when the binary companion's orbit is only modestly misaligned with the primary star's spin," explains coauthor Rebekah Dawson of the Pennsylvania State University. "When you drive the system at just the right frequency, you get a big response."

Once the frequencies drift back out of resonance, the disk settles into a new orbital plane that's widely misaligned from its original plane. Although the companion star is still there, it's no longer as influential on the planetary alignment as it once was.

The researchers can't be sure of the system's original configuration, but they guessed several values for the initial disk–star orbital parameters, and they modeled each one. In every one of their simulations, the system found its way within a few million years to a configuration consistent with what is observed today. "There are lots of misaligned systems," says Dawson, "but in the others, we don't have such a smoking gun."

## What's out there

The evidence from K2-290 doesn't mean that the primordial mechanism is responsible for all planetary misalignments. "There's probably more than one way to mess up a system," says Winn, "and we're just beginning to explore what's possible."

It's far too soon to tell what the most common misalignment mechanism is—or even how prevalent misaligned systems are. Exoplanet studies are still overwhelmingly dominated by the systems that are easiest to observe, whose formation and dynamics may not be representative of planetary systems in general. Hot Jupiters remain by far the easiest planets to study by any method, although powerful new spectrographs like ESPRESSO are starting to bring smaller planets under spectroscopic scrutiny. And multiplanet systems are rendered virtually invisible when the planets' orbits don't all lie in the same plane.

Still, the K2-290 observations pile on yet more evidence that planetary systems are diverse, and observations from our own well-studied solar system aren't necessarily universal or even typical. "We'd have developed a very different theory of solar-system formation," says Albrecht, "if, when Galileo looked at the Sun with his telescope, he'd seen the sunspots going the other way."

**Johanna Miller**

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# A new look at the proton sea

The ensemble of particles that make up the proton manifests a puzzling asymmetry that continues to challenge theory and experiment alike.

Students of particle physics learn early that the proton is made of three quarks: two up and one down. But there must be more to the story than that. The proton's rest mass is 938 MeV. The three quarks, with masses of just a few MeV each, make up only a tiny fraction of that.

Where does the remaining mass come from? Much of it is the kinetic energy of the quarks—they're not at rest inside the proton, and special relativity dictates that their effective mass increases with speed. Most of the mass lies in the details of how the strong force holds the proton together.

Gluons, the carriers of the strong force, are themselves massless, but the energy of the gluon field contributes to the total proton mass. And the field can spawn fleeting pairs of quarks and antiquarks, known as the sea, as represented in figure 1.

At the energy scales encountered in everyday life, protons behave like self-contained particles, and the sea and the

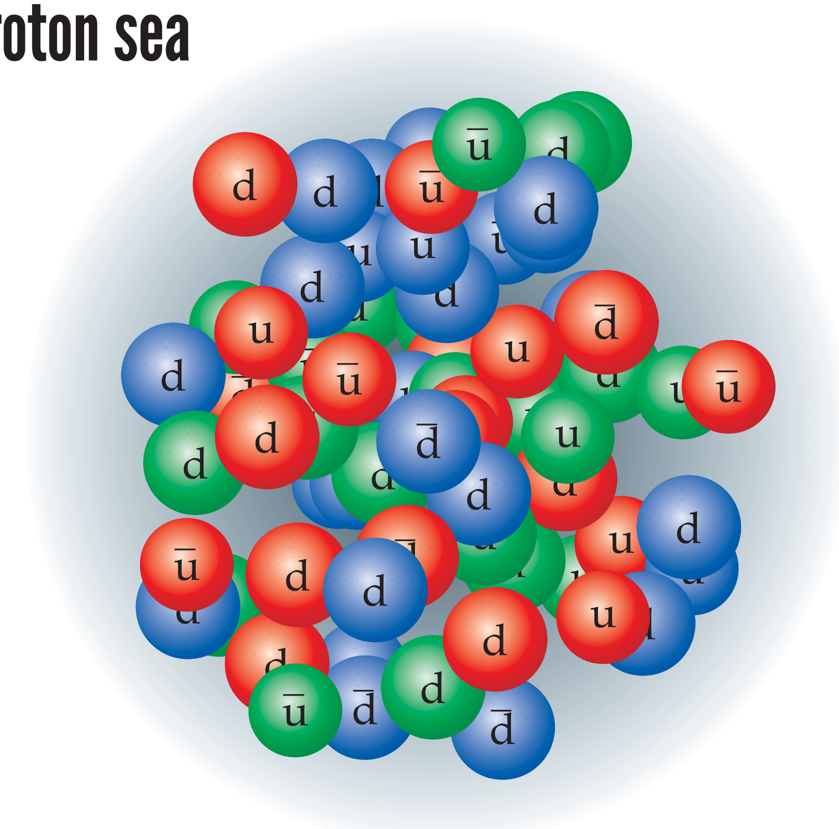

**FIGURE 1. THE PROTON** comprises not just two up quarks and a down quark but also a roiling sea of quark–antiquark pairs. The sea, which can't be accurately modeled by perturbative quantum chromodynamics, is an integral part of the proton's makeup and challenges theorists' understanding of how the strong force works. (Adapted by Donna Padian from an image by Paul Reimer.)

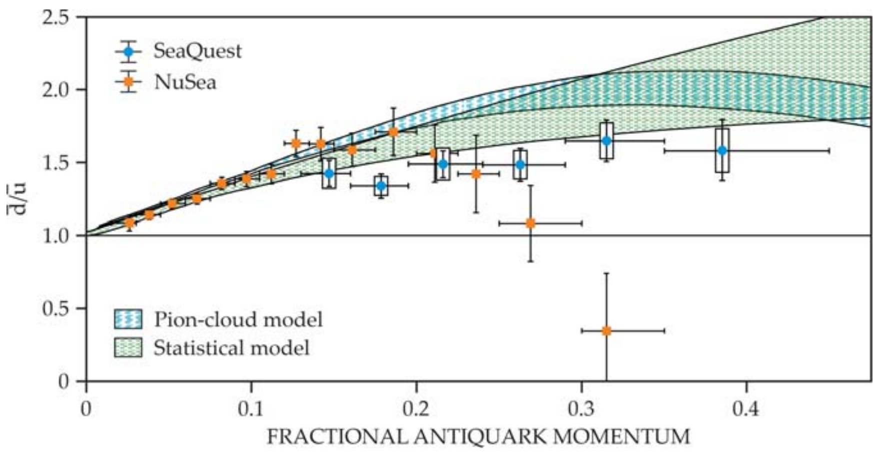


**FIGURE 2. THE COMPOSITION** of the proton's quark sea, characterized by the ratio between the numbers of down and up antiquarks, was probed 20 years ago by NuSea[2] and has now been further explored by SeaQuest.[1] The SeaQuest data, unlike the NuSea data, show a $\bar{d}/\bar{u}$ ratio that's always greater than 1, no matter what fraction of the proton's momentum an antiquark carries. That trend is a qualitatively better match to several theories, including the pion-cloud model[3] and a statistical model.[4] (Adapted from ref. 1.)

rest of their internal structure are mostly irrelevant. But at the high energies of particle accelerators, the reactions produced by a proton–proton collision really stem from collisions between the protons' component particles. Understanding the sea thus makes it possible to better predict what proton–proton colliders are capable of.

Now the SeaQuest experiment at Fermilab has released the results of the most thorough analysis of the sea to date.[1] The collaboration found that $\bar{d}$ antiquarks outnumber $\bar{u}$ antiquarks by about 50%. The result gives theorists a firmer foundation for their efforts to understand the inner workings of the proton, and it appears to help resolve a two-decade-old mystery left by the last experiment to study the sea.

## Blow ye winds

The key to navigating the sea is to identify a particle reaction that could result only from sea quarks, not the original three valence quarks. In a collision between some combination of d and u quarks, there's no distinction between valence and sea quarks. But a collision that involves antiquarks must involve the sea. (Quarks of other flavors, such as strange and charm, also occasionally show up in the sea, but they're not SeaQuest's focus.)

One reaction for homing in on the sea antiquarks is the Drell–Yan process: In a pair of colliding protons, a quark from one annihilates with an antiquark from the other to produce a virtual photon, which promptly decays into a muon and antimuon.

An experiment to study the sea through the Drell–Yan process typically shoots a beam of high-energy protons into a stationary target made of liquid hydrogen; the muon–antimuon pairs keep traveling in the original direction of the beam, where they're then detected. That configuration is most sensitive to collisions involving antiquarks from the target and quarks from the beam, rather than the other way around. So by swapping between targets made of hydrogen and deuterium, the experimenters can measure the difference between the antiquark seas of the proton and the neutron—and thus, with some symmetry assumptions, the $\bar{d}/\bar{u}$ antiquark ratio for the proton.

Some 20 years ago, SeaQuest's intellectual precursor—NuSea, also at Fermilab—used that approach to study the sea.[2] The results, shown in orange in figure 2, left theorists a bit bewildered. NuSea found that, for the most part, down antiquarks outnumbered up antiquarks in the sea. But among those rare antiquarks that carried more than 30% of the proton's total momentum, the flavor imbalance reversed, and $\bar{u}$ outnumbered $\bar{d}$.

## Across the line

That there should be any difference at all in the $\bar{d}$ and $\bar{u}$ numbers was initially a surprise. Gluon–quark interactions depend on energy and color—the strong force's analogue of electric charge—but not on flavor. Relative to the total energy available in the proton, the energy required to form a $u\bar{u}$ pair or a $d\bar{d}$ pair is nearly the same: The pairs should be produced in equal numbers. A more formal analysis using perturbative quantum chromodynamics, the simplest way of quantifying strong-force processes, gives the same answer.

To explain the $\bar{d}$ excess, theorists have developed more sophisticated models that incorporate additional phenomena. For example, Fermi statistics may play an outsized role: Quarks and antiquarks, being fermions, can't share quantum states with identical particles, so the presence of two up quarks in the proton already could significantly hinder the formation of a third.

Another idea, developed by Seattle University's Mary Alberg and the University of Washington's Gerald Miller, represents the sea quarks as a cloud of pions and other mesons that appear and disappear around the proton: At any given instant, the proton might really be a neutron (ddu) plus a positively charged pion ($u\bar{d}$)—or another proton (uud) plus a neutral pion (an equal superposition of $u\bar{u}$ and $d\bar{d}$). "This violates energy conservation," explains Alberg, "but it is allowed, for a fleeting moment, by the Heisenberg uncertainty principle." By adding up the contributions from all the possible channels, the theorists can model the composition of the sea.[3]

The theories can explain the overall $\bar{d}$ excess but not the $\bar{u}$ excess at high fractional momentum. There's no reason that Fermi statistics should ever favor the production of $u\bar{u}$ pairs over $d\bar{d}$ pairs. And the dominant $\bar{d}$ source in the pion-cloud model, the $\pi^+$–neutron channel, always dominates over any source of $\bar{u}$.

NuSea was unable to help resolve the mystery. Its $\bar{u}$ excess was seen only at the tail end of the data, and it wasn't possible to look any more closely. The experiment had been conducted on equipment that had been designed for another purpose, and it wasn't set up to capture the muon–antimuon pairs produced by antiquarks of high fractional momentum. As SeaQuest spokesperson Paul Reimer (who also worked on NuSea) puts it, "Just when the experiment was starting to show something interesting, it ran out of the ability to see anything."

## Go to sea once more

Right away, the idea emerged for SeaQuest, a purpose-built experiment designed to detect events from high-fractional-momentum antiquarks, but the fruition of the project was long in coming. "The first proposal was in 1999," explains Reimer, "but Fermilab wasn't in a position to run the experiment at that time, so very little work was done until about 2009. The experiment was commissioned in 2012, and data collection ran from 2013 until 2017."

By then, Fermilab's Tevatron, whose 800 GeV proton beam supplied the protons for NuSea, had been shut down. SeaQuest's only option was to use the 120 GeV protons from the lab's main injector, which remains operational. But the energy reduction was actually an improvement: The Drell–Yan cross section is inversely related to the collision energy, whereas cross sections for various background processes are directly related to energy. Put all together, then, SeaQuest was almost 50 times as effective at studying sea quarks as NuSea was.

A major experimental challenge—and a big part of why SeaQuest's data analysis has taken so long—came from the fluctuating intensity of the main injector beam. To detect Drell–Yan events, researchers comb their data for muons and antimuons whose timing and speed indicate that they were produced in the same place at the same time. If too many protons arrive at the target at once, there's a chance that particles produced in separate reactions could look like they came from the same Drell–Yan event.

"We could have just thrown away all the data from when the beam intensity was too great," says Reimer, "but then we would have lost a lot of our statistics. So we had to find a way to deal with it and extrapolate down to what we would have seen at low intensity."

The results just released, shown in blue in figure 2, buck the NuSea trend and show a continued $\bar{d}$ excess at high fractional momentum. Although the data are qualitatively more consistent with the predictions of many models, including those shown in the figure in green and blue, it's not yet possible to say which theoretical explanation of the sea is most accurate.

Should the NuSea data thus be superseded by the more easily explained SeaQuest data? Reimer is hesitant to go that far. "We've found no reason to think that either data set is incorrect," he says. "All I can say is that the NuSea data are on the very edge of that experiment's acceptance, whereas SeaQuest was designed to study this region."

In search of more clues, SeaQuest is transforming into SpinQuest. The new experiment will study collisions of beam protons with spin-polarized targets, in the hope of better understanding how the proton gets its spin. The proton spin contains contributions from the spins of all the valence and sea quarks, all of their orbital angular momenta, and the gluons holding everything together. So why, with such an ever-fluctuating ensemble of components, is the proton's spin always ½?

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# One frog species finds a solution to the cocktail party problem

A mechanism in the lungs of tree frogs helps filter incoming noise and other amphibian sounds from the calls of their own species.

When people attend large, noisy gatherings, hearing a conversation is often difficult. The so-called cocktail party problem also affects the green tree frog (pictured in figure 1) and other frogs in habitats teeming with the sounds of various animals and with anthropogenic sources of noise. Environmental background noise can reach volumes of 60–80 dB (relative to the standard sound-pressure-level reference), about the same amplitude as a vacuum cleaner. To be heard, tree frogs produce loud calls, often 100 dB in amplitude from 1 m away, an order of magnitude louder than the background noise.

Against the cacophony, frogs and other animals may, for example, incorrectly identify species-specific call patterns or struggle to locate sound sources. In exceptionally loud environments, other species abandon acoustic communication altogether and resort to visual cues, such as waving their legs. (For more about acoustic biology, see the article by Megan McKenna, Physics Today, January 2020, page 28.)

If your goal is to study evolutionary adaptations that improve the signal-to-noise ratio of incoming acoustic information, frogs make interesting subjects. For about 200 million years, they've been


**FIGURE 1. TREE FROGS**, like the male pictured here, inflate their vocal sacs—the flexible membrane of skin below the mouth—to amplify their mating calls in noisy habitats. To hear those calls even better, members of the species reduce the volume of ambient noise by taking advantage of the anatomical connection between their lungs and tympanum, or eardrums, via the eustachian tubes and the glottis, shown in the inset. (Photo courtesy of Norman Lee; inset adapted from ref. 3.)