

To Roger — who's music is still thrilling, 37  
years later. With much appreciation,  
Eugene

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QUASI-STELLAR RADIO SOURCES: 88-GHz FLUX MEASUREMENTS\*

RONALD A. SCHORN

Jet Propulsion Laboratory, Pasadena, California

EUGENE E. EPSTEIN, JOHN P. OLIVER,† AND STEVEN L. SOTER‡

Aerospace Corporation, El Segundo, California

AND

WILLIAM J. WILSON§

Space Systems Division, United States Air Force, El Segundo, California

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ABSTRACT

The flat or turned-up nature of the high-frequency spectra of a number of QSS and related objects has been confirmed by measurements at 88 GHz (3.4 mm). "Light" curves are presented for 3C 273 and 3C 279. The 3.4-mm flux variations of 3C 273 are substantially larger than those observed at longer wavelengths. 3C 84 and the QSS 3C 345, 3C 446, 3C 454.3, and 4C 39.25 have also been detected, but CTA 102 has not. The Seyfert galaxies NGC 1068, NGC 4151, and 4C 05.20 have been observed; NGC 1068 and 4C 05.20 were detected, but NGC 4151 was not.

To extend to very high frequencies the microwave spectra of quasi-stellar radio sources (QSS) and to search for variations in their radio emission, we have been making observations since April, 1965 (Epstein 1965; Epstein, Oliver, and Schorn 1966; Schorn, Epstein, Oliver, Soter, and Wilson 1967), at 88 GHz (3.4 mm) with the 15-foot antenna of the Space Radio Systems Facility of Aerospace Corporation. We used our standard dual-beam observing procedure (Epstein 1967). We have discussed elsewhere the calibration procedures and the technique for correcting the daytime observations for atmospheric attenuation (Epstein, Oliver, Soter, Schorn, and Wilson 1968). The nighttime attenuation corrections were made with the aid of radiosonde measurements of precipitable water vapor and an empirical relationship (determined from a year of daytime data) between radiosonde-determined values of precipitable water vapor and the attenuation determined from solar observations. Attenuation correction factors ranged from 1.2 to 1.6, the higher values occurring during the summer months.

The crystal-mixer receiver, with an RC time constant of 1 sec and an IF band width of 1.5 GHz, had output rms noise fluctuations of  $\sim 2^\circ$  K. (Due to improvements in the receiver and the conversion of the crystal mixer, these fluctuations were decreased to  $\sim 0.4^\circ$  K during the spring of 1967.) The 3.4-mm antenna temperatures of the QSS are  $\leq 0.1^\circ$  K—i.e., quite weak relative to the receiver noise. (An antenna temperature of  $0.1^\circ$  K corresponds to  $\sim 40$  flux units.) Hence we have had to integrate for  $\sim 15$  hr to achieve signal-to-noise ratios of even a few to one. At 3 mm there are no relatively strong point sources, so we are unable to make our measurements as ratios to some standard source (as is done at longer wavelengths). Consequently, our measurements are absolute ones. Therefore, we perform the following checks.

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† Also at the University of California, Los Angeles.

‡ Now at the Center for Radio Physics and Space Research, Cornell University, Ithaca.

§ Now at Massachusetts Institute of Technology, Cambridge.

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P.C.S. It's too bad we couldn't confirm or negate your speculation on CTA 102!

1. Each set of data is broken down into 23.5-min samples. The antenna temperatures recorded during the samples are plotted as a histogram. We verify that the histogram resembles a Gaussian distribution and that the histogram width is consistent with the radiometer's short-term noise fluctuations.

2. To assure that our dual-beam observing procedure yields no systematic bias, we make observations every few months of "blank" sky (directions in which there are no known radio sources). These tests have always resulted in measured signals within 1.5 standard errors of zero.

3. To check over-all system performance, we observe Saturn frequently. This planet has a 3.4-mm antenna temperature of  $\sim 0.3^\circ$  K. Figure 1 shows our results. We have assumed that Saturn's 3-mm brightness temperature is constant and that the rings (which were nearly edge-on during 1965-1967) made a negligible contribution to the measured signal. There is no systematic trend in the values, and the scatter among the values is consistent with the estimated standard errors. These facts indicate that our

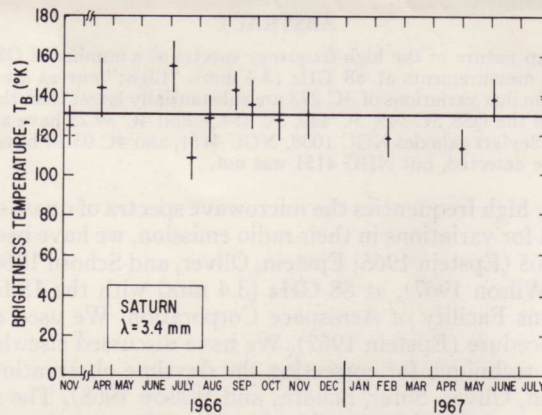


FIG. 1.—The 3.4-mm brightness temperatures of Saturn versus time. The vertical bars are statistical standard errors. The short horizontal bars indicate the time interval during which the measurements were made. There is no systematic trend in the brightness-temperature values, and the scatter among them is consistent with the errors. These facts indicate that the long-term calibration, atmospheric attenuation correction, error estimation, and observing procedures are satisfactory.

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Another obvious check is to observe sources whose 3-mm fluxes can be predicted with reasonable confidence. Cygnus A and Virgo A are two such sources, and our measured fluxes agree with the values extrapolated from the long-wavelength data (see Fig. 2).

Figures 3 and 4 present 88-GHz "light" curves for 3C 273 and 3C 279. 3C 273 shows definite flux variations of a factor of  $\sim 2$  in times on the order of months. Comparison with the 19.6-mm "light" curve (not illustrated here) of Kellermann and Pauliny-Toth (1967) shows that the relationship between the 19.6-mm and 3.4-mm light curves is ambiguous. It is hard to say, for example, whether the curves both show a maximum at about the same time in 1966, whether they show maxima displaced slightly in time, or whether the different curves illustrate different phenomena. It is clear, however, that the 3.4-mm variations are larger than the 19.6-mm variations, and that the two curves are roughly similar in shape. Due to a current lack of optical data, we have not been able to correlate our observations with optical-brightness variations. Although the size of

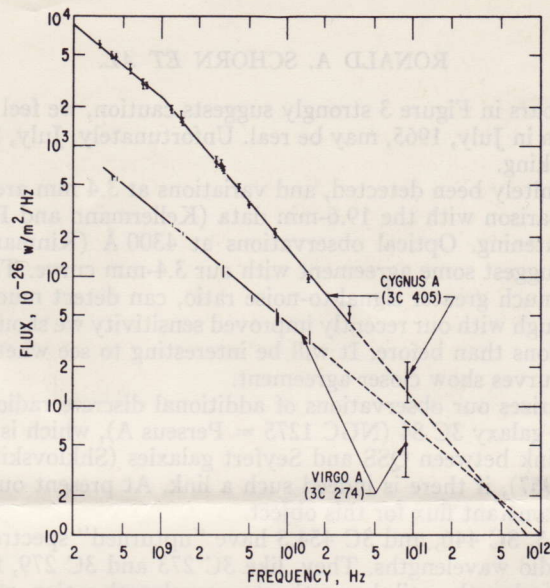


FIG. 2.—Radio spectra of Cygnus A and Virgo A. The long-wavelength data for Cygnus A are from Schraml and Turlo (1967), and those for Virgo A are from Baars, Mezger, and Wendker (1965).

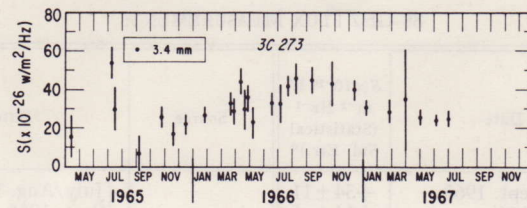


FIG. 3.—The 3.4-mm flux of 3C 273 versus time. The statistical standard errors are shown; the estimated total-system calibration errors are  $\sim 10$  per cent. Each point represents  $\sim 15$  hr of observing time; the very large error for the March, 1967, point is due to the fact that much less than 15 hr of data were taken.

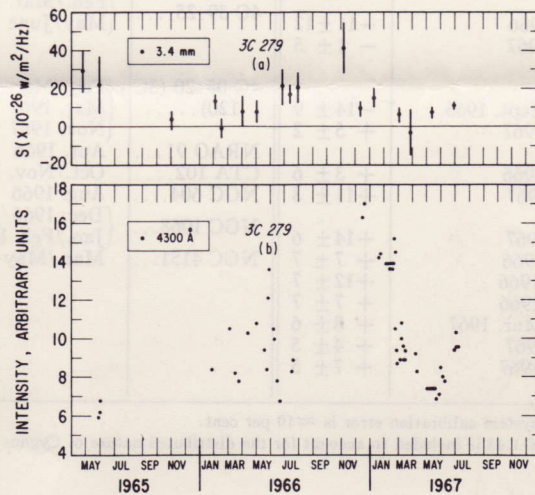


FIG. 4.—(a) The 3.4-mm flux of 3C 279 versus time. The statistical standard errors are shown; the estimated total-system calibration errors are  $\sim 10$  per cent. Each point represents  $\sim 15$  hr of observing time; the very large error for the March, 1967, point is due to the fact that much less than 15 hr of data were taken. (b) 4300 Å light curve of 3C 279.

the 3.4-mm error bars in Figure 3 strongly suggests caution, we feel that the large and rapid flux variation in July, 1965, may be real. Unfortunately, July, 1965, data at other frequencies are lacking.

3C 279 has definitely been detected, and variations at 3.4 mm are indicated, though not certain. Comparison with the 19.6-mm data (Kellermann and Pauliny-Toth 1967) is not very enlightening. Optical observations at 4300 Å (Kinman 1967), shown in Figure 4, faintly suggest some agreement with our 3.4-mm curve. The optical observations, because of much greater signal-to-noise ratio, can detect much faster variations than we can, although with our recently improved sensitivity we should be able to detect more rapid variations than before. It will be interesting to see whether future 3.4-mm and optical light curves show closer agreement.

Table 1 summarizes our observations of additional discrete radio sources. We have detected the radio galaxy 3C 84 (NGC 1275 = Perseus A), which is a prime candidate for a connecting link between QSS and Seyfert galaxies (Shklovskii 1965; Pacholczyk and Wisniewski 1967), if there is indeed such a link. At present our 3.4-mm data are consistent with a constant flux for this object.

The QSS 3C 345, 3C 446, and 3C 454.3 have "upturned" spectra (positive spectral index) at short radio wavelengths. They, like 3C 273 and 3C 279, fall off in intensity with decreasing wavelength until the centimeter wavelength region, where their intensity levels off or actually increases. We have detected all three of them. Observations at

TABLE 1  
88-GHZ FLUX MEASUREMENTS

Source	Date	$S \times 10^{-26}$ W $m^{-2} Hz^{-1}$ (Statistical Std. Err.)*	Source	Date	$S \times 10^{-26}$ W $m^{-2} Hz^{-1}$ (Statistical Std. Err.)*
3C 84.....	{Aug./Sept. 1965	+34 ± 11	3C 454.3....	{July/Aug. 1966	+12 ± 8
	Mar. 1966	+14 ± 5		Sept. 1966	+ 8 ± 8
	July/Aug. 1966	+28 ± 7		Nov. 1966	+46 ± 18
	Aug./Sept. 1966	+27 ± 7		Dec. 1966	+18 ± 6
	Oct. 1966	+16 ± 6		Jan. 1967	+20 ± 3
	Feb. 1967	+23 ± 5		June/July 1967	+15 ± 3
	June/July 1967	+23 ± 3		{Oct. 1967	+11 ± 6
3C 196.....	{Oct. 1966	-11 ± 12	4C 39.25....	{Feb./Mar. 1967	+10 ± 4
	Feb. 1967	- 1 ± 5		{May/June 1967	+ 6 ± 2
C3 274 (Vir A).....	{Aug./Sept. 1965	-14 ± 9	4C 05.20 (3C 120).....	{Feb./Mar. 1967	+11 ± 4
	June 1967	+ 5 ± 2		Mar. 1967	+16 ± 5
3C 345.....	{June 1966	+ 3 ± 6	NRAO 91....	Nov. 1967	+13 ± 9
	July 1967	+11 ± 3	CTA 102....	Apr. 1966	-10 ± 10
3C 405† (Cyg A).....	July 1967	+14 ± 6	NGC 1068....	Oct./Nov. 1965	+ 1 ± 5
	{Aug. 1966	+ 7 ± 7	NGC 4151....	Aug. 1966	- 9 ± 7
3C 446.....	Sept. 1966	+12 ± 7	NGC 1068....	{Dec. 1966/Jan. 1967	+11 ± 4
	Nov. 1966	+ 7 ± 7		{Jan./Feb. 1967	+ 8 ± 4
	Feb./Mar. 1967	+ 8 ± 6		Mar./May 1967	+ 0 ± 3
	July 1967	+ 4 ± 5			
	Nov. 1967	+ 7 ± 5			

\* The estimated total-system calibration error is  $\approx 10$  per cent.

† A correction factor of 1.43 is included to account for the distributed nature of Cygnus A.

19.6 mm (Kellermann and Pauliny-Toth 1967) indicate that 3C 454.3 has increased slowly in intensity during 1966–1967. The 3.4-mm data also suggest a “brightening,” but the evidence is far from conclusive.

We have detected one other QSS, 4C 39.25, which also shows an upturned spectrum. Similarly, the radio source NRAO 91 has a positive spectral index at short wavelengths but, up to the present, has been below our threshold for detection. The spectrum of CTA 102 falls off rapidly, giving no indication of an upturn at short wavelengths. As might be expected in this case, we have been unable to detect it; therefore we are unable to comment upon the discussion by McGuinn, Clark, Crosby, Clarke, and Hillman (private communication).

A number of observations of the Seyfert galaxies NGC 1068, NGC 4151, and 4C 05.20 (Sargent 1967) have been made. NGC 1068 and 4C 05.20 have been detected, while NGC 4151 has not. Shklovskii (1965) and Pacholczyk and Wisniewski (1967) have suggested that objects such as these are the “burnt-out” remnants of QSS. Our 3.4-mm observations are consistent with this suggestion but, of course, do not prove it.

On the basis of all our results, it appears that we are on the verge of making some most interesting correlations. So far we have detected only objects with turned-up spectra. An increasing number of these objects are being identified at centimeter wavelengths, making available a wider selection of objects for study at 3 mm, where radio variability seems more pronounced. Further simultaneous and frequent observations should provide powerful constraints on models of quasi-stellar radio sources.

The continued improvements in our observing system, and its efficient operation during these years of observing, have been the work of G. Berry, T. Mori, and W. Johnson. Drs. M. McColl and M. Millea developed the low-conversion-loss crystal mixers in use since May, 1967. Detachment 50, 6th Weather Wing, U.S. Air Force Air Weather Service, kindly provided the precipitable water-vapor values.

*Note added December 13, 1967.*—In November, 1967, the signal strength of 3C 273 had changed to  $+41 \pm 8$  flux units.

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