Mem. S.A.It. Vol. 83, 734

Memorie della

Multiperiodicities and magnetic field behaviour in cataclysmic variables

How can we enrich the scenario of theoretical models?

S. Gaudenzi, V. F. Braga, and S. De Bianchi

Dept. of Physics, Universita` La Sapienza, Roma Piazzale A.Moro 5, 00185 Roma, Italy
e-mail: silvia.gaudenzi@roma1.infn.it, bravi4@hotmail.com, silvia.debianchi@uniroma1.it

Abstract. After Benzi et al. (1981) introduced stochastic resonance and applied it to studies on climate change (Benzi et al. 1982), this intriguing and powerful tool revealed the possibility of making predictions on fluctuations of non linear systems where multiple equilibrium states are possible. We investigate the possible association between soliton generation and stochastic resonance, in order to enrich the scenario of CVs theoretical models. We advance the hypothesis that processes within CVs disks can be also modeled through stochastic resonance and soliton propagation. This interpretation could account for outbursts cycle, Dwarf Nova Oscillations (DNOs), as well as Quasi Periodic Oscillations (QPOs).

Key words. Stochastic resonance – Solitons – Dwarf Nova Oscillations – Quasi Periodic Oscillations – Cataclysmic Variables – Multiperiodicity

1. Introduction

1.1. Aim of the work

The aim of this work is to introduce two interpretative keys, soliton and stochastic resonance, in the mosaic of the existing theoretical models explaining CVs multifrequency behaviour. We will then focus on DNOs and QPOs, by treating CVs as if they were laboratories qualified to 'test' the generation of solitons through stochastic resonance, in order to enrich the scenario of theoretical models.

Send offprint requests to: S. Gaudenzi

1.2. Brief presentation of our key concepts

Stochastic resonance, as an interpretative key concept, was first introduced to explain long term climatic variation and successively applied as a possible mechanism in many physical and biological complex systems. Benzi (2010) claims:

> The first numerical simulation providing strong evidence of Stochastic Resonance was performed by Angelo Vulpiani and myself [...] Together with Alfonso Sutera and Giorgio Parisi, we were trying, at that time, to understand whether a relatively small periodic forcing can be amplified by internal non linear stochastic dynamics, leading to a possible understanding of the 100 Ky cycle observed in

climate records. [...] we were able to provide a quite general understanding of how the mechanism works and how to generalize it for chaotic systems [...] the name of stochastic resonance was introduced because of a short discussion [...] in a climate meeting in Erice [...] John Imbrie, one of the most famous scientist working on paleoclimate, asked whether what we found was somehow similar to a resonance and my answer was: not exactly! It is a kind of stochastic resonance! In some sense, we can think of a resonance as follows. In the standard resonance mechanism, think for instance of a damped harmonic oscillator, the amplification of the external forcing can be related, mathematically, to a singularity in the complex plane of the Green function of the problem. The real part of the singularity is, of course, the resonance frequency. In chaotic or stochastic systems, there are singularities in the complex plane but on the imaginary axis. The mechanism of stochastic resonance provides a way to shift the singularity in the complex plane.

In principle, all the phenomena around us are characterized by complexity, which is revealed by the modulated co-existence of both chaos and coherence. The concept of complexity has been introduced for the first time by the 1970 Nobel Prize Phil Anderson with the following words: More is different. This definition allows us to suggest that complexity could be measured by a chaos (or coherence) degree value. Coherence in fact can be defined as the inverse property of chaoticity, where the chaoticity of a system is associated to a fast, exponential rate of divergence of trajectories beginning at near points in the phase space (Battisti et al. 2009). This rate of divergence could then provide a measure of the chaoticity (or coherence) degree. Time is the physical variable connecting chaos and coherence: the coherence time in fact is defined as the time after which the system becomes chaotic. Stochastic resonance indeed suggests its own physical role in obtaining coherence from chaos and vice-versa. Moreover, coherence can be associated to the propagation of solitonic waves.

Solitons are localized wave-packets, emerging in a boundary space characterized by a change of phase, able to conserve their shape and speed when propagating in different media and under mutual collisions: they are typical of integrable nonlinear equations. However, they also arise in physical systems described by nonintegrable wave equations. Let us consider some significant cases taken from different branches of physics.

(Shukla et al. 2002) describe the formation in dense plasmas of stationary neutrino envelope solitons and nonstationary shocks due to nonlinear interaction between intense neutrino beams, behaving as a driving force, and ion sound waves. Brodin&Marklund (2007) study the special case of weakly nonlinear shear Alfvn waves in the one-dimensional limit for an electron-positron pair plasma: they obtain wave steepening and subsequent soliton formation only if the spin properties of constituents are included. In the biophysical context, some very intriguing aspects emerge. In a very recent study (Prez-Garca et al. 2011) the fundamental physio-pathological features of an aggressive type of brain tumors, glioblastomas, are described through bright solitons acting as attractors of the tumor-host dynamics. Finally, solitonic acoustic waves emerge also to explain nerves pulses propagation in biological membranes (Heimburg&Jackson 2005) (Heimburg 2010) (Appali et al. 2010). The presently accepted Hodgkin-Huxley (HH) model explains nerve pulse propagation by ion currents along concentration gradients by considering only voltage dependent aspects, predicting energy losses in form of heat (Hodgkin&Huxley 1952). However, no heat emission during the pulse is observed. Within the soliton model theory (based on thermodynamics) the nerve pulse is a solitary wave generated by the lipid phase transition (fluid/gel state) in the membrane; the propagation is due to the combined effect of nonlinearity and dispersion and no heat dissipation is predicted. This approach, we suggest, seems to complete the HH model, by claiming that nerve pulses not only can be triggered by voltage, but also by mechanical stimuli and local cooling. To sum up, stochastic resonance and soliton emerge in correspondence of transition phases in nonlinear systems interacting within fluctuating and periodic fields in correspondence of an excitation mechanism.

1.3. Link with CVs

An association arises between the above-described theoretical approaches and Low Inertia Magnetic Accretor (LIMA) model (Warner&Woudt 2002) for what concerns DNOs and QPOs in CVs. Indeed, the same physical constraints characterizing nerve pulse propagation or promptly climate changes are implied within LIMA model where the hypothesis of an excitation mechanism - which is caused by winding up and reconnection of magnetic field lines - implies phase transition phenomena described by nonlinear solutions.

2. LIMA and QPO low-high frequency correlations

In order to pursue our task, we shall associate the physical constraints for stochastic resonance and solitons to the physical features of CVs models taken into account. We shall concentrate on two models developed in the last decade, LIMA and Alfvn Wave Oscillation model (AWO model) (Zhang et al. 2007), which give an account for the multiperiodic behaviours of Dwarf Novae (DNe) and Nova-Like variables.

2.1. LIMA and AWO model

Warner&Woudt (2002) developed LIMA model to account for DNOs in VW Hyi, by extending this interpretation to the observations of OY Car, UX UMa, V2051 Oph, V436 Cen, WZ Sge and SS Cyg. They suggest that accretion onto an equatorial belt of the accretor, whose existence was theorized by PaczyÅski (1978), causes the belt to vary its angular velocity. The rapid deceleration of the belt is attributed to propellering. For our analysis and the comparison with the AWO model, the dynamics of the deceleration zone is crucial, because it is there that a transition phase can occur. Indeed they claim that temporary expulsion, rather than accretion of gas occurs within this zone, by considering the large drop observed in EUV flux. They show that the QPOs are most probably caused by a vertical thickening of the disk, moving as a travelling wave (soliton) near the inner edge of the disk. This thickened area periodically obscures and reflects radiation from the central source and it is visible even in quite low inclination systems. Therefore they advance the hypothesis of the presence of an excitation mechanism caused by winding up and reconnection of the magnetic field.

On the other hand, Zhang et al. (2007) suggested that an empirical linear relation, spanning five orders of magnitude in frequency, exists between ν_{high} and ν_{low} of high/low frequency QPOs in black hole candidates, neutron stars and white dwarfs in binary systems. In order to determine this relation, their model ascribes ν_{high} to the Alfvn wave oscillation frequency at a preferred radius and ν_{low} to the same mechanism at another radius. In the case of CVs, ν_{high} and ν_{low} are identified as ν_{DNO} and ν_{QPO}. Apparently, a common QPO feature for a wide class of CVs and Low Mass X-Ray Binaries (LMXBs) seems to hint that the mechanism to produce this relation has no strong direct dependence on parameters such as mass, radius, spin, presence/absence of a hard surface of compact object and magnetic field; see, e.g., Mauche (2002). They suggests rather that the variation of low or high frequencies is modulated by the variation of both a compactness parameter (A) and a position parameter (X, depending on accretion rate $\dot{M}$).

2.2. Links between models

We shall relate now AWO with Warner and Woudt's model, by considering specific modulations and excitation factors.

Consider the dynamics of the equatorial belt in the context of LIMA model. Warner&Woudt (2002) suggest that the propagation of material and electromagnetic waves runs along the lines of the magnetic field $\boldsymbol{B}$ with a velocity that varies, depending on the zone, and reaching the Alfvn velocity (v_{Alf}), when moving along the magnetic field lines. The waves propagate there at a constant velocity (v_{Alf}), and they usually, but not regularly, experience a change of shape (from short to long outburst and viceversa). According to Warner&Woudt (2002):

1. the matter flow accreting on the Keplerian radius has a subsonic velocity until the waves propagate along the magnetic field lines, at a velocity $v_{Alf} \approx c$;
2. it is conceivable that QPOs with periods of hundreds of seconds could be excited by the stream overflow process;
3. LIMA model can account for frequency doubling.

It implies indeed that the frequency doubling observed in CVs can be one of the peculiar aspects of DNOs, as shown in the case of SS Cyg (Mauche&Robinson 2001) and VW Hyi (Warner&Woudt 2006). We then speculate about the possibility of a correlation between the photo-excitation process and the presence of specific molecules within the system. They could trigger frequency doubling in the transition from Horizontal Branch Oscillations (HBOs) to Flaring Branch Oscillations (FBOs) via Normal Branch Oscillations (NBOs), corresponding to the Horizontal, Flaring and Normal branch (HB, FB, NB) in the hardness-intensity diagram or in the colour-colour diagram (CD). Hasinger&Van der Klis (1989) analyzed, in the context of neutron stars, Z sources that trace, on time scales of hours to a day, roughly Z-shaped tracks (hence the name 'Z source') in CDs, consisting of three branches (HB, NB, FB) connected end-to-end (see Fig. 1). What is relevant for the present perspective is that, in that context, the curve length (defined to increase from HB via NB to FB) performs a random walk: it varies stochastically but shows no jumps. We interpret this process as the signature of stochastic resonance within the system.

As Warner and Woudt recall, three radii

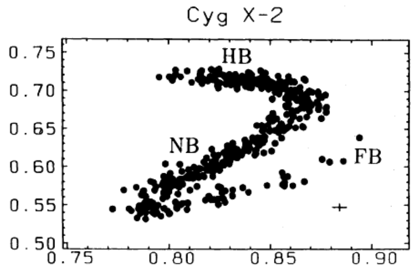

Fig. 1. CD of the Z source LMXB Cyg X-2. Hard colour: 6.4-19.1/4.6 6.4 keV, Soft colour: 3.2-4.7/0.9-3.2 keV (Hasinger&Van der Klis 1989), reproduced with permission ©ESO.

characterize the accretion from a disk into a magnetosphere (Ghosh&Lamb 1979):

- the corotation radius r_{co}, where the angular velocity Ω of the magnetosphere matches the Keplerian velocity;
- r_0, at which the magnetosphere begins to influence the fluid flow in the disk;
- r_A, where the disk flow matches the magnetospheric rotational velocity and accretion along field lines can occur.

At radii $r_A < r < r_{co}$, the disk flow speed is greater than the speed of the field lines. This has been modeled in Miller&Lamb (1992), by following Hartmann et al. (1988). Because of the different velocity between the field lines and matter flow, the former are dragged forward by the plasma, producing a spin-up torque on the primary (or its equatorial belt). Conversely, we can think of that region as one where the torque from the magnetosphere decelerates the accretion flow until it matches the magnetospheric angular velocity (Ghosh and Lamb's 'boundary layer'). This deceleration zone is a plausible site where a transition phase occurs and from which disk oscillations are enhanced. As Mahadevan (1995) suggests there is a correlation between cyclotron/synchrotron emission and Comptonization of a hot thin accretion disk. On the other hand, as Lamb suggests, there can be a deceleration in the accretion flow due to an absorbing or scattering medium and, as

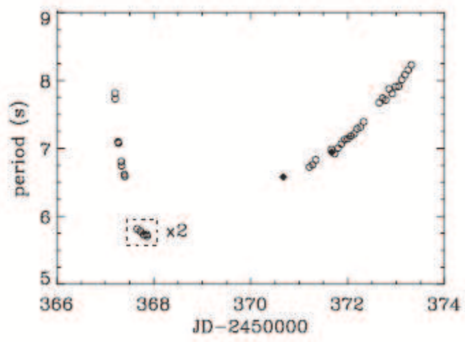

Fig. 2. DNO Period vs time plot. Boxed data are plotted at a double period and represent DNOs occurring when frequency doubling is active. Filled diamonds are UBVR data (Mauche&Robinson 2001). Reproduced by permission of the AAS.

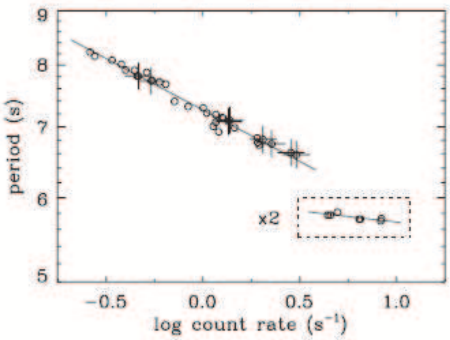

Fig. 3. DNO Period vs count rate plot. Boxed data are plotted at a double period and represent DNOs occurring when frequency doubling is active. Crosses data are from the rising branch (Mauche&Robinson 2001). Reproduced by permission of the AAS.

we shall see, this medium can be responsible for NBOs, in which frequency doubling can occur, and for deceleration in FBOs.

Thus FBOs could be the signature of a HBO caused by the flow of material on the equatorial belt. NBOs are oscillations in the optical depth of a Comptonizing flow that surrounds the accretion flow source. FBOs are often ascribed to radial inflow matter or they can be also due to the diminished emission (a dip) caused by the introduction into the line of sight to the source of an absorbing or scattering medium. The presence of this medium can attenuate the observed flux and cause QPOs (to prove this we need to confront QPOs and dips in a CV and see whether they overlap). Our proposal is that, in order to explain the frequency variation for the parameters ν_{HBO} and ν_{NBO} characterizing DNOs, one could relate the frequencies ν_{HBO} and ν_{NBO} to r_{co} and r_A, with ν_{FBO} referring to r_0. Now, Ventura (1991) [p. 451] shows that HBO and NBO frequencies entertain a correlation with X-ray intensity. He suggests two physically distinct origins for HBO and NBO, given the kinds of correlation between their frequency and the X-ray intensity. If we take NBO source to be dependent on the accretion flow source, we have to investigate the possibility of a) the presence of crystals or molecules triggering Comptonization, by acting as a fluctuating field; b) the frequency doubling generated in that zone and affecting the QPOs. An element enabling deceleration and frequency doubling could be an intrinsic source of these systems.

3. Plasma and particle physics meet astrophysics

In a recent study Kourakis et al. (2007) have shown the relationship between soliton solutions and the frequency modulation excited by the presence of fullerenes (C_{60}) in plasma. We suggest that the modulation of the frequency doubling in DNOs can be obtained through a model accounting for the QPOs spectra due to the presence of C_{60} in the accretion disk. Furthermore, we claim that soliton solutions, which can be obtained, are compatible with stochastic resonance as a final dynamical effect.

3.1. Frequency doubling

DNOs usually appear on the rising branch of the outburst and persist until the decay. Their period follows a cyclic behaviour, decreasing during the rise and increasing during the decay. Mauche&Robinson (2001) found a further peculiarity of the DNO period behaviour when they observed EUV DNO frequency doubling in the October 1996 outburst of SS Cyg. As shown in Fig. 2, frequency doubling occours half a day before the EUV outburst maximum.

Fig. 3 is significative too, where a variation of the stiffness of the period-intensity relation is reported. The exponent suddenly increases of a factor $\approx$ 5 during the doubling phase and suddenly comes back to the normal value, after the doubling phase. Mauche and Robinson refer to this event as a phase transition, which prevents the DNO period to be lower than 2.8 s, even with a very high luminosity (or, equivalently, $\dot{M}$).

So, the frequency doubling can be interpreted as a phase transition. Mauche&Robinson (2001) also propose the existence of a hysterisis cycle which determines the times of transition, but it cannot be confirmed by these data where a large gap is present.

Mauche&Robinson (2001) obtained another remarkable result in their article, not directly related to frequency doubling. They verified that optical DNOs coincide with EUV DNOs both in period and in phase. The negligible phase difference implies that optical emission either is the Rayleigh-Jeans tail of the EUV emission or comes from the inner third of the disk: this would be an anomaly, since in all CVs all the regions of the disk significantly contribute to optical emission. Moreover, optical DNOs seem to disappear when the phase transition takes place.

Frequency doubling has been observed in VW Hyi (Warner&Woudt 2006). Let us consider the differences between SSCyg and VW Hyi:

1. VW Hyi is studied in the optical, and not EUV, band; optical radiation from VW Hyi, unlike SS Cyg, is due to reprocessing, on the whole disk, of high energy radiation;
2. not only frequency doubling, but frequency tripling too is observed;
3. not only DNOs, but QPOs too experience frequency doubling/tripling;
4. only the decay phase is analyzed.

Both SS Cyg and VW Hyi show frequency doubling and they are relevant to determine if only peculiar systems undergo frequency doubling or whether it occurs in all CVs, despite of being undetectable in most of them because of a suppressed amplitude of the doubled frequency DNO (dfDNO).

If so, we have to search for a side effect of frequency doubling, to be detected even when the dfDNOs amplitude becomes too low. Maser emission is a relaxation process that we take as a candidate to be a marker of frequency doubling.

3.2. Fullerenes

As Gaudenzi et al. (2011) underline, by dealing with SS Cyg, the system shows a variable behaviour of E(B-V) due to two components. The first one is the interstellar one, the second an intrinsic one. They suggest that fullerenes and buckyonions are a reasonable source of the additional, intrinsic component. The latter is responsible for both the observed modulations with the orbital phase and for the variations during the quiescent phase. The modulation with orbital phase is caused by simply the change in orientation of the observer to the system, while the variations of the reddening with $t\%$ can be owing to a dynamic process of formation, evanescence, and escape or accretion of absorbing material. Fullerenes and buckyonions, by forming and destroying within SS Cyg system during quiescence, contribute to the observed effect of a variable reddening. It should be possible in the future to show that fullerenes and buckyonions are accreted and/or ejected during outbursts. By assuming that DNOs are clearly related to outburst cycles (Warner&Woudt 2002), we advance the hypothesis that common processes may be at the basis of outburst cycles, DNOs/QPOs properties and presence or absence of C_{60}. The fundamental observative parameter is E(B-V): it monitors the 2175 absorption bump that is believed to be caused by C_{60} and buckyonions (Iglesias-Groth

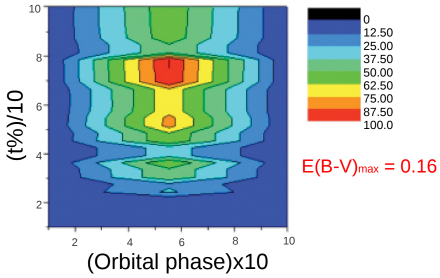

Fig. 4. $E(B-V)$ contour in the orbital phase - quiescence percentile time (Φ - $t\%$) plane. The maximum value $E(B-V)_{max} = 0.16$ *mag* corresponds to 100% of $E(B-V)$ depicted in red (Gaudenzi et al. 2011), reproduced with permission ©ESO.

2004).

As reported in Fig. 4, in SS Cyg, E(B-V) varies with both the orbital phase (Φ) and the percentile quiescence time ($t\%$). It would be interesting to investigate the relationship between C_{60} properties and the E(B-V) dependence on Φ and $t\%$. We shall briefly concentrate on the processes, which are supposed to cause dependence by $t\%$, given the lack of a complete model concerning disk viscosity. This model, indeed, is essential to account for Φ dependence. Concerning the latter, we only remark that E(B-V) takes the highest value at $\Phi = 0.50$. Therefore, C_{60} molecules could be reasonably supposed to be significantly denser in the region of the disk opposite to the secondary, whose inferior conjunction is established at $\Phi = 0.50$ by convention.

3.2.1. Dependence on $t\%$

We suppose that the variation of E(B-V) with $t\%$ involves some assembly/destruction processes of C_{60} molecules. Capture/expulsion could also play a role but at first we assume it to be secondary. In Hussein et al. 2008, a model for C_{60} fragmentation and reassembly is proposed: depending on the parameter ϵ_s (minimum energy of the single covalent bond between C atoms within a C_{60} molecule) different solid-gaseous (the liquid phase seems to be absent) phase transition temperatures are obtained. Precisely, Hussien et al. (2008) obtain a transition temperature of 5855 K, matching the temperature of an intermediate annulus of the disk. Furthermore, they found evidence for two-phase coexistence: continuous oscillation of C_{60} between a solid-like hollow cage and a gas-like state. This is what we need for both stochastic resonance and soliton propagation: the presence of two equilibrium states. When noise enhances the phase transitions, the chaoticity of coexistence is broken and a more coherent state (where one of the two phases is dominant) is reached.

4. Conclusions

Stochastic resonance and soliton solutions are key-concepts that can enrich the scenario of theoretical models, not only in the domain of astrophysics, but also in other branches of physics. We shall investigate in future studies whether our approach could on one hand throw light on the role played by fullerenes within CVs and clarify on the other phenomena occurring in DNOs as frequency doubling or tripling: indeed they could be the sign of a transition phase which, we speculate, can be also revealed by the presence of a side effect that we provisionally identify with maser emission.

Acknowledgements. We are pleased to thank Dr. G. Hasinger, Dr. M. Van der Klis, Dr. C. W. Mauche and Dr. E. L. Robinson for authorizing us to use the pictures n. 1, 2 and 3.

References

Appali R., Petersen S., van Rienen U., 2010, Adv. Radio Sci., 8, 7579
Benzi R., 2010, Nonlinear Proc. Geoph., 17, 431
Benzi R., Sutera A., Vulpiani A., 1981, J. Phys. A: Math. Gen., 14, L453-L457
Benzi R., Parisi G., Sutera A., Vulpiani A., 1982, Tellus, 34, 10
Battisti A., Lalopa R. G., Tenenbaum A., D'Alessandro M., 2009, PhRvE, 79, 046206
Brodin G., Marklund M., 2007, PhPl, 14, 112107

Gaudenzi S., et al. 2011, A&A, 525, 147
Ghosh P., Lamb F. K., 1979, ApJ, 232, 259
Hasinger G., Van der Klis M. 1989, A&A, 225, 79
Hartmann D., Woosley S. E., Arons, J., 1988, ApJ, 332, 777
Heimburg T., 2010, eprint arXiv:1008.4279
Heimburg T., Jackson A. D., 2005, Proc. Natl. Acad. Sci. USA, 102, 97909795
Hodgkin A. L., Huxley A. F., 1952, P. Roy. Soc. Lond. B Bio., 140, 177
Hussien A., Yakubovich A., Solov'yov A., Greiner W. 2008, eprint arXiv:0807.4435
Iglesias-Groth S., 2004, ApJ, 608, L37
Kourakis I., Verheest F., Cramer N. F., 2007, Phys. Plasmas, 14, 022306
Mahadevan R., 1995, astro-ph/9509138, A&A submitted
Mauche C. W., 2002, ApJ, 580, 423
Mauche C. W., Robinson E. L., 2001, ApJ, 562, 508
Miller G., Lamb F. K., 1992, ApJ, 388, 541
PaczyÅski, B. 1978, in *Nonstationary Evolution of Close Binaries*, ed. A. Zytkov (Warsaw: Polish Sci. Publ.), 89
Prez-Garca V. M., Calvo G. F., Belmonte-Beitia J., Diego, D., Prez-Romasanta L., 2011, eprint arXiv:1103.1461
Shukla P. K., Stenflo L. Tsintsadze L. N., Tsintsadze N. L., 2002, PhPl, 9, 3625
Ventura J., 1991, in *Neutron Stars: Theory and Observation*, Springer
Warner B., Woudt P. A., 2002, MNRAS, 335, 84
Warner B., Woudt P. A., 2006, MNRAS, 367, 1562
Zhang C. M., Yin H. X., Zhao Y. H., 2007, PASP, 119, 393