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A VLA SEARCH FOR THE OHIO STATE "WOW"

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ABSTRACT

In 1977 a search for extraterrestrial intelligence at the Ohio State University Radio Observatory recorded a strong, narrowband, and apparently intermittent emission near the 21 cm hydrogen line. The detection displayed the antenna pattern signature of a transiting celestial radio source but was not repeated in subsequent transit observations. The event has been advanced by some as a candidate interstellar signal and dismissed by others as probable interference; no independent attempt to replicate the event with a spectral resolution comparable to Ohio State's has been reported. We used the Very Large Array to search for a possible underlying source—artificial or natural—which could account for the detection by occasionally brightening because of scintillation, intrinsic variability, or some other mechanism. With a sensitivity greater than 100 times the original observations, we found two continuum sources within the Ohio State coordinate error boxes, but they displayed no unusual spectral features, showed no sign of flux variability, yielded normal spectral indices based on additional observations at 6 cm, and were too weak to account for the Ohio State detection. No narrow-bandwidth point sources were detected over a band of 1.5 MHz to a flux limit of about 20 mJy at the nominal coordinates. We conclude that the "Wow" was not due to a continuous source usually below Ohio State's several jansky detection threshold but occasionally increasing in flux by a factor of less than ~100. Our search does not significantly constrain the possibility of intermittent sources because we dwelled for only 5–22 minutes per field.

Subject headings: extraterrestrial intelligence — radio lines: general

1. INTRODUCTION

On 1977 August 15 a search for extraterrestrial intelligence (SETI) at Ohio State University recorded a strong (30 σ), narrowband (≤ 10 kHz), and apparently intermittent emission near the 21 cm H I line (Kraus 1979). The detection persisted for six integration periods totaling 72 s and displayed the characteristic antenna pattern signature of a transiting radio source, although in just one of two beams, suggesting that it may have been intermittent or variable. Its frequency was reported as 1420.356 ± 0.005 MHz (J. D. Kraus 1990, private communication) and in a subsequent analysis given as 100 kHz higher (Ehman 1998)—in either case near the 1420.405 MHz frequency of the H I emission line corrected to the local standard of rest, a frequency that has been suggested for interstellar signaling (Cocconi & Morrison 1959; Drake & Sagan 1973). The narrow bandwidth, match to the antenna pattern, and high intensity were so suggestive of an interstellar radio signal that one of the project scientists wrote "Wow!" on the printed record, which has become a name for the event.

The apparent coordinates of the emission were R.A. = $19^{\mathrm{h}}22^{\mathrm{m}}22^{\mathrm{s}}$ or $19^{\mathrm{h}}25^{\mathrm{m}}12^{\mathrm{s}}$ (both $\pm 5^{\mathrm{s}}$), decl. = $-27°03' \pm 20'$ (1950) (J. D. Kraus 1990, private communication); a subsequent review suggested right ascensions 3^{s} and 5^{s} later, respectively, with an uncertainty of $\pm 10^{\mathrm{s}}$ (Ehman 1998). Two right ascensions result from the vertically polarized dual-feed antenna system forming two beams; which beam emission was detected in was not recorded because celestial sources were expected to appear in both beams—first in one, then the other $2^{\mathrm{m}}50^{\mathrm{s}}$ later in right ascension. The fact that the Wow was detected in only one beam could mean that it was not fixed on the sky and thus was likely due to man-made interference. However, the intensity pattern detected in that one beam so closely matched the signature of a transiting celestial source that we consider an alternative explanation for the single-beam detection: that the intensity of a source fixed on the sky varied significantly between beams, perhaps because of interstellar scintillation.

Ohio State made approximately 100 additional transit scans at the same declination over the next few years but did not detect the emission again (Dixon 1985). The subsequent nondetections could, of course, be interpreted as evidence that the original detection was due to man-made interference, but the evidence for a celestial source (discussed in a following section) is quite strong.

1.1. *Evidence Against a Noise Origin*

The Wow cannot be ascribed to a random noise fluctuation because a single 30 σ noise peak would not be expected in thousands of years at the Ohio State sampling rate and because six consecutive peaks over 5 σ in the same channel and mimicking the antenna pattern cannot be due to noise. Ohio State's 50-channel filter-bank receiver produced 50 samples every 12 s, each sample the average of 10 1 s integrations in a 10 kHz channel, with 2 s for processing (Dixon 1985). The resulting 3.6×10^5 samples day^{-1} would be expected to yield a few peaks over 4 σ each hour and one as high as 5 σ each day in the presence of noise alone, assuming a Gaussian distribution. In contrast, some fast Fourier transform (FFT) spectrometers used in more recent SETI experiments produce $\sim 10^{10}$ samples day^{-1} having an exponential distribution and yield noise peaks as large as 24 σ during 1 day and 30 σ over 1 yr (Colomb et al. 1995).

1.2. *Evidence for a Celestial Origin*

Radio telescopes operating in transit mode provide a strong test for celestial origin because the power received from a point source fixed in the celestial coordinate system varies as the beam of the antenna system sweeps across the source. The resulting intensity curve is characteristic of the antenna system's gain pattern, and the Wow intensities fit a Gaussian model of the Ohio State antenna pattern very well ($r = 0.99$), shown in Figure 1. Only signals entering through the skyward pointing main beams would be expected to display the antenna pattern, ruling out ground-based transmitters.

The observed intensity curve also indicates the length of time taken for a point source to pass through the beam, which depends on antenna beamwidth, cosine of declination, and the sidereal rate. For the Ohio State antenna, the expected duration of a point-source transit is 30 s between half-power points at $\delta = 0^\circ$ and increases to 36 s at the $\delta = -27^\circ$ of the Wow. The 39 s width of the observed intensity curve is consistent with the expected duration for a point source fixed in celestial coordinates at the declination observed, considering the uncertainty in time.

Airborne or orbital vehicles would not in general remain in the beam for a time comparable to a transiting celestial source. Low Earth-orbiting satellites in east-west orbits are ruled out because they would cross the beam ($8'$ half-power beamwidth [HPBW] in right ascension) in only a few seconds, assuming a motion of 4° per minute. A satellite in a polar orbit could conceivably cross the beam on a north-south line (where the beam is elongated to $40'$) with a fortuitous combination of velocity, range, and inclination that might mimic the transit duration of a celestial source. While the possibility of an interference origin cannot be entirely ruled out, it does not appear so likely as to justify dismissing the Ohio State data.

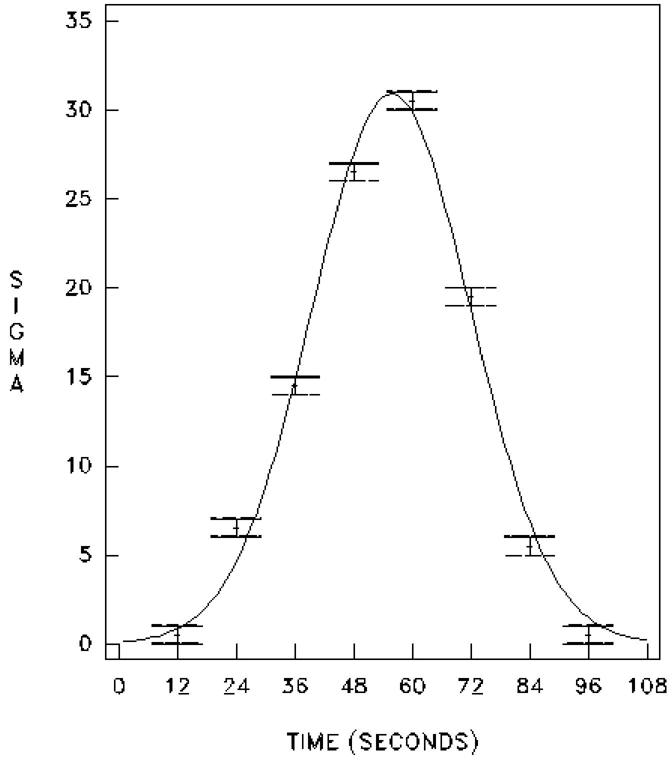

FIG. 1.—Gaussian curve fit to observed intensities of the Ohio State Wow emission. Error bars show the uncertainty in time (± 6 s) and intensity ($\pm 0.5\ \sigma$).

1.3. *Limitations of the Ohio State Telescope*

Ohio State's failure to detect the Wow repeatedly may have been due to limitations of the telescope. One limitation was relatively low sensitivity, about 2×10^{-22} W m^{-2} per channel referenced to a 3.5 σ detection threshold. Reobservations could not rule out an underlying source with a flux less than a few janskys, which might occasionally brighten to produce a detection.

A second limitation was the difficulty of detecting a possibly intermittent or varying source with a fixed transit telescope. The apparent source locale could be viewed for only 144 s day^{-1} (two beams, 72 s full width), and an intermittent or variable source might have been below the detection threshold during the brief time its position was viewed in subsequent transits.

A third limitation was the relatively narrow band (500 kHz) of frequency covered by Ohio State's spectrometer. The Wow was detected in channel 2, near the edge of the band, and it is conceivable that it drifted into or out of the band during the few minutes between the passage of the two beams. That would require a fortuitous frequency drift rate—in the range ± 100–± 150 Hz s^{-1}—but is an alternative explanation for the single-beam detection.

1.4. *Possible Origins*

The Wow frequency was near the 21 cm H I emission line, but there are several reasons to think it was not due to hydrogen. First, the line is usually detected over ~ 100 kHz, yet this emission was not detected in adjacent 10 kHz channels (Ohio State subtracted a running baseline from each channel to remove the effect of such spatially extended sources). Second, H I flux would not be expected to vary on a timescale of minutes to produce the single-beam detection. Intermittent astrophysical radio sources are known but usually vary on a timescale either much shorter than minutes (e.g., pulsars) or much longer and are usually broad band. Relatively narrow spectral features are known (e.g., masers), but not at 21 cm. One goal of our observations was to search for an underlying astrophysical source, normally below Ohio State's detection threshold, which might account for the Ohio State detection by interstellar scintillation (Cordes & Lazio 1991), intrinsic variability, or some other mechanism.

The Ohio State emission had several characteristics that make it seem worth investigating as a candidate interstellar signal as well. First, the ≤ 10 kHz bandwidth is suggestive of radio communication, which often uses essentially monochromatic carriers. Second, radio transmissions can vary in amplitude or switch on and off entirely, which could account for the single-beam detection. Third, there is strong evidence for a celestial origin, and narrow-bandwidth emissions from celestial sources are exactly what many searches for extraterrestrial intelligence seek. A second goal of our observations was to search for an underlying artificial source, possibly enhanced by scintillation to produce the Wow detection.

Interstellar scintillation is known to cause flux variations of a factor of 2 in pulsar observations and has been noted as a possible cause of one-time apparent detections of narrowband signals in SETI (Cordes, Lazio, & Sagan 1997). According to this work, a large scintillation gain (possibly combined with receiver noise fluctuations) could occasionally produce a brief detection of a source normally below the receiver system detection threshold. Since the probability of a large scintillation gain g is extremely low, $\exp(-g)$, the source might not be detected again even with many observations using a telescope of the same sensitivity. Reobserving with greater sensitivity, however, increases the probability of detection dramatically because one need not wait for a statistical peak in scintillation gain. A $\sim$10-fold increase over Ohio State's sensitivity would allow a scintillation hypothesis to be tested decisively, because the probability of such a large scintillation gain is extremely low, less than 10^{-5}.

Scintillation is, of course, not the only mechanism that might account for an interstellar signal being detectable on one occasion and not on others. One might imagine, for example, a highly directional transmission such as radar propagating from the surface of a rotating planet, sweeping across observers periodically—perhaps once each extraterrestrial "day" (Sullivan, Brown, & Wetherill 1978). However, a decisive test of this sort of hypothesis would be difficult without some idea of the period (in this case, the length of the day) and extended observations. A scintillation hypothesis can be tested decisively with the simple expedient of more sensitive observations, which is the strategy we employed.

1.5. *Prior Searches*

In 1987 and 1989 the Harvard/Smithsonian-META system (Horowitz et al. 1986) was used to observe the nominal Ohio State positions for 4 hr periods in a search for extremely narrow bandwidth and possibly intermittent radio signals over several 400 kHz segments of the 21 cm band (Gray 1994). With 0.05 Hz resolution, the 8.4×10^6 channel META spectrometer could detect ultranarrowband radio signals to a limit of 4×10^{-24} W m^{-2} (with a 19.5 σ threshold, which noise peaks exceed only a few times per hour) but would not have detected the Ohio State signal if it had been wider than $\sim$10 Hz or if it had not been Doppler corrected to a constant frequency. No useful bounds were placed on natural sources because the extremely narrow channels were insensitive to normal spectral line and continuum radio sources.

No other searches for the Wow at large radio telescopes appear in a summary of SETI experiments (Tarter 1995).

2. OBSERVATIONS

We searched for evidence of an underlying source of the Ohio State emission using the Very Large Array[1] (VLA) in observing runs in 1995 and 1996. Our observations improve on Ohio State's sensitivity by a factor of greater than 100, offering the prospect of detecting weak underlying sources. Our observations improve on the META search by using channel widths comparable to Ohio State's receiver, eliminating spectrometer resolution as a variable, and by covering the large uncertainty in declination. Our observations improve on all previous work by covering a larger range of frequency and by obtaining much higher spatial resolution.

The full VLA has not previously been used for observations of interest to the SETI community, so a few comments on terminology and suitability are appropriate; theory and methods are discussed elsewhere (e.g., Perley, Schwab, & Bridle 1994). The VLA is a 27-element interferometer that can produce high spatial resolution maps or images of the radio sky. The size of the image is determined by the beamwidth of a single 25 m antenna (30′ at 21 cm), but the spatial resolution is determined by the baselines between antennas, which can range up to tens of kilometers. Our 21 cm observations using the so-called BnA array configuration, for example, covered 1800″ × 1800″ primary fields, which were mapped to 1024 × 1024 pixel images containing $\sim 10^5$ synthesized beams, each with a beamwidth of 3″.9. In spectral line mode, images at many adjacent frequency channels yield a data cube with the dimensions of right ascension, declination, and channel. Data cubes can also be treated as sets of spectra—1024^2 spectra at discrete coordinates in this example, although not all independent.

Synthesis imaging interferometers offer several advantages for SETI purposes. One is that interference maps to a point source only in the direction of the celestial pole—the only point where the time lags at all antennas are all the same. Another advantage, for observations near emission lines, is that the VLA's high spatial resolution configurations are relatively insensitive to large-scale structures such as hydrogen gas. A final advantage is that high spatial resolution allows radio source positions to be matched with optical objects; radio detections coinciding with stellar positions would be potentially interesting, since stars are rarely detectable radio sources (Becker et al. 1996; Wendker 1995). One disadvantage of the VLA for some purposes is limited spectral resolution, but we wished to replicate the Ohio State receiver's 10 kHz resolution, and the VLA's 6.1 and 12.2 kHz spectral line modes were an adequate match. The need to move the array off-source for phase calibration at frequent intervals (<1 hr) would be a disadvantage in a search for intermittent sources, but only continuous sources were within the scope of our investigation.

Observations in 1995 were carried out using the BnA configuration with a spatial resolution of 3″.9. This configuration has the southeast and southwest arms of the array in the B configuration (with a maximum antenna separation of 11.4 km), while the north arm is in the largest A configuration (with baselines up to 36.4 km), and provides a circular synthesized beam for sources where $\delta < -15°$. The observations covered a band of 0.78 MHz with 127 channels and a resolution of 6.1 kHz. Both left- and right-circular polarizations were observed, but only the Stokes I images are discussed throughout this paper. Two fields centered on the nominal Ohio State coordinates were observed for 20 minutes each, with 10 minute integrations made 15′ north and south and 5 minute integrations 30′ north and south, for a total of 10 partly overlapping fields. Observations north and south covered twice the Ohio State declination uncertainty, to include sources outside of the Ohio State declination HPBW.

Observations in 1996 used the D configuration array, where the longest baseline is approximately 1 km, yielding a spatial resolution of 44″. These observations measured the 6 cm flux of sources previously detected at 21 cm to obtain spectral indices and also included a more sensitive search for narrowband 21 cm sources over a wider range of frequency. The two nominal fields were observed at 21 cm for

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[1] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

43 minutes each, with 127 channels and a resolution of 12.2 kHz, covering a band 1.5 MHz wide—doubling our prior sensitivity in one case and improving sensitivity by 50% in the other case. Additional 5 minute snapshots were made at 21 cm, covering 6.25 MHz with 31 channels at 195 kHz resolution. Sensitivity in the various fields is summarized in Table 1.

2.1. *Continuum Sources*

We first identified apparent continuum sources, to check their spectra for peculiar features and to later exclude them from tests for narrow-bandwidth sources. The AIPS task IMAGR was used to create "channel 0" maps, an average of the flux over the 75% of channels least attenuated by bandpass filtering. Channel 0 maps provide the highest sensitivity to continuum sources but could detect a single-channel source such as the Wow (assuming a flux of 60 Jy) at a signal-to-noise ratio (SNR) of ~100 if it were continuous and an SNR of ~10 if present for only 2 minutes during our longest integration. The primary goal of this step, however, was to identify continuum sources, not to search for a presumably rare brightening of the Ohio State source.

Sources were identified and cataloged from channel 0 maps using the AIPS routine SAD ("search and destroy"). This unfortunately named feature extraction task searches for islands of flux in an image, fits a Gaussian model of the synthesized beam, and records coordinates, flux, and other parameters for the candidate source in a catalog—optionally subtracting (hence, destroy) the fitted feature to leave a map of residuals. Features with peak flux at least 8 times the typical noise in 6.25 MHz maps (0.9–1.9 mJy, depending on the field) were accepted as real sources and are plotted in Figure 2. Table 2 lists the sources detected, all of which were unresolved. All of the sources were also detected in the subsequent NRAO VLA Sky Survey (Condon et al. 1998).

2.1.1. *Continuum Sources in the Error Boxes*

Two apparent continuum sources were detected in the Wow coordinate error boxes, defined by the Kraus right ascensions and a $\pm 6^{\mathrm{s}}$ uncertainty (the Ehman positions with a $\pm 10^{\mathrm{s}}$ uncertainty are covered in the analysis of entire fields in a subsequent section). That is not surprising, because the error boxes covered approximately 10% of the area observed, and 23 continuum sources were detected over the entire area. The sources were at R.A. = $19^{\mathrm{h}}22^{\mathrm{m}}22^{\mathrm{s}}.0$ and $19^{\mathrm{h}}25^{\mathrm{m}}13^{\mathrm{s}}.1$, both quite close to the right ascensions given by Ohio State, with fluxes of 32 and 16 mJy, respectively. Ohio State's single-channel sensitivity of several janskys was, however, far too low to detect continuum sources with such fluxes. We examined them in some detail to verify that they were continuum sources.

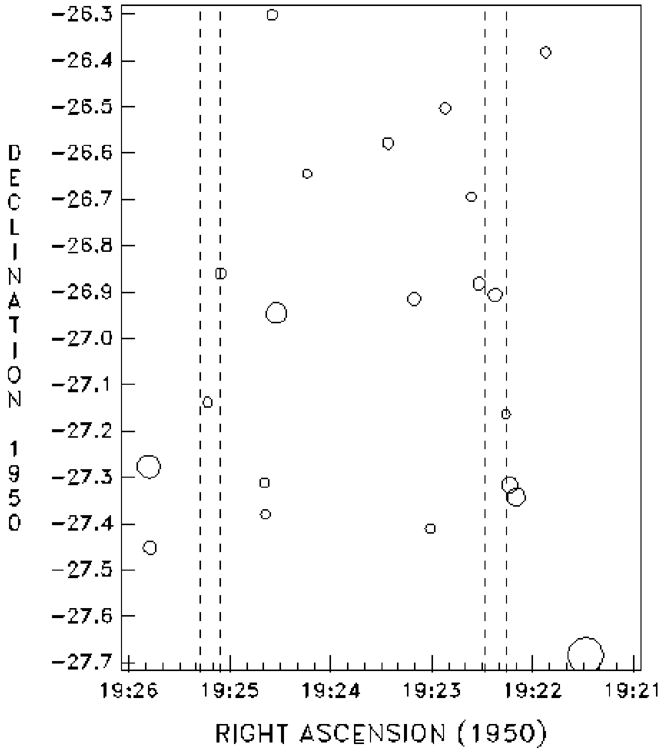

FIG. 2.—Continuum sources detected at 21 cm. Source coordinates are at circle centers, and the area of each circle indicates relative flux. The error boxes surrounding each of the two right ascensions given by Ohio State are shown by dashed lines.

TABLE 1

SENSITIVITY OF 21 cm OBSERVATIONS

	1995 SEP 25 ($3''.9$ RESOLUTION)		1996 MAY 7 ($44''$ RESOLUTION)		
FIELD NAME	Continuum (0.78 MHz)	Line, Typical[a] (6.1 kHz)	Continuum (1.5 MHz)	Line, Typical[a] (12.2 kHz)	Continuum (6.25 MHz)
1922-265......	2.1	17	...	...	1.3
1922-267......	1.4	8	...	...	1.2
1922-270......	1.0	5.5 (7.4 max.)	0.8	3.5 (6.1 max.)	1.5
1922-273......	1.7	8	...	...	1.4
1922-275......	2.6	13	...	...	1.6
1925-265......	2.0	14	...	...	1.0
1925-267......	1.5	9	...	...	0.9
1925-270......	1.0	5.3 (7.3 max.)	0.5	3.7 (5.4 max.)	1.3
1925-273......	1.9	9	...	...	1.9
1925-275......	2.4	15	...	...	1.4

NOTE.—Table entries are rms in mJy beam^{-1}.

[a] Typical for channels 15–60 and 70–110. Bandpass filtering attenuated channels near the edge of the band, and channels near band center had higher noise because of H I emission.

TABLE 2

CONTINUUM SOURCES[a]

		CORRECTED FLUX[c,d] (mJy)		
R.A. (1950)[b]	Decl. (1950)[b]	21 cm (1996)	6 cm (1996)	Spectral Index
19 21 28.1	−27 41 09.7	225	46.0	1.28
19 21 51.9	−26 23 00.5	22.1	...	...
19 22 09.5	−27 20 39.6	58	18.7	0.92
19 22 13.3	−27 19 02.9	48	14.5	0.97
19 22 15.6	−27 09 52.9	13.7	...	...
19 22 22.0	−26 54 28.4	32.5	11.3	0.86
19 22 31.5	−26 52 58.2	28.0	6.7	1.16
19 22 36.0	−26 41 42.7	17.6	6.7	0.79
19 22 51.7	−26 30 14.3	20.1	...	...
19 23 00.5	−27 24 44.2	18.1	...	...
19 23 10.3	−26 54 58.9	29.9	7.8	1.09
19 23 25.5	−26 34 49.6	22.6	...	...
19 24 30.4	−26 56 26.0	10.9	...	...
19 24 13.7	−26 38 43.4	14.9	...	...
19 24 32.0	−26 56 48.1	75.2	16.7	1.22
19 24 34.6	−26 18 09.3	20.7	...	...
19 24 34.7	−26 57 25.2	...	6.0	...
19 24 38.5	−27 22 51.2	16.1	...	...
19 24 39.1	−27 18 48.3	18.1	...	...
19 25 05.3	−26 51 40.5	20.5	28.7	−0.27
19 25 13.1	−27 08 22.1	16.1	4.8	0.98
19 25 47.2	−27 27 11.7	30.1	...	...
19 25 48.0	−27 16 41.9	94.3	13.2	1.59

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Ellipses indicate not observed at frequency shown.

[a] Sources over 8 σ in 6.25 MHz channel 0 images.

[b] Coordinates from higher resolution BnA configuration when available.

[c] Channel 0 bandwidth was 5.95 MHz for the 21 cm observations and 37.5 MHz for the 6 cm observations.

[d] Fluxes corrected for primary beam pattern with AIPS task PBCOR.

Spectra of the two sources, shown in Figure 3, display emission over all channels as expected of continuum sources. There is no evidence of prominent single-channel features that might have been enhanced by scintillation or other mechanisms to produce the Ohio State detection. To verify that these sources radiate over the wide frequency range expected of continuum emission mechanisms, we later obtained 6 cm fluxes for all sources detected in 1995. The spectral indices fall in the range expected (0.5–1.1) for normal continuum sources (Kraus 1986), typically extragalactic objects with synchrotron emission mechanisms.

No large variation in 21 cm flux was found between the 1995 and 1996 epochs, evidence that the sources are not variable on that timescale. Optical survey images were examined for coincident stellar objects, yielding a blank field at one position and a very faint possible optical counterpart for the source at the R.A. = $19^{\rm h}22^{\rm m}22^{\rm s}$ position; we have not determined whether it is stellar or Galactic. No evidence was found that either source is unusual.

2.1.2. *Continuum Sources in All Fields*

We also investigated the channel 0 sources outside the error boxes—approximately $1^{\rm m}$ of right ascension on either side of the nominal right ascensions. None displayed unusual spectral features, and all of the sources detected in 1995 were also detected at 6 cm in 1996. Two sources had somewhat unusual spectral indices (see Table 2). We conclude that these too are continuum sources, with no unusual features to suggest they might be the source of the Wow emission.

2.2. *Narrowband Search*

We next sought to identify narrow-bandwidth emissions from unresolved sources. Data cubes with 127 channels were made with IMAGR, having 6.1 kHz resolution (1995 observations) and 12.2 kHz resolution (1996 observations), with a typical single-channel noise of 5–17 and 3.6 mJy, respectively. SAD was used to create a catalog of candidate features in each single-channel image, ignoring those below a 4.2 σ signal-to-noise ratio—a threshold below the amplitude of most but not all expected noise peaks, selected to reduce the large number of "features" that noise alone is expected produce in such large data sets (totaling more than 10^8 discrete samples). The flux threshold for each channel was based on the image rms noise, which had the effect of raising the threshold flux in midband channels that sampled confused, extended Galactic H I emission. The list initially included some continuum sources, but features near coordinates of continuum sources were ignored.

To identify any sources with flux significantly stronger than the noise peaks, we computed a flux threshold above which noise peaks are not expected. For n independent samples the probability of error P_e, that one or more samples will exceed a value of Z_m in the absence of a real

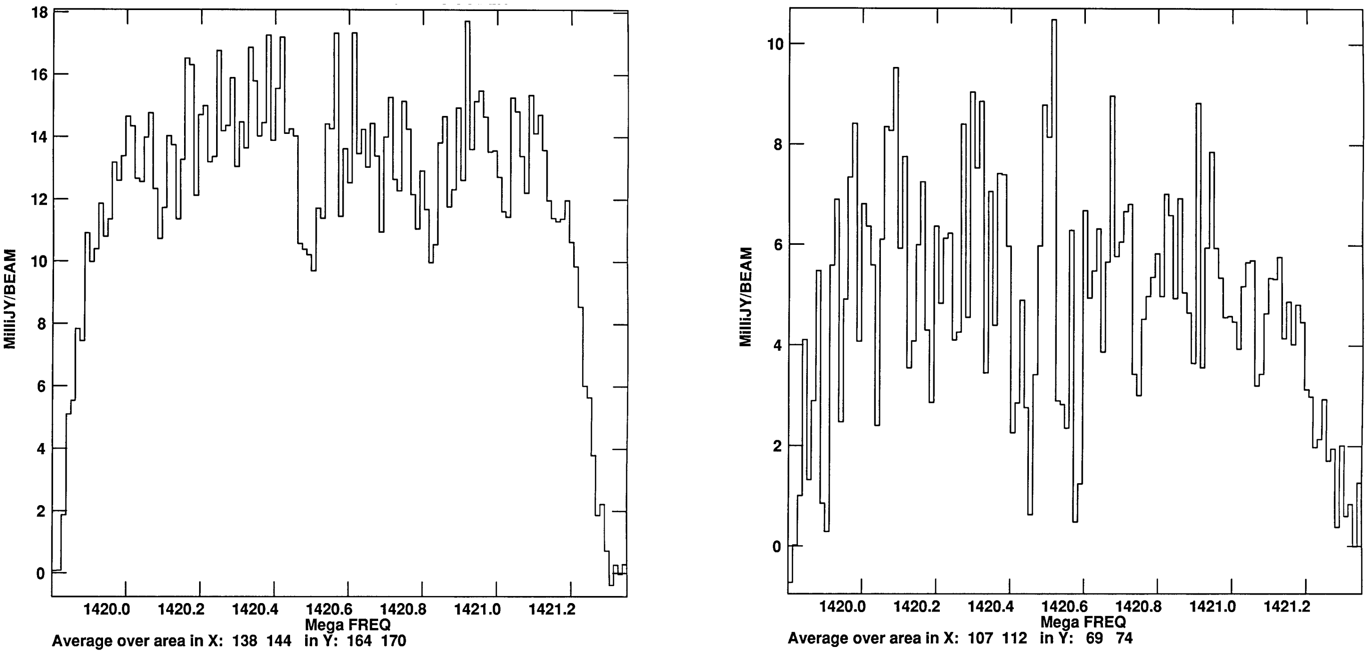

FIG. 3*a* FIG. 3*b*

FIG. 3.—Spectra of sources at (*a*) R.A. = $19^{\mathrm{h}}22^{\mathrm{m}}22^{\mathrm{s}}\!.0$, decl. = $-26°54'28''\!.4$ and (*b*) R.A. = $19^{\mathrm{h}}25^{\mathrm{m}}13^{\mathrm{s}}\!.1^{\mathrm{s}}$, decl. = $-27°08'22''\!.1$. The resolution is 12.2 kHz.

signal, is (after Thompson, Moran, & Swenson 1994, p. 264)

$$P_e = 1 - \left[1 - \exp\left(\frac{Z_m^2}{2\sigma^2}\right)\right]^n .$$

The number of independent samples was taken as the number of synthesized beams in an image, times the number of spectral channels in each beam. In the relatively high resolution BnA array configuration the two-dimensional Gaussian response to a point source covers an area of about 17 arcsec^2 and $n_{\mathrm{beams}} = 1.9 \times 10^5$ for a field $1811'' \times 1811''$ (a 1024^2 pixel image with a 9 pixel edge ignored because of increased noise). In the lower resolution D configuration a point source covers an area of about 2194 arcsec^2 and $n_{\mathrm{beams}} = 1.5 \times 10^3$ over a $1830'' \times 1830''$ field (a 256^2 pixel image with a 24 pixel edge outside the 30′ primary beam ignored). For each 127-channel data cube, n was taken as 127 times larger than the number of samples in the field to account for the number of channels in the cube. To test a detection hypothesis we choose threshold fluxes Z_m so that $P_e = 0.01$; Table 3 shows the thresholds for various data sets.

2.2.1. *Wow Error Boxes*

Single-channel sources with positions inside the Ohio State coordinate error boxes would be of greatest interest. In the 1996 D configuration data set two 5.6 σ features just meet the threshold for the error boxes but fall short of the 5.9 σ threshold for the entire data set; a noise peak as high as 5.2 σ is expected ($P_e = 0.5$) in the data set. We also analyzed "extended" error boxes from 1995 BnA-array observations: 10 partly overlapping fields covering about $1\overset{\circ}{.}5$ in declination (twice the Ohio State uncertainty) and with the same bounds in right ascension. No peaks exceeded a 6.6 σ threshold for that data set.

2.2.2. *All Fields*

We also searched for single-channel sources anywhere in the fields observed, to accommodate possible errors of up to 1^{m} in the Ohio State right ascensions. The data sets included two fields at 12.2 kHz resolution and 10 partly overlapping fields at 6.1 kHz resolution. No features met a 5.9 σ threshold for the two D cubes or a 6.9 σ threshold for the 10 BnA cubes. Figure 4 shows the distribution of single-channel peaks over 4.2 σ for the two data sets.

TABLE 3

THRESHOLD FOR SINGLE-CHANNEL FEATURES

DATA SET	NUMBER OF SAMPLES	RMS (mJy)	SIGNAL THRESHOLD ($P_e = 0.01$) (σ)	($P_e = 0.01$) (mJy)
2 127-Channel Cubes (1996 D Array)				
Wow error box	5.3×10^4	3.6	5.6	20
Entire fields	3.8×10^5	3.6	5.9	21
10 127-Channel Cubes (1995 BnA Array)				
Extended error box......	2.1×10^7	5.4–17	6.6	37–112
Entire fields	2.4×10^8	5.4–17	6.9	40–117

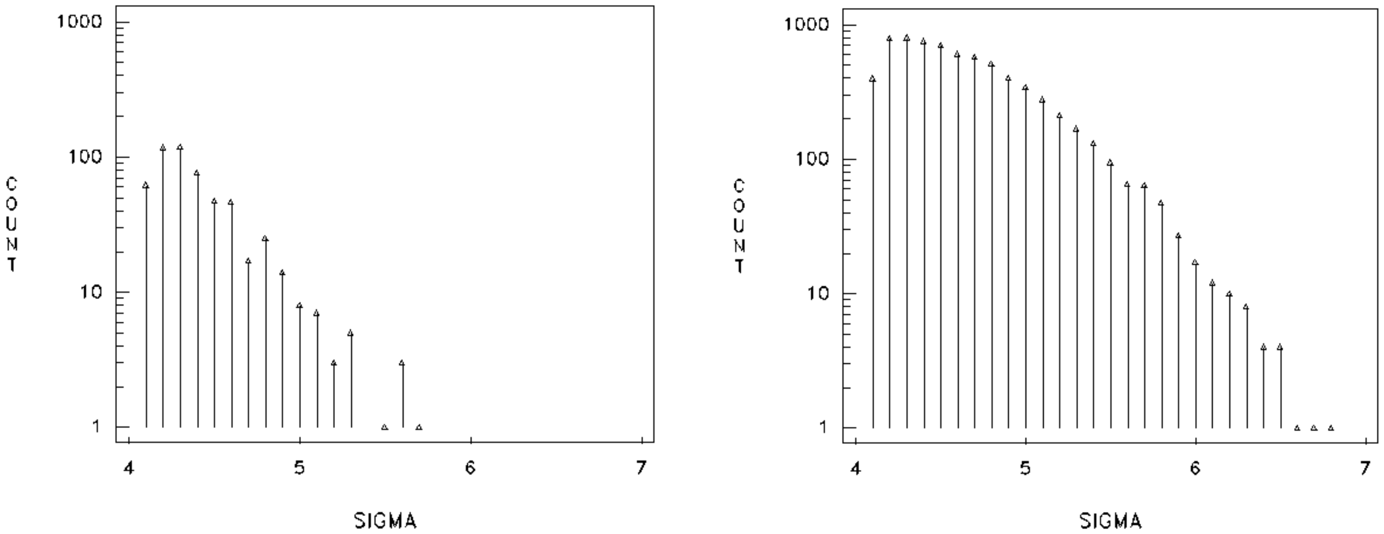

FIG. 4*a*

FIG. 4*b*

FIG. 4.—Distribution of single-channel peaks $\geq 4.2\ \sigma$ in 127-channel data cubes, with channel 0 sources removed. (*a*) Two data cubes with 12.2 kHz channel width. (*b*) Ten data cubes with 6.1 kHz channel width.

2.2.3. *Other Techniques Used*

Real but weak sources of interest might, of course, lurk below a $P_e = 0.01$ threshold. We also screened the data for single-channel sources by (1) searching for repeated detections of weak features at the same coordinates in overlapping fields or during different observing runs, (2) searching for radio features with coordinates coinciding with objects in optical survey images or the Guide Star Catalog (Lasker et al. 1990), (3) direct inspection of portions of the UV data, (4) examining statistics on UV data, (5) analyzing 10 minute time ranges of data to identify intermittent sources attenuated by averaging over longer periods, (6) applying continuum subtraction using the AIPS task UVLIN, (7) searching for highly polarized features, and (8) exploring data cubes with visualization software. None of these techniques identified convincing single-channel pointlike sources.

3. CONCLUSIONS

No narrowband emission resembling the Ohio State Wow was found in searches of the apparent source positions using the VLA, to flux limits as low as 22 mJy at the nominal positions, and better than 120 mJy $\sim 0\overset{\circ}{.}5$ north and south, with detection thresholds of 5.9 σ and 6.9 σ, respectively. Two continuum sources were detected inside Ohio State's coordinate error boxes but displayed no unusual spectral features, no unusual spectral indices, and no temporal variation.

Our observations were sensitive enough to detect a putative underlying narrowband source $\sim$500 times weaker than the approximately 60 Jy Wow. The null result is good evidence that the Wow detection was not a continuous source, either natural or artificial, enhanced by scintillation sufficiently for Ohio State to detect on just one occasion, because the probability of a scintillation gain on the order of 100 is vanishingly small. Covering a range of frequency 3 times wider than Ohio State's observations, our observations also constrain the possibility that the original detection was due to a source drifting in frequency over a range of approximately 1.5 MHz. Our observations do not significantly constrain the possibility of highly intermittent emissions because we dwelled for no longer than 22 minutes on any field.

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