construction offers wide ranging experimental as well as practical opportunities.

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LETTERS TO NATURE

A millisecond pulsar

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The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 arc s, despite its low galactic latitude (−0.3°)[1]. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim\nu^{-2}$) spectrum at decametric wavelengths[2]. This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

A literature search in 1979 led to the suggestion that the steep-spectrum, IPS source was superposed on a flat-spectrum ($\nu^{-0.1}$) object with a diameter of ~60 arc s located to the west of the 4C position by one interferometer lobe (−31.6 s). Lobe identification errors in the 4C catalogue can occur in regions of confusion such as the galactic plane.

The superposition of two source components, one very compact with a steep spectrum and the other extended with a flat spectrum, was reminiscent of the radio properties of the Crab nebula and its pulsar in the pre-pulsar era[3]. The conjecture was made that the compact component in 4C21.53W was a pulsar as yet undetected due to pulse broadening of its radiation over one period by interstellar scattering. However, the IPS measurement placed an upper limit on interstellar scattering which, in turn, placed a limit on the pulse broadening. The conclusion was that only a very short period pulsar, $P \leq 10$ ms, would have been missed in metre wavelength searches owing to this effect. Searches for such a short period pulsar at centimetre wavelengths, where pulse broadening would be much reduced, were conducted at Arecibo Observatory and at Owens Valley Radio Observatory in 1979 without success.

After the 1979 pulsar searches, Erickson (personal communication) located a steep-spectrum compact source, 4C21.53E, east of the 4C position by one 4C interferometer lobe (+31.6 s). This observation provided evidence against the superposition hypothesis. Furthermore, Very Large Array (VLA) observations at 5 GHz by one of us (D.C.B.) showed that 4C21.53E was a compact double source with separation of 0.8 arc s.

Interest in the extended western object, 4C21.53W, returned when decametric observations at the Clark Lake Radio Observatory showed that both 4C21.53E and 4C21.53W had very steep spectra below 100 MHz (ref. 4). In addition, the Clark Lake observations indicated that the western source showed IPS at 34 MHz. The inferred brightness temperature exceeded $>10^{12}$ K.

Observations of 4C21.53W with the Westerbork Synthesis Radio Telescope (WSRT) at 609 MHz in January 1982

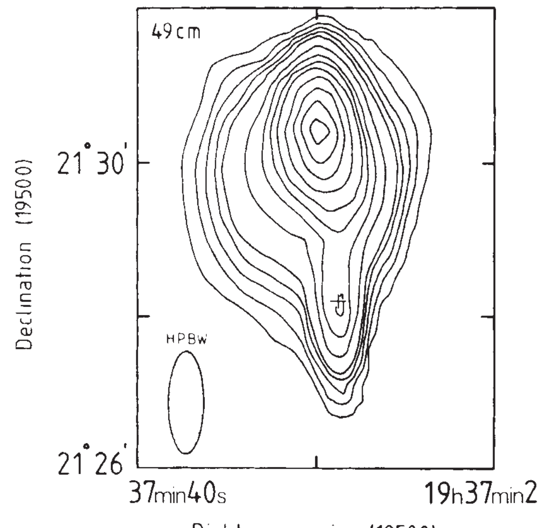

Fig. 1 Image of extended (north) and compact (south, +) components of 4C21.53W from a 12-h synthesis with the WSRT at 608.5 MHz on 15 January 1982. The synthesized beamwidth shown at the lower left is 31.3 × 80.4 arc s in RA and Dec, respectively.

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Table 1 Flux densities of 4C21.53W

Frequency (MHz)	Instrument	Total flux density (Jy)	Compact flux density (Jy)	Compact polarization (%)	Extended flux density (Jy)
430	Arecibo	1.60 ± 0.30	~0.3*	—	~1.3 ± 0.30
609	WSRT	1.15 ± 0.05	0.130	28 ± 2	1.02 ± 0.05
1,380	Arecibo	0.96† ± 0.05	~0.02*	—	0.94 ± 0.05
1,415	WSRT	0.93 ± 0.02	0.017	15 ± 2	0.91 ± 0.02
2,380	Arecibo	0.90† ± 0.05	—	—	0.90 ± 0.05
5,000	Bonn[6]	0.91†	—	—	0.92

* Estimated from compact source spectral index between 609 and 1,415 MHz.
† Corrected for beam sizes.

confirmed a suspected position discrepancy based on a Culgoora measurement at 80 MHz (ref. 5) and a Bonn measurement at 5,000 MHz (ref. 6) (Fig. 1). We suspected that the Culgoora position was dominated by the steep-spectrum component and that the Bonn position was dominated by the flat-spectrum, extended component. The division of 4C21.53W into two components, evident in Fig. 1, confirmed our suspicion. The southern and northern components were named 4C21.53W(com) or 1937+214 and 4C21.53W(ext) or 1937+215, respectively. A brief observation at the VLA confirmed the position and steep spectrum of 1937+214. A map of 4C21.53W at 1,415 MHz from a 12-h observation with the WSRT in August 1982 clearly resolved the compact and extended source component (Fig. 2). Recent WSRT observations and 1979 total power observations from Arecibo are summarised in Table 1. The spectra are decomposed into compact and extended object contributions. The Bonn measurement[6] is included for completeness. Erickson's decametric observations of this source are reported elsewhere[7].

The spectrum of the extended source is approximately that of an H II region, $\nu^{-0.1}$. The H 166α recombination line was detected at the Arecibo Observatory at the position of the extended source in November 1982. The line temperature is ~1% of the continuum temperature. The velocity of the line is +2 km s^{-1} and its FWHM is ~25 km s^{-1}. These properties are comparable with those of an ordinary H II region. The small velocity does not distinguish between kinematic distances of 0 and 8.5 kpc.

The proximity of these two components of 4C21.53W on the sky suggests a possible physical connection. The morphology of the 21-cm continuum maps indicates that the exciting star may be displaced 43 arc s northwards from the centre of the H II region defined by the near-circular, low-level contours. On the other hand, the compact source is displaced 117 arc s southward from the centre. We will return later to the possible connection between these objects.

Interest in further pulsar searches was rekindled following the discovery of a steep-spectrum component in 4C21.53W at decametric wavelengths[4]. Momentum for the search increased when the 609-MHz WSRT map was available. A pulsar search sensitive to periods >4 ms was carried out by Boriakoss (personal communication) at the Arecibo Observatory in March 1982 without success. Detection in September 1982 of strong linear polarization at the compact source position in the WSRT maps made a pulsar detection a near certainty.

A new pulsar search was conducted with the 305-m antenna at the Arecibo Observatory on 25 September 1982 at the position of the compact 15 mJy component detected in the 1,400-MHz synthesis observations. Two harmonics of a millisecond periodicity, 1.558 ms, were discovered at the compact source position. The signal was present for only 3 min of a 7 min sample, and was not seen on a following day at either 1,400 or 2,380 MHz.

In November 1982 the pulsar search was intensified at Arecibo. In addition, we planned a search for interstellar scintillation (ISS) based on the possibility that the compact object was small, but not pulsing. Deep ISS modulation was detected at 1,400 MHz at the position of the compact source (Fig. 3). The amplitude was consistent with the flux density found in synthesis observations. The frequency and time correlation lengths, roughly 2 MHz and 5 min, respectively suggested a relatively small dispersion measure to the object, <100 electrons pc cm^{-3}. This observation indicated immediately that the compact source 4C21.53W(com) or 1937+214, was extremely small as only pulsars have shown ISS previously. In addition, the modulation bandwidth and time scale were consistent with the single detection in September. On the following day the millisecond pulsar was confirmed.

The waveform of the pulsar contains a main pulse and an interpulse of comparable intensity separated by ~180° (Fig. 4). This morphology repeats precisely the main pulse/interpulse morphology of the Crab pulsar. The Crab pulsar has an additional 'precursor' component preceding its main pulse at metre wavelengths. The full widths at half intensity of the pulse components in Fig. 4 are <125 μs, or 8% of the period. The pulses are readily detected with the Arecibo telescope at 1,400 and 430 MHz with a fast signal averager and integrations of a few hundred pulses when positioned on a peak of the ISS modulation pattern (Fig. 3). The waveforms at both frequencies are similar.

The first observations have resulted in the following parameters: RA (1950.0) 19h 37 min 28.72 s, Dec (1950.0) 21° 28′ 01.3″, Barycentric period 0.001 557 807 (JD 244 5282), Dispersion measure 75 electrons pc cm^{-3}. The accuracy of all values is a few parts in the last decimal place. The distance is estimated as 2,500 pc using an average n_e of 0.03 cm^{-3}. There is no evidence for binary motion in timing measurements during the second week in November. Timing observations have been

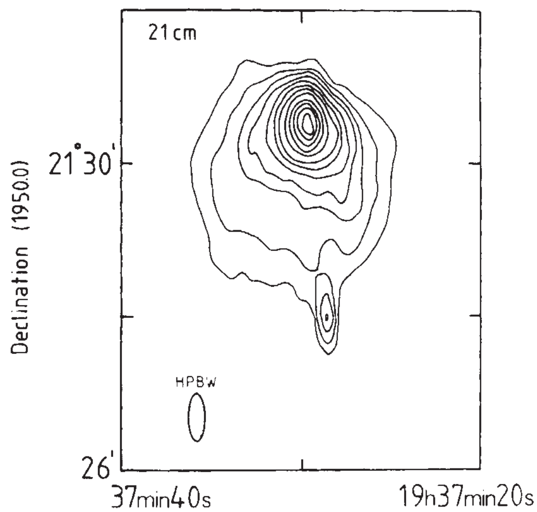

Fig. 2 Image of extended (north) and compact (south) components of 4C21.53W from a 12-h synthesis observation with the WSRT at 1,415 MHz on 8 August 1982. The synthesized beamwidth shown at the lower left is 13.3×37.0 in RA and Dec respectively.

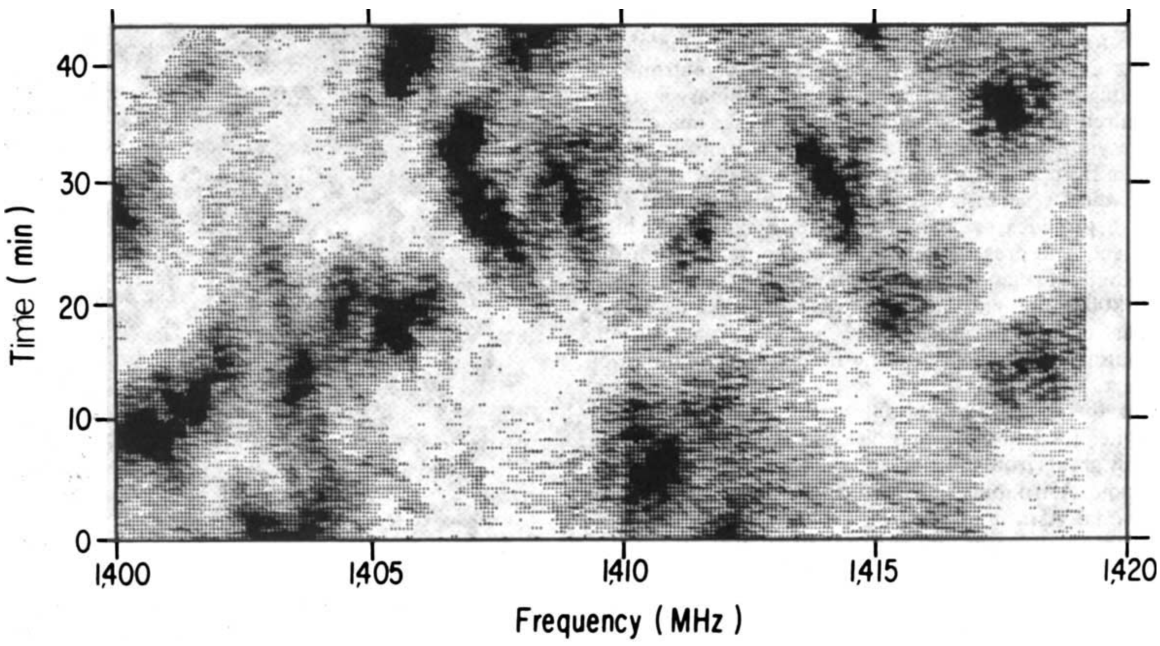

Fig. 3 Interstellar scintillation observation of compact component in 4C21.53W from Arecibo observations on 6 November 1982. Individual spectra were obtained for two polarizations in two 10-MHz bands every 30 s using a 252-channel, 1-bit autocorrelator. Spectra from the two polarization channels were summed and smoothed to a resolution of 100 kHz. The peak intensity in this dynamic spectrum is ~50 mJy.

initiated to determine the period derivative at the Arecibo Observatory. A previous estimate of the period derivative[8], based on a comparison of measured periods in September and November, has not been substantiated by timing data in November. We suspect that the September measurement was corrupted by sampling errors. Analysis of the November observations results in an upper limit to $\dot{P}$ of 10^{-15} s per s.

Our original hypothesis that 4C21.53W was a fast pulsar superposed on an extended synchrotron-emitting nebula was only half correct. Now we are faced with a more profound enigma: the existence of a pulsar rotating near the maximum rate possible for a neutron star with a surprising lack of evidence of energetic activity in the vicinity of the pulsar.

The present rotation rate, 642 Hz, is very near the maximum rate of 2,000 Hz where centrifugal forces balance gravitational forces at the surface of a 1 $M_{\odot}$ neutron star with 10 km radius. Matter on the equator would have a velocity of $0.13c$. Changes in the equilibrium figure of the pulsar resulting from energy losses to magnetic dipole and gravitational quadrupole radiation (discussed below) may occur as abrupt starquakes if there is such a close balance between gravitational and centrifugal forces. The balance could be tipped in favour of gravity if the pulsar is denser than $\Omega^2/G \sim 2\times10^{14}$ g cm^3. The amplitude and frequency of starquakes, observable in pulse arrival time measurements, may be able to distinguish between standard (1 $M_{\odot}$) and high density models for the millisecond pulsar.

The present rotational energy content is 7×10^{51} erg for a neutron star moment of inertia 10^{45} g cm^2. This energy is comparable to the entire mechanical energy output of a supernova event. A higher density star, as suggested above, could reduce the present energy content if its moment of inertia were smaller than 10^{45} g cm^2. Both the rapid spin and the large energy content are indicative of a young object as energy losses to magnetic dipole and gravitational quadrupole radiation are strong functions of the rotation rate, Ω^4 and Ω^6, respectively[9]. The minimum energy loss for this pulsar will be the observed radio emission which amounts to 3×10^{30} erg s^{-1} assuming a beam solid angle of 1 sr.

The age of this pulsar is puzzling. The maximum spin rate for a neutron star is ~2,000 Hz. A model for the Crab pulsar by Ostriker and Gunn[9] predicts a period decay from this rate to 100 Hz in 1 yr due to gravitational quadrupole radiation. We do not observe such a rapid decay. Furthermore, there is a surprising absence of evidence of any debris from a recent neutron star formation event. Our radio maps show no synchrotron-emitting nebula in the vicinity of the pulsar. Einstein observations place a limit of 1.5×10^6 K for the surface temperature of a neutron star at the pulsar position for the indicated distance of 2 kpc, and exclude the possibility of a synchrotron nebula (D. J. Helfand, personal communication). These X-ray limits do not allow for possible heavy extinction. There is no source at the pulsar position in the COS B catalogue[10]. Lick Observatory observations reveal a 20 mag optical star at the position of the pulsar[11]. In direct analogy to the Crab pulsar, we expect this object will show optical pulsations.

We conclude that despite the large spin and rotational energy, this pulsar is not young. Evidently it has found a way to preserve a large fraction of its orignal energy. Minimal energy loss requires low values for the perpendicular magnetic dipole moment and the gravitational quadrupole moment. The first binary pulsar, 1913+16, is an example of a rapidly rotating neutron star (17 Hz) with a very low moments based on period derivative measurements. Observations of the spin decay will determine the dominant energy loss mechanism.

Two factors lead us to suggest that the pulsar and the H II region are related: (1) The two objects are in the same area of sky in a region of relatively low radio confusion. (2) The brighterst part of the H II region and the pulsar are displaced to opposite sides of the near circular, low-level contours of the H II region.

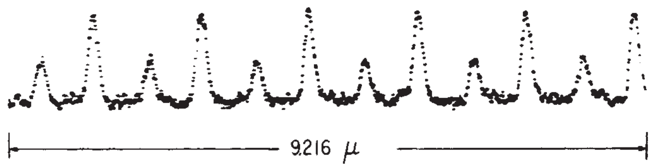

Fig. 4 Waveform of the millisecond pulsar from a signal averager oscilloscope display. Sample spacing is 9 μs. The full trace is roughly six periods, 9,216 μs. The integration lasted ~75 s. The waveform consists of a main pulse and an interpulse separated by nearly 180° of rotational phase. Errors in timing the signal averager and a 20 μs RC time constant are responsible for most of the pulse width.

We propose that the pulsar and the exciting star of the H II region were formerly members of a binary system. One of the components evolved and went through a quiet neutron-star formation stage. Formation of neutron stars in binary systems is also required to explain X-ray and radio pulsar binaries. A large and asymmetric energy and momentum transfer to the neutron star from the other component must have provided the escape velocity necessary to disrupt the binary orbit. This transfer also provides a means for creating a massive, high density object. The present separation of the pulsar from the centre for the H II region suggests an epoch for the disruption event of 7,800 yr ago and a distance of 2 kpc if we assume a typical pulsar transverse velocity of 150 km s^{-1}. Proper motion of the pulsar would be southward in declination of 0.015 arc s yr^{-1}.

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Optical identification of the millisecond pulsar 1937+214

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Backer *et al.*[1] have reported the discovery of a pulsar with the period of 1.558 ms, identified with the source 1937+214 (=4C21.53). The extreme rotational velocity and high energy loss rate of this object make it a very interesting astrophysical phenomenum not only as an important clue for the physics of neutron stars and supernova remnants, but also as a potential strong emitter of gravitational radiation (S. White and J. Arons, personal communication). I present here an optical identification candidate for the millisecond pulsar: it is a 20th mag red object, undetectable on the Palomar Sky Survey prints. Finding charts and offsets from nearby stars are given.

The data were obtained on the night of 14 October 1982 UT, on the Lick Observatory 1-m telescope, in conditions of good seeing (FWHM≅1 arc s). A red-sensitive TI 500×500 thin CCD was used as a detector, together with a sky-suppression red filter, purchased earlier by H. Spinrad. This wide red bandpass has an effective wavelength at about 6,500 Å and the width of ~1,400 Å. Three CCD exposures, one of 300 s and two of 600 s, were obtained. The frames were flatfielded with a 'dome flat', filtered to remove cosmic ray events, and had bad columns masked (standard CCD reduction procedure). The three frames were then offset into coincidence, and digitally stacked together, to increase the signal-to-noise ratio.

Part of the resulting image containing the object is shown in Fig. 1. Figure 2 shows a slightly larger region, enhanced by a new, highly nonlinear algorithm, which will be described elsewhere. The candidate object was found on all three CCD frames, although only the stack is shown here. Figure 3 shows a much larger field, as enlarged from a Palomar print.

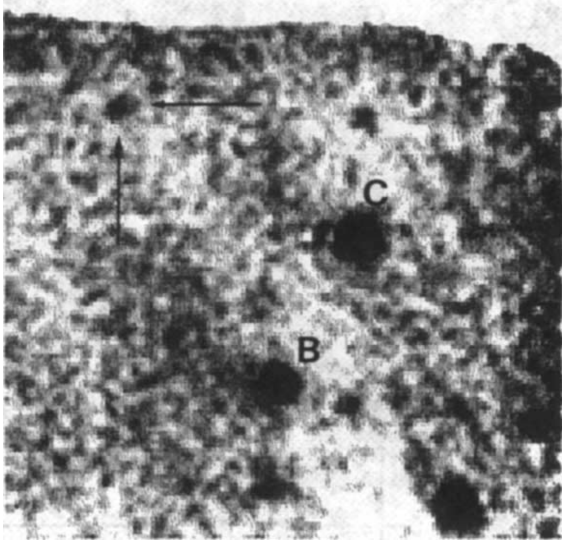

Fig. 1 A section of the CCD stack frame. The pulsar candidate is marked with the arrows. Stars B and C are those from Table 1. The field size is about 50 arc s, the pixel size 0.38 arc s. North is up, east to the left.

I have performed aperture photometry on the digital data of this source. In a pseudo-diaphragm of 6 arc s diameter, I obtain

$$m_r = 20 \pm 1$$

(the error may be an overestimate). The zero-point of the photometry was determined from a standard star, Feige 15, whose exposure was taken immediately after the pulsar field exposures. There is no extended emission associated with this source, down to the limit of these data.

I have also searched for the extended source (H II region ?), detected in radio observations, a few arc min to the north from the pulsar, and apparently associated with it. The result of this attempt was negative, but my data (one 600-s exposure) are of insufficient quality to place any interesting limits on the possible existence of extended optical structure there.

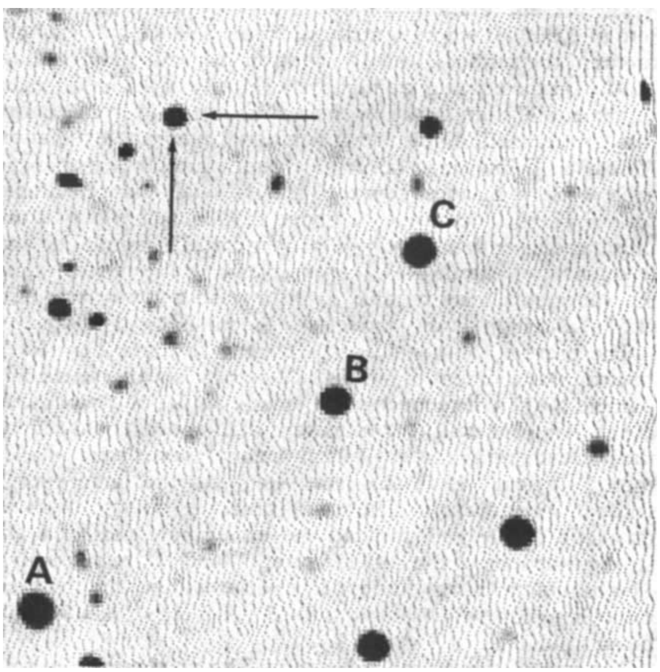

Fig. 2 Similar to Fig. 1, but strongly enhanced with a new, nonlinear technique. The field size is about 1 arc min. Faint 'objects' are not to be seriously believed.

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