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Stellar flaring periodicities

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Abstract. Long term monitoring of the radio flux density of a sample of cool, rapidly rotating stars in binary systems has revealed periodicities in their flaring activity. In one system, V773 Tau A, the flaring periodicity is caused by inter-binary collisions of large magnetic structures like solar helmet streamers. In another system, UX Arietis, the flaring periodicity depends on an intrinsic mechanism originating in the stellar interior, that implies preferred areas for the (periodical) emergence of magnetic flux tubes. The periodical interaction between old and new flux tubes triggers magnetic reconnection and periodical flares. Connecting that behaviour to the Sun, the Rieger periodicities (solar cycles with a time scale of months) are reviewed.

Key words. Stars: activity – Stars: coronae – Stars: radio emission – Stars: flares

1. Introduction

The solar magnetic field in the inner corona is dominated by loops. These are arc-like structures, reaching a typical height of 0.1 $R_{\odot}$, and having a pair of sunspots as photospheric footprints. In the outer corona, on the contrary, one finds filamentary, open or ray-like structures. Intermediate structures are represented by the helmet streamers: semi-open configurations extended over several solar radii (Endeve et al. 2004; Suess & Nerney 2004).

The nature of the corona is dynamic and variable. TRACE images (e.g., see Fig. 2 in Harra, this volume) show magnetic structures continuously emerging from the surface. When the emersion of a new loop occurs in an area, where already other magnetic structures are located, the new loop interacts with the older ones. Such a loop-loop interaction causes magnetic reconnection and the sudden release of magnetic energy triggers a flare observable across the whole electromagnetic spectrum. Examples of such intruding loops at radio wavelengths are shown in the high-resolution images of the Nobeyama Radio Interferometer (Nishio et al. 1997).

The issue we want to address in this review is: Are these loop-loop collisions casually occurring or are they due to recurrent, and hence predictable, physical processes ?

Sunspots are the footprints of the interacting magnetic loops, therefore sunspots and flares are related to each other: Any eventual periodical flaring activity of that kind must imply a similar periodicity in the spot occurrence. Well known is the 11-yr periodicity of sunspots. Here we review much shorter, spot/flare periodicities, with timescales of months. In the first part of this paper we will examine flaring periodicities that can be considered "intrinsic", that is inherent to physical processes occurring in the interior of the star.

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These processes cause a periodical emersion of magnetic flux tubes always in the same area of the stellar surface causing periodical loop interactions and therefore periodical flares. In the second part we will analyze an additive cause of flaring periodicity that may occur in binary stellar systems. Also in this case, the flares depend on magnetic interactions, but "external" to the star. The interacting magnetic structures, extended coronal streamers, in fact belong to two distinct stellar coronae.

2. Intrinsic Stellar Flaring Periodicities

2.1. Solar Rieger Periodicities

In the past, several researchers reported (see Rieger, this volume) on hints of periodicities in the solar flaring activity, but it was not until 1984 that Rieger and collaborators discovered a clear periodicity of 154 days in the occurrence of γ-ray solar flares (Rieger 1984). The folding of γ-ray data with this period showed that, whereas some flares occurred at any phase, a good fraction of them, i.e., 35%, occurred periodically.

After this historical discovery, Rieger-like periodicities, that are periodicities of a few months only, have been confirmed not only in flares in X-rays (Rieger 1984), Hα (Ichimoto et al. 1985) and at radio wavelengths (Bogart 1985) and over the whole electromagnetic spectrum, but also in coronal mass ejections (Lou et al. 2004), in variations of the solar neutrino flux (Sturrock et al. 1999), in daily sunspot numbers (see discussion below), and even in variations of the horizontal solar diameter (Delache et al 1985; Ribes et al. 1989). The Rieger periodicities are the results and the signposts of fundamental processes occurring in the stellar interior.

If large periodical flares occur because of interaction of successive (periodically) emerging loops, then the same periodicity should appear in the sunspot occurrence. Starting with this basic assumption, several researchers begun to re-analyze sunspot archives, focusing on shorter periodicities than that well known of 11-yr. The available archives of sunspot data consist of both sunspot areas and group sunspot numbers. In the first case the area of a sunspot is measured in a fraction (millionth) of the Sun's visible hemisphere. The second method deals with the fact that sunspots usually appear in groups. Normally, it is easy to count the number of groups as they are spread out across the disk. Difficulties occur, if sunspots appear close together. Whereas the analysis of these two solar archive data revealed Rieger Periodicities in both sunspot areas and groups (Oliver et al. 1998, Ballester et al 1999), it also became evident that the two periodicities are not always simultaneously present.

Ballester and collaborators (1999) notice, in which way there are two forms of periodical emergence of magnetic flux:

1. In some solar cycles, sunspot groups show up periodically, but every time in different regions. As a result of this first form of periodicity there is a simultaneous increase of both the total sunspot area and the group sunspot number and Rieger periodicities are present in both data sets.
2. During other solar cycles the emergence of the magnetic flux tubes remains confined in about the same areas. The emergence enhances the magnetic complexity (area) of sunspot groups, but not the number. Rieger periodicities are determined in sunspot areas, confirming a periodical emergence, but cannot be clearly determined in sunspot groups.

Rieger flaring periodicity was discovered in the solar cycle 21. In this cycle the same period was determined in sunspot areas, but not in sunspot groups. Ballester and coauthors (1999) point out that for having flaring periodicities, two conditions must be met: *i*) there must be the same periodicity in the emergence of magnetic flux tubes, and *ii*) the emergences must occur in the same area of the solar surface, so that successive emergences can cause periodical loop-loop collisions and hence periodical flares.

The search for Rieger periodicities has strong connections with two other fields of research: that one of preferred longitudes and that one of solar r-modes. That the sunspots emerge at particular latitudes is well known: during the 11-year cycle sunspots appear within an equatorial belt of about ±35° (Holzwarth this volume). In the last years one found evidence for a confinement also in longitude. Large sunspot groups are formed around preferred longitudes persistent over years and indicate the presence of a non-axisymmetric dynamo mode (Berdyugina this volume). The existence of these preferred longitudes can clearly be seen only if changes of the latitude of the sunspot formation in the 11-year cycle and differential rotation are taken into account. Both effects cause a smearing of the active longitude pattern (Berdyugina this volume).

The modulated emergence of the magnetic flux tubes to the surface, causing the Rieger periodicity, might be induced by Rossby-type waves, a particular case of r-modes (Sturrock et al. 1999, Lou 2000, Sturrock 2003). As a matter of fact, the detection of 100 m high hills in the solar photosphere with the Michelson Doppler Imager on board of SOHO by Kuhn et al. (2000), has been interpreted as the photospheric signature of long-period r-modes.

Discovered in 1984 and not yet fully understood the Rieger flaring periodicity has been considered a solar peculiarity. In reality, it is a more general stellar phenomenon. This is indicated by the fact that similar periodicities have been observed on another stellar system, UX Arietis (next section) and also by the fact that other active stars indeed show preferred longitudes for spot formation (Berdyugina this volume).

2.2. The Active Star in UX Arietis

The system UX Arietis belongs to the RS CVn class: tightly-orbiting binary systems, consisting of an F or G type dwarf and a G or K type sub-giant. The components of RS CVn systems are fast rotators due to the strong tidal interaction that tend to synchronize the stellar spins and orbital motion. Quite extended (covering up several percents of the stellar surface) cool spots (Strassmeier this volume) on the more active star of the system and intense X-rays and radio flares are observed (Hall 1976; Owen et al. 1976; Budding et al. 2002).

The spots on the active star of the system UX Arietis (K0 IV star) are persistent but quite variable (Elias et al. 1995; Gu et al. 2004). Figure 1 shows 30 yr photometric V observations of UX Ari by Aarum Ulvas & Henry (2003). Variations of the extended, cool spots on the surface of the cool primary component induce variations in the light curve up to 0.3 mag in 30 yrs. The possibility of long-term (yr) periodicities similar to the solar 11-yr are discussed by Aarum Ulvas & Henry (2003). Here, we address the issue of possible short-term (months) cycles.

Wavelet analysis decomposes a one-dimensional time series into a two-dimensional time-frequency space and displays the power spectrum in a two dimensional color-plot, presenting how the Fourier periods (y) vary in time (x) (Torrence & Compo 1998). The Morlet wavelet results are presented in Fig. 1 bottom. The power of the frequency component is in arbitrary units (the color red stands for the dominant one). A dominant periodicity is evident in the range 256-512 days (red area) in the time interval 4500-7000 days. Unfortunately no radio data are available in this time interval. However, even if with less power, the period is present also in the interval 7500−11000, and this interval of 9 years is covered by radio observations as well. Fig. 2 a shows the last 9 years of the optical data expanded, Fig. 2 d the simultaneous radio observations. Periodicities in the range 256-512 days for both radio and optical data are evident (red area). The black contour lines give the 95% significance level obtained by assuming a red noise background spectrum (Torrence & Compo (1998)).

The data have been further analyzed with the Phase Dispersion Minimization method and a period of 294 days was found to be the best common period for both data sets (radio and optical data) (Massi et al. 2005). Figure 3 presents the two 9-year datasets folded with P=294 days. First, all phase intervals (see Fig. 3) are filled with data and no obvious lack of data is present in the curves. Second, optical data (Fig. 3 top) show a maximum (i.e.,

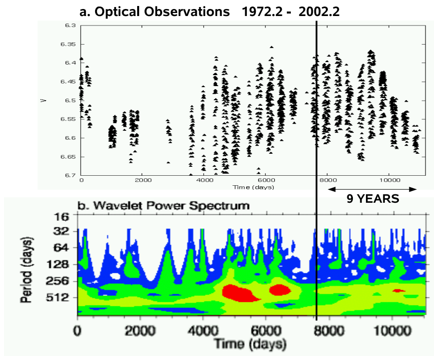

Fig. 1. Top: Photometric V observations from Aarum Ulvås & Henry (2003) over 29 years of the stellar system UX Arietis. Bottom: Time/period diagram from wavelet (Torrence & Compo (1998)) analysis of the data. The power is in arbitrary units with the red colour for the dominant one Most of power is in the range 256–512 days. The last 9 years are given expanded in Fig. 2a and their wavelet analysis in Fig. 2b.

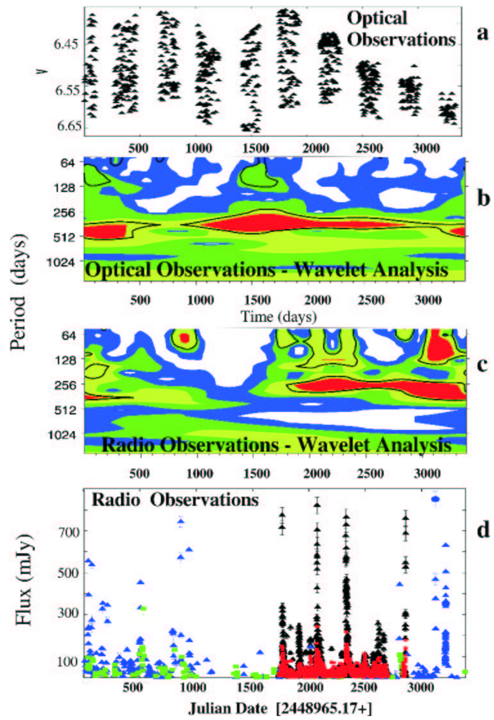

Fig. 2. 9 years of radio and optical measurements (1992.9-2002.2) and their corresponding wavelet spectra. The x-axis of all figures is the same and equal to the Julian Date [JD−244896 5.17] (Massi et al. 2005). Dominant periodicities for both radio and optical data are evident in the range 256-512 days (red area).

a minimum spot coverage) at phase Φ=0.4 exactly where the radio data (Fig. 3 bottom) show a minimum (i.e. minimum in flaring activity). This remarkable relationship between two completely independent curves strongly support the real existence of the 294-day cycle found in the timing analysis.

A short term cycle, like the Rieger cycle, therefore is present in UX Arietis, in both spots and flare occurrence. During the initial phase (>0.4) of the cycle, the spotted surface progressively increases. Therefore new magnetic structures emerge at the stellar surface. Since flares are observed (phase 0.6-1.2), this implies that the new and older magnetic structures interact with each other. That means, there must be an overlap in their emergence area. At the peak of the optical curve (Φ = 0.4, 1.4) where the spot activity is minimum, the flaring activity dramatically stops.

We conclude that the process invoked for the Sun of a periodical emergence of magnetic flux in preferred areas may also be applied to UX Arietis and can explain the cyclic flaring activity triggered by interactions between successive cyclic emergences of magnetic flux in the same area.

3. Binary Interaction: V773TAu

The system V773 Tau A is a weak-line T Tauri binary system with an orbital period of 51.075 days (Welty 1995) and a moderately eccentric orbit (e=0.3) (Fig. 4).

3.1. Interbinary Collisions: Giant Coronal Structures

V773 Tau A shows observational evidence for very large coronal structures, extending at least 12 R_*. This evidence comes from three different observing methods of the radio emission.

The first method consists of a long (522 days) monitoring of the flaring activity. The Fourier power spectrum of the data, shown in

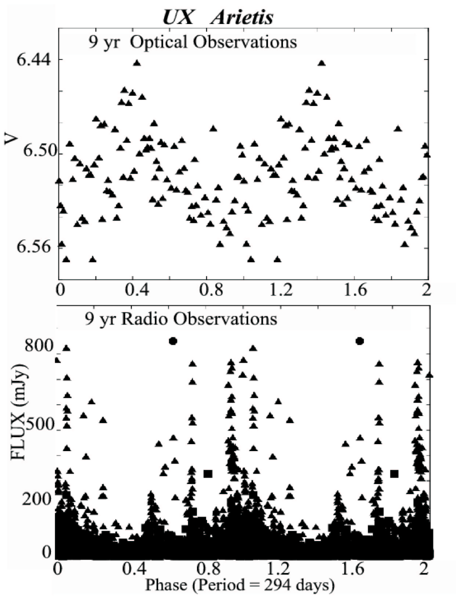

Fig. 3. Bottom: Folding of the radio data with a period of 294 days. The phase interval 0–1 is repeated twice. There is a clear lack of energetic flares at Φ=0.4. Top: Folding of the photometric V data with the same period of 294 days, as the radio data. The data are averaged over phase bins of 0.01. The peak for V at Φ=0.4 corresponds to a minimum in spot coverage and is well synchronized with the "hole" of radio flaring activity (Massi et al. 2005).

Fig. 5, gives a dominant peak at 52 ± 5 days, which is consistent with the orbital period. By folding the data (Fig. 6) with the orbital period, the clustering of the flares result to be at periastron passage (Massi et al. 2002). The detailed monitoring around one periastron passage reveals a modulation of the radio emission consistent with the rotational period (3 days) of the star. A scenario compatible with the 52 days periodicity (the orbital period) and the ≃ 3 days modulation (the stellar rotation), is that of giant loops anchored on the two stars and interacting at each rotation. The level of interaction increases if the stars get closer, and reaches its maximum around periastron passage. The periastron separation is 56 solar radii, $R_\odot$, which for a stellar radius, $R_* = 2.4\ R_\odot$ (Welty 1995), corresponds to 23 R_*. Producing the observed flares either one star owns structures of 23 R_*

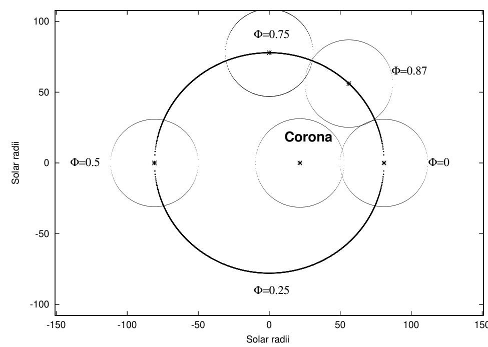

Fig. 4. Sketch of the binary system V773 Tau A . The orbit parameters are those of table 2 by Welty (1995). One star is plotted in the focus of a slightly eccentric orbit (e=0.3), the other star is shown at its four different positions along the orbit. Magnetic coronal structures (here simplified as spheres), extending several stellar radii (1 $R_* = 2.4 R_\odot$, interact and produce strong flares around periastron passage (Massi et al. 2002).

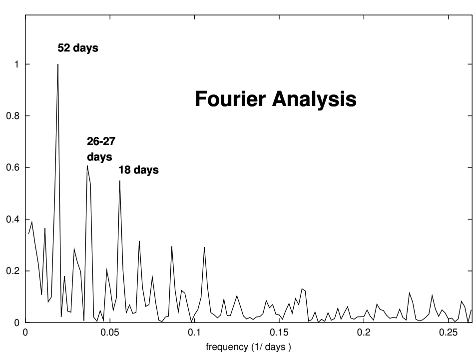

Fig. 5. Fourier power spectrum of the radio observations of V773 Tau A . The dominant peak is at 52±5 days and consistent with the orbital period 51.075 days (Welty 1995). The second peak (corresponding to 27.4±1.4 and 25.9±1.3 days) could be one harmonic of the dominant peak. The third peak at 17.9±0.6 days is a mode interaction feature: $\frac{1}{\frac{1}{52}+\frac{1}{27.4}} = 17.9$ and disappears when the Phase Dispersion Minimization method (Stellingwerf 1978) is used instead of the Fourier analysis (Massi et al. 2002).

or, if one assumes similar stellar coronae, both stars have structures of about 12 R_*.

The second observing method showing large structures in the system V773

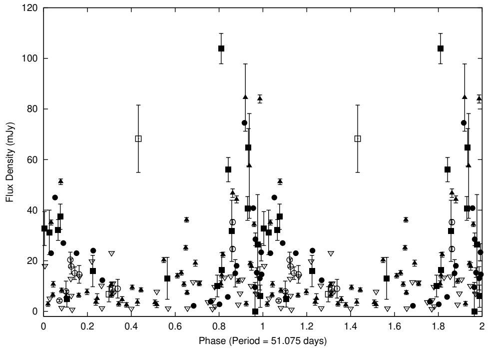

Fig. 6. Radio observations of V773 Tau A folded with the orbital period of 51.075 days. Phase 0 (1, 2) refers to the passage at periastron.

Tau A is direct imaging by Very-Long-Baseline Interferometry. Phillips et al. (1996) observing close to periastron passage mapped an halo with two peaks of different intensity separated by 0.17 AU (15 R_*).

The third method proving large structures is the study of the onset of a flare. A complete flare (Fig. 7) was observed at periastron passage with the IRAM Plateau de Bure Interferometer (Massi et al. 2006). In a scenario, in which reconnection takes place far out where the two stars' magnetospheres interact (i.e. at H_1), the shock induced by magnetic reconnection can propagate down to H_0 along the magnetic structure at the local Alfvén velocity

$$v_A(H) = \frac{B(H)}{\sqrt{4\pi m_H n(H)}} \simeq 7\,10^9 \left(\frac{H}{R_*}\right)^{-2} \text{ cm/s} \quad (1)$$

(for a dipole magnetic field with $B(R_*) = 1000$ G and a particle density $n \sim 10^9 (H/R_*)^{-2}$ cm^{-3}), thus inducing successive particle acceleration events. The shock propagation speed can be related to the flare rise time, $t_{\rm rise}$,

$$t_{\rm rise} = \int_{H_0}^{H_1} \frac{dH}{v_A(H)}, \quad (2)$$

For $t_{\rm rise}$, $\simeq$ 4.5 hours and H_0 of 1 R_*, the resulting height H_1 is of 13 R_*.

All three methods point to a structure $\geq$ 12 R_*. This is much larger than X-ray emitting coronal loops. Skinner et al. (1997) interpreted the light curve of a hard X-ray flare in V773 Tau A as the rotational modulation of the emitting flaring region, and determined a size of $H \leq 0.6\,R_*$. Tsuboi et al. (1998) interpreting the decay of another hard X-ray flare due to radiative cooling, obtained a size of $1.4\,R_*$. In both cases, the X-ray emission traces much smaller regions than the radio one. In addition, the multiwavelength campaign on V773 Tau A carried out by Feigelson et al. (1994) showing radio variability combined with a steady X-ray flux, further confirms the presence of two different structures.

3.2. Leakage of Electrons: Semi-Open Coronal Structures

There is an additional difference between radio- and X-ray emitting regions, besides the difference in size. As discussed below, there are hints of leakage of the particles responsible for the radio emission indicating a partially open configuration.

The decay of the flare, shown in Fig. 7, clearly shows that the emitting electron distribution, responsible for the observed radio synchrotron emission, is subject to some losses. However, the decay time of 2.31 hours is not attributable to synchrotron losses. For synchrotron losses of the emission of electrons trapped in a structure of 12 R_* being responsible for a decay time of only two hours one should assume a photosperic magnetic field two orders of magnitude higher than the few kG usually observed in T Tauri stars. On the other hand collisional losses cannot account for the observed decay time, since collisions are important only for high density plasmas in contrast to the upper limit on the plasma density < 10^9 cm^{-3} derived from Faraday depolarization (Phillips et al. 1996). Finally, also inverse Compton losses cannot account for the rapid decay, for a T Tauri star (Massi et al. 2006).

Since the fast decay of the emission cannot be attributed to energetic losses of the electrons, it might be caused by the leakage of the particles themselves, i.e. the electrons are able to leave the trapping region and escape into free space. Particles remain trapped in magnetic structures, if spiraling around field

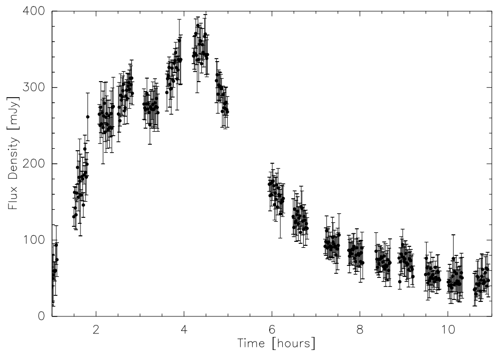

Fig. 7. V773 Tau A flare at $\lambda = 3$ mm (Massi et al. 2005).

lines reach a point (the "mirror point"), where the magnetic field lines converge and the field strength is sufficient to cause the particles to reverse direction and travel back to the other mirror point. A magnetic mirror point is incapable of trapping charged particles which are moving parallel, or nearly parallel, to the direction of the magnetic field. In Massi et al. (2006), we model the magnetic configuration as two mirror points at a distance of about 10 R_* one from the other. Already this simple model is able to reproduce the fading of the emission in about 2 hours by electron leakage during each reflection at the two mirror points.

Looking for a solar analogy of an extended semi-open structure, helmet streamers are the ideal candidates.

4. Conclusions

The main results on flaring periodicities are the following:

1. There exist intrinsic stellar flaring periodicities. They have been observed on the Sun and on the system UX Arietis. They are connected with middle-term (months) periodicities in flux emergence. The emergence occurs in preferred areas. The factor triggering periodic flares therefore is magnetic reconnection between old and new periodically emerging magnetic fluxes in preferred areas
2. An additional cause of flaring periodicity may occur in binary stellar systems. Also in this case the flares are due to magnetic reconnection events associated to the interaction of magnetic structures, but the interacting magnetic structures belong to the two distinct stellar coronae. The most likely explaination for such interacting magnetic structures are helmet streamers, semi-open structures extending over several stellar radii.

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