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The Giant Spiral Galaxy M101:

IV. Observations of Variable Continuum Radio Emission from Supernova 1970g and Measurements of the Continuum Radio Structure of the Giant H II Complex NGC 5455

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Summary. Over the past few years a series of radio observations at $\lambda\lambda$ 2.8, 6.0, 21 and 49.2 cm has been made on the supernova 1970g and on the nearby giant H II complex NGC 5455 in the galaxy M 101. The following results have now been obtained:
1) NGC 5455 contributes a non-variable flux density of 7.1 ± 0.6 mJy at λ 21 cm. The radio source is thermal, and coincides both in position and general shape with the optical object.
2) The optical position of the supernova has been re-determined to an accuracy better than 0″.5.
3) In December 1971, variable radio emission was observed near NGC 5455 at a level of 5.6 ± 0.7 mJy at λ 21 cm. A similar value was observed in December 1973; however in October 1974 the intensity had decreased to an undetectable level. The position of this variable source coincides with that of supernova 1970g, which is located about 6″ to the north-west of the optical centroid of NGC 5455.
4) A nonthermal radiation mechanism is suggested by the present data. Several implications for theoretical models of the origin and time development of radio emission during the early phases of supernovae are discussed.

Key words: supernova — H II regions — spiral galaxies

I. Introduction

Radio emission possibly associated with the bright type II supernova 1970g in M 101 was first reported at λ 11 cm by Gottesman *et al.* (1972). Since this was the first time that radio emission may have been detected in a recent supernova, their result prompted us to re-examine the observations which were made with the Westerbork Synthesis Radio Telescope (WSRT) at λ 21 cm in November 1971/January 1972 during a study of the distribution and motions of neutral hydrogen in M 101 (Allen *et al.*, 1973, paper I of this series), and to compare those measurements with the earlier observations of the continuum emission from the non-thermal disc and the giant H II complexes in M 101 which were made in December 1970/January 1971 (Israel *et al.*, 1975, paper II of this series). From that comparison, evidence for variable radio emission at λ 21 cm near the position of SN 1970g was reported by Goss *et al.* (1973). Since then, we have obtained further observations at $\lambda\lambda$ 49.2, 21 and 6.0 cm with the Westerbork telescope and at λ 2.8 cm with the 100-m radio telescope at Effelsberg.
In this paper, we present all results which are now available from our observations. The temporal variation of the supernova radio flux density is confirmed and extended. The radio structure of the neighbouring giant H II complex NGC 5455 (located about 6″ to the south-east of the supernova) was first described and discussed in paper II; further information is provided from the new observations presented here.
In Section II we describe a re-determination of the optical position of the supernova. The results of the radio observations are summarized in Section III and discussed in Section IV. Finally, in Section V we present some further remarks on the interpretation of the variable radio emission from the supernova.

II. A Re-determination of the Optical Position of SN1970g

The optical position of the supernova was originally reported by van Altena (1970) to be: $14^h01^m14^s.64 \pm 0^s.06$, $54°28'54''.7 \pm 0''.5$ (1950). An independent measurement by us of a film copy of a 48-inch plate taken on September 30/October 1, 1970, and on a second plate taken four days later (both kindly provided to us by S. van den Bergh) gives a substantially different position of R.A. (1950) $= 14^h01^m14^s.25 \pm 0^s.15$, Declination (1950) $= +54°28'$

58″ ± 1″.5. The position has since been measured by Dr. J. Kristian using both 48-inch and 200-inch plates, by Dr. C. Lari using van den Bergh's plate, and has been remeasured by van Altena (private communication from Kristian). All three determinations now agree to within 0″.2 and from these we adopt the value:

$$\text{R.A. } (1950) = 14^h01^m14^s.31$$
$$\text{Declination } (1950) = 54^h28^m56^s.2\,.$$

III. Radio Observations and Results

The operation, calibration, and instrumental parameters of the Westerbork telescope for normal continuum observations are described in paper II and in the references given there. Additional details of the measurement procedures will be mentioned here when necessary. The position, amplitude, and size of sources which appear on the synthesis maps have been determined with an algorithm which fits a two-dimensional gaussian to the observed response. Quoted source sizes are gaussian full width at half maximum, after deconvolving a gaussian representation of the telescope beam. Systematic corrections and uncertainties in the parameters determined with the source-fitting algorithm have been established by analysing artificial sources with known properties which have been inserted into normal map fields. Total flux densities have in addition been determined for extended sources by integrating the maps over a defined region and dividing by the integral of the synthesized beam over the same area; this method is preferred to the estimate obtained by fitting a gaussian function since the structure of the source resulting from the combination of the H II region and supernova is variable in time. Flux densities and contour maps have been corrected for the Westerbork primary beam attenuation and refer to Stokes I unless otherwise indicated. Uncertainties quoted here are $\pm 1 \times$ r.m.s.; upper limits are $3 \times$ r.m.s.

a) λ 49.2 cm WSRT *Measurements*

A field including M 101 has been observed at three different epochs, each for 2×12^h. The first two sets of measurements were averaged into one map and presented in paper II. We have examined all three sets separately for the properties of the source which is closely coincident with NGC 5455 (cf. Fig. 1b of paper II). The results are given in Table 1.

Besides low-level radio interference, an important source of uncertainty in the λ 49.2 cm measurements is confusion from structure in the underlying non-thermal radio emission from the disc of M 101 itself. Fortunately, NGC 5455 lies just outside of the region of the strongest disc emission. We have an estimate of the disc emission at the position of NGC 5455/SN 1970g by two methods: First, cross-cuts were made through the source at various position angles and the background emission was interpolated to the position of the source. Second, the disc emission at λ 21 cm (where confusion is not serious because of the higher resolution) was used to predict the disc emission at λ 49.2 cm using a mean flux density spectral index of −0.5 which has been determined for several places in the galaxy (cf. paper II). Both methods agree; the correction applied is only 3.5 mJy[1]). For four additional H II regions (NGC 5447, 5461, 5462, and 5471) the flux densities at λ 49.2 cm are equal to those measured at λλ 21 and 6.0 cm to within the noise after applying similar corrections.

There is little evidence for time variations in the total flux density of NGC 5455/SN 1970g at λ 49.2 cm from the observations as presented in Table 1; however, the uncertainty in the flux density values can be reduced somewhat by subtracting the observations from each other and measuring the parameters of the source remaining at the position of the supernova. In this way the underlying disc emission with its contribution to the flux density uncertainty can be removed. The result for September 1973 minus January 1975 is 2.4 ± 1.8 mJy; for March 1974 minus January 1975 it is 3.0 ± 1.8 mJy, both suggesting a possible decrease in the flux density at λ 49.2 cm some time between March 1974 and January 1975. Further observations at later epochs are needed to verify this conclusion.

b) λ 21 cm WSRT *Measurements*

The observations at λ 21 cm are presently the most extensive of the series, with measurements at five different epochs spanning a time interval of about four years. The results are given in Table 2. The data were obtained with the standard continuum system at λ 21.2 cm during December 1970, December 1973 and October 1974. The WSRT 80-channel spectrometer (Allen *et al.*, 1974) was used in December 1971 and June 1973. For the H I line observations of December 1971 (cf. paper I) the profiles in the neighbourhood of NGC 5455 were examined in order to isolate those channels which were free from H I line emission, and an average continuum map was then made using 11 of the 16 available 129 kHz channels. Source parameters determined from the individual channel maps are in agreement with the mean value given in Table 2. The June 1973 observation was also made with the Westerbork spectrometer; however, a frequency setting was chosen so as to exclude all neutral hydrogen in M 101, and 8 channels were available to produce an average continuum map. Compared to the December 1971 data, the June 1973 observations contain fewer channels and less coverage both in hour angle and in available interferometer baselines, so that a relatively higher uncertainty is present in the results.

The older data reported in Goss *et al.* have been reanalysed along with the more recent measurements, and the values in Table 2 represent our best results up

[1]) 1 mJy = 10^{-29} W m^{-2} Hz^{-1}.

Table 1. λ 49.2 cm WSRT observations of the combined emission from SN 1970g and NGC 5455[b])

Mean date of observation	Total duration of observation	HPBW $\alpha \times \delta$	Centroid α(1950)	Centroid δ(1950)	Flux density (mJy)[a])
September 1973	2×12^h	$58'' \times 72''$	$14^h01^m13^s.5 \pm 1^s.0$	$54°28'40'' \pm 10''$	12 ± 2
March 1974	2×12^h	$57'' \times 71''$	$14^h01^m14^s.8 \pm 1^s.0$	$54°28'50'' \pm 10''$	13 ± 2
January 1975	2×12^h	$58'' \times 72''$	$14^h01^m14^s.7 \pm 1^s.0$	$54°28'52'' \pm 10''$	10 ± 2

[a]) 1 mJy $= 10^{-29}$ W m^{-2} Hz^{-1}. The source is unresolved by the synthesized beam at this wavelength.
[b]) A3.5 mJy contribution from the underlying nonthermal disk of M 101 has been subtracted.

Table 2. λ 21 cm WSRT observations of the combined emission from SN 1970g and NGC 5455

Mean date of observation	Total duration of observation	Observing frequency (MHz)	HPBW $\alpha \times \delta$	Centroid α(1950)	Centroid δ(1950)	Integrated flux density (mJy)
December 1970	4×12^h	1415.0	$24''.6 \times 30''.2$	$14^h01^m14^s.8 \pm 0^s.2$	$54°28'52'' \pm 3''$	6.6 ± 1.0
December 1971	16×12^h	1419.4	$24''.5 \times 30''.1$	$14^h01^m14^s.5 \pm 0^s.1$	$54°28'54'' \pm 1''$	12.2 ± 0.9
June 1973	3×5^h	1415.8	—	—	—	9.6 ± 2.7
December 1973	1×12^h	1415.0	$25''.2 \times 31''.1$	$14^h01^m14^s.4 \pm 0^s.2$	$54°28'51'' \pm 3''$	12.8 ± 1.3
October 1974	2×12^h	1415.0	$24''.7 \times 30''.4$	$14^h01^m14^s.5 \pm 0^s.2$	$54°28'50'' \pm 4''$	7.5 ± 0.8

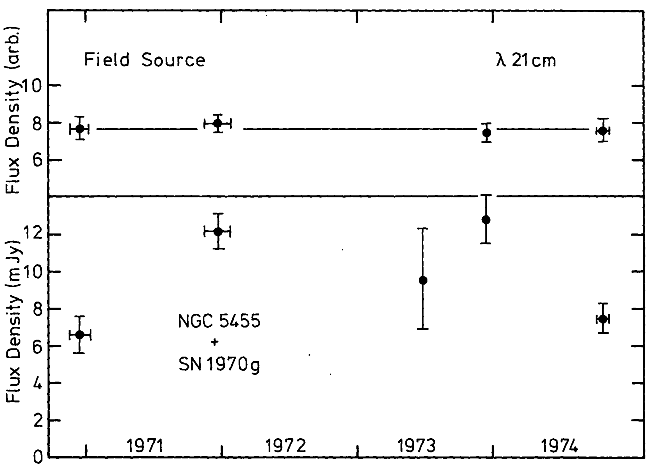


Fig. 1. Time variation in the total flux density of the radio sources associated with NGC 5455 and SN 1970g at λ 21 cm. The horizontal bars represent the time interval over which data samples were taken. The length of the vertical bars is $\pm 1\sigma$. The results for a 40 mJy field source are shown for comparison. These are normalized to give a clearer indication of the gain stability

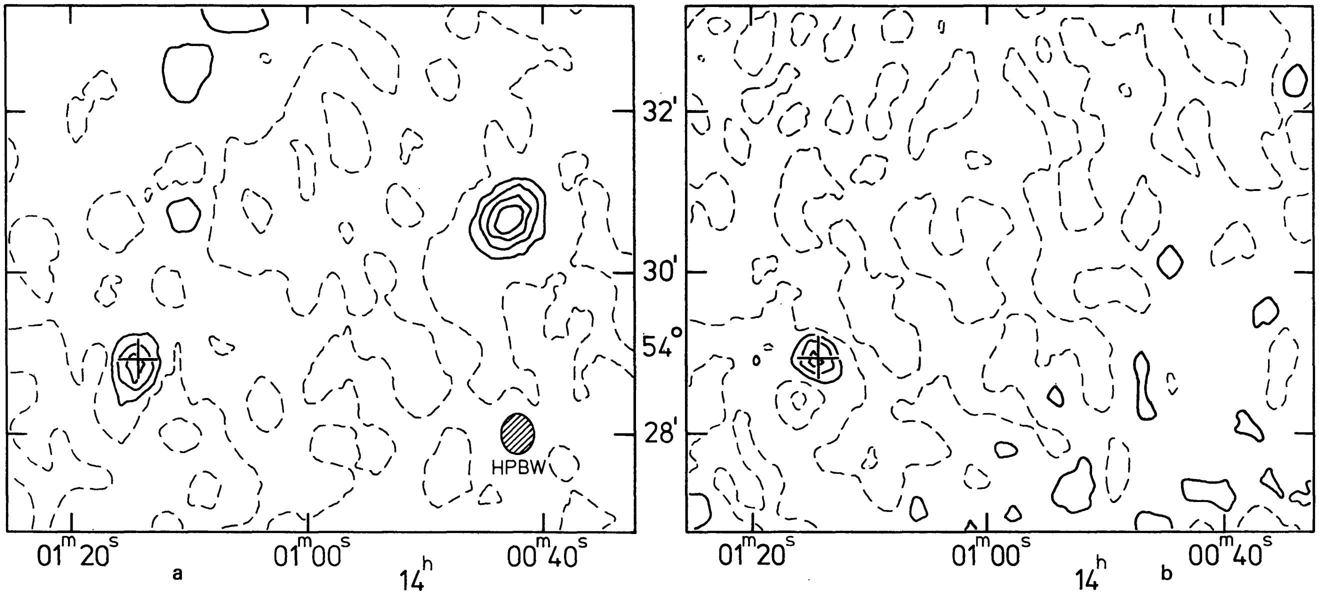
to the present time. Expect for the June 1973 value, the total flux densities in Table 2 have been determined by integrating the maps over a rectangle of size $53'' \times 63''$ centered at $14^h01^m14^s.8$, $54°28'52''$. For June 1973, the value was read off a contour map of the area.

Besides the source associated with NGC 5455/SN 1970g, up to 7 field sources were also measured on the synthesis maps at each epoch in order to check the Westerbork system gain and phase zero constancy. In Fig. 1 we show the time development of the total intensity of NGC 5455/SN 1970g and of a typical field source. A clear increase observed in December 1971 is followed by similar values in 1973; however, in October 1974 the flux density returned to almost the same value recorded about four years earlier. The horizontal bar on the data points indicates the range of time within which the observation samples were obtained, and the length of the vertical bar indicates $\pm 1\sigma$.

On a map of the difference between the December 1970 and the October 1974 observations the source-fitting program yields a flux density of -0.5 ± 0.7 mJy at the position of the supernova. We therefore assume that on both of these maps only the giant H II complex NGC 5455 is present; the two maps are averaged together in Fig. 2a. NGC 5455 is clearly visible on the left, and the complex NGC 5447 also appears at the right side of this figure. The cross gives the optical position of SN 1970g from Section II. The continuum disc of M 101 can be seen as a slight increase of the base level in the north-east corner of Fig. 2a. This map was subtracted from the synthesis data of December 1971, and the resulting difference map plotted in Fig. 2b. NGC 5447 and the disc of M 101 have now disappeared, and an obvious source appears at the position of the supernova. The faint extended emission in the south-west corner of Fig. 2b arises from neutral hydrogen present in the channels used for the 1971 map; as mentioned previously the region around the supernova is free from line radiation.

Additional confirmation of the identification of the variable radio emission with the supernova is provided by a marginal shift in the position of the maximum in Fig. 2a towards the position of the supernova in Fig. 2b. This shift is shown in Fig. 3.

The intensity of a source can be determined more accurately if the number of degrees of freedom in the fit can be reduced, for example if the position and size are already known. A difference map of the supernova emission in December 1973 was therefore produced in the same way as Fig. 2b for December 1971, and the



Figs. 2a and b. (a) Contour map of the mean of the December 1970 and the October 1974 observations at λ 21.2 cm. NGC 5455 is at the left, NGC 5447 at the right; both sources are significantly extended. The cross marks the supernova position. Contour interval 1.37 mJy/beam. The r.m.s. noise is 0.41 mJy/beam. The zero and negative contours are dashed.
(b) Contour map of the December 1971 data minus the map of Fig. 2a. Contour interval 1.64 mJy/beam, r.m.s. noise 0.60 mJy/beam. Only the source associated with the supernova remains. The zero and negative contours are dashed

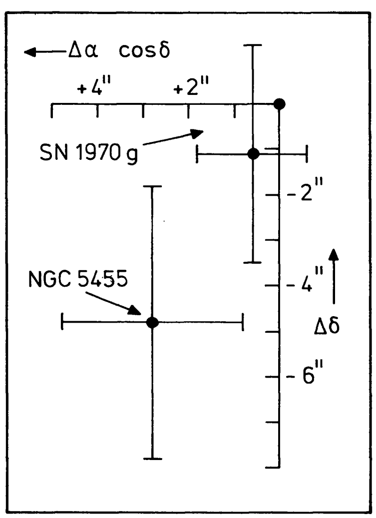


Fig. 3. The radio position of NGC 5455 from Fig. 2a and of SN 1970g from Fig. 2b are shown relative to the supernova optical position reported in Section II. The lengths of the error bars are $\pm 1\sigma$

amplitude of an assumed point source at the optical position of the supernova was determined with the source-fitting algorithm. The results are given in Table 3 and provide the strongest evidence for variability. The characteristics of the June 1973 map differ so strongly from the others that such a subtraction was not easily possible.

The parameters of NGC 5455 at λ 21.2 cm as determined from the average map of Fig. 2a are given in Table 5.

Table 3. Amplitude of an assumed point source at the optical position of the supernova, determined on the December 1971 and December 1973 λ 21 cm after subtraction of the average map of Fig. 2b

Average date of observation	λ 21 cm point source flux density (mJy)
December 1971	5.6 ± 0.7
December 1973	4.0 ± 0.9

c) 6.0 cm WSRT *Measurements*

Observations at λ 6.0 cm have been obtained at two epochs with the Westerbork telescope. The results are listed in Table 4. The measurements are consistent with the hypothesis that the supernova did not appear on either of the maps, and they have therefore been combined in order to provide a better map of NGC 5455 itself. In Fig. 4 this map is drawn over an enlargement of NGC 5455 taken from a 200-inch plate by A. Sandage (PH 745*S*) provided to us by J. Kristian.

The parameters of NGC 5455 determined from this map are given in Table 5. The total flux density has been determined by integration over an area of $23'' \times 35''$ centered at $14^h01^m14^s\!.58$, $54°28'50''\!.0$.

d) λ 2.8 cm *Measurements with the 100-*m *Effelsberg Telescope*

Goss *et al.* reported an upper limit of 6 mJy at λ 2.8 cm obtained with the Effelsberg telescope at the position of the supernova in February 1973. We have obtained

Table 4. λ 6.0 cm WSRT observations of the combined emission from SN 1970g and NGC 5455

Mean date of observation	Total duration of observation	HPBW $\alpha \times \delta$	Centroid $\alpha(1950)$	Centroid $\delta(1950)$	Integrated flux density (mJy)
February 1973	2×12^h	$7''.2 \times 8''.9$	$14^h01^m14^s.72 \pm 0^s.09$	$54°28'52''.5 \pm 1''.4$	6.5 ± 1.2
January 1975	2×12^h	$7''.1 \times 8''.7$	$14^h01^m14^s.76 \pm 0^s.11$	$54°28'51''.3 \pm 2''.6$	5.6 ± 1.2

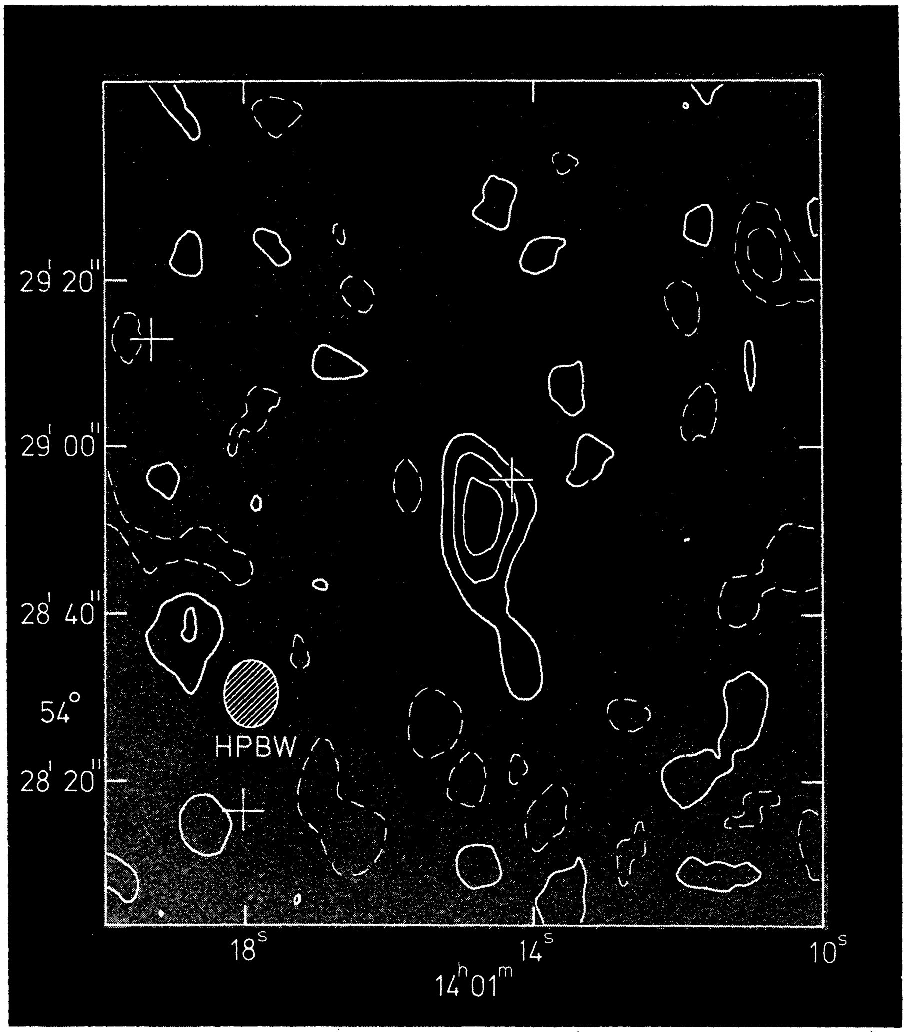


Fig. 4. Contour map of the λ 6.0 cm WSRT observations of NGC 5455 (average of February 1973 and January 1975) drawn over a photograph of the region taken by A. Sandage with the 200-inch telescope. The cross near the H II region marks the supernova position. Contours 0.75 mJy/beam, r.m.s. noise 0.5 mJy/beam. Negative contours are dashed; the zero contour is omitted

additional observations at Effelsberg in April 1973. All measurements were made using an on-off technique in addition to switching against a reference beam. The combined integration time was 300 min; however, the sensitivity was entirely limited by fluctuations in the emissivity of the atmosphere. The disposition of other sources in the field was known from the λ 21 cm Westerbork synthesis map, and care was taken to exclude them from the reference positions during the measurement sequence.

By combining both the February and April 1973 observations, we obtain a marginal detection of 5 ± 3 mJy averaged over several different position angles of the linearly polarized feed of the telescope. The supernova and NGC 5455 are separated by only 6″, and both sources appear in the telescope beam at Effelsberg (HPBW = 1′.3 at λ 2.8 cm). Since this value of flux density would be expected from NGC 5455 alone, we have no evidence that the supernova appeared in our λ 2.8 cm observations.

Table 5. Radio properties of the giant H II complex NGC 5455

Wavelength (cm)	Centroid α(1950)	Centroid δ(1950)	Integrated flux density (mJy)	Major axis size	Minor axis size	Position angle
21.2	$14^h01^m14\overset{s}{.}64 \pm 0\overset{s}{.}23$	$54°28'51\overset{''}{.}5 \pm 3\overset{''}{.}1$	7.1 ± 0.6	$23\overset{''}{.}9^{+8''}_{-11''}$	$5''^{+9''}_{-5''}$	0°
6.0	$14^h01^m14\overset{s}{.}73 \pm 0\overset{s}{.}06$	$54°28'51\overset{''}{.}9 \pm 1\overset{''}{.}4$	6.2 ± 0.9	$13'' \pm 3''$	$<4\overset{''}{.}5$	−3°
2.8	—	—	5 ± 3	—	—	—

IV. Discussion of the Results

a) *The Giant* H II *Complex* NGC *5455*

In Table 5 we have assembled the most precise radio measurements of NGC 5455 which are presently available from our own observations. The flux densities differ slightly from those reported in paper II; however, the differences are within the uncertainties, and the values in Table 5 are about twice as precise as those given in Table 4 of paper II. The spectrum of the total flux density is entirely consistent with the form (frequency)$^{-0.11}$, to be expected from an optically thin ionized gas, thereby excluding any substantial non-variable non-thermal contribution to the total radio intensity of NGC 5455.

The discrepancy of about a factor 5 between the actual λ 21 cm flux density and that predicted from the Hβ flux as measured by Searle (1971) was reported in paper II and is hereby confirmed. The origin of this discrepancy in NGC 5455 and in other giant H II complexes in M 101 is discussed further in paper II. As Searle has pointed out (private communication), the most likely explanation requires about 1.8 magnitudes of internal extinction in the H II complex. The absorbing material must be distributed in such a way as to produce an Hα/Hβ ratio which appears extinction-free.

In paper II, we presented evidence that essentially all the radio flux density from NGC 5455 arises in a core of angular size about $3'' \times 11''$ (optical dimensions determined by us). We have re-investigated this conclusion using the more sensitive λ 6.0 cm data of Fig. 4 in the following way:

The gaussian-fit algorithm gives a total flux density of 5.4 ± 0.7 mJy, and the source sizes quoted in Table 5. This is not significantly less than the total flux density of 6.2 ± 0.9 mJy obtained from integration over a retangle of dimensions $23'' \times 35''$ as described in Section IIIc. The conclusion of paper II with regard to the core-envelope structure of NGC 5455 is hereby confirmed and made more precise; more than about 85% of the free-free radio emission of NGC 5455 arises in a core of radio size $(<4\overset{''}{.}5) \times (13'' \pm 3'')$, and any envelope component of dimensions up to $23'' \times 35''$ cannot contribute more than about 15% to the total flux density.

The λ 21.2 cm angular sizes quoted in Table 5 are consistent with the more precise λ 6.0 cm values. The optical angular sizes for NGC 5455 in Table 8 of Sandage and Tammann (1974) are $14'' \times 30''$ for the halo and $7'' \times 8\overset{''}{.}5$ for the core. There is therefore no obvious correspondence between the radio and optical dimensions; however, since the nature of what is being measured in the two cases is different, no simple interpretation can be made.

The conclusions presented in paper II as to the electron density, number of exciting stars, etc. in NGC 5455 are essentially unchanged. The ionization needed to explain the radio flux density requires about 300 05 stars in a region of space about 200 pc in diameter.

b) *Supernova* 1970 g

We recall that the data of maximum optical brightness of SN 1970g is thought to be in the period July 20–30, 1970. In Fig. 5 we have collected all our observations as well as those of Gottesman *et al.* (1972) at λ 11 cm. We have not considered the λ 3.8 cm data of Gottesman *et al.* since our observations of the structure of NGC 5455 at λ 6.0 cm suggest that their failure to reliably detect any emission is probably due to resolution of the giant H II complex with their 2″ beamwidth. The λ 11 cm data of Gottesman *et al.* has been treated in the following manner: From the published values of measured flux density, hour angle coverage, and baseline configuration, we have tried to make a rough correction for resolution of NGC 5455 by calculating the visibility function of a source with angular dimensions $(<4.5'') \times (13'')$ and total flux density of 6.0 mJy. For example, the May 1971 λ 11 cm observation should be increased from 3.8 to 7.3 mJy.

The diagram on the right side of Fig. 5 gives our best estimates for the thermal emission from NGC 5455. The signal-to-noise ratio is generally low, and it is difficult to make many firm statements about time variability of SN 1970g. The λ 11 cm and λ 21 cm data are in agreement up to the beginning of 1971, and show no evidence for emission from the SN at an age of about 0.4 years. In early 1971 an increase in emission was probably detected by Gottesman *et al.*; we have no corroborating evidence at that time. By December 1971 we have a definite increase at λ 21 cm; however, the λ 11 cm flux density limit indicates no emission at that time in excess of that due to NGC 5455. The supernova apparently remained detectable at λ 21 cm at least until December 1973. In October 1974 the emission

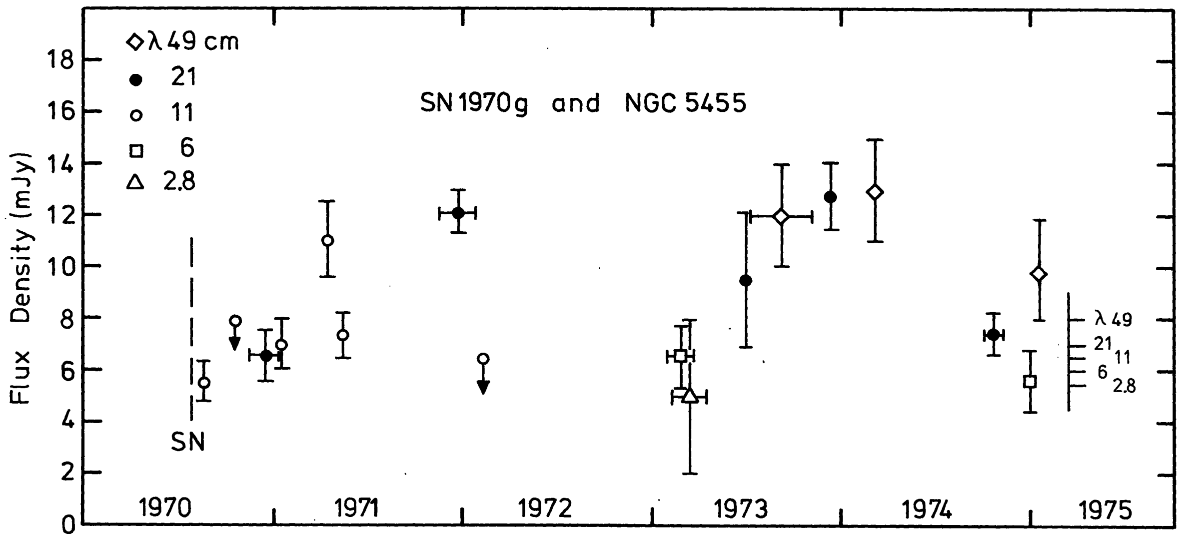


Fig. 5. Collection of all available measurements of the combined radio emission of SN 1970g and NGC 5455, including the λ 11 cm data by Gottesman *et al.* (1972) adjusted as described in the text. The expected thermal emission from NGC 5455 is shown on the right-hand side of the figure

of NGC 5455 could be observed, and an upper limit to the emission from the supernova is about 1 mJy.

The contribution of NGC 5455 at λ 49.2 cm estimated from an assumed optically thin thermal spectrum[2]) is 7.8 ± 0.7 mJy. The values of the flux density for September 1973 and March 1974 exceed this thermal contribution by a factor of about 1.5; however, the January 1975 value is not significantly in excess of the estimate for the thermal contribution. The mean flux density of 12.5 ± 1.4 mJy obtained by averaging the values for September 1973 and March 1974 implies a contribution from SN 1970g of 4.7 ± 1.6 mJy. At λ 21 cm for the same epoch we found 4.0 ± 0.9 mJy. If we further assume that the supernova was not detectable at λ 6.0 cm at that time (< 1.5 mJy on Fig. 4), the errors on the flux densities allow a range of spectral index (assuming a power law spectrum) from −0.6 to −0.8 for the radio emission of the supernova at an age of about 3.4 years. The spectral index was apparently also significantly negative in January 1972 at an age of about 1.5 years.

A lower limit to the radio surface brightness can be obtained for the supernova in December 1971 if we assume that the size of the object at an age of about 1.4 years cannot exceed 1.4 light years ($1.3 \times 10^{-2''}$ at 7 Mpc). With the value of the flux density given in Table 3, we compute that the surface brightness should exceed about 3×10^7 K at λ 21 cm.

The high brightness temperature, negative spectral index, and general temporal behaviour of the radio emission are consistent with a model of increased non-thermal radio emission which moves with time from higher to lower frequencies. This conjecture will be discussed further in the following section.

[2]) Other H II complexes in M 101 appear to have optically thin thermal spectra (paper II) but if part of NGC 5455 is becoming optically thick the contribution of SN 1970g should be increased.

V. Further Remarks Concerning Interpretation of the Observations

The new radio observations described above as well as the optical results that have appeared on SN 1970g since the paper by Goss *et al.* (1973) (Barbon *et al.*, 1973; Kirshner *et al.*, 1973; Kirshner and Kwan, 1975) provide new information on the event and permit further examination of the alternative models which were mentioned by Goss *et al.*

The following points can be made:

a) *Time Scale of the Radio Outburst*

The λλ 21 and 49.2 cm data show that the radio emission which has been detected from SN 1970g at an age > 1 year is not due to a short burst or radio flare, but rather to some mechanism with a time scale of several years.

b) *Uniqueness of* SN 1970g

Evidence in favor of the statement that the optical emission of SN 1970g is not unusual for type II SN is available from the comparison of its light curve and spectrum with those of other type II SN (Ciatti *et al.*, 1971; Barbon *et al.*, 1973) and in particular its similarity in physical properties to SN 1969l in NGC 1058 (Kirshner *et al.*, Kirshner and Kwan). What about the radio emission? Attempts to detect radio emission from other extragalactic type II SN have been unsuccesfully made by de Bruyn (1973). He provides useful upper limits for about a dozen of them; in particular for the closely-similar SN 1969l, he obtains a limit at λ 21 cm of 2 mJy at an age of 1.5 years. Using a distance of 12 Mpc for NGC 1058 and 7 Mpc for M 101 leads to similar optical magnitudes at maximum light for the two SN, and would imply a λ 21 cm flux density < 6 mJy for SN 1969*l* at the latter distance. This is just the level of the detected emission of SN 1970g at the same age. Other young SN observed by de Bruyn (1973) generally emit <3 to 5 mJy (normalized to 7 Mpc) at λ 21 cm at ages from 3 to 35 years. The positive detection of SN 1970g reported here is therefore not in contradiction with de Bruyn's upper limits.

c) Implications for Models of Supernova Radio Outbursts

The phenomena we seek to explain are the following:

— The radio emission appears at centimeter wavelengths about half a year to one year after maximum light.

— At λ 21 cm the radio power spectral density reaches a value of about 2.8×10^{18} W Hz^{-1} sterad^{-1} (6 mJy at 7 Mpc) at an age of 1.4 years, and is still at about that level at an age of 3.4 years. This corresponds to about ten times the present power output of Cas A. By an age of 4.2 years the emission has declined to less than about 1×10^{18} W Hz^{-1} sterad^{-1}.

— The emitted radio spectrum is almost certainly non-thermal.

— The brightness temperature at λ 21 cm at an age of 1.4 years is at least 10^7 K (for the case that the radio source would have expanded at the speed of light).

— The highest intensity appears similar at $\lambda\lambda_{11}$, 21 and 49.2 cm.

— The data give some indication that the peak arrives later and lasts longer at longer wavelengths.

In Goss *et al.* (1973) we made a division into two classes of models for the origin of the radio emission. In the first class, the emission is generated within a volume bounded by the ejected material that gives rise to the optical emission; in the second class of models the emission comes from the edge of the envelope (if such a boundary really exists) or even further out. The present data do not yet allow a choice to be made between the two kinds of models. For the "outside" model an important constraint seems to be the fact that the emission appears at least half a year after the explosion.

We will now elaborate in some detail on the "inside" model. The justification for this is that several authors (Ostriker and Gunn, 1971; Pacini and Salvati, 1973) have predicted large non-thermal luminosities from young type II supernovae. Their results are based on the association of type II SN with pulsars, i.e. energetic neutron stars. The "inside" model also leads to some interesting speculations about the structure of the envelope. As was mentioned in Goss *et al.* and de Bruyn (1973), the envelope is expected to remain optically thick at radio wavelengths for a period much longer than one year. The optical results of Kirshner *et al.* support this conjecture; from the observed Hα luminosity of SN 1970g in April 1971 as determined from the spectral scan in their Fig. 3, we derive a free-free optical depth at λ 11 cm of at least 10^4! This is for the line-emitting region only, the "reversing layer" in the notation of Kirshner *et al.*; the smeared-out electron density is of the order of 10^7 cm^{-3}. Since the first radio emission was detected in April 1971 by Gottesman *et al.*, we must conclude that the "inside" model is tenable only if the largest fraction of the gas is in filaments which shield only a small fraction of the radio-emitting volume. Note that the filamentary structure in the Crab Nebula satisfies this criterion. We depart from our previous suggestion that a uniform envelope is at a temperature of 10^7 K or more (thereby decreasing the free-free optical depth to less than unity), since the optical data of Kirshner *et al.* and Barbon *et al.* suggest a temperature near 10^4 K about one year after maximum light.

Is there any evidence in the optical data that the envelope has a filamentary structure? Kirshner *et al.* report that they have detected emission from what is probably [O I] (and perhaps also [Ca II]). These forbidden lines can only be produced in strength in a partially neutral gas where the electron density is low ($\lesssim10^5$ cm^{-3}). Since the lines existed at a time when the minimum electron density in the Hα-eming region was about 10^7 cm^{-3}, it appears that there is good observational evidence that density fluctuations did indeed exist. Perhaps the [O I] and [Ca II] lines originated in the partially-neutral cores of dense filaments as seems to be the case in the Crab Nebula (Davidson, 1973; Davidson *et al.*, 1974). It is important to determine whether these lines indeed arise in the same volume as the Hα line; this could be determined by high-spectral-resolution studies of all these lines in a future supernova. The development of these lines in type II SN should be followed to establish whether their appearance really coincides with that of the radio emission. Further theoretical work is also needed in order to determine the conditions under which filaments can form in such a young expanding supernova shell.

If SN 1970g at an age of a few years bears any resemblance to a miniature version of the Crab Nebula, with an internal pulsar energy source, it is useful to make a comparison of the relativistic energy content of both nebulae. Synchrotron equipartition calculations, done for an age of 1.5 years (radius $\approx5\times10^{16}$ cm), result in an energy content of a few times 10^{46} erg (2×10^{48} erg for the Crab Nebula) and a magnetic field strength of about 10^{-2} Gauss (a few times 10^{-4} Gauss for the Crab Nebula). The total energy estimate is a lower limit, and there are several plausible ways of increasing this number. The synchrotron model for the radio source also suggests another cause of the observed increase in radio emission at $\lambda\lambda$ 11 and 21 cm at an age between half and one year; this is related to the fact that synchrotron self-absorption within the source sets an upper limit to the emission for a given magnetic field strength, frequency and age. A straightforward calculation shows that an age of 1.5 years the synchrotron self-absorption turnover in the spectrum should lie near 600 MHz. This frequency scales with age according to well known formulae (e.g. van der Laan, 1966) and depends somewhat on the details of the source evolution. We estimate that the turnover at λ 21 cm would occur at an age of about 0.5 to 1 year. This picture is consistent with the known characteristics of the observations mentioned at the beginning of this section. Simultaneous observations of future SN at several frequencies with good signal-to noise ratio are needed in order to choose between free-free absorption and synchrotron self-absorption as being the cause of the sudden increase in the radio emission.

d) The Future of SN 1970g

What can be said about the future radio evolution of SN 1970g? Since the supernova exploded in the outer parts of a fairly dense H II complex we may expect that after about a hundred years the expanding envelope will be significantly decelerated. Models such as that by Gull (1973) then predict a sudden increase in the radio luminosity when the ratio of swept-up mass to ejected mass is of order 0.3. The radio luminosity then falls roughly as $t^{-1.7}$. According to Gull's model, equating the swept-up mass to 0.3 of the ejected mass M_e gives a time scale for turn-on of

$$t_{\max} = \frac{200}{V_e}\left[\frac{0.3 M_e}{\varrho_i}\right]^{1/3} \text{ years},$$

with V_e the average ejection velocity in 10^4 km s^{-1}, M_e the ejected mass in $M_\odot$, and ϱ_i the average number density of hydrogen atoms in the ambient interstellar gas. Values for these parameters are, of course, very uncertain. Assuming $V_e = 10^4$ km s^{-1}, $\varrho_i = 1$ cm^{-3} and $M_e = 1 M_\odot$ gives $t_{\max} \approx 135$ years, although an uncertainty of a factor 3 either way must be admitted. Taking this time scale at face value, one could scale the present flux density of e.g. Cas A to find that the maximum radio flux density of SN 1970g would be of order 1 mJy at λ 21 cm. It is reasonable to expect that, by that time, radio telescopes of sufficient sensitivity will exist to study the time evolution of the radio emission in detail.

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