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A SEARCH FOR PERIODIC EMISSIONS AT THE WOW LOCALE

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ABSTRACT

The Ohio State University Radio Observatory recorded a strong, narrowband emission near the 21 cm hydrogen line in 1977 during a search for extraterrestrial intelligence, an event known as the "Wow" signal. The few independent attempts to replicate the detection have failed. We have investigated the possibility of a periodic source—perhaps rotating and illuminating us once each cycle of many hours, like a lighthouse—which prior observations would have been unlikely to detect. We used the University of Tasmania Hobart 26 m radio telescope to search for intermittent and possibly periodic emissions at the Wow locale by tracking the apparent source positions for nearly 14 hr continuously on multiple days. No emissions resembling the Wow were detected over a bandwidth of 2.5 MHz to a flux density limit of about 18 Jy, with a detection threshold of 5.9 σ and rms noise of 3 Jy. We conclude that the Wow was not due to a source within our flux density limits and repeating more often than every 14 hr, although the possibility of a longer period or non-periodic source cannot be ruled out.
Subject headings: extraterrestrial intelligence — radio lines: general

1. INTRODUCTION

The Wow was a strong (30 σ, or about 60 Jy), narrowband (<10 kHz) emission recorded near the 21 cm H I line at Ohio State University in 1977 (Kraus 1979; Ehman 1998[1]) during a search for extraterrestrial intelligence (SETI), but not detected again in subsequent follow-up observations at Ohio State. The event is interesting because the time-dependent intensity of the emission matched the antenna pattern signature of a transiting celestial source (Gray & Marvel 2001), which would not be expected of interference.

Two attempts to independently replicate the detection have been reported, both unsuccessful. One attempt (Gray 1994) used the ultranarrowband Harvard/Smithsonian-META system (Horowitz et al. 1986). With 0.05 Hz channels and a chirped receiver, the observations were sensitive only to very narrowband and Doppler-corrected artificial radio signals; none were detected. A second attempt used the Very Large Array (Gray & Marvel 2001). With spectral resolutions of 6.1 and 12.2 kHz, those observations approximated Ohio State's 10 kHz bandwidth and were much more sensitive (20 mJy), capable of detecting weak underlying continuous sources that might have been briefly enhanced by interstellar scintillation to produce the Ohio Sate detection. Dwelling on the apparent source locale for no more than 22 minutes, those observations were unlikely to detect intermittent sources.

The Ohio State detection occurred in only one beam of a dual-beam transit antenna system (Dixon & Cole 1977), and a simple explanation is that the signal may have been present only during the time one beam swept past. The two beams were side by side and separated by $2^{m}50^{s}$ of right ascension; celestial sources were usually detected first in one for 72 s, then in the other.

[1] Available at http://www.bigear.org/wow20th.htm.

One way to account for an emission present only part of the time is a rotating source, in which case the emission might appear periodically. Pulsars are a familiar example. In the context of interstellar radio signals, an example scenario would be a directional broadcast from a fixed antenna on the surface of a rotating planet, sweeping across observers once each "day" like a lighthouse. Terrestrial ballistic missile early warning system radars are an example of such emissions that are potentially detectable over interstellar distances (Sullivan, Brown, & Wetherill 1978).

A second possible explanation for the single-beam detection is a signal drifting in frequency, because the detection occurred in channel 2 of a 50 channel filter-bank receiver. It is possible that a signal with a fortuitous frequency drift rate, in the range of ± 100 to ± 150 Hz s^{-1}, drifted into or out of the band observed during the time between the passage of the two beams.

We investigated a periodic emission hypothesis because it is possible to test by the simple expedient of sufficiently extended observations. We also incidentally investigated a drifting frequency hypothesis by observing over a band 5 times wider than Ohio State's. Other hypotheses can be conjured up, of course, including local interference, which is impossible to rule out.

1.1. *Statistics of the Wow Detection*

In this section we calculate the probability of the original Wow detection, assuming emissions of various periods and durations, with the goal of estimating how long observations must be to detect a hypothetical periodic source.

We treat each transit observation as a trial, which might or might not be looking in the right direction at the right time to observe a periodic source. The binomial distribution gives the probability P_B of an event occurring x times in n independent trials, given the probability p of the event occurring in a single trial (Zombeck 1990, p. 410). The original detection is taken as one success in 18 trials because the Ohio State transit antenna was typically kept at a constant declination for 3 days and moved in half-HPBW increments (Dixon 1985); strong continuous sources could be detected on 9 days, and the two beams yield 18 trials.

The probability of a detection success during one daily transit of one beam is simply the fraction of the terrestrial day a signal is present—for example, $p = (144 \times 24)/86,400 = 0.04$ for a 144 s signal repeating 24 times per day—and the two beams yield two trials per day. We consider signal durations of 72 (a lower limit for the Wow, since it was present during the full transit of one beam), 144, and 288 s. Durations shorter than about 100 s guarantee detection in only one of the two beams, so that the trials are independent. Durations longer than about 250 s could be detected in both beams, which begins to violate the assumption of independent trials.

The probability of detecting a periodic source exactly once in 18 trials is given in Figure 1 for various periods and durations. For periods under about 2 hr the probability reaches over 0.35. For periods over 12 hr the probability of detection falls below 0.10, and over 24 hr is less than 0.05 for all durations considered. The Wow detection would seem rather lucky for a source with such a long period, although the Ohio State survey ran for several years and covered approximately half of the sky, so if many such sources existed, detecting one would not be too surprising. This analysis suggests that a search for periodic emissions should be extended in time, as long as 10 or 20 hr, but not very much longer.

We note that the range of periods where detection is not too improbable (up to 10–20 hr) includes the length of short planetary days. Sidereal rotation periods probably cannot be much less than 6 hr because of dynamical considerations (Lightman 1984). In our solar system four of nine planets have periods between 10 and 17 hr, two others 24–25 hr, while the remaining three are much longer. The range of periods consistent with the Wow thus includes the intriguing scenario of an emission from the surface of a rotating planet, although periodicity could arise from other mechanisms as well.

1.2. *Confirming Rotating Source Emissions*

Ohio State's ~100 follow-up transit observations would not significantly constrain the possibility of a source with a period of more than several hours because they sampled sources for only 72 s twice each terrestrial day. For sources that are themselves periodic, periodic sampling makes a second, confirming detection extremely difficult because in many cases the source will be out of phase with the observations for many subsequent transits.

A simple discrete computer simulation was performed to investigate this effect, using as its starting point Ohio State's detection, and continuing over 500 subsequent days at 1 s intervals, for source periods up to 36 hr in 0.01 hr increments. The source emission was taken as illuminating the Earth for 144 s during each extraterrestrial day—long enough for the observed 72 s detection, yet brief enough to avoid detection in Ohio State's other beam. A simulated detection was declared whenever the two simulated rotating beams overlapped for even a few seconds.

The simulation results show that Ohio State's subsequent observations scattered over several hundred days would have had few opportunities for additional detections, making them a poor test for emissions with periods comparable to planetary days. For nearly half of the periods considered, a second detection would not occur for 100 days or more, when both the terrestrial antenna and the source point in the same direction again, illustrated in Figure 2.

There is no evidence that the Wow was periodic, but a rotating source is one mechanism that naturally accounts for the single detection and failure of subsequent detection efforts.

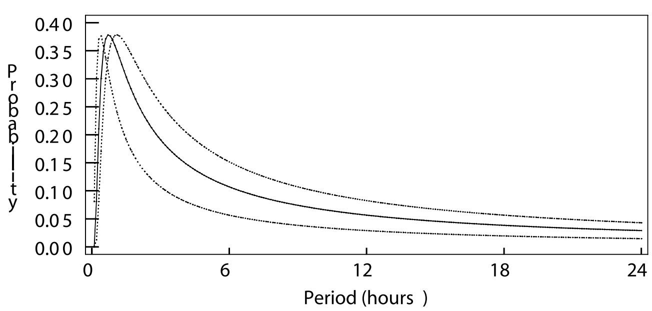

FIG. 1.—Probability of exactly one detection in 18 trials. The solid line represents a signal duration of 144 s every *n* hours. The upper dotted line represents a signal duration twice as long, the lower dotted line half as long. The probability of exactly one detection falls off rapidly for periods less than about 1 hr as a result of multiple detections.

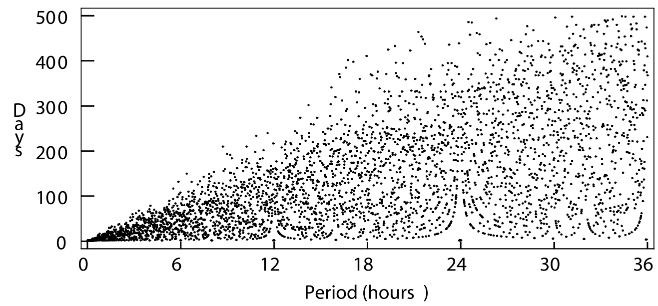

FIG. 2.—Number of days until a second opportunity for detection using the Ohio State transit telescope, for sources with periods up to 36 hr. Prospects are especially poor for sources with periods near but not equal to the terrestrial 23.9345 hr day.

2. OBSERVATIONS

The apparent coordinates of the Wow emission were R.A. $= 19^h22^m22^s$ or $19^h25^m12^s$ (both $\pm 5^s$), decl. $= -27°03' \pm 20'$ (B1950.0; J. D. Kraus 1990, private communication). The two right ascensions result from the dual-feed antenna system forming two beams. Ohio State recorded the difference in intensity between the two beams, but not the sign, so there was an ambiguity in which beam the emission was detected. Revisions to the coordinates have been proposed (Ehman 1998) but are small enough to neglect in the present work.

Since objects at the Wow declination are visible for only 4–6 hr daily from most observatories in the northern hemisphere, a southern hemisphere site was necessary. We used the University of Tasmania Hobart 26 m radio telescope, which allowed us to track continuously for 14 hr—the maxi-

TABLE 1
Summary of Observations

Field Name	Date	Day of Year	R.A. (B1950.0)	Decl. (B1950.0)	Length of Observation (hr)	Frequency (MHz)
1922N	1999 Mar 22–23	81/82	19 22 22	−26 48	14.1	1420.5870
1922	1998 Oct 5	278	19 22 22	−27 03	14.0	1420.3146
1922S	1999 Mar 17–18	76/77	19 22 22	−27 18	14.1	1420.5837
1925N2	1999 Apr 9–10	99/100	19 25 12	−26 48	14.1	1420.3135
1925	1998 Oct 9	282	19 25 12	−27 03	14.3	1420.3135
1925S2	1999 Mar 20–21	79/80	19 25 12	−27 18	14.1[a]	1420.5855

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees and arcminutes.
[a] 1 hr missing mid-run.

mum time the target coordinates are above that telescope's horizon.

We tracked each of the two nominal positions during two days in 1998, for nearly 14 hr each. Additional observations were made in 1999, 15′ north and south of the nominal coordinates, to fully cover the Ohio State 40′ declination HPBW with the Hobart beam. Observations are summarized in Table 1.

2.1. *Instrumental Configuration and Data Reduction*

The instrumental configuration for the observations is summarized in Table 2. Lags from a one-bit digital autocorrelation spectrometer were transformed from the time to the frequency domain using a modified version of the observatory spectral line analysis software (Ellingsen 1996). Quotient spectra were formed to remove the effect of front-end and correlator bandpass filters, using the relation $Q = (S/R) - 1$ for each channel, where Q is the quotient, S is the spectrum of interest, and R is a reference spectrum.

To produce a flat baseline, a third-degree polynomial was fitted to those regions of the spectrum free from H I emission and interference. A noise diode on the receiver was compared to the system total power once every 10 minutes to determine the system temperature. The system was calibrated against Virgo A, assumed to have a flux density of 211 Jy at 1420 MHz (Baars et al. 1977).

Reference spectra are typically obtained through off-source observations, but one of our goals was to observe continuously over many hours. Since we were searching for a strong, time-variable signal, we were able to use an alternative approach: averaging smoothed on-source spectra taken at times near those of the signal spectrum. Reference spectra were formed by averaging groups of 30 s spectra between system calibrations at 10 minute intervals. This procedure has the drawback of including spectral features of potential interest in the reference spectrum, which would then be removed from the quotient spectrum. To avoid this, we used several techniques to exclude features from the reference spectra. To remove single-channel features, we median-smoothed each reference spectrum. To remove broader features, including H I, apparent radio frequency interference (RFI), and potentially interesting intermittent features, we first used only prior spectra to form a reference, then identified features in subsequent spectra, then "bridged" the reference spectrum with a straight line connecting channels across the base of the feature, an iterative procedure.

TABLE 2
Instrument Description

Parameter	Value
Telescope	Mount Pleasant Radio Observatory
Antenna	University of Tasmania 26 m
HPBW at 21 cm (arcmin)	28
Spectrometer resolution (kHz)	4.88
Observed bandwidth (kHz)	9.765 (due to Hanning smoothing)
Channels	512 (each polarization)
Polarizations	Two linear (crossed dipoles)
Integration time (s).......................	30
System temperature (Jy)...............	1200 (120 K)

2.2. *Sensitivity*

The theoretical rms (σ) channel sensitivity of a spectrum obtained with the Mount Pleasant system is

$$\sigma = \frac{\pi}{2} \frac{T_{\rm sys}\sqrt{(N_{\rm chan})}}{\sqrt{(2BtN_{\rm pol})}} ,$$

where $T_{\rm sys}$ is the system temperature in Jy, $N_{\rm chan}$ is the number of spectral channels, B is the observed bandwidth of the spectrometer, t is the integration time in seconds, and $N_{\rm pol}$ is the number of averaged polarizations. The factor of $\pi/2$ is the decrease in sensitivity due to the 1 bit approximation made in the correlator, and the factor of $\sqrt{2}$ is the increase in sensitivity due to Hanning smoothing. This yields $\sigma = 2.46$ Jy for a single 30 s spectrum and 0.55 Jy for a reference spectrum consisting of 20 averaged spectra. The sensitivity expected for our quotient spectra is then 2.5 Jy (from standard propagation of errors), which is close to the 2.6–3.0 Jy rms obtained during our various observations.

Our 3 Jy sensitivity was sufficient to yield an unambiguous detection of a 60 Jy source—the estimated Wow flux—with a signal-to-noise ratio of 20.

2.3. *Interference Identification and Excision*

The radio frequency interference environment was sampled for approximately 1 hr before and after each observing run, usually with the antenna pointed overhead. Signals detected during these off-source observations were assumed to be local interference, and those channels were ignored in subsequent analysis.

3. RESULTS AND DISCUSSION

3.1. H I

The hydrogen emission line was prominent in all spectra, with a measured flux of 220 ± 20 Jy. The H I peak was 15–20 kHz below the LSR-corrected H I frequency, indicating that interstellar hydrogen in the directions observed has a radial velocity of 3–4 km s^{-1}.

We used several strategies to accommodate the possibility that a signal of interest might be obscured by the H I background. To identify signals partly buried in H I, we calculated a running baseline flux for each channel, averaging the nine prior measurements in the channel, and subtracted it from the flux for each spectrum, effectively removing the constant H I profile. Ohio State used a somewhat similar running baseline removal method. To identify signals entirely buried in H I emission during one set of observations—and not fixed in the same LSR reference frame—we staggered observations over approximately 6 months, so the H I emission would be Doppler shifted to different sky frequencies.

3.2. *Statistical Analysis*

To identify spectral features of possible interest, we computed a flux density 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 signal is (after Thompson 1991)

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

We choose threshold fluxes Z_m so that $P_e = 0.05$, shown in Table 3 for various data sets.

3.3. *Spectral Features*

Several apparent narrowband features above our detection threshold remained after excluding known interference and removing the H I profile. Some were traced to a fault in the local oscillator (LO) used for Doppler tracking, which caused sudden frequency shifts of 5 kHz at certain settings, shifting the H I profile one channel and causing the running baseline calculation to encounter a spurious flux density increase. Removing those, two apparent features remained.

Field 1922N contained a 14 σ feature spanning two channels in both linear polarizations. It does not resemble the Ohio State event sufficiently to be of interest for two reasons. First, it lasted only one 30 s integration period (compared to at least 72 s for the Wow), and second, its frequency was 456 kHz higher than the Wow. Field 1922N contained a second possible feature, weak but noted because its frequency corresponds to the Wow. At 5.6 σ it was below our 5.9 σ detection threshold ($P_e = 0.05$) and below the 5.7 σ maximum expected over all observations ($P_e = 0.5$) but above the typical 5 σ maximum noise peak during a single day's observations. It appears as a sudden increase at the peak of the H I profile, during just one integration period, approximately 15 Jy above the flux in adjacent channels and observations. No simultaneous increase was found in the other polarization, evidence that it was not an LO shift. A check of those channels over the entire observing period found no other peaks of interest. Although the feature matched the Wow frequency, it was too near the statistical noise peaks to consider as a redetection.

Given that RFI was observed in some channels, we must presume that features are RFI in the absence of evidence otherwise, such as obvious resemblance to the Wow in frequency and strength, or a characteristic such as repetition. Excluding these features as probable RFI, no spectral features remain that noticeably exceed the noise.

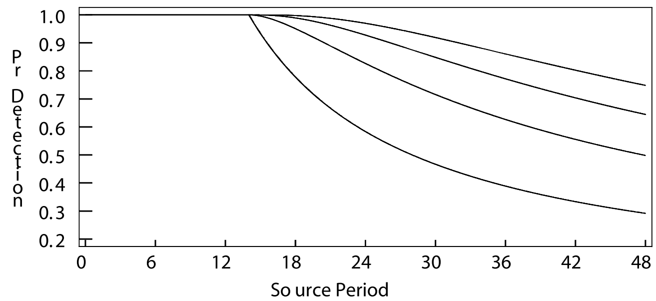

FIG. 3.—Probability of detecting sources of various periods. The lower line represents one observing run of 14 hr, and the higher lines represent the binomial probability of detection for two, three, or four 14 hr runs, respectively.

3.4. *Constraints on Periodic Sources*

Our observations would have detected a sufficiently strong source with a period shorter than 14 hr. For sources with longer periods, the probability of detection is shown in Figure 3. During a single run that probability is approximately $14/t$, where *t* is the period in hours, which applies to the areas observed more than 15′ north and south of the nominal positions, observed only one time. The nominal

TABLE 3
THRESHOLD FOR SINGLE-CHANNEL FEATURES

FIELD NAME	NUMBER OF SAMPLES	rms (Jy)	SIGNAL THRESHOLD ($Pe = 0.05$) (s)	SIGNAL THRESHOLD ($Pe = 0.05$) (Jy)	MAXIMUM OBSERVED (s)	
					Features Included	Features Excluded
1922N	1631232	2.82	5.9	16.6	13.3	4.74
1922	1624064	3.0	5.9	17.7	4.9	. . .
1922S	1610752	2.66	5.9	15.7	5.18	. . .
1925N2	1605632	2.66	5.9	15.7	6.5	4.97
1925	1642496	2.9	5.9	17.2	4.8	. . .
1925S2	1473536	2.97	5.9	17.4	7.71	5.05
All	9587712	2.9	6.2	18.0	. . .	. . .

positions were observed twice—directly, and partly covered during observations north and south—for a binomial probability of detection of over 0.90 for sources with periods of up to about 20 hr.

These constraints on period are statistical and therefore approximate, as a result of our small number of observing runs. A single 14 hr observing run, for example, would have no chance of detecting a source with a 24 hr period if the run happened to start just after the emission ended.

3.5. *Wow and* H I *Frequency*

We note that the Wow frequency given by Kraus corresponds to the frequency of the peak H I emission found in our observations: both were some 20 kHz below the LSR, implying a radial velocity of approximately 4 km s^{-1}. This could be taken as dynamical evidence that the Ohio State source was moving with the gas and hence was unlikely to be terrestrial interference, but that may be a coincidence. Since the Ohio State receiver had only 50 channels, there was a 2% chance that any detection would fall in the channel corresponding to the H I peak.

3.6. *Rotating Sources in SETI*

Several SETI surveys have reported one-time detections with some characteristics expected of interstellar signals, including narrow bandwidth (<1 Hz) and the terrestrial Doppler signature (Horowitz & Sagan 1993; Colomb et al. 1995). None have been confirmed during follow-up observations, typically tracking the apparent source coordinates for on the order of 1 hr.

One explanation that has been advanced is brief flux density enhancements of continuous emissions, caused by interstellar scintillation and noise variations (Cordes, Lazio, & Sagan 1997), but the probability of large scintillation gains is small. Rotating sources may provide an alternative explanation. Such sources might appear intermittent during transit survey observations and fail to be confirmed with brief reobservations, but they might prove easily repeatable with sufficiently extended observations—perhaps a single "day" for planetary sources. While the length of extrasolar days is unknown and probably quite variable, observations over 25 hr would, for example, encompass the periods of more than half the planets in our solar system. It may be prudent to anticipate that the length of extrasolar planetary days could affect interstellar broadcasts.

4. CONCLUSIONS

No signals resembling the Ohio State Wow were detected in observations dwelling for up to 14 hr at the coordinates where the signal was reported. This result constrains a putative periodic emission to a period greater than 14 hr because our observations were sufficiently sensitive and extended in time to detect emissions with a shorter period at least once. Since the probability of the original detection has been shown to be rather low (<0.10) for sources with periods over approximately 12 hr and a range of durations, the Ohio State detection would have been rather lucky if due to a periodic emission with a much longer period.

Our observations cannot entirely rule out the possibility of a period longer than 14 hr or an emission that is not periodic at all. We also cannot rule out the possibility of a signal outside of the 2.5 MHz band we observed, although it was 5 times wider than Ohio State's frequency coverage and sufficiently wide to encompass the Doppler shifts expected of a planetary-based signal broadcast at the H I frequency.

While these observations were undertaken to investigate the Ohio State signal, they also constitute a general search for periodic signals near H I over approximately 1 deg^2 of sky, for periods as long as short planetary days. No prior SETI experiments appear to have searched for signals with such long periods (Tarter 1995). The sensitivity of the search was sufficient to detect a 1000 MW broadcast at over 100 lt-yr, assuming a 300 m transmitting antenna, or 10^{16} W radiated isotropically.

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REFERENCES

Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99
Colomb, F. R., Hurrell, E., Lemarchand, G. A., & Olald, J. C. 1995, in ASP Conf. Ser. 74, Progress in the Search for Extraterrestrial Life, ed. G. S. Shostak (San Francisco: ASP), 345
Cordes, J. M., Lazio, T. J. W., & Sagan, C. 1997, ApJ, 487, 782
Dixon, R. S. 1985, in IAU Symp. 112, The Search for Extraterrestrial Life: Recent Developments, ed. M. D. Papagiannis (Dordrecht: Reidel), 305
Dixon, R. S., & Cole, D. M. 1977, Icarus, 30, 267
Ehman, J. R. 1998, The Big Ear Wow! Signal: What We Know and Don't Know About It after 20 Years, OSURO working paper
Ellingsen, S. 1996, Ph.D. thesis, Univ. Tasmania
Gray, R. H. 1994, Icarus, 112, 485
Gray, R. H., & Marvel, K. B. 2001, ApJ, 546, 1171
Horowitz, P., Matthews, B. S., Forster, J., Linscott, I., Teague, C. C., Chen, K., & Backus, P. 1986, Icarus, 67, 525
Horowitz, P., & Sagan, C. 1993, ApJ, 415, 218
Kraus, J. D. 1979, Cosmic Search 1, 31
Lightman, A. P. 1984, Am. J. Phys., 52, 211
Sulivan, W. T., Brown, C., & Wetherill, C. 1978, Science, 199, 377
Tarter, J. 1995, Summary of SETI Observing Programs (Mountain View: SETI Institute)
Thompson, A. R. 1991, in Interferometry and Synthesis in Radio Astronomy, ed. A. R. Thompson, J. M. Moran, & G. W. Swenson, Jr. (Malabar: Krieger), 264
Zombeck, M. V. 1990, Handbook of Space Astronomy and Astrophysics (2d ed.; Cambridge: Cambridge Univ. Press)