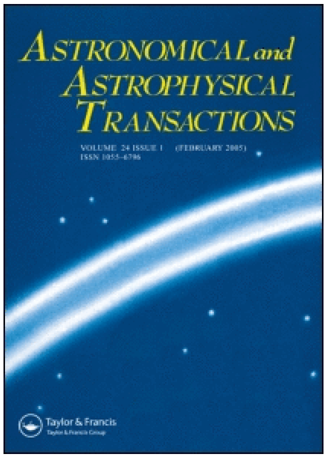

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Variations and secular decrease of the flux density of Cassiopeia a at frequencies 151.5, 290 and 927 MHZ according to long-term (1977-1994) measurements

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VARIATIONS AND SECULAR DECREASE OF THE FLUX DENSITY OF CASSIOPEIA A AT FREQUENCIES 151.5, 290 AND 927 MHZ ACCORDING TO LONG-TERM (1977–1994) MEASUREMENTS

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Basing on long-term (1977–1994) measurements at frequencies 151.5, 290 and 927 MHz the mean rates of the secular decrease of Cassiopeia A flux density were estimeted as $d_{151.5} = -(1.11 \pm 0.22)\%$ year^{-1}, $d_{290} = -(0.79 \pm 0.09)\%$ year^{-1} and $d_{927} = -(0.72 \pm 0.06)\%$ year^{-1}, respectively. The decrease of Cassiopeia A flux density is not uniform in time. Moreover, an increase of the flux density was observed (1979–1980). It is argued the cause of the time variations of d_ν is stochastic variability of the total radio emission of numerous compact radio features located in the diffuse envelope of Cassiopeia A.

KEY WORDS **Cassiopeia A, secular decrease, compact radio features**

1 INTRODUCTION

In 1960, Shklovsky (1960) predicted a secular decrease of Cassiopeia A radio emission flux density ($S_\nu^{\text{Cas A}}$). Shortly after this prediction the secular decrease in radio emission of Cassiopeia A was discovered by Högbom and Shakeshaft (1961) at a frequency of 81.5 MHz. Long-term measurements unexpectedly revealed a frequency dependence of the secular decrease rate, defined as

$$d = (dS_\nu^{\text{Cas A}}/dt)(S_\nu^{\text{Cas A}})^{-1}. \quad (1)$$

The frequency dependence of d ($d = d(\nu) \equiv d_\nu$) manifests itself in the secular flattening of Cassiopeia A radio spectrum at meter, decimeter and centimeter wavebands (Dent *et al.*, 1974; Stankevich, 1977; Baars *et al.*, 1977; Vinyajkin *et al.*, 1980; Ivanov and Stankevich, 1987). As to a time dependence of d, the available observational data are not sufficient to make an unambiguous conclusion. Models of radio evolution of a spherically symmetric, expanding supernova remnant (SNR) without injection and acceleration of particles and generation of magnetic field predict that

$$S_\nu \propto R^{-f(\alpha)}, \tag{2}$$

where R is the radius of the SNR, $f(\alpha)$ is a function of spectral index ($S_\nu \propto \nu^{-\alpha}$). For an adiabatically expanding SNR with a constant magnetic flux, $f(\alpha) = 4\alpha + 2$ (Shklovsky, 1960), for an SNR expanding with conservation of the total energy stored in particles and magnetic field, $f(\alpha) = (3/2)(\alpha + 1)$ (Shklovsky, 1976). If an SNR expands at constant speed V ($R = V(t - t_0)$, where t_0 is the epoch of the supernova explosion), d is given by

$$d = -\frac{f(\alpha)}{t - t_0}. \tag{3}$$

To determine the time dependence of S_ν^{CasA} and to choose an adequate model for Cassiopeia A radio evolution, long-term flux density measurements are necessary. In such measurements it is very desirable to use the same radio telescope and measurement method during the whole observational program. This allows to obtain a homogeneous observational series.

2 THE MEASUREMENTS

In 1977–1980, measurements of Cassiopeia A flux density at the frequencies of 151.5, 290 and 927 MHz (calibrated using the flux density of Cygnus A) were initiated at the radio observatory of NIRFI at Staraya Pustyn' (near Niznij Novgorod). Details of the observations at the three frequencies are as follows:

(a) 151.5 MHz. The measurements were made with a two-element interferometer consisting of 14-m radio telescopes. The baseline is 31λ and the orientation is nearly east–west. The interference fringes of both Cassiopeia A and Cygnus A were registered near their upper culminations.

(b) 290 MHz. The measurements were made with the 10-m radio telescope using the "on–off" method. The coordinates of the "off"-positions for Cassiopeia A are $\alpha_{\mathrm{off1;2}}^{\mathrm{Cas\,A}} = \alpha^{\mathrm{Cas\,A}} \pm 1^h30^m$ and $\delta_{\mathrm{off1;2}}^{\mathrm{Cas\,A}} = \delta^{\mathrm{Cas}}$, those for Cygnus A are $\alpha_{\mathrm{off1950}}^{\mathrm{Cyg\,A}} = 19^h40^m30^s$ and $\delta_{\mathrm{off1950}}^{\mathrm{Cyg\,A}} = 32^\circ$.

(c) 927 MHz. The measurements were made with the other 10-m radio telescope using the "on–off" method. The coordinates of the "off"-positions for Cassiopeia A are $\alpha_{\mathrm{off1;2}}^{\mathrm{Cas\,A}} = \alpha^{\mathrm{Cas\,A}} \pm 0^h40^m$ and $\delta_{\mathrm{off1;2}}^{\mathrm{Cas\,A}} = \delta^{\mathrm{Cas\,A}}$, those for Cygnus A are $\alpha_{\mathrm{off1950}}^{\mathrm{Cyg\,A}} = 20^h12^m$ and $\delta_{\mathrm{off1950}}^{\mathrm{Cyg\,A}} = 45^\circ05'$.

Both 290 and 927 MHz measurements were made during such intervals of time when $|h^{\mathrm{Cas\,A}} - h^{\mathrm{Cyg\,A}}| < 7^\circ$ (where h is the elevation angle, the mean value of h during a measurement run is $\langle h \rangle = 72^\circ$).

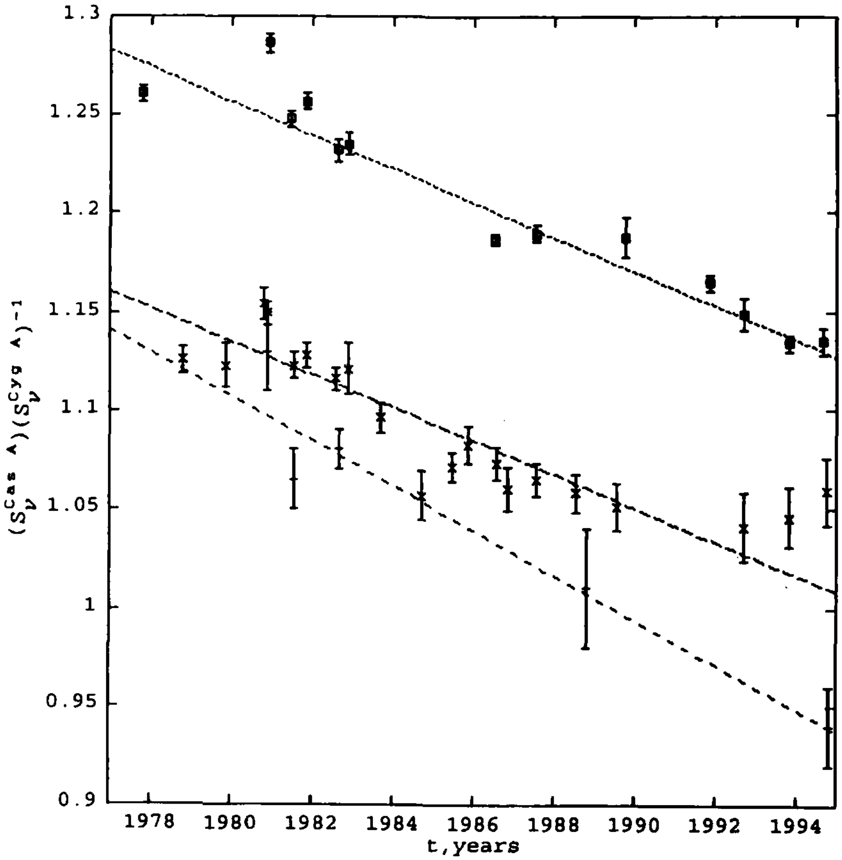

Figure 1 The flux density ratio for Cassiopeia A relative to Cygnus A at frequencies 151.5 MHz (-), 290 MHz (x) and 927 MHz (□). The straight lines show weighted least-squares fits.

3 RESULTS

Table 1 lists the values of the 151.1 MHz flux density ratio $r_{151.5} = (S_{151.5}^{\mathrm{Cas\,A}}) \cdot (S_{151.5}^{\mathrm{Cyg\,A}})^{-1}$ for Cassiopeia A relative to Cygnus A. These values and those at 290 and 927 MHz (r_{290} and r_{927}) are given in Figure 1. It should be noted that r_{290} and r_{927} were obtained from directly measured ones by multiplying by 1.19 and 0.89, respectively, to take into account the difference in the brightness temperature of the galactic radio emission in the directions to Cygnus A and to the "off"-positions for Cygnus A. The straight lines in Figure 1,

$$r_\nu = m_\nu(t - \langle t \rangle) + c_\nu, \tag{4}$$

were obtained from a least squares fit with allowance for the weight of each measured value $r_{\nu i}$ ($i = 1, 2, \ldots, N_\nu$, where N_ν is the total number of epochs at the frequency

Table 1.

Epoch, t	$(S_{151.5}^{Cas\,A})\cdot(S_{151.5}^{Cyg\,A})^{-1}$
1980.9	1.13 ± 0.02
1981.6	1.065 ± 0.015
1982.7	1.08 ± 0.01
1988.8	1.01 ± 0.03
1994.8	0.94 ± 0.02

of ν; $N_{151.5} = 5$, $N_{290} = 20$ and $N_{927} = 13$). Table 2 lists the values of the mean rate $d_\nu = m_\nu/c_\nu$ of the secular decrease of Cassiopeia A flux density in the periods given in the first column. The least squares fitting with the model $A(t-t_0)^{-f(\alpha)}$ (A is a constant, $t_0 = 1658$ from van den Berg, 1971) for $r_{\nu i}$ allows to determine the values of d_ν using Eq. (3). The result is $d_{151.5}(\langle t\rangle = 1987.85) = -(1.13 \pm 0.22)\%$ year^{-1}, $d_{290}(1986.8) = -(0.76\pm0.09)\%$ year^{-1} and $d_{927}(1986.25) = -(0.72\pm0.06)\%$ year^{-1}. These values of d_ν pratically coincide with those given in the first three lines of Table 2.

One can see from Figure 1 that the decrease of $S_\nu^{\mathrm{Cas\,A}}$ with time is not uniform. Moreover, the flux density of Cassiopeia A even increased in 1979–1980. This event can be seen at all three frequencies. In the maximum of the burst (the late 1980) an excess above the straight line is $(2.7 \pm 1.8)\%$ at 151.5 MHz, $(2.2 \pm 0.7)\%$ at 290 MHz and $(3.0 \pm 0.4)\%$ at 927 MHz. Thus, the relative amplitude of the burst is frequency-independent within errors. This means that the spectrum of the burst is the same as for Cassiopeia A as whole. The influence of the 1979–1981 burst on the values of d_{290} and d_{927} can be deduced from the comparison of the second and fourth lines and the third and fifth lines of Table 2, respectively. The values of d_ν given in the first, fourth and fifth lines of Table 2 correspond to the same period with $\langle t\rangle = 1987.8$ and, at least, do not contradict the conclusion about the secular flattening of the radio spectrum of Cassiopeia A.

Table 2. The values of $d_\nu = m_\nu/c_\nu$

Period (years)	*The mean epoch $\langle t\rangle$ (year)*	*The value of d_ν (% year^{-1})* $\nu = 151.5\,MHz$	$\nu = 290\,MHz$	$\nu = 927\,MHz$
1980.9 -1994.8	1987.85	-1.11 ± 0.22		
1978.8 -1994.8	1986.8		-0.79 ± 0.09	
1977.8 -1994.7	1986.25			-0.72 ± 0.06
1980.8 -1994.8	1987.8		-0.89 ± 0.11	
1980.95-1994.7	1987.8			-0.80 ± 0.07
1980.8 -1986.85	1983.8		-1.31 ± 0.13	
1987.55-1994.8	1991.2		-0.20 ± 0.11	
1980.95-1986.55	1983.8			-1.15 ± 0.15
1987.6 -1994.7	1991.2			-0.76 ± 0.11

From Figure 1 and the last four lines of Table 2, one can see that the d significantly depends on time. A significant slow-down in the secular decrease of the flux density of Cassiopeia A over the last 7 years, as compared with previous 7 years, is clearly seen. As to the 151.5 MHz data, the sampling is too rare to draw a similar conclusion.

4 DISCUSSION

Let us first consider the cause of the observed deflections of the measured values of Cassiopeia A flux density from the power law,

$$S_\nu^{\mathrm{Cas\ A}} \propto (t - t_0)^{-f(\alpha)} \simeq (\langle t\rangle - t_0)^{-f(\alpha)}[1 - f(\alpha)\frac{t - \langle t\rangle}{\langle t\rangle - t_0}]. \quad (5)$$

High resolution radio maps of Cassiopeia A show an existence of numerous compact features (knots) in the diffuse envelope (e. g. Rosenberg, 1970; Dickel and Greisen, 1979; Tuffs, 1986; Arendt and Dickel, 1987). From a detailed comparison of the radio maps of Cassiopeia A at 5 GHz obtained with the Cambridge 5-km radio telescope in 1974.9 and 1978.9 Tuffs (1986) found that the flux densities of 133 compact features increased and those of 172 compact features decreased. Thus, the flux densities of the compact features $S_{\nu n}^{\mathrm{cf}}$ ($n = 1, 2, \ldots, N$, where N is the total number of the compact features) change with time. Since the variations of the flux densities of different compact features are statistically independent,the total flux density of N compact features $S_{\nu\Sigma}^{\mathrm{cf}} = \sum_{n=1}^{N} S_{\nu n}^{\mathrm{cf}}$ is a random quantity. According to Eq. (5), the radio emission of the diffuse envelope of Cassiopeia A most likely decreases monotonically. Thus, the observed variations of $S_\nu^{\mathrm{Cas\ A}}$ are caused by fluctuations in the total radio emission of N compact features. The relative root-mean-square (rms) value F of the fluctuations of $S_\nu^{\mathrm{Cas\ A}}$ is

$$F = \frac{\sigma_{S_\nu^{\mathrm{Cas\ A}}}}{S_\nu^{\mathrm{Cas\ A}}} \sim k\frac{1}{N^{1/2}}, \quad (6)$$

where $k = S_{\nu\Sigma}^{\mathrm{cf}}/S_\nu^{\mathrm{Cas\ A}}$ is the ratio of the combined radio emission of on the compact features of Cassiopeia A to the total radio emission. With $N \simeq 300$ and $k \simeq 1/3$, (6) yields $F \simeq 2\%$. According to Arendt and Dickel (1987),the half-decay time of the flux density of the knots is $\tau_{1/2} \sim 10$ years and so the rms value of the fluctuations of d is $\sigma_d \sim 0.2\%$ year^{-1}. The estimated value of σ_d agrees satisfactorily with the observed variations of d_ν. To obtain a value of d averaged over its fluctuations, it is necessary to have measurements over a period much longer than the decay (increase) time of the flux density of the knots.

Substituting the values of d and $\langle t\rangle$ from the first three lines of Table 2 and $t_0 = 1658$ into Eq. (3) yield the values of $f(\alpha)$ given in Table 3. The weighted mean with respect to the three values of $f(\alpha)$ from Table 3 is $\langle f(\alpha)\rangle_w = 2.5 \pm 0.2$. As

Table 3. The estimated values of $f(\alpha)$

Frequency (MHz)	*d (% year^{-1})*	*$\langle t\rangle - t_0$ (years)*	$f(\alpha)$
151.5	-1.11 ± 0.22	329.85	3.66 ± 0.73
290	-0.79 ± 0.09	328.8	2.60 ± 0.30
927	-0.72 ± 0.06	328.25	2.36 ± 0.20

mentioned in the Introduction, in the model of SNR evolution with conservation of the total energy in both magnetic field and relativistic electrons we have $f(\alpha) = (3/2)(\alpha + 1)$. Substituting $\alpha = 0.75$ in this formula gives $f(0.75) = 2.6$ in a good agreement with the measured value 2.5 ± 0.2. On the other hand if $f(\alpha) = 4\alpha + 2$ then $f(0.75) = 5$ in a sharp contradiction with observations.

5 CONCLUSIONS

We performed long-term measurements of the flux density of Cassiopeia A relative to that of Cygnus A at frequencies 151.5, 290 and 927 MHz using the time facilities and methods throughout the observation period. As a result, the mean rates of the secular decrease in radio emission of Cassiopeia A have been obtained:$d_{151.5} = -(1.11 \pm 0.22)\%$ year^{-1} (over the period 1980.9–1994.8), $d_{290} = -(0.79 \pm 0.09)\%$ year^{-1}(1978.8 − 1994.8) and $d_{927} = -(0.72 \pm 0.06)\%$ year^{-1}(1977.8 − 1994.7). The observational data are a in a good agreement with a model of SNR evolution with conservation of the total energy in both magnetic field and relativistic electrons. The observed time variations of the secular decrease rate are caused most likely by a stochastic variability of the total radio emission of about 300 compact features identified in Cassiopeia A.

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