Birefringence Effect as a Tool for Astrophysical Plasma Study

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Group delay between two magnetoionic modes is discovered and spectrally confirmed ($\Delta t_g \propto f^{-3}$) for the first time for quasiperiodic narrow band millisecond solar radio pulsations. Analysis of cross delays and autodelays proves that both X and O modes originate at the same source, so the radiation is weakly polarized originally. This finding allows one to specify the emission mechanism of the pulsations to be a nonlinear plasma mechanism operating at the second harmonics. Physical parameters of the solar corona are determined by the use of the theory of the nonlinear plasma mechanism; they agree well with independent observations of solar millisecond pulsations.

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Astrophysical radiation originates and propagates in a magnetized plasma in most of the cases. Dispersion and gyrotropy of the plasma reveal themselves in many observable effects. For example, the wave dispersion gives rise to a delay in arrival of two signals emitted simultaneously at different frequencies, which has widely been observed for pulsars providing interstellar dispersion measures. The birefringence effect manifests itself in (i) Faraday rotation that is observed for various galactic and extragalactic objects and (ii) delay between extraordinary and ordinary waves emitted simultaneously at the same frequency, which has never been observed in astrophysics.

Generally, the group delay effect can be observed if the respective rotation measure is large enough. This is particularly the case for a solar (and a stellar) corona where the rotation measure can be as large as 10^5-10^6 rad/cm^2.

Nonthermal solar radio emission displays frequently so called superfine temporal structures, for example, millisecond solar radio spikes and millisecond pulsations [1–3]; the short time scales of the emission are favorable to observe the group delay.

A lot of theoretical models based on electron cyclotron maser (ECM) emission or the plasma mechanism of radio emission have been proposed to explain various kinds of the superfine structures (for a review, see [3]), while none of them is commonly accepted at the moment.

This Letter analyzes a crucial experiment on the discovery of group delay between oppositely polarized waves together with autodelays for each polarization. They allow specifying the emission mechanism producing millisecond pulsations of solar radio emission to be a nonlinear plasma mechanism operating at the second harmonics.

The nonlinear plasma mechanism includes two steps. The first step is generation of plasma waves under the simultaneous action of linear growth (produced by fast electrons) and nonlinear wave-wave interaction. The second step is the conversion of the plasma waves into transverse (X and O) waves at the fundamental and/or the second harmonics [4].

This mechanism was proposed 30 years ago theoretically [5], but there has not been found sufficient evidence for the mechanism to operate in the solar corona.

Generally, to specify an emission mechanism producing some kind of observed emission, the polarization of the radiation *at the source* is very important. Here, we analyze an event recorded during the rise phase of a continuum microwave burst on 2 November 1997 at frequencies $f = 2.81-2.89$ GHz from 03:02:17 UT to 03:02:21 UT by the spectrometer at 2.6–3.8 GHz of the Beijing Astronomical Observatory [6] with 8 ms time resolution and 10 MHz frequency resolution; see Fig. 1. This event displays quasiperiodic pulsations of both intensity (L and R) and the degree of polarization. Selected fragments of the records in Fig. 2 display clearly that the oppositely polarized pulsations are shifted in respect to each other by a considerable part of the period.

No emission mechanism is known to produce such oscillatory behavior of the degree of polarization (see [3]). The presented analysis proves the oscillations of polarization to be the result of the birefringence effect that reveals itself in different group velocities of ordinary and extraordinary waves in magnetized plasma of the solar corona.

The cross correlation and Fourier analyses of the oscillating L and R signals at different frequencies give

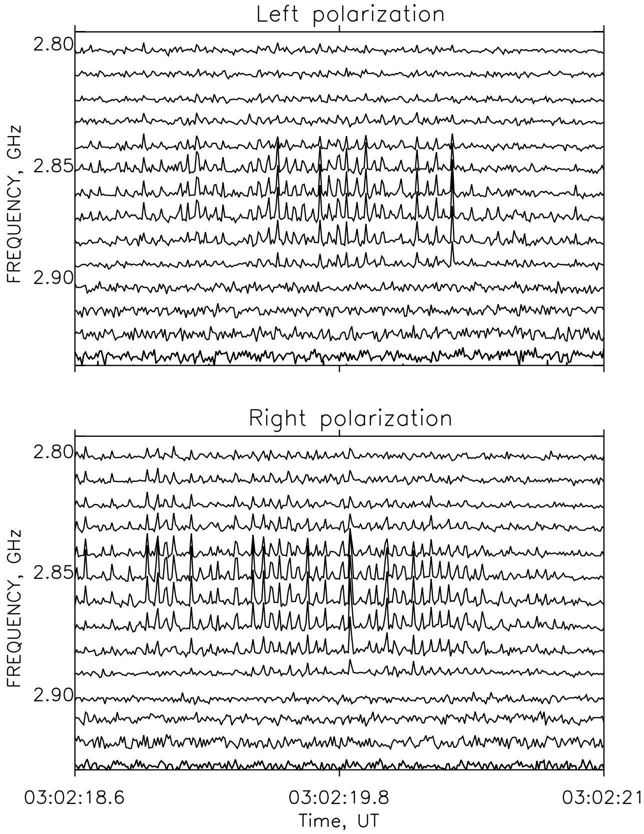

FIG. 1. Dynamic spectra of the pulsations for L and R polarizations of the narrow band event around 2.85 GHz.

the value of the period of oscillations, $\tau_p = 40 \pm 1$ ms, and reveal a delay $\Delta t = 20 \pm 2$ ms between opposite polarities.

The physical origin of the delay can be specified by the study of its frequency dependence. This task requires an as precise as possible determination of the signal phase $\Delta\phi$ which relates to the time delay $\Delta t = \tau_p \Delta\phi$.

According to the Nyquist theorem [7–9] a digitized signal carries rather precise information on the quasiperiodic signal phase if there are more than two points per period. This condition is excellently fulfilled for our case because the sampling rate of the spectrometer is 8 ms, so we have five points per each period. The presence of noise in the

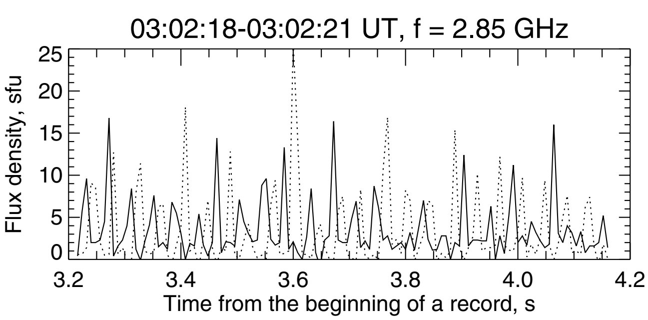

FIG. 2. Extended time segments of the pulsation event at $f = 2.85$ GHz during a 1 s time segment in R (solid line) and L (dotted line) polarizations. A time shift between the components is well visible.

data contributes an error to the phase determination, and, respectively, to the time delay between R and L quasiperiodic components:

$$\delta t = \frac{\sigma_N}{\sqrt{2}\,\sigma_S} \frac{\tau_p}{\sqrt{K}}, \tag{1}$$

where K is the total number of periods of the oscillating function, σ_N is the standard deviation of the noise signal before the beginning of pulsations or after the end of them; σ_S is the standard deviation of the signal during the pulsations. We obtained $\delta t = 0.3\text{–}0.8$ ms at various frequencies for our data set.

Figure 3 displays the determined values of the cross delay between L- and R-polarized emission and Fig. 4 displays the autodelays for each mode in respect to the signal at $f_o = 2.81$ GHz vs frequency. The frequency dependence in Fig. 3 fits the theoretical law for the group delay between the two magnetoionic modes.

Indeed, the group delay arising from the difference in group velocities of O and X waves at high frequencies, $\omega^2 \gg \omega_{pe}^2, \omega_{Be}^2$, in the magnetized plasma of solar corona is

$$\Delta t_g = \frac{2}{c} \int_0^\infty \frac{\omega_{pe}^2(z)\omega_{Be||}(z)}{\omega^3}\, dz = \frac{2}{c} \frac{\omega_{ps}^2 \omega_{Bs||}}{\omega^3} H_{\rm eff}, \tag{2}$$

where $\omega_{Bs||} = \omega_{Bs} \cos\theta$; ω_{ps} and ω_{Bs} are the plasma frequency and gyrofrequency at the source, θ is the angle between magnetic field and the line of sight, c is the speed of light, and $H_{\rm eff}$ is the effective scale of inhomogeneity in the solar corona.

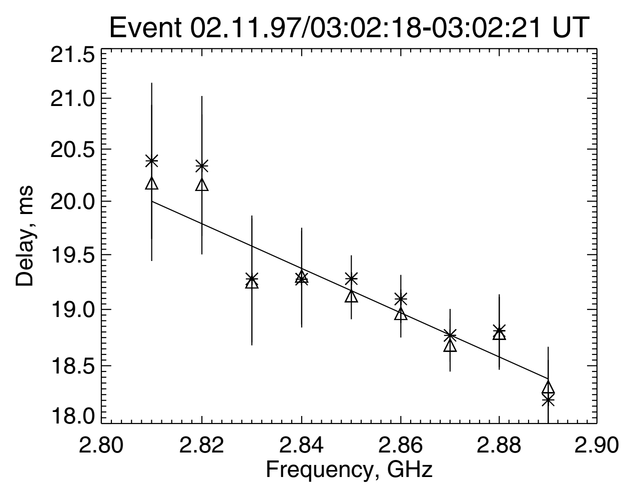

FIG. 3. Frequency dependence of the delay between R- and L-polarized components of oscillations in the log-log scale. The delays are taken at the frequencies of Fourier maxima for R (asterisk) and L (triangle) components. The calculated linear regression log(delay) $= a + b\,$log(frequency) gives, with the probability 95%, $b = -2.99 \pm 0.89$ and the correlation coefficient $r = 0.95$ for the points taken at L-component Fourier maxima, and, respectively, $b = -3.35 \pm 0.68$ and $r = 0.94$ for the points taken at R-component Fourier maxima. The solid line is the theoretical dependence, $\propto f^{-3}$.

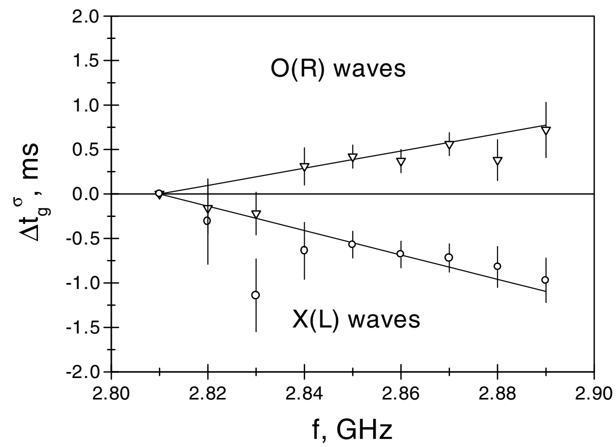

FIG. 4. The autodelays for R (triangles) and L (spheres) components in respect to the signals at $f_o = 2.81$ GHz. The solid lines represent the calculated autodelays for an inhomogeneous source according to Eq. (3) when $z_x(\omega) = z_o(\omega)$, $H_x = H_o$, $æ = 0.3$. The group velocities are calculated by exact expressions for cold magnetized plasma.

The frequency dependence of the group delay ($\Delta t_g \propto f^{-3}$) is shown in Fig. 3 by the solid line. The observational points agree well with the theoretical curve for the group delay. Thus, we can conclude that the observed delay (at least the bulk of it) is the group delay arising within the path between a site where the polarization originates and the observer, and the observed oscillations of the degree of polarization arise due to the shift of oppositely polarized components of originally weakly polarized signal.

Let us discuss now the autodelays for both O and X waves (Fig. 4). Obviously, the group velocity increases with frequency, so a high-frequency signal should arrive before the low-frequency one (for each mode) if they are generated simultaneously at a point source. Figure 4 shows that this is the case for the X mode, while the low-frequency O mode arrives before the high-frequency O mode, which cannot be explained by the group effect alone. Thus, we should take into account the nonzero size of the source along the line of sight. For the extended source located in gradually inhomogeneous solar corona, higher frequency emission is generated deeper in the corona and it covers a longer distance to the observer than lower frequency emission. For the event under study, the effect of inhomogeneity dominates the group delay for O waves and partly compensates it for X waves.

The autodelays for the extended source are easy to calculate in linear over the $\Delta\omega/\omega$ approximation taking into account the narrow bandwidth of the pulsations, $\Delta\omega/\omega \approx 3\%$:

$$\Delta t_\omega^\sigma = \frac{z_\sigma(\omega)}{v_{g\sigma}(\omega_o)} + \frac{\Delta\omega}{\omega_o}\left(\omega \frac{\partial v_{g\sigma}^{-1}(\omega)}{\partial\omega}\right)_{\omega=\omega_o} H_\sigma\,, \quad (3)$$

where H_σ is the effective length that σ waves propagate in the corona, $z_\sigma(\omega)$ is the level where most of the σ-mode radiation at the frequency ω originates, $\Delta\omega = \omega - \omega_o$; we accept $\omega_o = 2\pi \times 2.81$ GHz, $z_\sigma(\omega_o) = 0$. It is important to note that $z_x(\omega)$ and $z_o(\omega)$, the zero levels $z_x(\omega_o) = 0$ and $z_o(\omega_o) = 0$, and the effective lengths H_x and H_o are generally different from each other, particularly if the radiation originates as fully polarized, then propagates some distance to "a depolarization site," and then the two modes propagate together to the observer. For the further analysis we accept (which is correct in the linear approximation)

$$z_\sigma(\omega) = æ_\sigma \frac{\Delta\omega}{\omega_o} H_\sigma\,, \quad (4)$$

where $æ_\sigma$ is a dimensionless number ($æ_\sigma = 1$ if coronal gradients are constant through the line of sight).

The solid lines in Fig. 4 are plotted for the case $H_x = H_o = H_{\mathrm{eff}}$ [H_{eff} is the effective scale contributing to the cross delay, Eq. (2)], $z_x(\omega) = z_o(\omega) = z(\omega)$ (respectively, $æ_x = æ_o = æ$). The æ value is determined to be $æ \approx 0.3$ from the analysis of the sum of autodelays ($\Delta t_x + \Delta t_o$) with the use of Eq. (3). Consequently, local coronal gradients at the source are 3 times stronger than averaged coronal gradients. The observational points in Fig. 4 fit well (within the error bars) the theoretical curves. Thus, we conclude that O and X waves originate simultaneously at the same source.

This finding gives rise to an important conclusion about the emission mechanism producing the pulsations. Indeed, the polarization degree of the pulsating emission at the source is found to be rather weak. It is exceedingly important that the second harmonic plasma emission is the only coherent mechanism providing weakly or moderately polarized radio emission, while both ECM (at any gyroharmonics) and fundamental plasma emission produce fully (100%) polarized radio emission at the source [2,3].

The distinctive feature of the nonlinear plasma mechanism is the production of quasiperiodic pulsations with the typical period of tens of ms [4], so we do not need any additional assumption to explain the intensity oscillations themselves.

Thus, the thoroughly developed theory of the nonlinear plasma mechanism [4,5,10–12] can be applied to find many parameters involved. We restrict our discussion to a few particular parameters only.

First of all, Eq. (2) reaches its maximum for harmonic plasma emission if $Y = \omega_{pe}/\omega_{Be} = \sqrt{2}$. Because the preceding observations with lower temporal resolution (~30 ms) did not reveal any confident delay of $\Delta t > 30$ ms between the two polarized components of the solar millisecond quasiperiodic pulsations [13], we can assume the favorable coronal conditions. This yields an estimate of the plasma frequency to gyrofrequency ratio Y to be close to the optimal value $\sqrt{2}$. Together with the second harmonic condition $\omega \approx 2\omega_{\mathrm{UH}}$ and the dispersion relation for upper-hybrid waves,

$$\omega_{\mathrm{UH}}^2 = \tfrac{1}{2}(1 + 3k^2 d_e^2)\{(\omega_{pe}^2 + \omega_{Be}^2) + [(\omega_{pe}^2 + \omega_{Be}^2)^2 - 4\omega_{pe}^2\omega_{Be}^2\cos^2\theta]^{1/2}\}, \quad (5)$$

this yields the number density $n \approx 1.7 \times 10^{10}$ cm^{-3} and the magnetic field $B \approx 290$ G at the source.

Analysis of Eq. (5) together with the observed spectral bandwidth $\Delta\omega/\omega \approx 3\%$ gives rise to an important conclusion about the angular distribution of the upper-hybrid waves at the source. Indeed, isotropic distribution of the waves would provide the bandwidth $\Delta\omega/\omega \approx$ 10%–20%, so the waves should be concentrated within the angle $\Delta\theta < 30°$ to ensure the smaller observed bandwidth. Since upper-hybrid waves are known to originate primarily transverse to the magnetic field [4,10,11] and distribution of the waves remains clearly anisotropic during the pulsations, the radio waves are generated mainly along the magnetic field, which follows from the conservation laws. This agrees well with earlier discovered directivity of radio pulsations: no flares connected with pulsations were observed between 70° and 90° (both east and west) from the central meridian [13].

Furthermore, it is easy to estimate [with Eq. (2)] the effective scale of coronal inhomogeneity $H_{\rm eff} \approx 5 \times 10^9$ cm (that corresponds to the rotation measure RM $\approx 5.3 \times 10^5$ rad/cm^2) and the source size

$$L = z(2.89 \text{ GHz}) = æ \frac{\Delta f}{f_o} H_{\rm eff} \approx 400 \text{ km} \qquad (6)$$

with the use of Eq. (4). On the other hand, the size of the region emitting at any individual frequency can be estimated from the observed flux using standard theory of harmonic plasma emission [4] as $l \approx 100$ km. These two scales agree well with each other: each 100 km region of the source produces emission with a “natural” bandwidth of 20–30 MHz ($\sim$1%, as follows from the model [10,11]), and all the regions compose the 400 km source providing the total bandwidth of the pulsations ($\sim$3%) due to source inhomogeneity.

Thus, the discovery of group effects (both cross delays and autodelays) provides us with new important knowledge in solar physics. First, the group (cross) delay between two magnetoionic modes is spectrally confirmed for the first time in astrophysics. This gives rise to the direct measurement of the coronal rotation measure (and further estimates of number density, magnetic field, and effective scale of coronal inhomogeneity). Second, the careful analysis of cross and autodelays allows us to conclude confidently that the radio emission originates at the source as weakly polarized. This finding restricts strongly the underlying emission mechanism: it eliminates both ECM and fundamental plasma emission, while it is pretty consistent with nonlinear harmonic plasma emission.

The use of the respective theory of the nonlinear plasma mechanism provides a rather detailed and consistent source plasma diagnostics. Moreover, the interpretation agrees with preceding observations of solar millisecond pulsations. For example, the anisotropy of exited upper-hybrid waves ensures the directivity of pulsating events found earlier [13] in a natural way.

Quasiperiodic millisecond radio pulsations have been regularly observed by various observatories [13,14]. However, the lack of polarization measurements or insufficient temporal resolution did not allow discovery of the group delay effect. We analyze here the only one event recorded soon after the Beijing radio spectrometer (providing the highest combined temporal and spectral resolution achieved so far [6]) had been installed. There is a much larger data set now waiting for comprehensive analysis. A preliminary look at the data shows that the events with measurable time delays are rather common.

The observational capabilities are permanently increasing that should enable various observatories to measure group effects and use them further for the astrophysical plasma study. For the solar case the study of the group delay effect in the corona can currently be used as a powerful tool to specify the emission mechanism providing a particular type of solar radio emission with superfine temporal structure.

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