

detected by the spectrometer and those in the quantum well."

Bellotti and his coauthors think that the high-energy peak could instead correspond to electrons that gain kinetic energy in the strong near-surface electric field—depicted at the far right in figure 1 as a sharp downward bending of the band energies—and that the lower-energy peaks could be due to photoemission from Cs surface states. Jörg Hader of the University of Arizona in Tucson has another idea: The high-energy peak may be due to reabsorption of LED light by free charge carriers.

Even if Weisbuch and company have the correct interpretation, their meas-

urements aren't yet precise enough to rule out drift leakage as a co-contributor to droop. It's also possible that Auger recombination is the main source of droop under some conditions but not others. The relationship between LED efficiency and injection current is complex and known to depend on temperature, pressure, and various particulars of the device construction: the bandgap and crystalline orientation, the number of quantum wells, the properties of the EBL, and so forth.

Bellotti expects that further electron emission spectroscopy experiments should help to disentangle LEDs' complex web of interdependencies and, in turn, help designers of future

LEDs to better negotiate inherent tradeoffs: "This is a very important new diagnostic tool. Instead of jumping too quickly to far-reaching conclusions, we should make sure that it becomes a launch pad for multidisciplinary collaborations that lead to a solution of the problem."

Ashley G. Smart

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Extreme binary pulsar shows no deviation from general relativity

A previously unexplored regime of massive neutron stars and fast companions disappoints anticipations of new gravity physics.

Einstein's general theory of relativity (GR), the standard theory of gravity, has passed every high-precision test in the solar system, where gravitational fields are relatively weak. In those familiar precincts, the 97-year-old theory correctly predicts the gravitational bending, redshifting, and delaying of light; the precession of planetary orbits; and the strict equivalence of gravitational and inertial mass. But because GR has problems with quantization, spacetime infinities, cosmological inflation, and the unification of the fundamental forces, theorists widely anticipate that the true macroscopic gravity theory must diverge significantly from it in places with much stronger gravitational fields.

The gravitational field exerted by an extended object of mass M is said to be strong, in the sense of GR, when its Schwarzschild radius

$$R_s(M) \equiv 2GM/c^2$$

is comparable to some physically relevant distance. The closest thing to a strong field in the solar system is at the surface of the Sun, whose radius is more than 10^5 times its R_s of 3 km.

The situation is dramatically different for neutron stars, ultradense stellar remnants of core-collapse supernovae. A solar-mass ($1 M_\odot$) neutron star has a radius of order 10 km, only a few times its R_s . And whereas the gravitational bind-

ing energy of an ordinary star is a negligible fraction of its mass, the binding energy of a neutron star can reduce the total mass of its unassembled constituents by as much as 20%. Strong-field effects predicted by proposed variations on GR generally have highly nonlinear dependence on gravitational binding energy.

The binding energies of neutron stars grow monotonically with increasing stellar mass. So several attractive variant theories suggest detectable deviations from GR in and around neutron stars above some critical mass. But no such deviations have been seen. And now an international team centered at

the Max Planck Institute for Radio Astronomy (MPIR) in Bonn, Germany, has reported one more confirmation of GR, from the discovery and monitoring of a neutron-star system whose extreme properties had made it the most promising candidate to date for the revelation of new gravity physics.¹

An extraordinary binary

The system is a binary pair, labeled J0348+0432, in which the most massive neutron star yet weighed is closely orbited every 2.46 hours by a much lighter white-dwarf star. Though 7000 light-years away, J0348 is quite observer friendly. The white dwarf's unusually bright hydrogen spectrum yields high-resolution Doppler-shift data and much

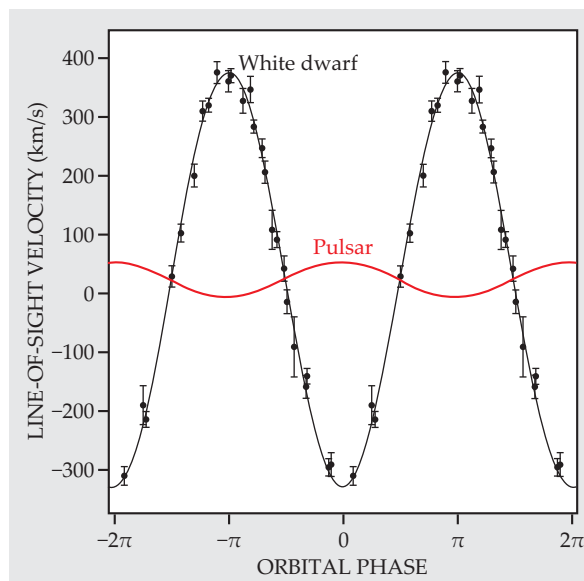


Figure 1. Line-of-sight components of the orbital velocities of the radio pulsar J0348 and its white-dwarf companion, measured, respectively, by radio-pulse timing and spectral Doppler shift. They oscillate synchronously with the binary's 2.46-hour orbital period. The ratio of oscillation amplitudes yields a mass ratio of nearly 12. (Adapted from ref. 1.)

information about its intrinsic properties. And the neutron star is a radio pulsar whose lighthouse-like radio beam, sweeping Earth every 39 milliseconds, provides an exquisite long-term timing reference.

That timing capability serves the team's principal goal: to compare the binary orbit's decay rate with that predicted by GR. But such measurements have been confirming GR ever since Joseph Taylor and Russell Hulse discovered the first binary pulsar four decades ago (see the Reference Frame by Dan Kleppner, *PHYSICS TODAY*, April 1993, page 9). So why expect better of J0348?

The orbits of "clean, relativistic" binaries—those with relativistic velocities and negligible losses due to tidal dissipation or mass transfer—lose energy primarily by gravitational radiation. In GR, the lowest-order gravity-wave production by an extended dynamical source is quadrupole radiation. But many variations on GR predict that dipole radiation will, under the right circumstances, sap a binary's orbital energy much faster than the quadrupole radiation. The right circumstances would be very high neutron-star mass and orbital velocity, and a lightweight binary companion to provide the requisite asymmetry for GR-violating dipole radiation. The Taylor-Hulse binary, like many of the early test systems, lacks that asymmetry. It comprises two neutron stars, both with masses close to $1.4 M_{\odot}$.

The new binary pulsar was first spotted by team member Ryan Lynch (McGill University) in accumulated data from a 2007 radio-telescope survey. In follow-up optical observations, MPIR graduate student John Antoniadis studied the periodic Doppler shifting of the white dwarf's spectrum. "It was quickly evident," he recalls, "that the pulsar was quite a heavyweight."

Figure 1 shows the 2.46-hour oscillation of the line-of-sight velocity components of the white dwarf and the pulsar as measured, respectively, by spectral Doppler shifts and pulsar timing. The ratio of their oscillatory amplitudes measures the ratio $q \equiv M_p/M_{wd}$ of their masses to be 11.7 ± 0.1 .

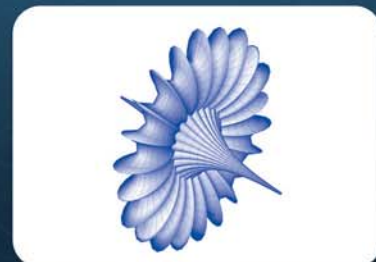
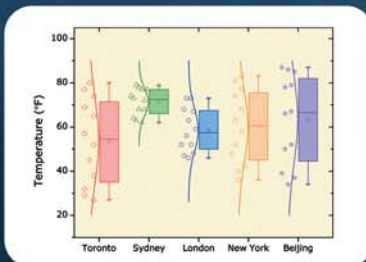
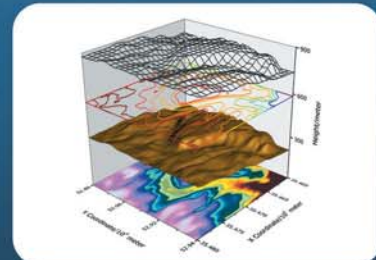
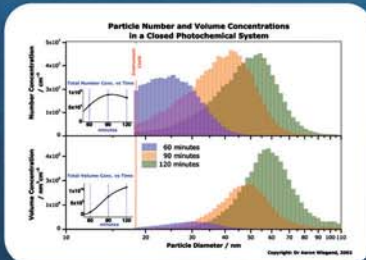
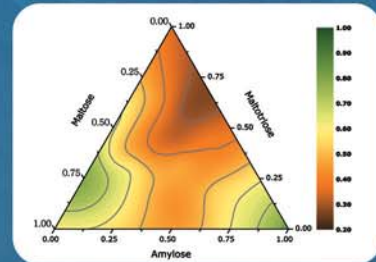
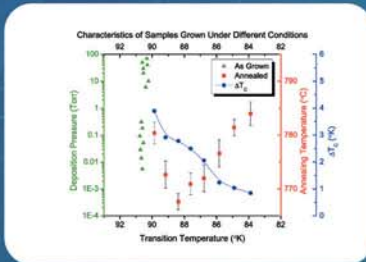
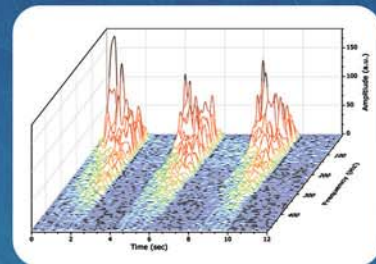
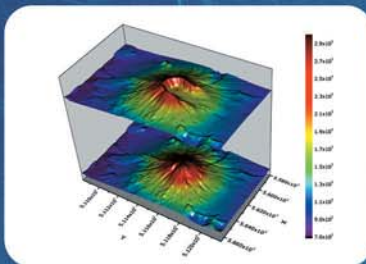
To pin down M_{wd} , Antoniadis produced a model of the white dwarf from its surface temperature and gravity, determined from the intensities and pressure broadening of spectral lines. The model yields a mass of $0.17 M_{\odot}$. That's atypically light. But white-dwarf models are surprisingly reliable, because those end-stage stars are rather simple objects. With all its fusion fuels exhausted, a



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white dwarf is sustained against collapse mainly by the Pauli principle's electron-degeneracy pressure.

Thus the pulsar mass $M_p = qM_{wd}$ was determined to be a record $(2.01 \pm 0.04) M_\odot$. The two masses plus the orbit's period and its line-of-sight velocity components yield a detailed description of the binary orbit: Its plane is inclined 40° from the plane of the sky, and the white dwarf's orbital velocity is about 0.2% of the speed of light. Its separation from the pulsar is about half the diameter of the Sun.

Figure 2 compares J0348 with other binary pulsar systems, with regard to pulsar mass, orbital velocity, and gravitational binding energy. The figure shows another $2-M_\odot$ pulsar orbited by a white dwarf. But that binary's orbital velocity is much slower (see PHYSICS TODAY, January 2011, page 12). On the other hand, the plot shows a unique double pulsar—two pulsars orbiting their center of mass with a relative velocity slightly faster than that of J0348. But neither pulsar's mass exceeds the well-trodden regime below $1.4 M_\odot$. And besides, the double pulsar lacks the desired asymmetry a white-dwarf companion brings. “We found the new binary sitting all by itself in an intriguing, previously untested gravitational regime,” says Norbert Wex (MPIR).

No deviation yet

Given the new binary's measured parameters, GR predicts that its present 2.46-hour orbital period P_b should be decreasing by about $8 \mu\text{s}$ per year as the orbit shrinks due to energy loss by gravitational radiation. To test that prediction, Lynch and Paulo Freire (MPIR) began continual pulsar timing with Puerto Rico's Arecibo radio telescope in April 2011. Now, based on two years of timing data, the orbital period's measured time derivative $\dot{P}_b$ is 1.05 ± 0.18 times the GR prediction. So thus far there's no evidence of new physics.

Figure 3 illustrates the degree of concordance between the measurements and the theory. The yellow swath is the 1-standard-deviation confinement imposed on the binary's mass plane by the $\dot{P}_b$ measurement, assuming that GR is the correct theory. The fact that the intersection of the measured q and M_{wd} lines, which involve no assumptions about GR, falls nicely in the middle of the calculated $\dot{P}_b$ swath indicates that GR has thus far passed the team's radiative test. With increased observing time t over the next few years, the uncertainty on $\dot{P}_b$ should shrink rather rapidly—like $t^{-5/2}$.

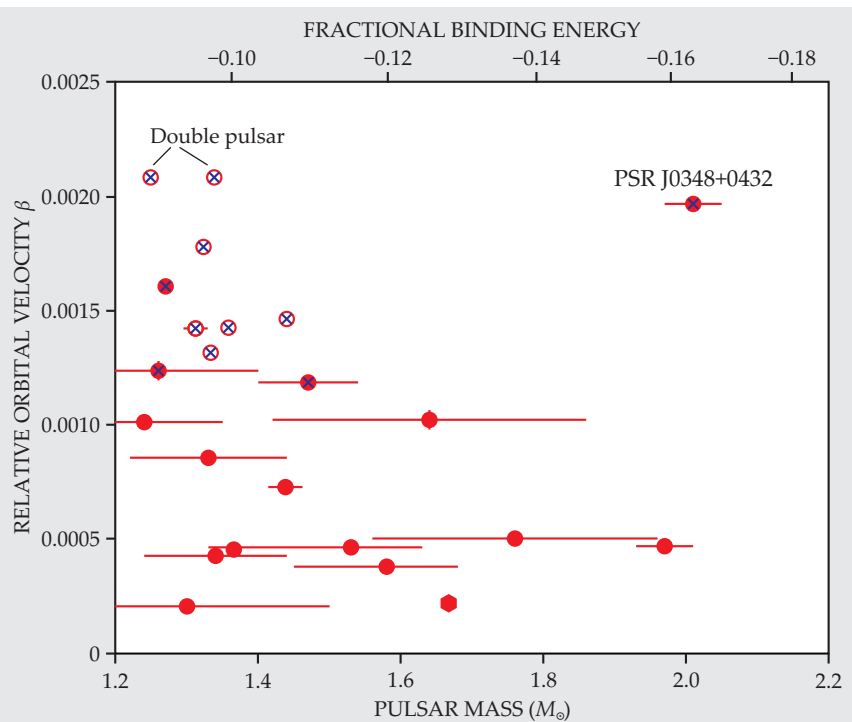


Figure 2. All binary radio pulsars with measured masses and no significant tidal or mass losses are plotted by mass (with corresponding gravitational binding energy) and orbital-velocity parameter β , which is essentially the relative velocity of the two stars, divided by c , in their center-of-mass frame. Solid and open circles indicate, respectively, pulsars with white-dwarf or neutron-star companions. One pulsar (the hexagon) has an ordinary stellar companion. Blue crosses mark binaries for which orbital decay has been measured. Sitting alone at extreme mass and orbital speed is J0348. (Courtesy of Norbert Wex.)

Scalar-tensor theories

The MPIR observations have already made significant inroads into alternative theories that expect orbital decay rates to increase steeply—by orders of magnitude—at some critical neutron-star mass. A seminal theory of that kind was introduced in 1993 by Thibault Damour and Gilles Esposito-Farèse in France.² Their theory, like many others, is an elaboration of the 1961 theory by Carl Brans

and Robert Dicke, which posited that gravity is mediated not only by Einstein's metric-tensor field but also by an additional scalar field. The original Brans–Dicke theory was eventually refuted by precision tests within the solar system. But elaborations that proposed nonlinear couplings of the scalar field to matter held out prospects for observable consequences in strong-gravity regimes. (See the article by Clifford Will in PHYSICS TODAY, October 1999, page 38.)

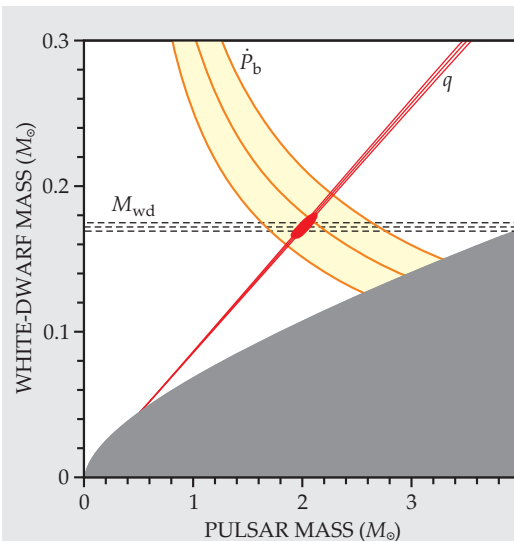


Figure 3. Constraints imposed on the masses of the binary pulsar J0348 by measurements of the white-dwarf mass M_{wd} , the mass ratio q , and the time derivative $\dot{P}_b$ of the orbital period. In each case, the triplet of lines indicates one standard deviation. The $\dot{P}_b$ curves are calculated assuming the correctness of general relativity (GR). The other lines are independent of that assumption. The intersection of the q and M_{wd} lines, shown as a 95%-confidence ellipse, falls nicely inside the $\dot{P}_b$ swath, indicating the degree to which the measurements confirm GR. The gray area is non-physical. (Adapted from ref. 1.)

Separating scales to model bursting bubbles

Bubbles of soap and other liquids have long been known to adopt the shape that minimizes their surface area. An isolated bubble is a sphere; bubbles in a foam or cluster meet so that their surfaces form 120° angles at junctions. But the shapes of the bubble surfaces in a cluster don't succumb so easily to analytical description. The numerical techniques to treat arbitrary stable bubble geometries¹ didn't begin to mature until the early 1990s.

And that equilibrium picture is far from a complete physical description of a bubble cluster, an inherently nonequilibrium system. Under pressure gradients and gravity, fluid drains from the liquid films that constitute the bubble walls. When one of the films gets too thin, it ruptures. The remaining bubbles are left to rearrange into a new configuration, and the cycle begins again. Each of the processes affects the others, but they occur on such different time scales—ranging from a fraction of a millisecond to tens or hundreds of seconds—that re-creating them all in a single numerical simulation has been computationally prohibitive.

Now mathematicians Robert Saye and James Sethian (University of California, Berkeley) have created a framework for capturing the essential physics from the various scales while efficiently using computer resources.² For each of the three processes—drainage, rupture, and rearrangement—they developed a separate numerical model with its own equations, simplifying assumptions, and characteristic time step. By treating each process in turn with the appropriate model, they can transmit the critical information from one scale to another and produce realistic simulations of large bubble clusters.

For small systems, such as two bubbles merging into one, the researchers can compare their numerical results with experiment, and they find excellent agreement. For larger systems, such as the simulated 27-bubble cluster shown in the figure, matching the initial conditions between simulation and experiment would be too difficult. But the simulations reproduce the qualitative features seen in real bubble systems, including rupture cascades in which the bursting of a small bubble induces several larger bubbles to burst in rapid succession.

The researchers anticipate that by modifying their models to include additional physics—evaporation, liquid-solid phase transitions, and so forth—they'll be able to address a variety of "bubble problems" that have industrial and scientific applications. For example, solid plastic and metal foams, materials of interest for their light weight, are produced by hardening liquid foams. (See the article by John Banhart and Denis Weaire, *PHYSICS TODAY*, July 2002, page 37.) Simulations of the processes involved in their production may suggest new ways of controlling their properties.

Johanna Miller



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In particular, Damour and Esposito pointed out an unanticipated consequence of such nonlinear scalar elaborations: Within a particular range of coupling parameters, those theories imply that the coupling strength of the scalar field to neutron-star matter increases steeply at some critical binding energy. They call that abrupt transition spontaneous scalarization and compare it to the onset of ferromagnetism. Given a fast enough white-dwarf companion, scalarization would strongly increase a binary's dipole radiation and manifest itself as an increase of a few orders of magnitude in the orbit's decay rate.

Having found no such excess in the uniquely auspicious J0348 binary, the

MPIR team effectively excludes almost all of the Damour–Esposito parameter space that predicts spontaneous scalarization. "More generally," says Wex, "we've placed an upper limit on the effective coupling strength of long-range extra gravity fields to matter in a previously unexplored strong-gravity regime."

Most proposed extra gravity fields are "long range" in the sense that, like the GR tensor field, the Brans–Dicke scalar field, and the electromagnetic field, their quanta are massless. The J0348 results would be insensitive to short-range fields with quanta heavier than 10^{-19} eV—that is, a Compton wavelength shorter than the binary's 10^3 -km gravitational wavelength, which is given by $cP_b/2$.

"There are still lots of long-range scalar–tensor theories with strong-field effects that would be consistent with the [MPIR] team's data," says theorist Clifford Will (University of Florida). Many of those predict neutron-star effects much less dramatic than scalarization. Continued monitoring of J0348 should serve to test some of those still viable elaborations of GR.

Bertram Schwarzschild

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physics update

These items, with supplementary material, first appeared at <http://www.physicstoday.org>.

A neutron star suddenly slows its spin. A neutron star is a compact ball of matter in extremis—a sunlike mass stuffed into a sphere about 20 km across—left behind by a supernova explosion. Set spinning by the explosion, such a star is thought to consist of a kilometer-thick crust of electrons and nuclei encasing a rich superfluid. Thanks to their magnetic fields, neutron stars emit dipole radiation and accelerate charged particles outward through their crust; thus they are always losing energy and angular velocity. Curiously, that process is occasionally interrupted by "glitches" in which a star

abruptly spins up by a small amount. Those events, according to models, may be attributable to the faster-moving superfluid exerting enough stress to sometimes fracture the crust and transfer angular momentum. While monitoring a hypermagnetized neutron star known as a magnetar on 28 April 2012 using NASA's *Swift* observatory, astronomers noticed something unexpected: an "anti-glitch," the abrupt 2- μ s slowing of the spin from the star's roughly 7-s period. Just a week earlier, the same magnetar had produced a 36-ms x-ray burst, a telltale sign of events in the star that led to the anti-glitch. But in addition to the sudden slowing, *Swift* recorded an extended period after the anti-glitch when the magnetar's spin rate slowed further still. No theory accounts for the observations, but the researchers suspect two possible mechanisms: