Non-thermal Electron Energization During the Impulsive Phase of an X9.3 Flare Revealed by Insight-HXMT

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Abstract

The X9.3 flare SOL20170906T11:55 was observed by the CsI detector aboard the first Chinese X-ray observatory Hard X-ray Modulation telescope (Insight-HXMT). Using the wavelets method, we report 22 s quasiperiodic pulsations during the impulsive phase. The spectra from 100 keV to 800 keV show the evolution with the gamma-ray flux of a power-law photon index from $\sim1.8$ before the peak, $\sim2.0$ around the flare peak, to $\sim1.8$ again. The gyrosynchrotron microwave spectral analysis reveals a $36^6/6\pm0^6/6$ radius gyrosynchrotron source with mean transverse magnetic field around 608.2 Gauss. The penetrated $\geq10$ keV non-thermal electron density is about $10^6.7 \text{cm}^{-3}$ at peak time. The magnetic field strength followed the evolution of high-frequency radio flux. Further gyrosynchrotron source modeling analysis implies that there exists a quite steady gyrosynchrotron source, and the non-thermal electron density and transverse magnetic field evolution are similar to higher-frequency light curves. The temporal spectral analysis reveals that those non-thermal electrons are accelerated by repeated magnetic reconnection, likely from a lower corona source.

Unified Astronomy Thesaurus concepts: Solar flares (1496)

1. Introduction

A super flare releases the bulk of its energy by various radiation processes in the whole wave bands. From 2017 September 4 to 10, a large number of big flares occurred, including tens of M-class and four X-class flares (Sun & Norton 2017), this also had a huge impact on the space environment. Even though the SOL2017-09-06T11:55 X9.3 flare is the strongest in solar cycle 24, there are limited observational data from ground to space compared with the X8.2 flare on September 10, which has been well-studied by large numbers of multi-wavelength data and numeric modeling (Chen et al. 2020). Furthermore, Lysenko et al. (2019) gave a comprehensive study of gamma-ray emission from the X9.3 flare, including the electron-positron 511 keV line, neutron capture line, and that the different spectral components are very sensitive to the distribution of accelerated ions. However, the broken power-law photon spectrum shows a minor difference of $\Delta \gamma \leq 0.5$, which could be interpreted as single power-law non-thermal electrons via the bremsstrahlung process emitting high-energy hard X-ray photons.

Electrons above tens of keV and also the very efficient emitters can produce radio emissions in the corona, especially for those electrons higher than 30 keV that spiral in the corona magnetic fields emitting very high-frequency radio emissions by the gyrosynchrotron process. These electrons are accelerated and injected into magnetohydrodynamic plasma flux tubes. The receptive energy releases would lead to plasma instabilities or magnetohydrodynamic wave modulation (Carley et al. 2019; Kupriyanova et al. 2020). In turn, this modulates the accelerated particles to produce a quasiperiodic pulsations (QPPs), both in radio and X-ray bands (Nakariakov & Melnikov 2009; Nakariakov et al. 2016). The QPPs exist in solar flares from all wave bands, within a time range from seconds to few minutes (Inglis et al. 2016). Recently, by timing analysis of the flare SOL20170906T11:55, Li et al. (2020) found a $\sim 20$ s QPP in the hard X-rays, $\gamma$-rays and 1.250 GHz radio band. In addition, more complicated QPPs were probed by Karlický & Rybák (2020) using the 22–5000 MHz data, which presented drifting and bidirectional pulsation structures.

In a typical flare, energetic electrons are accelerated upwards and downwards during the magnetic reconnection, with a rather short timescale—as short as $10^{-5}$ s. Energetic electrons reach the dense bottom of the corona or chromosphere, losing their energy through collisions, and produce hard X-ray impulses (Siversky & Zharkova 2009). These mildly relativistic energetic electrons are very effective emitters of hard X-ray photons in the flare source. It should also be noticed that in the corona, the electron gyrofrequencies $f_\text{Hz} \sim 2.8 \times 10^8 B[G]$ will yield in the order of GHz radio emissions, due to a few hundred Gauss magnetic field. Consequently, the simultaneous fine resolution of spatial and timing observations of hard X-ray and radio observations with gyrosynchrotron process will reveal the local plasma source properties, magnetic field configuration and energetic electrons distribution in the local source region (Chen et al. 2020; Fleishman et al. 2020; Zhu et al. 2021). This is particularly important because the coronal magnetic field is very difficult to measure. However, Yang et al. (2020a, 2020b) have recently measured the magnetic field in the off-limb corona by combing spatial distribution of the plasma density and the phase speed of the prevailing transverse magnetohydrodynamic waves, based on near-infrared imaging spectroscopy observations.

In our study, we will present the timing and spectral analysis of the X9.3 flare impulsive phase from the Insight-HXMT observation and Radio Solar Telescope Network (RSTN, San vito) data. We will show the hard X-ray light-curves observed from HXMT/CsI detector and its QPPs by wavelet analysis.
We also apply the same method to the RSTN data, presenting an interesting time delay for hard X-ray for the same QPP. We selected several time intervals within the hard X-ray impulsive phase to perform the spectral analysis, and found a very hard power-law distribution of photon flux in the range 100–800 keV, but with a variability during the impulsive phase. The radio spectra tend to be very complex, thus we only model the peak time with a homogeneous cylinder hot plasma tube with simplified magnetic configuration by gyrosynchrotron process. The results indicate that during the impulsive phase, the non-thermal electrons density and magnetic field are rather steady. In Section 2, the observations of Insight-HXMT and RSTN are introduced. We show the model that we used to estimate the corona plasma properties in Section 3. The detailed spectral analysis combined with Insight-HXMT and RSTN are presented in Section 4. The magnetic field and electron evolution of the GS source are studied in Section 5. Finally, the conclusion and summary are given in Section 6.

2. Observations

Insight-HXMT\(^7\) is a dedicated hard X-ray telescope that is designed for all-sky surveys of pulsars, neutron stars and black holes in X-ray binaries from 1 to 250 keV (Zhang et al. 2020) with a high energy telescope (HE), medium energy telescope (ME) and low energy telescope (LE). It also has the capacity to monitor electromagnetic counterparts of gravitational wave sources from 0.1 to 3 MeV with the HE. The HE telescope is constructed with 18 cylindrical NaI/CsI detectors. The NaI detector was designed for nominal field of view observations from 20 to 250 keV, while the CsI detector was designed for gamma-rays from 80 to 800 keV (normal-gain mode) and 200–3000 keV (low-gain mode), respectively (Liu et al. 2020). Due to the crystal thickness limit and small field of view of the NaI detector, GRBs or Solar flares are very hard to detect with the NaI detector. However, the CsI detector has a very large effective area that is sensitive to high-energy gamma-rays. In-orbit calibration by combining Crab pulse radiation and on-ground simulation shows that the CsI detector performs in a very stable state. Meanwhile, joint cross in-orbit calibrations with Fermi/GBM,Swift/BAT and KONUS-WIND prove that the CsI detector has been well calibrated (Luo et al. 2020), and tends to be a very promising large effective area detector for >100 keV gamma-ray emission source.

The active region 12673 became very productive during 2017 September 4–10, and the SOL2017-09-06T11:55 X9.3 flare came to be the strongest flare in the last solar cycle. In Figure 1, we can see that the light-curves from soft X-ray, hard X-ray and radio bands showed a very significant enhancement during the flare. However, because the Reuven Ramaty High-energy Solar Spectroscopic Imager (RHESSI) and Fermi (The Fermi Gamma-Ray Space Telescope) entered night shade during the main phase of the X9.3 flare, we got very limited gamma-ray emission observations for this event.

The HXMT CsI detector and KONUS-WIND (KW) NaI detector both detected the flare peak phase, and HXMT performed a stable observation with low-gain mode during the main hard X-ray impulsive phase (see the light curves in Figure 1, the hard X-ray light curves have already subtracted the background). In the soft X-ray band measured by Geostationary Operational Environment Satellite (GOES), the thermal bremsstrahlung emission started growing at around 11:53:45 UT. Given that RHESSI and FERMI both entered night shade, we lacked observations of this impulsive phase with these two instruments. The HXMT observations show a good agreement with KONUS-WIND G2 band (82–331 keV) and G3 band (331–1252 keV) observation during the hard X-ray impulsive phase. Because the HXMT CsI detector has a higher threshold for incoming gamma-ray photons than KONUS-WIND, only photons energy bigger than 200 keV could fully penetrate and deposit into the detector (considering that the photons could be also scattered by satellite itself, which means the incoming photon energy is bigger than the deposit photons). Moreover the count rate difference may be due to the effective area differences between HXMT and KONUS-WIND (Luo et al. 2020). KONUS-WIND has 80–160 cm\(^2\) effective area for each detector (Aptekar et al. 1995), but HXMT/CsI has got less than 10\(^2\) cm\(^2\) below 100 keV and raises to more than 10\(^2\) cm\(^2\) above 200 keV. During the flare, we could also get that the Sun’s position is (R.A. \(\sim\) 165\(^\circ\), decl. \(\sim\) 6\(^\circ\)), and the HXMT detector position is (R.A. \(\sim\) 233\(^\circ\), decl. \(\sim\) 57\(^\circ\)), which indicate that the flare photons come from pitch angle \(\sim\) 63\(^\circ\) and incident from the back side. By synthesis of these views of the difference between HXMT/CsI and KW, we can see the count rate discrepancy of these two instruments. At low-energy bands, the KW G1 and G2 observed photons up to 10\(^2\) keV, which is much higher than HXMT. It should be noted that in Figure 1, we have multiplied 0.1 for G2 band light curves for a better comparison with HXMT observations.

In the last panel of Figure 1, we show the centimeter microwave measurements from RSTN (San vito) at 1.4, 2.7, 4.9, 8.8 and 15.4 GHz (Guidice et al. 1981; Tsap et al. 2018). The radio emission at 1.4 GHz has a rather lower flux density than those at higher frequencies during the X9.3 flare, the pattern of 2.7 GHz flux showed several impulsive peaks during the impulsive phase. Radio emissions at 4.9 GHz, 8.8 GHz and 15.4 GHz started brightening from 11:56 UT, showing relatively similar trends with hard X-ray observations and which indicate strong gyrosynchrotron processes. The few seconds time delay between hard X-ray and GHz radio peaks may come from an energetic electron acceleration timescale difference in the flare region. The dashed lines in Figure 1 are the regions of interest (ROI) time intervals for further hard X-ray and radio spectral analyses, with 4 s integration.

We also used the wavelet method to investigate the quasiperiodic pulsation for the flare light curves, as shown in Figure 1. The wavelet transform technique is based on Torrence & Compo (1998), who provide a distinguished method for intrinsic timing pattern detection. This has already been used in detection of quasiperiodic pulsation in many respects, also including solar flares. For the X9.3 flare, it was found the modulation periods 24–30 s from 11:57 UT to 11:58 UT in hard X-rays, and with a slightly short period 20 s from 11:55:30 UT to 11:57 UT. However, in the radio spectrum 22–5000 MHz, there exists a significant broad-band QPP that ranges from a few seconds to 50 s during the main phase of the X9.3 flare (11:55 UT to 12:07 UT) (Karlický & Rybák 2020; Li et al. 2020).

In this study, we use the Morelet function as the mother function of wavelet transform, and the time resolution is 0.5 s for hard X-ray data and 1.0 s for the RSTN data. We also hypothesise that the background noise from hard X-ray, \(\gamma\)-ray and high-frequency radio band (>GHz) is white noise. Consequently, in the wavelet analysis we have taken a white noise spectrum for

\(^7\) http://hxmten.ihep.ac.cn
significance calculation, and the confidence level was set to 95%. Figure 2(a) shows the 100–800 keV HXMT light-curve wavelet transform, a very distinct periodic pattern present from 11:57 UT to 11:59 UT with QPPs at period of \( \sim 22.3^{\pm}1.5 \) s, and the period of \( 80 \pm 41 \) s, which is in agreement with QPPs detected by KONUS-WIND data (Li et al. 2020). The QPP at \( \sim 80 \) s was almost located inside the COI, which could be not distinguished from edge data effect. The RSTN radio light curves wavelet transform is presented in Figure 2(b). The lower frequency (1.4 GHz) wavelet power spectrum indicated various QPPs and drifts, which were confined by Karlický & Rybák (2020). The 2.7 GHz curve has a similar QPP period at \( \sim 20 \) s with the 100–800 keV curve but with few seconds ahead in time. However, higher frequencies do not show any obvious short timescale QPPs. As shown in Figure 2(b), the longer time wavelet shows a QPP period at \( \sim 80 \) s, which also corresponds with hard X-rays, suggesting that the gyrosynchrotron source tends to be rather steady in a few minutes during the impulsive phase.

3. Plasma Configuration and Modeling

Thermal bremsstrahlung emission from hot corona plasma contributes to the gradual phase of flares in general, and the intensive impulsive emission mainly comes from gyrosynchrotron emission process (Zhang et al. 2018). To quantify the non-thermal energy releasing process from the X9.3 flare, especially the non-thermal energetic electrons that were the primary contributor of the impulsive peak phase for hard X-ray emission, we have to combine the limited hard X-ray and radio observations to build an evolutionary gyrosynchrotron source model. However, the magnetic reconfiguration that powers the flare energy release always indicates the complex topology and timing evolution of corona plasma and magnetic field configuration (Anfinogentov et al. 2019). In the X9.3 flare, as shown in Figure 1, we have a radio flux up to \( 10^3 \) sfu. Hence, here we assume such a simple model that a homogeneous column source with line-sight length \( L \), with a thermal electron density \( n_e \) estimated using
EM = ∫n^2 dV, and the energetic electrons accelerated lose their energy in the dense hot plasma column tube, and spiral in the corona magnetic field emitting higher frequency radio radiation through gyrosynchrotron process.

In Figure 3, we derive the corona plasma emission measure and mean temperature from GOES (Garcia 1994). The GOES measured soft X-rays at 0.5–4.0 Å and 1.0–8.0 Å, which are sensitive to a few Million Kelvin (MK) to tens of MK plasma. We can see the onset of the X9.3 flare from GOES observations starting from 11:53:45 UT. The corona temperature rises rapidly to more than 20 MK during the peak phase and it reaches a peak around 11:57 ~ 11:58 UT, when the plasma emission measure was boosted concurrently and reached its peaks at around 12:03:45 UT. This rapid corona heating leads to the super-thermal electrons being trapped in the plasmoid or loops, which also could be a possible interpretation of drift QPPs in the lower radio frequency range (Kliem et al. 2000).

For the given homogeneous flare source, the optical depth \( \tau = 0.2 \frac{EM}{\nu^2 A_{\text{source}}} \) is inversely proportional to the square of emission frequency \( (v) \), at lower frequencies it is optically thick \( (\tau \gg 1) \) and for higher frequencies it is optically thin \( (\tau \ll 1) \). Meanwhile, \( \frac{1}{\tau} \) indicates that the cool dense plasma is very efficient in producing thermal bremsstrahlung emission but the GOES soft X-ray band is sensitive to \( \gtrsim 10 \) MK plasma. Consequently, we often see that the inferred thermal bremsstrahlung radio emission is a few times lower than the observation flux if we only use GOES data. Moreover, the thermal bremsstrahlung radio flux is proportional to the optical depth \( \tau \). Therefore, during the plasma heating phase, the higher frequency (15.4 GHz) usually becomes optically thin. When the hot plasma starts to cool down, it becomes optically thick to lower frequencies where the radio emission mainly comes from a coherent mechanism (e.g., plasma emission or cyclotron emission) (Dulk 1985; White et al. 2011). The inferred thermal bremsstrahlung flux in RSTN radio band is of the order of 50–180 sfu during the X9.3 flare, which is about 100 times lower than the observation flux. This only implies the thermal emission for higher-frequency radio emission sat background level. The gyrosynchrotron emission dominates the main phase for the centimeter radio observation during the X9.3 flare.

Even though Anfinogentov et al. (2019) has presented the existence of a long lived gyroresonant (GR) emission source during September 6, we lack radio image observation during the X9.3 flare peak phase (only the Metsähovi Radio Observatory operated by the Aalto University in Finland got 37 GHz Radioheliograph maps, see Figure 9 in the Appendix, but Metsähovi Radio Observatory observation has rather low spatial and temporal resolution solar maps for source size estimation). Thus, we have taken the NoRH 17 GHz maps at 23:36 UT (peek time of a M class flare at September 6) to estimate the lower limit of the radio source size. The source beam size in this study was estimated by measuring the beam diameter (the source \( \gtrsim \frac{1}{c} \) of max source intensity and then the equivalent beam diameter \( R_{\text{source}} = \sqrt{A_{\text{source}}/\pi} \), as shown in Figure 4. Thus, the inferred 17 GHz source is about 33″ after applying solar rotation from 23:36:00 UT to 11:55:49 UT,
Figure 4. The X9.3 flare active region at 11:55:49 UT, background image is the HMI LOS magnetic, over-plot contours from Hinode/XRT Be_thin observation and NoRH 17 GHz observations at 23:36 UT with solar rotation correction evolution. The contour levels are 1/e and 50%, the beam diameter for soft X-ray is 64″, and for 17 GHz is 33″.

which was perceived as a gyrosynchrotron (GS) source lower limit. However, the Hinode/XRT Be_thin observations presented a soft X-ray source with about 64″ beam diameter, which is a ≥MK hot plasma source that extended along the light bridge at the beginning of the X9.3 flare. We also estimated the 50% contour source beam size of 17″ and 15″ for soft X-ray and radio, respectively. Both correlate well with the photosphere line-of-sight magnetic field, which indicates that the main GS source is located near the light bridge at the foot point of the flare.

4. Spectral Analysis

To model the GS source in the X9.3 flare, we have taken the hypothesis that the injected beaming energetic electron configuration is a power-law distribution with low-energy and high-energy cutoffs. For a single power-law hard X-ray spectrum, the energetic electrons penetrate into the dense corona and lose all their energy in the thick target emitting hard X-rays (White et al. 2011). The electron distribution can be given by:

$$\frac{d^2N}{dEdV} = 3.04 \times 10^{24} A_0 b(\gamma) \left( \frac{E}{E_{0.5keV}} \right)^{-\gamma} \left( \frac{E}{E_0} \right)^{\delta - 1.5} \text{ electrons cm}^{-3} \text{ keV}^{-1}. $$

(1)

In Equation (1), $A_0$ is the photon spectrum normalization factor at $E_0$, and $A_X$ is the hard X-ray source area, $b(\gamma)$ could be calculated in given $\gamma$, and then the electron distribution has a power-law index of $\delta = \gamma + 1.5$. Since low-energy electrons lose energy and deplete more quickly than high-energy electrons, the photon spectrum index is softer than the injection energetic electron spectrum. From HXMT observations, we can get the injected energetic electrons distribution.

We have no hard X-ray spatial information during the X9.3 flare impulsive phase, which makes it difficult to calculate precise energetic electrons flux. Thus, we first derived the hard X-ray spectrum from HXMT observations within energy range 100–800 keV by the HXMT GRB analysis software$^8$ and XSPEC (Arnaud 1996)$^9$ software from HEASOFT (NASA High Energy Astrophysics Science Archive Research Center 2014). A single power-law model is applied in the spectral fitting, as shown in Figure 5(a). The hard X-ray spectrum at the main peak of HXMT light curves at 11:56:32 UT to 11:56:36 UT can be well fitted with a single power law with a $\chi^2 = 1.351$, and the photon index $\gamma$ is about 1.98 ± 0.036. It should be noted that we used a statistical error in the fitting. The HXMT photon index $>100$ keV is slightly harder when compared with the spectral fitting results based on KONUS-WIND data from Lysenko et al. (2019). The KONUS-WIND spectra fitting added the nuclear line components above 500 keV plus the power-law component. In addition, the KONUS-WIND data only had spectral data before 11:57:17 UT, but HXMT caught the full phase. Consequently, we could make a continuous spectral analysis within the ROI time intervals, as shown in Section 2.

We considered a cylinder gyrosynchrotron radiation source that evolves over time, and performed the fast numerical gyrosynchrotron fitting for RSTN radio data. The gyrosynchrotron fitting already included the contributions of gyrosynchrotron, electron-ion collisions free-free emission and electron-neutral hydrogen atoms free-free emission ( Fleshman & Kuznetsov 2010). Given that the active region is located on the solar disk, we assume a 90° angle between the transverse magnetic field and the line-of-sight beam, with dynamic background plasma estimated from GOES observations (the plasma temperature T$_{goes}$ and emission measure EM$_{goes}$), and beaming non-thermal electron distribution from the HXMT observation.

The RSTN microwave observations provided a continuous radio spectrum throughout the ROI time intervals during the main phase of the X9.3 flare. We also used the 11.2 GHz data from Metsähovi Radio Observatory 1.8 m radio telescope for better parameter constraint. We assume that the cylinder gyrosynchrotron radiation source line-sight column density L is 10$^9$, which is a typical flare radiation source column depth setting (Krucker et al. 2013; Chen et al. 2020); the source area radius $R_{source}$ is a free parameter; the radio emission beam diameter size lower limit from later NoRH 17 GHz image at 23:36 UT of a M class flare is about 33″ (see Figure 4); and the upper limit of about 64″ is constrained by the Hinode soft X-ray Be_thin observation.

We then inferred the thermal electron density $n_{e,th} = \sqrt{\frac{EM_{goes}}{L_e R_{source}^2}}$ and the plasma temperature $T_{goes}$ from GOES data. It should also be noticed that the EM and temperature derived from GOES data are lower than SDO/AIA (cool plasma) estimation but higher than RHESSI estimation (hot plasma). In this study, we have taken factors of 10$^{-0.6}$ and 10$^{0.3}$ for a moderate background plasma source configuration, as suggested by Ryan et al. (2014). Moreover, the penetrated non-thermal electron beams were set with a power-law distribution index $\delta = \gamma_{HXMT} + 1.5$. The optically thin side of radio spectra, which refer to high frequencies, were largely dictated by the energetic electron distribution($\delta$). For the electron beam energy cutoff, the statistical study by Alaoui et al. (2019) showed lower-energy cutoff $E_{e,min}$ from few tens keV to hundreds keV for non-thermal electron beams in big

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8. http://hxmtweb.ihep.ac.cn/documents/497.html
9. https://heasarc.gsfc.nasa.gov/xanadu/xspec/
flares. Hence, we fix the low-energy cutoff for energetic electrons at 10 keV and a high-energy cutoff at $E_{\text{c,max}} \sim 10$ MeV suggested by Chen et al. (2020). For a comprehensive energetic electron beam configuration, the initial non-thermal electron density $n_{\text{e,th}}$ is set as a free parameter.

The peak frequency of gyrosynchrotron radio spectra is sensitive to both the number density of energetic non-thermal electrons $n_{\text{e,th}}$ and the magnetic field strength $B$ (Fleishman & Kuznetsov 2010). Consequently, we set the corona transverse magnetic field $B$ as a free parameter in our fitting. The corona magnetic field is very difficult to measure directly. Recently, Yang et al. (2020a) and Chen et al. (2020) reported corona magnetic field results inferred from magnetohydrodynamic waves and gyrosynchrotron, respectively. In particular, the spatial and temporal resolved corona magnetic field from the EOVSA radio data for the September 10 X8.2 flare indicate that the mean magnetic field for GHz radio source is about few hundred Gauss. Furthermore, the radio emission of the X9.3 flare extended to submillimeter range (Giménez de Castro et al. 2018), reached $10^3$ sfu at 212 GHz and 405 GHz, thus revealing the strong GS source. Krucker et al. (2013) have proposed a thermal gyrosynchrotron plus non-thermal gyro-synchrotron model. They tried to explain such strong GS emission in similar X-class flares but they constrained a 5200 Gauss magnetic field. This is beyond photosphere magnetic limit for the typical active region, which is not reasonable. NLFFF reconstruction of the SDO/HMI magnetogram also showed a long live few kiloGauss (KG) magnetic field present in the base corona (Wang et al. 2018). Given that the magnetic field decreased along the height above the base corona (Fleishman et al. 2020), they suggested that the mean corona magnetic field in gyrosynchrotron numerical fitting for the X9.3 flare could be a few hundred Gauss.

Even though both Chen et al. (2020) and Sharma et al. (2020) suggested that the MCMC algorithm would perform the best error estimation, we have noted that RSTN and MRO radio observations have very limited data points during the X9.3 flare for proper error estimation. Consequently, we chose the “Nelder-Mead” fitting algorithm, which integrates in the lmfit\(^{10}\) package as the best algorithm in our fitting after trying various algorithms. Due to the limited radio data, and for the optically thick side of the spectra, thermal plasma free–free absorption and Razin suppression became increasingly important. This leads to very complex spectrum evolution at lower frequencies and may lead to rather big uncertainties. The 1.4 and 2.7 GHz data showed complicated behavior during the impulsive phase (see Figure 1). Hence, we estimated the error and $\chi^2$ by minimize the residuals only using higher frequencies data during the impulsive phase. The peak time spectral fitting is shown in Figure 5(b), and the data for the higher frequencies have been well fitted in the error space, which are marked with a red-dotted line. At 11:56:32 UT to 11:56:36 UT, when the HXMT main peak time interval occurred, we got a radius of about $36\pm0.6$, and a $10^\circ$ depth source, which is consistent

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\(^{10}\) https://lmfit.github.io/lmfit-py/
with the NoRH source estimation. The local mean transverse magnetic field $B$ was estimated at $\sim608.2$ Gauss. Moreover, the penetrated non-thermal power-law distribution electron density is about $10^{6.7}$ cm$^{-3}$ for $E_e$ from 10 keV to 10 MeV.

## 5. Magnetic Field and Non-thermal Electron Evolution of GS Source

As shown in Figure 5, we derived the non-thermal electron index from HXMT observations as initial electron beam constraints for the GS numerical model. We then estimated the transverse magnetic field and the non-thermal electrons density in the flaring GS source. To take advantage of the continued HXMT/CsI observations, we fitted to the CsI spectrum for all ROI intervals marked at Figure 1 with a simple power-law model. In Figure 6, the power-law photon index $\gamma$ follows the trail of the light curve during the ROI time intervals, with a little difference from 1.7 to 2.1. This is consistent with the results present by Lysenko et al. (2019). Even though Lysenko et al. (2019) shows a soft-hard-soft pattern from 11:56 UT to 11:57:20 UT at low-energy part and a decrease along GS emission while the energy dissipates. The non-thermal electrons lose their energy in the “thick target” immediately, the density of the non-thermal electrons decreases, which heats the base corona or even the chromosphere. This may explain the mid-IR emission that was discussed in Giménez de Castro et al. (2018). However, during the whole flaring process, neither the GS source beam size or the mean transverse magnetic field showed drastic changes (see the results presented in Figure 7). These findings also support our hypothesis of the GS source and its initial configuration.

If we consider a rough magnetic field model in the solar atmosphere $B(h) = 0.5(h/R_\odot)^{-1.5}$, then we can derive the height above photosphere, which varies from 7′′8 to 10′′0 (about 5.7–7.4 Mm); as shown in the second panel in Figure 7. The height evolution suggests a lower corona GS source. Meanwhile, we can see a persistent expansion of the background hot plasma source during the acceleration phase, and a decrease along GS emission while the energy dissipates. This implies that the bulk of the magnetic reconnection energy is dissipated by accelerated non-thermal electrons and background plasma heating.

Based on the discussion in the previous sections and the GS source model fitting results, the theoretical time profile of RSTN observations can be estimated from the gyrosynchrotron approximation. In this study, the gyrosynchrotron approximation Equation (2.15) that was described in White et al. (2011) can be rewritten as follows:

$$S_{\mathrm{sfu}} = 2.1 \times 10^{-28} \left(\frac{\nu}{1\,\text{GHz}}\right)^{1.20-0.90\delta} B^{-0.20+0.90\delta} \int N_e L dA.$$  

(2)

The total number of non-thermal electrons is $N_{\text{tot}} = \int N_e L dA$, where $L$ is the column depth, $N_e$ is the non-thermal electron density. However, in a homogeneous cylinder model, $N_{\text{tot}} = \pi R_{\text{los}}^2 L$, where $R_{\text{los}}$ is the GS source beam radius estimated from GS modeling. We can then derive the modeling flux from Equation (2) (see Figure 8). During the main impulsive phase, the modeling flux is well correlated to the observed flux near 11.2 GHz. However, in the decay phase, the correlation is not good. This may be due to the complexity of GS source evolution in the active region.
6. Conclusion and Summary

Using the HXMT CsI hard X-ray data, we conduct a comprehensive timing and spectral analysis of the largest flare during solar cycle 24 with GHz radio data. The correlation of hard X-ray observations and radio observations reveal that both emissions might originate from a common energetic electron source. Based on this hypothesis, we built a simple homogeneous cylinder GS source model, utilized both hard X-ray and radio spectra, and we figured out the evolution of the GS source during the X9.3 flare.

The HXMT/CsI data indicate a power-law distribution for the hard X-ray continue photon spectrum, which originates from a softer power-law distribution for non-thermal electrons. However, for the same population of non-thermal electrons, the production efficiency for different wave bands is rather similar in higher magnetic field strengths. However, for a weak magnetic field, a hard X-ray is much more efficient than radio by lower-energy electrons (Krucker et al. 2020). During the impulsive phase, the gyrosynchrotron microwave spectral fittings strongly indicated that magnetic reconnection released the bulk of energy, which can accelerate a large population of non-thermal electrons. These energetic electrons are then accelerated to the dense corona base, losing their energy immediately and heating the background plasma at the same time. Indeed, these non-thermal electrons are accelerated by a huge amount of magnetic energy. They will produce rich radio emissions through the magnetized plasma in the corona and will emit hard X-ray photons by the bremsstrahlung process.

As shown in Figure 8, the theoretical radio flux is mismatched with observations with a few times difference. The time delay between observations and GS modeling indicated that the hard X-ray source is different from the GS source and energetic electron beams may take few seconds to travel. Low-energy non-thermal electrons easily lose their energy through the magnetized plasma and are even trapped in the loops. However, for high-energy electrons, they could be injected deeper to the lower corona. These low-energy electrons also could be accelerated repeatedly by repeated energy releases from the magnetic reconnection point, which may explain the common QPP behaviors of hard X-rays and 2.7 GHz. The QPP at $\sim 22$ s is almost three times bigger than the time lag, probably because the energetic electrons acceleration timescale is much shorter than repeated magnetic energy release during the impulsive phase or the non-thermal electrons are accelerated from a lower corona source. The QPP

Figure 7. The radio spectral fitting results during the impulsive phase of the flare: in the top panel, the light blue curve is the MRO 11.2 GHz light curve and the red dot with error bar is the inferred electron power law index $\gamma_e$; in the middle panel, we show the mean transverse magnetic field evolution and the transparent blue curve is the MRO 11.2 GHz light-curve; in the bottom panel, the red star with error bar is the logarithm non-thermal electron density and the blue square with an error bar is the line-of-sight radio emission source size from the spectral fittings.
at \sim 80\ s supports a long lived GS source over the whole flare. Even though the estimated mean transverse corona magnetic field also demonstrated a low corona origin source, we still have to realize the complexity of flaring process.

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Appendix

Figure 9 shows the gyrosynchrotron source observed by Metsähovi Radio Observatory from 11:56:56 to 11:59:08 UT.
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References
Alaoui, M., Krucker, S., & Saint-Hilaire, P. 2019, SoPh, 294, 105
Anfinogentov, S. A., Stupishin, A. G., Myshyakov, I. I., & Fleishman, G. D. 2019, ApJL, 880, L29
Aptekar, R. L., Frederiks, D. D., Golenetskii, S. V., et al. 1995, SSRv, 71, 265
Arnaud, K. A. 1996, ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Carley, E. P., Hayes, L. A., Murray, S. A., et al. 2019, NatCo, 10, 2276
Chen, B., Shen, C., Gary, D. E., et al. 2020, NatAs, 4, 1140
Dulk, G. A. 1985, ARA&A, 23, 169
Dulk, G. A., & Marsh, K. A. 1982, ApJ, 259, 350
Fleishman, G. D., Gary, D. E., Chen, B., et al. 2020, Sci, 367, 278
Fleishman, G. D., & Kuznetsov, A. A. 2010, ApJ, 721, 1127
Freeland, S. L., & Handy, B. N. 2012, SolarSoft: Programming and Data Analysis Environment for Solar Physics, ascl:1208.013
Garcia, H. A. 1994, SoPh, 154, 275
Giménez de Castro, C. G., Raulin, J. P., Valle Silva, J. F., et al. 2018, SpWea, 16, 1261
Guidice, D. A., Cliver, E. W., Barron, W. R., & Kahler, S. 1981, BAAS, 13, 553
Inglis, A. R., Ireland, J., Dennis, B. R., Hayes, L., & Gallagher, P. 2016, ApJ, 833, 284
Karlický, M., & Rybář, J. 2020, ApJS, 250, 31
Kliem, B., Karlický, M., & Benz, A. O. 2000, A&A, 360, 715
Krucker, S., Giménez de Castro, C. G., Hudson, H. S., et al. 2013, A&ARv, 21, 58
Krucker, S., Masuda, S., & White, S. M. 2020, ApJ, 894, 158
Kupriyanova, E., Kolotkov, D., Nakariakov, V., & Kaufman, A. 2020, STP, 6, 3
Li, D., Kolotkov, D. Y., Nakariakov, V. M., Lu, L., & Ning, Z. J. 2020, ApJ, 888, 53
Liu, C., Zhang, Y., Li, X., et al. 2020, SCPMA, 63, 249503
Luo, Q., Liao, J.-Y., Li, X.-F., et al. 2020, JHEAp, 27, 1
Lysenko, A. L., Anfinogentov, S. A., Svinink, D. S., Frederiks, D. D., & Fleishman, G. D. 2019, ApJ, 877, 145
Nakariakov, V. M., & Melnikov, V. F. 2009, SSRv, 149, 119
Nakariakov, V. M., Pilipenko, V., Heilig, B., et al. 2016, SSRv, 200, 75
Nasa High Energy Astrophysics Science Archive Research Center (Heasarc) 2014, HEAsoft: Unified Release of FTOOLS and XANADU, ascl:1408.004
Ryan, D. F., O’Flannagain, A. M., Aschwanden, M. J., & Gallagher, P. T. 2014, SoPh, 289, 2547
Sharma, R., Battaglia, M., Luo, Y., Chen, B., & Yu, S. 2020, ApJ, 904, 94
Siversky, T. V., & Zharkova, V. V. 2009, A&A, 504, 1057
Sun, X., & Norton, A. A. 2017, RNAAS, 1, 24
Torrence, C., & Compo, G. P. 1998, BAMS, 79, 61
Tsap, Y. T., Smirnova, V. V., Motorina, G. G., et al. 2018, SoPh, 293, 50
Wang, H., Yurchyshyn, V., Liu, C., et al. 2018, RNAAS, 2, 8
White, S. M., Benz, A. O., Christie, S., et al. 2011, SSRSv, 159, 225
Yang, Z., Bethge, C., Tian, H., et al. 2020a, Sci, 369, 694
Yang, Z., Tian, H., Tomczyk, S., et al. 2020b, ScChE, 63, 2357
Zhang, P., Guo, Y., Wang, L., & Liu, S. 2018, A&A, 615, A48
Zhang, S.-N., Li, T., Lu, F., et al. 2020, SCPMA, 63, 249502
Zhu, R., Tan, B., Su, Y., et al. 2021, ScChE, 64, 169