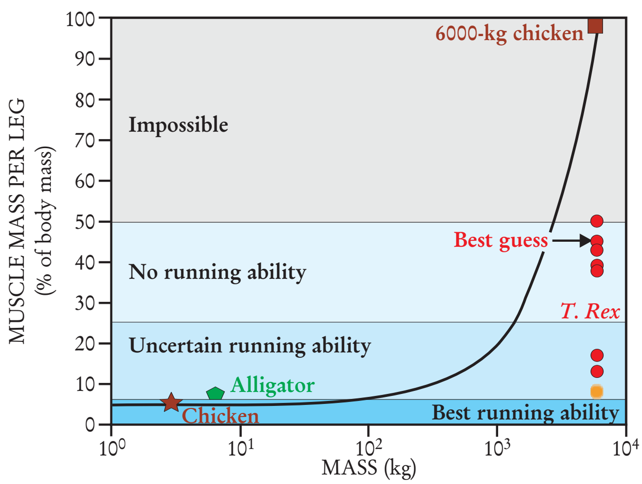

FIGURE 2. ESTIMATED EXTENSOR MUSCLE MASS per leg needed to run fast, as a fraction of total body mass. Larger animals need relatively more leg muscle to run. This dependence is illustrated by the solid line, calculated for a chicken scaled up to the size of *T. rex*. For several models of *T. rex* anatomy, the estimates (red) all require more leg muscle for running fast than the creature was likely to have had (orange dot). (Adapted from ref. 6.)

To translate this GRF into a forward velocity, the researchers applied the notion of dynamic similarity. Originally proposed by Alexander,[3] this concept considers the ratio between an animal's kinetic and potential energy as expressed in the Froude number, $Fr = v^2/gh$, where v is the forward velocity, g the acceleration due to gravity, and h the hip height. Animals moving with the same Froude number should have similar gaits and exert similar relative forces. A fast-running ostrich experiences a GRF of 2.7 times its body weight at $Fr = 16$; a *T. rex* with a similar relative GRF should have a similar Froude number, which corresponds to about 20 m/s—in line with the faster speed estimates.

Hutchinson and Garcia tested their running model with living species: a chicken (a fast runner) and an alligator (unable to run on two legs). The model predicted that a chicken must have at least 5% of its body weight as extensor muscles in each leg to run fast, almost a factor of two below the actual fraction of 9%. But for an alligator to run on its hind legs, the model predicted it would have to have a leg muscle fraction of 8%, and indeed alligators have much less than that. Thus in both cases, the model gave results consistent with observations.

For chickens and alligators, both distant relatives of extinct dinosaurs, the anatomical details the model required—joint angles, limb lengths, and weight distribution—were available from dissection. But for dinosaurs, only limb lengths are readily available from fossils. Weights can be estimated with various methods such as scaling, and by normalizing variables to total body mass, the researchers could reduce the effects of weight uncertainty. That left posture as the largest unknown.

In what Andrew Biewener (Harvard University) calls a nice quantitative addition to their study, Hutchinson and Garcia examined various values for *T. rex*'s posture parameters, thereby getting a sense of the model's sensitivity and uncertainty. The results for the different sets of values are shown as the solid red circles in figure 2.

The color bands of figure 2 follow from anatomical constraints and current knowledge of living animals. Having a leg muscle mass greater than 50% of the total body mass is impossible, because then the two legs combined would be more massive than the whole. For consistency with extant vertebrates, which have a total muscle mass that's half their total body mass or less, the researchers also rule out running when the required leg muscle mass fraction is more than 25%. For required fractional muscle masses below 25%, running ability depends on the actual leg muscle mass, as for the alligator. Empirically, the most agile running bipeds don't require more than 5% of their body weight to be leg extensor muscle.

"Despite fairly generous assumptions," says Garcia, "muscle masses would need to be unreasonably high for *T. rex* to be a fast runner." Even with the most favorable posture parameters, the researchers report that required extensor muscle is larger than the actual muscle mass of 7–10% they estimate based on scaling models.

Given the extensive unknowns, the pair hesitate to put a specific upper bound on the maximum speed of *T. rex*. "Speeds of 11 m/s [25 mph] would be pushing it," says Hutchinson, "but 20 m/s [45 mph] is not reasonable."

This work hasn't settled the debate over *T. rex* speed. Hutchinson is working on applying the model to other, larger living animals such as ostriches and rhinoceroses to test the conclusions, something many critics are eager to see.

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Sodium Detected in the Atmosphere of an Extrasolar Planet

For years, planetary scientists have been scouring the heavens in search of planets outside our own solar system. One very long-term goal is to discover a twin to our planet Earth and to search for biological features in its atmospheric spectrum. A shorter-term goal is to understand planetary formation processes more generally.

> As predicted by models, sodium atoms in the atmosphere of a remote planet are abundant enough that researchers have been able to see them. But they're also scarce enough to prompt some rethinking of the models.

Since the first sighting of an extrasolar planet in 1995, the search has netted nearly 80 planets, but we know little more about them than their minimum masses and their orbital parameters.[1] It's been tough enough to glean that much information, which in most cases has been inferred from the tiny, periodic wobble that the planet's orbital motion produces in the Doppler shift of its parent star. It's far tougher to detect the planet's atmospheric constituents. But now a team of researchers[2] has managed to detect atmospheric sodium atoms in a planet orbiting a star known as HD 209458, which has about the mass of the Sun. Like most extrasolar planets seen to date, the planet orbiting HD 209458 is a gas giant, similar in size to Jupiter, but its orbit—only $^1/_{25}$ that of Earth's—is much tighter.

Neutral sodium atoms don't tell as much about the chemistry and composition of a planetary atmosphere as do molecules such as carbon monoxide and water, but sodium is easier to detect. The observation opens the door to further discovery. "Seeing sodium atoms is a proof-of-concept," said Timothy Brown of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and a member of the team that found the sodium. "With a little more precision, we are confident that we can look for carbon monoxide and water."

Eclipsing a star

The sodium signal was teased out of data taken with the Hubble Space Telescope's imaging spectrograph by a collaboration of four researchers: David Charbonneau of Caltech, NCAR's Brown, Robert Noyes of the Harvard–Smithsonian Center for Astrophysics, and Ronald Gilliland of the Space Telescope Science Institute.

The team used a technique that requires a planet to pass between its parent star and an observer, as illustrated in figure 1. With such an orbital path, the planet blocks part of the light as it moves in front of its star. Fortunately, one planet among the 80-odd extrasolar planets sighted to date fits the bill.[3,4] That's the one in orbit about HD 209458. The relatively short year of this planet, only 3.5 days, is a convenient observational period.

Researchers should be able to measure the absorption of stellar light by the planet's atmosphere as the planet transits its star. In principle that sounds easy enough: Just look for a dip in the stellar spectrum at the wavelength of a sodium absorption line during the planet's transit of the star. (The experimenters targeted the prominent atomic sodium doublet near 589 nm.) But the planet's atmosphere takes only the tiniest nibble out of the star's spectral lines. The biggest chunk in the sodium absorption spectrum comes from the sodium atoms in the star itself. An additional piece is cut out by the bulk of the planet as it crosses the stellar face, blocking light at all wavelengths.

The stellar flux integrated over all wavelengths (white line with a dip in figure 1) goes down by only about 1.5% during the planetary transit. The flux at sodium wavelengths (blue line) should drop during transit by an additional few hundredths of 1% because of absorption by sodium atoms in the planetary atmosphere, or so modelers had predicted[5–7] before the recent measurement. Despite the obvious challenge, Charbonneau and colleagues thought the line would be observable.

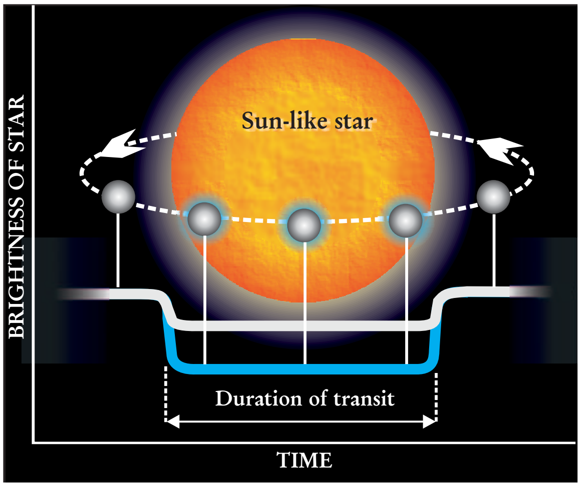

Figure 1. Brightness of a star fades as an orbiting planet (gray) passes in front of it (see dip in the horizontal white line). The sodium atoms in the planet's atmosphere reduce the brightness still further (blue line with dip) at wavelengths near 589 nm. This schematic exaggerates the spectral absorptions. The dip in the white line is just 1.5% of the total brightness; the blue dip is an additional 0.02%. (Courtesy of the Space Telescope Science Institute.)

The team measured the spectrum of HD 209458 during three planetary transits in the spring of 2000. Because the experimenters were trying to detect such a small signal, they had to be very careful of biases. One of these was a possible spurious signal caused by the wavelength-dependent variation in stellar intensity from the star's center to its periphery. Another was wavelength-dependent instrument sensitivity.

Once the researchers were assured that such biases produced sufficiently small effects, they took the number of photon counts in a window around the sodium doublet and subtracted the average number of counts seen in the adjacent wavelength bands. The counts at sodium wavelengths were, as expected, slightly below the average of the sidebands during the planetary transit, as seen in figure 2.

Not enough sodium atoms

The measured dip in photon flux due to sodium absorption was $(2.32 \pm 0.57) \times 10^{-4}$, expressed as a fraction of the total stellar flux. That value is in the ballpark of the predictions made by modelers beforehand,[5–7] but is only about a third of what was expected.

So what could be wrong? "Lots of things," reply the modelers, who are already going back and tweaking their initial assumptions. To make their earlier predictions, they had assumed that the gaseous planet would have the same metallic abundances as the parent star. They had also calculated the fraction of sodium present as atomic species, based on the temperature deduced from the known distance of the planet from the star. The low observed sodium absorption might mean that the planet had less sodium than its star to begin with, that the sodium had been ionized or had formed molecular compounds, or that the planet has high clouds, which block all wavelengths, causing the atmospheric sodium absorption to be an even smaller fraction of the total.

The sodium observations have provided a first data point on extrasolar planetary atmospheres. "Now we can try to constrain our models," commented one of the modelers, Sara Seager of the Institute for Advanced Study. With so many variables, however, it will take many more than one data point.

Close-in gas giants

Most extrasolar planets identified to date bear little resemblance to Earth. They all tend to be gaseous giants, with masses about that of Jupiter. Like the planet around HD 209458, a significant number orbit quite close to their parent stars. They are not a representative sample of the universe, because the method of identification—Doppler spectroscopy—skews the selection toward planets in tighter orbits. Recent Doppler discoveries have found giant planets in orbits more similar to Jupiter's. But to detect planets much less massive than Jupiter and more like Earth will require other techniques.

NASA's Kepler satellite, due to be launched in about five years, will use a different search tactic to look specif-

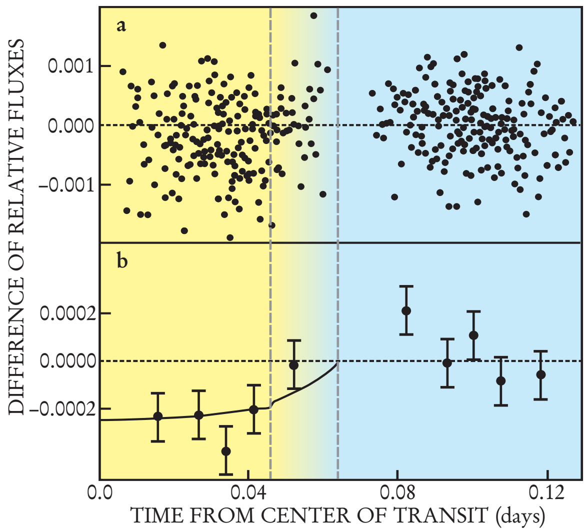

FIGURE 2. SODIUM absorption is seen when the stellar flux averaged over all wavelengths is subtracted from the flux in the sodium window. **(a)** Difference of relative flux versus time. **(b)** When binned in time, the data show that sodium absorption is 2×10^{-4} of the total stellar flux when the planet is passing in front of the star (yellow background) and zero when it is not (blue background). (Adapted from ref. 2.)

ically for planets similar to our own.[8] Kepler will train its sights on 100 000 stars for four years, hoping to see any Earth-sized planets that happen to transit these stars.

Other experiments and missions now being planned will look for such atmospheric constituents as water vapor and methane in the extrasolar planets that have already been spotted. These molecules are expected to show up in the near infrared. Some searches will continue to use ground-based rather than space-based telescopes. With the ground-based instruments, you get a larger observing area, but you then have to weed out the very large background of terrestrial atmospheric absorption.

Looking at the differential absorption during a stellar transit isn't the only way to identify atmospheric constituents, according to Jonathan Lunine of the University of Arizona. One alternative is to use interferometry to look directly at the planet, especially if the planet is far enough from its star. Typically, the planet is obscured by the bright starlight, but an interferometer could be configured to let experimenters cancel out the rays directly from the star and look at the light reflected off the planet's surface or at its thermal emission. Another approach is to directly block the starlight using a coronagraph.

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Correction

We wish to clarify our recent news story about an important sign correction in the standard-model calculation of the muon's anomalous magnetic moment (see PHYSICS TODAY, February 2002, page 18). We were remiss in failing to make clear the central role of Marc Knecht, Andreas Nyffeler, and colleagues at the University of Marseille, in being the first to discover—and make a convincing case—that the long-accepted sign of the hadronic light-by-light scattering contribution to the anomalous moment was wrong. Last November, Knecht and Nyffeler reported a detailed analytic and numerical calculation (ref. 3 in our story) that yielded the correct sign. Furthermore, in an accompanying paper with Michel Perrottet and Eduardo de Rafael (our ref. 4), they clinched the case for the corrected sign with an effective-field-theory approach to the hadronic light-by-light scattering. We also apologize to those who may have taken offense to our reference to the prevalent use of the Pauli metric in the Netherlands as an "ethnic idiosyncracy [sic]." ■