FLARE PHYSICS IN ACCRETION DISCS

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ABSTRACT

In this paper we attempt, for the first time, to simulate the magnetic activity of an accretion disc based on our understanding of solar flares. We use a probabilistic cellular automaton model with two free parameters, the probability of spontaneous emergence of magnetic flux above the surface of the disc, S_0, and the probability of diffusive disappearance of flux below the surface, D, both of which are dependent on the mass input rate $\dot{M}$. The model describes a changing collection of flux tubes which stick out of the disc and are anchored inside the disc at their footpoints. Magnetic flux tubes transfer angular momentum outwards at a rate which is analytically estimated for each single loop. Our model monitors the dynamic evolution of both the distribution of magnetic loops and the mass transfer which results from angular momentum transport due to this distribution. The energy release due to magnetic flaring is also recorded and exhibits temporal fluctuations. We have found that our approach allows steady accretion in a disc by the action of coronal magnetic flux tubes alone. If we express the effective viscosity caused by coronal loops in the usual Shakura-Sunyaev α parameter of viscosity we find values which are in good agreement with observed values.

Key words: accretion discs, coronal magnetic fields, solar flares.

1. INTRODUCTION

A long-standing problem in the physics of accretion discs around protostars and compact objects in X-ray binaries and in Active Galactic Nuclei is the nature of the **anomalous viscosity** in the disc which exceeds the ordinary gas viscosity by a factor of at least 10^6 (Frank *et al.* 1992). Often magnetic turbulence in the disc is considered to be the prime candidate to explain this anomalous viscosity (Hawley & Balbus 1999).

Coronal magnetic loops? In most papers on accretion discs angular momentum transport by loops rising on both sides above the disc has been underestimated. It is well-known that a magnetic loop sticking out of the accretion disc into a force free corona is an efficient transmitter of angular momentum from the inner to the outer footpoint of the loop (Aly & Kuijpers 1990). Further, the X-ray emission from accretion discs in X-ray binaries shows strong fluctuations, and is observed to come in bursts. In the present work we have investigated if the anomalous viscosity can be caused by a collection of magnetic loops anchored in an accretion disc. As angular momentum transport by coronal loops is intrinsically *non-local* our study is a numerical one. Global angular momentum transport by magnetic loops from the inner parts of a disc to the outer parts can only exist if the individual loops overlap each other in radial extent.

First result: In particular, we have asked ourselves if it is possible to construct an anomalous viscosity which, on average, mimics a standard Shakura-Sunyaev disc solution (Shakura & Sunyeav 1973) with relatively large value of the 'alpha'-parameter. This turns out to be possible.

What have we learned? The step forward taken in this work consists of providing a physical process – *magnetically active loops in an accretion disc corona* – which can explain the large value of the viscosity parameter in accretion disc models. This study relies heavily on our knowledge of the physics of magnetic flares in the solar corona, and of the formation of active regions on the Sun.

2. A CELLULAR AUTOMATON FOR DISC LOOPS

Our **geometry** is a 2-D Keplerian disc around a neutron star between 2.5 – 13 stellar radii. We model one side of the disc only, and assume that the events occur symmetrically on both sides of the disc at the same time. We divide the disc into a 2-D circular grid consisting of $\sim$ 300 rings. Each ring is divided into a number of cells such that each cell, when magnetically active, has a constant amount of magnetic

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flux independent of distance to the center. The local magnetic field strength of an active cell is calculated from Shakura-Sunyaev (SS) disc 'reference' solutions, dominated by gas pressure. These solutions are fixed by the values of the central compact mass $M = 1.4$ $M_\odot$, the accretion rate $\dot{M}$ and the viscosity parameter α. The last two quantities are, initially, given values as are typically observed but, later on, calculated iteratively by our code until a – on the average – steady state sets in.

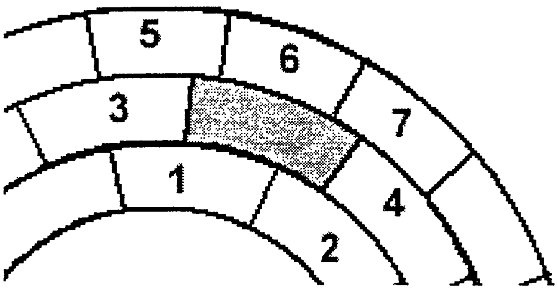

Figure 1. The nearest neighbours of a cell in our grid. The neighbouring cells are the only grid elements with which a cell is interacting.

The **loop evolution** is implemented as follows. We asume that each individual loop interacts locally with cells neighbouring its footpoints (Fig. 1). We initialize the automaton by randomly distributing bipolar loops of various sizes and orientation so that approximately 1% of the surface is covered by magnetic flux. We then let the loops evolve dynamically according to the following rules:

- **Spontaneous emergence**: Each empty cell is given a probability S for hosting the footpoint of a magnetic loop in the next time step. The other footpoint then appears at the same time at a random position within a prescribed radial separation (up to 50 rings away). In reality, the magnetic field strength will depend on the local value of the density. However, as we calculate the local field strength from a reference SS-model under the assumption of equipartition between gas and magnetic pressures we incorporate the effect of an accumulating local density on the field by letting S depend on the density according to $S = S_0\sqrt{\rho/\rho_0}$ where the density ρ_0 is from the SS-model in the present iteration. S_0 *is a free parameter of the model and is taken to be space-independent.*

- **Stimulated emission**: Existing loops stimulate the emergence of new loops in cells neighbouring their footpoints. The probability of stimulated emergence per time step t_{ts} in a neighbouring cell is taken to be

$$P = \sqrt{\frac{GM}{r^3}}t_{ts}, \quad (1)$$

and is based on an estimate for the rise time of a loop through the disc which, for a thin disc, equals the typical shearing time (the local Keplerian rotation period divided by 2π).

- **Diffusive disappearance**: For every neighbour free of magnetic flux, an existing loop has a probability D to disappear in the next time step. D *is the second free parameter of the model.*

- **Torque from flaring loops**: Loops with radial footpoint separation greater than a certain value (about the half-thickness of the disc $H(r)$) cannot oppose shearing by the ambient Keplerian flow, and are taken to undergo reconnection (flaring) instantaneously as soon as the shear in the loop has increased by 45^o. During this period we estimate the angular momentum transport from inner to outer footpoint, and transport corresponding amounts of mass from the inner (outer) footpoint to the ring adjacent to the inner (outer) footpoint and on the inner (outer) side of it. The result is net accretion, i.e. more mass slides inwards than is ejected outwards. Thereafter, the flaring loop is taken out. Loops with radial footpoint separation smaller than $H(r)$ reach corotation, and their effect on angular momentum transport is estimated during the time required to reach corotation. After that these loops are also taken out.

- **Energy release from flaring loops**: We monitor the energy release by magnetic flares, which is estimated to have a value per flare

$$f_c \frac{B^2_{z,phot} L A_{phot}}{8\pi}, \quad (2)$$

where $B_{z,phot}$ is the vertical component of the magnetic field at the surface (photosphere) of the disc, f_c is the local surface filling factor by magnetic fields (so that $f_c B_z$ is the vertical field component in the force free corona just above the disc), L is the linear separation between footpoints, and A_{phot} is the cross-section of the loop at one footpoint at the photosphere (A_{phot}/f_c is the cross-section of the tube in the corona). The released energy is assumed to be emitted in X-rays, and should remain much smaller than the blackbody radiation from the disc for reasons of consistency with a SS-description.

3. RESULTS

In our simulations we find that the action of magnetic loops does indeed take over the transport of angular momentum and mass $\dot{M}$, as forced initially by the $\alpha-$prescription in a Shakura-Sunyaev disk, and at a new and *self-consistent steady state* characterized by $\alpha_{final}, \dot{M}_{final}$ (Figs. 2 – 4). In a SS-disk the motion is mainly Keplerian with an additional small inward (radial) velocity component given by $v_r \sim \alpha c_s H/r$, where c_s is the local sound speed ($c_s/v_{Kep} \sim H/r$) and H is the disc half-thickness at radius r. Figs. 5 – 11 show characteristic properties of a simulation with $\alpha_{final} = 2.5$ obtained for $D = 0.1$, $S_0 = 0.05$. The modeled region of the disc spans from 2.5 – 13 R_* ($R_* = 10$ km and $M_* = 1.4$ $M_\odot$) and the stabilized accretion rate is $\dot{M} = 1.14 \cdot 10^{17}$ g/s $= 0.076$ $L_{Eddington}$.

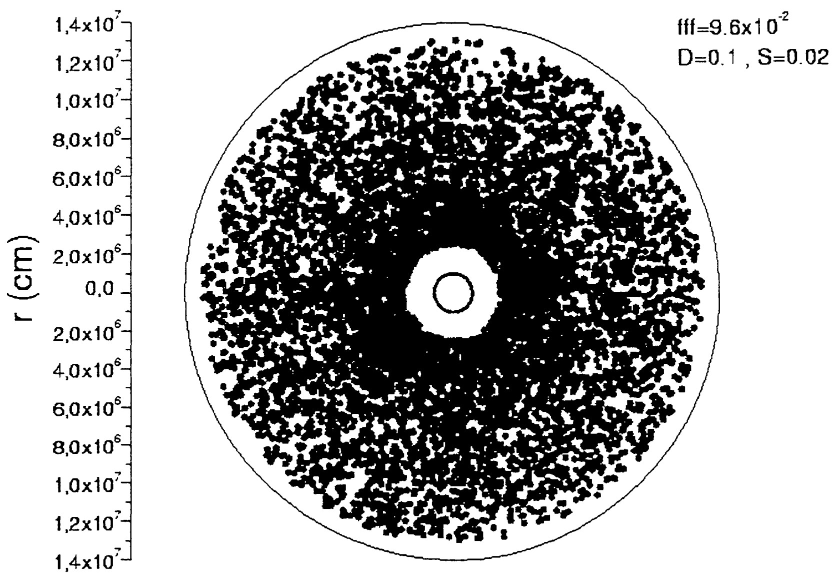

Figure 2. A face-on snapshot of the modeled region of the disc, where the spatial distribution of the coronal magnetic loops can be seen. The steady state filling factor has an 'intermediate' value of $f_c = 0.096$ *(*$D = 0.1$, $S_0 = 0.02$*). The circle at the center is the neutron star.*

- Fig. 5 shows the energy released per time step of 0.4 msec. The magnetic energy release varies between 2 – 3 $\cdot 10^{34}$ erg/s or about 0.001 of the total accretion luminosity;

- The global flux filling factor as a function of time is shown in Fig. 6. It varies around 16 %;

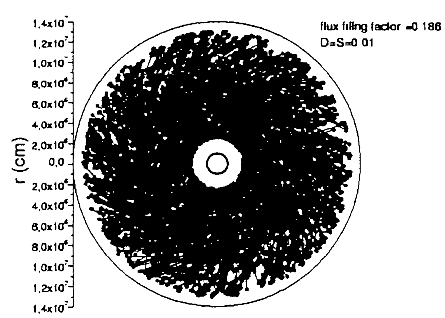

Figure 3. Disk with a high density of flux tubes. The steady state filling factor is $f_c = 0.186$ *(*$D = S_0 = 0.01$*).*

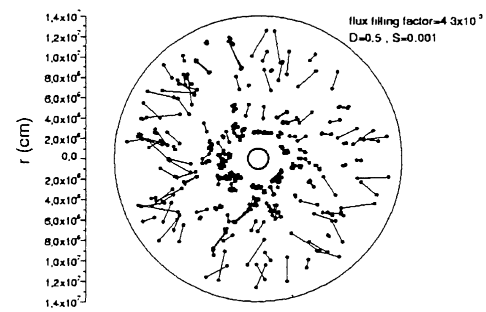

Figure 4. A low density of flux tubes. The steady state filling factor is $f_c = 0.0043$ *(*$D = 0.5$, $S_0 = 0.001$*).*

- The local flux filling factor f_c as a function of ringnumber is shown in Fig. 7;

- The fluctuations of the mass of the inner ring as a function of time are shown in Fig. 8 (one time step is 0.4 msec) relative to that of the initial SS reference model;

- Similarly, Fig. 9 shows the fluctuations of the mass of the outer ring with time;

- Fig. 10 shows the total mass in the disc as a function of time. It stabilizes at the end to a value $\dot{M} = 1.14 \cdot 10^{17}$ g/s = 0.076 $L_{Eddington}$;
- The power spectrum of the energy release time series of Fig. 5 is essentially white noise (Fig. 11).

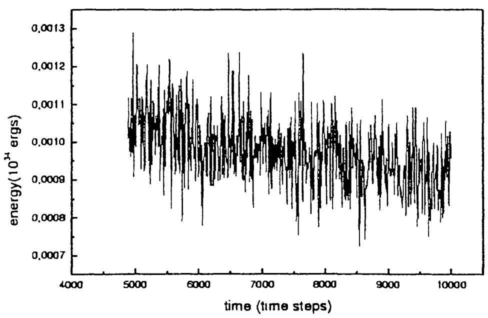

Figure 5. The energy released per time step of 0.4 *msec as a function of time. The magnetic energy release varies between* 2 - 3 $\cdot$ 10^{34} *erg/s or about* 0.001 *of the total accretion luminosity. The simulation is for a large viscosity,* α_{final} = 2.5, *obtained for* D = 0.1, S_0 = 0.05. *The modeled region of the disc spans from* 2.5 - 13 R_* *(*R_* = 10 *km and* M_* = 1.4 $M_\odot$*).*

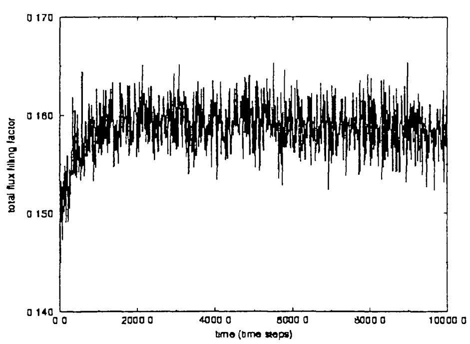

Figure 6. The global flux filling factor as a function of time for the case of Fig. 5.

The model is well-behaved and stable for a range of combinations of the probabilities S_0 and D controlling the magnetic activity. Our results suggest that the combination of probabilities $\{S_0, D\}$, for which the system stabilizes at *specific* $\dot{M}$ is not unique, but can be chosen from a certain range of values.

The model described here is only a first step in the study of the magnetic activity in accretion discs using Cellular Automata. It contains several simplifying assumptions, for example, the absence of non-active loops. Further study is also required in order

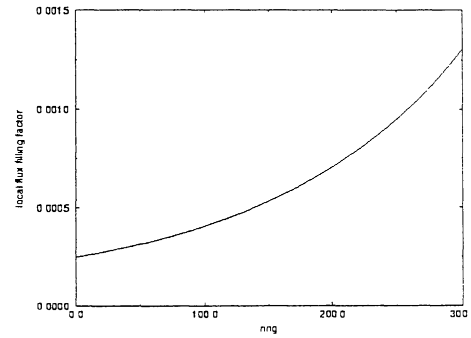

Figure 7. The local flux filling factor f_c *as a function of ringnumber (corresponding to* 2.5 - 13 R_**). Parameter values are as in Fig. 5.*

to determine the limits of the region on the $\{S_0, D\}$ plane outside of which the configuration of the model becomes unstable (the grid fills up or empties completely) with respect to magnetic activity and mass density. Finally, as a next step we plan to incorporate Self-Organized Criticality (SOC) which is known to lead to power-law distributions (instead of the white noise power spectrum) as is observed for the X-ray fluctuations. A more extended version of this work is submitted to A&A.

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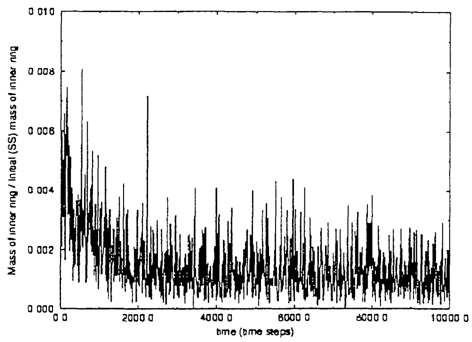

Figure 8. The fluctuations of the mass of the inner ring as a function of time (one time step is 0.4 msec) relative to that of the initial SS reference model. Parameter values are as in Fig. 5.

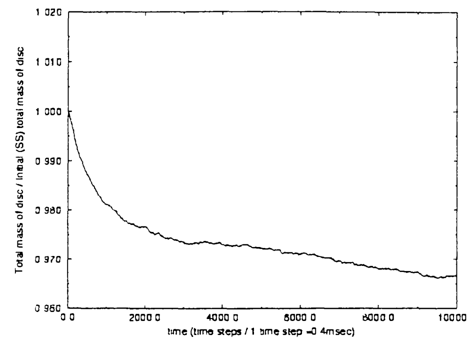

Figure 10. The total mass in the disc relative to that of the initial SS-disk. At the end the mass stabilizes and the mass loss rate gets a value $\dot{M} = 1.14 \cdot 10^{17}$ g/s $= 0.076$ $L_{Eddington}$*. Parameter values are as in Fig. 5.*

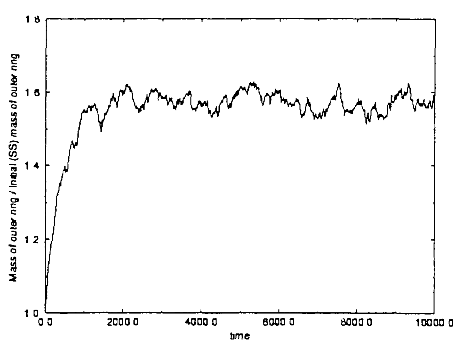

Figure 9. The fluctuations of the mass of the outer ring as a function of time. Parameter values are as in Fig. 5.

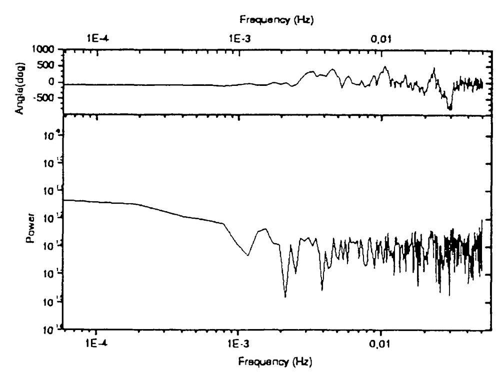

Figure 11. The power spectrum of the energy release time series of Fig. 5 is essentially flat (white noise). Parameter values are as in Fig. 5.