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ПЕРЕХОДНОЕ ИЗЛУЧЕНИЕ В ТУРБУЛЕНТНОЙ АСТРОФИЗИЧЕСКОЙ СРЕДЕ

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TRANSITION RADIATION IN TURBULENT ASTROPHYSICAL MEDIUM

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Современные наблюдения и модели широкого круга астрофизических объектов убедительно свидетельствуют о том, что многие параметры в этих объектах сильно флуктуируют, в том числе, на весьма малых масштабах. Все многообразие возникающих при этом механизмов излучения, его спектров и иных характеристик составляет предмет стохастической теории излучения. Одним из таких механизмов является переходное излучение, возникающее при взаимодействии быстрых частиц с неоднородностями среды. В данной работе излагаются общие подходы, исповедуемые стохастической теорией излучения, и конкретные методы, используемые при вычислении переходного излучения быстрых частиц в магнитоактивной случайно-неоднородной плазме. Важность теории переходного излучения для астрофизики иллюстрируется на одном детально проработанном примере ее использования для анализа одного из многих аналогичных солнечных радиовсплесков, включая специально разработанные алгоритмы прямой подгонки наблюдаемых спектров радиоизлучения с помощью формул теории переходного излучения.

Modern observations and models of various astrophysical objects suggest that many of their physical parameters fluctuate substantially at different spatial scales. The rich variety of the emission processes, including transition radiation but not limited to it, arising in such turbulent media constitutes the scope of stochastic theory of radiation. We review general approaches applied in the stochastic theory of radiation and specific methods used to calculate the transition radiation produced by fast particles in the magnetized randomly inhomogeneous plasma. The importance of the theory of transition radiation for astrophysics is illustrated by one example of its detailed application to a solar radio burst, including specially designed algorithms of the spectral forward fitting.

1. Introduction

The phenomenon of transition radiation was discovered theoretically by two Nobel Prize winning (2003 and 1958 respectively) physicists, Ginzburg and Frank (1946). Ginzburg and Frank considered a simplest case when a charged particle passed through a boundary between two dielectrically different media and so generated waves due to a variation of the dielectric constant at the boundary. Remarkably, no acceleration of the particle is necessary to produce the emission due to transition through the boundary.

It is easy to understand that a similar effect of electromagnetic emission will take place if a medium is uniformly filled by turbulence that produces fluctuations of the dielectric constant throughout the whole volume rather than at an isolated boundary. Many astrophysical sources, especially those under strong energy release, are believed to be filled by turbulent, randomly inhomogeneous plasma and fast, nonthermal particles. In this situation, an efficient contribution of the transition radiation to the overall electromagnetic emission should be produced. Therefore, distinguishing this contribution from competing mechanisms is important. Below we describe the fundamentals of the transition radiation produced in a magnetized turbulent plasma, and demonstrate its high potential for astrophysical applications.

2. Fundamentals of Stochastic Theory of Radiation

Stochastic theory of radiation now represents a broad field of physics with many applications (see monograph by G.D. Fleishman. ‘Stochastic Theory of Radiation’, 2007). In astrophysical sources the nonthermal radiation arises as charged fast particles move through a turbulent plasma with random fluctuations of plasma density, electric, and magnetic fields. An immediate consequence of the random magnetic and electric fields at the source is that the trajectory of a charged particle is a random function of time. This means that calculating the emission requires some appropriate averaging of the relevant equations and parameters over the possible particle paths.

The presence of the density inhomogeneities acts differently. Indeed, these inhomogeneities have little effect on the fast particle trajectories; rather they give rise to fluctuations of the plasma dielectric tensor. These fluctuations allows for the plasma current stimulated by the fast particle field to emit powerful transition radiation. Since the plasma has a resonance around the plasma frequency, the intensity of the transition radiation is extremely large around this plasma frequency. The corresponding peak in the transition radiation spectrum is referred to as resonant transition radiation (RTR) and is of exceptional importance for astrophysical applications. Indeed, the microturbulence accompanied by the density fluctuations is likely to exist in various cosmic objects from geospace to distant cosmological sources of gamma ray bursts. In many instances, however, the number density of the plasma in the astrophysical object and the corresponding plasma frequency is so low that the radiation cannot be observed at the Earth because of ionosphere opacity and absorption of this radiation in the interstellar medium.

In some cases, nevertheless, the plasma frequency of a source is large enough for the corresponding radiation to be observable. For example, this is true for radio bursts produced in the solar corona. In our previous publications (2005) we demonstrated that about 10% of all microwave solar continuum bursts are accompanied by decimetric resonance transition radiation (RTR) and presented ample evidence in favor of transition radiation for one of the events, 06 April 2001, including detailed study of spatially resolved observations.

Specifically, Nita et al. (2005) summarized and checked against observations the following main properties of RTR, expected in the case of solar bursts. The emission (1) originates in a dense plasma, $f_{\rm pe} \gg f_{\rm Be}$, where f_{pe}

and f_{Be} are the electron plasma- and gyro-frequencies; (2) has a relatively low peak frequency in the decimetric range, and so appears as a low-frequency component relative to the associated gyrosynchrotron spectrum; (3) is co-spatial with or adjacent to the associated gyrosynchrotron source; (4) varies with a time scale comparable to the accompanying gyrosynchrotron emission (assuming a constant or slowly varying level of the necessary microturbulence); (5) is typically strongly polarized in the ordinary mode (*o*-mode), since the extraordinary mode (*x*-mode) is evanescent, as for any radiation produced at the plasma frequency in a magnetized plasma; (6) is produced by the lower-energy end of the same nonthermal electron distribution that produces the gyrosynchrotron emission, with intensity proportional to the instantaneous total number of the low-energy electrons in the source; (7) has a high-frequency spectral slope that does not correlate with the spectral index of fast electrons (in contrast to gyrosynchrotron radiation, which does). Here we analyze this event in even more detail and apply the observations to the flare plasma diagnostics.

3. Two-component radio burst 06 April 2001

Fig. 1 gives an overview of the event under study. It displays the dynamic spectrum of the radio burst 06 April 2001 recorded by Owens Valley Solar Array (OVSA) in

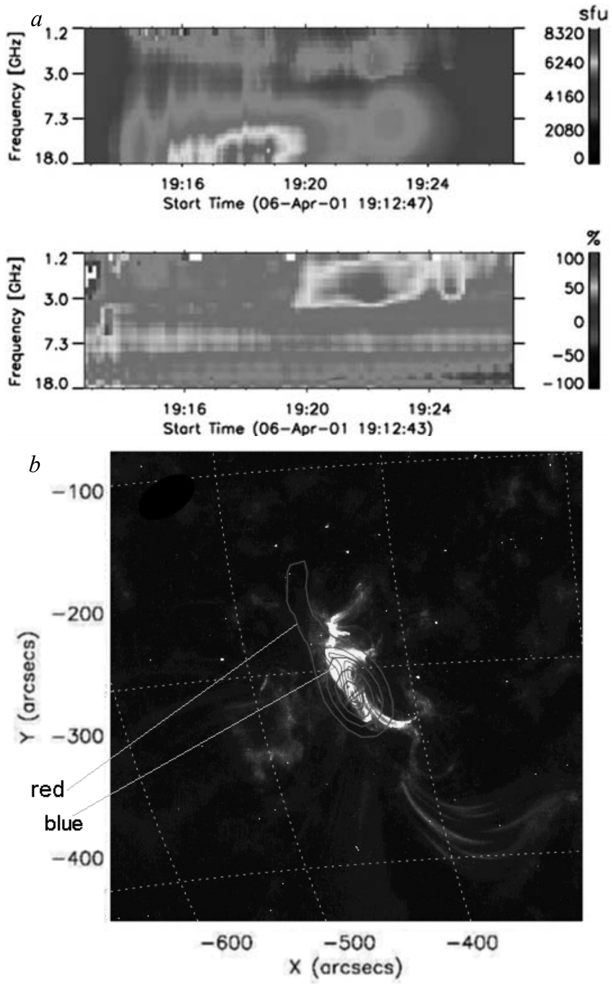

Fig. 1. Overview of the event. *a* – dynamic spectra of the total power (top) and circular polarization (bottom). The period of RTR is the highly polarized (red) emission in the lower panel. *b* – OVSA maps of radio emission at 2 GHz (red) and 7.4 GHz (blue) superimposed on the TRACE 171 Å image.

the frequency range 1–18 GHz (Nita et al. 2005) in total intensity and polarization, as well as images of the dm and cm sources superimposed on a Transition Region and Coronal Explorer (TRACE) 171 Å image. This figure shows that the event indeed consists of two distinct spectral components, whose sources coincide spatially with each other and with a dense loop visible in the TRACE UV image. The dm component is highly right-hand circularly (RCP) polarized.

Fig. 2 displays contour levels of the dm emission at 95, 97 and 99% of the peak intensity at eight dm OVSA frequencies in RCP (thick lines) and LCP (thin lines) superimposed on the photospheric magnetogram (left) and on the SXR SOHO image of a dense hot loop (right). A number of things can be noted in this figure. The stronger, RCP, component of the dm emission originates from the region of the negative magnetic polarity throughout all the dm frequency channels; therefore, it is O-mode radiation. All the RCP contours coincide spatially with the brightest part of the hot dense loop visible in SXR, i.e., this emission goes from a region with relatively large plasma density, although exact position of the peak brightness changes with frequency. The trend of this change is such that the lower frequency radiation tends to originate at the loop-top, while higher frequency radiation tends to originate from the loop legs. The behavior of the weaker LCP component bears both similarities and differences with the RCP component. First, the LCP emission at 1.2–2 GHz comes from the region of positive magnetic polarity, so it is also O-polarized radiation. Second, the lower frequency LCP sources are displaced relative to the brightest part of the SXR loop. And finally, the higher frequency LCP sources (at 2.4–3.2 GHz) are located in a region with negative magnetic polarity; therefore, it is X-mode polarized radiation, unlike other dm radiation. These spatial relationships are in excellent agreement with expectations derived from the spectral behavior of this radio burst: indeed, since the LCP contribution of the RTR component is very weak, the LCP emission at 2.4–3.2 GHz is interpreted as a continuation of the X-polarized microwave gyrosynchrotron radiation, rather than RTR contribution.

In addition to previously established properties of the dm continuum component (Nita et al. 2005) and spatial relationships discussed above, we consider here the characteristic decay time constants at both dm and cm spectral components. Specifically, we looked into the decay phases of the light curves at all frequencies and determined the range of time when the decay profile can be approximated by an exponential function. Then, the characteristic decay constant at each light curve was considered as a characteristic decay time at this frequency. Fig. 3 displays these time decay constants vs frequency for the dm and cm components separately. The dependences are remarkably different for these two emission components, although both of them can be easily understood if the decay constants are specified by the fast electron life times against the Coulomb collisions at the source. Indeed, for the gyrosynchrotron emission, higher emission frequency means greater mean energy of the emitting electrons. These higher energy electrons have a longer life time against the Cou-

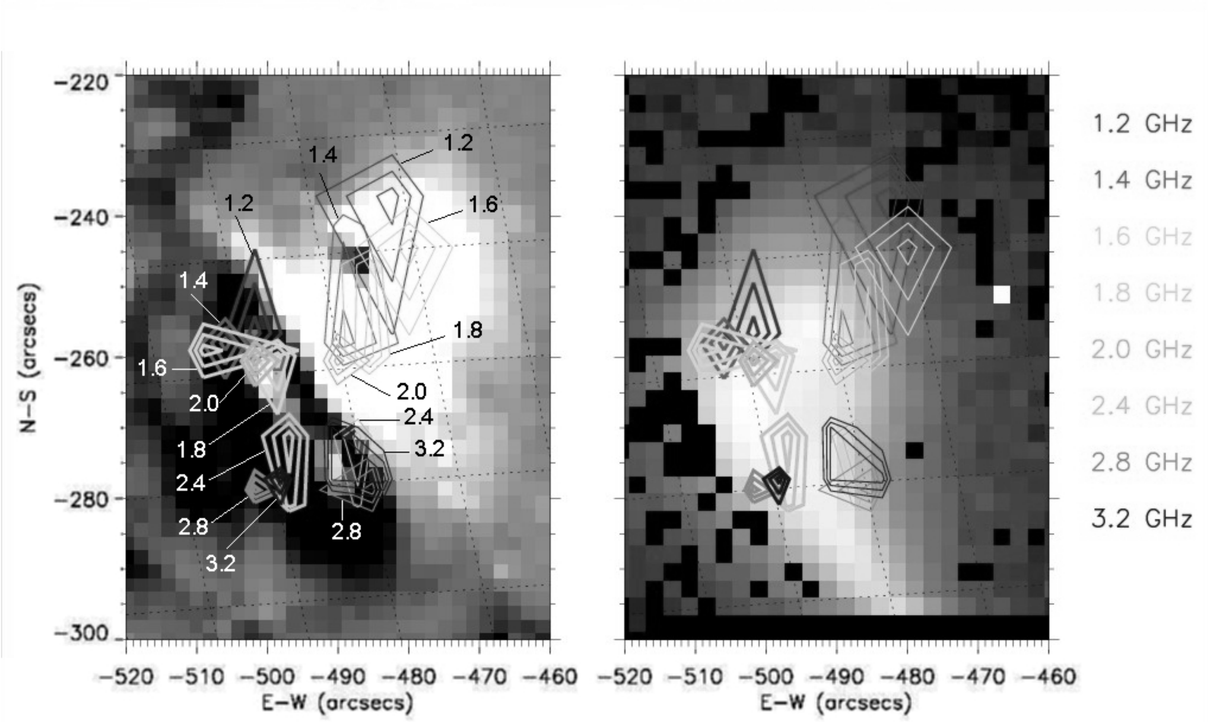

Fig. 2. OVSA maps of the RCP (thick lines) and the LCP (thin lines) dm emission at 8 distinct frequencies superimposed on the magnetic field distribution (left) and SXR SOHO map (right).

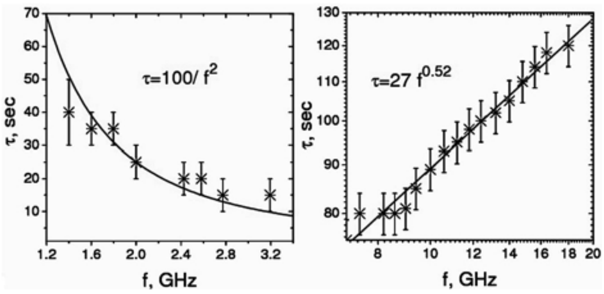

Fig. 3. The decay constant of the radio emission vs frequency for the dm component (left) and cm component (right).

lomb collisions, which explains the observed increase of the decay constant with frequency. For the RTR contribution, howeẂver, higher emission frequency corresponds to a higher plasma frequency in the corresponding source level, therefore, denser plasma and, consequently, shorter life time of the fast electrons, which is really observed. Thus, the more detailed study performed here confirms further the interpretation of the dm continuum component as an RTR contribution.

4. Flare plasma diagnostics based on the transition radiation

Now, as we have a solid interpretation of the dm continuum component as produced by RTR by fast electrons moving in a dense plasma, we can make a next step and apply the observations for the flaring plasma diagnostics. We assume that the inhomogeneity of the flare volume can be described by a Gaussian distribution of the source volume over the plasma frequency with some mean plasma frequency (mean plasma density) and dispersion (provided by scatter of the plasma density through the source), $F(f_{pe})=A\ \exp(-(f_{pe}-f_0)^2/\Delta f^2)$. Depending on how other relevant parameters change with the plasma density at the source, the RTR intensity can be parameterized as proportional to $f^a \exp(-(f-f_0)^2/\Delta f^2)$ with different values of the parameter a. For clarity, we use two distinct values a=0 (model 1 – no dependence on frequency besides the Gaussian factor) and a=2 (model 2 – rather strong frequency dependence).

Then, we fit the sequence of the observed dm spectra with these two model functions to obtain a sequence of the fitting parameters, which are the peak flux, the mean plasma density f_0, and the dispersion Δf. Fig. 4 displays the sequence of the recorded spectra and corre-

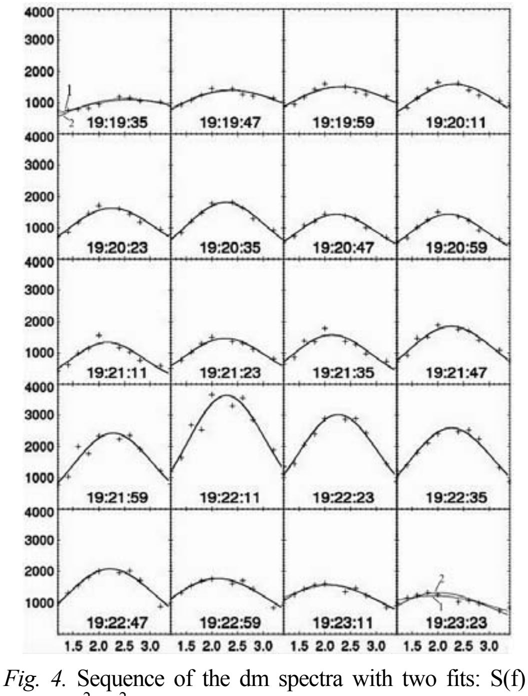

Fig. 4. Sequence of the dm spectra with two fits: $S(f) \sim f^a \exp(-(f-f_0)^2/\Delta f^2)$. Model 1 (a=0, curve 1) and model 2 (a=2, curve 2).

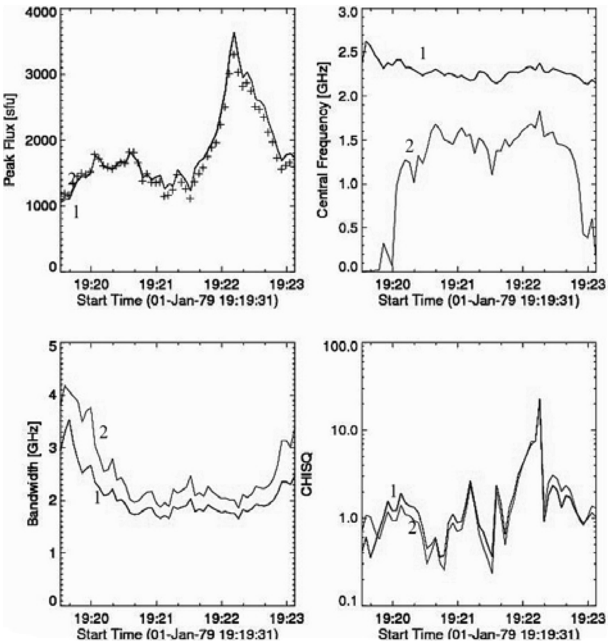

Fig. 5. Evolution of the fitting parameters and chi-square measure for model 1 (curve 1) and model 2 (curve 2).

sponding fits. It is clear that fits with both values of a are comparably good and even indistinguishable for most of the instances.

Fig. 5 gives the sequence of the fitting parameters together with the chi-square plot. Again, we cannot select between the two models based on the chi-square criterion, since they are very similar to both considered models. Both models give the same peak flux values and similar bandwidth of the distributions. However, the central frequency of the distribution behaves differently in the two models: it is almost constant with 10 % variations in model 1, while it varies substantially in model 2. Thus, using the requirement of reasonable smoothness of the derived physical parameters we conclude the model 1 (which assumes that all other parameters besides the plasma density are constant through the source) is preferable.

5. Discussion

Nita et al. (2005) proved that the dm continuum component of this solar radio burst is produced by RTR and derived the level of the microturbulence in the plasma to be $<\Delta n^2>/n^2 = 10^{-5}$. This finding is potentially very important for other cosmic objects. Indeed, the obtained microturbulence level is not particularly strong and much stronger turbulence is expected in many cases, especially, when there is a strong release of the energy at the source. Sometimes, such energy release gives rise to a relativistic expansion of the source, so the emission spectrum is Doppler-boosted and RTR produced at the local plasma frequency can be observed at the Earth even from relatively tenuous sources with low plasma frequency.

In this study we present more evidence in favor of RTR generation at the dm continuum solar bursts and use this emission component to derive additional plasma parameters. In particular, we determine the mean plasma frequency and its dispersion at the source in the course of time. Interestingly, these two parameters do not change much during the time of the dm burst. We note that these parameters are obtained from the total power spectra recorded without spatial resolution. Fig. 2 demonstrates that the radio sources at various frequencies do not coincide exactly. Therefore, in cases where a sequence of spatially resolved spectra are available we would be able to study the structure of the flaring plasma density in much greater detail as well as the distribution of the microturbulence over the source.

Generally speaking, the RTR contribution is also informative about the fast electrons producing it. In the example presented in Fig. 3 we show the emission decay constants, which can be associated with the fast electron life times. In our case we used exponential fragments of the light curves at the late decay phase of the emission, since no exponential phase was found in the early decay phase. We found the life time to be within 10-40 sec, which corresponds to the electrons of 300 keV or larger in the case of dense flare plasma available in this event. On the other hand, we can expect that most of the RTR emission (around the peak of the burst) is produced by the electrons with E=100–200 keV (Nita et al. 2005). This apparent contradiction can be easily resolved if we recall that the lower energy electrons have the life time of only a few seconds in the given dense plasma, so they die even before the light curves reach the exponential decay stage, and we observe the RTR contribution from preferentially higher energy electrons late in the event.

Conclusions

RTR represents a distinct emission mechanism, which is observable in many solar burst and probably relevant to many other cosmic sources. Application of the available theory to observations allows for advanced plasma diagnostics, including study of the plasma density and the turbulence distributions, and fast particle kinetics. The theory of RTR is currently developed for usual plasmas, but is not available for the case of relativistic plasmas. Given that the turbulence level in the relativistic plasmas is expected to be very high, the extension of the RTR theory to the relativistic case is highly desirable.

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REFERENCES

1. Fleishman G.D. Stochastic Theory of Radiation. M. Izhevsk, RCD, 2007. 452 p.
2. Fleishman G.D., Nita G.M., Gary D.E. // ApJ. 2005. V. 620. P. 506.
3. Ginzburg V.L., Frank I.M. // Zh. Eksp. Teor. Fiz. 1946. V. 16. P. 15.
4. Nita G.M., Gary D.E., Fleishman G.D. // ApJ. 2005. V. 629. P. L65.

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