Influence of Fine Structures on Gyrosynchrotron Emission of Flare Loops Modulated by Sausage Modes

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Abstract

Sausage modes are a leading mechanism for interpreting short-period quasi-periodic pulsations (QPPs) of solar flares. Forward modeling their radio emission is crucial for identifying sausage modes observationally and for understanding their connections with QPPs. Using the numerical outputs from three-dimensional magnetohydrodynamic simulations, we forward model the gyrosynchrotron emission of flare loops modulated by sausage modes and examine the influence of fine structures of loops. The temporal evolution of the emission intensity is analyzed for an oblique line of sight crossing the loop center. We find that the low- and high-frequency intensities oscillate in phase in the periods of sausage modes for models with or without fine structures. For low-frequency emissions where the optically thick regime arises, the modulation magnitude of the intensity is dramatically reduced by the fine structures at some viewing angles. On the contrary, for high-frequency emissions where the optically thin regime holds, the effects of fine structures or the viewing angle are marginal. Our results show that the periodic intensity variations of sausage modes are not wiped out by fine structures, and that sausage modes remain a promising candidate mechanism for QPPs, even when the flare loops are fine-structured.

Unified Astronomy Thesaurus concepts: Magnetohydrodynamical simulations (1966); Solar coronal radio emission (1993); Solar corona (1483)

1. Introduction

Quasi-periodic pulsations (QPPs) refer broadly to the oscillatory intensity variations commonly observed in solar flare emissions across a broad range of passbands (see the reviews by, e.g., Nakariakov & Melnikov 2009 and Kupriyanova et al. 2020). In spite of the abundant observed instances, the physical mechanisms responsible for QPPs still remain inconclusive (Van Doorsselaere et al. 2016; Zimovets et al. 2021). Sausage modes can cause periodic compression and rarefaction of flare loops, and are thus thought of as one of the mechanisms accounting for QPPs in solar flares (see the recent review by Li et al. 2020). In terms of observations, candidate sausage modes have been reported in the radio band (e.g., Melnikov et al. 2005; Kolotkov et al. 2015), in the extreme ultraviolet (EUV; e.g., Su et al. 2012; Tian et al. 2016), as well as in X-ray (e.g., Zimovets & Struminsky 2010).

The classical theory of sausage modes (Edwin & Roberts 1983) assumes that sausage modes are supported by an axisymmetric monolithic loop. However, high-resolution observations (e.g., Brooks et al. 2012; Curtain et al. 2013; Peter et al. 2013; Aschwanden & Peter 2017) suggest that coronal loops are fine-structured or multistranded. Multistranded loop models have been invoked to explain such observations as the coronal fuzziness (Tripathi et al. 2009; Guarraisi et al. 2010) and the time lag of EUV light curves (Warren et al. 2003; Viwall & Klimchuk 2012). Transverse kink oscillations in multistranded loops have attracted substantial attention both in analytical studies (e.g., Luna et al. 2008, 2010; Van Doorsselaere et al. 2008) and magnetohydrodynamic (MHD) simulations (e.g., Terradas et al. 2008; Ofman 2009; Pascoe et al. 2011; Magyar & Van Doorsselaere 2016; Guo et al. 2019). For flare loops, fine strands tend to be common as well (e.g., Zimovets et al. 2013; Tian et al. 2016). This led Guo et al. (2021; hereafter, G21) to examine the influence of fine structures on sausage modes in flare loops, the primary conclusion being that the global sausage mode is still identifiable in spite of the fine structures of the loops.

One key question to answer, then, is whether the fine structures can influence the emissions from multistranded flare loops experiencing sausage perturbations. It is necessary to address this issue for the radio band, in particular, where high temporal resolution can be achieved. For solar radio emissions, the gyrosynchrotron (GS) emission is known to dominate at the millimeter and centimeter wavelengths (Bastian et al. 1998). GS emissions of flare loops can be modulated by the sausage modes therein. In turn, these modulations also provide signatures for identifying the sausage modes in flare loops. Along this line of thinking, a variety of forward-modeling analyses with different levels of sophistication have been performed, from models where a homogeneous emission source has been assumed (e.g., Nakariakov & Melnikov 2006; Reznikova et al. 2007; Fleishman et al. 2008; Miossian & Fleishman 2012), to models where inhomogeneity (e.g., Reznikova et al. 2014, 2015) or loop curvature (e.g., Kuznetsov et al. 2015) have been taken into account.

In this work, we forward model the GS emission of flare loops modulated by sausage modes. What is new about our approach is that we take into account the fine structures of flare loops and examine the influence of these fine structures on the GS emission. Section 2 shows the numerical model. In Sections 3 and 4, we present the forward-modeling results. Section 5 summarizes this study.
2. Numerical Model

The MHD model that we use for forward-modeling purposes is described by G21, in which three-dimensional time-dependent simulations are performed to examine how fast sausage modes are influenced by fine structures in straight field-aligned flare loops. Two MHD models, labeled “noFS” and “FS,” are constructed in G21. For both models, the equilibrium magnetic field $B$ is $z$-directed, and all equilibrium quantities are $z$-independent. For the noFS model, the loop is axisymmetric, with its density being prescribed by

$$\rho_{\text{noFS}} = \rho_c + (\rho_1 - \rho_c)f(x, y),$$

where $[\rho_1, \rho_c] = [5 \times 10^{10}, 0.8 \times 10^9] m_p \text{cm}^{-3}$ represent the mass densities at the loop axis and infinitely far from the loop, respectively. In addition, $m_p$ is the proton mass. The function $f(x, y) = \exp[-(r/R)^\alpha]$ is used to control the density profile, with $r = \sqrt{x^2 + y^2}$, $\alpha = 5$, and the nominal loop radius $R = 5 \text{ Mm}$. The temperature distribution follows the same functional form as the density, with the temperature at the loop axis being $T_i = 10 \text{ MK}$ and that far from the loop being $T_e = 2 \text{ MK}$. The magnetic field ($B_z$) is prescribed in such a way that transverse force balance is maintained, and the resulting $B_z$ increases from $50 \text{ G}$ at the axis to $77.3 \text{ G}$ far from the loop. The length of the flare loop is $L = 45 \text{ Mm}$.

The FS model modifies the noFS model by introducing fine structures as randomly distributed small-scale density variations to the loop interior:

$$\rho_{\text{FS}}(x, y) = \rho_{\text{noFS}}(x, y) + (\rho_1 - \rho_c)f(x, y)g(x, y),$$

where

$$g(x, y) = \frac{\sum_{j=1}^{N_{\text{strands}}}[\exp(-\tilde{r}_j)^\alpha]\cos(\pi\tilde{r}_j)]}{\left[\sum_{j=1}^{N_{\text{strands}}}[\exp(-\tilde{r}_j)^\alpha]\cos(\pi\tilde{r}_j)]\right]_{\text{max}},$$

with

$$\tilde{r}_j = \frac{\sqrt{(x - x_j)^2 + (y - y_j)^2}}{R_{\text{FS}}}.$$  

In the above equations, $R_{\text{FS}} = 0.8 \text{ Mm}$ is the nominal radius of the fine strands, and $[x_j, y_j]$ represents the randomly generated position for an individual strand. We take the number of fine structures to be $N_{\text{strands}} = 20$. The temperature profile remains unchanged relative to the noFS model, whereas the magnetic field strength $B_z$ is adjusted to ensure transverse force balance. Figure 1 displays how the thermal electron density is distributed in the $x$-$y$ plane (left column) and the $y$-$z$ cut through with $x = 0$ (right column), for both the noFS model (top row) and the FS model (bottom row). When computing the GS emission, we assume that nonthermal electrons exist only inside the loop, namely in the cylinder with the nominal loop radius. We restrict ourselves to a line of sight (LoS) that is in the $x = 0$ plane and makes an angle of $45^\circ$ with the $z$-axis. Consequently, only the segments marked by the red dotted lines in Figure 1 are of interest, and they are $\sim 14 \text{ Mm}$ in length. However, we distinguish between two orientations, where the observer on the Earth is placed in opposite directions. We refer to the two situations as “LoS+” and “LoS-”, respectively. The coordinate along an LoS, $\zeta'$, increases away from the observer.
The system in both models is perturbed by a radially directed axisymmetric initial velocity, prescribed by

\[ v_{\text{xyzt}}(x, y, z; t = 0) = v_0 \frac{r}{\sigma_r} \exp \left[ \frac{1}{2} \left( 1 - \frac{r^2}{\sigma_r^2} \right) \right] \sin \left( \frac{\pi z}{L} \right) \frac{x}{r} \]

and

\[ v_{\text{y}}(x, y, z; t = 0) = v_0 \frac{r}{\sigma_r} \exp \left[ \frac{1}{2} \left( 1 - \frac{r^2}{\sigma_r^2} \right) \right] \sin \left( \frac{\pi y}{L} \right) \frac{y}{r}, \]

where \( v_0 = 10 \text{ km s}^{-1} \) is the velocity amplitude, and \( \sigma_r = 5 \text{ Mm} \) characterizes the spatial extent of the initial perturbation. An axial fundamental sausage oscillation is established in both models, despite the transverse fine structuring in the FS model. The fine strands nonetheless experience some kink-like motions (see G21 for details). Figure 2 shows the thermal electron number density \( (N_e) \) and the magnetic field strength \( (B) \) as functions of \( z' \) and \( t \) at the LoS+ orientation for both the noFS model (left column) and the FS model (right column). The variations of \( N_e \) and \( B \) relative to the equilibrium values (at \( t = 0 \)) are also given. For the noFS model, one sees that the temporal variations of \( B \) at all \( z' \) are in phase, whereas those of \( N_e \) outside the interval \( 2 \text{ Mm} \leq z' \leq 12 \text{ Mm} \) are in antiphase with the variations in this interval. Moving on to the FS model, one still readily discerns periodic variations in both \( N_e \) and \( B \). In fact, their profiles for \( z' \gtrsim 8 \text{ Mm} \) are strikingly similar to what occurs in the noFS model. The most obvious differences between the two models lie in the range \( z' \lesssim 8 \text{ Mm} \), where fine structures are present and move in a rather complicated manner. These fine structures may move back and forth along the LoS in response to the dominant sausage oscillation. Occasionally, they may deviate away from the LoS, as a result of their kink-like behavior, as well.
3. Gyrosynchrotron Emission: Reference Computations

We compute the GS emission using the fast GS code (FGS) developed by Kuznetsov et al. (2011; see also Fleishman & Kuznetsov 2010). In short, FGS computes the local values of the absorption coefficient and emissivity, thereby accounting for inhomogeneous sources by integrating the radiative transfer equation. Similar to Reznikova et al. (2014), we assume that the number density of the nonthermal electrons \( N_b \) is proportional to that of the thermal electrons \( N_e \), and specifically takes the form \( N_b = 0.005N_e \). Here, the constant of proportionality is such that the resulting \( N_b \), is compatible with observations of typical flares (e.g., Fleishman et al. 2022).

The spectral index of the nonthermal electrons is \( \delta = 3.5 \), with the energy range being 0.1–10 MeV. The pitch-angle distribution of the nonthermal electrons is taken to be isotropic. We assume that both LoS+ and LoS− thread a beam with a cross-sectional area of 48 km \( \times \) 48 km when projected onto the plane of sky, in view of the spatial resolution that the Atacama Large Millimeter/submillimeter Array can achieve (Wedemeyer et al. 2016).

Figure 3 shows (a) the number density of the nonthermal electrons \( N_b \), (b) the magnetic field strength \( B \), and (c) the Razin frequency \( f_R \) as a function of \( z' \) at \( t = 0 \) for the LoS+ orientation for both the noFS model (orange curves) and the FS model (blue curves). The pertinent profiles for the LoS− orientation can be readily deduced. Here, \( f_R \) is evaluated as \( 20N_e/B_\perp \) (in CGS units; see Reznikova et al. 2014), with \( B_\perp \) being the instantaneous \( B \) component transverse to the LoS. The relevance of \( f_R \) is such that when the thermal electron density is high, the spectral peak of the GS emission is formed due to the Razin effect, which considerably suppresses the intensity at frequencies below \( f_R \) (Razin 1960). Figure 3(d) shows the spectral profiles for the noFS model (orange curve) and the FS model (blue curve) at \( t = 0 \). We discriminate the profiles for LoS+ and LoS− by using solid and dashed–dotted curves for the FS model only. For the noFS model, the results are identical at both orientations, due to the symmetry of this LoS. Both the spectral profile and the peak frequency of the FS model are different from the results of the noFS model. These differences are caused by the physical parameters (e.g., Figures 3(a) and (b)) and Razin frequencies (Figure 3(c)) along the LoS. Observing the loop at LoS+ or LoS− for the FS model, one sees that the intensity does not change at high frequencies, but changes at low frequencies. Figure 3(e) shows the optical depth \( \tau \) as a function of frequency \( f \) at \( t = 0 \) for both models. Here, \( \tau \) is obtained by integrating the local \( \tau \) along the LoS, with \( \tau \) being the average of the absorption coefficients of the X and O modes, weighted by their local intensities. Similar to Figure 3(d), we discriminate the \( \tau \) for LoS+ and LoS− for the FS model only, though we do not see any substantial difference between the two orientations. From Figure 3(e), one...
Figure 4. Intensity (left) and its relative variation (right) at five frequencies for the noFS model (top), the FS model (LoS+; middle), and FS model (LoS−; bottom). The curves of relative variation are smoothed with a window of two periods.

Figure 5. Modulation amplitudes at different frequencies for the FS and noFS models.

Table 1

| Model       | Fine-structured? | Nonthermal Electrons |
|-------------|------------------|----------------------|
| noFS        | No               |                      |
| FS          | ρ, B_z           | \( N_0 = 0.005N_e, E = [0.1, 10] \) MeV, SPL, \( \delta = 3.5 \) |
| FS_conB     | ρ, T             |                      |
| FS_conNb    | ρ, B_z           | \( N_0 = 0.0055N_e, E = [0.1, 10] \) MeV, SPL, \( \delta = 3.5 \) |
| FS_DPL      | ρ, B_z           | \( N_0 = 0.005N_e, E = [0.01, 10] \) MeV, DPL, \( \delta_1 = 1.5, \delta_2 = 3.5 \) |
| noFS_DPL    | No               |                      |

Notes.

a Single power law.
b Double power law.
sees that at frequencies $f \gtrsim 5$ GHz, the optical depth is less than unity, and thus the loop is optically thin for both models.

Figure 4 shows the temporal evolution of intensity (left column) and the variations with respect to $t = 0$ (right), taking the results at five frequencies as examples. For the noFS model (top row), the intensities at all frequencies, including the optically thick 2.5 GHz, oscillate in phase in the period of the sausage mode. The result of the low- and high-frequency emissions oscillating in phase when the Razin effect dominates agrees with those of Reznikova et al. (2007) and Mossessian & Fleishman (2012), where a homogeneous emission source was assumed. This result also agrees with Reznikova et al. (2014) at some viewing angles, when an inhomogeneous emission source was examined. At high frequencies, the loop is optically thin, thus every voxel along the LoS contributes to the total emission, making the intensity variation follow the oscillation of the global sausage mode. At low frequencies (e.g., 2.5 GHz), however, the loop is optically thick, so the emission mostly comes from the volume where the optical depth is about unity (see the dotted lines in Figure 2). It is inappropriate to compare our results with the approximate formula proposed by Dulk & Marsh (1982), where the Razin effect was not considered. Furthermore, the physical parameters vary smoothly at the loop boundary, making the intensity of the optically thick emission more difficult to estimate using these approximate formula. For the noFS model (middle and bottom rows), the intensities at all frequencies also oscillate in phase. The most striking difference, relative to the noFS model, is the relative intensity variation of 2.5 GHz. The modulation amplitude at this frequency is reduced by the fine structures, with the reduction being more significant for LoS+. This effect is attributed to the optical thickness. In the optically thick regime, the intensity is dominated by the layer where the optical depth reaches unity, thus the fine structures or the orientation observing them would influence the intensity and its variation. At high frequencies, the intensity variations are not obviously influenced by the fine structures or the viewing angle.

Figure 5 plots the modulation amplitude as a function of frequency for both models. We obtain the modulation amplitude at each frequency by fitting the relative variation (the right column in Figure 4) with a sinusoidal curve. For the noFS model, the modulation amplitude reaches its minimum around the peak frequency, and increases rapidly with decreasing frequency, consistent with the results of Mossessian & Fleishman (2012) and Kuznetsov et al. (2015). For the FS model, the modulation amplitudes at low frequencies are dramatically reduced, with the effect being more pronounced for LoS+. At high frequencies, the modulation amplitudes are

Figure 6. Similar to Figure 4, but for the FS_conB model.

Figure 7. Modulation amplitudes of the FS model (dashed lines) and the FS_conB model (solid lines).
not obviously influenced by the fine structures. This effect is also due to different optical depths at different frequencies. As an example, we plot in Figure 2 the positions where the optical depth of the 2.5 GHz emission reaches unity for LoS+ (white curves) and LoS− (yellow curves). For LoS+, the emission is dominated by the finely structured region, which destructs the coherent variations of physical parameters along the LoS, and hence leads to the decrease of the modulation amplitude. For LoS−, however, the emission coming from the structuring is greatly reduced, and the contribution from the region of coherent variations dominates. The end result is that the modulation amplitudes are larger at LoS− than at LoS+ for low-frequency emissions where the loop is optically thick.

4. Gyrosynchrotron Emission: Further Computations

The resultant GS emission depends on multiple parameters that characterize, say, the magnetic field strength, the nonthermal electrons, and the background thermal plasma. The ideal way to examine the influences of these parameters is to perform a parametric study, with only one parameter being changed each time. However, the inclusion of fine structures also introduces structuring on such parameters as the magnetic field strength in the FS model, due to the force balance condition. In addition, the randomly distributed fine structures do not guarantee that the total number of nonthermal electrons remains the same as in the noFS model. In this section, we thus perform further MHD simulations and forward-modeling analyses besides the noFS model and the FS model. Table 1 summarizes the details of all the models.

4.1. Magnetic Flux

In the FS model, the magnetic field strength is also fine-structured, but the total magnetic flux is not the same as in the noFS model. We conduct another MHD simulation, to be labeled “FS_conB,” where the equilibrium magnetic field has the same profile as in the noFS model. The force balance in the FS_conB model is maintained in such a way that the density structuring is counteracted by the temperature structuring. Figure 6 shows the emission intensities and their relative variations at five frequencies. Though the intensities are slightly different when compared with the FS model, the relative variations at five frequencies. Though the intensities are slightly different when compared with the FS model, the relative variations at five frequencies. Though the intensities are slightly different when compared with the FS model, the relative variations are quite similar. Figure 7 compares the modulation amplitudes of the FS_conB model and the FS model. We find that the modulation amplitudes are different at some frequencies, whereas the general trend remains the same as the FS model.
4.2. Number of Nonthermal Electrons

When computing the GS emission, we assume that the number of nonthermal electrons is proportional to that of the thermal electrons, i.e., $N_b = 0.005N_e$. The resultant number of nonthermal electrons inside the loop is 8.5% lower in the FS model than in the noFS model. To make sure that the total number of nonthermal electrons in the FS model is exactly the same as in the noFS model, we perform another forward-modeling computation, to be labeled “FS_conNb,” where $N_b = 0.0055N_e$ is assumed. Figures 8 and 9 present the results of the FS_conNb model. One sees that the intensity variations and the modulation amplitudes are quite similar to those for the FS model.

4.3. Lower Energy Cutoff for Nonthermal Electrons

In the abovementioned forward-modeling analysis, the lower energy cutoff of the nonthermal electrons is $E_{\text{min}} = 0.1$ MeV,
which is higher than the typical value inferred from hard X-ray observations. The electrons with lower energies can influence the self-absorption at low frequencies, but their contribution to the GS emission is usually negligible (Holman 2003). To address the influence of the lower-energy nonthermal electrons in our model, we perform additional forward-modeling analyses, to be labeled “noFS_DPL” and “FS_DPL.” For these two models, the energy of the nonthermal electrons ranges from $E_{\text{min}} = 0.01$ MeV to $E_{\text{max}} = 10$ MeV. The spectrum of the nonthermal electrons takes a double-power-law shape with a break at 0.5 MeV, with the spectral index being $\delta_1 = 1.5$ in the low-energy band and $\delta_2 = 3.5$ in the high-energy band, similar to Reznikova et al. (2014). Figure 10 shows the intensities and their variations. Relative to Figure 4, one finds that the intensities are somehow different, while the relative variations are similar. Figure 11 compares the modulation amplitudes for the FS and noFS models. We find that the influence of the lower-energy nonthermal electrons on the modulation amplitudes of the GS emission in our model is minor.

5. Summary and Conclusion

Using three-dimensional MHD models, we study the influence of fine structures on the GS emission of flare loops modulated by axial fundamental sausage modes. The numerical models used for our reference computations are the same as those in G21, where two MHD models, namely the noFS and FS models, are simulated. The noFS model sees an equilibrium flare loop as a density-enhanced monolithic cylinder, whereas the FS model modifies noFS by randomly introducing transverse fine structures to the loop interior. In both models, sausage modes are excited by an axisymmetric velocity perturbation. We compute GS emissions using FGS (Fleishman & Kuznetsov 2010; Kuznetsov et al. 2011). We assume that the number density of the nonthermal electrons is proportional to that of the thermal electrons. The spectral index of the nonthermal electrons is 3.5, with its energy range being $0.1$–$10$ MeV. The pitch-angle distribution is assumed to be isotropic. The temporal variation of the emission intensity is analyzed for an LoS crossing the loop center (the red lines in Figure 1). We find that the low- and high-frequency intensities oscillate in phase in the period of the sausage mode for both the noFS model and the FS model. The fine structures only influence the intensity variation of the low-frequency emissions, dramatically reducing the modulation amplitudes. How significant this effect may be also depends on the orientation of the observer (i.e., LoS+ or LoS−). At high frequencies, the modulation amplitudes are not obviously influenced by the fine structures. Further computations (see Table 1) with different MHD models or nonthermal electron distributions are also examined, the results being largely similar to the reference computations. These results are helpful for understanding the GS emission as modulated by sausage modes in flare loops, as well as for identifying sausage modes using radio observations. Combining our forward-modeling results with the MHD simulations of G21, we conclude that the periodic oscillations of sausage modes are not wiped out by the fine structures of loops, and sausage modes are a promising mechanism for interpreting flare QPPs, even when the flare loops are fine-structured.

Our results show that the modulation amplitudes of the GS emission intensities at low frequencies are dramatically reduced by the fine structures of loops. This effect is mainly attributed to the optical thickness of the low-frequency emissions. However, such parameters as the total number of nonthermal electrons or the total magnetic flux can also influence the GS emissions and potentially affect the modulation amplitudes. The difference in the nonthermal electron numbers is 8.5% between the FS model and the noFS model. The influence of this difference on the modulation amplitudes is marginal, as shown in Figure 9. The influence of the total magnetic flux is slightly stronger. From Figure 7, one sees some difference between the FS model and the FS_conB model at low frequencies. Despite this difference, the modulation amplitudes of the FS_conB model are still obviously smaller than those of the noFS model. These results demonstrate that the optical thickness is the dominant factor in reducing the modulation amplitudes of low-frequency emission intensities.

Even though the modulation amplitudes at low frequencies are significantly larger, the emission intensities at these frequencies are quite low, making their detections challenging. This is because the emission at low frequencies is significantly suppressed by the Razin effect. For flare loops with lower density, where the Razin suppression is not important, the intensity at low frequencies could be larger. In this case, the peak frequency is determined by self-absorption, so all frequencies below the peak should be optically thick. Our abovementioned effects relating to the optically thick regime are expected to be more pronounced and to occur over a wider frequency range.

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