Microwave Diagnostics of Pitch-Angle Anisotropy of Electrons Accelerated in Solar Flares

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Plan of the talk

1. Astrophysical objects with synchrotron / gyrosynchrotron radiation

2. Basic mechanisms and models of electron acceleration in solar flares

3. Search for constraints on electron acceleration models from microwave observations with high spatial resolution

4. Basics of Magneto-bremsstrahlung mechanism of radio emission

5. Influence of the electron pitch-angle anisotropy

6. New observational discoveries with radio instruments having a high spatial resolution

7. Modeling spatial distributions of microwave emission of flaring loop:
   - Electron distributions; Fokker-Plank codes;
   - GS-emission distributions; Fast GS codes
Astrophysical objects with synchrotron radiation

Spiral galaxies  \( (W_R = 10^{32} \text{ watt}) \)
Wide-Field Radio Image of the Galactic Center
\( \lambda = 95 \) cm
(Kassim, LaRose, Lazio, & Hyman 1999)

Credits: Lang, Morris, Roberts, Yusef-Zadeh, Goss, Zhao
Astrophysical objects with synchrotron radiation

Radio galaxies and quasars,

\[ W_R = 10^{38} \text{ watt} \]

VLA 5-GHz radio image of Cygnus A (3C405)
Quasar 3C175
YLA 6cm image (c) NRAO 1996
Supernovae remnants
Crab nebula

Radio

Optics
Synchrotron spectrum of Crab nebula
Extra-galactic Supernovae

SN 1993J in M81

VLBA observations
17 May 1993 – 25 Feb 2000

Bartel, Bietenholz, Rupen et al.
aries.phys.yorku.ca/~bartel/SNmovie.html
Cyclotron / Gyrosynchrotron / synchrotron emission on stars and planets

- **Magnetic $A_p$ stars**. $A_p$ stars have very strong magnetic field (up to $\sim 30$ kG).

- **Red dwarfs (like our Sun)** are characterized by magnetic activity including flares with strong gyrosynchrotron emission.

- **Jupiter-like planets** with strong magnetospheres.
Solar flare loops and CME flux ropes
1. Particle Acceleration Processes

There exists a wide variety of acceleration mechanisms:

(1) electric DC-field acceleration (*current sheets, twisted loops*)

(2) stochastic acceleration (*wave turbulence, microflares*)

(3) shock acceleration (propagating MHD shocks; standing MHD shocks in reconnection outflows)

(4) betatron acceleration (in collapsing magnetic traps)

Their properties are not the same. They may act in different places inside a flaring loop, and they may produce electrons with different types of pitch-angle distribution, Possibly, all of them can operate in solar flares!
Particle acceleration inside the reconnection region

Regular acceleration in the large scale electric field

“Bursty” acceleration in small-scale electric fields in magnetic X and O points

Electric current instabilities

(from Aschwanden 2002)
Acceleration in a Current Sheet
(X-type reconnection)

Energy gained:

\[ W = E \times L_{\text{eff}} \]

Large-scale electric field in Petschek (or Sweet-Parker) current sheet

**Injection along or across to the loop axes (?)**

(e.g. Syrovatskii, 1976; Litvinenko & Somov, 1995; Somov & Kosugi, 1997; Shibata 2000- …)

Zharkova & Gordovsky: injection **along the MFL** (given presence of z-component of B in a current sheet)
DC-Acceleration in Twisted Magnetic Loops

(Zaitsev, Urpo, Stepanov 2000; Zaitsev & Stepanov 2008)

Acceleration along the loop axes

Acceleration can be in the loop top (due to prominence) or near a footpoint
Stochastic acceleration in micro-current sheets


Acceleration is **isotropic** or partly across the magnetic field lines.

Acceleration sites are distributed along a whole loop(s)
Stochastic acceleration on wave turbulence

Theory of stochastic electron acceleration provides a possible mechanism for the acceleration of electrons into a broad spectrum extending to the high energies that are observed (Hamilton & Petrosian 1992; Larosa et al. 1994; Miller et al. 1996; Pryadko & Petrosian 1997; Petrosian & Liu 2004; Yan & Lazarian 2004; Petrosian et al. 2006).

Acceleration is **isotropic** (Petrosian and colleagues 2004-2010), or partly **along** the magnetic field lines (Miller and colleagues 1996, 1997). Acceleration site is localized near the reconnection region (**loop top**) (Liu et al., 2008).
First order Fermi acceleration in a local collapsing magnetic trap along the loop axes.

The local magnetic trap is between a reconnecting current sheet (RCS) and the termination shock wave (SW).
- $v_0$ is the velocity of the coronal plasma inflow into the current sheet,
- $v_1$ is the super-Alfven velocity of the ultrahot plasma outflow from the current sheet,
- $v_2$ is the postshock plasma velocity, and
- $v_3$ is the spreading velocity of the compressed and shock-heated plasma along magnetic field lines toward the footpoints of the flare magnetic loop,
- MO is a magnetic obstacle (MO).

(from Somov and Kosugi, 1997)
Betatron Acceleration in a Collapsing Magnetic Trap

\[ \nabla \times E = -\frac{1}{c} \left( \frac{dB}{dt} \right) \]

Mostly, the electron acceleration goes across the loop axes.

Fig. 1. The scheme of the collapsing magnetic trap in the standard 2-D flare model.

(Bogachev and Somov, 2004; Karlicky, Kosugi, 2004)
Are there any constraints from observations?

Only observations can tell us which mechanism is dominant in a specific flare configuration. In this talk I will try to show how we can get the constraints.

Why microwave gyrosynchrotron emission is so interesting?

1) cm-mm emission brings us the information about the acceleration and transport processes of mildly relativistic and relativistic electrons in coronal flaring loops;

2) It allows us to diagnose the magnetic field inside magnetic loops at coronal heights.

Any other types of flaring loop emissions can not provide us with such a data.
Nobeyama Radioheliograph
Nobeyama Radioheliograph
Chinese Spectral Radioheliograph (MUSER) is a radio synthesis imaging telescope dedicated to observe the Sun, working on multiple frequencies in decimeter to centimeter range.

The observing radio frequency ranges are 400 MHz - 2 GHz (CSRH-I: 40 x 4.5m antennas) and 2 GHz - 15 GHz (CSRH-II: 60 x 2m antennas).
MUSER station
Microwave burst on 24 Aug 2002

Consider brightness evolution during the main temporal peak

Dynamics of microwave spectrum, the flare on July 15, 2002  (OVSA)
Microwave flare loop on 22 Aug 2005

Stocks I, 17 GHz

Stocks I, 34 GHz

Spectral slope
34 GHz / 17 GHz
Magneto-Bremsstrahlung Emission Mechanism

\[ f_B = \frac{eB}{2\pi m_e c} - \text{gyrofrequency} \]

\[ f_B = 2.8 \times 10^6 \, B, \, \text{Hz} \]

Power of emission:
\[ P = \frac{2}{3} \frac{q^2 a^2}{c^2} \]

Lorenz Force makes the acceleration of electrons
\[ F = \left( \frac{e}{c} \right) v \times B - \text{Lorenz force} \]
\[ a = ev_{\text{perp}} \frac{B}{m_e c} \]
A) **Cyclotron emission**: 
\[ E_{\text{kin}} \ll mc^2 \]
\[ V = v \ll c \]

\[ f_B = \frac{eB}{2\rho m_e c} - \text{gyrofrequency} \]

\[ f_B = 2.8 \times 10^6 \, B, \, \text{Hz} \]
Electron energy and the directivity of magneto-bremsstrahlung emission

\[ \theta \sim \gamma^{-1} = \frac{mc^2}{E} \]

\[ \gamma = (1-\beta^2)^{-1/2} \]

\[ \beta = \frac{v}{c} \]

Accelerating charge aplet

\[ \beta = 0 \quad \gamma = 1 \]

Angle = 90
B) Gyroresonance emission

\[ E_{\text{kin}} << mc^2 \]

\[ V = v \sim 0.1-0.3 \, c \]

\[ \Delta \theta \approx 1 - \frac{v^2}{c^2} \equiv \frac{1}{\gamma_L^2} \]

\[ f = sf_B = seB/2\pi m_e c = 2.8 \times 10^6 \, sB \, \text{Hz} \quad (s = 1, 2, 3, \ldots) \]
Electron energy and the directivity of magneto-bremsstrahlung emission

Lienard-Wiechert potentials:

\[ A = \left[ \frac{ev}{c(R - Rv/c)} \right]_{t - \frac{R}{c}}, \quad \varphi = \left[ \frac{e}{R - Rv/c} \right]_{t - \frac{R}{c}} \]

\[ R - \frac{Rv}{c} = R \left( 1 - \frac{v}{c} \cos \theta \right) \approx R \left( 1 - \beta + \beta \frac{\theta^2}{2} \right) \]

\[ \theta \sim \gamma^{-1} = \frac{mc^2}{E} \]

\[ \gamma = (1 - \beta^2)^{-1/2} \]

\[ \beta = \frac{v}{c} \]
C) Gyrosynchrotron emission:

\[ E_{\text{kin}} \sim mc^2, \ 100-500 \text{ keV} \]

A relativistic effect of the directivity changes the sinusoidal dipole pattern to an asymmetric shape.

In Fourier transform, the number of strong spectral peaks (harmonics) increases a lot.

\[ \Delta t \sim \frac{1 - \beta^2}{\omega_B} \approx \frac{1}{\omega_B} \left( \frac{m_e c^2}{\mathcal{E}} \right)^2 \]

\[ \rightarrow \]

\[ \eta = 0.2, \ \mu_1 = 0, \ \mu_0, \ 0.2, \ 0.3, \ 0.6, \ 10. \]
D) Synchrotron emission:

\[ E_{\text{kin}} \gg mc^2, \ V=\gamma c \]

While electron energy increases, the emission lines at high harmonic numbers become broader due to Doppler effect, so that they blend together into a continuum emission. At mildly relativistic energies (100-500 keV), the effect becomes stronger, and the lines go up to harmonics 10-100.

Also, the lines itself are shifted to lower frequencies due to the relativistic increase of the electron mass:

\[ f_b = \frac{eB}{mc}, \ m = m_0/\left(1-v^2/c^2\right)^{1/2}. \]
Synchrotron emission frequency spectrum from a relativistic electron:

\[ E_{\text{kin}} \gg mc^2, \ V=c \]

- Energy at which an electron emits most effectively at frequency \( \omega \)

\[ \epsilon_{\text{max}} \sim m_e c^2 \left( \frac{\omega}{\omega_B} \right)^{1/2} \]

\[ P_{\omega}^{\text{max}} \approx \frac{1.6 \ e^2 \omega_B}{2\pi \ c} \]

\[ \omega_{\text{max}} \approx 0.3 \omega_c \approx \frac{1}{2} \omega_B \left( \frac{\epsilon}{m_e c^2} \right)^2 \]
Microwave spectrum and flaring loop diagnostics

<table>
<thead>
<tr>
<th>Emission parameter</th>
<th>Flaring loop parameter</th>
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</thead>
<tbody>
<tr>
<td>- high frequency slope</td>
<td>- spectral index of nonthermal electrons</td>
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<tr>
<td>- intensity of emission at $f &gt; f_{peak}$</td>
<td>- total number of high energy electrons</td>
</tr>
<tr>
<td>- frequency of spectral maximum (peak frequency $f_{peak}$)</td>
<td>- magnetic field strength;</td>
</tr>
<tr>
<td>- peak flux $F_p$</td>
<td>- column number density of nonthermal electrons;</td>
</tr>
<tr>
<td>- low frequency slope</td>
<td>- $n_0/B$</td>
</tr>
<tr>
<td>- intensity of emission at $f &lt; f_{peak}$</td>
<td>- magnetic field inhomogeneity in a radio source (see for review: Bastian, Benz &amp; Gary, 1998; Fleishman &amp; Melnikov, 2003)</td>
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Influence of electron pitch-angle anisotropy on parameters of gyrosynchrotron emission
Gyrosynchrotron emission directivity

The angular width of the emission beam:

\[ \theta \sim \gamma^{-1} = \frac{mc^2}{E} \]
Influence of the electron distribution anisotropy on the frequency spectrum

The angular width of the emission beam:
\[ \theta \sim \gamma^{-1} = \frac{mc^2}{E} \]
\[ f_{\text{max}} \propto f_B (E/mc^2)^2 \]

For solar flare conditions, the broad band microwave emission are mainly generated by mildly relativistic electrons.

At lower frequencies the beam is wider, and at higher frequencies the beam is narrower.

→ the anisotropy does influence the emission spectrum
Observational evidence for electron pitch-angle anisotropy in a microwave GS source

Radio waves’
Quasi-longitudinal propagation

Quasi-transverse propagation

Quasi-longitudinal propagation

Differences in:
- intensity,
- spectrum and
- polarization

2017
Results of simulations:

Electron pitch-angle distribution of the loss-cone type:

\[ f_2(\mu) \sim \exp\{-\mu^2/\mu_0^2\} \]
\[ \mu = \cos(\varphi), \quad \varphi = B^V. \]

→ considerable change of microwave parameters for the quasi-parallel propagation (\(\eta = 0.8\)):
- **Decrease of intensity**;
- **Increase of polarization degree**
- **Increase of the spectral index**

(Fleishman & Melnikov 2003)
Results of simulations:

*Electron pitch-angle distribution of the beam type:*

\[ f_2(\mu) \sim \exp\left\{-(\mu-\mu_1)^2/\mu_0^2\right\} \]

\[ \mu = \cos(\phi), \quad \phi = B^V. \]

→ considerable change of microwave parameters for the quasi-transverse propagation (\(\eta = 0.2\)):

- *Decrease of intensity;*
- *Change of polarization degree to O-mode*
- *Increase of the spectral index*

2. New observational discoveries using microwave instruments with high spatial resolution

a) bright loop top microwave sources;

b) frequency spectral index dependence on position along a loop;

c) ordinary mode polarized emission from some parts of a loop;

d) shrinkage and expansion of microwave loops.

Here I constrain myself by the consideration of only broadband microwave emission of solar flares. This emission is generated mostly by the gyrosynchrotron mechanism
2.1. Discovery of looptop microwave sources in optically thin part of the frequency spectrum

Kundu et al 2001
Melnikov et al 2002

Statistical results:
Martynova, Melnikov, Reznikova 2007
Tzatzakis, Nindos, Alissandrakis 2008
Huang, Nakajima 2009
Spatial profiles of brightness at 34 GHz at the burst maximum

\[ T_{bLT}/T_{bFP} : 3; 33; 6; 10; 6. \]

(Melnikov, Reznikova, Shibasaki, 2002, 2006)
Disagreement with the existing microwave loop models

The brightness peaks of optically thin GS emission have to be near the footpoints of extended loops with a nonuniform magnetic field as shown by Alissandrakis and Preka-Papadema (1984), Klein et al (1984) due to strong dependence of GS intensity on the magnetic field strength.

For example, if the electron power law spectral index $\delta=4$, then

$$I_f \propto NB^{3.4}(\sin \theta)^{2.2}$$

The possibility to have a hump in brightness near the loop top due to the effect of optical thick emission (Preka-Papadema & Alissandrakis 1992, Bastian et al 1998) is ruled out in our case since for all the events under study the frequency spectral index between 17 and 34 GHz is negative and, therefore, the microwave emission from the loops is optically thin at least at 34 GHz.
2.3. Polarization of the loop-top and footpoint sources in a flaring loop

Footpoints are the most bright sources in polarization (Stokes V). The opposite loop footpoints have opposite polarization sense.

It is expected for the optically thin gyrosynchrotron sources.
The microwave emission is O-mode polarized at 17 GHz!!!


The authors interpreted this effect as a consequence of beamed electron flux.

Flare sources in UV and microwaves (right and left circular polarization). Dotted contour shows the magnetic neutral line. Background is the MDI magnetogram.
Inversion of the circular polarization degree along flaring loops

The most remarkable property is that in the upper part of the loops, the polarization degree changes its sign to the opposite (from extraordinary to ordinary mode). This can not be obtained for isotropic or loss-cone type of pitch angle distribution of emitting electrons! → The evidence of perpendicular anisotropy (Morgachev et al 2014; 2015)
3. Theoretical modeling and numerical simulations of microwave emission of flaring loops

   a) development of numerical codes for modeling spatial electron and microwave distributions on the basis of the nonstationary Fokker-Plank kinetic equation;

   b) development of a numerical code for fast gyrosynchrotron emission calculations;

   c) development of GX-simulator for obtaining spatial distributions of microwave characteristics;
3.1. Modeling electron and microwave spatial distributions

It is clear from a simple collisionless consideration that electron distribution along a magnetic loop must depend on a specific position and pitch-angle distribution of the acceleration/injection.

The loss-cone condition:

$$\theta < \arcsin \left( \frac{B_s}{B_m} \right)$$
Kinetics of Nonthermal Electrons in Magnetic Loops

In a magnetic loop, a part of injected electrons are trapped due to magnetic mirroring and the other part directly precipitates into the loss-cone. The trapped electrons are scattered due to Coulomb collisions and loose their energy and precipitate into the loss-cone.

A real distribution strongly depends on the injection position in the loop and on the pitch-angle dependence of the injection function \( S(E, \mu, s, t) \), and also on time (Melnikov et al. 2006; Gorbikov and Melnikov 2007).

Non-stationary Fokker-Plank equation (Lu and Petrosian 1988):

\[
\frac{\partial f}{\partial t} = -c \beta \mu \frac{\partial f}{\partial s} + c \beta \frac{d \ln B}{ds} \frac{\partial}{\partial \mu} \left[ \frac{1 - \mu^2}{2} f \right] + \frac{c}{\lambda_0} \frac{\partial}{\partial E} \left( \frac{f}{\beta} \right) +
\]

\[
+ \frac{c}{\lambda_0 \beta^3 \gamma^2} \frac{\partial}{\partial \mu} \left[ (1 - \mu^2) \frac{\partial f}{\partial \mu} \right] + S(E, \mu, s, t)
\]
Numerical codes for gyrosynchrotron emission calculations

The exact formulae for the gyromagnetic radiation are known for several decades (Eidman 1958, 1959; Melrose 1968; Ramaty 1969).

\[
j_\sigma(\omega, \vartheta) = \frac{4\pi^2 e^2 \omega^2}{c} \left(1 + K_\sigma^2 + \Gamma_\sigma^2\right) \sum_{n=1}^{\infty} \int \gamma_e \beta^2 d^3p (1 - \mu^2) f(p) \left[ \frac{\Gamma_\sigma \sqrt{1 - \eta^2} + K_\sigma (\eta - \beta \mu_\sigma)}{n_\sigma \beta \sqrt{(1 - \mu^2)(1 - \eta^2)}} J_n(z) + J_n'(z) \right]^2 \times \delta(\gamma_e \omega - n_\omega B_\epsilon - \gamma_e \beta n_\sigma n_\mu \omega),
\]

\[
x_\sigma(\omega, \vartheta) = -\frac{\pi\omega_{pe}^2}{(1 + K_\sigma^2 + \Gamma_\sigma^2) \{2n_\sigma [\partial(\omega n_\sigma)/\partial \omega] \}} \frac{c}{v_\sigma N} \sum_{n=1}^{\infty} \int d^3p (1 - \mu^2) \left[ \frac{\Gamma_\sigma \sqrt{1 - \eta^2} + K_\sigma (\eta - \beta \mu_\sigma)}{n_\sigma \beta \sqrt{(1 - \mu^2)(1 - \eta^2)}} J_n(z) + J_n'(z) \right]^2 \times \delta(\gamma_e \omega - n_\omega B_\epsilon - \gamma_e \beta n_\sigma n_\mu \omega) \left[p \frac{\partial}{\partial p} - (\mu - n_\sigma n_\beta) \frac{\partial}{\partial \mu}\right] f(p).
\]

Numerical codes which use these exact formulae allow to calculate GS emission and absorption coefficients with arbitrary energy and pitch-angle distributions of emitting electrons (Fleishman & Melnikov 2003).
Radio brightness distribution

Case 1: Injection at the loop top
Case 2: Injection near a footpoint

17 GHz
Spatial distribution of the spectral index (solar disk, Theta = 45 deg)

Case 1: Injection at the loop top

Case 2: Injection near a footpoint

Spectral steepening $\rightarrow$ Signature of the perpendicular anisotropy

Spectral steepening $\rightarrow$ Signature of the longitudinal anisotropy
High frequency spectral index variations along a loop.

Microwave spectrum near footpoints is considerably softer (by ~ 0.5-1) than near the loop top during the main peak of bursts

Distribution of the polarization degree

Case 1: Injection at the loop top

Case 2: Injection near a footpoint

Increase in X-mode polarization degree $\Rightarrow$ signature of the perpendicular anisotropy

Ordinary mode circular polarization $\Rightarrow$ Signature of the longitudinal anisotropy

$P$, %

$s$, $10^9$ cm

$\omega = \text{17.0 GHz}$
Inversion of the circular polarization degree along flaring loops

The most remarkable property is that in the upper part of the loops, the polarization degree changes its sign to the opposite (from extraordinary to ordinary mode). This can not be obtained for isotropic or loss-cone type of pitch angle distribution of emitting electrons! → The evidence of perpendicular anisotropy (Morgachev et al 2014; 2015)
Modeling the spatial dynamics of the polarization degree

The polarization degree in the loop top has a positive value at a frequency of 17 GHz and a negative value in the footpoints (similar to observations).

It is clearly seen that the polarization remains negative ($P = -0.5...-1$) at the footpoints and remains positive ($P = 0.2...0.5$) at the loop top during the model burst.

In the transition region (highlighted by circles) during the burst, the circular polarization sign changes with time (from the right polarization to the left one). A similar change in the polarization sign was observed in our study of the flare loop.

The polarization degree along the loop varies slightly (from $-0.7...-1$ at the footpoints to $0.1...0.3$ at the top) at a frequency of 7 GHz. At 5 GHz there are no temporal and spatial changes in the polarization sign at all.

(Morgachev et al. 2015)
Conclusions

• It is shown that spatially resolved microwave observations are able to provide us with new knowledge on acceleration sites, energy, and pitch-angle distributions of accelerated electrons in flaring magnetic loops. As a consequence they may provide us with new constraints on particle acceleration mechanisms and models.

  ▪ Building new radio instruments with high spatial, spectral and temporal resolution is crucially important for solving the key problems in the physics of solar flare particle acceleration.

  NoRH \(\rightarrow\) MUSER, SRH
Thank you for your attention!