favored by reduced replication at the semipermissive temperature and that there is more episomal DNA in pSV2-gpt transformed COS ts2 cells held at 37° than at 40°C. The potential to modulate copy number by temperature shift might be particularly useful for the isolation of transformed cells designed to overproduce toxic products. In principle, the copy number of the transfected gene could be kept low during maintenance and passage of these cells and then amplified thousands of times (*6*) by shifting to the permissive temperature to induce replication and overproduction.

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RESEARCH ARTICLE

Discovery of New Variable Radio Sources in the Nucleus of the Nearby Galaxy Messier 82

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There is growing evidence that short-lived periods of very large energy release in galaxies are due to intense bursts of star formation. Such bursts, whose intensity far exceeds that found in our own Galaxy, are thought to involve very massive stars which end as supernovae. Observations with the National Radio Astronomy Observatory's (NRAO's) Very Large Array (VLA) in New Mexico by Kronberg *et al.* (*1*) have revealed about 40 discrete radio sources in the inner, visually obscured nucleus of the enigmatic galaxy Messier 82 (M82). These radio sources, more luminous than any comparable objects in our Galaxy, are candidates for the supposed supernovae associated with the starburst source of energy.

A radio photograph of the 4.87-GHz map made in February 1981 with a resolution of 0.34 arc second is shown in Fig. 1. None of the myriad of radio sources has been optically identified because of the high visual extinction in M82's nucleus. However, the similarity of their radio luminosities to those of recently discovered extragalactic radio supernovae (*2*) strongly suggests that we are seeing an entire dynamic population of radio sources arising from supernovae associated with an intense burst of massive star formation in M82's nucleus.

Observations. It is well established that the brightest of the M82 nuclear sources, 41.9+58, has been declining in flux density since at least the early 1970's (*3, 4*). In doing so, it has maintained a nearly constant spectral index ($\approx$0.9) in the optically thin part of its spectrum above 1 GHz.

Since the February 1981 observations, we have done repeated, multifrequency mapping of M82 with the VLA in order to search for time variability in this large, concentrated population of presumed radio supernovae and supernova remnants. Messier 82 was mapped at 4.87 GHz (wavelength λ = 6 cm) in April, May, and June 1982 and again in August and October 1983, thus covering a time span of 2.7 years at the same resolution and sensitivity. Measurements have also been made at 1.4, 15, and 23 GHz for some of the above epochs, but they are, so far, less suitable for the purpose of studying variability than the more complete 4.87-GHz measurements.

Calibration and errors. The flux density scale of all observations is relative to the strong radio source 3C286, whose brightness is accurately known. Its adopted integrated (zero-spacing) flux was 7.41 Jy at 4.87 GHz. Each VLA observing run between April 1982 and October 1983 was made within the same 8-hour local sidereal time range, thus giving similar interferometer baseline coverage. Local amplitude and phase calibration in February 1981 was performed via the nearby calibrator 0917+624 (*1*), whose flux density was tied to that of 3C286. In April 1982 and succeeding epochs, the local calibrator was 1044+719.

After applying the external calibrations, self-calibration in phase was used to improve the dynamic range of the

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maps. Interferometer baselines less than 50,000 λ were removed to reduce the effect of large structure. The final maps were then analyzed with NRAO Astronomical Image Processing System (AIPS) routines to obtain best-fit integrated and peak flux density values for all sources which were clearly detectable above the ambient background level and which were either smaller than or comparable to our half-power beam width of 0.34 arc second. (This is 5.3 parsecs at M82 for an adopted distance of 3.2 megaparsecs.) In deriving the flux densities, a best-fit mean and slope of the local background radiation was subtracted from each source flux. In the following analysis we use peak flux densities throughout, since these are less contaminated by the background radiation. Since our sources are unresolved, or nearly so, the peak and integrated fluxes are close. Significantly extended sources (whose integrated flux densities are considerably greater than the peak values) were omitted from the variability analysis, since their integrated flux densities are difficult to accurately separate from the background radio emission in M82.

Three principal sources of error are present in the comparison of flux densities between different epochs. These are (i) the uncertainty in the flux scaling to the primary calibrator source, (ii) the error of fit to the best peak flux, and (iii) the offset error involved in estimating the true background level which was subtracted. The derived flux densities for our calibrators are given in Table 1. The dispersion in the flux of 1044+719 is 2 percent, which can be considered an upper limit to the calibration scale error, since some of this variation may be intrinsic to the source. Also, from other monitoring programs at the VLA, scaling errors of order 2 percent have been achieved in analyses similar to the one we have just described. We thus estimate error component (i) to be 2 percent.

The best objective estimate of error components (ii) and (iii) was obtained from the statistics of flux density differences between the closely spaced epochs, over which genuine flux density variations are assumed to be insignificant. The adopted errors are a quadratic sum of these three error components. In Table 2 we give the flux densities at the beginning and end of the 2.7-year period, along with the percentage change and its error, and corresponding half-lives assuming a simple exponential rate of decay.

The flux densities of progressively fainter sources become proportionately more uncertain owing to the residual lumpy, complex background of continuum radio emission in M82. The latter is more difficult to reproduce in an identical way from session to session. For sources ranging from 2.5 to 1 mJy we would expect fictitious changes in flux due to measurement errors of 8 to ≃30 percent, respectively.

Results and discussion. In Fig. 2 we show flux density–time plots for the ten

Abstract. *Widespread variability has been discovered in a large population of radio sources close to the nucleus of an active galaxy. The galaxy, Messier 82 (M82), and others similar to it show evidence for enhanced nuclear activity and unusually strong far-infrared emission. The observational data, obtained with the National Radio Astronomy Observatory's Very Large Array in New Mexico over the past 3 years, provide the first direct "look" at a starburst—the phenomenon of sudden, rapid star formation which occurs near the nucleus of a small fraction of galaxies. Nearly all the brightest of about 40 radio sources in M82's nucleus decreased in intensity over 2.7 years up to October 1983. One source, which in February 1981 was ten times as bright as our Galaxy's most luminous supernova remnant, turned off within only a few months. Most of the other ten strongest sources are declining so rapidly that they will fade into the background within 30 years. Thus, new supernovae are expected to appear in M82's nucleus every few years. The discovery has revealed the "engine room" of the mysterious activity in M82 and, by implication, similar active galaxies which have disturbed nuclei and which are unusually luminous in the far infrared. An estimate of the rate of energy input by the radio-visible supernovae closely matches the far-infrared luminosities which were recently measured for M82 and other similar galaxies.*

Table 1. Calibrator flux densities relative to 3C286 (flux density = 7.41 Jy at λ = 6 cm).

Calibration source	Date	Flux density (Jy)	
0917+6250	February 1981	1.322	
1044+7119	April 1982	0.913	
	May 1982	0.938	S = 0.934 Jy*
	June 1982	0.920	σ = 0.019 Jy†
	August 1983	0.961	
	October 1983	0.938	

*Mean flux density. †Standard error.

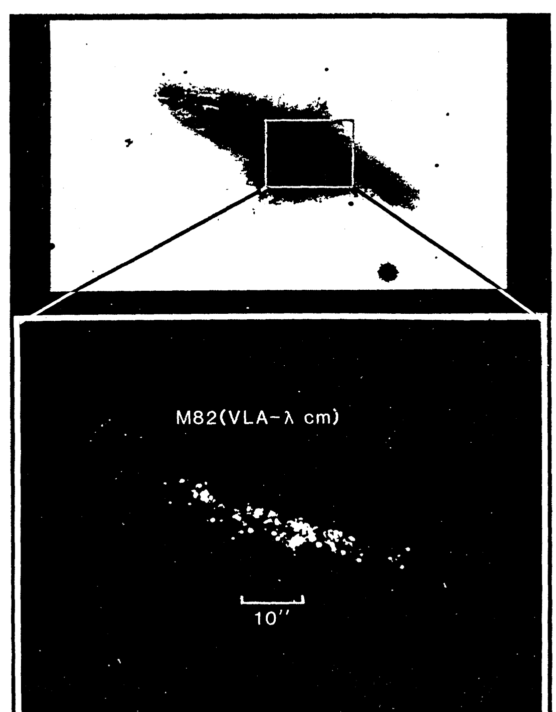

Fig. 1. VLA map of M82 at 4.87 GHz (λ = 6 cm) with a resolution of 0.34 arc second as observed by Kronberg *et al.* (*1*), shown in relation to the optical image of the galaxy.

sources which were stronger than 2.5 mJy in February 1981. The sources are labeled with a nomenclature which gives their positions, and they are indicated on the contour map in Fig. 3. With the possible exceptions of 41.3+596 and 45.7+652, all have decreased with varying half-lives which are less than ~20 years. We now describe the results in more detail.

The brightest source, 41.9+58. This source has decreased monotonically at an average rate of 9 percent per year at 5 GHz from 1981.1 to 1983.8. This agrees very well with the average rate of decrease at 6 cm, for which we have records beginning with Hargrave's (*5*) measurement in 1973.6 (Fig. 3). The agreement in rate of decrease of 41.9+58 in our present data with all previous data above ≈2 GHz gives further confidence to our flux density calibration and hence the variability estimates for other sources having flux densities well above the noise and diffuse radio background levels.

Table 2. Comparison of the October 1983 5-GHz flux densities with those in February 1981 from Kronberg *et al.* (*1*) for the ten brightest sources in February 1981.

Source name	Flux density in February 1981 (Jy)	Flux density in October 1983 (Jy)	Change (%)	Approximate half-life* (years)
39.1+573	4.30 ± 0.22	3.50 ± 0.21	−18.6 ± 7.9	9
40.7+550	7.39 ± 0.25	6.75 ± 0.24	−8.7 ± 4.9	21
41.3+596	3.28 ± 0.21	3.11 ± 0.21	−5.2 ± 9.3	35
41.5+597	7.07 ± 0.24	<1.5		
41.9+58	108.54 ± 2.18	79.49 ± 1.60	−26.8 ± 2.8	6
43.2+583	5.18 ± 0.23	4.12 ± 0.22	−20.5 ± 6.9	8
43.3+591	10.92 ± 0.30	9.56 ± 0.28	−12.4 ± 4.0	14
44.0+595	24.22 ± 0.52	21.22 ± 0.47	−12.4 ± 3.1	14
45.2+612	7.52 ± 0.25	6.52 ± 0.24	−13.3 ± 5.0	13
45.7+652	2.55 ± 0.21	2.26 ± 0.21	−11.4 ± 12.4	16

*This assumes a precisely exponential luminosity decay law. Corresponding errors are not given since there is as yet no evidence for the form of the luminosity decay law.

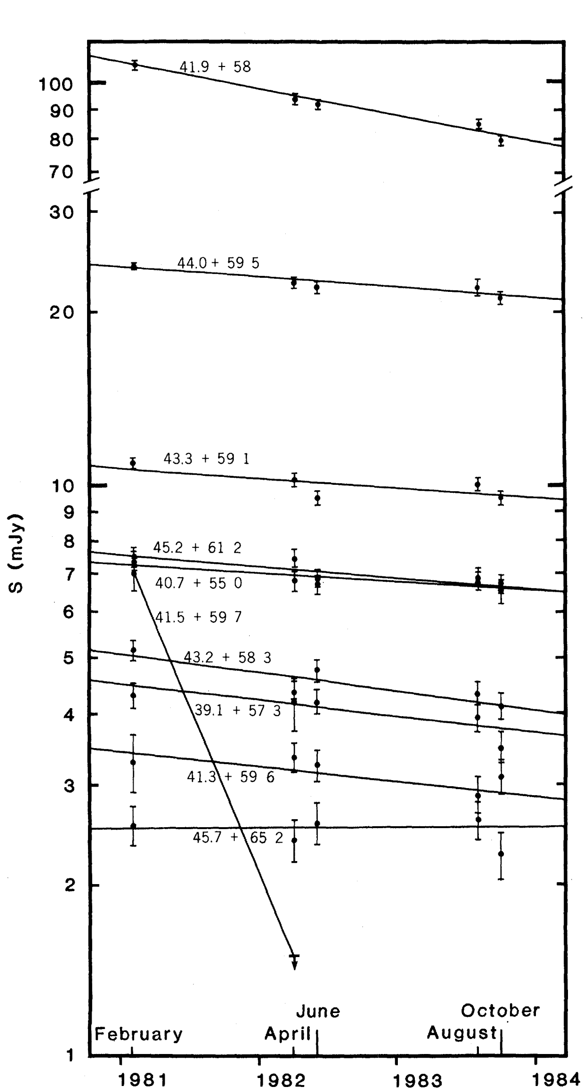

Fig. 2. Plots of flux density (*S*) against time for the ten M82 sources which were stronger than 2.5 mJy in February 1981, as measured between February 1981 and October 1983. For each source a least-squares straight-line best fit is shown.

Discovery of a "rapid turnoff" source, 41.5+597. The most dramatic change has occurred for source 41.5+597, which in February 1981 was the sixth brightest source at 7.1 mJy. Fourteen months later, and in all subsequent sessions, it was less than 1.5 mJy. It had a spectral index of −1.1 in February 1981 and was unresolved at both 4.9 and 15 GHz, which gives a firm size upper limit of 0.15 arc second. It is clear that the flux density variation of this source is distinct from all the others, which suggests that it arises in a different kind of object.

It is interesting to compare 41.5+597 in M82 with the Type I supernova observed in 1983 in the radio by Sramek *et al.* (*6*). This object, SN 1983.51 in M83, had a peak radio luminosity of 10^{20} W Hz^{-1}, compared with our value of 1.1×10^{19} measured for 41.5+597 in February 1981. Also, Sramek *et al.* found SN 1983.51 to have a decay time of less than 100 days, which makes its behavior consistent with 41.5+597 in M82. As noted above, the spectral index between 5 and 15 GHz of 41.5+597 in February 1981 was −1.1 (*1*), which is very close to the value of −1.0 obtained by Sramek *et al.* for SN 1983.51. If 41.5+597 is also a similar Type I supernova, then the February 1981 observing session was very close in time to the supernova event.

Search for variability among the remaining sources brighter than 2.5 mJy in February 1981. Figure 2 shows that the flux densities of nearly all the discrete sources stronger than 2.5 mJy decreased between 1981.1 and 1983.8. Of the ten sources which had $S > 2.5$ mJy in February 1981, we find that at least eight showed a systematic decrease in their flux density at $\lambda = 6$ cm between 1981.1 and 1983.8. This result indicates that the brightest population members are evolving on a remarkably short time scale. Thus, new radio sources should appear on comparable time scales, and our VLA observations are continuing with this expectation. More important, this phenomenon of rapid variability affords us the first opportunity of directly estimating the rate of energy input to the interstellar medium of an active galaxy.

Summary and conclusions. We have discovered that virtually all of the brightest radio sources in M82 are decreasing in luminosity on the remarkably short time scale of a few years. At the current rates of decrease, eight of the ten brightest sources in Fig. 1 which were brighter than 2.5 mJy in early 1981 will be fainter than this level in less than ~35 years.

At least one source, 41.5+597, has a remarkably fast decay time of less than 1 year, whereas another, comparably bright one, 41.3+596, has been uncommonly stable over the 2.7-year period. These facts reveal that individual variability characteristics and perhaps even the peak radio luminosities within our population can be widely different, and any modeling of this dynamically evolving population must account for this fact.

To maintain such a rapidly decreasing population of luminous sources, our results require a refreshment rate of one new radio source every few years. Our preliminary estimate (which depends on the form of the luminosity decay) requires a new supernova every 3 to 5 years. The very rapid decay of source 41.5+597 strongly suggests that its first observation in February 1981 was very close to the supernova outburst. This rate could be even higher if "rapid turn-off" sources such as 41.5+597 are a very frequent event—that is, more frequent than every ~3 years. In order to "catch" sources such as 41.5+597, a monitoring interval is needed which is less than their typical half-life—that is, a few months. Because our monitoring interval has generally been much less frequent, we cannot yet estimate the frequency of the very fast sources like 41.5+597.

Thus, our discovery of rapid flux decay provides an opportunity to directly measure the energy input to the optically obscured nucleus of a galaxy which is undergoing an active starburst phase. Assuming that each supernova releases 10^{51} ergs (the canonical energy of a supernova), our experimental results for M82 give a rate of energy release of $\sim 10^{43}$ erg sec^{-1}. This number could be significantly increased if fast decayers such as 41.5+597 are frequent and are also supernovae (see above). This is

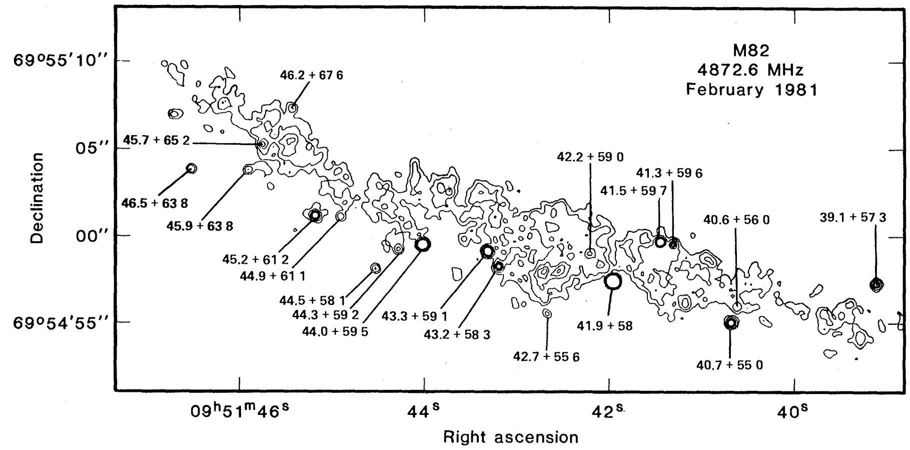

Fig. 3. Radio contour version of the VLA 6-cm map shown in Fig. 1, showing the positions of the ten brightest sources plotted in Fig. 2. A more complete list of 32 sources and their flux densities is given in Kronberg *et al.* (*1*).

close to the total far-infrared excess luminosity of M82, which is $\approx 6 \times 10^{43}$ erg sec^{-1} (*7*).

We can therefore conclude that, to the accuracy of the energy input estimates currently possible, supernovae are sufficient to explain the "excess" power source in M82. Since the Infrared Astronomy Satellite (IRAS) has recently shown many other radio-enhanced galaxies to have strong infrared excess emission like that of M82, our results suggest that we have isolated the "engine room" of starburst galaxies in general. In particular, it seems that it is not necessary to invoke a single supermassive star or a gravitationally collapsed object to explain the large energy input in galaxies like M82. Rather, "conventional" supernovae occurring in a sufficiently intense starburst scenario are sufficiently frequent to provide the power source.

The rate of supernova production in the inner nucleus of M82 is approximately 50 times higher than that for the entire disk of our Galaxy, whose linear dimensions are 30 times as large. Also, the 19 brightest radio sources in M82 range from twice to 150 times the radio luminosity of Cassiopeia A, the most luminous single radio source in the Milky Way.

Our radio monitoring of M82 supernovae with the VLA is continuing. We expect that a new supernova of the more "slowly" decaying type—that is, with a half-life up to a few decades—should appear within the next few years. Because of the very large opacity of M82 in optical bands, it will probably not be visible optically. However, it should be detectable at infrared wavelengths longer than about 1.5 μm.

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