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Nonstationary Phenomena in the Radiation of Young Supernova Remnants*

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Abstract

The time variation of the radio emission from the supernova remnants Cassiopeia A, the Crab Nebula and Tycho Brahe (SN 1572) is investigated. There is a frequency dependence on the rate of decrease in the flux density of Cassiopeia A for the period 1957 to 1984. The (positive) spectral index has a secular decrease and also, for frequencies above 320 MHz, slight oscillations with a six-year period. The radio emission from the Crab Nebula was constant from 1953 to 1975 but has since decreased accompanied by a change in spectral index. The average decrease of the flux density of SN 1572 from 1963 to 1983 was 0·52% per year, close to the value predicted for adiabatic expansion.

1. Introduction

The possibility of variation in discrete source intensity radiation was first predicted by Shklovskii (1976) for supernova remnants (SNRs). It was shown that a uniform flux decrease at all frequencies must be observed in the SNR Cassiopeia A due to the adiabatic broadening of the envelope. Investigation of this effect is of great importance in the study of the evolution of this class of objects. Thus, experimental investigations starting in the 1960s were continued in subsequent years. At present, a flux variation has been detected in four SNRs: Cassiopeia A, Tycho Brahe objects of the envelope type, the Crab Nebula, and 3C 58 plerions. Now, there have been many remarkable papers on the investigation of the dynamics of remnant broadening over the difference of maps synthesised for close epochs (Tan and Gull 1985; Tuffs 1986). Nevertheless, integral measurements of the radiation energy from an object such as a star give, on the whole, new results. Among them, one should note the variations in the spectrum slopes detected in the Crab Nebula and Cassiopeia A; in the latter case the variations are evidently periodic. In the present paper we present experimental results on the secular and nonstationary variations in radio emission spectra of SNRs.

2. SNR Observations

The evolution of radio emission from the SNR Cassiopeia A has been studied at the radioastronomical station Kara Dag by making absolute measurements of the

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intensity in the source radiation spectrum. When comparing absolute measurements in the frequency range 0·5–10 GHz it assumed that the rate of flux decrease depends on the frequency and is well approximated by the function (Stankevich 1977)

$$\Omega(\nu) = -1{\cdot}25\times10^{-3}(15{\cdot}2 - \ln \nu) \quad (\mathrm{yr}^{-1}), \tag{1}$$

where the frequency ν is in MHz. The same dependence describes the flux variations at lower frequencies up to 81·5 MHz (Tan and Gull 1985; Tuffs 1986). The frequency dependence of the flux density decrease may be due to a decrease in the source spectral index. A decrease in the mean spectral index has been detected experimentally and the corresponding data for different epochs have been given by Stankevich *et al.* (1973) and Barabanov *et al.* (1983).

Further study of the evolution of radiation from the young SNR Cassiopeia A has revealed a complex phenomenon (Ivanov and Stankevich 1986*b*). Together with the stated regularities for the mean characteristics of the spectrum, considerable variations of the spectrum index and flux values have also been detected, including their increase in separate epochs. To obtain the exact energy distribution over the source radiation spectrum, absolute measurements in the range 0·5–10 GHz were carried out at 25–30 frequencies for the minimum necessary time of 3–4 months. The results can be presented as an instant spectrum of the source for the corresponding epoch. In most cases the spectrum is well described by the linear (on a logarithmic scale) dependence

$$\log S(\nu) = B - \alpha \log \nu, \tag{2}$$

where $S(\nu)$ is the flux density at frequency ν, α is the spectral index and B is the spectrum parameter.

Beginning in 1967 instant spectra were measured regularly with a two-year interval. In some cases in the spectrum of Cassiopeia A disturbances were observed in the local frequency interval with a duration of several years (Barabanov *et al.* 1977). These bursts were interpreted as radio emission from separate large condensations in the period of their activity. Then, the spectral index of the envelope radiation is calculated only over the undisturbed spectrum. The spectra of 1971 and 1973 were exposed to such a 'cleaning'. Parameters of all instant spectra are given in Table 1.

The mean rate of the flux decrease for the period 1969·6–1984·6 is given by

$$\Omega(\nu) = -1{\cdot}584\times10^{-3}(11{\cdot}06 - \ln \nu), \tag{3}$$

and $d\alpha/dt = -1{\cdot}584\times10^{-3}$ is the mean rate of the spectral index decrease. For the modern epoch, the frequency dependence (3) is characterised by a greater rate of spectral index decrease, and the values $\Omega(\nu)$ are essentially smaller than in earlier epochs, as shown in Table 2.

Ivanov *et al.* (1982*b*) noted that the mean rates of the flux decrease at 960 MHz were 2·2 times smaller in the interval 1972·3–1981·4 than in the interval 1964·2–1972·3. This fact testifies to the non-uniform decrease of the Cassiopeia A intensity with time.

The rate of the flux decrease $\Omega(\nu) = S_\nu^{-1} dS_\nu/dt$ defined even for a long period of time (15 years), depends strongly on the choice of the initial and final epochs. Figs 1*a* and 1*b* show a spread of fluxes at 550 MHz and 9770 MHz about the mean straight lines. It should be stressed that the spread in the data is not caused by measurement errors: the accuracy of definition of the spectra α and B parameters

Table 1. Parameters for the SNR Cassiopeia A

Epoch	α	B	$S_{1\,\mathrm{GHz}}$ (J)	$\sigma(S_{1\,\mathrm{GHz}})$ (%)	Frequency range (GHz)
1967·6±0·1	0·7991±0·0151	5·8918±0·0438	3122·5±1·8	0·58	0·5–1
1969·6±0·2	0·8498±0·0052	6·0301±0·0161	3025±10	0·36	0·5–10
1971·6±0·2	0·8211±0·0122	5·9308±0·041	2934±38	1·29	0·6–10
1973·6±0·2	0·8088±0·0047	5·8929±0·0149	2928±11	0·39	0·5–10
1975·7±0·2	0·8320±0·0044	5·9620±0·014	2924±11	0·38	0·55–10
1977·7±0·15	0·8119±0·0047	5·8916±0·0152	2857±12·5	0·43	0·5–10
1979·6±0·2	0·8120±0·0044	5·8872±0·0141	2826±11	0·39	0·55–10
1981·6±0·15	0·8135±0·0054	5·8858±0·0169	2788±10	0·38	0·5–4
1983·6±0·1	0·8119±0·0038	5·8730±0·0123	2737±9	0·33	0·5–10
1984·6±0·15	0·81415±0·0038	5·8771±0·0121	2721±9	0·33	0·5–10

Table 2. Mean rate of flux decrease for various epochs

Epoch	$-\frac{d\alpha}{dt}\times 10^3$	$\frac{\Omega(\nu)}{\dot{\alpha}}+\ln\nu$	$-\Omega(\nu)$ (% per year)					Ref.
			550 MHz	960 MHz	1420 MHz	3000 MHz	9770 MHz	
1962–73	1·26	14·60	1·045	0·975	0·925	0·83	0·68	1
1961–71	1·203	15·13	1·06	0·994	0·947	0·857	0·715	2
1961–77	1·25	15·18	1·11	1·04	0·99	0·897	0·75	3
1957–76	1·3	14·38	1·05	0·977	0·926	0·83	0·676	4
1967–84	1·584	11·06	0·75	0·66	0·6	0·48	0·3	5

References: 1, Dent *et al.* (1974); 2, Stankevich *et al.* (1973); 3, Stankevich (1977); 4, Baars *et al.* (1977); 5, present work.

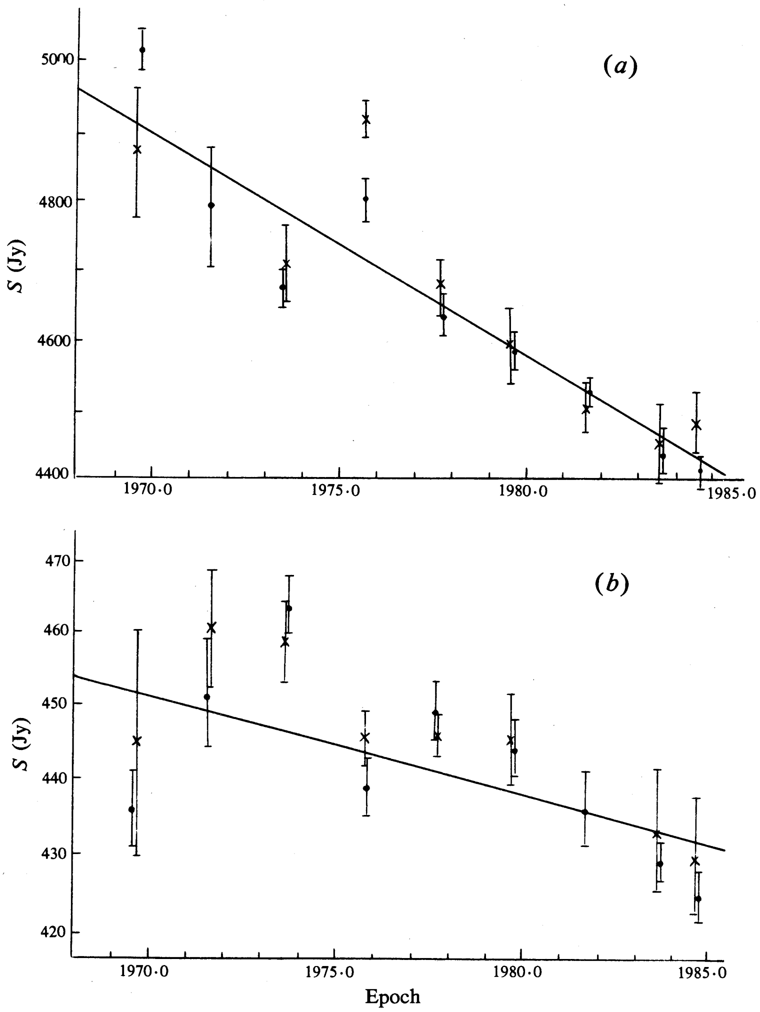

Fig. 1. Dependence of the flux density on the epoch of measurement for (*a*) 550 MHz and (*b*) 9770 MHz. The crosses are direct measurements and the points are calculated over the spectrum.

(Table 1) is almost sufficient in each case for finding fluxes at any frequency with a random error of $\leqslant 1\%$. Thus, at 550 MHz the errors amount to $0 \cdot 5\%$ and at 9770 MHz to $0 \cdot 9\%$, but at the same time deviations reach $\pm 1 \cdot 7\%$ and $\pm 3 \cdot 7\%$ at each frequency respectively, i.e. more than 3σ. A similar situation occurs at other frequencies, while deviations for early epochs were larger. The consequences of rapid variations in the flux is the variability of $\Omega(\nu)$ and its dependence on the initial and final epochs of measurements and on the interval duration between them. Thus, for a two-year period, depending on the initial epoch, the mean rate at 550 MHz changes in the interval $-2 \cdot 43\% \leqslant \Omega(550) \leqslant 0 \cdot 64\%$, and still larger variations take place at 9770 MHz in the interval $-2 \cdot 8\% \leqslant \Omega(9770) \leqslant 1 \cdot 8\%$, i.e. in some time intervals the flux increases with time.

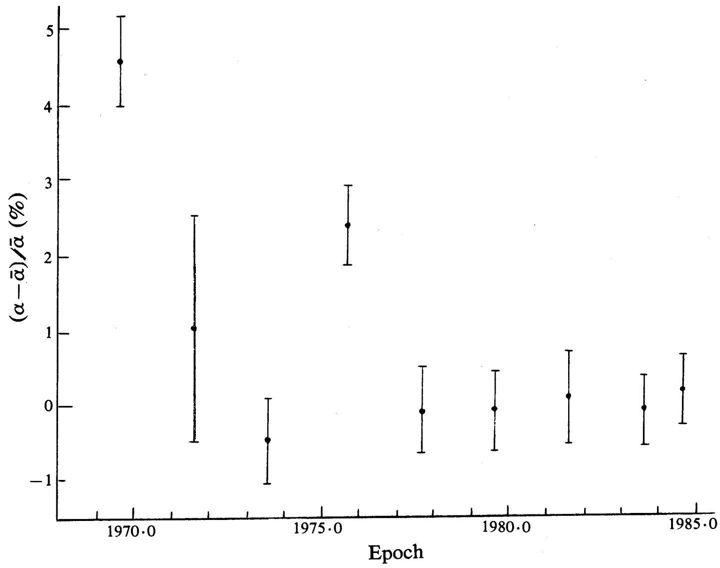

Fig. 2. Relative deviations of the spectral index α from the mean value $\bar{\alpha}$, depending on the epoch of measurement.

Together with the secular decrease of the spectral index, its essential variations were noted even earlier (Stankevich *et al.* 1973). The distribution of spectral indices for the period 1969·6–1984·6 is given in Fig. 2, where $\bar{\alpha}$ is the mean value for the eight years 1977–84. The deviation of α reaches 4·5% with a separate error of measurement of $\Delta\alpha/\alpha = 0{\cdot}5\%$. Thus, it should be considered that rapid variations of instant spectra is a property of the source itself.

From the above examples it follows that, for the investigation of the spectrum evolution of Cassiopeia A radiation, it is necessary to have a detailed picture of flux and spectrum distributions in time; in this case, even a two-year interval between measurements proves to be a large one. To create a complete picture requires using data from all published relative and absolute measurements (Ivanov and Stankevich 1983). With this aim we chose measurements made in the period from 1953 to 1972 by antennas with a sufficiently high resolution, where fluxes of Cassiopeia A as well as of one of the three powerful sources Cygnus A, Virgo A or Taurus A were measured simultaneously in one and the same scale, relatively or absolutely, with an indication of the measurement epoch.

Radio emission of the Crab Nebula at cm and dm wavelengths did not show any marked variability from 1953 to 1975. Only from 1977 were variations in the spectrum detected, which could allow one to use it for early epochs as a reference spectrum. The constancy of Cygnus A and Virgo A radiation has been shown by many measurements, including our observations. Spectra of the reference sources were defined in a new accurate absolute scale of fluxes, based on absolute calibration by the method of 'artificial Moon' (Ivanov and Stankevich 1986*a*). Fluxes of Cassiopeia A for an epoch of measurements over the unique absolute scale have been found, on the assumption that we know from the literature, ranging from the earliest papers (see e.g. Hey and Hughes 1954; Kraus *et al.* 1954) up to more recent times (see e.g. Vinyajkin 1983), the relation between fluxes of Cassiopeia A and the reference sources. Fluxes obtained in this way may be directly compared with the absolute measurements described above.

The relation between the fluxes of Cygnus A, the Crab Nebula and Virgo A (Ivanov and Stankevich 1986*a*) were accepted as the standard ones. In some papers (Baars and Hartsuijker 1972; Davis *et al.* 1965) the measured relations of fluxes are smaller than the standard ones, the relative deviations exceed a random error and reach a large value for Cygnus A. This testifies to the nonlinearity of receivers used for the measurements. The flux $S^*(\nu)$ measured by such a receiver is a function of the real flux $S(\nu)$. This function can be written as a polynomial of second degree:

$$S^*(\nu) = aS^2(\nu) + bS(\nu) + c. \tag{4}$$

If we know the values of $S^*(\nu)$ for three standard sources, then we can find the parameters a, b and c from equation (4). Then, the flux value of Cassiopeia A corrected for the nonlinearity is the solution of a quadratic equation.

Table 3. Parameters of the restored 'instant' HF spectra for Cassiopeia A

Epoch	α	B	Frequencies (MHz)
1953·5±0·4	0·85	6·08	250 and 3200
1956·3±0·4	0·8386	6·0287	400 and 1390
1957·5±0·5	0·8805	6·1631	400 and 1419
1959·2±0·3	0·8242±0·0066	5·9727±0·0205	178, 440, 1200, 1400, 2930, 8000
1960·3±0·3	0·7874±0·0013	5·86106±0·0039	81·5; 1400, 3125
1961·5±0·4	0·7975±0·0089	5·8798±0·0279	240, 412, 750, 3000 and 9375
1962·7±0·2	0·8290±0·0122	5·9781±0·0378	320, 562, 707·5; 860, 927, 3175, 9375
1963·5±0·4	0·8134±0·0133	5·9238±0·0446	612, 1400, 9375
1964·5±0·5	0·8405±0·0053	6·00975±0·0175	535, 556, 740, 960, 3150, 4995, 6660, 8000
1965·5±0·5	0·8309±0·0107	5·9757±0·0388	1100, 1590, 1840, 4080, 4995, 6660, 8250, 15 500
1966·5±0·5	0·7972±0·003	5·8496±0·0100	81·5; 152, 516, 532, 994·5; 8000, 15 300, 15 500
1968·4±0·3	0·8266	5·9332	1420 and 8550
1970·6±0·2	0·8261	5·9528	1420 and 16 043
1973·2±0·4	0·8041	5·8749	402·5 and 22 285

As a result, we obtained an ensemble of corrected data including nearly 100 values of Cassiopeia A fluxes in the frequency range 22–70000 MHz for the period 1953 to 1972. From data which differ in the time of measurement by no more than a year, 'instant' spectra have been derived, which are referred in time to the mean epoch of measurements. Fourteen 'instant' spectra have been derived altogether, alternating in 1–2 year periods.

The spectra obtained overlap a wide frequency range in a number of cases and show that there is a break in the meter wavelength range. The characteristic form of the spectrum can be illustrated by the example of 1973–74. The spectrum in the frequency range 10–0·5 GHz for the epoch 1973·6 was measured by the method of 'artificial Moon', and its parameters are $\alpha = 0{\cdot}8088$ and $B = 5{\cdot}8929$ (see Table 1). Measurements at seven frequencies in the range $26{\cdot}3 \leqslant \nu \leqslant 236$ MHz for the epoch 1974·0 (Ericson and Perley 1975) are of the type (2) with the parameters $\alpha = 0{\cdot}7025$ and $B = 5{\cdot}62$ (without taking account of the flux at 38 MHz). On the whole, the complete spectrum consists of two sections of different slope, crossing each other at the frequency $\nu_n = 370$ MHz. A similar picture was observed in other years (1957, 1959, 1961 and 1966).

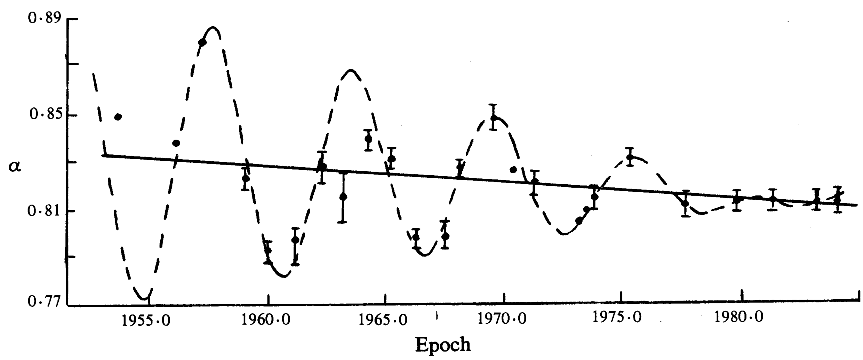

Fig. 3. Spectral index of Cassiopeia A over the period 1953 to 1984.

The frequency of the break may be found from the expression

$$\log \nu_n = \frac{B_1 - B_2}{\alpha_1 - \alpha_2}.$$

Further, we call a section of the spectrum for $\nu \geqslant \nu_n$ the HF spectrum and the section $\nu \leqslant \nu_n$ the LF spectrum. Table 3 gives parameters of the restored 'instant' HF spectra, and errors are given if the spectrum contains no less than three points. Parameters of the Cassiopeia A spectra given in Tables 1 and 3 form a unique system of data defined on one absolute flux scale, and cover collectively the time interval from 1953 to 1984.

Fig. 3 shows values of the spectral index of instant spectra in the period from 1953 to 1984 for Cassiopeia A. Values vary markedly around the mean value

$$\alpha(t) = 0{\cdot}8123 - 0{\cdot}00081\,t, \tag{5}$$

with an amplitude decreasing to 1981. The envelope of deviations (shown by the dashed curve in Fig. 3) can be given in the form

$$\alpha(t) = 0{\cdot}8123 - (0{\cdot}00081 \pm 0{\cdot}00227)\,t, \tag{6}$$

where t is in years and $t = 0$ for the epoch 1981·8. Finally, the location of points in the diagram may be presented as a choice from a certain periodic succession, i.e. the deviation of experimental points from the approximate dependence

$$\alpha(t) = 0{\cdot}8123 - \{0{\cdot}00081 + 0{\cdot}00227\cos(60t)\}\,t \tag{7}$$

does not exceed 1·5%. An obvious exception is the spectrum of 1963, which is possibly a consequence of insufficient data.

The average flux decrease for 31 years at high frequencies is given by

$$\overline{\Omega}(\nu) = -8{\cdot}1\times10^{-4}(14{\cdot}5 - \ln\nu)\,. \tag{8}$$

The flux density $S(\nu)$, decreasing on average, also oscillates with a small amplitude and these oscillations are defined by variations of the spectral index. A comparison of instant spectra shows that, taking into account (8), they are crossed at frequency $\nu_0 = 2013$ MHz. The flux at this frequency linearly decreases at the rate of 0·56% per year and has no oscillations:

$$\log S(\nu_0, t) = 3{\cdot}1961 - 0{\cdot}002425\,t\,. \tag{9}$$

The general behaviour of the HF spectrum, taking into account (7) and (9), we give in the same form as equation (2):

$$\log S(\nu, t) = \log S(\nu_0, t) - \alpha(t)\log(\nu/\nu_0)\,. \tag{10}$$

Using (10), we calculate the luminosity in the range 0·5–10 GHz as

$$\log\mathscr{L} = 27{\cdot}963 - 0{\cdot}00235\,t\{1 - 0{\cdot}105\cos(60t)\}\,, \tag{11}$$

where the luminosity $\mathscr{L}$ for the epoch 1981·8 is $9{\cdot}2\times10^{27}$ W, t is in years and $t = 0$ for the epoch 1981·8. The luminosity of the source uniformly decreases at the rate of $\mathscr{L}^{-1}\mathrm{d}\mathscr{L}/\mathrm{d}t = -0{\cdot}54\%$ per year, and the amplitude of probable oscillations decreases from 1·5% of $\mathscr{L}$ in 1953 to zero in 1981.

From (10) it is seen that the rate of flux decrease changes depending on the choice of the epoch of initial and final observations. The difference between the mean rates of flux decrease of (1) and (3) in comparison with (8) is explained by the observable selection. A comparative analysis of all experimentally obtained values of the flux rate decrease [19 values of $\Omega(\nu)$] and the calculated ones from (10) for the corresponding epochs shows that in more than 50% of the cases they coincide, and in four cases the difference is large. In the remaining cases the difference is no more than ±0·05% per year.

In the LF spectrum for 1959, 1961 and 1974, the spectral index remained within the following limits: $\alpha(1959) = 0{\cdot}738\pm0{\cdot}020$, $\alpha(1961) = 0{\cdot}687\pm0{\cdot}056$ and $\alpha(1974) = 0{\cdot}702\pm0{\cdot}008$. The secular flux variation has been studied at the frequencies 81·5 and 152 MHz (Agafonov and Stankevich 1981) and the flux density of Cassiopeia A uniformly decreases with the rates of $\Omega(81{\cdot}5) = (1{\cdot}29\pm0{\cdot}06)\%$ per year and $\Omega(152) = -(1{\cdot}1\pm0{\cdot}2)\%$ per year, values larger than for example the calculated value from (8) of $\Omega(81{\cdot}5) = -0{\cdot}82\%$ per year. No variations exceeding the mean values by 2% have been detected at these frequencies. An exception is the relative measurements of Cassiopeia A/Cygnus A at 38 MHz summarised for the 30-year period (1954–84) by Walczowski and Smith (1985). These authors interpreted the data as quasi-sinusoidal oscillations with a 9-year period, the amplitude of which amounts to more than 10% of the mean flux density.

According to the experimental data available, the secular variation of the flux at low ($\nu < 300$ MHz) and high ($\nu > 300$ MHz) frequencies is essentially different. This cannot be explained in the framework of the one-component model of the source. Slowing down of the flux decrease at cm wavelengths may be presented only with the introduction of an additional increase in the time component of the radiation. This could result from a continuous injection of relativistic particles, the radiation spectrum of which falls at frequencies below 300–400 MHz, and where at high frequencies it coincides with the spectrum of the envelope.

A result of the detection of soft X-ray radiation from all known galactic SNRs is that the mass of ionised gas has been shown to be large: Kepler ($7M_\odot$), Tycho ($4M_\odot$) and Cassiopeia A ($15M_\odot$). Since the plasma is strongly turbulent, it can be expected that plasma and Compton mechanisms of relativistic electron radiation are essential for these sources. The decrease of the flux density of the SNR occurs due to the decrease of the synchrotron radiation intensity during adiabatic broadening of the remnant. At high frequencies this is partially compensated by plasma radiation. To explain the observed mean frequency dependence of the Cassiopeia A flux decrease, it is sufficient that the energy density of Langmuir waves amounts to 2% of the thermal component.

A peculiarity is the periodicity of oscillation in the Cassiopeia A spectral index. If it is real, then the only explanation may be the variability of injection of relativistic electrons into the envelope. Here the source of relativistic electrons may be a compact object rotating or precessing with a 6-year period.

Since point X-ray sources with temperatures larger than 2×10^6 K have not been detected in Cassiopeia A, this object differs from the relativistic ones. Again, a compact source has been detected at decametric wavelengths, which in its radiation spectrum and angular dimensions is similar to the source in the Crab Nebula around the pulsar (Bovkoon and Zhouck 1981). The oscillation periodicity and the mechanism still require further investigation.

3. The Crab Nebula

In 1977 a decrease in the flux density of the Crab Nebula at 927 MHz was detected (Vinyajkin and Razin 1979). Measurements at a number of wavelengths have shown that for the epoch 1981 the average decrease in the radiation power of the Crab Nebula over the spectrum amounts to 3·5% (Ivanov *et al.* 1982*a*, 1982*b*). For a uniform decrease of flux, the mean rate would be $(0\cdot2\pm0\cdot06)\%$ per year, but irregular variations after 1975 probably took place. Further measurements in 1983–84 showed that, together with the intensity variation, the slope of the source spectrum decreased.

To determine the evolution of the source radiation one needs instant spectra for different epochs, including those for previous years. In the past, such measurements for the Crab were not systematically performed; still, according to the set of absolute and relative measurements the possibility exists of determining the behaviour of its spectrum back to 1953.

First, we consider the energy distribution over the Crab spectrum for the period 1953–74. In the basic radioastronomical scales, the spectrum of the Nebula is presented in the form of equation (2) and its parameters are given in Table 4. Values of the spectral index are spread in the rather wide interval $0\cdot247 \leqslant \alpha \leqslant 0\cdot3$, though the same experimental data were used in each of the scales. Naturally, this is a reflection of the drawbacks of the absolute scale.

Table 4. Parameters for the Crab Nebula

Epoch	Scale	α	B	Revised scale	
				α_R	B_R
1961·0	CKL	0·27±0·02	3·792	0·330	3·989
1964·0	KPW	0·26	3·783	0·322	3·966
1964·4	BMW	0·247±0·015	3·729	0·331	3·975
1965·0	BH	0·263±0·01	3·783	0·302	3·884
1965·0	BGPW	0·299±0·009	3·915	0·333	4·0

Table 4 gives parameters of the source spectrum reduced to a new scale (Ivanov and Stankevich 1986*a*) by the same method as described in Section 3 for Cassiopeia A. In the revised scale values of the spectral index increase, and their spread is over the considerably smaller range $0\cdot302 \leqslant \alpha \leqslant 0\cdot333$. One can achieve a better definition of the Crab spectrum parameters using the original published data. With this aim we chose practically all papers from 1953 to 1974 where there was high relative accuracy by antennas with a sufficiently high resolution and where fluxes of the Crab Nebula and Cygnus A were measured simultaneously on one and the same scale, relatively or absolutely. Using the reference spectrum of Cygnus A (Ivanov and Stankevich 1986*a*), we calculated fluxes S_k on our scale, giving 29 values in the range 81·5–22·285 MHz, referred to epochs 1953·3–1973·5. The Crab spectrum calculated for these data has the parameters

$$\alpha = 0\cdot3298 \pm 0\cdot0036, \qquad B = 3\cdot9804 \pm 0\cdot0119. \tag{12}$$

All points well fit the spectrum (12), supporting the fact that from 1953 to 1974 there was no variability exceeding the measurement errors.

Table 5. Spectrum parameters for the Crab Nebula

Epoch	α	B
1964·2–1965·9	0·3193±0·0073	3·9406±0·0241
1971·8–1973·7	0·3316±0·007	3·9834±0·0223
1980·7–1981·7	0·3275±0·0074	3·9607±0·0246
1983·9–1984·8	0·2857±0·0049	3·8107±0·0164

There is a sufficient amount of data to restore the Crab spectrum for the epochs 1964·2–1965·9. At that time detailed comparisons were made between the Crab and Cassiopeia A radiation intensities at eight frequencies in the range 513–1840 MHz and for measurements (Baars *et al.* 1965; Wilson and Penzias 1966; Allen and Barrett 1967; Medd 1972; Stankevich *et al.* 1973) at 3150–14 500 MHz. The corresponding parameters of the spectrum are given in Table 5.

Our absolute measurements of the Crab spectrum in the range 500–10 000 MHz are given by the method of 'artificial Moon' in autumn of 1971 and in spring and autumn of 1973; the spectrum parameters are also given in Table 5.

The parameters of the spectrum (12) and those of Table 5 are well correlated with each other. But if the spectrum (12) is built over the data collected for a 20-year period, the spectra of 1965 and 1973 were measured for two years. Coincidence of these spectra again testified to the stability of the Crab from 1953 to 1974. A similar conclusion has been made by Ivanov *et al.* (1982*a*) in a comparison of the relative and absolute observational results at wavelengths of 31·5 and 3·07 cm for a 20-year period after 1961.

In 1980–81 absolute measurements of the Crab radiation were made which show a decrease in flux by 2·8%, independent of frequency. In the subsequent years 1983 and 1984 repeated measurements showed that the source spectrum was changed (Ivanov 1986). As shown in Table 5 over nine years a strong decrease in spectral index $\Delta\alpha = 0{\cdot}044$ occurred, amounting to 14% of the epoch 1974 value.

If the phenomenon detected is interpreted as a flux decrease with time, then a strong frequency dependence occurs: the flux drop increases with a frequency decrease. In the range 500–9770 MHz the source luminosity also decreases by 3%. On the whole, from these results it follows that the observed intensity and spectrum variation began after 1974–75 and developed irregularly in time. Thus, the effect may not be a consequence of adiabatic losses from Nebula broadening.

The evolution of SNRs containing a pulsar has been investigated theoretically in a number of papers. Reynolds and Chevalier (1984) showed that in the modern epoch the flux of the Nebula radiation must decrease uniformly at all frequencies by 0·26% per year. If variations of the spectral index in the radio range are possible, then they can only be at the early stages of evolution, at an age of the order of 100 years (Bandiera *et al.* 1984), i.e. considerably less than the age of the Crab.

Table 6. Parameters for the Tycho Brahe SNR

Epoch	Frequency (MHz)	Ω (% per year)	$\nu(t)$ (arc sec per year)	Reference
1964–72	960	$0{\cdot}8\pm0{\cdot}1$	—	Stankevich *et al.* (1973)
1964–81	960	$0{\cdot}5\pm0{\cdot}15$	—	Ivanov *et al.* (1982*b*)
1963–78	1400	$0{\cdot}4\pm0{\cdot}5$	—	Dickel and Spangler (1979)
1971–79	1400	$0{\cdot}23\pm0{\cdot}19$	$0{\cdot}256\pm0{\cdot}026$	Strom *et al.* (1982)
1980–83	2695	$0{\cdot}7\pm0{\cdot}5$	$0{\cdot}27\pm0{\cdot}014$	Tan and Gull (1985)

The flux drop and the spectrum variation might occur due to diffusion of radiating particles outside the Nebula. The intensity of their radiation in the interstellar magnetic field $H = 3\times10^{-6}$ G at 610 MHz must be equal to $\Sigma_{610} = 7{\cdot}6\times10^{-20}(0{\cdot}3\,nc^2/\sigma)\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$, where σ is the area of diffusion in nc^2. In 1975–76 a search of the weak halo was made at 610 MHz within 1·5° of the centre coinciding with the pulsar and an upper limit was obtained (Wilson and Weiler 1982) for the radiation intensity of $\Sigma_{610} < 2\times10^{-20}\ \mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$. At that time particle injection might have begun, and thus it is desirable to repeat the experiment at the present time. In the Crab the balance between injection and loss of relativistic particles is probably essential during their interaction with active regions around the pulsar. Armstrong and Coles (1978) reported a linear decrease of pulsar flux density by 45% between 1971 and 1975; evidently, this might reflect a decrease in injection rate of relativistic electrons into the central region of the Nebula.

4. The Tycho Brahe SNR

For the Tycho Brahe SNR SN 1572 a flux decrease has been detected at wavelengths of 11·21 and 31 cm. The corresponding data are given in Table 6. A detailed picture of source radiation evolution is not still clear; thus, one can speak only of mean values. The mean rate of flux decrease over all measurements for 1980–83 amounts to $S^{-1}\mathrm{d}S/\mathrm{d}t = -0{\cdot}46\%$ per year.

If there is no diffusion of relativistic electrons into the interstellar medium, the rate of flux decrease has the form

$$\frac{1}{S}\frac{\mathrm{d}S}{\mathrm{d}t} = -A(\alpha)\frac{v(t)}{R(t)}, \tag{13}$$

where $v(t)$ and $R(t)$ are the velocity of broadening and radius of the SNR for the observational epoch. When $v(t)/R(t) = 11\%$ per year, $A(\alpha)$ is equal to 4·33, close to the value $A(\alpha) = 2(2\alpha+1) = 4{\cdot}44$ from the theory of adiabatic broadening of the source with $\alpha = 0{\cdot}61$.

5. Conclusions

As a result of detailed investigations of the radiation of Cassiopeia A and the Crab Nebula, variations have been detected in the energy distribution over the spectrum. These variations are not just the consequence of nebula broadening and relativistic electron acceleration inside the envelope. Of particular importance are the results on the rapid variation (including periodic) of the spectral index of Cassiopeia A, since they raise a problem on the existence and activity of the stellar remnant of the supernova burst, a problem not manifested earlier in other observations. This problem is also associated with the origin of a compact source inside the remnant, which according to the spectrum and angular dimensions is similar to the compact source in the Crab Nebula.

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