ASTRONOMY

# The Universe Measured with a Comb

A technique for wavelength calibration promises to revolutionize observational astrophysics, in areas including planet searches and cosmology.

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In 1962, Allan Sandage predicted that an expanding universe should cause a drift in the redshift of cosmological objects, but noted: "With present optical techniques there is apparently no hope of detecting such small changes in redshifts for time intervals smaller than $10^7$ years" (*1*). Future extremely large telescopes (with diameters of 30 to 40 m), equipped with powerful spectrometers, could in principle enable such a measurement. However, measuring a systematic change in radial velocity of only 1 cm $s^{-1}$ per year over the course of about 20 years—a measurement referred to as the Sandage-Loeb experiment (*2*–*4*)—would still be impossible if it were not for the recent development of a new and exquisite wavelength calibration technique called "laser frequency combs" (*5*). On page 1335 of this issue, Steinmetz *et al.* apply this technique for the first time to an astrophysical experiment (*6*), and the results look promising.

The Doppler effect provides astronomers with a precise method to measure radial velocities of stars and galaxies using the observed shift in wavelength (or frequency) of their spectral features relative to laboratories on Earth: The higher the radial velocity, the stronger the effect. And when the light entering the spectrometer comes from distant objects like galaxies or quasars—thus crossing cosmological distances to reach the telescope—their spectra provide information about the geometry and history of the universe as a whole.

Because the universe expands, distant objects can always be assigned with a redshift, a quantity that cosmologists relate to distance and time by fitting various parameters to cosmological models. The past decade has seen a series of breakthroughs in cosmology. The Wilkinson Microwave Anisotropy Probe (WMAP) mission delivered images of the cosmic microwave background that support a

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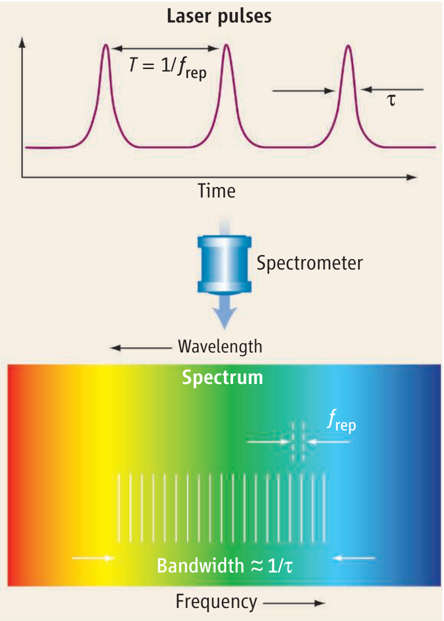

**The basics of a laser frequency comb.** A mode-locked laser creates femtosecond pulses at gigahertz frequencies, $f_{rep}$ (**top**), that are synchronized with an atomic clock. A spectrum of the pulses (**bottom**) is composed of many modes that are uniformly spaced in wavelength (or frequency) and cover a spectral bandwidth given roughly by the inverse of the pulse duration. Each mode's wavelength (or frequency) does not have to be measured, but instead is given by a mathematical relation that includes $f_{rep}$, known a priori with very high accuracy. Laser frequency combs could therefore become the perfect wavelength calibration technique for astrophysical experiments that require high accuracy and long-term stability.

flat universe, and studies measuring distances to Type Ia supernovae or the large-scale distribution of galaxies, among others, have established that the universe not only expands, but that the expansion is accelerating—presumably due to the effect of an unknown component in the mass-energy budget of the universe called "dark energy." Many projects aim to elucidate what dark energy really is, but all of them rely on a given cosmological model; only the Sandage-Loeb experiment could track the history of the expansion directly, without any previous assumption on the geometry of the universe.

What has been the impediment to fully exploiting present instrument capabilities? Traditional spectral calibration techniques use a crowd of emission or absorption lines at known laboratory wavelengths as reference to map the detector pixels into wavelengths. However, calibration units are subject to uncertainties that unavoidably degrade the wavelength solution: Lines are not evenly distributed in the spectral range of interest, have a wide range of intensities, and sometimes appear blended. These systematic effects become the perennial stumbling block for precision spectroscopy. They limit the capabilities of current high-resolution spectrometers and hinder experiment repeatability, crucial for any long-term monitoring.

The recently developed laser frequency combs (*3*, *6*–*9*) may offer the solution. Such a comb is the spectrum of a femtosecond "mode-locked" laser that delivers pulses at repetition rates $f_{\mathrm{rep}}$ of ~1 GHz (determined by the round-trip time in the laser cavity). When these pulses pass through a spectrometer, a regular train of modes is produced in the frequency domain, each of them evenly separated by $f_{\mathrm{rep}}$ (see the figure) and spanning a spectral bandwidth given by the inverse of the pulse duration. Because time—and thus frequency—is the most accurately measured quantity in physics thanks to atomic clocks, each mode's frequency (or wavelength) is accurately known a priori and can be used as a perfect ruler to calibrate astronomical spectra.

Steinmetz *et al.* now report the first astronomical spectrum (of the Sun) calibrated with a laser frequency comb. Besides slightly outperforming current best standards of accuracy using just a small bandwidth, the team was also able to characterize the stability of the instrument in an unprecedented fashion. Use of larger bandwidths should allow wavelengths to be measured with a stable precision of 1 part in 10 billion, opening a new era in astronomical spectroscopy.

Full implementation of laser frequency combs in large telescopes will require coverage of the entire optical range. Once this challenge is overcome, at least two other astrophysical experiments besides the future Sandage-Loeb test should benefit from the use of this technique.

First, some astronomers have wondered whether the atomic physics responsible for the redshifted absorption lines seen in the spectra of distant quasars has remained the same over cosmological times. The values of fundamental constants or combinations of constants—like the proton-to-electron mass ratio or the fine-structure constant—determine the relative positions of the lines in the quasar spectra. Thus, one could in principle compare the value of those constants then ("at high redshift") and now (on Earth) to determine whether they have remained constant. By choosing particular methods and sets of lines, different groups have arrived at diverging conclusions. After a decade of research, the debate is now centered on the systematic effects inherent to the observations. Laser frequency combs could help to identify the origin of these systematic effects.

Second, the precision and stability offered by laser frequency combs could greatly help astronomers looking for exoplanets (which orbit stars other than the Sun). Such planets imprint small changes on the radial velocity of their solar system, and monitoring the radial velocities of bright stars has thus become the most reliable way of finding planets. However, the smaller the planet, the smaller the drift in radial velocity. Discovering Earth-like planets orbiting solar-like stars in the "habitable zone" (where life could exist) requires a precision of about 5 cm $s^{-1}$ and a stability of about 1 year. This should be an easy task for this new technique.

### References and Notes

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