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Solar 3.04 cm Hydrogen Line Emission Revealed in Observations of the Active Region NOAA 10105

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Abstract—RATAN-600 observations of a microwave source located above the active region NOAA 10105 obtained on September 7–20, 2002 with a frequency resolution of ∼10% have revealed a spectral feature near 3.04 cm that can be interpreted as a neutral hydrogen line. This feature was observed September 11, 2002, in both absorption and emission, and was detected in the spectra of various portions of the source (sunspot, flocculus, and background). The maximum line depth of $(35 \pm 5)\%$ of the source brightness was observed at the start of the observations (9.2^{h} UT) in the flocculus in absorption. The line intensity decreased rapidly with time, becoming less than the measurement errors by 9.7^{h} UT. It is most likely that the 3.04 cm emission is related to a 2B chromospheric flare (M2.2 X-ray burst) observed at $\sim 7.5^{h}$ UT in the floccular field, near the main sunspot of NOAA 10105. In this case, the total duration of the event was about two hours. These observations are consistent with earlier statistical studies, and refines these based on data with higher spatial resolution. Recommendations for further observational studies of the solar 3.04-cm hydrogen line are presented; requirements for theories of the 3.04 cm line taking into account nonequilibrium states of the active-region plasma are indicated.

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1. INTRODUCTION

The line at 9850 MHz (3.04 cm), attributed to the transition $2^2P_{3/2}$–$2^2S_{1/2}$ between the fine structure levels of the neutral hydrogen atom, occupies a particular place in the complex solar spectrum. This is essentially the only solar hydrogen line that can be detected in the radio band. The interest of solar $H_{3.04}$ observations was first pointed out by Wild in 1952 [1], with this ideas being supported by De Jager in 1959 [2]. However, the estimates of [1–3], all carried out for a model of the quiescent Sun, suggest that we should not expect strong emission (or absorption) in the $H_{3.04}$ line if the level populations are determined by collisions occurring in thermal equilibrium. At the same time, it was stated that the probability of observing this line should significantly increase under strongly nonequilibrium conditions. Some difficulties encountered in observational studies of this line, including masking by the strongly polarized continuum of solar active regions, were discussed in [4].

The first attempt to detect this line was undertaken at the NERA observatory [2] and gave inconclusive results. Attempts to detect the solar $H_{3.04}$ line then continued over some thirty years (1958–1988) [5–8]. According to [8], which summarizes results obtained for low-spatial-resolution observations of the quiescent Sun (188 spectrograms), the maximum intensity of the $H_{3.04}$ line reaches $(1.55 \pm 0.02)\%$ of the continuum. Dravskikh and Dravskikh [8] also present a line profile that they suggest is in fairly good agreement with the profile predicted in [1], although they note that their results require confirmation by higher-resolution observations.

Solar observations with a resolution of $\sim 28''$ obtained with the RATAN-600 radio telescope (at a wavelength of 3 cm) were started in 1976. The spectral range and spectral resolution of these observations have been continuously improved thanks to the work of Bogod et al. [9, 10]. Due to the indicated capabilities, RATAN-600 observations are quite applicable to studies of this hydrogen line.

Some features of the active region NOAO 10105 at frequencies near the $H_{3.04}$ line were already noted as part of studies of the sources of the S-component of the solar radio emission based on RATAN-600 observations [11]. The objective of our present study is to refine the spatial and temporal distributions of the line, identify the most probable origin of this feature, and assess prospects for further studies.

2. OBSERVATIONS AND DATA PROCESSING

The RATAN-600 data used for our study were obtained in September 2002 (see ftp://ftp.sao.ru/pub/sun/). The one-dimensional spatial resolution for a wavelength of $\sim$3 cm is $\sim 28''$ and the frequency resolution in the range 1.83–30 cm is 5%–10%. Nobeyama Radio Heliograph (NoRH) data at 1.76 cm (ftp://solar.nro.nao.ac.jp)/ and Siberian Solar Radio Telescope (SSRT) data at 5.2 cm (ftp://iszf.irk.ru/ ssrt/) were also used.

We analyzed the data using a technique developed by A.N. Korzhavin and realized in the standard software of [12]. However, instead of using the Stokes parameters I and V, as is usual, we considered the R and L polarizations, which display the $H_{3.04}$ line more clearly.

Our method of searching for the solar $H_{3.04}$ line was similar to that proposed in [5]. We analyzed the data at frequencies approaching that of the line and determined the spectral flux density at three neighboring points, at 2.90, 3.06, and 3.21 cm. The corresponding frequencies are 10.35, 9.80, and 9.35 GHz, respectively, and the bandpass for each frequency is $\sim$300 MHz. Assuming that the background spectrum was monotonic within the range, we searched for deviations from this spectrum at 3.06 cm. We expect that the fundamental idea behind this method will also be applied to further observations with higher spectral and spatial resolutions.

3. RESULTS

At the photospheric level, the morphology of the active region NOAA 10105 resembled a very large single sunspot surrounded by a bright flocculus (see Fig. 1). A detailed description of this active region can be found in [13].

The RATAN-600 solar scans obtained with high resolution in one dimension show NOAA 10105 as a bright source that can be divided into two regions (see Fig. 2): the eastern region A, which is a bright compact source associated with the main sunspot, and the less bright, extended western region B, identified as a floccular field.

A narrow-band spectral feature detected close to the $H_{3.04}$ line was observed September 11, 2002: the scan obtained at 3.06 cm differed from the scans obtained on other days, and also from those obtained at 2.90 and 3.21 cm (see Fig. 2). This was most evident for the extended region B. The monotonicity was not disrupted in a jump-like fashion, as we would expect for radiation in the transition region; instead, there was a “dropping” of the 3.06 cm point against the monotonic background spectrum. Figure 3 presents the results of the standard RATAN-600 data processing applied to the measurements of the spectral flux density. The $H_{3.04}$ line can be seen in all elements of the active region, including the sunspot source, floccular source, and quiescent Sun, but region B of the floccular field demonstrates the maximum strength, which reaches $\sim(30 \pm 5)\%$ (in the R polarization).

To improve the reliability of the results, we also processed the RATAN-600 data for NOAA 10105 in another way, using the antenna temperature T determined for individual points of the scan (marked A, B, and C in Fig. 2) against the background level of the “sky”. The observations were analyzed in this way both at local noon ($\sim 9.2^{\rm h}$ UT) and 0.5, 1.0, and 1.5 h after noon. Figure 4 presents the results obtained in the form of the line depth $\frac{dT}{T}$ calculated using the antenna temperature $T_{3.06}$ detected at the point of maximum brightness for the sources A and B observed at 3.06 cm:

$$\frac{dT}{T} = \frac{T_{3.06} - \bar{T}_{3.06}}{\bar{T}_{3.06}} \times 100,$$

where $\overline{T}_{3.06}$ is the antenna temperature at 3.06 cm in the absence of emission in the $H_{3.04}$ line; this temperature was calculated via a linear interpolation of the antenna temperatures measured at 2.90 and 3.21 cm. The maximum $H_{3.04}$ line detected in this way corresponds to $9.2^{\rm h}$ UT and reaches $(35 \pm 5)\%$, in good agreement with the analysis of the flux measurements. In the subsequent 0.5–1 h, the line depth decreased to the background level.

We also compared this event with GOES data (see Fig. 5a). Our analysis shows that nearly the entire GOES profile for the event observed from $7.5^{\rm h}$ UT to $10.5^{\rm h}$ UT (except for a second maximum at an observation time of 1.5^{h}) can be attributed to events occurring in NOAA 10105. Note that the weak SF flare was accompanied by an eruption. On the whole, the RATAN-600 observations were carried out after the main maximum; this period could be classified as a post burst increase (PBI) of an M2.2 impulsive event, whose maximum was observed at $\sim 7.5^{\rm h}$ UT. We conclude that the $H_{3.04}$ line is very likely genetically related to the chromospheric flare (2B) and X-ray event (M2.2), with these flares occurring in the floccular field located near the main NOAA 10105 sunspot.

Our results on the solar $H_{3.04}$ line represent a significant refinement compared to the results of [8], and

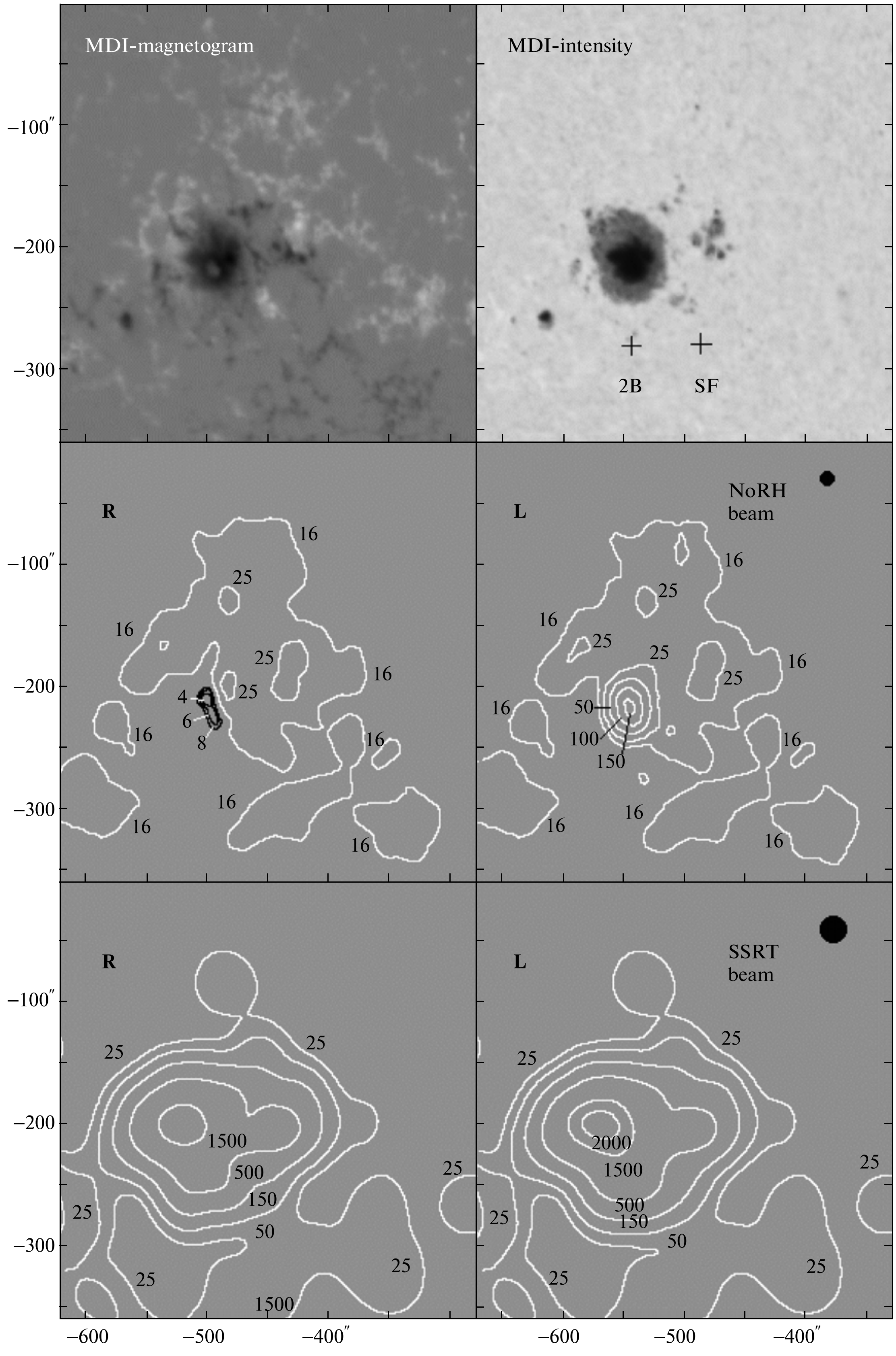

Fig. 1. SOHO (upper row), NoRH (middle row), and SSRT (lower row) observations of NOAA 10105 on September 11, 2002. The NoRH and SSRT maps are presented for the R (left) and L (right) polarizations; the brightness temperature is indicated in thousands of Kelvin. The daggers in the magnetogram indicate chromospheric flare locations.

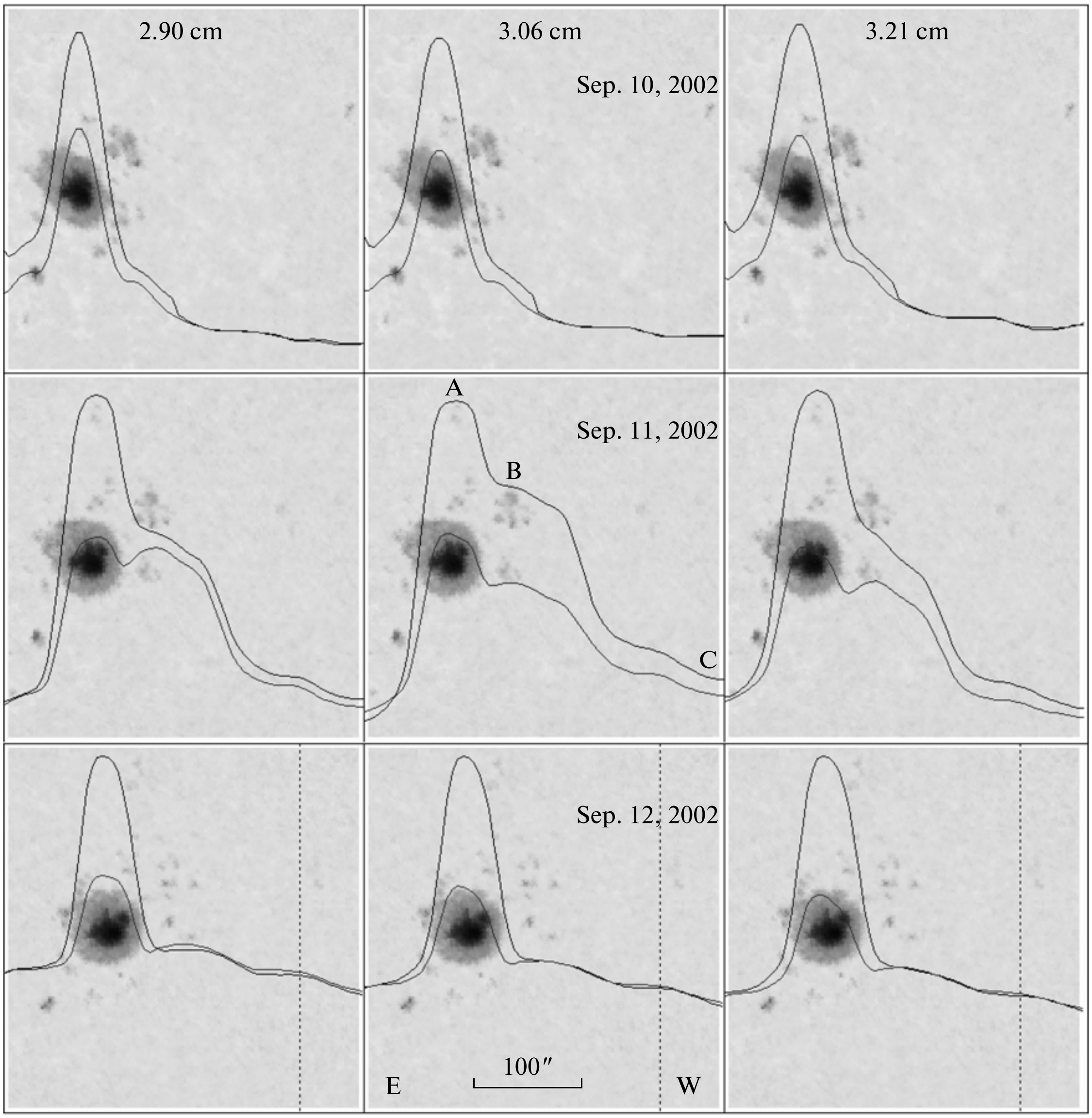

Fig. 2. RATAN-600 scans of NOAA 10105 at 2.90 cm (left column) for September 11–13, 2002, 3.06 cm (middle column), and 3.21 cm (right column). The scans are superimposed on the SOHO photoheliograms for the corresponding days. The three main regions in the image are marked by A (sunspot), B (flocculus), and C (background). The scans are presented in R (lower curves) and L (upper curves) polarizations.

can address the questions of (a) what was observed (the effect interpreted as the $H_{3.04}$ line is described in detail), (b) where it was observed (the particular component of the solar radio emission is indicated), and (c) when it was observed (the duration is estimated and genetic relations are found).

The unanswered question is "why;" namely, we must propose a scenario and identify the processes disrupting the equilibrium and strengthening the $H_{3.04}$ line.

4. DISCUSSION

Our results for the particular active region NOAA 10105 are consistent with $H_{3.04}$ line data detected earlier [8] for the radiation of the quiescent Sun. The term "quiescent Sun" was not used entirely correctly in [8], and should be replaced by "quasi-quiescent Sun," which could be defined as the entire disk including the B and S components of the radio emission detected during periods without large flares or other sporadic events. Our studies show that the amplitude of $\sim$1.5% of the continuum reported in [8] could be due to a single event.

What is the mechanism exciting the hydrogen atoms and giving rise to the $H_{3.04}$ line emission in the context of our NOAA 10105 observations? The analysis of a single event cannot be expected to provide an answer to this question or yield a valid scenario

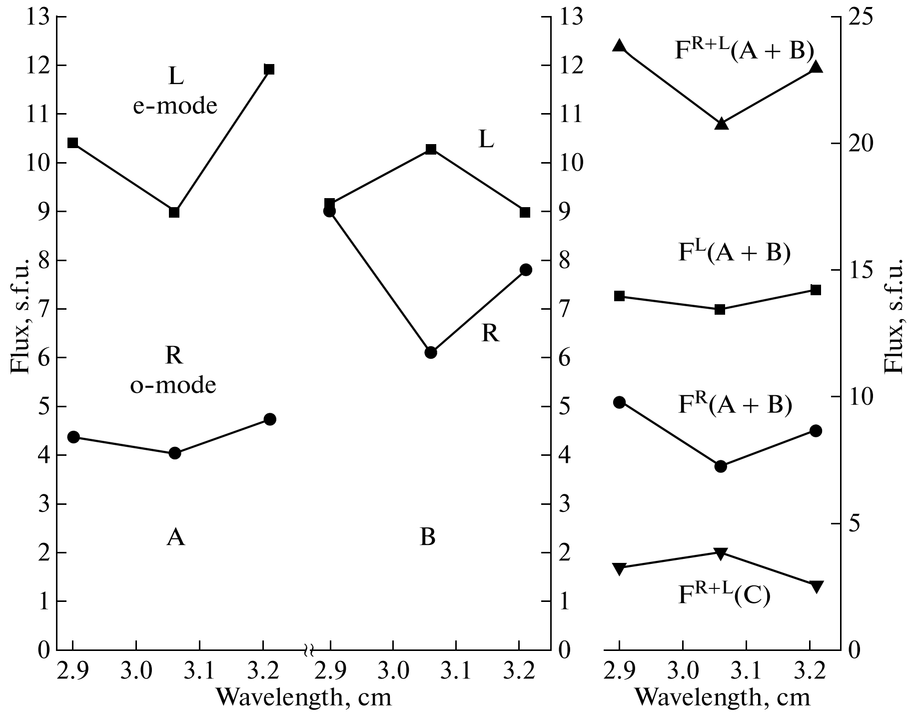

Fig. 3. RATAN-600 spectral flux densities of the source located above NOAA 10105 at 2.90, 3.06, and 3.21 cm on September 11, 2002, both individually for the sunspot A and floccular brightening B (left) and for their total spectrum (A + B, right). Spectra are shown individually for the R and L polarizations (F^{L}, F^{R}) and for the total flux (F^{R+L}).

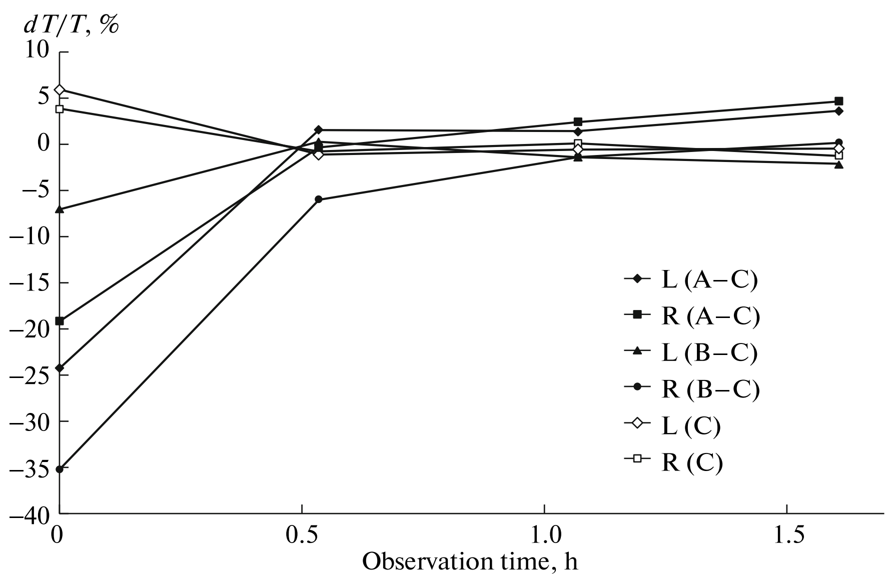

Fig. 4. $H_{3.04}$ line depths. Individual RATAN-600 data for regions A and B of the radio source located above NOAA 10105 observed at four azimuths on September 11, 2002. The observation time is measured from local noon (UT = $9^{h}10^{m}21^{s}$).

that can explain the required "pumping." At the same time, we note the eruption that occurred in NOAA 10105 ∼1 h before our RATAN-600 observations of the $H_{3.04}$ line. As a rule, eruptions are accompanied by ejections of cool material. According to modern models, the ejections are accompanied by dimmings, that is, the observation of low-brightness regions in the lower corona [14, 15]. Processes such as coronal ejections remain incompletely studied in the radio band. Analyses of individual cases [16, 17] show that these are complex phenomena accompanied by both heating and cooling of the particular

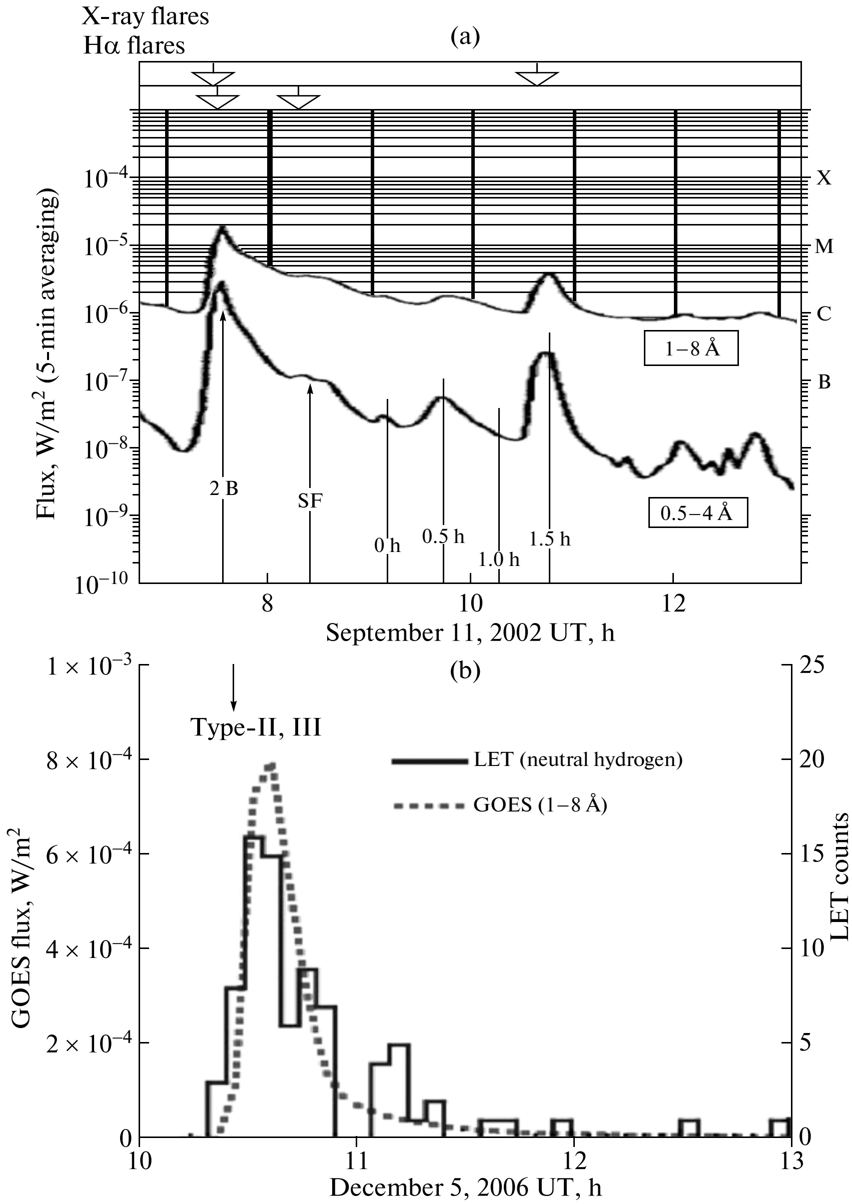

Fig. 5. (a) GOES observations of the M2.2 burst. The RATAN-600 observation times 0^h, 0.5^h, 1.0^h, and 1.5^h and the times of chromospheric flares are shown on the time axis. (b) LET (low energy telescope) neutral atomic hydrogen for the X-ray event observed by the STEREO A and B spacecraft on December 5, 2006. The LET profile is superimposed on the GOES profile. The plot is taken from [18].

regions of the solar atmosphere surrounding the ejection. It seems quite plausible that the ejection of material could increase the fraction of neutral hydrogen while simultaneously exciting the atoms, resulting in an increase in the intensity of the $H_{3.04}$ line.

On the other hand, it is well known that the number and temperature of hot particles in the solar atmosphere can increase substantially above active regions during flares. Our estimates based on observations of bursts in the radio and ultraviolet show that the brightness temperature of the radio emission reached high values of ∼10–20 MK at the maximum of the M2.2 flare. Apparently, the region was cooled during ∼3 h after the heating, and the RATAN-600 observations examined the very end of the PBI.

We can also consider the neutral atomic hydrogen detected during the X9 flare observed by the STEREO spacecraft [18]. Figure 5b, taken from [18], shows the GOES profile of the X-ray event superimposed on the burst profile for neutral particles with energies of 1.6–15 MeV. It is interesting that these particles were detected during both the event maximum and the decay; this indirectly supports our results on the $H_{3.04}$ line for NOAA 10105. According to the estimates of [18], only a very small fraction ($\sim 10^{-5}$) of the total number of fast neutral hydrogen atoms generated by the flare escaped into interplanetary space. In radio astronomy, we observe effects due to all available atoms. In addition, we observe both fast and other neutral hydrogen atoms, including those resulting from slower protons moving toward the solar surface through the region with a lower degree of ionization than the corona. Substantial directed motions spread the neutral material over large distances from the flare. The region occupied by the post-flare hydrogen can significantly exceed the volume of the flare itself.

Another feature of the radio observations is that the neutral hydrogen line is fairly narrow ($\sim$2.5% of the total width and $\sim$1% of the width of the main maximum [1]). In the case of rapid motions of large volumes of neutral hydrogen generated by the flare, the Doppler effect can result in significant and variable distortions in the $H_{3.04}$ line (frequency shifts, broadening, and profile changes), which reflect the spatial and temporal behavior of the flows.

Studies of the $H_{3.04}$ line of the Sun must certainly be developed further. Our results suggest that $H_{3.04}$ line studies with fairly high two-dimensional spatial resolution (a resolution of $\sim 3' \times 3'$ and a mirror diameter $D \sim 30$ m will be quite sufficient for a first step) and receivers tuned to 9850 MHz with a bandpass no narrow than $\pm$500 MHz are most promising. The relative accuracy of measurements of the spectral flux density should be no worse than 1%.

In addition to experimental studies, the theory of the solar $H_{3.04}$ line should be developed taking into account the violation of equilibrium states due to rapid plasma motions in strong magnetic fields. In the absence of theoretical models, it is very difficult to interpret the observations, in particular, those on the polarization of the emission. It will be very helpful to experimental studies if theorists can calculate other expected features of the $H_{3.04}$-line radiation. Estimates of the percentage of neutral material in the solar atmosphere represent a final goal of such studies, and are required for the refinement of some models for coronal heating [19].

5. SUMMARY

RATAN-600 observations of enhanced radio emission above solar active regions have revealed a spectral feature in the emission of NOAA 10105 (September 2002), which can be interpreted as the $H_{3.04}$ neutral hydrogen line in absorption, and also in emission for some components.

We have found evidence for a genetic relation between the line and the chromospheric 2B and X-ray M2.2 flares. The line was detected during the post-burst increase (PBI) stage of the events.

The line displayed the following features:

—the line radiation was most visible in the lower corona above the flocculus;

—the duration of the line emission was less than two hours;

—the maximum line depth reached (35 ± 5)%;

—the maximum degree of polarization of the line emission reached $\sim$30%.

Compared with the results obtained earlier in [8], our new studies represent a more reliable detection, since the line was detected against the radiation of a particular active region (with a flux of $\sim$10 s.f.u.) instead of the radiation of the total solar disk (with a flux of $\sim$300 s.f.u.).

Further theoretical and observational studies of the Sun in the $H_{3.04}$ neutral hydrogen line are necessary. We have formulated requirements for the observational facilities.

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