Solar Type U Burst Associated with a High Coronal Loop

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Abstract An inverted U burst with equally developed ascending and descending branches observed by the Giant Ukrainian Radio Telescope (GURT) on 18 April 2017 in meter wavelengths band is discussed. This U burst was attributed to the high coronal loop in active region NOAA 12651 above the limb. Under the assumption that, associated with the burst, a coronal loop confines isothermal plasma stratified according to the Boltzmann density relation, geometrical and physical parameters of the loop were estimated. According to our model coronal loops may contain plasma which is up to 20 times denser than the surrounding coronal plasma. In general, the proposed model gives the relation between the plasma temperature and the height of the loop in such a way that under the given parameters of the associated U burst, higher loops contain cooler plasma and vice versa. An alternative method of coronal loop height determination was suggested. Assuming that the observed U burst and the preceding Type III burst were generated by the same exciter, we define the height of the loop from the delay of the former with respect to the latter at a certain frequency. We show that determining the heights of the loops by another independent method, e.g. interferometric or tied-array imaging may reduce the uncertainty of the inside-the-loop plasma temperature determination.

Keywords Radio bursts: dynamic spectrum · Meter-wavelengths and longer (m, dkm, hm, km) · Type III · Corona: structures
1. Introduction

Since their very discovery in 1958 (Maxwell and Swarup, 1958), solar inverted U bursts have been considered as a special case of the Type III bursts, which were first observed eight years earlier (Wild and McCready, 1950). This time gap seems natural because type U bursts are much more rarely observed compared to Type IIIIs (Suzuki and Dulk, 1985). Bursts of these two types are cognate primarily due to common exciters of the emission, which are sub-relativistic electron beams accelerated above active regions and traveling along solar magnetic field lines (Suzuki and Dulk, 1985). The decisive difference between them is the shape of guiding magnetic field lines and thus the trajectories of the exciter movement. Type III electrons move along open field lines at distances up to 1 AU generating bursts with monotonically decreasing drift rates known as Type III bursts. As a consequence, these bursts can be continuously traced in frequency from GHz down to kHz. In contrast electrons responsible for inverted U burst generation follow closed magnetic structures—coronal loops. In this case the radial velocity of the electron beam alters its sign to the opposite after passing the apex of a coronal loop causing change of frequency drift sign of the burst from negative to positive and forming the ascending and descending branches of a burst. Thus unlike Type III bursts the dynamic spectra of inverted U bursts are bounded by the turning frequencies. These turning frequencies are observed in rather wide frequency range from 3.8 GHz (Wang et al., 2001) down to 0.7 MHz (Stone and Fainberg, 1971). Nevertheless the bursts of this type are most common in the metric and decametric bands (Suzuki and Dulk, 1985; Dorovskyy et al., 2010; Reid and Kontar, 2017). More detailed and extended analysis made by Leblanc and Hoyos (1985) showed that U bursts’ turning frequencies most often occur in the frequency range 25 – 30 MHz.

Ascending branches of U bursts far away from the turning point morphologically resemble typical Type III bursts, although they drift slightly slower than Type III bursts do at the same frequency. Such drift rates were usually attributed to slightly slower exciters (Fokker, 1970; Dorovskyy et al., 2010). When U bursts are observed, their descending legs are usually weaker, more diffuse and less extended in frequency than the ascending ones (Poquerusse, Bougeret, and Caroubalos, 1984). In most cases descending legs of U bursts are even absent, resulting in so called J bursts. U and J bursts are characteristic of high solar activity periods and sometimes may appear in groups. The turning frequencies of the bursts in one group may remain stable or decrease with time pointing out that some coronal loops are stationary while the others rise with time (Leblanc, Poquerusse, and Aubier, 1983; Dorovskyy et al., 2010).

As well as Type III bursts, solar U bursts sometimes show harmonic structures consisting of fundamental and harmonic emission with the former component delayed with respect to the latter by a few seconds (Dorovskyy et al., 2015). Then if single individual J or U bursts are observed it is natural to conclude that they can be generated either at the fundamental or at the harmonic frequency. The comparative rareness of U bursts with respect to Type III bursts is unexpected, given the abundance of loop structures in the solar corona. Reid and Kontar (2017) explained this effect in such a way that electron beams need to travel a path at a certain distance to become unstable to the Langmuir waves, which is larger than the linear length of loops. The authors also add that higher density and lower density gradient of the inside-the-loop plasma in turn reduce the Langmuir wave’s growth rate, thus increasing the starting heights of the U bursts. From this analysis it follows that the emission of U bursts begins far away from the electron injection region and hence observed U bursts apparently correspond to the upper part of coronal loops.

Retrieving of coronal loop geometry from associated U burst parameters has been one of the most relevant tasks in study of this type of bursts. According to Reale (2014) coronal...
loops can be visible in EUV band if the density of the confined plasma exceeds $10^8\text{ cm}^{-3}$. Such densities are characteristic of the lower layers of the corona. Thus loops being as high as a few solar radii and containing less dense plasma can be nowadays diagnosed exclusively by means of radio astronomy. In the absence of spatial parameters measurements the heights of the loops are usually defined through the turn over frequency of associated U burst (e.g. Stone and Fainberg, 1971; Leblanc and Hoyos, 1985; Dorovskyy et al., 2010). In all cases one of the known density profile models were assumed. As a rule these models were obtained for the solar corona in general rather than for coronal structures, such as loops or streamers. At the same time spatial measurements performed at certain frequencies by different authors (e.g. Suzuki, 1978; Reid and Kontar, 2017) show that the sources of U bursts are located higher in the corona than expected from the models pointing out that density stratification inside these structures most probably differs from that outside them. The present paper is an attempt to estimate the main parameters of the top part of the coronal loop using the time and frequency properties of the associated U burst with both legs unprecedentedly well developed. The assumptions adopted here are similar to those in the analysis of the U bursts harmonic pair (Dorovskyy et al., 2015).

2. Observations and the Inverted U Burst Properties

On 18 April 2017 active region NOAA 12651 appeared from behind the eastern limb of the Sun. During that day two comparatively powerful flares occurred above this region: a C2 flare at around 9:30 UT and a C5 flare with peak intensity at 20:00 UT. Both of these flares were linked to CMEs which traveled eastward according to SOHO/LASCO white light images. Besides the CMEs different types of solar activity in radio band were associated with these flares. Since solar observations with the radio telescope GURT are usually held between 5 and 16 UT we will focus at the events associated with the first C2 flare.

In meter and decameter bands this flare manifested itself as a complex long-lasting event starting at 9:34 UT with a Type III burst with decay followed by an inverted type U burst, group of powerful Type III bursts, Type II burst with herring-bone structure, and Type IV burst observed with Nancay Decameter Array (NDA; Lecacheux, 2013), URAN-2 radio telescope (Brazhenko et al., 2005) and with one section of the newly built Giant Ukrainian Radio Telescope (GURT; Konovalenko et al., 2016). One section of radio telescope GURT operates in the frequency band 10 – 80 MHz and consists of 25 cross-dipoles making up an effective area of 350 m$^2$ and beam width of about 20$^\circ$ at 40 MHz. The time and frequency resolutions were set to 100 ms and 9 kHz, respectively. All these bursts were briefly described by Melnik et al. (2019). And the Type III burst with decay was the subject of the research in that paper. We should only add that the complex event was preceded by a series of inverted J bursts with turning frequencies of around 30 MHz. The series totaled up to 10 individual J bursts and lasted from 9:29:00 till 9:33:30 UT. This fact indicated the existence of rather high coronal loops above the active region as well as the conditions conducive to escaping of radio emission from loop structures. The apexes of these J bursts were also observed by the URAN-2 radio telescope providing also the polarization data. All mentioned bursts except the Type IV burst were weakly polarized with a degree not exceeding 5%, indicating that all Type J and Type III bursts were most probably generated at the second harmonic of local plasma frequency despite no signs of the fundamental components were visible. The latter fact may happen due to large distance from Sun center and much narrower radiation pattern of the fundamental emission source.
Figure 1  The dynamic spectrum of the event associated with the C2 flare on 18 April 2017 recorded by NDA.

The fragment of the whole event recorded by NDA is shown in Figure 1. Figure 2a represents the inverted U burst with equally developed branches observed by GURT. It is clear that due to insufficient sensitivity and low time resolution (1 s) of NDA data compared to GURT it does not allow detailed analysis of the burst of interest.

The discussed U burst first appears at 9:34:30 UT at frequency around 75 MHz (Figure 2a). The intensity of the observed U burst peaks at low frequency around 56 MHz (see spectrum in Figure 3) reaching about 15 dB above the background level and starts to fall above 70 MHz equalizing with the background level at 76 MHz. This fall is an aggregate effect of the input low-pass filter and antenna efficiency deterioration at high frequencies but not the actual flux fall. The GURT data is still not calibrated so we do not present the values of fluxes here. Nevertheless the exact values of the burst fluxes are not as important for the present research as the frequency and temporal parameters. Equally developed branches of the burst allow one to determine the drift rates of the ascending and descending ones at the same frequency far enough from the turn over point. This unique opportunity is of great importance for retrieving the coronal loop parameters.

Due to the low intensity of the burst at high frequencies and overall smooth appearance of the burst, an accurate measurement of the drift rates and time intervals from the power dynamic spectrum in Figure 2a seems difficult. The differential in time dynamic spectrum (Figure 2b) is better suited for these purposes owing to its high sensitivity to the intensity variations. Here light areas correspond to the positive intensity gradients, dark areas delimit the negative intensity gradients and the border between these areas points at the intensity peak. For the analysis of U burst key properties three reference points have been chosen. Point C indicates the turn over point of the burst, while points A and B are placed on the ascending and descending legs of the burst at equal frequency shifts from the turning frequency (Figure 2b). The frequency of points A and B should be as far from the turning frequency as possible allowing at the same time reliable determination of drift rates and times. In our opinion frequency of 70 MHz suits these requirements the best. At this frequency, the flux peaked at 9:34:32.0 UT (point A on the ascending branch) and at 9:34:40.2 UT (point B on the descending one). Assuming plasma emission mechanism we may conclude that it takes 8.2 s for a beam to travel along the loop from point A to point B. The burst apex time (point C location on the time axis) is the time when the drift rate of the burst equals 0. This time appeared to be 9:34:36 UT. Detection of the correct location of point C on the frequency axis is a bit more complex due to the irregular shape and flatness of the U burst spectrum at the turn over time (Figure 3). Taking the turn over frequency as the frequency of maximum intensity does not seem to be correct in this case.
1. Inverted Type U burst with equally developed legs observed by GURT: (a) power dynamic spectrum and (b) differential in time dynamic spectrum. Here letters A and B denote the sources of radio emission of 70 MHz belonging to the ascending and descending legs of the U burst, respectively, and letter C indicates the turnover point of the burst at the frequency of 58 MHz.

2. Inverted U burst instantaneous spectrum taken at the turnover time 9:34:36 UT. Here vertical dashed lines indicate the frequencies where the radio emission intensity drops by an order of magnitude. This level is marked with a horizontal dashed line. The median frequency of the bounded band $f_c$ is marked with an arrow.

Instead we took the turning frequency as the median frequency of the spectral band bounded by the frequencies where spectrum has steepest slopes. This band is marked with red dashed lines in Figure 3. The turnover frequency defined in such a way equals $58 \pm 1$ MHz. The absolute values of drift rates of the ascending and descending branches at the reference points A and B appeared to be equal to $4 \pm 0.2$ MHz·s$^{-1}$ and of opposite sign. This drift rate is four times lower than the drift rate of the preceding Type III burst at the same frequency (Melnik et al., 2019).

3. Analysis and Discussion

For a given electron beam velocity the linear length of the top part of the coronal loop corresponding to the U burst segment bounded by the points A and B can be easily found. In Type III bursts analysis the speed of the exciter is usually calculated from the drift rate of the burst at given frequency supposing one of the known corona models. When heliographic data are absent the same corona models are used for estimation of the heliocentric heights of the emission sources at different frequencies. In our opinion this method cannot be applied...
Figure 4  The geometrical model of the loop segment corresponding to the observed U burst. Here points A, C and B indicate the sequential positions of the U burst source in the sky plane, corresponding to the points marked with the same letters on the dynamic spectrum in Figure 2b, $v_0$ is the fast electrons velocity vector at point A, $h_L$ is the geometrical height of the loop segment and $w_L$ is the transverse width of the arch.

to U bursts because the plasma confined inside the loop is effectively isolated from the ambient plasma by the magnetic field of the loop. Furthermore, according to Reale (2014) the temperature and density of the plasma inside the loop may considerably differ from those outside the loop. Thus density profiles inside the loop in general may not follow any of commonly accepted models and we cannot estimate the exciter speed from the drift rate of the U burst.

On the other hand, Aurass and Klein (1997) showed that if the ascending branch of a U burst and Type III burst are observed within a few seconds from each other they most probably have common electron ejection source. In our case the ascending leg of the discussed U burst is preceded by a Type III burst by 7.5 s. This Type III burst with decay has been deeply analyzed by Melnik et al. (2019). The authors found that the velocity of the electron beam responsible for the high frequency part of the Type III burst (before the decay) was $0.2c$ if the fundamental emission was assumed and $0.33c$ for the harmonic one where $c$ is the speed of light. There were several pros and cons to both the fundamental and the harmonic emission mode. Nevertheless taking into account weak polarization and large distance from Sun center of the source authors were inclined to the latter. This conclusion and the temporal proximity of the Type III burst and the discussed type U bursts give good reason to take the speed of electrons responsible for the Type U generation equal to $0.33c$.

The most plausible geometrical approximation of the upper part of the loop is a semi-ellipse lying in the plane parallel to the density gradient (Figure 4). Here points A, B and C correspond to the reference points of the same name on the U burst dynamic spectrum (see Figure 2b), $v_0$ is the electron beam velocity at point A, $h_L$ and $w_L$ denote the height and the width of the loop segment. Taking the electron velocity equal to $0.33c$ we define the linear length of the coronal loop segment $L$ as $1.18R_\odot$, where $R_\odot$ is the solar radius. The values of $h_L$ and $w_L$ will be found from the further analysis.

It is commonly accepted that Type III electrons do not change their velocity while traveling along magnetic field lines (see for example Mel’nik, Lapshin, and Kontar, 1999; Melnik et al., 2019). However, recent analysis (e.g. Krupar et al., 2015; Reid and Kontar, 2018) showed that at large distances from the Sun Type III electrons use to decelerate with a rate of about $3 \cdot 10^{-5}c$ cm$^{-1}$, where $c$ is the speed of light. Apparently for distances near $1R_\odot$ such deceleration can be neglected and the electron beam velocity may be considered as constant. Almost equal time intervals AC and CB and equal absolute drift rates of the observed U burst at points A and B in Figure 2b confirms this for electron beams moving along the top of the coronal loop.

The coronal loop is a closed magnetic structure which effectively isolates the plasma confined inside it from the ambient corona. Thus we may expect a considerable difference
between the plasma parameters, namely temperature and density, inside and outside a loop (Reale, 2014).

Let us assume that the confined plasma density follows the Boltzmann relation as in (Mann et al., 1999):

\[ n(r) = n_0 \exp \left( \frac{A}{r} \right), \]  

where \( n_0 \) is the reference density, \( r \) is the distance from the solar center and \( A \) is the characteristic scale defined as

\[ A = \frac{\bar{\mu} GM_\odot m_p}{kT}. \]  

Here \( \bar{\mu} \) is the mean molecular weight, which equals 0.6 for solar corona (Priest, 1982), \( G \) is the gravitational constant, \( m_p \) is the proton mass, \( M_\odot \) is the mass of the Sun, \( k \) is the Boltzmann constant and \( T \) is the temperature.

To determine the density profile for the loop of interest the values of \( T \) and \( n_0 \) are needed. As noted by Reale (2014) measurement of the temperature is not a trivial task due to small optical thickness of coronal plasma and absence of direct measurements. There is currently no unified view of the problem of the temperature distribution along a loop. Some authors (e.g., Landi and Landini, 2004) state that inside-the-loop plasma is isothermal while others (e.g., Reale and Ciaravella, 2006) speak in favor of non-uniform temperature distribution both along and across a loop. Assuming that the plasma of the loop of interest is heated at its footpoints only it seems reasonable to take the isothermal plasma model as was suggested by Aschwanden (2001).

So we performed calculations for two fixed temperatures—1.4 MK as it was taken by Mann et al. (1999) and twice as high a temperature in order to find the basic relations between U burst parameters and the properties of the associated coronal loop as well as trends of their dependencies on temperature. For given temperatures the characteristic scales \( A \) equal \( 6.92 \cdot 10^{11} \) cm and \( 3.46 \cdot 10^{11} \) cm, respectively.

The value of \( n_0 \) can be retrieved from the drift rate of the burst as follows. In general for plasma emission mechanism the drift rate of the burst can be defined as

\[ \dot{f} = \frac{df}{dt} = \frac{df}{dn} \cdot \frac{dn}{dr} \cdot \frac{dr}{dt}. \]  

Assuming the harmonic emission mode the first term of Equation 3 is

\[ \frac{df}{dn} = f_p n_e, \]  

where \( f_p \) is the local plasma frequency at the source of radio emission and \( n_e \) is the electron density.

The second term is retrieved from 1 as

\[ \frac{dn}{dr} = -n_e \cdot \frac{A}{r^2}. \]  

And the third term of Equation 3 is the radial component of the electron beam velocity \( v_r = v_0 \cdot \cos \theta \), where \( \theta \) is the angle between the electron beam velocity vector \( v_0 \) and the density gradient. Finally taking into account Equations 4 and 5 we can rewrite Equation 3 as

\[ |\dot{f}| = \frac{A \cdot f_p \cdot v_0 \cdot \cos \theta}{r^2}. \]
In Equation 6 and hereinafter we will operate with absolute values of the frequency drift rate since the sign does not play a role in further calculations.

After rewriting 6 for $r$ we obtain

$$r = \sqrt{\frac{A \cdot f_p \cdot v_0 \cdot \cos \theta}{\dot{f}}}.$$  

(7)

Equation 7 allows us to find the height of the radio emission source using measured drift rate of the U burst at given frequency. As was said earlier we have chosen the reference points A and B at frequency 70 MHz on both legs of the U burst. For the assumed geometrical approximation of the top of the loop angle $\theta = 0$. Taking $v_0 = 0.33c$, $T = 1.4$ MK, $\dot{f} = 4$ MHz s$^{-1}$, $f_p = 35$ MHz and assuming harmonic emission mode we obtain the heliocentric height of points A and B in the loop $r_A = r_B = 3.55R_\odot$.

Then knowing the exact height of the sources A and B of radio emission and the local plasma density at the source it is possible to find the value of $n_0$ in Equation 1. It equals $9 \cdot 10^5$ cm$^{-3}$. Thus we get the density dependence on heliocentric height for the individual coronal loop associated with the observed type U burst in the form

$$n(r) = 9 \cdot 10^5 \cdot \exp\left(\frac{10}{R}\right) \text{ cm}^{-3},$$  

(8)

where $R$ is the heliocentric height expressed in solar radii.

The height of points A and B in Figure 4 has been already determined thus we need to find the height of point C to complete the geometry of the loop segment. It can be done using Equation 8 which determines the local plasma frequency at every point inside the loop. Assuming harmonic emission mode the plasma frequency at point C should equal 29 MHz. From Equation 8 it follows that the heliocentric height of the loop apex corresponding to the U burst turnover frequency is $4.1R_\odot$. Thus the elevation of the point C above points A and B, i.e. the value of $h_L$ in Figure 4 equals $0.55R_\odot$. For a given half-perimeter of the ellipse and one of its semi-axes the width of the loop $w_L$ (Figure 4) was found to be $0.26R_\odot$. The appearance of the top of the loop for temperature $T = 1.4$ MK and normal orientation of the loop is shown in Figure 5 with red color. In this case plasma density inside the loop at points A and B is about 20 times as high as that of the surrounding plasma which is supposed to follow the Saito equation (Saito et al., 1970). Very close values were obtained for plasma enhancements inside much lower loops observed in X-rays (Stewart and Vorpahl, 1977). The authors found that the plasma inside a loop being $0.1R_\odot$ high was 16 times denser than outside it.

The calculations for the twice as high temperature $T = 2.8$ MK give the value $n_0 = 2.06 \cdot 10^6$ cm$^{-3}$ and heliocentric height of the points A and B as $2.51R_\odot$. The loop apex in this case reaches the height of $3.09R_\odot$ from the solar center as shown in Figure 5 with yellow curve. Then the height and the width of the top part of the loop (values $h_L$ and $w_L$ in Figure 4) are $\sim 0.58R_\odot$ and $\sim 0.11R_\odot$, respectively. It means that the apex of hotter loop is located lower in the corona. The loop segment connecting points A, C, and B is about 20 times as high as that of the surrounding plasma which is supposed to follow the Saito equation (Saito et al., 1970). The authors found that the plasma inside a loop being $0.1R_\odot$ high was 16 times denser than outside it.

The loop approximation by the normally directed semi-ellipse is of course a special case. In general coronal loop may deviate from the gradient direction. The analysis shows that tilted semi-ellipse may also fit the parameters of the observed type U bursts in such a way that heliocentric heights of all points in the loop are decreasing with increasing declination
Figure 5  Trajectories of the Type III electrons (green line) and inverted U burst electrons (red line for plasma temperature 1.4 MK and yellow line for 2.8 MK). Solid curves correspond to the observed Type U burst. The locations of Type III and Type U bursts sources at frequency of 70 MHz are denoted with solid circles.

Figure 6  Trajectories of the Type III and inverted U burst sources initiated by the electrons ejected from the same source. Green solid curves denote open magnetic field lines and red solid lines indicate closed ones.

angle. For example if the loop with a temperature of 1.4 MK is tilted by 45° to the radial direction its apex will be as high as 3.36$R_\odot$, which is about 18% less than in the case of normal loop. In this case the difference between the plasma densities inside and outside the loop also decreases. In addition the inclination of the loop plane results in slight increase of the semi-ellipse aspect ratio. For the above case the aspect ratio increases from 0.24 for a normally oriented loop to 0.31 for the inclined one.

Finally let us suppose that the inverted Type U burst and preceding Type III burst have been generated by the same electron beam with velocity of 0.33$c$. The case when the electron beam could be injected simultaneously into one or more closed and open magnetic field structures was supposed earlier (Caroubalos, Couturier, and Prokaxis, 1973; Dorovskyy et al., 2010). Such a scenario is schematically shown in Figure 6. We assume that magnetic field completely isolates the plasma inside the loop thus no cross-field diffusion is supposed to take place.

According to our model for normally oriented loop containing 1.4 MK plasma and the harmonic emission mode the heliocentric height of the source of radio emission of the U burst at 70 MHz equals 3.55$R_\odot$. Apparently electrons responsible for the preceding Type III burst generation travel through less dense plasma resulting in lower position of the burst source at the same frequency of 70 MHz. The idea is to use this height difference to unambiguously determine the loop height and thus its temperature in absence of spatial data. Interferometric observations performed with the UTR-2 radio telescope (Melnik et al., 2017) show that positions of Type III bursts sources at frequencies 20 and 25 MHz are in good agreement with the Newkirk corona model (Newkirk, 1961). At the same time recent imagespectroscopic observations by LOFAR (Gordovskyy et al., 2019) indicate that in three cases
out of 12 the Type III burst sources appeared to be substantially higher in the corona than was expected from any known model. This can occur for example when in some cases Type III electrons propagate through disturbed corona and in other ones through different open coronal structures such as magnetic flux tubes (Duncan, 1979) and streamers (Gopalswamy, Kundu, and Szabo, 1987). All these hypotheses are model dependent. To illustrate the method let us assume that the Type III electrons travel through the standard corona with density following the Saito dependence (Saito et al., 1970). In this case the source of the preceding Type III burst emission at frequency of 70 MHz is located at 1.5$R_\odot$ assuming harmonic emission. Thus it will take \( \sim 4.7 \) s for an electromagnetic wave to travel from the Type III source to the height of 3.55$R_\odot$ where the U burst source of the same frequency is located. At the same time, the exciter moving with the velocity of 0.33$c$ will cover the distance between the two sources for \( \sim 14.1 \) s. The total delay of the U burst maximum with respect to Type III maximum at the frequency of 70 MHz appears to be 9.6 s and is very close to the observed delay of 7.5 s. Taking into account that all heights obtained in the present analysis are model dependent the hypothesis of common exciter for both of these bursts seems plausible. Apparently if this assumption is true then the delay of the U burst with respect to the preceding Type III burst together with spectral parameters of these bursts unambiguously define the temperature and the height of the loop. In our particular case the observed delay corresponds to the temperature of the inside-the-loop plasma of 1.9 MK. Consequently the top of this loop reaches a height of 3.6$R_\odot$. If we suppose that Type III electrons move inside a streamer with increased density it will result in higher loop containing cooler plasma.

It is evident that temporal and spectral parameters of an individual U burst with equally developed legs cannot provide exact values characterizing the physical properties and the geometry of the associated coronal loop. At the same time detailed analysis of the dynamic spectra of such bursts give us a general relation between the height of the loop and the temperature of the confined plasma in such a way that lower loops contain hotter plasma and vice versa. This conclusion agrees well with the results received by Dorovskyy et al. (2015) from analysis of the U burst harmonic pair mutual delay. Thus knowing one of these two parameters we can define another one. From the current state of available observation facilities, such as interferometric observations with the UTR-2 radio telescope (Dorovskyy et al., 2018; Melnik et al., 2018) or tied-array imaging realized with LOFAR (Reid and Kontar, 2017; Gordovskyy et al., 2019) it seems more realistic to define the height of the loop as well as its deviation from the normal direction. This will enable us to yield the temperature of the confined plasma, which is difficult to measure by other means at such heights. The proposed model also explains the systematically lower drift rates of the ascending branches of type U bursts compared to the drift rates of standard Type III bursts at the same frequency. The sources of U bursts are located much higher in the corona than the sources of Type III bursts at the same frequency, and then the density gradient at the U burst source is lower, resulting in lower drift rates.

4. Conclusions

A unique inverted U burst with equally developed ascending and descending legs was observed on 18 April 2017 by one section of the radio telescope GURT. This allowed one to retrieve the extended information about the coronal loop from the parameters of the associated inverted U burst even with lack of radio source imaging. The loop apparently originated from the limb active region NOAA 12651. Under the assumption of a planar loop of semi-elliptic shape and gravitational stratification of the isothermal plasma inside the loop we
found that the heliocentric height of the source of radio emission is unambiguously defined by the electromagnetic wave frequency, the frequency drift rate of the U burst at corresponding frequency, the plasma temperature and the inclination of the loop plane from the radial direction. For the case of the observed U burst, radial orientation of the loop plane and temperature equal to 1.4 MK the heliocentric height of the loop apex was found to be $4.1R_\odot$. From this result it follows that the sources of U bursts are in general higher than those of Type III bursts at the same frequency. Equally developed legs of the burst enable to find the length of the loop segment corresponding to the visible Type U burst as $1.18R_\odot$. It was also shown that the electron beam responsible for this U burst generation did not accelerate or decelerate while traveling along the loop. In our opinion this electron beam could also be responsible for the preceding Type III burst with decay. In addition we found that with other things being equal the lower loops contain hotter plasmas and vice versa, which agrees well with previously obtained results for U burst harmonic pair (Dorovskyy et al., 2015). It is clear from the analysis that determination of one of mutually connected parameters, e.g. temperature or height of the loop by some other independent method will unambiguously reveal the other one. Thus completing of traditional high resolution spectral analysis by retrieving of spatial parameters of the U burst sources through interferometric observations or tied-array imaging is highly desirable. The analysis shows that the inverted U burst and the Type III burst which preceded it by 7.5 s could be generated by the same fast electron beam injected simultaneously along open and closed magnetic structures. One more important result obtained in the paper is the evidence that the electron beams preserve their speed while traveling along high coronal loops at least within distances around $1R_\odot$ and even while moving towards the Sun.

Our model also suggests that U bursts with lower turning frequencies, e.g. around 25 MHz may originate from the coronal loops which are $\sim 13R_\odot$ high. Such loops can be the subject of both remote observations by ground-based highly efficient radio telescopes (e.g. LOFAR, NenuFAR, and UTR-2) and in-situ analysis by Parker Solar Probe (PSP) during its closest perihelia.

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