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НИЗКОЧАСТОТНОЕ ГАЛАКТИЧЕСКОЕ ИЗЛУЧЕНИЕ

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LOW-FREQUENCY GALACTIC RADIATION

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Данная работа посвящена прямому моделированию низкочастотного галактического радиоизлучения в рамках современных представлений о структуре фаз межзвездной среды. Моделирование выполняется с целью связать наблюдаемое космическим аппаратом ULYSSES низкочастотное радиоизлучение со свойствами межзвездной плазмы. Рассматриваются следующие основные компоненты межзвездной среды: горячая разряженная плазма, диффузионный теплый газ и облака Рейнольдса. Интенсивность синхротронного излучения вычисляется с учетом эффекта Разина. Моделирование включает присутствие местного поглощающего облака вблизи Земли и его анизотропию. Модельные спектры интенсивности излучения находятся в хорошем согласии с имеющимися наблюдательными спектрами излучения в радиодиапазоне, включая его низкочастотную часть. Обсуждаются последующие шаги, необходимые для анализа и интерпретации временной модуляции фонового излучения, наблюдаемого аппаратом ULYSSES.

This work presents direct modeling of low-frequency galactic radio emission within the current concept of the interstellar medium phase structure. The goal of this modeling is to link the low-frequency radio emission observed by ULYSSES with properties of the interstellar plasma. Main components of the interstellar medium taken into account are: hot low-density plasma, diffuse warm gas, and Reynolds clouds. Synchrotron radiation intensity is calculated with account of the Razin effect. The modeling takes into account the near-Earth local absorbing cloud and its anisotropy. Modeling spectra of the radiation intensity agree well with the observation radio spectra including the low-frequency part. We discuss further steps required to analyze and interpret time modulation of the background radiation observed by ULYSSES.

Introduction

Diffuse radio emission of the Galaxy has a nonthermal nature and thus believed to provide information on Galactic magnetic fields and relativistic electron component of cosmic rays, as standard synchrotron emission is commonly adopted to be the dominant radiative process contributing to radio emission. It has long ago been recognized that this emission at low frequencies becomes dependent on properties of the interstellar medium (ISM) in addition to the magnetic field and relativistic electron properties. Two main ISM effects on the radio emission are the free-free absorption by ionized ISM components (which depends on the plasma density and temperature) and the Razin Effect (which depends on the plasma density and the magnetic field). Since these effects depend on parameters of the ISM plasma (known to be highly inhomogeneous), the resulting radio emission depends significantly on the ISM structure in the observer's surroundings. Therefore, observing and analyzing the low-frequency radio emission can provide us with additional tool of the ISM study. Accessing the Galactic spectrum at frequencies lower than 10 MHz requires observations from space missions outside the Earth's ionosphere.

Such space measurements have been repeatedly performed during more than 40 years by now ([1], [2]). A recent example is the WAVES experiment on the Wind spacecraft observing at hundreds of frequencies below 13.8 MHz. The Wind spacecraft was at a sophisticated orbit in the Sun-Earth system that placed it far away from the Earth for most of the time. It was spin stabilized with the spin axis perpendicular to the ecliptic plane. The WAVES antennas used there were the long wires of 104 m length located at the spin plane of the spacecraft, i.e., at the ecliptic plane. The spacecraft rotated with the 3 s period. An «X antenna», 2×50 m long, was used for frequencies less than 1 MHz, and an «Y antenna», 2×7.5 m long at an angle of 90° to the «X antenna», was used for frequencies between 1 and 13.8 MHz.

After that, low-frequency observations of the galactic background radio emission were performed within the ULYSSES experiment that is probably the best for this goal. Indeed, this spacecraft was one of few spacecrafts traveling far away from the Sun. The most important fact is that during a Jupiter bypass (in 1992), ULYSSES performed a maneuver that increased its inclination to the ecliptic plane by 80.2 degree. Two these factors allowed us to decrease the noise level from the Sun's and Earth's sources significantly; consequently, it will be possible to increase the signal-to-noise ratio in the Galactic radio spectrum. Figure 1 presents overview of the Galactic radio spectrum. The spectrum peaks around f~3 MHz; all measurements made by different spacecrafts are in good agreement above f~0.5 MHz, but start deviating from each other at lower frequencies that is related to a fast decrease in spectrum resulting in a poorer signal-to-noise ratio.

Modeling of synchrotron radiation from multi-component ISM

As was mentioned before, the multiphase ISM structure has a major effect on the Galactic background radiation at low frequencies. Most of the galactic disk volume is filled with three different kinds of gas: hot coronal plasma (temperature T~10^6 K, density of thermal electrons n_e~10^{-3} cm^{-3}, filling factor α~0.2–0.6), diffuse warm gas (T~10^4 K, n_e~0.03 cm^{-3}, α~0.5), and Reynolds clouds (also called the HII regions with low surface brightness, T~10^4 K, n_e~0.2 cm^{-3}, α~0.2). Our purpose is to calculate contributions from all these phases to both opacity and emissivity based on available observational constraints and theoretical considerations, and to formulate the synthetic model describing the observed low-frequency spectrum.

We start our consideration from a statistically uniform

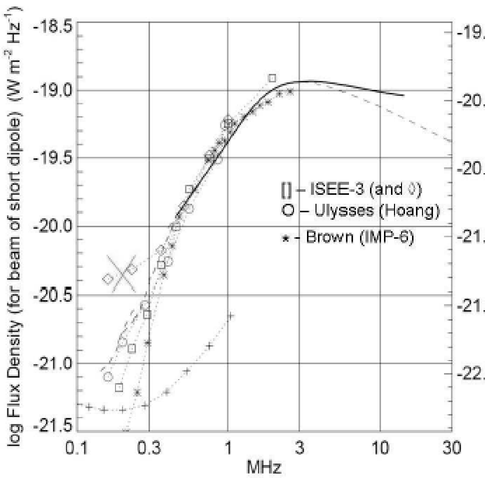

Fig. 1. Low-frequency spacecraft observations of the galactic background radio emission. Left scale: flux density per beam of the Galactic background radiation for a short dipole in free space in the range of 0.1–30 MHz. Right scale: specific intensity averaged over 8π/3 sr beam of a short dipole. Asterisk marks the minimum specific intensity from Brown [1]. Data marked with circles have been obtained from the Ulysses experiment. The curve with marks+presents estimates of the receiver noise level of WAVES [2].

simplified model of the radio source which assumes that emitting and absorbing materials are uniformly mixed:

$$\overline{I}_f = \frac{\overline{\varepsilon}_f}{\overline{k}_f}\left(1 - e^{-\overline{\tau}_f}\right), \qquad (1)$$

where $\overline{\varepsilon}_f$ is the averaged emissivity of medium, $\overline{\tau}_f = \overline{k}_f\ L_{\text{eff}}$ is the averaged optical thickness, $\overline{k}_f$ is the averaged absorption coefficient, L_{eff} is the effective length of radio source. Approximation of the statistical uniformity of radio source breaks down at sufficiently low frequencies when the optical depth of a single absorbing cloud in the disk becomes larger than one [3] that will later be properly taken into account. However, before making this necessary correction, we estimate averaged values in (1).

Intensity of radiation

As is discussed, radiation intensity within the statistically uniform model is described by Eq. (1) that can be transformed as follows:

$$I_{\text{disk}}(f) = \frac{\overline{\varepsilon}_f L_{\text{eff}}}{\overline{k}_f L_{\text{eff}}}\left(1 - e^{-\overline{\tau}_f}\right) = \frac{\overline{\varepsilon}_f L_{\text{eff}}}{\overline{\tau}_f}\left(1 - e^{-\overline{\tau}_f}\right), \qquad (2)$$

by introducing the effective disk semi-thickness L_{eff}. Substitution of the effective disk emissivity and effective optical depth for Eq. (2) yields a variety of (statistically uniform) models of Galactic synchrotron spectra shown in Fig. 2. The colored asterisks show observations of the Galactic background radiation made by dipole antennas in [1] and a number of ground-based experiments. We, therefore, can firmly conclude that any statistically uniform model of the synchrotron radiation is intrinsically inconsistent with observations below approximately 1 MHz. Thus, the model must be modified in order to account for local ISM properties beyond the statistically uniform approximation better.

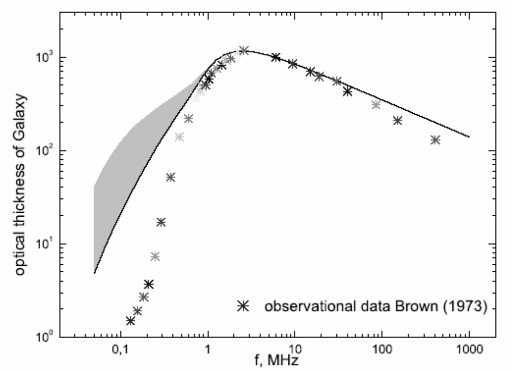

Fig. 2. Entire range of the radiation intensity spectra.

Effect of the local cloud

As is discussed, the absorption and, consequently, the spectrum shape at low frequencies depend critically on whether the solar system is located between clouds or in the cloud. As the solar system is in fact located in the local cloud, there is an additional absorption of the incident Galactic radiation [3]. Korsakov et al. [3] demonstrated that taking the enhanced local absorption into account improves the spectrum fit significantly. In presence of the local absorbing cloud, solution to the radiation transfer equation can be written in the form:

$$I(f) = I_{\text{disk}}(f)e^{-\tau_L} + I_L(f)(1 - e^{-\tau_L}),$$

where $I_{\text{disk}}(f)$ is the outer Galactic radiation (calculated in the previous section) incident on the local cloud, τ_L is the free-free optical depth of the local cloud [3]

$$\tau_L = 0.15\left(\frac{T}{7000K}\right)^{-1.35}\left(\frac{\overline{n}_e}{0.3\ \text{см}^{-3}}\right)^2\left(\frac{l_l}{1.5pc}\right) f_{\text{MHz}}^{-2.1},$$

l_l is the size of the local cloud surrounding the solar system. Numbers in denominator of this formula represent typically adopted physical parameters of the local cloud. Intensity $I_L(f)$ is the synchrotron radiation of the local cloud that can be calculated similarly to those from any other ISM component. Figure 3 shows that the account of the local cloud effect results in significant steepening of the low-frequency Galactic spectrum; this provides a much better fit to the data.

We conclude that the statistically uniform model with a single electron spectrum and a single magnetic field strength at all three main volume ISM phases complemented by account of the free-free absorption in the local cloud provides fit consistent with observations (at least at frequencies above approximately 0.25 MHz, where the Galactic background radiation measurements made during different space missions agree with each other). This fit starts deviating from the observational data at high frequencies above 40 MHz. However, adoption of a broken power-law spectrum of relativistic electrons (and, consequently, a broken power-law synchrotron spectrum) and/or addition of the extragalactic component can easily improve fit at these high frequencies.

Preliminary discussion

We did not vary the local cloud parameters within any plausible bounds, but used their mean values.

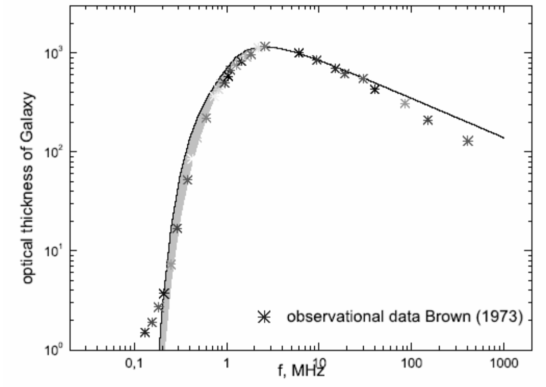

Fig. 3. Entire range of the radiation intensity spectra subject to the free-free absorption in the local cloud.

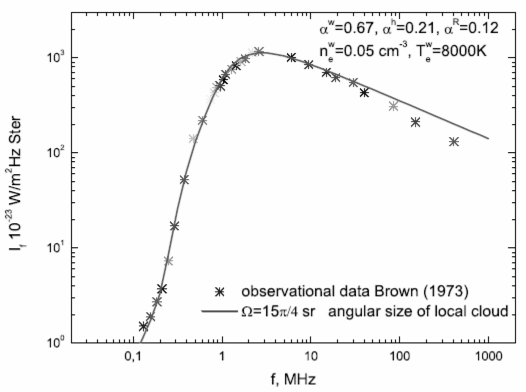

Fig. 4. Model spectrum of the Galactic background radiation providing the best fit to the low-frequency observations reported by Brown [1]. Parameters are presented on the plot.

Within this simplified approach, we can summarize the ISM model providing the best fit to the observational data on the low-frequency Galactic radio emission: warm ionized gas

$$(\alpha^{w} = 0.67,\ T_e^{w} = 8000\ \text{K},\ n_e^{w} = 0.05\ \text{см}^{-3}),$$

hot ionized gas

$$(\alpha^{h} = 0.21,\ T_e^{h} = 10^{6}\ \text{K},\ n_e^{h} = 0.003\ \text{см}^{-3}).$$

Reynolds clouds

$$(\alpha^{R} = 0.12,\ T_e^{R} = 10^{4}\ \text{K},\ n_e^{R} = 0.2\ \text{см}^{-3})$$

and local cloud

$$(\Omega_L = 15\pi/4,\ T_e^{R} = 7000\ \text{K},\ n_e^{R} = 0.3\ \text{см}^{-3}).$$

Fig. 4 presents the model spectrum of the low-frequency galactic radiation for this set of parameters. This ISM structure must then be used in preliminary study on anisotropy of the Galactic radiation.

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