A 3.5-Gyr-old galaxy at redshift 1.55

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One of the most direct methods of constraining the epoch at which the first galaxies formed—and thereby to constrain the age of the Universe—is to identify and date the oldest galaxies at high redshift. But most distant galaxies have been identified on the basis of their abnormal brightness in some spectral region[1–4]; such selection criteria are biased towards objects with pronounced nuclear activity or young star-forming systems, in which the spectral signature of older stellar populations will be concealed. Here we report the discovery of a weak and extremely red radio galaxy (53W091) at $z = 1.55$, and present spectroscopic evidence that its red colour results from a population of old stars. Comparing our spectral data with models of the evolution of stellar populations, we estimate that we are observing this galaxy at least 3.5 Gyr after star-formation activity ceased. This implies an extremely high formation redshift ($z > 4$) for 53W091 and, by inference, other elliptical galaxies. Moreover, the age of 53W091 is greater than the predicted age of the Universe at $z = 1.55$, under the assumption of a standard Einstein–de Sitter cosmology (for any Hubble constant greater than 50 km s^{-1} Mpc^{-1}), indicating that this cosmological model can be formally excluded.

It is relatively easy for a short-lived burst of star-formation[5], or re-processed light from an active nucleus[6,7], to dominate the appearance of a galaxy in the rest-frame optical–ultraviolet, concealing the presence of an older underlying stellar population[8]. It is thus the reddest objects at a given redshift which are of greatest importance for constraining the first epoch of galaxy formation[9–11], and the correlation between the ultraviolet and radio properties of powerful radio galaxies[12,13] indicates that radio-based searches for passive elliptical galaxies at $z > 1$ should be confined to millijansky flux-density levels. We are therefore investigating the properties of radio galaxies with flux densities at 1.4 GHz $S_{1.4\mathrm{GHz}} > 1$ mJy selected from the Leiden–Berkeley deep survey (LBDS) and its extensions[14–17]. We now possess optical–infrared photometry down to $V \approx 26$ mag and $K \approx 20$ mag for a complete sample of 77 galaxies, enabling us to estimate redshifts both from spectral fitting[13] and from a modified version of the infrared Hubble diagram[18]. From this sample we have isolated a subset of 10 extremely red ($R - K > 5$) potentially high-redshift (estimated redshift $z_{\mathrm{est}} > 1.5$) objects for intensive spectroscopic study.

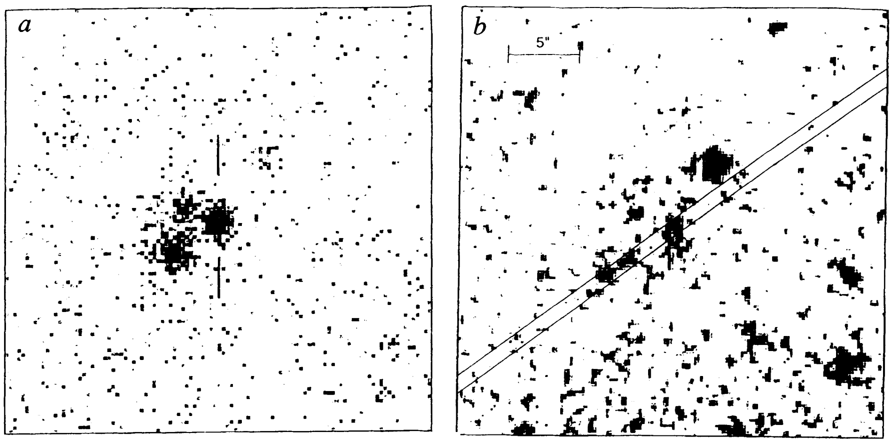
The galaxy 53W091, one of the reddest in the sample ($R = 24.6 \pm 0.20$ mag and $K = 18.75 \pm 0.05$ mag within a 4-arcsec aperture) was observed for 1.5 hours on 25 July 1995 with the Low Resolution Imaging Spectrograph (LRIS) on the 10-m W. M. Keck Telescope on Mauna Kea, Hawaii. This observation yielded the detection of a faint and very red continuum, but no emission-line redshift. Therefore, in an attempt to constrain the galaxy redshift, we obtained deep J- and H-band images with IRCAM3 on the United Kingdom Infrared Telescope in August 1995. The ease with which the galaxy was detected at J and H ($J = 20.5 \pm 0.1$ mag, $H = 19.5 \pm 0.1$ mag; Fig. 1*a*) revealed that, if its red $R - K$ colour was in part due to a redshifted 4,000 Å break (the most prominent spectral feature displayed by an old stellar population at optical wavelengths), this feature must lie at observed wavelength $\lambda_{\mathrm{obs}} < 1.2\,\mu$m, constraining the redshift to $z < 2$.

Finally, on 31 August and 1 September 1995 we re-observed 53W091 for a total of 4 hours, again with LRIS on the 10-m Keck Telescope (Fig. 1*b*). The spectrum produced by co-adding all 5.5 hours of integration is shown in Fig. 1*c*, plotted in the rest frame of the radio galaxy assuming $z = 1.552$. This unambiguous redshift was deduced from numerous absorption lines and two strong spectral breaks (at rest wavelength λ_{rest} =2,635 and 2,897 Å), features whose existence in the near-ultraviolet spectrum of the Sun and other low-mass dwarfs is long-established[19], and which are evident in the ultraviolet spectra of low-redshift ellipticals such as M32 (Fig. 1*c*). This is, to our knowledge, the first time that such a high galaxy redshift has been derived successfully from late-type absorption features; indeed, with $V \approx 26$ mag, this is probably the faintest galaxy for which an absorption-line redshift has ever been determined.

The strength of such stellar features combined with the lack of detectable emission lines (Mg II is seen in absorption, in contrast to the situation in 3C65 (ref. 9)) indicates that the ultraviolet–optical light from radio galaxies selected at milijansky flux densities is essentially free from the contaminating effects (either direct or indirect) of their active nuclei. Moreover, the similarity of this near-ultraviolet spectrum to that of low-mass main-sequence stars suggest that the red optical–infrared colour of this galaxy results from an evolved stellar population rather than, for example, a significant contribution from a dust-obscured quasar[20–22] (a viewpoint supported by the very similar appearance of 53W091 at optical and infrared wavelengths; Fig. 1).

To investigate the extent to which our data can constrain the age of 53W091, we first calculated the best-fit age produced by an updated version of the evolutionary synthesis models of Guiderdoni and Rocca-Volmerange[23]. Considering a model in which 53W091 is formed in a single burst of star-formation and evolves passively thereafter, we find that the observed optical spectrum and the infrared colours ($R - K = 5.8, J - K = 1.7, H - K = 0.8$) are all perfectly reproduced by the models only at a time of 4 Gyr after cessation of star-formation activity. Next, we considered the most recent versions of the models of Bruzual and Charlot[24]. It is known that red optical–infrared colours are produced more rapidly by these models, and indeed we found that at $z = 1.55$ the observed optical–infrared colour is reproduced after only 1.5 Gyr. But the dependence of $R - K$ colour on age is controversial (see below) and so it was with interest that we found these same models could not reproduce the shape of the Keck spectrum until an age >3 Gyr, while to produce spectral breaks at $\lambda_{\mathrm{rest}} = 2,635$ and 2,897 Å of the strength observed in 53W091 requires an age >4 Gyr. Third, we considered the models of Bressan, Chiosi and Fagotto[25], which, assuming solar metallicity, yielded a best-fit age of 3 Gyr (again in good agreement with the above results).

We derived ages using these three alternative models of galaxy evolution because it is well known that different models can produce significantly different ages from a given set of data[26]. But much of the difference between these models lies in different treatments of post-main-sequence evolution, and although this is expected to have a significant effect on the predicted infrared–optical luminosity of the galaxy, its effect on the predicted near-ultraviolet spectral energy distribution (SED) should be minimal (an expectation apparently borne out by the fact that all three models are in good agreement over the age required to reproduce the ultraviolet SED). Indeed, because it is well documented that the near-ultraviolet spectrum ($\lambda < 3,000$ Å) of a stellar population with an age of a few Gyr should be determined simply by the



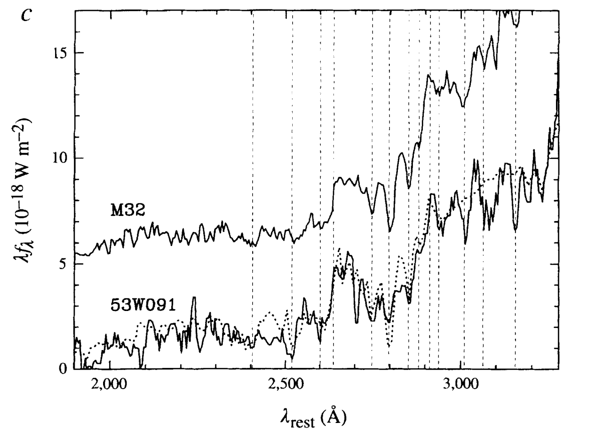


FIG. 1 Imaging and spectroscopy of 53W091. *a*, An infrared image of 53W091 produced by combining the IRCAM3 J- and H-band images. The field is 30-arcsec square and the radio galaxy identification is indicated by two bars. The position of this object is coincident with the centroid of the radio source (right ascension 17 h 21 min 17.81 s, declination $+50^\circ 08' 47.5''$ (1950)) to within 0.5 arcsec. *b*, A 10-minute R-band image of the same field taken with the 10-m Keck Telescope, with lines superimposed to indicate the position and orientation of the LRIS slit which was used to obtain the optical spectrum. The position of the optical identification is coincident, to within the errors, with that of the near-infrared identification (in contrast to the highly wavelength-dependent morphologies often displayed by more powerful high-redshift galaxies such as 3C324[8]). In this 1-arcsec seeing optical image the radio galaxy is resolved, with a deconvolved full-width at half-maximum of 1.3 arcsec. The orientation of the LRIS slit (126°) was chosen to be close to the parallactic angle (which varied between 100° and 150° during the spectroscopic observations) and to enable a spectrum to also be obtained of a second red galaxy which lies a few arcsec southeast of 53W091. This galaxy appears to be at the same redshift as 53W091, ($z = 1.55$), and, interestingly, has an almost identical SED, providing further circumstantial evidence that the optical–infrared properties of 53W091 are essentially unaffected by its active nucleus. At radio wavelengths, 53W091 is a steep-spectrum source ($\alpha^{0.61\rm GHz}_{1.41\rm GHz} = 1.3 \pm 0.13$, where $f_\nu \propto \nu^{-\alpha}$) with $S_{1.41\rm GHz} = 22.5 \pm 1.0$ mJy (ref. 17), and is extended (by ~4 arcsec) along a position angle of 131° (ref. 16). *c*, The 5.5-h Keck spectrum of 53W091 (lower solid line) from 25 July, 31 August and 1 September, plotted in terms of rest wavelength (assuming $z = 1.552$) and compared both with the (scaled) ultraviolet spectrum of the nearby elliptical M32 (upper solid line) and with the best-fitting model spectrum (dotted line). (The model spectrum was produced by synthesizing the spectrum produced by a Scalo IMF with a main-sequence turn-off mass of $1.35 M_\odot$ (equivalent to spectral type F2), corresponding to an age of 3.5 Gyr.) The data for M32 and 53W091 have been rebinned to the same (5 Å) resolution, with an additional median smooth being applied to the latter. For ease of comparison, the spectrum of M32 has been scaled to the same amplitude as that of 53W091 at $\lambda_{\rm rest} = 2,897$ Å and then offset vertically by 5×10^{-18} W m^{-2}. The unambiguous nature of the redshift is demonstrated by the existence of at least 11 absorption features and two strong spectral breaks in the spectrum of 53W091 (indicated by vertical dashed lines) which are all reproduced in the rest-frame spectrum of M32 (in particular the 'top-hat' feature between 2,640 and 2,750 Å is a feature unique to this spectral range, and rules out the (remote) possibility that the break observed at 7,400 Å could be the 4,000 Å break at lower redshift). These features (all except the reddest three of which are also reproduced in the model spectrum) are essentially those which are seen in the near-ultraviolet spectra of F and G stars, as can be judged by comparison with the near-ultraviolet spectrum of the Sun[19], vindicating our belief that the red colours of the millijansky radio galaxies are a result of their evolved stellar populations. Such features have not been detected before in the spectrum of a high-redshift galaxy, not even in the Keck spectrum of the reddest powerful radio galaxy at $z \sim 1$, 3C65, in which they are apparently swamped by broad Mg II emission[11].

turn-off point of the main sequence[27], and as the main-sequence lifetime of A → G stars is probably the best understood area of stellar evolution, it should be possible to date 53W091 in an appealingly model-independent manner by simply determining the spectral type of the main-sequence turn-off point. We have therefore used the latest stellar atmosphere models of Kurucz[28] to investigate the spectra produced by main-sequence stars at a variety of ages, and find that the single stellar spectral type which best describes the near-ultraviolet light from 53W091 between $\lambda \approx 2{,}000$ and 3,500 Å is F5 (with an effective temperature $T_{\rm eff} = 6,500$ K). Furthermore, an independent comparison with the International Ultraviolet Explorer satellite spectra of stars of various spectral types produces exactly the same result. However, to set a realistic limit on the age of this galaxy, one must integrate over the initial mass function (IMF) of stars from very low masses ($\sim 0.1 M_\odot$) up to the stellar mass at which the synthesized spectrum becomes unacceptably blue. Assuming a Scalo IMF[29], we find that the best-fitting main-sequence turn-off point occurs at spectral type F2 ($T_{\rm eff} = 6,900$ K), equivalent to a stellar mass of $1.35 M_\odot$. The main-sequence lifetime of a star of this mass is well established (to within 5%) to be 3.5 Gyr. Such an age is reassuringly consistent with the ages indicated by the different evolutionary synthesis codes considered above, and the fact that this simple model provides such an excellent description of the data confirms that we are justified in ignoring the contribution of post-main-sequence stars (Fig. 1*c*).

We have considered carefully the robustness of our result, paying particular attention to the ways in which we could possibly have over-estimated the age of 53W091. First, if the validity of the models at near-ultraviolet wavelengths is accepted, an age younger than 3 Gyr is strongly excluded by the overall shape of the ultra-violet SED of 53W091 (Fig. 2*a*). Of course, the inferred age may in principle be reduced by truncating the stellar IMF at almost exactly $1.35 M_\odot$, but this requires considerable fine tuning (any significant population of A stars will dominate the spectrum for ~3 Gyr) and, if true, it would be expected that the galaxy would display other signs of youth, such as strong emission lines which are not seen.

Second, an independent check of our derived age is provided by comparing the ultraviolet properties of 53W091 with those of nearby early-type galaxies whose ages have been determined by other means. In Fig. 2*b* the normalized rest-frame ultraviolet SED of 53W091 is compared with the IUE spectra of M32 and NGC2681[30]. Recent studies of M32 both at optical[31] and ultraviolet[27] wavelengths agree that the most recent star-formation activity in this galaxy occurred 4–5 Gyr ago, whereas in NGC2681 star formation appears to have ceased 1–2 Gyr before the epoch of observation[32]. The level and shape of the rest-frame ultraviolet SED of 53W091 is undoubtedly more like that of M32, again consistent with an age of 3–4 Gyr for this high-redshift galaxy.

A third concern is that in comparing the ultraviolet SED of 53W091 both with models and with nearby ellipticals we may have over-estimated the age of 53W091 by ignoring the possible reddening effect of dust. But if this were the case, then it would be expected that reddening-independent features such as the strengths of the spectral breaks at $\lambda = 2{,}635$ Å, 2,897 Å would indicate a younger age. In fact these two features in the spectrum of 53W091 appear stronger than the corresponding breaks in the ultraviolet spectrum of M32, and when compared with the predictions of the main-sequence model, each break independently yields an age >3.5 Gyr (Fig. 2*c*). This impressive agreement leads us to conclude that although a dusty torus may be present in the centre of this galaxy (obscuring the active nucleus) its effect on the integrated starlight of the galaxy is negligible.

The only remaining issue is the sensitivity of the derived age to the assumed value of metallicity. We have therefore investigated the effect of varying the metallicity both in our own main-sequence models, and in the full spectral synthesis code of Bressan. Both models yield very similar results; the derived age increases to 4.5 Gyr if 1/5 of solar metallicity is assumed, but is reduced by 0.5 Gyr (to 3 Gyr) if the metallicity is doubled to twice solar (Fig. 2*c*). Thus, although the age–metallicity degeneracy is hard to break (similar results are obtained by fitting either to the overall SED or to the strength of the two breaks), we conclude that very large values of metallicity are required to reduce the derived age of 53W091 to less than 3 Gyr.

Having considered the ways in which we might have over-estimated the age of 53W091, we should stress that we regard it as more plausible that 3.5 Gyr may be a significant under-estimate of the true age of this galaxy. First, the spectral breaks indicate a larger age. Second, and more importantly, all of the model fits discussed above assume that this large elliptical galaxy was formed in an instantaneous burst after which star-formation completely ceased; if one assumes a burst of significant duration, or subsequent star-formation activity the derived age increases accordingly (for a 1-Gyr formation starburst, the best-fit age is 4.5 Gyr even if solar metallicity is assumed).

We now consider briefly the far-reaching implications of a 3.5-Gyr-old galaxy at $z = 1.55$. This is the first time that such an unambiguously old object has been discovered at such large look-back times, and its existence sets strong constraints both on the first epoch of galaxy formation and on cosmological models. The

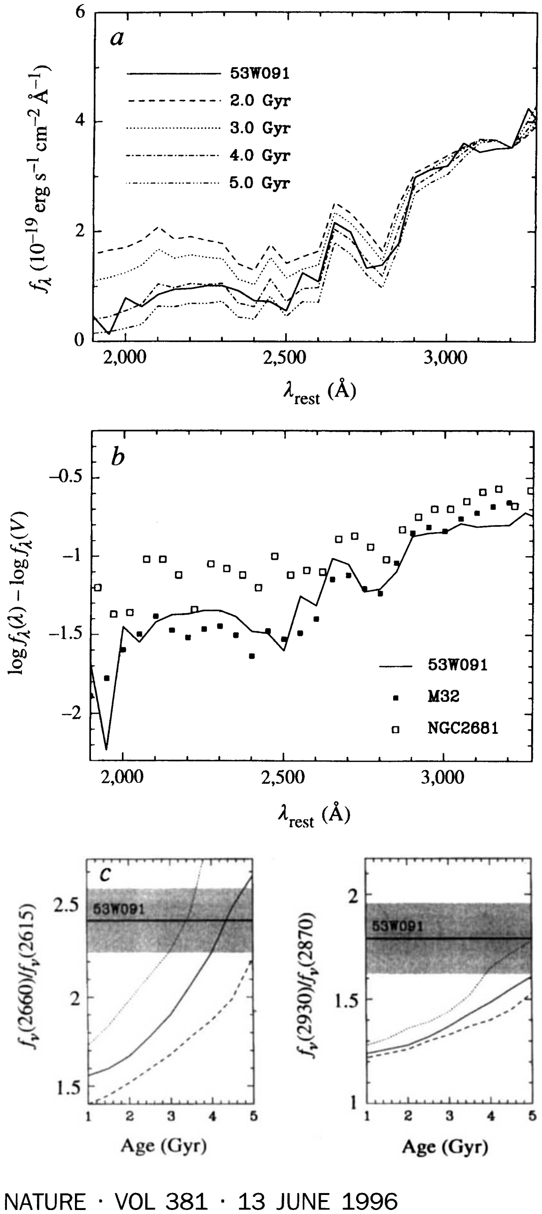


FIG. 2 Constraints on the age of 53W091. *a*, The spectrum of 53W091 (solid line), binned to a resolution of 50 Å, plotted in terms of f_λ, and compared with the SED produced by the passively evolving main-sequence model at ages of 2, 3, 4 and 5 Gyr after cessation of star-formation activity. The model spectra have been normalized to the observed flux density at 3,200 Å to illustrate why ages $\leqslant 3$ Gyr can be formally rejected at a high level of significance on the basis of the overall shape of the ultraviolet SED. Models younger than 3 Gyr overpredict the flux density at $\lambda \approx 2{,}100$ Å by $\sim$100% (the relative flux-calibration of the spectrum is accurate to $\sim$10–15% across the full wavelength range). We stress that, in the regime of interest here, the connection between the spectral type of the main-sequence turn-off point and age is well-established (to within 5%), because stellar ages for main-sequence stars in the mass range 1–1.5$M_\odot$ are essentially unaffected by uncertainties such as assumed mass loss, choice of convection theory or equation of state, and the opacities in the corresponding temperature range are well known. *b*, The spectrum of 53W091 (solid line), binned to a resolution of 50-Å, and this time plotted in terms of $\log f_\lambda(\lambda) - \log f_\lambda(V)$ to allow direct comparison with the normalized ultraviolet SEDs of two nearby early-type galaxies, M32 (filled squares) and NGC2681 (open squares)[30]. The rest-frame V-band flux density, $f_\lambda(V)$, of 53W091 was determined from a weighted average of the observed J- and H-band flux densities, measured through an aperture equivalent to that used in the flux calibration of the optical spectrum. Recent studies of M32 both at optical[31] and ultraviolet[27] wavelengths are in agreement that the most recent star-formation activity in this galaxy occurred 4–5 Gyr ago, whereas in NGC2681 star formation appears to have ceased 1–2 Gyr before the epoch of observation[32]. The level and shape of the rest-frame ultraviolet SED of 53W091 is more like that of M32, consistent with an age of 3–4 Gyr for this high-redshift galaxy. *c*, The observed strength of the spectral breaks at 2,635 Å (left-hand plot) and 2,897 Å (right-hand plot) compared with the break strengths predicted by the evolving main-sequence model as a function of age for three different choices of metallicity—solar (solid line), twice solar (dotted line) and 0.2× solar (dashed line). In each plot the horizontal line indicates the break strength as measured from the spectrum shown in Fig. 1*c*, and the shaded area indicates the uncertainty in this estimate. The strength of the breaks in both the data and the models was determined from the ratio of the average value of f_ν in 30-Å bins centred on the two wavelengths indicated on the vertical axis of each plot. Based on the (reddening-independent) strength of these features the inferred age of 53W091 is >4 Gyr, and it is hard to reconcile the data with an age younger than 3 Gyr even if one assumes super-solar metallicity. The observed strengths of the corresponding breaks in the observed spectrum of M32 are 1.6 and 2.1 respectively, consistent with an age of $\sim$4 Gyr.

age of the Universe at this epoch is $1.6h^{-1}$ Gyr if $\Omega = 1$, increasing to $2.7h^{-1}$ Gyr for $\Omega = 0.2$, or at most $3.5h^{-1}$ Gyr for $\Omega = 0.2$, $\Lambda = 0.8$ ($h \equiv H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). Obviously the Einstein–de Sitter model is in difficulty, and even in a low-density Universe an age >3 Gyr at $z = 1.55$ requires a formation redshift $z_f > 4$ (for $h = 0.65$). It thus seems clear that at least some galaxies formed at redshifts greatly in excess of the recent formation era inferred from data on field galaxies[33], and the existence of similarly old galaxies at still higher redshifts would potentially allow one to infer a non-zero cosmological constant. □

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1. McCarthy, P. J. *A. Rev. Astr. Astrophys.* **31,** 639–688 (1993).
2. Steidel, C. C., Pettini, M. & Hamilton, D. *Astr. J.* **110,** 2519–2536 (1995).
3. Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M. & Adelberger, K. L. *Astrophys. J.* **462,** L17–L20 (1996).
4. Petitjean, P., Pécontal, E., Valls-Gabaud, D. & Charlot, S. *Nature* **380,** 411–413 (1996).
5. Dunlop, J. S., Guiderdoni, B., Rocca-Volmerange, B., Peacock, J. A. & Longair, M. S. *Mon. Not. R. astr. Soc.* **240,** 257–284 (1989).
6. di Serego Alighieri, S., Fosbury, R. A. E., Quinn, P. J. & Tadhunter, C. N. *Nature* **341,** 307–309 (1989).
7. Tadhunter, C. N., Scarrott, S. M., Draper, P. & Rolph, C. *Mon. Not. R. astr. Soc.* **256,** 53P–58P (1992).
8. Rigler, M. A., Lilly, S. J., Stockton, A., Hammer, F., Le Fèvre, O. *Astrophys. J.* **385,** 61–82 (1991).
9. Hamilton, D. *Astrophys. J.* **297,** 371–389 (1985).
10. Lilly, S. J. *Astrophys. J.* **333,** 161–167 (1988).
11. Stockton, A., Kellogg, M. & Ridgway, S. *Astrophys. J.* **443,** L69–L72 (1995).
12. Rawlings, S. & Saunders, R. *Nature* **349,** 138–140 (1991).
13. Dunlop, J. S. & Peacock, J. A. *Mon. Not. R. astr. Soc.* **263,** 936–966 (1993).
14. Windhorst, R. A., van Heerde, G. M. & Katgert, P. *Astr. Astrophys. Suppl. Ser.* **58,** 1–37 (1984).
15. Oort, M. J. A. & van Langevelde, H. J. *Astr. Astrophys. Suppl. Ser.* **71,** 25–38 (1987).
16. Oort, M. J. A., Katgert, P., Steeman, F. W. M. & Windhorst, R. A. *Astr. Astrophys.* **179,** 41–59 (1987).
17. Neuschaefer, L. W. & Windhorst, R. A. *Astrophys. J. Suppl. Ser.* **96,** 371–399 (1995).
18. Dunlop, J. S., Peacock, J. A. & Windhorst, R. A. in *Galaxies in the Young Universe* 84–87 (Springer, Berlin, 1995).
19. Morton, D. C., Spinrad, H., Bruzual, G. A. & Kurucz, R. L. *Astrophys. J.* **212,** 438–445 (1977).
20. McCarthy, P. J. *Publs. astr. Soc. Pacif.* **105,** 1051–1057 (1993).
21. Lacy, M., Rawlings, S., Eales, S. & Dunlop, J. S. *Mon. Not. R. astr. Soc.* **273,** 821–826 (1995).
22. Webster, R. L., Francis, P. J., Peterson, B. A., Drinkwater, M. J. & Masci, F. J. *Nature* **375,** 469–471 (1995).
23. Guiderdoni, B. & Rocca-Volmerange, B. *Astr. Astrophys.* **186,** 1–21 (1987).
24. Bruzual, G. B. & Charlot, S. *Astrophys. J.* **405,** 538–553 (1993).
25. Bressan, A., Chiosi, C. & Fagotto, F. *Astrophys. J. Suppl. Ser.* **94,** 63–115 (1994).
26. Charlot, S., Worthey, G. & Bressan, A. *Astrophys. J.* **457,** 626–644 (1996).
27. Magris, G. C. & Bruzual, G. A. *Astrophys. J.* **417,** 102–113 (1993).
28. Kurucz, R. *ATLAS9 Stellar Atmosphere Programs and 2km/s Grid CDROM* Vol. 13 (Smithsonian Astrophysical Observatory, Cambridge, MA, 1992).
29. Scalo, J. M. *Fund. Cosm. Phys.* **11,** 1–278 (1986).
30. Burstein, D., Bertola, F., Buson, L. M., Faber, S. M. & Lauer, T. R. *Astrophys. J.* **328,** 440–462 (1988).
31. Bressan, A., Chiosi, C. & Fagotto, F. *Astrophys. J. Suppl. Ser.* **94,** 63–115 (1994).
32. Windhorst, R. A. *et al. Astrophys. J.* **380,** 362–383 (1991).
33. Cowie, L. L., Hu, E. M. & Songaila, A. *Nature* **377,** 603–605 (1995).

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Evidence from a precessing pulsar orbit for a neutron-star birth kick

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Birth 'kicks' to neutron stars, resulting from asymmetric supernova explosions, have been proposed to explain the high velocities of pulsars[1,2], the existence of companionless, high-velocity massive stars[3,4], and a putative Galactic halo of neutron stars[5]. The kick hypothesis has been controversial, because most of the evidence for kicks is indirect, and a physical mechanism to produce asymmetric explosions is as yet unknown[6]. Here we report five years of radio observations of the pulsar PSR J0045 − 7319, which is in an eccentric orbit around a B star[7]. The data show significant deviations from a simple keplerian orbit, which we interpret as arising from advance of the pulsar's periastron and spin–orbiting coupling[8]. Both effects arise because of the B star's rotationally induced equatorial bulge, however spin–orbit coupling requires the B star's spin axis to be inclined with respect to the orbital angular momentum vector; we find that the inclination angle is between 25 and 41 degrees. In the likely event that the angular momenta were aligned before the supernova explosion, this misalignment provides direct evidence that the neutron star received a kick at birth.

Radio timing observations[7] made not long after the discovery of PSR J0045 − 7319[9] showed that the minimum mass of the pulsar companion is 4 solar masses ($4M_\odot$), and optical observations revealed a 16-mag main-sequence B star near the pulsar timing position. The association was confirmed by the detection of Doppler shifts of the companion's spectral lines at the expected orbital phase[10]. The amplitude of the B star's radial velocity variation determines the mass ratio in the system to be 6.3 ± 1.2. Assuming a $1.4M_\odot$ neutron star[11], the B star's mass is $M_c = (8.8 \pm 1.8)M_\odot$, implying an orbital inclination angle $i = 44° \pm 5°$. From the known system parameters, the pulsar's distance from its companion at periastron is $(3.7 \pm 0.5)R_c$, whereas at apastron, the separation is $(35 \pm 5)R_c$, where R_c, the companion radius[10], is $(6.4 \pm 0.7)R_\odot$. Multi-frequency timing observations have set a surprisingly tight constraint on mass loss from the B star[12], ruling out a wind as a possible source of timing perturbations. A companion rotating at a velocity typical of B stars should have a substantial equatorial bulge, and hence there should be a significant quadrupole term in the gravitational potential. As pointed out by Lai *et al.* (ref. 8), classical periastron advance and precession of the orbital plane should therefore be detectable, as the orbital and spin angular momenta couple, and precess about the fixed total angular momentum vector.

The forces that govern a pulsar's dynamics, be they classical or relativistic[13], can be studied with unparalleled precision using radio pulse arrival times, because pulsars are near-perfect clocks. A 'residual' is the time difference between an observed pulse arrival time and that predicted by the best available timing model. Residuals versus time and orbital phase for PSR J0045 − 7319, after the subtraction of a model including only astrometric, spin and keplerian orbital parameters, are shown in Fig. 1*a* and *b*, respectively. They show significant and systematic deviations from zero, indicating this simple timing model is inadequate[14]. Figure 1*c* and *d* show residuals after the subtraction of a timing model including astrometric, spin (P, $\dot{P}$, $\ddot{P}$, where P is the spin period), keplerian orbital parameters, as well as a time-variable longitude of periastron $\dot{\omega}$, projected semimajor axis, $\dot{x} \equiv \mathrm{d}(a \sin i)/\mathrm{d}t$, and orbital period $\dot{P}_b$ (see Table 1). The significant values of $\dot{\omega}$ and $\dot{x}$ are expected from a rotationally induced quadrupole, where $\dot{x}$ is interpreted as a time-variable inclination angle, $\mathrm{d}i/\mathrm{d}t$, with the semimajor axis a constant. The reduced χ^2 for the simple keplerian model is 45, whereas that for the model in Table 1 is 1.5. The F-test shows that the improvement in the fit