining". This is by nature a statistical process. It is forecasting that is of primary interest to this project. In particular, we are interested in forecasting CMEs. It turns out that there is interesting similarities between CMEs and earthquakes which are notoriously difficult to forecast. This similarity is manifested if we plot the strength of a solar flares (measured by some parameter) on the horizontal axis and the number of occurrences of such a solar flare on the vertical axis as shown in right panel of Fig. 2. The plot is a power-law. If we plot a similar plots for earthquakes (this time measuring their strengths by the Richter scale) we also obtain a power law with a very similar exponent. This phenomenon is an example of self-organized criticality (SOC). There are many different models of SOC, one of the most popular ones is due to Bak, Tang and Wiesenfeld (BTW).

In the field of forecasting, we should take our lessons from the most successful forecasting system we have at present, i.e., that of numerical weather forecast. This field has been invigorated by massive computation of complex weather models. But however complex such models are they can never match the complexity of reality. Hence, the models must be tuned with the real data obtained by numerous weather stations all over the world, including satellite observations. This crucial tuning process goes by the technical name of "Data Assimilations" (DA). The techniques of DA are essentially methods to fit solutions of partial differential equations with noisy observations. These are used extensively in almost all meteorological forecasting systems at present. But it has been seldom applied to study astrophysical systems, see however Dikpati et al. (2014). Ours is one of the pioneering projects which aims to do this task. To be more definite, the goals of our study are as follows:

- Forecasting of flares and CMEs are akin to forecasting earthquakes which is a notoriously difficult problem. Hence in this project we shall limit ourselves to a more moderate goal, that of investigating the "predictability" of the models of SOC using techniques of DA.

  The project shall be carried out in collaboration with M. Dikpati (NCAR, Boulder) and A. Brandenburg (NORDITA).

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