of the Exodus mentioned by Miss Budd. Indeed our Moses' death date is in reasonable agreement with the earlier one. Further, the statement's uncertainty window was carefully chosen to encompass both the *circa* 1250 BC date mentioned by Budd as well as the *circa* 1550 BC one suggested by the Jericho archaeological record. This Jericho destruction date seems to be supported by the preponderance of the data, notwithstanding Wood's analysis[3].

Yours faithfully,
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References

(1) L. Budd, *The Observatory*, **132**, 184, 2012.
(2) T. J. Manetsch & W. H. Osborn, *The Observatory*, **131**, 248, 2011.
(3) B. G. Wood, *Biblical Archaeology Review*, **16** (2), 44, 1990.

On the Discovery of the Period of the Crab Nebula Pulsar

The discovery of radio pulsars[1] gave rise to an explosion of knowledge of stars and their evolution, immediately attracting the interest and attention of astronomers world-wide. It also sparked widespread public interest in pulsars. Subsequent discoveries over the next year resulted in discoveries of similar sources, also 'ticking' with periods of about a second, which could be explained by pulsation of a white dwarf. The discovery of the period of the Crab Nebula pulsar with regular emission at a 33-ms period was the first detection of a source with a significantly shorter period, which could readily be explained by a rotating neutron star. The discovery of this pulsar has not been described previously.

Richard Lovelace, then a Cornell graduate student in physics working for Professor Edwin Salpeter, spent the period from 1968 April to December at the Arecibo Observatory, doing research on the newly discovered pulsars. He was assigned by Prof. Salpeter to develop computer codes for searching for pulsars in digital records[2], and had developed a 'fast-folding code', with which he discovered the 0·5579-s period of a new pulsar in Vulpecula[3].

Later that year, in September and October, after discussions with Arecibo Observatory visitors Len Tyler (a research associate at Stanford University) and Cornell Professor Tommy Gold (who was convinced that pulsars were magnetized rotating neutron stars — possibly rapidly rotating — rather than pulsating white dwarfs[4]), Lovelace began work on a new code designed to find pulsars with much shorter periods. The new code was based on a floating-point Fast Fourier Transform (FFT) code written by Tyler.

The Arecibo computer at the time was a Control Data Corporation CDC 3200 which had a magnetic core memory of 32K words of 24 bit length. Lovelace developed an integer-based FFT code using half-words (12 bits each) which accommodated FFTs of $N = 16\,384 = 2^{14}$ signal samples. For a sampling rate of Δt, the FFTs were calculated from spans of data of duration $T = N\Delta t$. This long sample length made possible a fine frequency resolution of $\delta f = f_N/8192$, with $f_N = (2\Delta t)^{-1}$ the Nyquist frequency. These choices were important (*i*) for increasing the output signal-to-noise ratio, (*ii*) for allowing a search over a wide range of pulsar periods — including the shorter periods expected of rotating neutron stars, and (*iii*) for discriminating against local power-line noise. (The latter was required because in 1968 the frequency variations of the local electric power from one span of data to the next were always much larger than the δf of our FFT's!) All 8192 values of the received signal power *versus* frequency were displayed on a line-printer page as a folded raster scan, *i.e.*, side-to-side in rows and from top-to-bottom with values 0, ..., 9, and 'X' for values greater than 9. The signal root-mean-square value was used to renormalize the signal so that its average Fourier power was <~1. The integer code ran relatively fast on this CDC computer, and for this reason it was named GALLOP[5,6].

The Arecibo computer was available to Lovelace between midnight and 8 am on weekdays, and essentially full time on weekends, which was convenient since Lovelace lived at the Observatory. It was his good fortune on the overnight computer run on 1968 November 9–10 to find in the FFT raster patterns of 196·5 MHz scans of the Crab Nebula* a highly significant peak at the frequency $f = ((4951+4952)/2)\ f_N/8192 = 30{\cdot}22$ Hz, where the Nyquist frequency was $f_N = 50$ Hz for these data comprising samples at 100 Hz. The corresponding pulse period was $P = 33{\cdot}09$ ms[5]. Part of the line-printer output of the discovery is shown in Fig. 1 of ref. 6.

This was an exciting discovery, but for a day or two it was met with scepticism by the observatory astronomers because the observed repetition frequency from the pulsar was close to the second harmonic of the local 60-Hz electrical power grid. As mentioned above, this was ruled out because the 60-Hz signal was known to change its frequency from one data span to the next. Follow-up measurements of the Crab pulsar established that the pulse period was 33·09 ms.

Observations at a 100-Hz sampling rate were Fourier analyzed using 163·8-s spans of data. Effectively, the Fourier transforms stacked about 5000 periods of the received pulsar signal, resulting in an improvement of the signal-to-noise ratio by a factor of $\sqrt{5000} \approx 70$.

Subsequently, the GALLOP code was applied to drift-scan observations of the Crab Nebula and this established that the pulsar's location was near the centre of the Nebula[6].

A few days prior to our discovery of the period of the Crab pulsar, D. H. Staelin (MIT) and E. C. Reifenstein (NRAO) announced the discovery of dispersed pulses from two sources in the vicinity (±2°) of the Crab Nebula[7]. In the paper describing the discovery[8] they report dispersed pulses from the sources NP 0527 and NP 0532, characterized in the abstract by the statement that "Both sources are sporadic, and, no periodicities are evident." Our pulsar search at Arecibo was independent of the NRAO work, and it was designed

*Scans of the Crab Nebula at 196·5 MHz were digitally recorded on magnetic tape earlier in the week by Lovelace's Arecibo collaborators H. D. Craft, J. M. Sutton, and J. M. Comella, for later computer analysis.

for discovering short-period pulsars. The NRAO observations[8] at 110–115 MHz were made with a 0·05-s time constant which precluded a measurement of the period of the Crab pulsar and no period was reported. Furthermore, at frequencies of 110–115 MHz, interstellar scattering broadens the Crab pulsar pulses to a width much larger than the pulse period. Fortuitously, at the 196·5 MHz frequency of the Arecibo observations the broadening was less than the pulse period. The identification of the Crab pulsar found at Arecibo with NP 0532 found at NRAO was established by the agreement of the dispersion measures observed at the two observatories[6].

The short period of the Crab pulsar made it very unlikely that the star was a pulsating white dwarf. It became clear that the pulsar was a rotating magnetized neutron star as advocated by Gold[4]. Indeed, several weeks after the discovery of the period, the 'spin-down' or expected lengthening of the period was observed[9]; the rotational energy released in the form of magnetized winds was later shown to be sufficient to power the electromagnetic emissions of the Nebula[10].

Yours faithfully,

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References

(1) A. Hewish *et al.*, *Nature*, **217**, 709, 1968.
(2) R. V. E. Lovelace, J. M. Sutton & E. E. Salpeter, *Nature*, **222**, 231, 1969.
(3) H. D. Craft, J. M. Sutton & R. V. E. Lovelace, *Nature*, **219**, 1237, 1968.
(4) T. Gold, *Nature*, **218**, 731, 1968.
(5) R. V. E. Lovelace, J. M. Sutton & H. D. Craft, *IAU Astronomical Telegram Circular*, no. 2113, 1968 November 18.
(6) J. M. Comella *et al.*, *Nature*, **221**, 453, 1969.
(7) D. H. Staelin & E. C. Reifenstein, *IAU Astronomical Telegram Circular*, no. 2110, 1968 November 6.
(8) D. H. Staelin & E. C. Reifenstein, *Science*, **162**, 1481, 1968.
(9) D. Richards, *IAU Astronomical Telegram Circular*, no. 2114, 1968 November 25.
(10) T. Gold, *Nature*, **221**, 25, 1969.