RADIO OBSERVATIONS OF COMPACT SOLAR SOURCES LOCATED BETWEEN SUNSPOTS

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Abstract. Data from SSRT form the basis for initiating a study of the properties of long-lived, compact microwave sources located outside sunspots. A step-like birth of such a source was detected and is described in this study. This sheds light on the relationship between the 'step-like' phenomenon detected with SSRT and the 'peculiar' source phenomenon observed at RATAN-600. 'Peculiar' sources precede large flares and are projected onto the photospheric neutral line. It seems likely that the build-up of a large flare is also step-like in character. We also discuss a source overlying the neutral line which accompanied a large active region that did not produce any large flare.

1. Introduction

The gyroresonance spot component and the diffuse component, the emission of a coronal condensation, are customarily classified as long-lived components of the microwave emission of an active region (AR). A further class of long-lived objects was recently identified. These are compact ($\approx 10''$), bright (T_B up to 10^7 K at 2–4 cm wavelengths) sources located near the inversion line of the longitudinal component of the photospheric magnetic field. They differ from the spot components by the low degree of circular polarization of the emission and by a steeper slope of the short-wavelength (2–4 cm) part of the spectrum (Vatrushin and Korzhavin, 1989). Akhmedov *et al.* (1987) called them 'peculiar sources' (PS). Subsequently, Borovik *et al.* (1989) suggested an unambiguous relation between the appearance of PS and periods of increased flare activity. Typically, the flares themselves do not cause PS to disappear. While appearing one or two days before a flare, these sources persist also after the flare. It should be noted that it is the longlived character that makes a source with such a set of properties peculiar. Otherwise, it would be a microwave burst.

This paper will make a preliminary analysis of observational data on long-lived microwave sources which would more correctly be termed the neutral-line-associated sources, NLS (see, e.g., Drago, Alissandrakis, and Hagyard, 1987). As will be apparent in the text to follow, they include not only PS with a 'peculiar' spectrum as detected at the RATAN-600 radio telescope. In addition to the data from this instrument, we have used the observations from the Siberian Solar radio telescope (SSRT) (one-dimensional

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solar scans are obtained every 2.5 min, the continuous observing interval is up to 8–10 hours, the angular resolution is up to 17″, and the operational wavelength is ≈ 5.2 cm). The radio scans from SSRT were handled following a technique reported by Zandanov and Sych (1989).

Let us briefly examine the main stages of such processing. For determining the character of structural changes in AR microwave emission sources, scans are swept in time by superimposing them on each other. This is done on the basis of the calculated time at which the Sun's center traverses the beam. Source scans are normalized by choosing a mean level of the area on the scan in the total intensity channel (I), which does not contain ARs. The brightness constancy condition for calibration regions is used to determine the normalization coefficient for each scan. The width of a calibration region is chosen to lie between 1′ and 2′. In the case of high solar activity, when the scans include a large number of sources and it is difficult to choose a calibration region, the value proportional to the solar integrated flux is calculated. For a graphic representation, a matrix is generated, each row of which contains the source response from one scan. The time scan of the responses is displayed in the form of an intensity map on the screen, or is printed out.

2. The Birth of an NLS that Preceded a Large Flare

A compact source located between sunspots was detected by processing the scans obtained with the SSRT on 23 July, 1987. A preliminary analysis of the data from RATAN-600 for this source indicated its 'peculiarity' and a possible interval of appearance (the interval between the noon scans of 22 and 23 July). The young group AR 4826, according to *Solar-Geophysical Data* (SGD), involving this source, developed actively and grew rapidly in its area. On 23 July, flux-increasing spot sources of microwave emission were accompanied by a dominant growth of a weakly polarized NLS lying in between. On 24 July, the NLS reached its highest intensity and changed little through the daytime observing interval (3–8 UT). On the same day, a flare of importance 2B occurred at the location of the NLS concerned (24 July, 09:55–11:14 UT, according to SGD).

Figure 1 presents a portion of the SSRT scan of 24 July and the corresponding sunspot group AR 4826. The instrumental resolution on that day was a maximum (≈ 17″). The conditions for identifying the NLS were also favourable: the group was still sufficiently far from the limb. The sunspot group had a typical bipolar structure with well-defined (at 5.2 cm) polarized components. Their position coincided with the leading and following sunspots. The NLS was located near the polarity inversion line of the photospheric magnetic field. Under the assumption of an axisymmetric gaussian profile of the source, its brightness temperature, T_B, is estimated at 8×10^6 K. The appearance of this source was recorded by the SSRT on 23 July in the total intensity (I) and circular-polarization (V) channels. Unfortunately, the angular resolution of the instrument on that day was only ≈ 34″ because only half of the antenna array was operational. The observing interval was 6 hours.

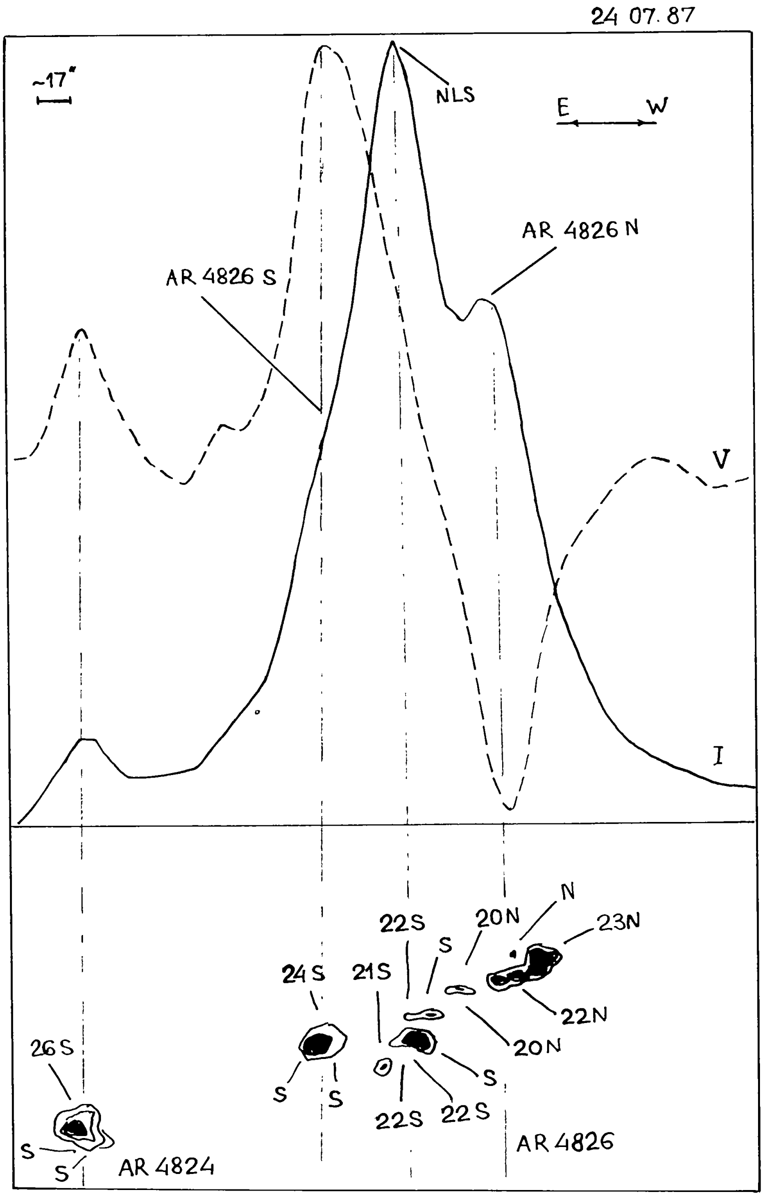

Fig. 1. The microwave emission sources of AR 4824 and AR 4826 obtained with the SSRT at 5.2 cm wavelength at 02:34 UT on 24 June, 1987. The solid and dashed lines represent the radio scans, respectively, in the total intensity channel (I) and in the circularly polarized channel (V). *Bottom*: a sketch of the photosphere for the given period, indicating the magnetic field strength, according to *Solnechnye Dannye* No. 7, 1987. NLS – the source located above the polarity inversion line of the photospheric magnetic field. Upper corner at the left – SSRT angular resolution.

Figure 2 shows the process of NLS birth. Each solid line here represents the time variation in intensity at a given position on the solar scan from the SSRT. The evolution of the central part of the radio scans of the NLS-associated AR 4826 is represented by the curve at the top (Figure 2(a)). The intensity scale is in arbitrary units. One can see that there exist two intervals of stepwise increase in NLS intensity (I and II in Figure 2). The duration of the fast rise averages about 12 min. Two small radio bursts located at 'steps' I and II, correspond to importance SN subflares. In order to make sure that the results are reliable, images of the time dependences of the leading and following sunspot

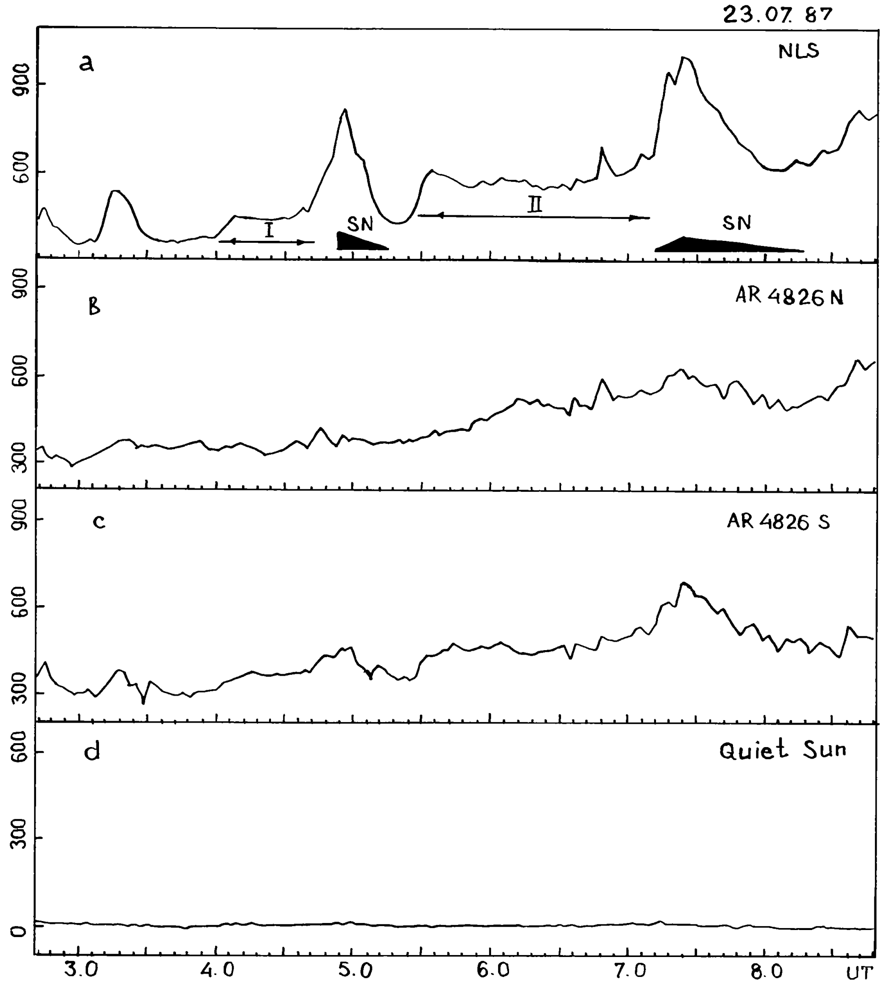

Fig. 2. The evolution of the AR 4826 source. Figure 2(a) gives the time variation in intensity of the central part of the NLS, indicating the intervals of stepwise increase in intensity. Under the curve: intervals of optical flares, indicating their respective strengths. Figures 2(b) and 2(c) show the intensity variation for the leading (AR 4826N) and following (AR 4826S) sunspots. For comparison, Figure 2(e) gives the amplitude variation of the 'quiet' Sun. The intensity scale is in arbitrary units.

intensities were obtained (Figures 2(b) and 2(c)). One can see that each of these spot sources shows its own time trend in intensity, which does not repeat the details of NLS development. A slight correlation is due to insufficient instrumental resolution. The region of the 'quiet' Sun (Figure 2(d)) does not show any significant amplitude variations through the observing period.

It should be noted that the phenomenon of a 'stepwise' increase in flux of microwave sources of AR was detected at the SSRT on some earlier occasion. In particular, Zandanov, Smolkov, and Uralov (1988) discussed the relationship of similar events, localized between sunspots, with the emergence of new magnetic flux. It has not yet been reliably confirmed, however, that step sources lie above the inversion line of the photospheric magnetic field. Therefore, identifying the 'steps' with the 'peculiar' source phenomenon is, in fact, a correct solution of the question of their spatial localization. It is possible that the overwhelming majority of events with a stepwise flux growth, observed with the SSRT are localized in the vicinity of the polarity inversion line. A more detailed statistical analysis of parameters of events with a step-like flux growth was made by Nefedyev *et al.* (1992). According to their results, the outward appearance and the parameters of the 'steps' discussed in this report are rather typical of events of this kind.

It should also be noted that stepwise growth in AR microwave emission flux can be associated with a rather fast (tens of minutes) growth in the sunspot area and, accordingly, a coronal gyroresonance source above it. Such an event, though only one, was detected by Zubkova *et al.* (1990). In this connection, it is interesting to note a paper of Drago, Alissandrakis, and Hagyard (1987) who discussed a strong nonthermal radio source associated with the sunspot birth and motion.

Although observational data for the NLS problem are scarce, the conclusion that they are an indicator of the evolutionary state of AR seems irrefutable. In particular, the appearance of the NLS under consideration preceded a strong flare. The NLS should be regarded as an indicator of a long-lived site, in which the so-called 'storage' and release (not necessarily flare-induced) of 'excess' magnetic energy take place. The 'storage' proceeds in steps, so their indicator is 'steps' in microwave emission. The NLS is an indicator of the fact that there have been several such steps.

The term 'storage' has, most likely, a philosophical meaning rather than implying some particular idea. A discussion of the physical model of PS is possible; however, it would be premature to do this here. At this point we wish only to point out a possible relation of the birth process of NLS to the model of emerging, current-carrying arcades (Uralov, 1990). In this case an NLS consists of several finer-scale sources located above the neutral line of the photospheric magnetic field. Each of them corresponds to its own pair of cross-interacting loops (in a 'magnetic knot'). Possibly, a chain of compact, bright ($T_B \approx 10^6$ K) stable (during the observing interval) microwave sources above the filament detected with the WSRT (Kundu and Alissandrakis, 1984), lends support to these conclusions. The appearance of a new 'magnetic knot' triggers a stepwise growth in flux of an appearing NLS. The stepwise growth appears also to indicate that the NLS corresponds to a closed magnetic field configuration.

3. The NLS in an Active Region That Did Not Produce Any Large Flares

That a bright microwave radio source is localized above a neutral line of the longitudinal component of the photospheric magnetic field is, of course, not a sufficient condition for predicting a large flare. This reasoning is confirmed by considering the example of AR 5200, according to SGD. This large sunspot group was evolving intensively, but during its solar disk passage (from 17 to 30 October, 1988) it never gave a large flare. The appearance of a radio source, associated with this group, on the SSRT scans occurred two days before the AR itself reached the east solar limb. The observations at 2.3, 2.7, 4, 5.2, 11.7, nd 21.7 cm wavelengths (RATAN-600 and SSRT) also reveal the presence of a powerful extended radio source, but without a well-defined structure. This, taken together, produces the impression that the entire active region is 'obscured' by the powerful magnetosphere. Figure 3 presents a portion of the SSRT scan for

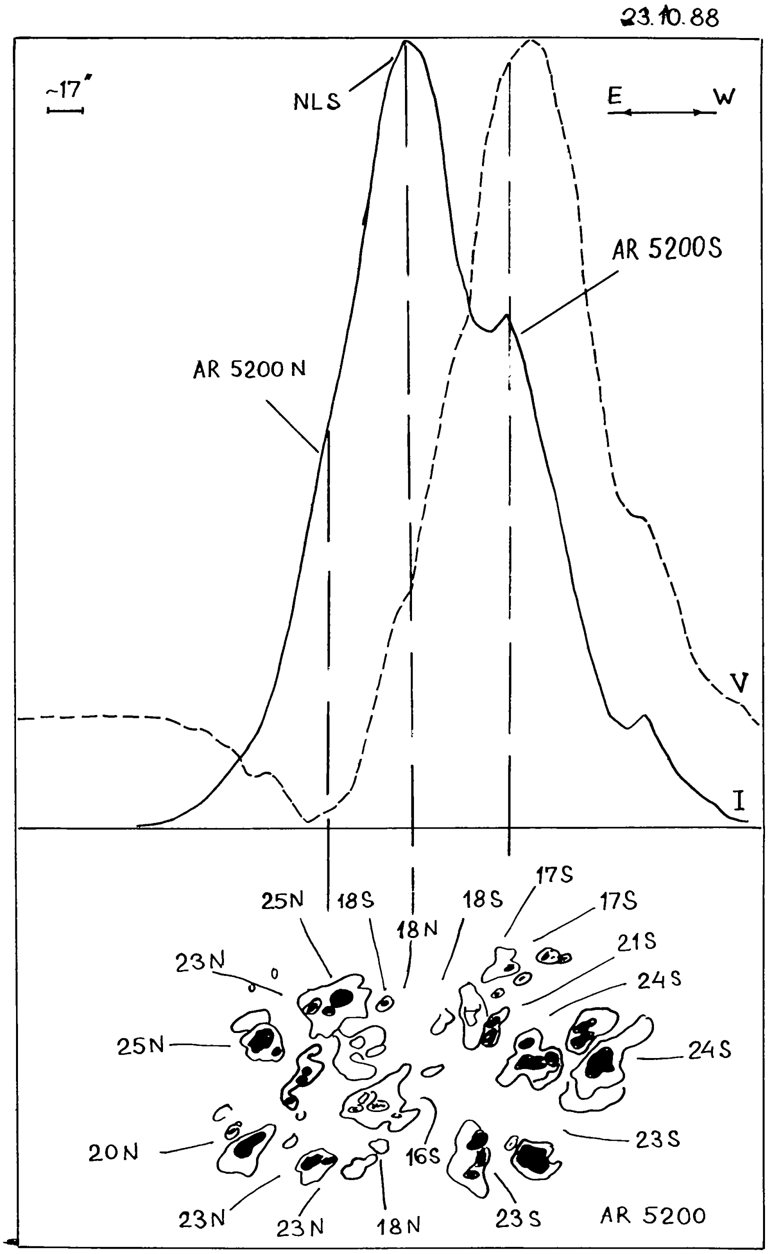

Fig. 3. Same as in Figure 1, but for the active region AR 5200. The radio scans were taken on 23 October, 1988, at 05:07 UT.

23 October, 1988 and the active region AR 5200 corresponding to it. The central part of the NLS lies in the vicinity of the line that separates the leading and following sunspot groups.

Figure 4 shows a sample of the NLS spectrum. Curve *A* represents the observed value of brightness temperature T_B obtained under the assumption of axial symmetry and a Gaussian form of the intensity profile in the source. Because of the large beam width of the radio telescope, the determination of $T_B(\lambda)$ at 11.7 and 21.7 cm wavelengths is uncertain. Qualitatively, the difference between the NLS under consideration and the PS reported earlier (Vatrushin and Korzhavin, 1989) may be summarized as follows.

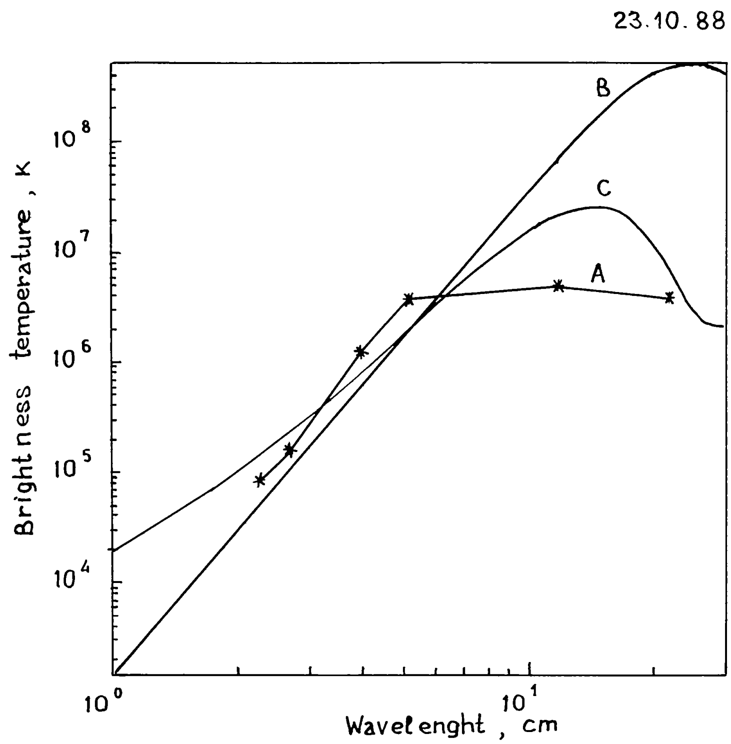

Fig. 4. The NLS spectrum. Line A gives the observed values of brightness temperature $T_B(\lambda)$. The temperature is estimated under the assumption of axial symmetry and a Gaussian form of the intensity profile in the source. Line B is the calculated dependence, $T_g(\lambda)$, of the gyrosynchrotron source, without taking into account the absorption in the overlying layers. Line C is the emission directed to the observer, with the calculated dependence $T_B(\lambda)$.

(a) The spectrum of the NLS concerned in the range 2–4 cm is by no means so steep as is the case with PS. In this range it is even to a greater extent similar to the spectrum of sources above sunspots.

(b) In known PS the spectral maximum of the flux is reached in the same range of 2–4 cm, at the highest values of $T_B \approx 10^7$ K. It may be arbitrarily assumed that in the wavelength range 3–4 cm the PS is a 'hot' one. In this regard, the NLS discussed here appears more likely a 'cold' one. Its spectral maximum is shifted toward longer wavelengths, falling presumably within the range 5.2–11.7 cm.

The interpretation of the spectrum of the NLS under consideration can have only a preliminary character because the data available are obviously insufficient. Nevertheless, one can suppose that the emission mechanism for these nearly stationary objects is not a thermal one. Indeed, in pure form the *ff*-mechanism is, in principle, unable to ensure a spectral maximum of the radio flux in any source model. The thermal gyroresonance mechanism requires strong magnetic fields which are impossible in the region between sunspots, and at the assumed height of about 10000 kilometers (or, perhaps, at higher altitudes). Invocation of a rather hot plasma with a temperature of 10^7–10^8 K, so that its gyrosynchrotron emission (Dulk and Marsh, 1982) falls within the microwave range event with more moderate fields, is also problematic. Primarily, this is because the spectrum would then be much steeper than that observed in its short-wavelength part. Such a spectrum occurs in the case of PS. It might be anticipated that the NLS under consideration is a permanent coronal source of nonthermal mildly-relativistic electrons with a rather soft energy spectrum, $n(E) \sim E^{-\delta}$, with a power-law index, δ, of about 4–5. In a very simple model of a homogeneous flat source its brightness temperature is

$$T_g(\lambda) = T_{\rm eff}(1 - e^{-\tau_g}) ,$$

where $T_{\rm eff}(\lambda, \sin\theta, \delta, B)$ and the absorption coefficient of gyrosynchrotron emission $K_g(\lambda, \sin\theta, \delta, B, N) = \mathrm{d}\tau_g/\mathrm{d}l$ are defined by the expressions reported by Dulk and Marsh (1982). θ is the acute angle between the magnetic field **B** and the line of sight **l**, and N is the number of isotropic electrons with energies $E \geq 10$ keV per cm^3.

However, it would be premature to compare directly the dependence $T_g(\lambda)$ with the $T_B(\lambda)$ observed. The point here is that the value of effective emission temperature at high frequencies $\nu \gg \nu_B$ (and just this case is of interest to us here) is $T_{\rm eff} \approx 10^8$–10^{10} K over a rather wide range of values of δ and θ. This means that at least a maximum value of $T_g = T_g^{\max}$ also falls within this interval. At the same time, such high brightness temperatures are not observed in the NLS concerned. In this connection, one can suppose that the NLS itself is embedded in a rather dense AR magnetosphere (and there are indications of this), whose absorption affects substantially the observed spectrum, at wavelengths longer than 10 cm at least. Assuming that the overlying corona is plane and isothermal, with a temperature T_0 and a barometric density distribution $n = n_0 e^{-z/\Delta}$, Δ = const., we have

$$T_B(\lambda) = T_g e^{-\tau_0} + (1 - e^{-\tau_0}) T_0 .$$

Here $\tau_0 = \mu_0 \Delta/2$ is the optical thickness of the AR corona located above the NLS. $\mu_0 \sim n_0^2 \lambda^2 / T_0^{3/2}$ is the absorption coefficient (free-free emission) near the NLS. It should be noted that the solution of the question of the real role of the absorption and/or scattering of the emanating emission in the formation of cm and dm radio bursts, constitutes a long-standing problem of solar radio astronomy. While in the last case this factor is usually ignored, it does not seem that this can be done in regard to the NLS.

The known expressions for emission mechanisms used here, are unable to ensure a satisfactory coincidence of the calculated and observed spectra in terms of a homogeneous model. Our choice, as μ_0, of its value corresponding to a particular emission mechanism was dictated only by our intention to visualize the screening effect of a brighter source. At the same time, using – instead of μ_0 – a certain effective coefficient with a steeper (as compared with λ^2) dependence on wavelength, a better result can be achieved. In doing so, one should possibly take into account the scattering effect of the emanating emission due to small-scale inhomogeneities of nonequilibrium coronal plasma. Curve B represents the calculated dependence $T_g(\lambda)$ for the following values of parameters:

$$\delta = 4 , \qquad \theta = 45 , \qquad B^{0.8} N^{0.2} \approx 10^3 .$$

Here it is assumed that the typical NLS thickness $L = 10^9$ cm, and its spectral maximum lies in the range 15–30 cm. In particular, when $B = 100$ G, the value of $N = 10^7$ cm^3, and this, by itself, is not a small correction to the main Maxwellian plasma component in the source. Under these assumptions, $T_g^{\max} = 5 \times 10^8$ K is attained at wavelength $\lambda_g^{\max} \approx 24$ cm, while the wavelength $\lambda_g^{\text{Peak}} \approx 20$ cm corresponds to the flux peak F_g. Curve C gives the calculated dependence $T_B(\lambda)$ of the emission directed to the observer. In this case we have

$$n_0 = 5 \times 10^9 \text{ cm}^3 , \qquad T_0 = 2 \times 10^6 \text{ K} , \qquad \Delta = 1.27 \times 10^{10} \text{ cm} ,$$

$$T_B^{\max} = 2.5 \times 10^7 \text{ K} , \qquad \lambda_B^{\max} = 14 \text{ cm} , \qquad \lambda_B^{\text{Peak}} = 11 \text{ cm} .$$

We wish again to stress the illustrative character of the estimates made above; they neglect, among other things, the real inhomogeneity of the radio source itself.

4. Conclusions

We have discussed only two NLS. One of them appeared together with the AR and was the forerunner of a large flare that occurred at the same location. In this case the fact of a stepwise increase of this NLS seems also to indicate a 'stepwise' character in the buildup of the flare-producing situation in the active region. The other NLS, which differed from the first by its stability, size and, probably, by spectrum and height, was an indicator of the opposite property of the AR, namely its inability to produce large flares. While the scale of the AR and its variability in the optical range suggested that such a flare would, nevertheless, occur.

It might be anticipated that sources above a neutral line reflect the physical conditions of the AR, in which they reside. The difference of physical characteristics of the NLS is probably associated with the factor of the AR's ability to produce large flares. However, the NLS can be recommended for use as a predictive agent only on the basis of studying a large number of such objects, in particular at the SSRT.

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