fusion processes in viral evolution may be important in the function of the resultant viral particle.

The eight-stranded antiparallel virus fold has now been found in many RNA and DNA viral capsids[39], yet its presence is not entirely universal (for example in the plant RNA tobacco mosaic virus[54,55], in the RNA phage MS2[56] and in the animal RNA Sindbis virus[57]). Hence, the eight-stranded antiparallel β-barrel fold is not a prerequisite for assembly of icosahedral structures[58]. Furthermore, the ΦX174 structure, in contrast to other icosahedral viruses, shows only little contact of the β-barrel fold with neighbouring subunits, as it essentially projects into the DNA core (Table 3). It has also been suggested[59,60] that the fold might be conserved to modulate viral stability by virtue of its hydrophobic interior. □

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1. Hayashi, M., Aoyama, A., Richardson, D. L. Jr & Hayashi, M. N. in *The Bacteriophages (The Viruses)* Vol. 2 (ed. Calendar, R.) 1-71 (Plenum, New York, 1988).
2. Burgess, A. B. *Proc. natn. Acad. Sci. U.S.A.* **64,** 613-617 (1969).
3. Edgell, M. H., Hutchison, C. A. III & Sinsheimer, R. L. *J. molec. Biol.* **42,** 547-557 (1969).
4. Siden, E. J. & Hayashi, M. *J. molec. Biol.* **89,** 1-16 (1974).
5. Hall, C. E., Maclean, E. C. & Tessman, I. *J. molec. Biol.* **1,** 192-194 (1959).
6. Thomas, W. J. & Horne, R. W. *Virology* **15,** 1-7 (1961).
7. Stouthamer, A. H., Daems, W. T. & Eigner, J. *Virology* **20,** 246-250 (1963).
8. Brown, D. T., Mackenzie, J. M. & Bayer, M. E. *J. Virol.* **7,** 836-846 (1971).
9. Incardona, N. L. & Selvidge, L. *J. Virol.* **11,** 775-782 (1973).
10. Jazwinski, S. M., Lindberg, A. A. & Kornberg, A. *Virology* **66,** 268-282 (1975).
11. Feige, U. & Stirm, S. *Biochem. biophys. Res. Commun.* **71,** 566-573 (1976).
12. Sinsheimer, R. L. *Prog. Nucleic Acid Res. molec. Biol.* **8,** 115-169 (1968).
13. Newbold, J. E. & Sinsheimer, R. L. *J. Virol.* **5,** 427-431 (1970).
14. Weisbeek, P. J., Van de Pol, J. H. & Van Arkel, G. A. *Virology* **52,** 408-416 (1973).
15. Dowell, C. E., Jansz, H. S. & Zandberg, J. *Virology* **114,** 252-255 (1981).
16. Newbold, J. E. & Sinsheimer, R. L. *J. molec. Biol.* **49,** 49-66 (1970).
17. Incardona, N. L. & Müller, U. R. *J. molec. Biol.* **181,** 479-486 (1985).
18. Doniger, J. & Tessman, I. *Virology* **39,** 389-394 (1969).
19. Incardona, N. L. *J. Virol.* **14,** 469-478 (1974).
20. Yazaki, K. *J. virol. Meth.* **2,** 159-167 (1981).
21. Mano, Y., Kawabe, T., Komano, T. & Yazaki, K. *Agric. Biol. Chem.* **46,** 2041-2049 (1982).
22. Fujisawa, H. & Hayashi, M. *J. Virol.* **23,** 439-442 (1977).
23. Aoyama, A., Hamatake, R. K. & Hayashi, M. *Proc. natn. Acad. Sci. U.S.A.* **78,** 7285-7289 (1981).
24. Mukai, R., Hamatake, R. K. & Hayashi, M. *Proc. natn. Acad. Sci. U.S.A.* **76,** 4877-4881 (1979).
25. Liljas, L. *Prog. Biophys. molec. Biol.* **48,** 1-36 (1986).
26. Sanger, F. *et al. Nature* **265,** 687-695 (1977).
27. Shaw, D. C. *et al. Nature* **272,** 510-515 (1978).
28. Godson, G. N. in *The Single-Stranded DNA Phages* (eds Denhardt, D. T., Dressler, D. & Ray, D. S.) 103-112 (Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, 1978).
29. Godson, G. N., Fiddes, J. C., Barrell, B. G. & Sanger, F. in *The Single-Stranded DNA Phages* (eds Denhardt, D. T., Dressler, D. & Ray, D. S.) 51-86 (Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, 1978).
30. Lau, P. C. K. & Spencer, J. H. *Gene* **40,** 273-284 (1985).
31. Huber, R. & Bennett, W. S. Jr *Biopolymers* **22,** 261-279 (1983).
32. Sinsheimer, R. L. *J. molec. Biol.* **1,** 37-42 (1959).
33. Willingmann, P. *et al. J. molec. Biol.* **212,** 345-350 (1990).
34. Eigner, J., Stouthamer, A. H., van der Sluys, I. & Cohen, J. A. *J. molec. Biol.* **6,** 61-84 (1963).
35. Weisbeek, P. J., Van de Pol, J. H. & Van Arkel, G. A. *Virology* **48,** 456-462 (1972).
36. Sanger, F. *et al. J. molec. Biol.* **125,** 225-246 (1978).
37. Jones, T. A. *J. appl. Crystallogr.* **11,** 268-272 (1978).
38. Caspar, D. L. D. & Klug, A. *Cold Spring Harb. Symp. quant. Biol.* **27,** 1-24 (1962).
39. Rossmann, M. G. & Johnson, J. E. *A. Rev. Biochem.* **58,** 533-573 (1989).
40. Rossmann, M. G. *et al. Nature* **317,** 145-153 (1985).
41. Tsao, J. *et al. Science* **251,** 1456-1464 (1991).
42. Harrison, S. C., Olson, A. J., Schutt, C. E., Winkler, F. K. & Bricogne, G. *Nature* **276,** 368-373 (1978).
43. Abad-Zapatero, C. *et al. Nature* **286,** 33-39 (1980).
44. Liljas, L. *et al. J. molec. Biol.* **159,** 93-108 (1982).
45. Cohen, S. S. & McCormick, F. P. *Adv. Virus Res.* **24,** 331-387 (1979).
46. Benevides, J. M., Stow, P. L., Ilag, L. L., Incardona, N. L. & Thomas, G. J. Jr *Biochemistry* **30,** 4855-4863 (1991).
47. Jazwinski, S. M., Marco, R. & Kornberg, A. *Virology* **66,** 294-305 (1975).
48. Chen, Z. *et al. Science* **245,** 154-159 (1989).
49. Saenger, W. in *Principles of Nucleic Acid Structure* (ed. Cantor, C. R.) 51-104 (Springer, New York, 1984).
50. Chapman, M. S., Minor, I., Rossmann, M. G., Diana, G. D. & Andries, K. *J. molec. Biol.* **217,** 455-463 (1991).
51. Argos, P. *et al. Biochemistry* **18,** 5698-5703 (1979).
52. Rossmann, M. G., Moras, D. & Olsen, K. W. *Nature* **250,** 194-199 (1974).
53. Matthews, B. W. & Rossmann, M. G. *Meth. Enzym.* **115,** 397-420 (1985).
54. Bloomer, A. C., Champness, J. N., Bricogne, G., Staden, R. & Klug, A. *Nature* **276,** 362-368 (1978).
55. Namba, K. & Stubbs, G. *Science* **231,** 1401-1406 (1986).
56. Valegård, K., Liljas, L., Fridborg, K. & Unge, T. *Nature* **345,** 36-41 (1990).
57. Choi, H. K. *et al. Nature* **354,** 37-43 (1991).
58. Ladenstein, R. *et al. J. molec. Biol.* **203,** 1045-1070 (1988).
59. Smith, T. J. *et al. Science* **233,** 1286-1293 (1986).
60. Rossmann, M. G. *Proc. natn. Acad. Sci. U.S.A.* **85,** 4625-4627 (1988).
61. Rossmann, M. G. & Blow, D. M. *Acta crystallogr.* **15,** 24-31 (1962).
62. Tong, L. & Rossmann, M. G. *Acta crystallogr.* **A46,** 783-792 (1990).
63. Stauffacher, C. V. *et al.* in *Crystallography in Molecular Biology* (eds Moras, D., Drenth, J., Strandberg, B., Suck, D. & Wilson, K.) 293-308 (Plenum, New York, 1987).
64. Rossmann, M. G. *Acta crystallogr.* **A46,** 73-82 (1990).
65. Rossmann, M. G. *et al. J. appl. Crystallogr.* (in the press).
66. Smith, T. J. *J. appl. Crystallogr.* **23,** 141-142 (1990).
67. Gibson, T. J. & Argos, P. *J. molec. Biol.* **212,** 7-9 (1990).

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LETTERS TO NATURE

Spatial distribution of γ-ray bursts observed by BATSE

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THE nature of the sources of cosmic γ-ray bursts is a long-standing problem in astrophysics. Lack of knowledge of their true spatial distribution and of their intrinsic brightness has hampered theoretical understanding of these enigmatic events. The Burst and Transient Source Experiment on the Compton Gamma-Ray Observatory has been detecting bursts at the rate of about one a day, and we report here an analysis of 153 events. The number versus intensity distribution does not follow the $-3/2$ power law expected for a spatially extended homogeneous distribution of sources, but at the same time the angular distribution is isotropic within statistical limits. Taken together, these results are inconsistent with the spatial distribution of any known population of galactic objects, but may be consistent with the bursts being at cosmological distances.

The Burst and Transient Source Experiment (BATSE) is described by Fishman *et al.*[1] It includes eight NaI (Tl) detectors, 1.27 cm thick by 50.8 cm diameter, sensitive to γ-rays in the energy range of 20 keV to 2 MeV. Directions to the burst sources are determined by comparing count rates from the separate detectors. The requirement that the relative detector count rates yield a consistent location provides an effective discriminator for false triggers. With a flux threshold of $\sim 10^{-7}$ erg cm^{-2}, BATSE combines unprecedented sensitivity to weak bursts with the capability of determining locations of all detected bursts in a single experiment. Bursts are triggered on-board when the count rate in the 50-300-keV energy range increases by 5.5 σ or more in at least two detectors simultaneously. The rates are tested on three timescales independently: 64 ms, 256 ms and 1,024 ms. In the period of 193 days since activation of the instrument on 21 April 1991 until 31 October 1991, a total of 153 bursts have been detected and located. This corresponds to a full sky rate of $\sim$800 bursts per year, a factor of $\sim$6 greater than seen by previous sensitive instruments[2].

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The intensity distribution of the bursts provides information on the radial distribution of the sources. Figure 1*a* shows a plot of the integral number of bursts brighter than a specified peak intensity for 140 analysed BATSE bursts; peak rates have not yet been calculated for thirteen bursts because of a data processing lag. The C_{max} intensity is expressed as the peak count rate divided by the trigger threshold count rate[3] C_{min}. The use of this parameter removes biases due to varying trigger thresholds and other systematic effects such as atmospheric scatter that are apparent in traditional log $N(>S)$-log S plots where S is the fluence (erg cm^{-2}) of the bursts. A homogeneous distribution of sources would follow the $-3/2$ power law shown in the figure. The data indicate a much flatter distribution, which is best characterized as a deficit in the number of weak bursts compared with what would be expected for a homogeneous distribution. An equivalent representation is the V/V_{max} distribution[3], where $V/V_{max}=(C_{max}/C_{min})^{-3/2}$. In this ratio, V is then the volume contained by a sphere extending to the location of the burst, and V_{max} is the volume of a sphere extending to the maximum distance at which the same burst would still be detectable by the instrument. The average value of V/V_{max} provides a statistical test of the hypothesis that the observed bursts are drawn from a spatially homogeneous sample. For a homogeneous distribution of sources, V/V_{max} is uniformly distributed between 0 and 1, with an average $\langle V/V_{max}\rangle = 1/2$. The V/V_{max} distribution is presented in Fig. 1*b* and has $\langle V/V_{max}\rangle = 0.348 \pm 0.024$. Several other recent experiments have obtained similar results for the intensity distribution of weak bursts[4,5]. BATSE has not been operating long enough to sample the stronger but rarer bursts that have been found by earlier instruments to follow the $-3/2$ power law[6-8]. Although the V/V_{max} distribution is an excellent test for homogeneity, it obscures important information relevant to model fitting. Specifically, the strong peak in the lowest V/V_{max} bin corresponds to all bursts above $C_{max}/C_{min}=4.6$. From Fig. 1*a*, it is clear that even these bursts are less numerous than would be expected from observations at higher intensities.

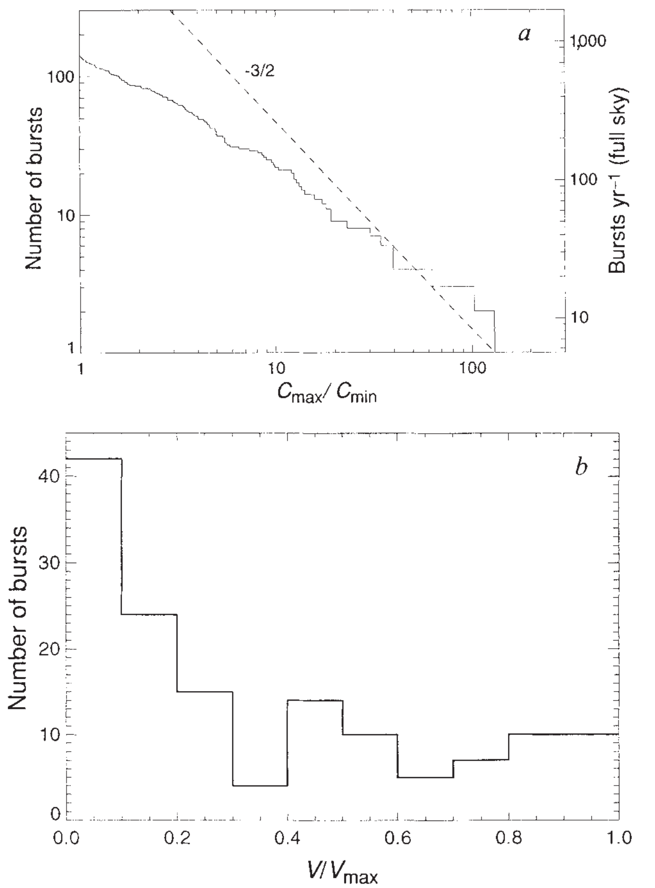

FIG. 1 *a*, Integral number distribution of 140 bursts as a function of peak rate. A $-3/2$ power law is expected for a homogeneous distribution of sources. The full sky rate is ~800 bursts per year. *b*, V/V_{max} distribution for 140 bursts. The average V/V_{max} is 0.348 ± 0.024. A uniform distribution is expected for a homogeneous distribution of sources.

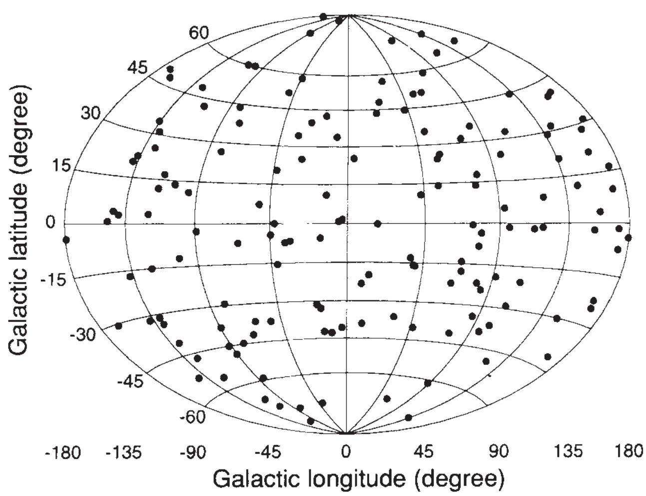

FIG. 2 The angular distribution of 153 bursts in galactic coordinates. There is no statistically significant deviation from isotropy.

The angular distribution of 153 bursts is shown in Fig. 2. There is no apparent clustering of bursts along the galactic plane or toward the Galactic Centre. There is also no indication of excesses in the directions to nearby galaxies or clusters of galaxies, including the Virgo cluster. Hartmann and Epstein[9] have promoted the use of the dipole and quadrupole moments to characterize angular distributions of bursts. A measure of the dipole moment in galactic coordinates is $\langle\cos\theta\rangle$, where θ is the angle between the burst source and the Galactic Centre. For BATSE bursts, $\langle\cos\theta\rangle = -0.002 \pm 0.006$, as compared with 0 ± 0.046 for an isotropic distribution. A measure of the quadrupole moment in galactic coordinates is $\langle\sin^2 b\rangle$, where b is the galactic latitude. For BATSE bursts, $\langle\sin^2 b\rangle = 0.310 \pm 0.006$, compared with 0.333 ± 0.023 for an isotropic distribution. The quoted errors for the measured values are the instrumental errors due to inaccuracy of the burst locations only. The quoted errors for the isotropic model distribution are the standard statistical errors for a sample of 153 events. Coordinate-free measurements of the moments are also statistically consistent with isotropy.

The BATSE results can be corrected for nonuniform sky exposure due to Earth blockage and time intervals when the trigger is disabled, such as during South Atlantic anomaly passages. The only anisotropy in the calculated exposure map is a 30% enhancement towards the celestial poles relative to the Equator. There is no appreciable dependence of exposure on galactic latitude or longitude. The corrected value of $\langle\cos\theta\rangle$ is 0.01; the corrected value of $\langle\sin^2 b\rangle$ is 0.31. Instrumental and statistical errors are the same as for the uncorrected case.

The accuracy of the burst locations is limited at present by systematic effects, primarily errors in the angular response of the detectors at high angle of incidence, and approximations in the atmospheric scattering corrections. Statistical errors contribute ~10° at the trigger threshold and average 3.5° for all bursts. Observations of 41 solar flares[10] yield a mean error of 5.6°. Four bursts have been independently located using the interplanetary network[11,12] and COMPTEL[13]. BATSE errors for these bursts are ~6°. The location errors will be reduced as systematic effects are understood.

These results indicate that the burst sources are distributed isotropically but not homogeneously. No known galactic objects have such a distribution. Disk models produce unacceptable quadrupole moments for distant sources or unacceptable $\langle V/V_{max}\rangle$ for nearby sources[14]. Galactic halo distributions[15] must be at least 50 kpc in radius without strong central condensation to satisfy the BATSE limits on the dipole moment. Populating a halo with neutron stars (the currently favoured candidates) may prove difficult. Nearby extragalactic models will have difficulty with the lack of correlations with M31 and the Virgo cluster[16]. The isotropy and V/V_{max} results can be reproduced by cosmological models[17,18], which require isotropy but yield $V/V_{max}<0.5$ because of redshift effects. These models will require further development to address details of the burst phenomenon, such as energy spectra, occurrence rate and luminosity. □

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1. Fishman, G. J. *et al.* in *Proc. Gamma Ray Observatory Science Workshop* (ed. Johnson, W. N.) 39-50 (NASA/GSFC, Greenbelt, 1989).
2. Golenetskii, S. *Adv. Space Res.* **8(2)**, 653-657 (1988).
3. Schmidt, M., Higdon, J. C. & Hueter, G. *Astrophys. J.* **329**, L85-87 (1988).
4. Atteia, J.-L. *et al. Nature* **351**, 296-298 (1991).
5. Ogasaka, Y., Murakami, T., Nishimura, J., Yoshida, A. & Fenimore, E. E. *Astrophys. J.* (in the press).
6. Mazets, E. *et al. Astrophys. Space Sci.* **80**, 1-143 (1982).
7. Matz, S. *et al.* in *Proc. Los Alamos Workshop on Gamma Ray Bursts* (eds Ho, C. Epstein, R. & Fenimore, E. E.) (Cambridge University Press, in the press).
8. Chuang, K. W., White, R. S., Klebesadel, R. W. & Laros, J. G. *Astrophys. J.* (in the press).
9. Hartmann, D., & Epstein, R. I. *Astrophys. J.* **346**, 960-966, (1989).
10. Brock, M. N. *et al.* in *Proc. Gamma Ray Bursts 1991* (eds Fishman, G. J. & Paciesas, W. S.) (in the press).
11. Cline, T. L. *et al.* in *Proc. Gamma Ray Bursts 1991* (eds Fishman, G. J. & Paciesas W. S.) (in the press).
12. Hurley, K. *et al.* in *Proc. GRO Annapolis Workshop* (in the press).
13. Schoenfelder, V. *et al. IAU Circ.* No. 5369 (1991).
14. Paczynski, B. *Astrophys. J.* **348**, 485-494, (1990).
15. Brainerd, J. J. *Nature* (in the press).
16. Atteia, J.-L. & Hurley, K. *Adv. Space Res.* **6(4)**, 39-43, (1986).
17. Paczynski, B. *Acta Astr.* **41**, 157-166 (1991).
18. Paczynski, B. *Acta Astr.* **41**, (in the press).

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A planetary system around the millisecond pulsar PSR1257+12

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MILLISECOND radio pulsars, which are old (~10^9 yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257+12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_\oplus$ and 3.4 $M_\oplus$, where $M_\oplus$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829−10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

The 6.2-ms pulsar PSR1257+12 (Fig. 1) was discovered during the search at high galactic latitudes for millisecond pulsars conducted in February 1990 with the 305-m Arecibo radiotelescope at a frequency of 430 MHz (ref. 2). The characteristics of this survey and the details of data analysis are described elsewhere[4]. The confirming observations made on 5 July 1990 have been followed by routine pulse timing measurements of the new pulsar. A total of 4,040 pulse time-of-arrival (TOA) observations have been accumulated so far, with the Arecibo radiotelescope, the 40-MHz, three-level correlation spectrometer and the Princeton Mark III pulsar processor at 430 MHz and 1,400 MHz. A typical uncertainty in the TOAs derived from 1-min pulse integrations is ~15 μs.

The standard analysis of the timing data has been carried out using the model fitting program TEMPO[5] and the Center for Astrophysics Solar System ephemeris PEP740R. With a growing time span of the TOA measurements, it had gradually become clear that the TOAs showed an unusual variability superimposed on an annual sinusoidal pattern caused by a small (~1′) error in the assumed pulsar position. To separate these effects unambiguously, a timing-independent, interferometric position of PSR1257+12 was measured with the Very Large Array (VLA) in its A-array configuration on 19 July and again on 18 September 1991. The ~0.1″ accuracy of the resulting pulsar position was achieved by referencing the fringe phase to a point-source calibrator 1.7° away.

A least-squares fit of a simple model, which involved the pulsar's rotational period, P, and its derivative, $\dot{P}$, as free parameters and the fixed VLA position (Table 1), to the timing data spanning the period of 486 days resulted in post-fit residuals shown in Fig. 2*a*. The residuals, which measure the difference between the predicted and the actual TOAs, show a quasiperiodic 'wandering' over the entire pulsar period. A closer examination of this effect has revealed that it was caused by two strict periodicities of 66.6 and 98.2 days in the pulse arrival times. This is further demonstrated in Fig. 2*b* and *c*, which shows post-fit residuals after fitting each of the two periods separately to the above data, assuming simple keplerian binary models involving a low-mass binary companion to the pulsar. Evidently, fitting for one of the assumed binary periods leaves the other one as a post-fit residual, implying that the pulse arrival times of PSR1257+12 are indeed affected by two independent periodicities. Further detailed analysis has shown that the periodicities are independent of radio frequency and that other millisecond pulsars routinely observed at Arecibo with the same data acquisition equipment show no such effect in their timing residuals.

Millisecond pulsars are extremely stable rotators. Systematic timing observations of objects like the 1.5-ms pulsar 1937+21 (ref. 6) have not revealed any timing noise, quasiperiodic TOA variations or 'glitches' at the level often found in the population of younger pulsars and believed to be related to neutron star seismology[7]. The frequency independence of the amplitude of

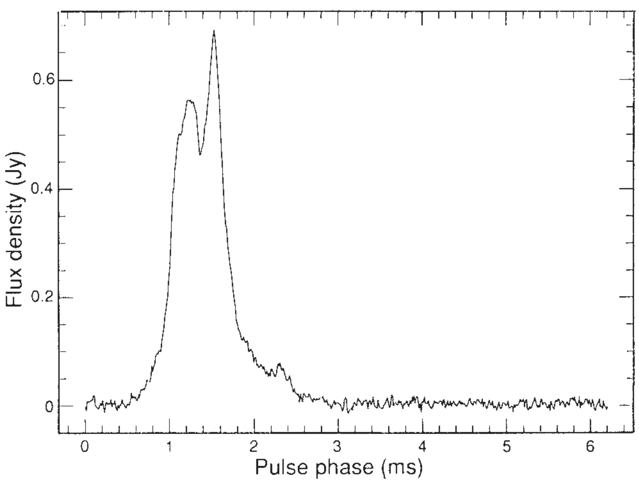

FIG. 1. The average pulse profile of PSR1257+12 at 430 MHz. The effective time resolution is ~12 μs.