MHD-Oscillations of Coronal Loops and Diagnostics of Flare Plasma

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Abstract. Effects of ballooning and radial oscillations of coronal magnetic loops on the modulations of microwave and X-ray emission from flare loops are considered. The damping mechanisms of loop MHD-modes are analyzed. The method for diagnostics of flare plasma parameters using peculiarities of the microwave and X-ray pulsations is proposed. The diagnostic method was applied for two solar flares: on May 8, 1998 and August 28, 1999 observed with the Nobeyama Radioheliograph.

1. INTRODUCTION

Solar and stellar flares reveal quite often quasi-periodic modulations in optical, X-ray, and radio emission. More than 30 years ago Rosenberg (1970) proposed to associate the short-period (~1 s) pulsations of type IV solar radio bursts with the magneto-hydrodynamic (MHD) oscillations of coronal loops. Coronal magnetic loops are fundamental structures of coronae of the Sun and late type stars (Bray et al 1991; Benz et al 1998; Schrjiver et al 1999). Subsequently, Rosenberg's idea was developed by many authors (see the reviews by Aschwanden (1987, 2003)), but no convincing evidence for the validity of this approach has been found until recently. In the late 1990s, ultraviolet observations from the TRACE satellite with a high spatial resolution revealed oscillations of coronal loops in active regions (Aschwanden et al 1999), which provided a strong impetus for the rapid development of a new promising direction of research called "coronal seismology". Such a great interest is largely explained by the possibility of a further improvement in the methods for diagnosing of plasma and magnetic fields in the region of flare energy release (see, e.g. Zaitsev and Stepanov 1982,1989; Nakariakov et al 1999; Kopylova et al 2002).

It is well known that the radial fast magneto-acoustic (FMA) oscillations of coronal loops can lead to the second (0.5-5 s) oscillations of emission from solar flares (Rosenberg 1970; Zaitsev and Stepanov 1982; Kopylova et al 2002). Oscillations with a period P = 10-30 s are attributed usually to Alfven or kink modes (Zaitsev and Stepanov 1989; Qin et al 1996; Nakariakov et al 1999). At the same time, if the plasma parameter $\beta = 8\pi\kappa_B nT/B^2$ in a loop is not too small the ballooning mode can be responsible for ten-second modulation (Kopylova and Stepanov 2002). An indications on the ballooning disturbances in solar flare loops are suggested by microwave observations with the Nobeyama Radioheliograph (Shibasaki 1998), Yohkoh data (The Yohkoh HXT Image Catalogue 1998) as well as by physical models (Sakai 1982; Shibasaki 2001).

The radial and ballooning oscillations look very similar in properties, because they cause a periodic variation of the magnetic field, gas pressure, and the loop cross section. Therefore, fast sausage and ballooning mode are very important in the context of prominent modulation of flare emission. Moreover they must be strongly damped. Their Q-factor cannot be too high ($Q \leq$ 10-30) in agreement with the observational data obtained in various wavelength ranges (e.g., Asai et al. 2001). In this case the Q-factor of the FMA oscillations in flare loops is determined by electron thermal conduction (Zaitsev and Stepanov 1982). In several cases, however, ion viscosity plays a more significant role in the dissipation of these modes (Kopylova et al 2002). Consequently, the damping mechanisms for the modes under consideration should be studied additionally.

In this talk, based on the technique proposed by Zaitsev and Stepanov (1982), we determine the flare plasma parameters from the pulsation characteristics of nonthermal gyrosynchrotron and

X-ray emission. This technique is widely used to diagnose the plasma of both solar (see e.g. Qin et al 1996) and stellar (Mullan et al 1992; Mathioudacis et al 2003) flares.

In Section 2 the physical properties of the ballooning and radial modes are analyzed and the peculiarities of dispersion relations are discussed. In Section 3, we consider the damping mechanisms for the FMA oscillations of coronal magnetic loops. In Section 4 the modulation of nonthermal gyrosynchrotron emission by FMA oscillations is considered and the method for diagnosing the flare plasma using microwave and X-ray pulsation is suggested. Section 5 is devoted to the application of the proposed method.

2. BALLOONING AND RADIAL OSCILLATIONS

Ballooning mode

Two approximations (drift and MHD) can be used to describe the ballooning mode of flute perturbations. The difference between these two approaches is that in the drift approximation, the magnetization currents are disregarded, while in the MHD approximation, the displacement current is ignored by formally assuming it to be equal to zero (Tsap and Kopylova 2004). In ideal MHD, which also remains valid for a magnetized isotropic plasma (Volkov 1964), flute perturbations develop through the imbalance between the forces exerted on a plasma volume. As follows from the linearized MHD equations, the expression for the second variation of the potential energy of a system with a sharp boundary can be represented as (Meyer et al 1977):

$$\delta W = \delta W_i + \delta W_e + \oint_S \frac{\langle p \rangle}{R} \xi_n^2 dS$$

where the subscripts correspond to the change in energy inside (i) and outside (e) the magnetic configuration, while the last term describes the effects of the centrifugal force $<p>/R$, $<p> = p_e + p_i$ is the gas pressure difference, and ξ_n is the transverse displacement. It is easy to show that in the solar corona, where the radius of curvature of magnetic field lines $R >> r$ (r is the small loop radius), the curvature effects in the first two terms on the right-hand side of this equation may be disregarded; i.e. it describes the well-studied oscillations of the magnetic flux tube. If, however, the radius of curvature R is small enough and if the gas pressure difference inside and outside the loop is large, then the surface integral can play a significant role. In particular, this integral is responsible for the generation of ballooning oscillations and flute instability. We particularly emphasize that the above equation is valid only for conservative systems; i.e. it describes only the non-emitting modes. Thus, by the ballooning oscillations of coronal loops, we mean the FMA modes slightly modified by the centrifugal force (the perturbations are elongated along the magnetic field) that do not generate MHD waves in the surrounding medium. Their period, as that for the corresponding modes of the magnetic flux tube (Nakariakov et al 2003), is determined by the longitudinal loop scale. The estimates obtained in ideal MHD using the method of normal modes also provide evidence for the analogy between the flute and FMA modes. As applied to the Earth's magnetosphere, Burdo et al (2000) used the system of linear differential equations of ideal MHD in curvilinear coordinates to show that the dispersion relations for magneto-acoustic and ballooning oscillations at small values of β and the gas pressure gradient are almost identical. This suggests that the modes under consideration are similar in physical properties; in particular, the same dissipative processes must govern their damping.

Let us consider small deviations of plasma tongue having the scale $L_1 = L/N$, where $L \approx \pi R$, N is the number of plasma tongues. Small oscillation domain in the contrast of the domain of ballooning instability corresponds to the real part of the frequency: $\omega^2 > 0$. Oscillations occur as the result of acting of two forces: the force dealing with gas pressure gradient and magnetic field line curvature $F_c \sim p/R$, and the back-ward force due to the magnetic field tension $F_t \sim B^2/R$.

The dispersion relation for the ballooning mode can be represented as (Mikhailovskii 1971):

$$\omega^2 - k_\parallel^2 c_A^2 = -\frac{p}{R\rho l} \qquad l = \begin{cases} a, & a >> \lambda_\perp \\ \lambda_\perp, & a << \lambda_\perp \end{cases} \tag{1}$$

Here $c_A = B/\sqrt{4\pi\rho}$ is Alfven velocity, $a = n\left(\partial n/\partial x\right)^{-1}$ is the typical scale of plasma density inhomogeneity across the magnetic field, $\lambda_\perp$ is the transverse scale of plasma tongue. Since the loop foot points are frozen in the photosphere, the relation $k_{||} = N\pi/L$ holds for the longitudinal component of the wave vector, where N is the number of oscillating regions that fit into the loop length L. Using Eq.(1) we determine the period of the ballooning oscillations

$$P_1 = \frac{L}{c_A}\sqrt{\frac{1}{N^2 - L\beta/(2\pi l)}} \tag{2}$$

Under typical solar flare loop condition $L \sim 10^{10}$ cm, $l \sim 10^8 - 10^9$ cm, and plasma beta $\beta \le 0.1$, we have $L\beta/(2\pi l) \le 1$. Hence the Eq. (2) for pulsation period can rewrite as

$$P_1 \approx \frac{L}{c_A N} \tag{3}$$

Radial mode

If no curved magnetic field the ballooning disturbances do not exist. In this case as the first approximation the eigen-oscillations of a coronal magnetic loop (magnetic flux tube) can be investigated using the homogeneous plasma cylinder with radius *r* and the length *L* with fixed ends. The magnetic field ***B*** is directed along the cylinder axis. Let us suppose that plasma inside the loop has density ρ_i, the temperature T_i, and the magnetic field B_i. The outside plasma parameters are ρ_e, T_e and B_e. Dispersion equation for eigen-oscillations of plasma cylinder with the frequency ω and parallel and perpendicular to the axis components of the wave vector $k_{||}$ and $k_\perp$ can be written as (Meerson et al 1978; Roberts et al 1983)

$$\frac{J_m'(\kappa_i r)}{J_m(\kappa_i r)} = \alpha \frac{H_m^{(1)'}(\kappa_e r)}{H_m^{(1)}(\kappa_e r)}. \tag{4}$$

Here $\kappa^2 = \dfrac{\omega^4}{\omega^2(c_s^2 + c_A^2) - k_\parallel^2 c_s^2 c_A^2} - k_\parallel^2, \alpha = \dfrac{\kappa_i\rho_i}{\kappa_e\rho_e}\dfrac{\omega^2 - k_\parallel^2 c_{Ai}^2}{\omega^2 - k_\parallel^2 c_{Ae}^2}$,

c_s is the sound velocity, J_m and $H_m^{(1)}$ are the Bessel and Hankel functions of the first kind, $k_{//} = s\pi/L$, s = 1,2,3,… In the case of slender (r/L << 1) and dense (ρ_e/ρ_i <<1) cylinder in the axial symmetrical case (m = 0) from Eq. (4) we obtain the period of fast magneto-acoustic (sausage) oscillations, which is most effective in the context of modulation of the emission:

$$P_2 = 2\pi/\omega_2 = \tilde{r}\Big/\sqrt{c_{si}^2 + c_{Ai}^2}, \quad \tilde{r} = 2\pi r/\eta_j, \tag{5}$$

where η_j = 2.4, 5.52, 8.65 correspond to zeros of the Bessel function $J_0(\eta)$.

3. DAMPING OF FMA OSCILLATIONS

Loop radial oscillations undergo acoustic damping caused by the emission of waves into the surrounding medium. The acoustic damping rate is (Meerson et al 1978)

$$\gamma_a = \frac{\pi}{2}\omega_2\left(\frac{\rho_e}{\rho_i} - \frac{k_{\|}^{\;2}}{k_{\perp}^{\;2}}\right) \tag{6}$$

Here $k_\perp = \eta_j /r$. There is no damping for $\rho_e/\rho_i < k_{||}^2/ k_\perp^2 \approx r^2/L^2$, e.g. for comparatively thick loop. In this case we have total internal reflection and plasma cylinder becomes an ideal resonator. Moreover, as it follows from observations, the density of the matter inside flare loops is two to three orders of magnitude higher than its density outside (Doshek 1994). So, there is a jump of impedance for FMA waves. As a result, the acoustic damping of the FMA oscillations of coronal loops becomes insignificant and dissipative processes inside the loop play main role.

Under solar flare condition the most important damping mechanisms for FMA modes are the electron thermal conductivity and ion viscosity (Stepanov et al 2004):

$$\gamma_c = \frac{1}{3}\frac{M}{m}\frac{\omega^2}{\nu_{ei}}\beta^2\cos^2\theta\sin^2\theta\,, \tag{7}$$

$$\gamma_v = \frac{1}{12}\sqrt{\frac{M}{2m}}\frac{\omega^2}{\nu_{ei}}\beta\sin^2\theta \tag{8}$$

Here, m and M are the electron and ion masses, respectively, $\theta = \arctan(k_\perp/k_{||})$ is the angle between the magnetic field **B** and the wave vector **k**, $\omega_{Bi} \approx 9.6 \times 10^3 B$ is the ion gyrofrequency.
Effective frequency of electron-ion collisions is

$$\nu_{ei} = \frac{5.5n}{T^{3/2}}\ln\left(10^4\frac{T^{2/3}}{n^{1/3}}\right) \approx 60\frac{n}{T^{3/2}} \tag{9}$$

The study of radial (sausage) mode damping of magnetic loops in the case of $k_{\|} = 0$ were performed by Kopylova et al (2002). It has been shown that the most important damping effect is ion viscosity. But for ballooning oscillations ($k_{\|} \neq 0$), the result can be different because as it follows from Eqs.(7) and (8), the damping rate depends strongly on the angle θ. To decide which process is more important we compare the decrements:

$$\frac{\gamma_v}{\gamma_c} \approx \frac{4\times 10^{-3}}{\beta\cos^2\theta} \tag{10}$$

For typical value of $\beta \approx 0.1$ from Eq. (10) we find that ion viscosity less important comparing the electron thermal conductivity if $\theta < 80^\circ$. As it was mentioned in Sec.2 Eqs. (7) and (8) can be used for ballooning mode also.

4. MODULATION OF GYROSYNCHROTRON EMISSION AND FLARE PLASMA DIAGNOSTICS

Both sausage and ballooning oscillations supply deep modulation of gyrosynchrotron emission of energetic electrons in a loop. Indeed, these oscillations cause changes in the magnetic field strength, and in the scale sizes of the emitting region. We will apply our diagnostics method to the flare events observed by NoRH at 17 and 34 GHz for which the optically thin gyrosynchrotron emission of non-thermal electrons is responsible.

The flux of optically thin gyrosynchrotron emission (Dulk and Marsh 1982)

$$F = \zeta \Omega d \propto B^{\xi} \qquad \xi = 0.9\delta - 1.22 \tag{11}$$

Here ζ is emissivity, Ω is source solid angle, d is the source depth, δ is the spectral index of energetic power-law electrons. We took into account also that due to the conservation of the magnetic flux $d \sim B^{-1/2}$, and $\Omega \sim B^{-1/2}$. Using Eq. (10) we can write the modulation depth as

$$\Delta = (F_{\max} - F_{\min})/F_{\max} = 2\xi \frac{\delta B}{B} \tag{12}$$

Here δB is the deviation of loop magnetic field during oscillations. In accordance with Eqs. (7) and (10) the Q-factor for $\theta < 80^\circ$ is determined by the electron thermal conductivity

$$Q = \frac{\omega}{\gamma_c} \approx \frac{2m_e}{m_i} \frac{P\nu_{ei}}{\beta^2 \sin^2 2\theta}\,. \tag{13}$$

Oscillations can excite due to the rapid enhancement of the gas pressure inside a loop $\delta p \approx n\kappa_B T$ at the impulsive phase of solar flare. Hence we can get the following relation:

$$\beta \approx 2\frac{\delta B}{B} = \frac{\Delta}{\xi} = \varepsilon\,, \tag{14}$$

From the formulas for periods (3) and (5), Q-factor (13) and modulation depth (14) we find the expressions for determination of temperature, density, and magnetic field of the flare loop using observation data on the pulsations of microwave emission (Table 1)

Table 1

Ballooning oscillations	Sausage oscillations
$T = 2.42 \times 10^{-8} \dfrac{L^2 \varepsilon_1}{N^2 P_1^2}$	$T = 1.2 \times 10^{-8} \dfrac{\tilde{r}^2 \varepsilon_2}{P_2^{\,2} \chi}$
$n = 5.76 \times 10^{-11} \dfrac{Q_1 L^3 \varepsilon_1^{\,7/2} \sin^2 2\theta}{N^3 P_1^4}$	$n = 2 \times 10^{-11} \dfrac{Q_2 \tilde{r}^3 \varepsilon_2^{\,7/2}}{P_2^{\,4} \chi^{3/2}} \sin^2 2\theta$
$B = 6.79 \times 10^{-17} \dfrac{Q_1^{\,1/2} L^{5/2} \varepsilon_1^{\,7/4} \sin 2\theta}{N^{5/2} P_1^3}$	$B = 2.9 \times 10^{-17} \dfrac{Q_2^{\,1/2} \tilde{r}^{5/2} \varepsilon_2^{\,7/4}}{P_2^{\,3} \chi^{5/4}} \sin 2\theta$

Here $\chi = 10\varepsilon_2/3 + 2$, temperature T in Kelvin degrees, density n in cm^{-3}, and magnetic field B in G.

5. APPLICATION OF DIAGNOSTIC METHOD

Let us consider as examples the effects of coronal loop oscillations on the radiation of solar flares on May 8,1998 and August 28,1999.

Single loop flare on May 8,1998

This M3.1 X-ray class event occurred in the active region NOAA 8210 with coordinates S15 W82 in the time interval 01:49-02:17 UT. Time profiles of impulsive phase of the burst in hard X-ray and radio emission is shown in Fig.1a. One can see that there is no evident time delay between

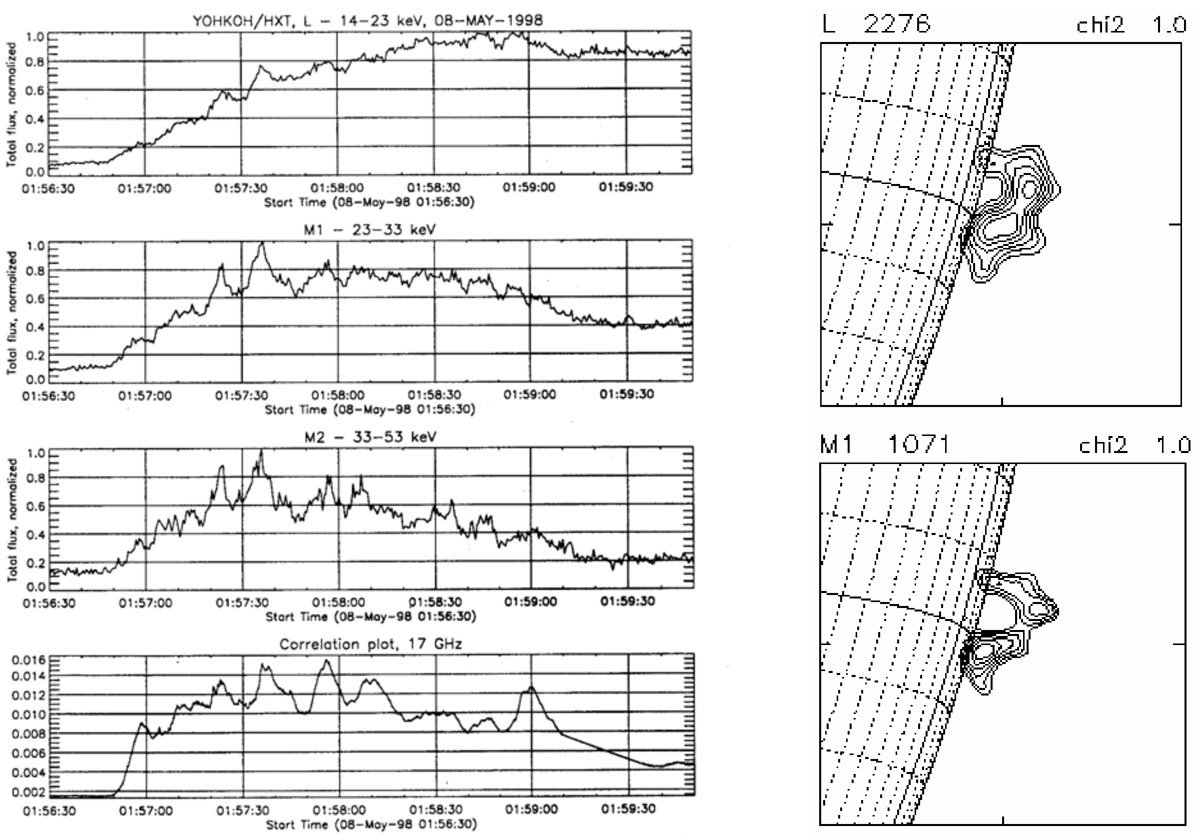

Fig. 1. (a) Time profiles for X-ray fluxes from the solar flare of May 8, 1998 in channels L (14–23 keV), M1 (23–33 keV), and M2 (33–53 keV) obtained onboard the Yohkoh satellite, and time profile of 17 GHz burst obtained with the Nobeyama Radioheliograph. (b) Images of hard X-ray source in channels L and M_1.

hard X-ray and 17 GHz pulses. Fig.1b shows that in L and M_1 channels the source has a "tongue-shape" form, which is typical for ballooning disturbances. Pulsations at microwaves and in hard X-rays can be connected with oscillations of plasma tongues. From Fig.1b it follows that four tongues (N = 4) are in the loop with the length $L \approx 8\times10^9$ cm. One can estimate $\mathrm{tg}\,\theta = k_\perp / k_\parallel \approx 2.25$, e.g. $\theta \approx 66^\circ$. Fourier analysis of the time profile of the impulsive phase of the flare (Fig.1a) gives the typical period $P_1 \approx 16$ s. Modulation depth of optically thin gyrosynchrotron emission is $\Delta \approx 0.3$, and pulsation quality $Q \approx 25$. Based on thick target X-ray model it is possible to estimate the spectral index of power-law electrons $\delta = 4.5$ and from Eqs. (12) and (14) the plasma beta

$\beta = \Delta / \xi \approx 0.11$. Using Table 1 we determine the temperature $T \approx 3.8 \times 10^7$ K, density $n \approx 4.3 \times 10^{10}$ cm^{-3}, and magnetic field $B \approx 230$ G in the flare loop.

Flare burst on August 28,1999

The impulsive phase of this M2.8 X-ray class solar flare was observed in the time interval 00:55-00:58 UT in the active region NOAA 8674 with coordinates S25 W11 (Yokoyama et al 2002).

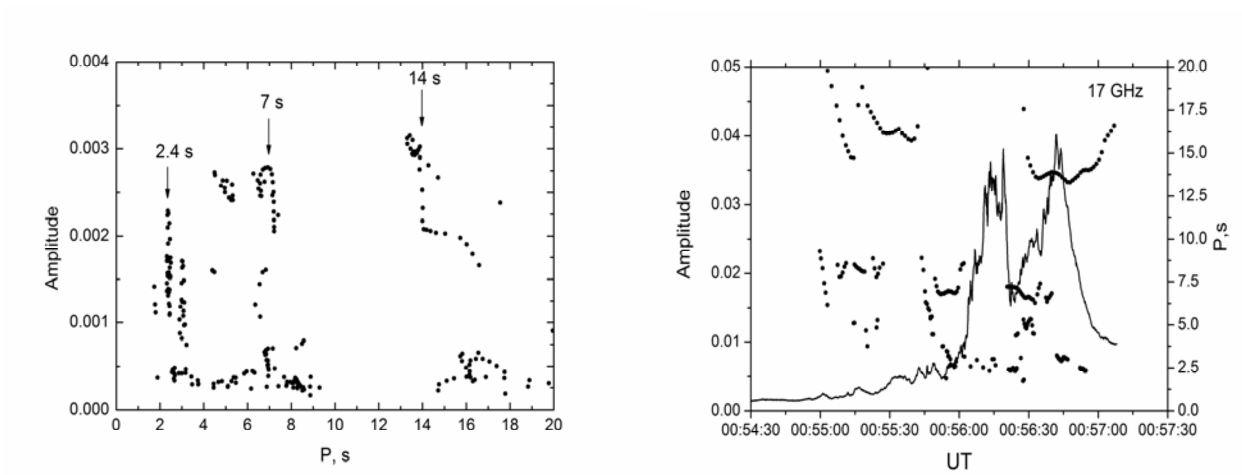

Fig. 2. (a) Dynamic spectrum of oscillations in 17 GHz flux constructed by means of a wavelet analysis for the solar flare of August 28, 1999. (b) Time profile for the emission obtained with the Nobeyama Radioheliograph, and the time variations of the oscillation period.

NoRH observations have shown that flare consists of two main sources (Yokoyama et al 2002). First compact (≤ 10”) source was located near the sunspot, and the second one – a large (≥ 70”) coronal loop, was just above the compact source. Time profile of radio flare reveals quasi-periodic pulsations (Fig.2). As it follows from Fig.2a the maximal amplitudes correspond to the three main branches of pulsations with the periods of about 14 s, 7 s, and 2.4 s. The following scenario can be suggested to the event of August 28,1999. The process of flare energy release can be accompanied by the coalescence of two neighboring loops through the development of ballooning instability in the compact loop. Indeed as it seen from Fig. 2b the oscillations with the period ≈ 14 s, which can be identify with the ballooning mode, has a time gap (00:55:45−00:56:30 UT) that coincides with the onset of propagation of the energetic electron front along the extended loop (Yokoyama et al. 2002). It would be natural to attribute this feature to a rise in the gas pressure and to the violation of oscillation conditions in the compact loop, which led to the development of ballooning instability and the injection of hot plasma and energetic particles into the extended loop. As soon as the compact loop was liberated from the excess pressure, the oscillations of plasma tongues resumed (Fig. 2b). We consider the 7 s oscillations as the second harmonic of the ballooning oscillations. Since the oscillations with the period ≈ 2.4 s emerged only after injection the plasma and energetic particles into the large loop (Fig. 2b), fast sausage radial mode is most likely responsible for this oscillations. The process of loop-loop interaction in this flare looks very similar to the Hanaoka events (Hanaoka 1999).

Period of ballooning oscillations for the fundamental mode ($N = 1$) of compact loop is $P_1 = L/c_A$, where $L \approx \pi \times 10'' \approx 2 \times 10^9$ cm. With the extended loop radius $r \approx 3 \times 10^8$ cm for the main radial oscillation mode we have $\tilde{r} = 2.6r \approx 7.8 \times 10^8$ cm. From the observation data we find for both modes the Q-factors, $Q_1 = 10$, $Q_2 = 15$, the modulation depth $\Delta_1 = 0.4$, $\Delta_2 = 0.1$, and power-law spectral indexes $\delta_1 = 5.5$, $\delta_2 = 4.0$ (Yokoyama et al 2002). Taking for example $\theta = 45^\circ$ for compact source and $\theta = 75^\circ$ for extended one from Table 1 we obtain the following plasma parameters for the extended and compact flaring loops correspondingly (Table 2).

Table 2.

Parameter	Extended loop	Compact loop
T , K	2.5×10^7	5.2×10^7
n , cm^{-3}	1.0×10^{10}	4.8×10^{10}
B , G	150	280
β	0.04	0.11

The plasma density and temperature for the flares under consideration can be estimated independently from GOES soft X-ray data (Stepanov et al 2004). For both flares the plasma temperature were estimated as $T \approx 1.5\times10^7$ K, and emission measure $n^2V \approx 10^{49}$ cm^{-3}. Taking the loop volume $V = \pi r^2 L$ for the events of May 8, 1998 and August 28, 1999 GOES data gives the plasma density 4×10^{10} cm^{-3} and 5×10^{10} cm^{-3} respectively, which do not contradict to microwave and hard X-ray diagnostics.

We have shown that proposed diagnostics method based on observations of modulation of solar flare emission and on the physical model of pulsation of flare magnetic loops is quite powerful one. This method opens new possibilities not only for determination of flare plasma parameters but also for understanding of flare physics, for example, the physics of loop-loop interaction.

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