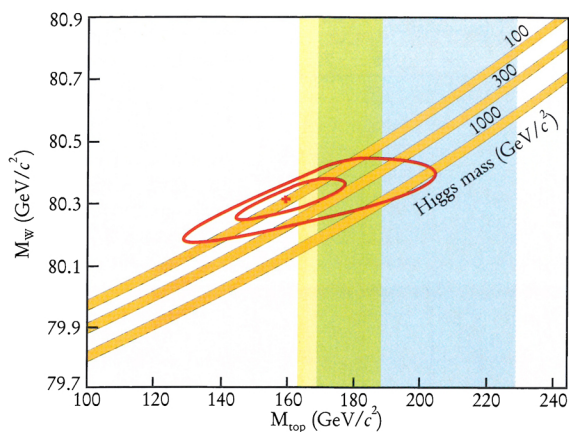




MEASURED PROPERTIES of the Z^0 boson and the strengths of the fundamental forces constrain the top, Higgs and W masses. The bands show possible Higgs masses as a function of the top and W masses. Shaded regions are consistent with the top masses measured by CDF (blue), D0 (yellow) and both experiments (green). Top, Higgs and W masses within the inner and outer contours are consistent with results from CERN's LEP collider and the Stanford Linear Collider at the one- and two-standard-deviation levels, respectively. (Figure courtesy of the D0 group.)

for resonances in the invariant $t\bar{t}$ mass distribution to probe strong-interaction dynamics at the top-mass scale and hunting for exotic species, such as supersymmetric particles, in top decays.

However, the most interesting physics to come from the top quark could be a complete surprise. Few would have guessed when the b quark was discovered that it would be interesting enough to merit the profusion of B factories now running or proposed. Many think the physics that will come from the top quark will be every bit as unexpected and exciting as that being realized with the b quark.

A top factory?

The physics of the top is still largely unexplored. However, what we ultimately learn from the top quark may depend as much on how enthusiastically we pursue it as on what it has to teach us. During the remaining months of the first Tevatron collider run, CDF and D0 hope to double their top samples, a reasonable goal if one assumes we are still on the steep portion of the learning curve when it comes to finding top quarks. Any glaring departures from the standard model might show up in such a sample. If no departures are evident we must wait until the second Tevatron collider run, scheduled to begin in 1999 with a fivefold increase in luminosity (and top-production rate) as a result of the Tevatron main-injector upgrade. CDF and D0 also plan to make significant upgrades to their spectrometers that should increase the efficiency with which they detect top quarks. With these changes the groups hope they will be able to find between a few hundred and a thousand tops per year. Over a few years this would allow them to tighten the limits on the Higgs mass and to take a fairly sensitive look for physics beyond the standard model.

The discovery of the first funda-

mental particle in over a decade has fired the imaginations of theorists and experimentalists alike. It has also stimulated the creativity of Fermilab's accelerator physicists, who have already coaxed the Tevatron collider to perform consistently at 15 times its design luminosity. Several ideas for further increasing the machine's performance have flourished in the year since our first glimpse of the top quark and are now being debated within the particle physics community. (See, for example, the letter by Jay Orear in *PHYSICS TODAY*, January, page 73, and the response by Sidney Drell, March, page 13.) One idea in particular has progressed over the past year, namely that of beefing up the Tevatron's antiproton flux by building an inexpensive 8-GeV antiproton storage ring with permanent magnets and cold electron beams to cool the antiprotons. The project is described by Fermilab accelerator physicist William Foster as "... an antimatter bottle made out of refrigerator magnets." Fermilab director John Peoples is confident that the storage ring could be built in tandem with the main injector, perhaps drawing on the money Fermilab has already saved in main-injector construction costs. Ultimately the increased luminosity would require further upgrades of the CDF and D0 detectors to han-

dle the increased interaction rate. Fermilab physicists hope the upgraded Tevatron could be producing tens of thousands of top quarks by around the beginning of the next century. A few years of running at this rate should enable the Tevatron experiments to either find or rule out the existence of several of the lightest particles predicted by supersymmetry.

In the latter half of the next decade CERN's Large Hadron Collider is scheduled to begin logging 10–14-TeV pp collisions and producing several hundred thousand top quarks per year. The LHC also gives us our best chance for directly observing the Higgs particle. Indeed, at the LHC with its five- to seven-fold increase in energy over the Tevatron, top quarks might be considered background to other, more interesting physics.

The relationship of the Tevatron to the LHC is unclear. Some contend that Tevatron upgrades would take funds away from the LHC and thereby slow the progress of particle physics. Others suggest that upgrading the Tevatron is a natural step toward the LHC. Kenneth Lane of Boston University, who strongly supports building the LHC, says, "The Tevatron is still the only training ground for the high-luminosity physics that will be done at the LHC." What CDF and D0 find during the remainder of their present run could influence the course of such arguments.

RAY LADBURY

'Asteroseismology' Offers a New Probe of Stellar Interiors

Just as the study of seismic waves lets us look into the bowels of the Earth, helioseismology has for more than 20 years been a rich source of information about the interior of the Sun. Apparently driven by internal convective motion, the Sun rings like a great spherical bell. Many thousands of resonant pressure-wave modes with periods on the order of 5

After a number of frustrated attempts, astronomers may at last be seeing seismic oscillation in nearby stars.

minutes have been painstakingly decoded from complex surface motions of dauntingly small amplitude. From the pattern of resonant frequencies one learns much about the composi-

tion, density and structure of the Sun. We now know, for example, that the Sun's convection zone is twice as deep as solar modelers believed before these oscillation modes were measured.

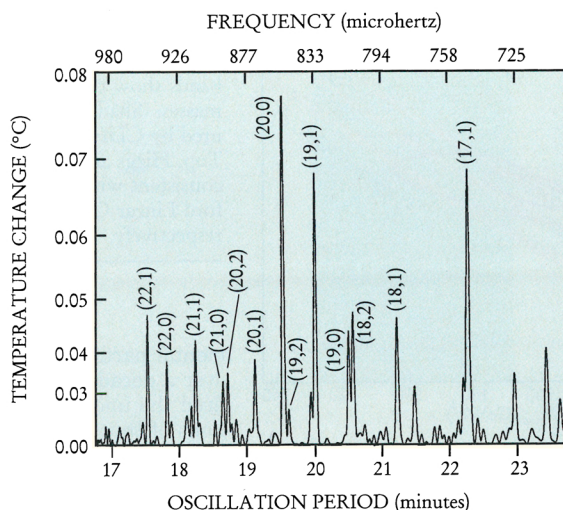
Astrophysicists would dearly like to have this kind of seismological data for stars beyond the Sun. Traditionally stars have yielded only very meager and indirect information about their interiors. How nice it would be to check theories of stellar evolution against measured oscillation modes for a great variety of stars.

Asteroseismology

A recent article in the *Astronomical Journal*¹ may be heralding the birth of "asteroseismology." Hans Kjeldsen and colleagues at the University of Aarhus, Denmark, and the European Southern Observatory report the strongest evidence to date of solar-like oscillations in another star—the subgiant η Boötis, 36 light-years away. But this is a tricky business. "Although we believe this evidence is convincing," they write, "we recognize from the number of previous claims in the literature that caution is appropriate."

It's hard enough to detect pressure-wave oscillations in the Sun, which is so close that one can measure spatial as well as temporal variation of Doppler shifts over its surface. All other stars are too far away for telescopes to reveal spatial seismic patterns; one can only measure averages over the stellar disk. That restricts the observer to modes described by the lowest-order spherical harmonics. The higher spherical harmonics (just like hydrogen wavefunctions with large l) have so many surface nodes that averages over the disk become very small.

Furthermore the oscillatory surface velocities whose Doppler shifts one might hope to measure are on the order of a meter per second. They shift spectral lines by parts in a billion. With the enormous photon flux from the Sun one can measure the 5-minute oscillation of such tiny Doppler shifts. But for stars, the limitations imposed by photon noise are just about fatal. Five years ago Timothy Brown (National Center for Atmospheric Research, Boulder, Colorado) and coworkers reported Doppler-shift observations of the prominent subgiant Procyon "consistent with" the 20-minute pressure-wave oscillations one would expect from a star of that size and mass.² But the noise prevented a clear identification of the characteristic, comb-like equal spacing between adjacent resonant frequencies that would signal a clear detection of solar-like oscillation. (See,



POWER SPECTRUM of temperature oscillations observed on the star η Boötis. Noise and side-lobe background have been mathematically diminished. Labels indicate eigenmode order and degree (n, l) for peaks attributed to seismic oscillation modes of the star, whose surface temperature is about 6000 K. Consecutive peaks of the same l are separated by about 40 μ Hz. (Adapted from ref. 1.)

for example, the figure above.)

One needs very high spectral resolution to detect minuscule Doppler shifts. But spectroscopy involves a trade-off between resolution and transmission. The greater the dispersion, the fewer the photons. Alternatively, photometric methods that seek to detect the very small total-luminosity changes engendered by stellar oscillation have thus far been unable to cope with atmospheric scintillation. That problem could of course be solved by an orbiting telescope dedicated to asteroseismology. But no one has as yet offered to fund such an undertaking.

Balmer absorption lines

Kjeldsen and company are pioneering a new technique that circumvents many of the problems inherent in Doppler and photometric attempts to do asteroseismology. They look for oscillatory variation in the effective depths of the star's Balmer absorption lines. Seismic pressure-wave modes would cause the surface temperature of a star like η Boötis to oscillate with an amplitude on the order of a part in a million. Because the Balmer lines come from absorption of starlight by surface hydrogen atoms *already* in the excited $n = 2$ state, their strength is extremely temperature sensitive. Increasing like T^6 , the effective depths of the Balmer absorption lines should exhibit greater oscillation amplitude than either the Doppler shifts or the star's total luminosity. Furthermore, measuring these oscillations in absorption strength does not require high-resolution spectroscopy, nor is it disturbed by atmospheric distortion.

For six nights last spring Kjeldsen's group monitored three promi-

nent Balmer absorption lines from η Boötis with the 2.5-meter Nordic Optical Telescope on the island of La Palma in the Canaries. For 10 hours each night they recorded a 5-second CCD exposure every 14 seconds. The next step was to create a Fourier power spectrum of this observed time sequence, in search of stellar oscillation modes.

Individual eigenmodes of pressure-wave oscillation are characterized by radial order number n and spherical-harmonic degree l . As with atomic wavefunctions, these indices give the number of radial and angular nodes. For high n and low, fixed l , the frequency difference between consecutive n modes is a constant that scales inversely as the square root of the mean stellar density. For the Sun, whose most prominent modes have periods in the vicinity of 5 minutes (corresponding to about 3 millihertz), this constant frequency spacing is 135 microhertz.

Scaling to η Boötis, which has about 1.6 times the mass of the Sun and 10 times its luminosity, one expects the most prominent pressure-wave modes to peak near 20 minutes (850 μ Hz, $n \approx 20$), with a constant frequency spacing of about 35 or 40 μ Hz. And the oscillation amplitudes should exceed those of the Sun by a factor of 5, making nearby subgiants like η Boötis and Procyon particularly attractive to aspiring asteroseismologists.

Finding the modes

Fourier analysis of the April 1994 η Boötis Balmer-line observations in search of 20-minute oscillation modes did indeed produce a spiky power spectrum peaked near 850 μ Hz. But that's not enough to prove the detec-

tion of seismic oscillation. From among the many spikes due to noise and artifacts of the Fourier analysis, Kjeldsen and coworkers had to extricate the sequences of equally spaced eigenfrequencies that are characteristic of solar-like oscillation.

The obvious method is to do a Fourier analysis of the power spectrum in search of a repeated frequency spacing of about the predicted size. But that kind of second Fourier analysis of a Fourier power spectrum is notoriously sensitive to spurious sidelobes caused by periodic interruptions of the observing period: Shutting down at dawn every day produces beat-frequency sidelobes at a spacing of $11.6 \mu\text{Hz}$ (the reciprocal of 24 hours) on either side of any true eigenmode peak.

Therefore Kjeldsen and company created what they call a comb-response function as an alternative to repeated Fourier analysis and its pitfalls. Unlike Fourier analysis, the comb-response function presupposes the presence of sequences of equally spaced frequency peaks. Testing this new analytic tool against simulated stellar oscillation data with obtrusive interruptions and lots of noise, the group was able to retrieve the correct eigenfrequencies reasonably well.

The end result of applying the comb-response analysis and additional cleaning algorithms to the power spectrum of last year's six-night observation of the η Boötes Balmer absorption lines is the figure on page 20. Fitting the peaks to theoretical formulae that give the eigenfrequencies in terms of the mode order numbers and empirical stellar parameters yields the n and l labels attached to the various peaks. The fitted spacing between consecutive peaks of the same l turned out to be $40.3 \mu\text{Hz}$, which is in reasonable agreement with what's predicted by scaling arguments applied to the helioseismological results.

This observed spacing and other parameters fitted from the η Boötes Balmer-line oscillation data bear directly on internal properties of the star that are not otherwise accessible. "But before we present a detailed comparison with astrophysical theory," says team member Søren Frandsen, "we want to make sure we haven't just been modeling noise and analytical artifacts. With all those diurnal sidelobes it gets very complicated."

Seeking confirmation

As we go to press, Kjeldsen and company are spending Easter week in pursuit of the obvious remedy. No one telescope (except near the poles

in winter) can escape the artifacts generated by having to stop observing every day at dawn. But two telescopes in widely separated time zones can do the trick. With one telescope in Chile and another in Australia, the group will spend the week monitoring the Balmer absorption lines of α Centauri. Aside from being very similar to the Sun, α Centauri has the distinction of being our nearest neighbor: It's only 4.3 light-years away. In addition to providing almost continuous coverage, both these telescopes are considerably larger

than the 2.5-meter instrument that provided the η Boötes data. "So our signal-to-noise ratio should also be much better," Frandsen told us. "If α Centauri confirms what we believe we found with η Boötes, asteroseismology will really be in business."

BERTRAM SCHWARZSCHILD

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Clouds Cast a Shadow of Doubt on Models of Earth's Climate

Clouds have always bedeviled those trying to model Earth's climate, because they are such complex systems, involving parameters whose size and time scales range over many orders of magnitudes. (See the article by Jeffrey Kiehl in *PHYSICS TODAY*, November 1994, page 36.) While struggling to represent clouds realistically in their models, atmospheric researchers have at least felt that they understood the basic physics of clouds. But now they are not so sure.

The conventional wisdom has been that clouds reflect some of the solar radiation entering the atmosphere but do not absorb any more radiation than a clear sky would. There have been hints, however, from experiments going back more than 40 years that clouds are not transparent but absorb an appreciable amount of solar radiation.¹ Until recently those experiments could be dismissed as inconclusive. But it's proving hard to ignore the evidence accumulated by three recent studies.²⁻⁴ Each of those studies measured by a different method the short-wavelength (0.25–4.0 microns) absorption by clouds, and all arrived at the same conclusion—that clouds are absorbing more short-wavelength radiation than is calculated by the radiative-transfer models used in simulations of Earth's climate.

The latest evidence leaves atmospheric scientists scratching their heads. If the measurements are correct, what is the theory missing? According to Tom Ackerman of Penn State, there are only a handful of possibilities, and none seems to be of the right size or nature to explain the observed discrepancies. More experiments are now planned to verify the existence of the larger-than-expected shortwave absorption and to determine its dependence on wavelength,

According to three recent experiments, clouds appear to be absorbing more of the incoming solar radiation than they should—at least if our current understanding of cloud physics is correct. Researchers plan additional experiments, capable of measuring the wavelengths at which the absorption occurs, to obtain more clues about the source of the discrepancy.

as a clue to the possible cause.

Deducing the cloud absorption

To find how much a cloud is attenuating the shortwave radiation, ideally one would like to station radiometers both above and below the cloud, recording the net shortwave flux at the two heights simultaneously. Moreover, one would want to take such measurements at stations around the globe and for long periods of time, because the nature of clouds varies temporally and spatially. In the real world, however, the possibilities are far more constrained. Information about the shortwave radiation at the cloud tops comes from the Earth Radiation Budget Experiment, which collected data only from 1984 to 1990; the data came from scanning instruments aboard several satellites. (See the article by V. Ramanathan, Bruce R. Barkstrom and Edwin F. Harrison in *PHYSICS TODAY*, May 1989, page 22.) Continuous, calibrated ground-based measurements are available from instruments at only a handful of stations worldwide. Additional data come from instruments aboard aircraft, but few of those airborne measurements have involved coordinated flights of stacked planes flying above and below the clouds.

In one of the recent studies, Robert Cess of the State University of