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Radio Emission and Observations from the Solar Transition Region

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Abstract: The transition region is a very thin but most peculiar layer in the solar atmosphere, located between the solar chromosphere and the corona. It is a key region for understanding the coronal heating, the solar eruptions triggering, and the origin of solar winds. Here, the gradients of all physical parameters are very high, including plasma density, ionization degree, temperature, and magnetic fields, etc. Therefore, the transition region should be highly dynamic, such as fast energy releasing and transporting, plasma heating, and even particle accelerating. They include two physical aspects: thermal and non-thermal processes. The thermal processes can be observed from the ultraviolet (UV) and extreme ultraviolet (EUV) emission by multi-wavelength images. The non-thermal processes, however, should be related to radio emissions especially at millimeter wavelengths, and the frequency range should span from several GHz to beyond 300 GHz, and the emission mechanism should be highly related to the magnetic fields and variations. The ultra-wide broadband spectral observations at millimeter wavelengths with high spectral resolutions may provide rich dynamic information about the transition region, such as non-thermal energy release and transmission, the flows of plasma and energetic particles, the magnetic fields and their variations, the generation and transportation of various waves, and the formation and evolution of the source regions of solar eruptions. Here, we discussed the spectral characteristics of millimeter-wave emission from the transition region and proposed a new conception of ultra-wide broadband millimeter-wave spectrometers to observe them.

Keywords: solar transition region; radio emission; magnetic field; gradient

1. Introduction: Why focus on the solar transition region?

In modern solar/stellar physics, we face a series of long-standing scientific challenges, including the mystery of coronal heating, the triggering mechanism of powerful eruptions, such as solar/stellar flares, coronal mass ejections (CME), and the origin of solar/stellar winds, etc. In order to answer these problems, we have to track and study how the massive amounts of matter and energy are transmitted and released from the solar/stellar interior into the upper atmosphere. Here, we encounter a very unique atmospheric layer – the transition region. Take the Sun as an example, Figure 1 shows that the solar transition region is a very thin layer with thickness of only a few hundred km and the height of about 2000 km above the solar photospheric surface and accompanying with complex motions [1, 2]. It separates the cold, partially ionized, and frequently collision chromosphere from the very hot, full ionized, and non-collision corona. As we know, the temperature changes slowly in the solar photosphere, chromosphere, or corona. However, in the thin solar transition region, the temperature quickly increases from about 2×10^4K at the top of the chromosphere to near one million K at the base of the corona, causing rapid changes in plasma density, magnetic fields, and other physical parameters [3, 4]. Therefore, it is not a simple thermal equilibrium layered structure, but a rapidly changing and complex dynamic region with highly heterogeneous magnetic fields and plasmas [5]. We know that the mystery of coronal heating is one of the eight major challenges in contemporary astronomy [6, 7]. The existing heating mechanisms can be roughly

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divided into three categories: wave heating [8, 9], reconnection heating [10, 11], and magnetic field gradient pumping heating [12, 13]. However, there is currently no consensus on which mechanism truly dominates the coronal heating process. It is particularly important that all mass and energy required for heating the corona, and even driving solar eruptions and solar winds need to be transported upwards through this thin layer. Therefore, the study of the solar transition region is crucial for solving the above three major problems in the field of solar physics - coronal heating, eruption triggering and the origin of solar wind.

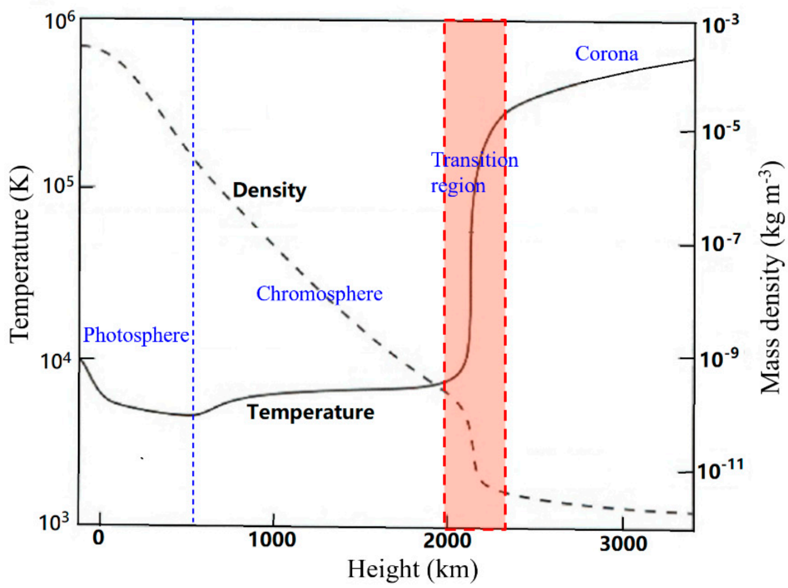

Figure 1. The position and the variation characteristics of temperature and mass density of the solar transition region (plotted from the results of Vernazza et al., 1981 [20]).

Observations show that there are many transient activities in the solar transition region, such as spicules, small-scale jets, and various small bright points [14]. Behind these phenomena are both thermal and non-thermal processes. So far, many solar telescopes are designed specifically to observe the solar transition region at ultraviolet (UV) and extreme ultraviolet (EUV) wavelengths, such as SUMER on SOHO [15], TRACE [16], IRIS [17], etc. These observations provided many information of the transition region, including the morphology and dynamics of spicules, small-scale jets, bright points, and networks. They are intrinsically thermal processes. However, if we want to fully reveal the physical essence of the solar transition region, in addition to carefully observing various thermal processes, observing non-thermal processes is also crucial. Here, the non-thermal processes include the rapid energy release by magnetic reconnection and the associated particle accelerations and propagations. All non-thermal processes are associated with the generation and propagation of various energetic particles, which interact with magnetic fields to produce radio emission. Therefore, radio observation is the most important way of detecting non-thermal processes in the solar transition region.

As we know, the solar radio emission spans frequency from sub-millimeter wave to beyond kilometer waves. Besides influence of the emission mechanism and propagation effect [18], generally, the shorter the wavelength, the closer the source region of radio emission is to the solar surface; the longer the wavelength, the farther away the source region of radio emission from the solar surface. For example, the radio emission at centimeter and decimeter wavelengths produces in the lower corona and always associated with the source regions of solar flares, while the radio emission at meter and decameter wavelengths generates from the higher corona and always related to the propagations of flaring non-thermal electron beams, CMEs and the related shock waves [19]. Then, the radio emission in the solar transition region should fall into millimeter wave band with shorter wavelengths.

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This work will attempt to discuss these questions. Section 2 discusses the emission mechanism of radio emission in the solar transition region. Section 3 introduces the history and current status of radio observations of the transition region. In Section 4 we propose a new conception of Solar Ultra-wide Broadband Millimeter-wave Spectrometers (SUBMS) for observing the non-thermal processes of the solar transition region. Section 5 comes to conclusions of this work.

2. Radio emission from the solar transition region

As we mentioned in Section 1, the plasma density in the transition region spans from about 10^{17} m^{-3} to 10^{19} m^{-3}, and the temperature quickly increases from about 2×10^4K at the top of the chromosphere to around 10^6 K at the base of the corona [20], and the corresponding plasma frequency is the range of from several GHz to around tens of GHz, which is the cutoff frequency for electromagnetic waves that can propagate from the transition region. The frequency of radio emission coming from the solar transition region must be higher than the above plasma frequency, generally in the millimeter wave band of tens of GHz or above. We know that some strong flare eruptions can also generate enhanced radio bursts at millimeter wavelengths. Then, what is the difference between flare-associated millimeter-wave radio bursts and millimeter-wave emissions from the solar transition region?

The flare-associated millimeter-wave bursts are generally produced in fast varying structures and in the coronal flaring source region. De Jager et al. (1987) [21] and Kaufmann et al. (1986) [22] investigated millimeter-wave bursts with fast quasi-periodic pulsating structures and the pulsating period of about 60 ms in the impulsive phase of a solar flare. These millimeter-wave bursts are contributed to gyrosynchrotron emission by non-thermal electrons and even synchrotron emission by ultra-relativistic electrons in a relatively strong magnetic field. Accompanying with these millimeter-wave bursts, almost identical hard X-ray temporal structures are simultaneously observed. For example, Kaufmann et al. reported that fast pulsed emission at 90 GHz were almost identical to the temporal structures of hard X-ray emission at 24-108 keV at 13:26 UT on 1984 May 21 [23]. Actually, this event occurred in the preflare phase just 2 min before the onset of a C2.5 flare (GOES soft X-ray observation shows that the flare started at 13:28 UT, peaked at 13:31 UT and ended at 13:55 UT). Further researches indicate that the flare-associated millimeter-wave emission is best correlating with hard X-rays emission above 500 keV [24].

Then, what is the millimeter-wave emission in the solar transition region like? We know that compared to the flaring source region in the corona, the solar transition region has higher density (10^{17} m^{-3} to 10^{19} m^{-3}), stronger magnetic field (from about 100 G to nearly 3000 G, corresponding from the solar quiet region, networks to the sunspot active region), and lower temperature (from 2×10^4K to 10^6 K), all of which are more conducive to the thermal bremsstrahlung emission and cyclotron emission by thermal electrons. Obviously, the thermal bremsstrahlung and cyclotron emission in the solar transition region should be in broadband continuum, which constitutes the fundamental background component of radio emission in the solar transition region. Now that the solar transition region is highly dynamic, there must be a series of non-thermal energy release and conversion processes, resulting in the generation of non-thermal electrons. What emission signals will be generated by the interaction between these non-thermal electrons, magnetic fields and the transition region plasma?

2.1. Non-thermal electrons in the solar transition region

Let's analyze how non-thermal energy is released in the solar transition region and how non-thermal electrons are generated?

Firstly, the high gradient of temperature and density in the solar transition region inevitably drives strong convections of the plasma and rapid variations of the magnetic field. The strong convections will produce strong turbulence and the magnetic field rapid variations may produce various small-scale magnetic reconnections. Both of strong turbulence and magnetic reconnection can accelerate electrons to high energy effectively and release non-thermal energy [25, 26].

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As for the turbulence acceleration, Li et al. [27] applied the MHD simulation to investigate the electron acceleration by turbulent current sheets, and found that the electrons can be accelerate to more than several hundreds of keV. As the turbulent processes in the transition region occur universally anytime and anywhere, whether in the quiet Sun or the solar active region. At the same time, the moving direction of non-thermal particles generated by turbulent acceleration in the transition region is almost randomly isotropic, so these non-thermal particles are approximately equivalent to a non-thermal component superimposed on the background of the thermal plasma.

The magnetic reconnections should be another important mechanism for particle accelerations in the solar transition region [28]. There are many small-scale explosive phenomena, such as micro-flares, nano-flares, spicules, bright points, and even the prevalence of small-scale jets from the networks of the transition region, which are associated with magnetic reconnection [29, 14]. We know that the physical essence of magnetic reconnection particle acceleration is the acceleration of charged particles by the induced electric field formed in the magnetic reconnection site, and the current sheet is its main manifestation. In the solar transition region, these current sheets are only local small-scale structures, and they are discontinuous and dispersed. Gordovskyy et al. [30] found that protons and electrons can be accelerated to very high energies up to tens of MeV in a small transient magnetic reconnection event. It is obvious that the non-thermal particles generated by magnetic reconnection acceleration in the solar transition region are locally and anisotropic in distribution.

2.2. Millimeter-wave emission by non-thermal electrons in the solar transition region

Since there are indeed non-thermal electrons in the solar transition region, how do these non-thermal electrons generate radio emission?

Firstly, the bremsstrahlung processes of the interaction between non-thermal electrons and the dense transition region plasmas may produce X-ray emission, accompanying with negligible radio emission. The non-thermal electrons moving in the transition region will gyrate around the magnetic field lines and produce gyro-emission by the gyrating accelerations. Considering the magnetic field strength in the solar transition region, and the gyro-frequency ($f_{ce}[MHz] = 2.8B[G]$) is in the range from about 300 MHz (in the solar quiet region) to about 8 GHz (around the sunspot region). Here, B is the magnetic field strength in the transition region. As for the non-thermal electrons with Lorentz factor (γ), the typical frequency is,

$$\mathrm{f[GHz]} \approx 2.8 \times 10^{-3} \gamma^3 B[G] \quad (1)$$

In the quiet region, we may suppose $\mathrm{B} = 100$ G, when the energy (E) of non-thermal electrons is 300 keV, then the emission frequency (f) should be about 1.5 GHz, and when $\mathrm{E} = 500$ keV, $\mathrm{f}\sim 6$ GHz, when $\mathrm{E} = 1.0$ MeV, $\mathrm{f}\sim 20$ GHz. In the transition region above the networks of the quiet Sun, the magnetic field should be supposed 500 G, then the above corresponding emission frequencies will be 7.3 GHz, 30 GHz and 100 GHz for $\mathrm{E} = 300$ keV, 500 keV and 1.0 MeV, respectively. They all fall in the range of centimeter-millimeter wavelength.

In the transition region above the sunspot active region, we may suppose $\mathrm{B} = 2000$ G. When $\mathrm{E} = 300$ keV, we may get $\mathrm{f}\sim 38$ GHz; when $\mathrm{E} = 500$ keV, we have $\mathrm{f}\sim 123$ GHz; and when $\mathrm{E} = 1.0$ MeV, $\mathrm{f}\sim 388$ GHz. They all fall in millimeter-wave range.

Overall, the typical frequency range of radio emission from the solar transition region should be from several GHz to several hundred GHz, that is to say, from centimeter wave to millimeter wave.

Obviously, the spectral characteristics of the above centimeter-millimeter wavelength emission depends on energy spectral of the non-thermal electrons when is dominated by the acceleration mechanism. As we discussed in Section 2.1, in transition region, particle accelerations are mainly associated with turbulences or magnetic reconnections. Turbulent acceleration of electrons can occur randomly in all transition region, and the distribution is isotropic, and the related radio emissions of the non-thermal electrons should be groups of spike bursts. Each spike should be very narrow frequency bands and very short timescale. Based on the scaling law extrapolation [31] of the centimeter-decimeter spike bursts, if there are spike bursts in the millimeter wavelengths, the typical frequency bandwidth is about 1% of its center frequency, and the typical lifetime is about 0.5-1.0 ms. The magnetic reconnection acceleration in the solar transition region are related to small-scale current

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sheets and produce non-thermal electron beams. These non-thermal electron beams may generate small-scale millimeter-wave bursts, such as narrowband type III bursts, similar as the small scale microwave bursts occurred in decimeter wavelengths [32]. Here, different from the decimeter-wavelength narrow-band type III bursts which are generated from coherent plasma emission mechanism, the transition region millimeter-wave narrowband type III bursts are generated from the interaction between the non-thermal electrons and the strong magnetic fields, and the emission is incoherent. And their frequency drifting rate should be,

$$\frac{df}{dt} = 2.8 \times 10^{-3} \gamma^3 \frac{dB}{dr} v_b \tag{2}$$

Here, the unit of the frequency drifting rate ($\frac{df}{dt}$) is $GHz \cdot s^{-1}$. $\frac{dB}{dr}$ is the magnetic gradient with unit of $G \cdot km^{-1}$, and v_b is the velocity of the non-thermal electron beams with unit of $km \cdot s^{-1}$. We know that, when $\mathrm{E} = 300$ keV, $v_b = 0.82\, c$; when $\mathrm{E} = 500$ keV, $v_b = 0.91\, c$, etc. That is to say, the velocity of the non-thermal electron beams is very close to the light speed (c). Approximately, we may simply assume $v_b \approx c$. Supposing the magnetic gradient in the transition region $\frac{dB}{dr} \approx 0.01\ G \cdot km^{-1}$[33], then $\frac{df}{dt} \approx 45\ GHz \cdot s^{-1}$ for $\mathrm{E} = 300$ keV, and $185\ GHz \cdot s^{-1}$ for $\mathrm{E} = 500$ keV, etc. These estimations show that the narrow band millimeter-wave type III bursts should have much more rapid frequency drifting rate than that of type III bursts at centimeter- decimeter- and even meter wavelength. This also requires that the temporal resolution (Δt) of a broadband millimeter-wave dynamic spectrometer should be $\Delta t < 1$ms to obtain relatively accurate frequency drifting rate. The frequency drifting rate is a key parameter for investigating the dynamic behavior of the non-thermal energy release.

Additionally, both of the millimeter-wave spike bursts associated with turbulence acceleration and the millimeter-wave type III bursts associated with magnetic reconnection acceleration always take place in large groups from the solar transition region. They should be the main forms of non-thermal energy release in the solar transition region. It is an important approach to apply broadband millimeter-wave dynamic spectrometer to detect and study the millimeter-wave spike bursts and millimeter-wave type III bursts. Such broadband millimeter-wave dynamic spectrometer should have frequency range of 20 - 100 GHz, temporal resolution $\Delta t < 0.2 - 0.5$ms, and frequency resolution $\Delta f < 50 - 300$ MHz.

3. History and current status of radio observations of the transition region

Now that the observations of broadband millimeter-wave dynamic spectrometer is so important for revealing the physical nature of non-thermal processes in the solar transition region, what is the current international observation status?

Unfortunately, there is currently no solar millimeter wave broadband dynamic spectrometer specifically designed for observing the solar transition region internationally. This is mainly because water and oxygen molecules in the Earth's atmosphere have too strong absorption in the millimeter wavelength, making it impossible to observe at many frequencies. Figure 2 presents the averaged atmospheric absorption index of the radio emissions at different frequencies. Here, we can see several strong absorption peaks. 50-75 GHz and 105-125 GHz are the strong absorption peaks by oxygen molecules, 175-220 GHz and 300-385 GHz are the strong absorption peaks by water molecules. Additionally, 20-26 GHz is also an obvious absorption peak by water molecules. It is precisely because of the existence of these absorption peaks that we are unable to construct a ground-based telescope system to obtain observations of the solar broadband dynamic spectrum in the millimeter wavelength. So far, there are only a few solar millimeter-wave telescopes available for observation at a few frequencies (Table 1).

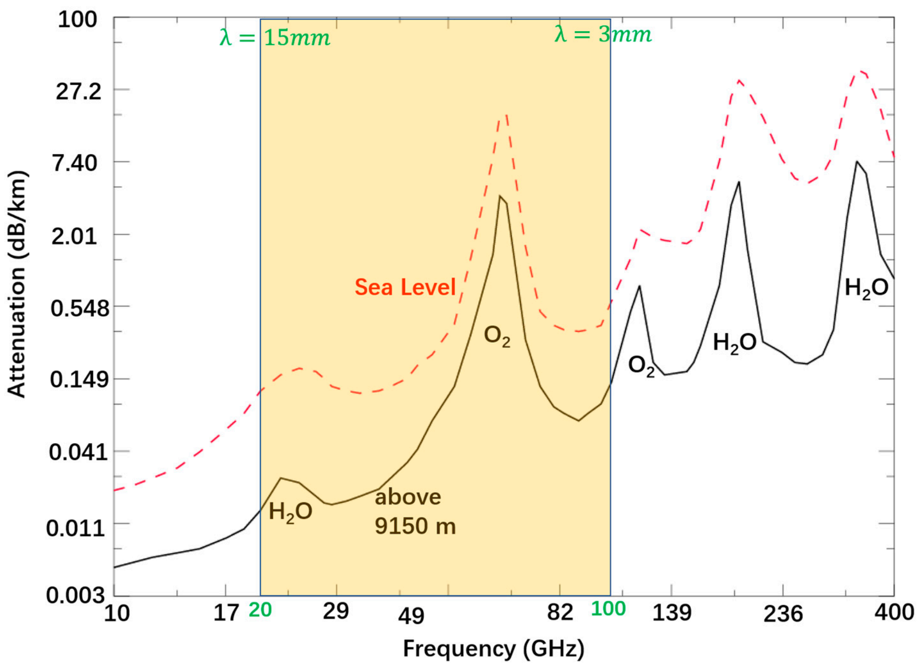

Figure 2. The averaged atmospheric absorption index in millimeter wavelengths at sea level and at height of 9150 m above the sea. The yellow part shows the frequency range of the proposed solar ultra-wide broadband millimeter-wave spectrometer (SUBMS).

Table 1. List of the existing solar millimeter-wave telescopes in the word.

Telescope	Frequency (GHz)	Status quo
Nobeyama RadioHiograph (NoRH), Japen [34]	Imaging at 17, 34	Closed in 2020
Nobeyama Radio Polarimeters (NoRP), Japen [35]	1.0, 2.0, 3.75, 9.4, 17, 35, 80	Daily (80 GHz is closed since 2012).
Itapetiga radome-enclosed telescope, Brazil [36]	7.0, 23.2, 30, 44.3, 90	Occasional observation based on events
Solar Submillimeter Telescope, SST, Agentina [37]	212, 405	Occasional observation based on events
Berkeley-Illinois-Maryland Array, BIMA, USA [38]	Imaging at 86	Occasional observation based on events
Atacama Large Millimeter/submillimeter Array, ALMA, Czeli [39]	Imaging at 100、239	Solar observation time: 2-3%
Chashan Broadband Solar millimeter spectrometer (CBS), China [40]	35-40 with frequency resolution: 0.5 GHz	Daily observation since 2022

From Table 1 we know that so far, there is no solar broadband millimeter-wave dynamic spectrometer in the world which may cover the typical frequency range of the solar transition region. The Chashan Broadband Solar millimeter spectrometer (CBS), China [40] is a broadband millimeter-wave dynamic spectrometer. However, its frequency range is only from 35 GHz to 40 GHz, and the bandwidth is 5 GHz, which is not enough wide to reveal the non-thermal process of the transition region. Therefore, we need a much more wider broadband millimeter-wave dynamic spectrometer.

4. A new conception of Solar Ultra-wide Broadband Millimeter-wave Spectrometers

In this work, we propose a new conception of solar ultra-wide broadband millimeter-wave spectrometer (SUBMS) which may cover the typical frequency range associated with the non-thermal electrons from the solar transition region (see the yellow part in Figure 2). The main parameters of SUBMS are listed in Table 2.

Table 2. main parameters of the Solar Ultra-wide Broadband Millimeter-wave Spectrometers.

Observing frequency	20-100 GHz (4 elements: 20-40、40-60、60-80、80-100GHz)
radius of antenna	98.3cm、65.5cm、49.2cm、39.3cm, respectively
Dynamic range	>30 dB
Polarization	RCP and LCP
Sensitivity	<0.1 sfu
Frequency resolution	100MHz、200 MHz、250MHz、400MHz, respectively
Frequency channel	200、100、80、50， respectively. Totally 430 channels
Time resolution	0.2 ms

As we discuss in Section 3, because of the strong absorption of oxygen and water molecules in the frequency range of 20-100 GHz, the proposed SUBMS cannot work on the ground. We have to put it on some spacecraft or China Space Station (Tiangong). Practically, before such telescope can be launched into the space, it is necessary to select some frequency bands for broadband dynamic spectrum observation experiments on ground-based telescopes in certain high-altitude and dry site. From Figure 2, we may find that 20-50 GHz and 75-100 GHz should be the relatively suitable windows for observing in ground-based telescopes. Because there has already CBS which covers the frequency range of 35-40 GHz, here we may select 20-35 GHz as a suitable frequency window. As for the constructing site, we may select Saisteng Mountain in Qinghai province, China. Here, there is a ready-made astronomical observation station, and the altitude is 4030 m with humidity <10%. Table 3 lists the main parameters of suitable ground-based broadband millimeter-wave spectrometers.

Table 3. main parameters of suitable ground-based broadband millimeter-wave spectrometers.

Observing frequency	20-35 GHz, 75-100 GHz
radius of antenna	112.4 cm, 39.3cm
Dynamic range	>30 dB
Polarization	RCP and LCP
Sensitivity	<0.1 sfu
Frequency resolution	50MHz or 250MHz
Frequency channel	300 or 100
Time resolution	0.2 ms or 0.4 ms
Construct site	Saisteng Mountain in Qinghai province, China, Altitude at 4030 m

After the experimental ground-based broadband millimeter-wave spectrometers obtain successfully the useful observation data of the broadband millimeter-wave spectrum from the transition region, then we may consider to promote the space-based solar ultra-wide broadband millimeter-wave spectrometer (SUBMS) at the full frequency range.

5. Conclusions

The solar transition region is a key part for revealing the mysteries of coronal heating, nature of solar eruptions and the origin of solar wind. Here, the huge gradient of temperature and density inevitably drives strong convective motion, which in turn drives the complex movement of magnetic field lines and generates various non-thermal energy releases, including the non-thermal electron beams which may produce groups of spike bursts and narrow-band type III bursts in the centimeter and millimeter wavelengths.

Millimeter-wave emission at frequency of 20-100 GHz is the typical emission response of the non-thermal processes in the solar transition region. The observations of broadband millimeter-wave dynamic spectrometers is the most important tool for obtaining the dynamic information of non-thermal processes in the solar transition region.

This work proposed a new plan of the Solar Ultra-wide Broadband Millimeter-wave Spectrometers (SUBMS). Due to the absorption of water and oxygen molecules in the Earth's atmosphere, it is very hard to obtain the broadband millimeter-wave dynamic spectrum in the full frequency range from the ground-based telescopes. We have to launch the telescope into space beyond the Earth's atmosphere. However, with a careful site selecting, broadband dynamic spectrum observations can also be obtained on the ground-based telescopes in some frequency bands of millimeter waves. Therefore, we also proposed to construct an experimental ground-based broadband millimeter-wave spectrometers in frequency range of 20-35 GHz or 75-100 GHz at a place of Saisteng Mountain in Qinghai province, China. If some valuable broadband dynamic spectrum observation can be obtained on the above ground-based telescopes in some millimeter-wave frequency bands, then we have enough confidence to develop and launch a space-based millimeter-wave telescope to observe the solar transition region with broadband dynamic spectrum in full frequency range. At that time, we will have the opportunity to truly reveal the energy release mechanism and mass propagate and transfer process in the solar transition region, and provide crucial evidence for explaining coronal heating, elucidating the origin of solar eruptions and solar winds.

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