doi:10.1038/nature10529

# Two populations of X-ray pulsars produced by two types of supernova

Christian Knigge[1], Malcolm J. Coe[1] & Philipp Podsiadlowski[2]

**Two types of supernova are thought to produce the overwhelming majority of neutron stars in the Universe[1]. The first type, iron-core-collapse supernovae, occurs when a high-mass star develops a degenerate iron core that exceeds the Chandrasekhar limit[2]. The second type, electron-capture supernovae, is associated with the collapse of a lower-mass oxygen–neon–magnesium core as it loses pressure support owing to the sudden capture of electrons by neon and/or magnesium nuclei[3,4]. It has hitherto been impossible to identify the two distinct families of neutron stars produced in these formation channels. Here we report that a large, well-known class of neutron-star-hosting X-ray pulsars is actually composed of two distinct subpopulations with different characteristic spin periods, orbital periods and orbital eccentricities. This class, the Be/X-ray binaries, contains neutron stars that accrete material from a more massive companion star[5]. The two subpopulations are most probably associated with the two distinct types of neutron-star-forming supernova, with electron-capture supernovae preferentially producing systems with short spin periods, short orbital periods and low eccentricities. Intriguingly, the split between the two subpopulations is clearest in the distribution of the logarithm of spin period, a result that had not been predicted and which still remains to be explained.**

Be/X-ray binaries (BeXs) are strong X-ray sources because their neutron stars accrete material at a relatively high rate. Their mass-losing Be-type companions are fast-rotating $8M_{\odot} - 18M_{\odot}$ main-sequence stars that are surrounded by circumstellar 'decretion disks'. These disks are fuelled by the injection of mass and angular momentum at the stellar surface[6]. Neutron star spin periods in BeXs are typically 1 to 1,000 s, and BeX orbits are usually elliptical, with orbital periods ranging from about 10 to 1,000 d. Most of the accretion takes place during periastron passages, when the neutron star passes close to, or even through, the Be star decretion disk.

BeXs are exceptionally abundant in the Small Magellanic Cloud (SMC), where a burst of star formation about 60 Myr ago[7] seems to have produced a large population of these systems[8,9]. In fact, the SMC contains a comparable number of BeXs to the Milky Way, even though the mass ratio of the two galaxies is about 1:100. By contrast, the number of BeXs in the Large Magellanic Cloud (LMC) is broadly in line with its stellar mass content when compared with the Milky Way.

In the context of studying neutron star formation channels, it is useful to focus on well-defined, simple and 'clean' populations of neutron-star-hosting systems (that is, systems in which the orbital parameters have not yet evolved since the supernova) that nevertheless have a wide range of properties. BeXs can provide this. This is not only because the neutron stars in BeXs all have the same type of companion, but also because the accretion process itself seems to be universal, with the neutron star spin in or near an equilibrium state in which the magnetospheric radius of the neutron star equals the Keplerian co-rotation radius[10–12]. This conclusion is suggested empirically by the location of BeXs in the $\log(P_{orb})$–$\log(P_{spin})$ plane (the Corbet diagram[13]; $P_{orb}$ and $P_{spin}$ are the orbital and spin periods, respectively), where they tend to lie along a line with slope $\alpha \approx 2$ (Fig. 1).

The correlation in Fig. 1 between $P_{spin}$ and $P_{orb}$ among BeXs is highly significant, but the data have large scatter. Despite this scatter, however, the one-dimensional projections of the data onto the $\log(P_{orb})$ and $\log(P_{spin})$ axes both suggest that the BeX population might be bimodal. More specifically, the two subpopulations suggested by the data in Fig. 1 have characteristic periods of $P_{orb} \approx 40$ d and $P_{spin} \approx 10$ s (short-period mode) and $P_{orb} \approx 100$ d and $P_{spin} \approx 200$ s (long-period mode). The bimodality of the BeX population seems to be more prominent in $\log(P_{spin})$ than in $\log(P_{orb})$. This is helpful, because there are additional BeXs, not shown in Fig. 1, for which $P_{spin}$ is known but $P_{orb}$ is not. For the purpose of analysing the $P_{spin}$ data on its own, we can therefore add these systems to the list of confirmed and probable BeXs.

Such an analysis is shown in Fig. 2. It confirms that the $\log(P_{spin})$ distribution of BeXs contains two distinct subpopulations with characteristic spin periods of $P_{spin} \approx 10$ s and $P_{spin} \approx 200$ s and similar dispersions of about 0.4 dex. The short-$P_{spin}$ and long-$P_{spin}$ subpopulations contribute about 35 and 65% to the total number, respectively. The split into these two subpopulations is highly statistically significant for the full sample and remains significant even if the data set is divided by host galaxy. The split also remains significant if we consider only spectroscopically confirmed BeXs. Finally, the evidence for two subpopulations even remains significant if we use non-parametric statistical tests (which are less powerful, but more robust than the KMM algorithm; see the Supplementary Information for details).

As shown explicitly in Fig. 2d, the double-Gaussian decomposition of the independent SMC and Milky Way + LMC samples are consistent with each other. This makes it highly unlikely that selection effects are responsible for the observed bimodality. In any case, it is hard to conceive of a selection bias that would select specifically against BeXs with intermediate values of $P_{spin}$ and/or $P_{orb}$. We therefore believe that the two modes of the $\log(P_{spin})$ distribution correspond to physically distinct BeX subpopulations.

In principle, there are at least three ways to account for the existence of these subpopulations. First, they could correspond to two distinct neutron star spin equilibria that are accessible at all orbital periods. However, even though the bimodality is stronger in $P_{spin}$ than in $P_{orb}$, the existence of the $P_{spin}$–$P_{orb}$ correlation effectively rules out this possibility. Second, $P_{orb}$ might be time dependent for BeXs, with the two subpopulations representing two distinct, long-lived evolutionary stages. However, the timescale for stellar-wind-driven changes in $P_{orb}$ in the BeX phase, $\tau_{P_{orb}} \approx 100$–$1{,}000$ Myr (refs 14,15), is substantially longer than the maximum duration of this phase, $\tau_{BeX,max} \approx 20$ Myr, the lifetime of an $8M_{\odot}$ star. Thus, $P_{orb}$ evolution also cannot account for the two observed subpopulations.

The third explanation that we consider is that the two subpopulations represent two distinct BeX formation channels. The most obvious possibility, with the farthest-reaching implications, is that the two channels are associated with the two distinct types of supernova event noted above. More specifically, an iron-core-collapse supernova marks the end point of the evolution of any sufficiently massive star, whereas an electron-capture supernova can occur only under highly restrictive

[1]University of Southampton, School of Physics and Astronomy, Southampton SO17 1BJ, UK. [2]University of Oxford, Department of Physics, Oxford OX1 3RH, UK.

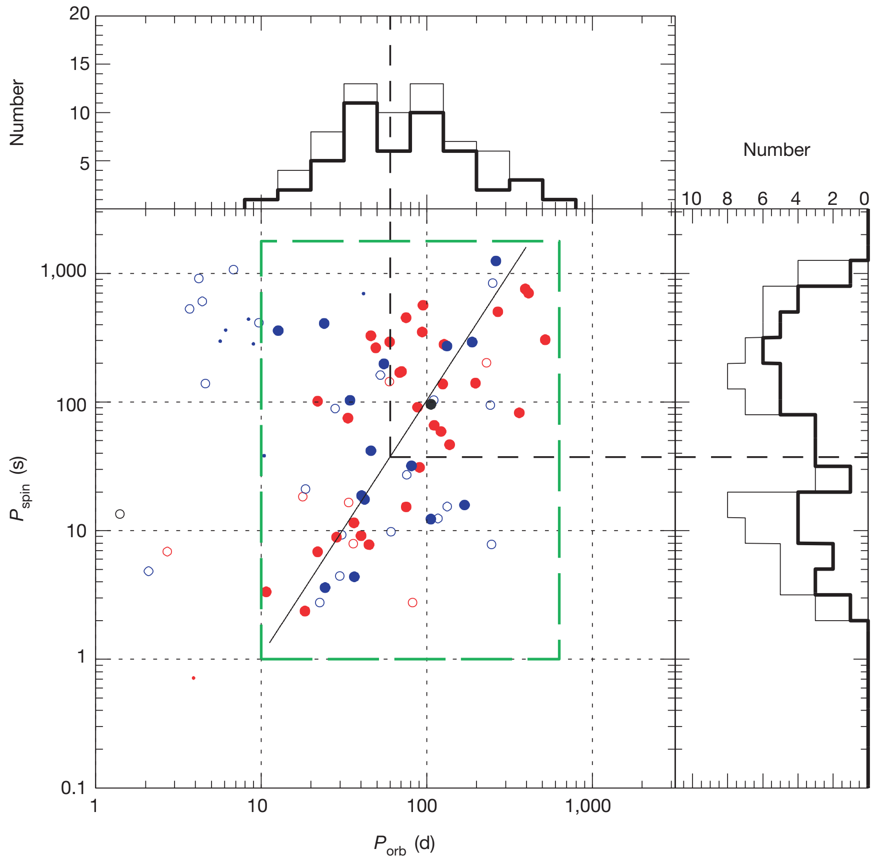


**Figure 1 | The Corbet diagram for high-mass X-ray binaries.** The central panel shows log($P_{orb}$) versus log($P_{spin}$) for neutron-star-hosting high-mass X-ray binaries. Filled circles correspond to spectroscopically confirmed BeXs, small dots to confirmed non-BeX systems and open circles to candidate BeXs. There are additional confirmed and candidate BeXs for which only $P_{orb}$ or $P_{spin}$ is known, but these are not shown. The dashed green lines mark a selection box that conservatively includes all confirmed BeXs for which $P_{orb}$ and $P_{spin}$ have been measured. Candidate systems outside this box are excluded from our sample of probable BeXs. The spin and orbital periods of confirmed and probable BeX systems are correlated. The Spearman rank correlation coefficient is $\rho = 0.49$ ($P = 3\times10^{-5}$, $N = 66$) for the full sample and $\rho = 0.49$ ($P = 4\times10^{-4}$, $N = 47$) for the confirmed systems (see Supplementary Information for a definition of $P$ values). The scatter around the correlation is $\sigma_{\log(P_{spin})} = 0.7$ dex relative to the best-fitting line with slope $\alpha = 2$ (solid black line). Different colours indicate different host galaxies: blue, Milky Way; red, SMC; black, LMC. The histograms shown in the top and right-hand panels show the numbers of BeXs with spin and orbital periods in the respective ranges covered by the selection box. In each of these panels, the thick line corresponds to confirmed BeXs only, and the thin line corresponds to confirmed and probable BeXs. The vertical dashed line is drawn at $P_{orb} = 60$ d, the location of the apparent dip in the log($P_{orb}$) distribution. This value of $P_{orb}$ corresponds to $P_{spin} \approx 40$ s (horizontal dashed line), which marks a more pronounced dip in the log($P_{spin}$) distribution.

conditions. In particular, an electron-capture supernova requires that the core reaches the critical density for electron capture to occur, $4.5\times10^{9}\,\mathrm{g\,cm^{-3}}$ (ref. 16). These conditions might be met in the late evolution of intermediate-mass stars[3,4] (those with initial masses satisfying $8M_\odot \lesssim M_{init} \lesssim 10M_\odot$), although the relevant mass range is uncertain and may be quite small[17,18]. However, it is much easier to meet the conditions for electron-capture supernovae naturally in binary systems[17].

The outcome of electron-capture supernovae differs from that of iron-core-collapse supernovae in two fundamental ways. First, electron-capture supernovae should produce somewhat less massive neutron stars ($\lesssim 1.3\,M_\odot$) than iron-core-collapse supernovae ($1.4\,M_\odot$) (ref. 3). Second, electron-capture supernovae are expected to impart much smaller kicks to the neutron stars they produce (average kick velocity of $\lesssim 50\,\mathrm{km\,s^{-1}}$) than are iron-core-collapse supernovae ($\gtrsim 200\,\mathrm{km\,s^{-1}}$) (ref. 17). In binary systems, where kicks induce orbital eccentricity, these differences could naturally give rise to two distinct subpopulations. The more conventional iron-core-collapse channel would produce high-eccentricity binaries containing high-mass neutron stars, and the electron-capture channel would produce low-eccentricity binaries containing low-mass neutron stars[16,17,19,20].

If this is the correct explanation for the two BeX populations we have discovered, they should differ not only in $P_{spin}$ and $P_{orb}$, but also in their characteristic orbital eccentricities, $e$. These have so far been measured for only about 20 BeXs. Figure 3 shows the distribution of these systems in the log($P_{spin}$)–$e$ plane. Even though there are only eight such BeXs with $P_{spin} \gtrsim 40$ s, it seems that long-$P_{spin}$ systems have preferentially higher eccentricities than short-$P_{spin}$ systems. The figure also shows the cumulative eccentricity distributions of the slow ($P_{spin} < 40$ s) and fast ($P_{spin} > 40$ s) BeX pulsar subpopulations. A Kolmogorov–Smirnov test shows that, despite the small number of systems for which eccentricity has been measured, the maximum difference between these distributions is marginally significant (Supplementary Information).

The two BeX populations that we have discovered are more clearly separated in $P_{spin}$ than in $P_{orb}$. Given that $P_{orb}$ does not evolve significantly within the BeX phase, whereas $P_{spin}$ does, $P_{orb}$ might be expected to be the more faithful tracer of the formation channels. However, the $P_{orb}$ distribution after the supernova must depend strongly on the $P_{orb}$ distribution before the supernova, and both low- and high-velocity kicks can in principle produce a wide range of post-supernova orbital periods[17]. This may explain why the bimodality is only marginally observed in the $P_{orb}$ distribution. By contrast, the equilibrium spin period is expected to depend on several system parameters other than $P_{orb}$ (refs 10–12). If any of these parameters differ systematically between BeXs produced by the iron-core-collapse and electron-capture

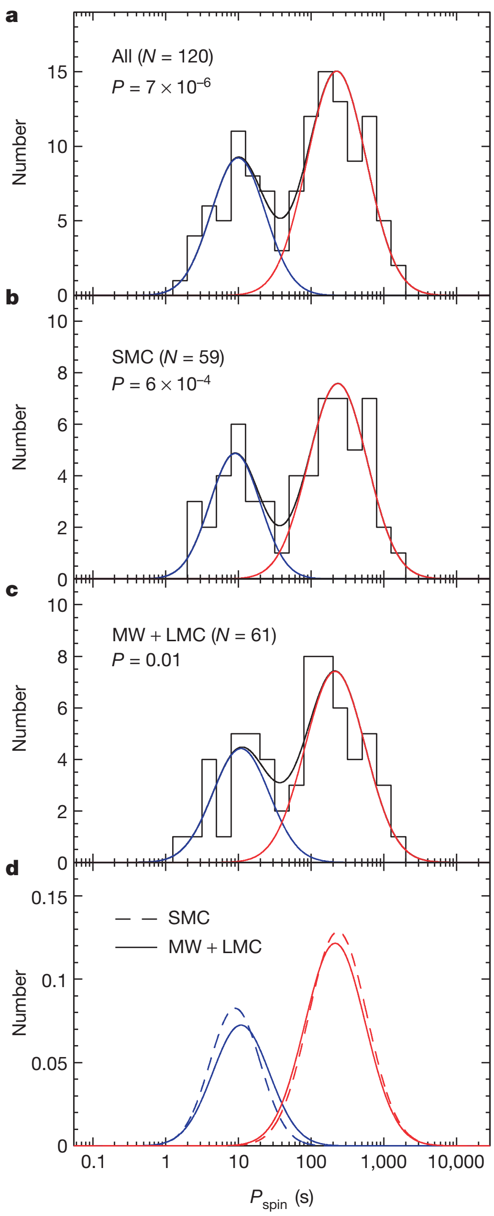


**Figure 2 | The log($P_{spin}$) distribution of confirmed and probable BeXs.** **a**, Distribution for all systems. **b**, **c**, Distribution broken down by host galaxy: SMC (**b**); Milky Way (MW) + LMC (**c**). All of these distributions are bimodal (modes shown in red and blue), and the double-Gaussian decomposition (black) suggested by the KMM algorithm[25] (an algorithm that detects bimodality in an observational data set) is shown in each panel. The number of systems contributing to each observed distribution and the associated $P$ value provided by the algorithm are also shown. Applying the KMM test to the subset of spectroscopically confirmed systems (not shown) gives $P = 8 \times 10^{-3}$ ($N = 64$). **d**, Direct comparison of the decompositions for the independent SMC and Milky Way + LMC populations, showing them to be mutually consistent. Additional details regarding the statistical evidence for the existence of distinct subpopulations in the $P_{spin}$ data are given in Supplementary Information.

channels, $P_{spin}$ may be a more reliable indicator of formation channel than $P_{orb}$.

Our results suggest numerous avenues for further research. First, it is important to expand the database of BeXs with reliable measurements of $P_{spin}$, $P_{orb}$ and $e$, to confirm and further quantify our findings. Second, if short-$P_{spin}$ BeXs are formed by low-kick-velocity electron-capture supernovae, they should have systematically smaller space velocities than long-$P_{spin}$ BeXs. This prediction might be testable[21,22]. Third, short-$P_{spin}$ systems should also have systematically lower neutron star masses than long-$P_{spin}$ systems[16,17,19,20]. This prediction might also be testable[23]. Fourth, although our discovery of two populations of BeX pulsars is robust, our suggested explanation for their origin is clearly speculative and demands a fuller investigation. Intriguingly, recent binary population synthesis calculations have shown that the electron-capture supernova channel may be very efficient at forming BeXs[24]. However, whereas the same population synthesis models also suggest that the electron-capture channel accounts for the overabundance of BeXs in the SMC[24], the two BeX populations that we have discovered seem to have similar relative abundances in the SMC and the Milky Way.

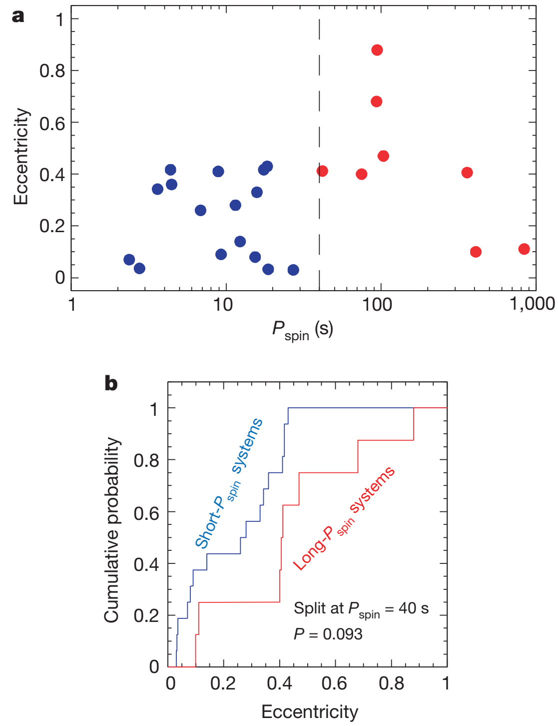


**Figure 3 | The dependence of eccentricity on $P_{spin}$ among BeXs.** **a**, $P_{spin}$ versus eccentricity for all confirmed and probable BeXs with measured spin periods and eccentricities. The vertical dashed line marks the approximate division between the short-$P_{spin}$ and long-$P_{spin}$ subpopulations (Figs 1 and 2). **b**, Cumulative eccentricity distributions of these two subpopulations. A Kolmogorov–Smirnov test provides marginal evidence for a difference between these distributions ($P = 0.093$), with the short-$P_{spin}$ population being characterized by lower eccentricities (see Supplementary Information for additional discussion).

**Received 5 May; accepted 2 September 2011.**
**Published online 9 November 2011.**

1. Heger, A., Fryer, C. L., Woosley, S. E., Langer, N. & Hartmann, D. H. How massive single stars end their life. *Astrophys. J.* **591,** 288–300 (2003).
2. Woosley, S. & Janka, T. The physics of core-collapse supernovae. *Nature Phys.* **1,** 147–154 (2005).
3. Nomoto, K. Evolution of 8–10 solar mass stars toward electron capture supernovae. I - Formation of electron-degenerate O + NE + MG cores. *Astrophys. J.* **277,** 791–805 (1984).
4. Nomoto, K. Evolution of 8–10 solar mass stars toward electron capture supernovae. II - Collapse of an O + NE + MG core. *Astrophys. J.* **322,** 206–214 (1987).
5. Reig, P. Be/X-ray binaries. *Astrophys. Space Sci.* **332,** 1–29 (2011).
6. Lee, U., Osaki, Y. & Saio, H. Viscous excretion discs around Be stars. *Mon. Not. R. Astron. Soc.* **250,** 432–437 (1991).
7. Harris, J. & Zaritsky, D. The star formation history of the Small Magellanic Cloud. *Astron. J.* **127,** 1531–1544 (2004).
8. Haberl, F. & Pietsch, W. X-ray observations of Be/X-ray binaries in the SMC. *Astron. Astrophys.* **414,** 667–676 (2004).
9. Coe, M. J., Edge, W. R. T., Galache, J. L. & McBride, V. A. Optical properties of Small Magellanic Cloud X-ray binaries. *Mon. Not. R. Astron. Soc.* **356,** 502–514 (2005).
10. Waters, L. B. F. M. & van Kerkwijk, M. H. The relation between orbital and spin periods in massive X-ray binaries. *Astron. Astrophys.* **223,** 196–206 (1989).
11. Li, X. & van den Heuvel, E. P. J. On the relation between spin and orbital periods in Be/X-ray binaries. *Astron. Astrophys.* **314,** L13–L16 (1996).

12. Liu, Q. Z., Li, X. D. & Wei, D. M. in *High Energy Processes and Phenomena in Astrophysics* (eds Li, X. D., Trimble, V. & Wang, Z. R.) 215–217 (Proc. IAU Symp. 214, Univ. Chicago Press, 2003).
13. Corbet, R. H. D. Be/neutron star binaries: a relationship between orbital period and neutron star spin period. *Astron. Astrophys.* **141,** 91–93 (1984).
14. de Jager, C., Nieuwenhuijzen, H. & van der Hucht, K. A. Mass loss rates in the Hertzsprung-Russell diagram. *Astron. Astrophys. Suppl. Ser.* **72,** 259–289 (1988).
15. Tout, C. A. & Hall, D. S. Wind driven mass transfer in interacting binary systems. *Mon. Not. R. Astron. Soc.* **253,** 9–18 (1991).
16. Podsiadlowski, P. *et al.* The double pulsar J0737–3039: testing the neutron star equation of state. *Mon. Not. R. Astron. Soc.* **361,** 1243–1249 (2005).
17. Podsiadlowski, P. *et al.* The effects of binary evolution on the dynamics of core collapse and neutron star kicks. *Astrophys. J.* **612,** 1044–1051 (2004).
18. Poelarends, A. J. T., Herwig, F., Langer, N. & Heger, A. The supernova channel of super-AGB stars. *Astrophys. J.* **675,** 614–625 (2008).
19. van den Heuvel, E. P. J. in *ESA SP-552: Proc. 5th INTEGRAL Workshop "The INTEGRAL Universe"* (eds Schoenfelder, V., Lichti, G. & Winkler, C.) 185–194 (ESA Spec. Publ. 552, European Space Agency, 2004).
20. Schwab, J., Podsiadlowski, P. & Rappaport, S. Further evidence for the bimodal distribution of neutron-star masses. *Astrophys. J.* **719,** 722–727 (2010).
21. Coe, M. J. An estimate of the supernova kick velocities for high-mass X-ray binaries in the Small Magellanic Cloud. *Mon. Not. R. Astron. Soc.* **358,** 1379–1382 (2005).
22. Antoniou, V., Zezas, A., Hatzidimitriou, D. & Kalogera, V. Star formation history and X-ray binary populations: the case of the Small Magellanic Cloud. *Astrophys. J.* **716,** L140–L145 (2010).
23. Coe, M. J., McBride, V. A. & Corbet, R. H. D. Exploring accretion theory with X-ray binaries in the Small Magellanic Cloud. *Mon. Not. R. Astron. Soc.* **401,** 252–256 (2010).
24. Linden, T., Sepinsky, J. F., Kalogera, V. & Belczynski, K. Probing electron-capture supernovae: X-Ray binaries in starbursts. *Astrophys. J.* **699,** 1573–1577 (2009).
25. Ashman, K. M., Bird, C. M. & Zepf, S. E. Detecting bimodality in astronomical datasets. *Astron. J.* **108,** 2348–2361 (1994).

**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

**Acknowledgements** Research support for this project was provided by the UK Science and Technology Facilities Council. We would like to thank T. Maccarone and T. Linden for discussions.

**Author Contributions** C.K. carried out the statistical analysis for this project and wrote most of the text. M.J.C. compiled the high-mass X-ray binary data set that forms the basis for our analysis, and collaborated with C.K. on all aspects of the project from its inception. P.P. contributed to the theoretical interpretation of the results and to the final text. All authors discussed the results and their presentation.

**Author Information** Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to C.K. (c.knigge@soton.ac.uk).