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Stellar flare diagnostics from multi–wavelength observations

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Abstract. Quasi–periodic pulsations in various wavebands are natural manifestations of emission of stellar flares. We suggest a diagnostic tool of stellar flares based on the coronal seismology and the solar–stellar analogy. Two approaches are used: (I) flare loop as a resonator for MHD oscillations and (II) flare loop as an equivalent electric circuit. Using optical, X–ray, and radio data we obtained flare plasma parameters for the red dwarfs EQ Peg, AT Mic, and AD Leo. The characteristic length of stellar flare loops $l \sim R_\star$ and their electric currents turned out to be one–two orders of magnitude lager than the solar ones. Advantages of proposed diagnostics in comparison to the scaling law methods are given.

Keywords. stars: late–type, flare, plasmas, magnetohydrodynamics, oscillations, coronae

1. Introduction

Cool dwarf stars are the dominant stellar component of the Galaxy. According to the Sloan Digital Sky Survey more than 50% of stars between M4–M9 have the high level of the magnetic activity (West *et al.* 2004).

Observations show that in contrast to solar flares the visual luminosity of such stars can increase by several orders of magnitude and their emission is often at a maximum in the optical wavelength range. Nonetheless, there is currently much evidence for a common origin of the flare energy release on the Sun and these stars (Gershberg 2005).

The main structural elements of the solar corona are magnetic loops. According to the universally accepted scenario of solar flares, accelerated particles precipitate at the footpoints of coronal loops (magnetic traps). As a result, the heated dense plasma of the lower atmosphere emits in Balmer lines and in the optical continuum, whereas its hottest part with a temperature $T = 10^7 - 10^8$ K, while evaporating, fills the loop structure and radiates in the UV and soft X–ray ranges. Microwave emission is determined by non–thermal electrons of the coronal magnetic trap.

Scaling law methods based on the consideration of the energy balance in a flare loop are usually used for the flare plasma diagnostics (e.g., Haisch 1983). Meanwhile such approach has serious disadvantages. For example, it is usually suggested that the thermal flux at the footpoints is equal to zero. As a result of this crude approximation as well as a large number of unknown parameters the estimates obtained by many authors differ markedly. Therefore, the methods of coronal loop diagnostics on flare stars should be developed.

2. Flare plasma diagnostics

Two approaches are used for diagnostics of flare loops based on coronal seismology. According to the first approach a flare loop is considered as a resonator for MHD oscillations. The second one results from the analogy between a flare loop and an equivalent electric RLC–circuit. Let us consider these models in more detail.

Sausage modes and phase relations Equations described the linear oscillations in of the magnetic tube are (Roberts, 1995)

$$\frac{\partial \delta P}{\partial t} = \rho v_A^2 \frac{\partial \delta v_z}{\partial z} - \rho_0 (v_A^2 + c_s^2) \nabla \cdot \delta \mathbf{v}, \tag{1}$$

$$\rho \left(\frac{\partial^2}{\partial t^2} - v_A^2 \frac{\partial^2}{\partial z^2} \right) \delta \mathbf{v}_\perp + \nabla_\perp \frac{\partial \delta P}{\partial t} = 0, \tag{2}$$

$$\rho \left(\frac{\partial^2}{\partial t^2} - c_T^2 \frac{\partial^2}{\partial z^2} \right) \delta v_z + \frac{c_T^2}{v_A^2} \frac{\partial}{\partial z} \left(\frac{\partial \delta P}{\partial t} \right) = 0, \tag{3}$$

where the standard notation is used, $\delta P = \delta p + B\delta B/4\pi$ is the disturbance of the total pressure and c_T is the cusp velocity.

In the case of harmonic oscillations

$$\left(\frac{\partial}{\partial t^2} - v_A^2 \frac{\partial^2}{\partial z^2} \right) \delta \mathbf{v}_\perp = \alpha_1 \delta \mathbf{v}_\perp, \quad \left(\frac{\partial}{\partial t^2} - c_T^2 \frac{\partial^2}{\partial z^2} \right) \delta v_z = \alpha_2 \delta v_z,$$

where α_1 and α_2 are real numbers, using (2) and (3), we have

$$\delta \mathbf{v}_\perp = -\frac{1}{\alpha_1 \rho} \nabla_\perp \frac{\partial \delta P}{\partial t}, \quad \delta v_z = -\frac{1}{\alpha_2 \rho} \frac{c_T^2}{v_A^2} \frac{\partial}{\partial z} \left(\frac{\partial \delta P}{\partial t} \right). \tag{4}$$

For standing waves, which are formed due to reflection of eigen–modes of coronal loops from the photosphere, assuming $\delta P \propto f(r) \exp(-i\omega t + im\varphi) \sin kz, \quad m = 0, 1, 2, \ldots,$ equations (4) give

$$\delta v_r \propto \frac{i\omega}{\alpha_1} \frac{\partial f(r)}{\partial r} \sin kz, \quad \delta v_\varphi \propto -\frac{\omega m}{\alpha_1} f(r) \sin kz, \quad \delta v_z \propto -\frac{\omega k f(r)}{\alpha_2} \cos kz. \tag{5}$$

As follows from equations (5) the phase shift on kz between components of velocities $\delta v_\perp$ and δv_z is $\pi/2$, and when $\delta v_\perp = 0$, then $\delta v_z \neq 0$, and vice versa. It means that sausage modes can not be excited in coronal loops with freezing footpoints, where $\delta v = 0$. However, this problem does not arise, if the ratio of amplitudes $|\delta v_z|/|\delta v_\perp|$ will be negligibly small.

Using equations (1)–(3), the Hain–Lüst equations, and equation for amplitude of sausage modes ($m = 0$), we can obtain (Tsap 2006)

$$\frac{|\delta v_z|}{|\delta v_r|} \approx \frac{ka}{\eta_0} \frac{\beta}{1+\beta}, \tag{6}$$

where $\eta_0 \approx 2.4$ is the first of the Bessel function J_0, the plasma parameter $\beta = 8\pi n T/B^2$. Equation (6) suggests that excitation of sausage oscillations in the thick ($l \sim a$) magnetic tubes with $\beta \sim 1$ is the problem since oscillations must be damped very quickly because of violation of freezing-in conditions of loop footpoints into the photosphere.

Mathiodakis *et al.* (2006) proposed that ten seconds oscillations from EQ Peg, observed with William Herschel Telescope, are caused by non–leaky sausage modes and got flare parameters using Haisch's scaling laws (Haisch 1983). However, these modes can be excited only in the thick magnetic flux tubes(Stepanov *et al.* 2005), and taking

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values adopted by Mathiodakis *et al.* (2006), from (6) we obtain $|\delta v_z|/|\delta v_r| \approx 0.2$. These oscillations are impossible due to freezing footpoints of a loop.

From MHD equations for sausage oscillations, assuming that the modulation depth M is determined by the flux of precipitated electrons towards the loop footpoints and Q–factor is determined by the electron thermal conductivity and ion viscosity, we have derived relations for the temperature, plasma density, and magnetic field (Stepanov *et al.* 2005)

$$T \approx 1.2 \times 10^{-8} \frac{\tilde{r}^2 M}{T_p^2 \chi}, \quad n \approx 3.49 \times 10^{-13} \frac{\tilde{r}^3 \tilde{\kappa} M^{5/2} Q \sin^2\theta}{T_p^4 \chi^{3/2}},$$

$$B \approx 3.81 \times 10^{-18} \frac{Q^{1/2} \tilde{r}^{5/2} \tilde{\kappa}^{1/2} M^{5/4} \sin\theta}{T_p^3 \chi^{5/4}}, \tag{7}$$

where $\theta = \arctan(k_\perp/k_\parallel)$ is the angle between the direction of the magnetic field $\mathbf{B}$ and the wave vector $\mathbf{k}$, $\tilde{r} = 2\pi a/\eta_0$, $\chi = 20/3\beta + 2$, $\tilde{\kappa} = 486\beta\cos^2\theta + 1$. According to flare optical oscillations observed on EQ Peg by Mathioudakis *et al.* (2006), $T_p \approx 10$ s, $M \approx 0.1$, and $Q \approx 30$. Suggesting the aspect ratio $a/l = 0.1$ and $\theta = \mathrm{arctg}(\eta_0 l/\pi a) = 76°$, radius of the loop cross section $a = 10^9$ cm, according to (7), we have $T \approx 6 \times 10^7$ K, $n \approx 2.7 \times 10^{11}$ cm^{-3} $B \approx 540$ G. These estimates are distinguished from values determined on the basis of Haish's scaling laws and adopted by Mathioudakis *et al.* (2006) ($n = 4 \times 10^{12}$ cm^{-3}, $B = 1100$ G).

Slow magnetoacoustic oscillations and X–ray pulsations Mitra–Kraev *et al.* (2005) presented soft X–ray observations with XMM–Newton, which revealed damped flare oscillations from the red dwarf AT Mic with a period $T_p = 750$ s and an exponential damping time $\tau \approx 2000$ s.

Using X-ray spectra and a multi–temperature model, Raassen *et al.* (2003) estimated for this event a flare temperature of $T \approx 2.4 \times 10^7$ K and an electron density of $n \approx 4 \times 10^{10}$ cm^{-3}. Therefore we can compare these results with results obtained by the coronal seismology method.

It is easy to show that damping of slow magnetoacoustic oscillations is determined by the electron thermal conduction and the damping rate is (Stepanov *et al.* 2006)

$$\frac{1}{\tau} \approx 75.6 \frac{T^{3/2}}{T_p^2 n} \ [\mathrm{s}^{-1}]. \tag{8}$$

At $T \approx 2.4 \times 10^7$ K, $T_p \approx 750$ s, and $\tau = 2000$ s, equation (8) gives the number density $n \approx 3.2 \times 10^{10}$ cm^{-3}. This is in good agreement with estimate of Raassen *et al.* (2003), which were found by an independent technique from X–ray spectra.

Pulsating microwave emission from AD Leo and LRC–circuit Zaitsev *et al.* (1998), taking into account the generalized Ohm's law, have established that a current–carrying magnetic loop can be considered as a LRC–circuit. The global electrodynamics equation, described electric current fluctuations of a loop $|\tilde{I}| \ll |I|$ has the form

$$\frac{1}{c^2} L \frac{\partial^2 \tilde{I}}{\partial t^2} + R(I)\frac{\partial \tilde{I}}{\partial t} + \frac{\tilde{I}}{C(I)} = 0, \tag{9}$$

where the circuit inductance and the effective capacity of a loop are

$$L = 4l \ln\left(\frac{4l}{\pi a} - \frac{7}{4}\right), \quad C(I) = \frac{4\pi a^4 \rho}{l(4I^2 + c^2 a^2 B_z^2)}.$$

When $I \gg caB_z/2$, at $n = 10^{10}$ cm^{-3}, $l = 10^{10}$ cm, $S = \pi a^2 = 10^{18}$ cm^2, from (9) we

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have

$$T_p = \frac{2\pi}{c}\sqrt{LC(I)} \approx 10\left(\frac{10^{12}A}{I}\right) \ [s]. \tag{10}$$

Bastian *et al.* (1990) observed on the May 4, 1987 the stellar flare on the AD Leo with the Arecibo radio telescope at 21 cm and revealed quasi–periodic pulsations with $T_p \approx 0.7$ s. Since the Q—factor of this oscillations was very high ($\gtrsim 200$) they could not be caused by magnetoacoustic modes of coronal loop because of strong dissipation. This suggests that the origin of observed pulsations is connected with fluctuations of $\tilde{I}$ in the current–carrying loop and, according to equation (10), the value of electric current $I \approx 10^{13}$ A, which is about two orders of magnitude higher than the typical value on the Sun. It should be noted that the similar high–Q oscillations with $T_p \approx 2$ s were also revealed on the May 19, 1997 at the Effelesberg radio telescope (Zaitsev *et al.* 2004). Using equation (10), we obtain $I \approx 5 \times 10^{12}$ A for this event. Hence, the electric currents in the stellar flares are one–two orders larger compared to the solar ones.

3. Conclusions

- Pulsations in the radio, optical, and X-ray emission are natural manifestations of the stellar flare activity.
- Coronal seismology is a powerful tool for the plasma and magnetic field diagnostics of flaring stars.
- Stars have stronger magnetic fields and more active surface convection in comparison with the Sun.
- Red dwarfs coronae are "dense packed" by hot coronal loops.
- Scale of the flare loops are comparable with the red dwarf radiuses.
- To comprehend physics of stellar activity more multi–wavelength observations are needed.

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References

Bastian T. S., Bookbinder, J., Dulk, G. A., & Davis, M. 1990, *ApJ*, 353, 265

Gershberg, R. E. 2005, *Solar-type activity in main-sequence stars* (Berlin: Springer)

Haisch, B. M. 1983, in: P. B. Byrne & M. Rodono (eds.), *IAU Colloq. 71: Activity in Red–Dwarf Stars*, (D. Reidel Publishing Co.), 255

Mathioudakis, M., Bloomfield, D. S., Jess, D. B. *et al.* 2006, *A&A*, 456, 323

Mitra-Kraev, U., Harra, L. K., Williams, D. R., & Kraev, E. 2005, *A&A*, 436, 1041

Raassen, A. J. J., Mewe, R., Audard M., & Güdel, M. 2003, *A&A*, 411, 509

Roberts, B. 1995, *in Advances in Solar System Magnetohydrodynamics*, eds. E. R. Priest and A. W. Hood (Cambrige: Cambrige University Press), 105.

Stepanov, A. V., Kopylova Yu. G., Tsap, Yu. T., & Kupriyanova, E. G. 2005, *Astron. Lett.*, 31, 612

Stepanov, A. V., Tsap, Yu. T., & Kopylova, Yu. G. 2006, *Astron. Lett.*, 32, 569

Tsap, Yu. T. 2006, *Kinematika i Fizika Nebesnykh Tel*, 22, 40.

West, A. A., Hawley, S. L., Walkowicz, L. M. *et al.* 2004, *AJ*, 128, 426

Zaitsev, V. V., Stepanov, A. V., Urpo, S., & Pohjolainen, S. 1998, *A&A*, 337, 887

Zaitsev, V. V., Kislyakov, A. G., Stepanov, A. V., Kliem, B., & Furst, E. 2004, *Astron. Lett.*, 30, 319