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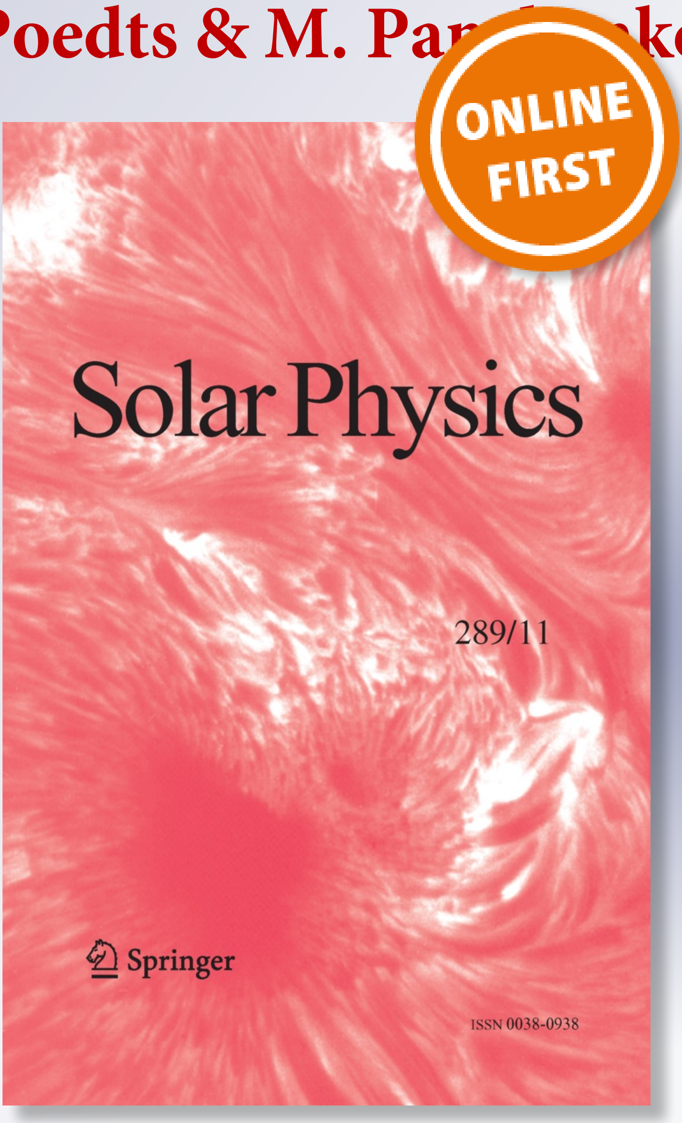
Solar Physics
A Journal for Solar and Solar-Stellar
Research and the Study of Solar
Terrestrial Physics

ISSN 0038-0938

Sol Phys
DOI 10.1007/s11207-014-0615-6



Springer

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NEW EYES LOOKING AT SOLAR ACTIVITY

Decameter U-burst Harmonic Pair from a High Loop

V.V. Dorovskyy · V.N. Melnik · A.A. Konovalenko · I.N. Bubnov · A.A. Gridin · N.V. Shevchuk · H.O. Rucker · S. Poedts · M. Panchenko

Received: 26 February 2014 / Accepted: 11 October 2014

Abstract The results of the first observations of solar sporadic radio emission within 10 – 70 MHz by the *Giant Ukrainian Radio Telescope* (GURT) are presented and discussed. Observations in such a wide range of frequencies considerably facilitate the registration of harmonic pairs. The solar U-burst harmonic pair observed on 8 August 2012 is analyzed. The burst key features were determined. Among them, the time delay between the fundamental and harmonic emissions was of special interest. The fundamental emission was delayed for 7 s with respect to the harmonic emission. A model for explaining the occurrence of such a delay is proposed, in which the emission source is located inside a magnetic loop containing plasma of increased density. In this case, the delay appears due to the difference in group velocities of electromagnetic waves at the fundamental and the harmonic frequencies.

Keywords Corona, radio emission · Corona, structures · Radio bursts, meter-wavelengths and longer (m, dkm, hm, km) · Radio bursts, type U · Radio bursts, harmonic pairs

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New Eyes Looking at Solar Activity: Challenges for Theory and Simulations
Guest Editors: Silja Pohjolainen and Marian Karlický

V.V. Dorovskyy (✉) · V.N. Melnik · A.A. Konovalenko · I.N. Bubnov · A.A. Gridin · N.V. Shevchuk
Institute of Radio Astronomy, Kharkov, Ukraine
e-mail: dorovsky@rian.kharkov.ua

V.N. Melnik
e-mail: melnik@rian.kharkov.ua

N.V. Shevchuk · S. Poedts
Catholic University Leuven, Leuven, Belgium

S. Poedts
e-mail: Stefaan.Poedts@wis.kuleuven.be

H.O. Rucker
Commission of Astronomy, Austrian Academy of Sciences, Vienna, Austria
e-mail: helmut.rucker@oeaw.ac.at

M. Panchenko
Space Research Institute, Graz, Austria
e-mail: mykhaylo.panchenko@oeaw.ac.at

1. Introduction

Solar U-bursts are known since 1958 (Maxwell and Swarup, 1958) and are considered to be a variant of normal type III bursts. Both type III and U bursts have similar exciters (sub-relativistic electron beams) and the same plasma emission mechanism (Suzuki and Dulk, 1985). The main difference between them is the trajectory of the propagation of the exciter. Unlike type III electrons, which propagate along open magnetic field lines, electrons responsible for the U-bursts move along magnetic loops that form the shape of an inverted letter U in the time–frequency plane. Type U bursts are studied in a wide frequency range, *viz.* in decimeter (Aschwanden *et al.*, 1992; Fernandes *et al.*, 2012), meter (Maxwell and Swarup, 1958; Aurass and Klein, 1997), decameter (Leblanc and Hoyos, 1985; Dorovskyy *et al.*, 2010), and hectometer bands (Stone and Fainberg, 1971). However, these bursts are mainly observed in meter and decameter bands (Leblanc, Poquerusse, and Aubier, 1983). The U-bursts registered at these frequencies may originate from coronal loops as high as $2-4\ R_\odot$ (Leblanc and Hoyos, 1985), where $R_\odot$ denotes the solar radius.

The plasma emission mechanism assumes the generation of electromagnetic waves not only at the local electron plasma frequency (the fundamental, or simply the F frequency), but also at doubled fundamental or harmonic (H) frequency. From the theoretical viewpoint, the instant ratio between the H and F frequencies should equal to two (Zhelezniakov, 1969). But many observations of different types of solar bursts show that this ratio lies between 1.6 and 2.0, with the average value equal to 1.8 (Stewart, 1974). One of the reasons of this effect can be the time delay of the F emission with respect to the H emission, as schematically shown in Figure 1(a, b).

When the fundamental component F of type III bursts is delayed by Δt with respect to the harmonic component H, it is shifted along the time axis from its initial position, shown by the dashed line, to the observed position, shown by solid line and marked as $\mathrm{F_d}$ (delayed fundamental) (Figure 1a). In this case, the measured H-to-F ratio $f_{\mathrm{H}}/f_{\mathrm{F_d}}$, at time t_0 will be lower than the initial ratio $f_{\mathrm{H}}/f_{\mathrm{F}}$ without the delay. Since type III bursts are usually smooth and do not have any specific markers in time or in frequency, we cannot retrieve the time delay from the dynamic spectrum. In contrast, type U bursts do have such specific markers, *e.g.* the turning points, which are localized in both time and frequency. Thus, solar U-bursts provide a unique possibility of detecting both the initial H-to-F ratio and the time delay of the one component with respect to the other component, since the delay does not change the turning frequency.

In this article, we discuss the results of recent observations of a solar U-burst harmonic pair in the decameter band, performed by the radio telescopes UTR-2 and GURT (Dorovskyy *et al.*, 2013). In particular, we focus on interpreting the time delay between the harmonic and fundamental components of the burst.

2. Observations

The harmonic pair of U-burst to be discussed here was observed on 8 August 2012 by one section of the new radio telescope GURT (Konovalenko *et al.*, 2011; Bubnov *et al.*, 2011), which is currently being built near the existing radio telescope UTR-2 (Kharkov, Ukraine).

The section is a square active antenna array consisting of five rows and five columns oriented along the East–West and North–South directions, respectively, or 5 × 5 cross-dipoles (Figure 2).

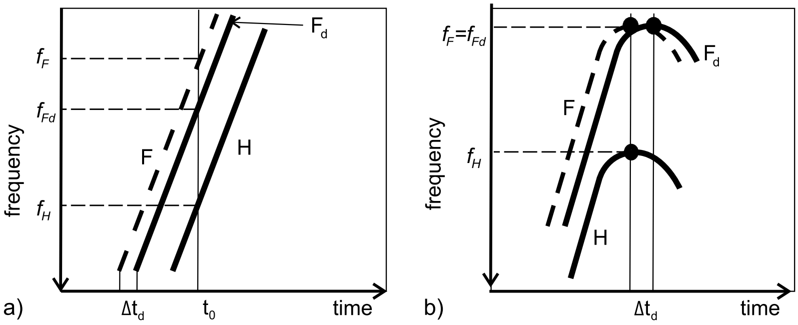


Figure 1 Effect of the time delay on the measured F-to-H ratio for type III (a) and type U bursts (b).

Figure 2 General view of the GURT section.

Table 1 Technical characteristics of the GURT section.

Frequency band	10 – 70 MHz
Sector of beam steering	± 70° from zenith
Section dimensions	18.75 × 18.75 m
Beam width[a]	20°

[a] Measured at 40 MHz frequency.

The individual dipoles are spaced at a distance of 5.75 m from each other along the rows and columns. All dipoles are mounted at 1.6 m above the ground and oriented at 45° to the meridian. The main technical characteristics of the GURT section are provided in Table 1.

The main aim of the observations carried out in 2012 was to test the ability of the newly built section to register different types of solar sporadic radio emission. The registration was performed by the digital spectropolarimeter DSP-Z that had two independent channels providing real-time FFT analysis with time and frequency resolutions of 1 ms and 4 kHz (Ryabov *et al.*, 2010). To cover the whole working frequency band of the GURT section, a special technique was used: the first DSP-Z channel registered the radio emission in the frequency range 8 – 33 MHz, and the second one operated within frequencies from 33 to 66 MHz. The resulting partial spectra were then combined using dedicated software. Despite the small effective area and the rather wide antenna beam of the GURT section, many

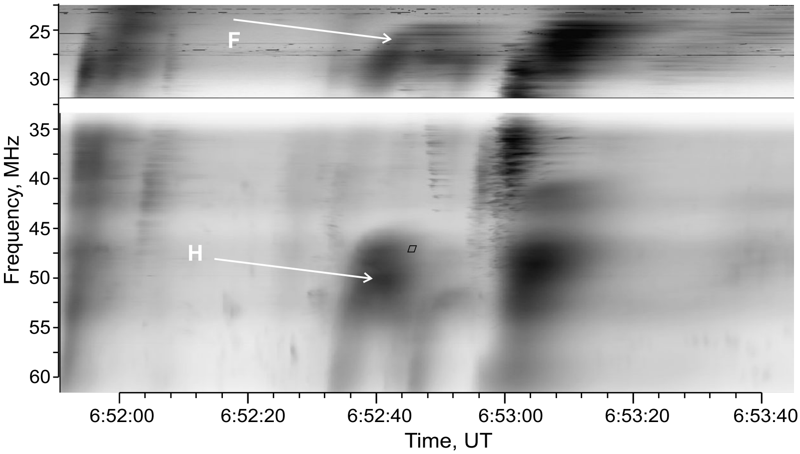


Figure 3 Dynamic spectrum of the U-burst observed on 8 August 2012. The fundamental component is marked as F, the harmonic component as H.

type III bursts were registered. Among all observed bursts, the U-burst recorded on 8 August 2012 was of especial interest. First, type U bursts with a well-developed descending branch are extremely rare, especially in the decameter band. Second, the U-burst registered at the lower half-band had the counterpart at the higher half-band, which might indicate a manifestation of a harmonic structure. Evidence of the harmonic relation between these two U-bursts are given below. The combined dynamic spectrum of the event is shown in Figure 3. Because the calibration system was not yet completed, it was not possible to measure the flux. Instead, we used the UTR-2 data for this purpose because there were simultaneous observations with this radio telescope. Hence, we found that the peak flux of the U-burst at frequencies 10 – 33 MHz did not exceed 30 s.f.u. (1 s.f.u. = $10^{-22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$). The U-burst appeared to be quite faint and diffuse, which could hinder detecting the time and frequency parameters. This matters, in particular, when the time of the flux peak due to flatness of the top of the burst profile is determined. Instead, we used the differentials of the time spectra, which are more sensitive to flux fluctuations. In the differential dynamic spectrum, the flux peak corresponds to the time when the sign of the flux derivative changes from positive to negative, or from white to black in the image (see Figure 4). This technique allowed us to considerably increase the accuracy and unambiguity of the burst parameters detection.

The measurement results are shown in Table 2.

The values marked with an asterisk in Table 2 were measured at frequencies 30 MHz and 60 MHz for the ascending branches of the F and H bursts. The turning time is the time when the frequency drift rate of the U-burst becomes zero.

The duration and drift rate of the U-burst ascending branch agree well with those of normal type III bursts in the decameter band (Melnik *et al.*, 2005; Abranin *et al.*, 1980; Abranin, Bazelyan, and Tsybko, 1990), except for the drift rates, which appeared to be slightly lower. The lower drift rates of the U burst can be ascribed to the stronger inclination of the beam trajectories with respect to the radial, as compared to that in type III bursts (Fokker, 1970).

We concluded that these two solar U-bursts were harmonically connected because

- the ratio of the turning frequencies of the bursts was close to two (Zhelezniakov, 1969);

Figure 4 Differential in time domain of the dynamic spectra of the fundamental (a) and harmonic (b) components of the burst. Flux peak lines are marked with arrows, and the turning points are circled.

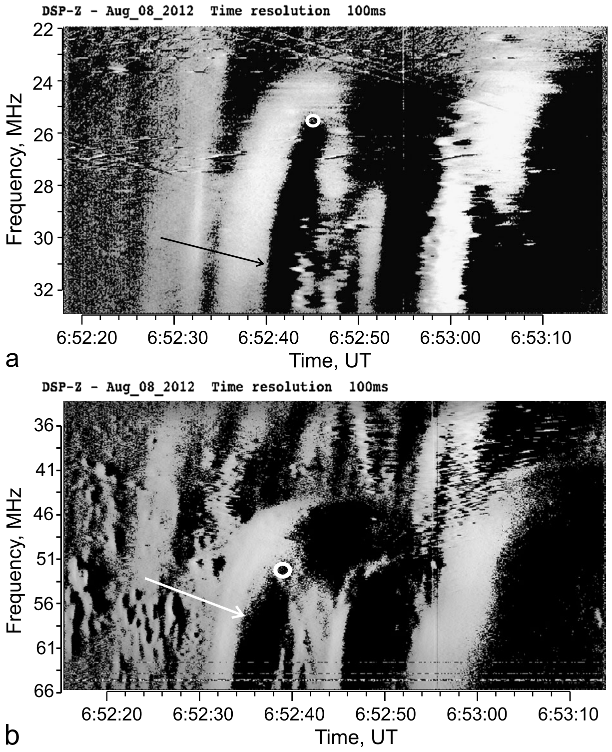


Table 2 The parameters of the U-burst harmonic pair.

	Fundamental	Harmonic
Half-flux duration*, s	7 ± 0.2	5 ± 0.2
Frequency drift rate*, $\mathrm{MHz\,s^{-1}}$	-2.2 ± 0.3	-4.2 ± 0.5
Turning frequency, MHz	25.5 ± 0.1	51.2 ± 0.3
Turning time, UT	$06^{\mathrm{h}}52^{\mathrm{m}}45.2 \pm 0.2^{\mathrm{s}}$	$06^{\mathrm{h}}52^{\mathrm{m}}38.3 \pm 0.5^{\mathrm{s}}$

* Measured at frequencies 30 MHz (F) and 60 MHz (H) for the ascending branches.

- the ratio between the drift rates of the corresponding parts of the ascending arms of the bursts were also close to two by analogy with normal type III harmonic pairs (Abranin, Bazelyan, and Tsybko, 1993);
- the two bursts were morphologically similar, with a well-defined time of the frequency turnover, but with the lower frequency turnover being delayed by 7 ± 0.5 s with respect to the upper frequency turnover.

To corroborate this conclusion, we note that because type U bursts are extremely rare events compared with type III bursts (Aurass and Klein, 1997), the probability of simple coincidence of two type U bursts originating from different loops is negligible. As noted above, type U burst harmonic pairs give a unique possibility to detect the real delay between them. That is why we have selected this parameter for deeper analysis. Thus, in the next section we attempt to interpret the observed time delay.

The spectral width of the fundamental component of the U-burst near the turning frequency equals ≈ 1.75 MHz. Since at this point the electrons move parallel to the solar surface, the above spectral width appears to be defined by the loop thickness.

3. Interpretation and Discussion

Assuming simultaneous emission of the two harmonically connected components of the burst, the delay of the fundamental component may arise either from different propagation speeds of the electromagnetic wave of the fundamental frequency (F wave) and that of harmonic frequency (H wave), or from a refraction effect.

The first scenario was analyzed by Robinson and Cairns (1998). Since in the frame of the plasma emission mechanism, the F wave is generated near the local plasma frequency, its group velocity is much lower than the group velocity of the H wave in the same region. Their analysis shows that the total delay time due to this mechanism in the standard corona equals about 1 s for the meter band. Similar results were obtained by computer modeling performed for the decameter band by Rutkevych and Melnik (2012). According to these computer simulations, the longest group delay of the F wave at frequency 25 MHz obtained for the Newkirk corona model equaled about 2 s.

The time delay caused by refraction effects was estimated by Thejappa, MacDowall, and Gopalswamy (2011). They reconstructed the trajectories of the two waves using data of the two STEREO satellites and showed that the time delay of the F wave depends inversely on the frequency, reaching 5.28 s at the highest frequency of their analysis, *i.e.* 1775 kHz. It is thus evident that neither of the two models can explain the long time delay that took place in our observations.

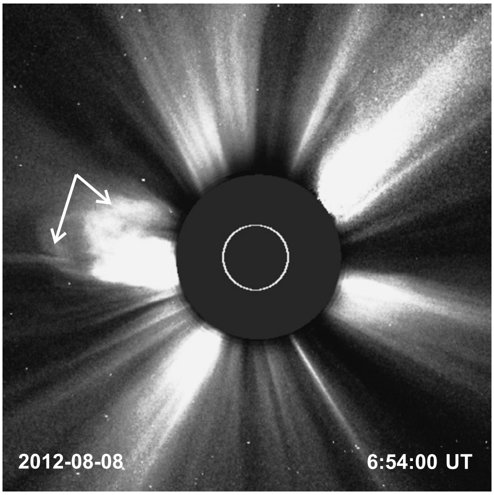
In our opinion, the observed delay between the turning points of the F and H components of the U-burst was determined nevertheless by the difference in their travel times from source to the observer, caused by the difference between the group velocities of the F and H waves, as was proposed by Robinson and Cairns (1998) and Rutkevych and Melnik (2012). But, in addition, we propose that the source of the burst was located inside a magnetic loop containing plasma of increased density and temperature.

U-bursts with turning frequencies of about 25 MHz are typically associated with coronal loops as high as $1.6-1.7\ R_{\odot}$ (Dorovskyy *et al.*, 2010). No such loops were visible in SOHO/LASCO C2 and C3, nor in STEREO/COR2-B images. Instead, the STEREO/COR2-A image showed loop structures that were $5-6\ R_{\odot}$ high (indicated by arrows in Figure 5). This may occur when the loop was situated on the western part of the solar disk. Apparently, taking into account the positions of all spacecraft (Figure 6a), such a loop would be mostly behind the limb for the STEREO-B satellite, would be shielded by the occulting disks of the SOHO coronagraphs, and thus could not be visible. At the same time, this loop would be almost on the limb for STEREO-A coronagraphs and could be clearly observed.

From analyzing the daily Sun charts and sunspots and their magnetic fields for that date (Figure 6b), and also using the magnetic field extrapolation technique available at the SDO website (http://sdowww.lmsal.com/suntoday/index.html?suntoday_date=2012-08-07#), we can reasonably assume the existence of magnetic field lines that connect Active Region NOAA 11537 (N19W56) with NOAA 11538 (S22W37) or NOAA 11540 (S26W10), forming corresponding coronal loops.

At the same time, it is known that coronal loops with heights of several solar radii are closely connected with solar transient events, such as CMEs (Leblanc, Poquerusse, and Aubier, 1983). We assume that the observed high coronal loops might be generated by a

Figure 5 Loop structures (marked with arrows) in the COR2-A image.



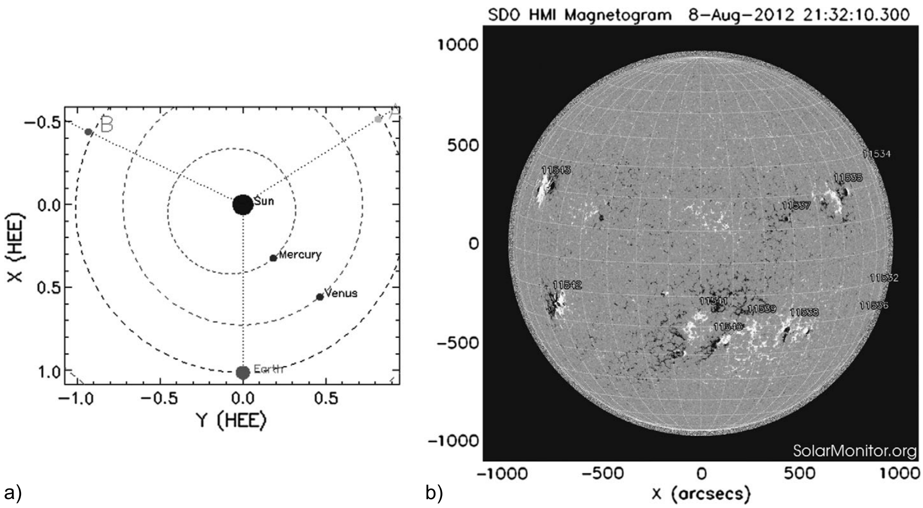
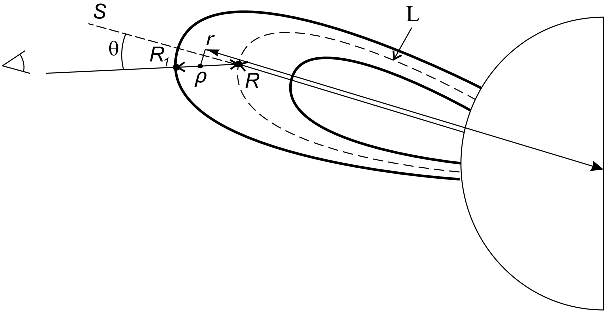


Figure 6 STEREO-A and -B spacecraft positions (a) and AR location on the solar disk (b) on 8 August 2012.

CME that appeared in the LASCO-C2 field of view about 5:48 UT according to the SOHO-LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2012_08/univ2012_08.html).

To fit the observed U-bursts turnover frequencies and the apparent loop height, we assume that the loop holds plasma of higher density than the ambient corona. Dense plasma inside the loop means that the time delay is formed while both F and H waves travel from the source to the loop boundary along the line of sight because outside the loop, the group velocities of both waves are close to the speed of light. A schematic representation of the corresponding loop is shown in Figure 7. Here, the position of the source with a local plasma frequency of 25.5 MHz is marked as R, the point where the emission leaves the loop is R_1, the trajectory of the fast electrons is L, and the angle between the symmetry line S of the

Figure 7 Schematic view of the loop associated with the U-burst.



loop and the direction to the observer is θ. Judging from the positions of the spacecraft (Figure 6a) and coronagraph images (Figure 5), we assume this angle to be about 20°.

In general, the time required for electromagnetic waves to travel from source R to loop boundary R_1 is defined by the equation

$$t = \int_{R}^{R_1} \frac{\mathrm{d}\rho}{V_{\mathrm{gr}}(R,\rho)} = \frac{1}{\cos\theta} \int_{R}^{R_1} \frac{\mathrm{d}r}{V_{\mathrm{gr}}(R,r)}, \tag{1}$$

where V_{gr} is the group velocity of the electromagnetic wave at distance r from the Sun (or at distance ρ from the source, as illustrated in Figure 7). Thus, to find the time delay, we need to obtain the dependence of the group velocities of both the F and H waves on the distance from source ρ in the segment $R - R_1$.

To analytically express the group velocities of the F and H waves, we assume that the burst is generated by fast electrons moving along the loop axis L with velocity v_0. These electrons may excite Langmuir waves l under conditions of Cherenkov resonance predominantly with wave number $k_{l,0} = \omega_{\mathrm{pe}}/v_0$, where $\omega_{\mathrm{pe}} = \sqrt{\frac{4\pi e^2 n(r)}{m_{\mathrm{e}}}}$ is the local plasma frequency, e is the electron charge, $n(r)$ is the plasma density at the heliocentric distance r, and m_{e} is the electron mass. We assume an isothermal plasma where electron and proton temperatures and densities are equal. When they are scattered off, thermal ions i in the process $l + i = t + i$, the Langmuir wave l is transformed into a transverse wave t at the fundamental frequency that equals the Langmuir wave frequency $\omega_{t_{\mathrm{F}}} = \omega_{l,0} = \sqrt{\omega_{\mathrm{pe}}^2 + 3k_{l,0}^2 v_{\mathrm{Te}}^2} = \omega_{\mathrm{pe}}\sqrt{1+\alpha}$, where $\alpha = 3v_{\mathrm{Te}}^2/v_0^2$, and v_{Te} is the thermal electron velocity.

In addition, the process of the coalescence of two Langmuir waves, $l + l = t$, results in radio emission at the doubled Langmuir wave frequency $\omega_{t_{\mathrm{H}}} = 2\omega_{l,0}$.

Taking into account the dispersion law of the transverse waves in plasma for both F and H radio emissions, we can write $\omega_t = \sqrt{\omega_{\mathrm{pe}}^2 + k_t^2 c^2} = N\omega_{\mathrm{pe}}\sqrt{1+\alpha}$, where $N = 1, 2$ for the F and H waves.

When traveling from the source to the observer, the transverse wave does not change its frequency ω_t. At the same time, the plasma density and thus the plasma frequency decrease, resulting in an increase of the wave number and group velocity of the transverse wave according to

$$k_t(r) = \frac{1}{c}\sqrt{N^2\omega_{\mathrm{pe}}^2(R)(1+\alpha) - \omega_{\mathrm{pe}}^2(r)}, \tag{2}$$

$$v_{\mathrm{gr}}(R,r,N) = \frac{k_t(r)c^2}{\omega_{t,0}} = c\sqrt{1 - \frac{n(r)}{N^2 n(R)(1+\alpha)}}, \tag{3}$$

where $n(R)$ is the plasma density at the source when $r=R$. From this equation it is evident that the group velocity of the F wave is lower than that of the H wave.

It follows from Equation (3) that the variation of the group velocities of both components of the harmonic pair on their way from the source to the loop boundary is defined by the plasma density profile inside the loop, *i.e.* $n_{\mathrm{e}}(r)$. We assume that the plasma inside the loop is gravitationally stratified and follows the Boltzmann distribution, as assumed, for example, in Mann *et al.* (1999). Thus, using a decomposition on short interval due to $\rho \ll R$, we finally obtain

$$n(R) = n_0 \exp\left(-\frac{\rho}{a}\right), \tag{4}$$

where $n_0 = 7.75 \times 10^6\ \mathrm{cm}^{-3}$ is the plasma density at the source ($\rho = 0$) for the observed turnover frequency of 25 MHz, $a = (\frac{\tilde{\mu} G M_{\odot} m_{\mathrm{p}}}{R^2 k T})^{-1}$, $\tilde{\mu}$ is the mean molecular weight, which for the solar corona equals 0.6 (Priest, 1982), G is the gravitational constant, $M_{\odot}$ is the mass of the Sun, m_{p} is the proton mass, k is the Boltzmann constant, and T is the plasma temperature.

Using Equations (3) and (4), Equation (1) can be rewritten as follows:

$$t = \frac{1}{c \cdot \cos\theta} \int_0^{\Delta R} \frac{\mathrm{d}\rho}{\sqrt{1 - \frac{\exp(-\rho/a)}{N^2(1+\alpha)}}}. \tag{5}$$

The exact analytical solution of the integral (5) gives us the difference between the arrival times of the fundamental and harmonic components to the observer in the form of

$$t_{\mathrm{F}} - t_{\mathrm{H}} = \frac{2a}{c \cdot \cos\theta} \left(\sqrt{\alpha + \Delta R/a} - \sqrt{\alpha} - \frac{\Delta R}{a\sqrt{3}}\right). \tag{6}$$

Taking into account that $\alpha \ll 1$, Equation (6) can be simplified depending on the ratio between $\Delta R/a$ and α,

$$t_{\mathrm{F}} - t_{\mathrm{H}} = \frac{\Delta R}{c \cdot \cos\theta \sqrt{\alpha}}, \quad \text{if } \Delta R/a \ll \alpha, \tag{7}$$

and thus

$$t_{\mathrm{F}} - t_{\mathrm{H}} = \frac{2a}{c \cdot \cos\theta} \sqrt{\frac{\Delta R}{a}}, \quad \text{if } \Delta R/a \gg \alpha. \tag{8}$$

The width of the dynamic spectrum Δf at the turning frequency f is apparently determined by the half-width of the top of the loop ΔR,

$$\Delta f = f(R) - f(R + \Delta R) \approx f(R) \frac{\Delta R}{2a}. \tag{9}$$

From this, it follows that

$$\frac{\Delta R}{a} = \frac{2 \Delta f}{f}. \tag{10}$$

From the experiment, the spectral width of the top of the U-burst equals $\Delta f \approx 1.75$ MHz, thus we obtain $\Delta R/a \approx 0.14$. Taking into account Equations (6) and (7), we deduce the next equalities:

$$\left(\frac{R}{R_{\odot}}\right)^2 \frac{v_{\mathrm{Te}}}{c} \frac{v_0}{c} = 0.082, \quad \text{if } v_0 < 4.6 v_{\mathrm{Te}}, \tag{11}$$

Table 3 Constraints on plasma temperature within the loop.

Conditions	$v_0 < 4.6v_{\mathrm{Te}}$		$v_0 > 4.6v_{\mathrm{Te}}$	
	$R = 4\ R_\odot$	$R = 6\ R_\odot$	$R = 4\ R_\odot$	$R = 6\ R_\odot$
T, °K	$> 6.5 \times 10^6$	$> 2.9 \times 10^6$	3.3×10^6	1.45×10^6

and

$$\frac{R}{R_\odot}\frac{v_{\mathrm{Te}}}{c} = 0.094, \quad \text{if } v_0 > 4.6v_{\mathrm{Te}}. \tag{12}$$

Assuming that the observed U-burst originates from high coronal loops ($R = 4 - 6\ R_\odot$), using Equations (11) and (12), we can formulate the constraints on the plasma temperature shown in Table 3.

Table 3 shows that the electron temperatures derived within the frames of our model vary in a wide range from 1.5 up to 6.5 MK, depending on the loop height and the value of α. Currently, no temperature measurements of such high coronal loops are available. But there are plenty of temperature measurements for the lower loops associated with dm type-U bursts. For example, Fernandes *et al.* (2012) showed that the temperatures of dm U-burst associated loops can reach values of $(0.25 - 1.55) \times 10^7$ K. Furthermore, considering that high coronal loops are assumed to be elevated by CMEs from the low corona up to heights of several solar radii (Leblanc, Poquerusse, and Aubier, 1983), it is reasonable to assume that hot plasma confined by transient loops may also exist at these heights. This gives the opportunity to justify the delay of the F component with respect to the H one in the pair observed in the experiment. No systematic study of the group delays in the U-bursts harmonic pairs has been carried out so far. Thus, the delay of 7 s cannot be considered as either standard or abnormal. However, several authors (*e.g.* Robinson and Cairns, 1998; Abranin, Bazelyan, and Tsybko, 1993; Rutkevych and Melnik, 2012; Itkina, Levin, and Tsybko, 1993) estimated the group delays in harmonic pairs at frequencies about 25 MHz to be roughly between 1 and 2 seconds. From this point of view, the observed delay of 7 s is definitely longer than usual.

Table 3 clearly shows that the higher loops contain colder plasma and vice versa. Knowing one of these parameters, we can define the other if the time delay between the F and H components is given. In our case, the most reliable reference point could be radio heliograph data. Because we lack these, we can only judge from coronagraph images (see Figure 6), where the brightest loop structure has an apparent height roughly equal to 4.5 $R_\odot$. Assuming $v_0 \approx 0.3c$, we can estimate the temperature inside this loop to be equal to $\sim 3.2 \times 10^6$ K. Under the obtained conditions, the plasma inside this loop probably is about 20 times more dense than the ambient coronal plasma.

4. Conclusions

During the first observations performed by the new radio telescope GURT, a U-burst harmonic pair with an abnormally large relative time shift was registered. It was shown that the delay of about 7 s cannot be achieved using existing models and standard corona parameters. The delay was probably caused by the different group velocities of the pair components when they moved across the magnetic loop toward the observer. The essential property of the proposed model is that the temperature and density profiles of the plasma held by the coronal loop differ from those of the surrounding corona. Judging from the dynamic spectrum and STEREO-A coronagraph images, we conclude that the source of the burst may be located within a high ($4-6\ R_{\odot}$) coronal loop. The emission at the turning frequencies of the fundamental (25.5 MHz) and harmonic (51.2 MHz) components both originate from the top of the loop. As long as the frequency of the fundamental component at the generation point is close to the local plasma frequency, its group velocity is much lower than that of the harmonic component. Thus, while traveling across the loop, the fundamental component lags. This delay is frozen outside the loop because both components of the pair have group velocities close to the speed of light due to the considerably more tenuous plasma. Using the value of the time delay of the fundamental component in the U-burst harmonic pair, we can detect the plasma temperature of the corresponding loop plasma. For the given harmonic pair, the temperature inside the loop may reach several million degrees. To increase the accuracy of temperature detection, it is necessary to identify more reliably from which loop the emission originates. We hope the complex approach to the analysis of radio and optical observations will make this possible.

Acknowledgements The work was partially performed with the support of the European FP-7 project SOLSPANET (F9P7-People-2010-IRSES). The authors are gratefully to the SOHO, STEREO and SDO teams for providing access to the experimental data. The CME catalog used in this article is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. SDO: The *Solar Dynamics Observatory* is the first mission to be launched for NASA's Living With a Star (LWS) Program.

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