Ensemble Asteroseismology of Solar-Type Stars with the NASA Kepler Mission

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In addition to its search for extrasolar planets, the NASA Kepler mission provides exquisite data on stellar oscillations. We report the detections of oscillations in 500 solar-type stars in the Kepler field of view, an ensemble that is large enough to allow statistical studies of intrinsic stellar properties (such as mass, radius, and age) and to test theories of stellar evolution. We find that the distribution of observed masses of these stars shows intriguing differences to predictions from models of synthetic stellar populations in the Galaxy.

An understanding of stars is of central importance to astrophysics. Uncertainties in stellar physics have a direct impact on fixing the ages of the oldest stellar populations (which place tight constraints on cosmologies) as well as on tracing the chemical evolution of galaxies. Stellar astrophysics also plays a crucial role in the current endeavors to detect habitable planets around other stars (*1*–*5*). Accurate data on the host stars are required to determine the sizes of planets discovered by the transit method, to fix the locations of habitable zones around the stars, and to estimate the ages and to understand the dynamical histories of these stellar systems. Measurements of the levels of stellar activity and their variations over time (*6*) provide insights into planetary habitability, the completeness of the survey for extrasolar planets, and the surface variability shown by our own Sun, which has very recently been in a quiescent state that is unique in the modern satellite era (*7*, *8*).

New insights are being made possible by asteroseismology, the study of stars by observations of their natural, resonant oscillations (*9*, *10*). Stellar oscillations are the visible manifestations of standing waves in the stellar interiors. Main-sequence and subgiant stars whose outer layers are unstable to convection (solar-type stars) display solarlike oscillations that are predominantly acoustic in nature, excited by turbulence in the convective envelopes (*11*, *12*). The dominant oscillation periods are minutes in length and give rise to variations in stellar brightness at levels of typically just a few parts per million. The frequencies of the oscillations depend on the internal structures of the stars, and their rich information content means that the fundamental stellar properties (e.g., mass, radius, and age) can be determined to levels that are difficult to achieve by other means and that the internal structure and dynamics can be investigated in a unique way.

Helioseismology has provided us with an extremely detailed picture of the internal structure and dynamics of the Sun, including tests of basic physics (*13*–*15*). Such investigations are beginning to be possible for other stars. Over the past decade, the quality of seismic observations on other solar-type stars has been improving steadily, from ground-based spectroscopy (*16*–*18*) and the French-led CoRoT (Convection Rotation and Planetary Transits) satellite (*19*, *20*). Now, Kepler is providing ultraprecise observations of variations in stellar brightness (photometry), which are suitable for the study of solarlike oscillations (*21*). During the first 7 months of science operations, more than 2000 stars were selected for observation for 1 month each with a cadence rapid enough to perform an asteroseismic survey of the solar-type population in the Kepler field of view. Here, we report the detection of solarlike oscillations in 500 of those stars. Previously, this type of oscillation had been detected in only about 25 stars.

As is evident from the frequency spectra of the oscillations exhibited by nine stars from the ensemble (Fig. 1), solarlike oscillators present a rich, near-regular pattern of peaks that are the signatures of high-order overtones. The dominant frequency spacing is the so-called large separation, $\Delta\nu$, between consecutive overtones (*22*). The average large separation scales approximately with the square root of the mean density of the star. The observed power in the oscillations is modulated in frequency by a Gaussian-like envelope. The frequency of maximum oscillation power, ν_{max}, scales approximately as $gT_{eff}^{-1/2}$, where $g \propto M/R^2$ is the surface gravity and T_{eff} is the effective temperature of the star (*23*, *24*).

Figure 2 shows all the stars on a conventional Hertzsprung-Russell diagram, which plots the luminosities of stars against T_{eff}. The temperatures were estimated (*25*) from multicolor photometry

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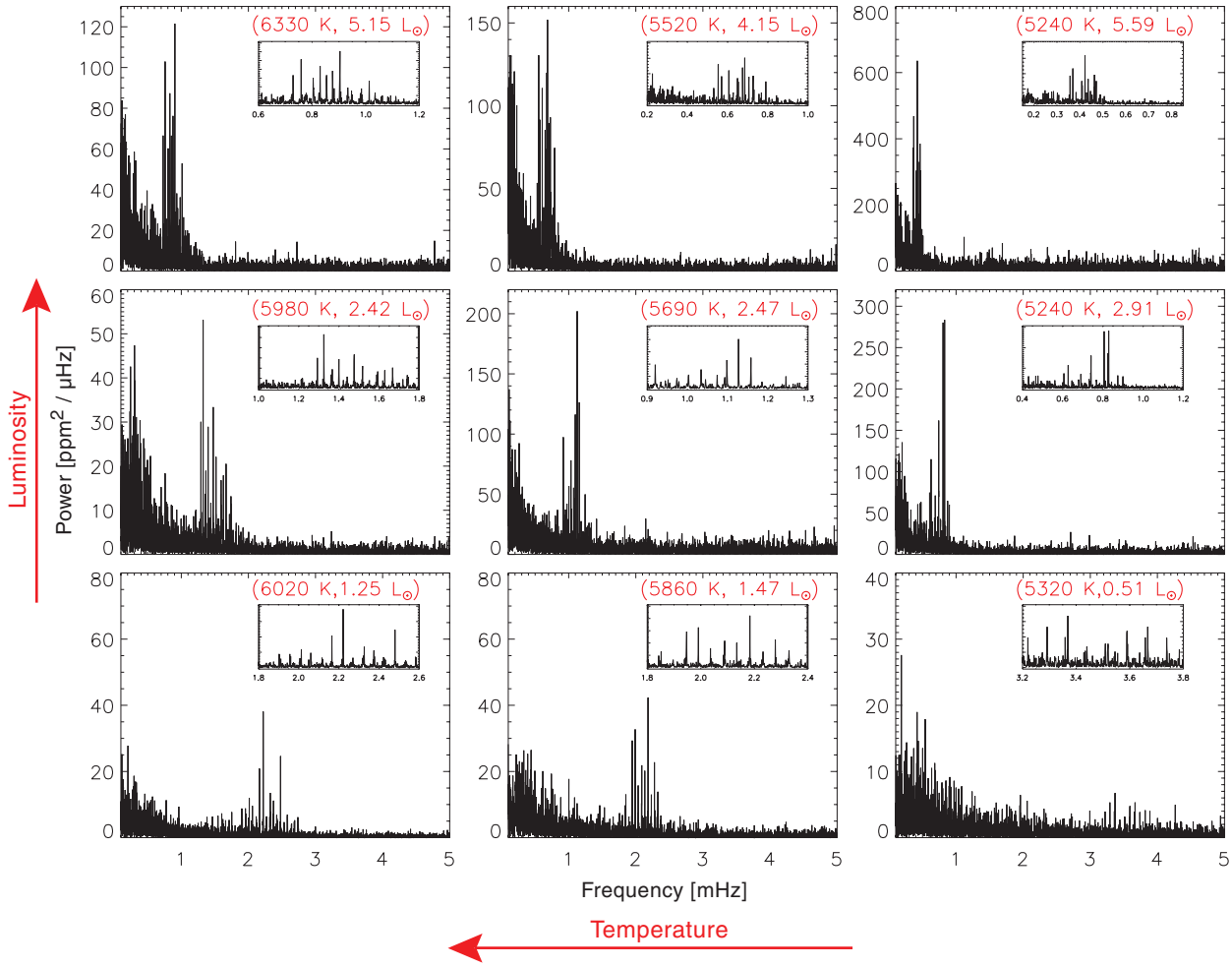

Fig. 1. Frequency spectra of the oscillations exhibited by nine stars from the ensemble. Each spectrum shows a prominent Gaussian-shaped excess of power because of the oscillations, centered on the frequency ν_{max}. (**Insets**) Clearer views of the near-regular spacings in frequency between individual modes of oscillation within each spectrum. The stars are arranged by intrinsic brightness [in units of solar luminosity ($L_\odot$)] and temperature, with intrinsically fainter stars showing weaker, less prominent oscillations than their intrinsically brighter cousins. ppm, parts per million.

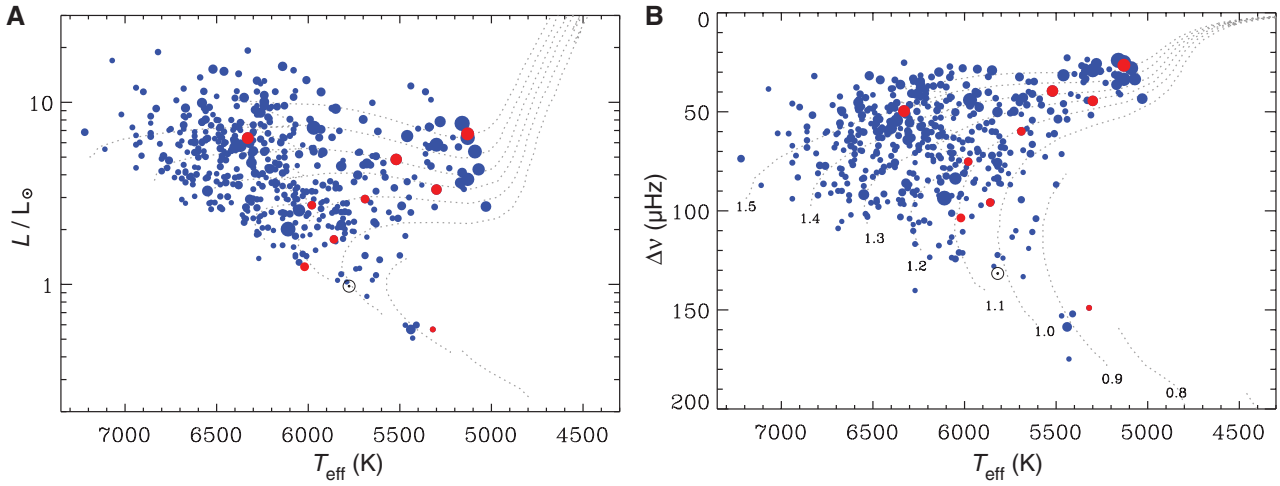

Fig. 2. (**A**) Estimates of the luminosities of the stars (in units of the solar luminosity) of the ensemble of Kepler stars showing detected solarlike oscillations, plotted as a function of effective temperature. Stars from Fig. 1 are plotted with red symbols. (**B**) Average large frequency separations, $\Delta\nu$, against effective temperature. The symbol sizes are directly proportional to the prominence of the detected oscillations (i.e., the signal-to-noise ratios). These ratios depend both on stellar properties (e.g., the photometric amplitudes shown by the oscillations and the intrinsic stellar backgrounds from convection) and the apparent brightness of the stars. The dotted lines show predicted evolutionary tracks (*33*) for models of different stellar mass (0.8 to 1.5 solar masses, in steps of 0.1). The Sun is marked with a solar symbol (⊙).

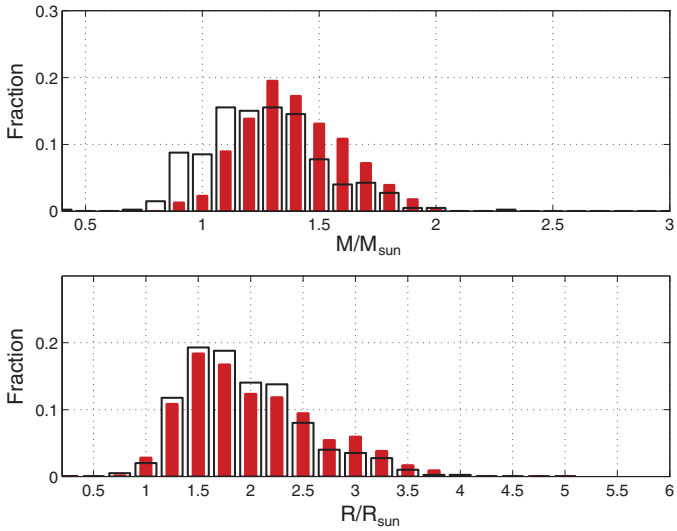

Fig. 3. Black lines show histograms of the observed distribution of masses (**top**) and radii (**bottom**) of the Kepler ensemble (*27*). In red, the predicted distributions from population synthesis modeling, after correction for the effects of detection bias (*27*). The population modeling was performed by using the TRILEGAL code (*34*, *35*).

available in the Kepler Input Catalog (*26*). Luminosities were estimated from the temperatures and the seismically estimated radii [see below and (*27*)]. We also plot $\Delta\nu$ against temperature, and, just like the conventional diagram, this asteroseismic version delineates different types of stars and different evolutionary states (the ν_{max} version is similar). Main-sequence stars, burning hydrogen into helium in their cores, lie in a diagonal swathe (from the lower right to top left) on each diagram. Both asteroseismic parameters, $\Delta\nu$ and ν_{max}, decrease along the main sequence toward hotter solar-type stars, where surface gravities and mean densities are lower than in cooler stars (and luminosities are higher). After exhaustion of the core hydrogen, stars eventually follow nearly horizontal paths in the luminosity plot toward lower temperatures as they evolve as subgiants, before turning sharply upward to become red giants (*28*, *29*). The values of $\Delta\nu$ and ν_{max} decrease comparatively rapidly through the subgiant phase. Detailed information on the physics of the interiors of these stars is emerging from analysis of Kepler data (*30*).

We have detected solarlike oscillations in relatively few stars that have $\Delta\nu$ and ν_{max} larger than the solar values. These stars are intrinsically fainter and less massive than the Sun, and we see fewer detections because the intrinsic oscillation amplitudes are lower than in the hotter main-sequence and evolved subgiant stars. This detection bias means that the most populous cohort in the ensemble is that comprising subgiants. Subgiants have more complicated oscillation spectra than main-sequence stars. The details of the spectra depend on how, for example, various elements are mixed both within and between different layers inside the stars. Seismic analysis of the Sun has already shown that merely reproducing the luminosity and temperature of a star will not guarantee that the internal structure, and hence the underlying physics, is correct. This inspired the inclusion of additional physics, such as the settling over time of chemical elements because of gravity, in stellar models (*13*). The Sun is a relatively simple star compared with some of the solar-type stars observed by Kepler.

We made use of the $\Delta\nu$ and ν_{max} of the ensemble together with photometric estimates of the temperatures to estimate the masses and radii of the stars in a way that is independent of stellar evolutionary models—by using the so-called direct-method of estimation (*27*)—and then compared the observed distributions with those predicted from synthetic stellar populations (Fig. 3). The synthetic populations were calculated by modeling the formation and evolution of stars in the Kepler field of view, which lies in the Cygnus region of the Orion arm of our Galaxy, the Milky Way (*27*). This modeling requires descriptions of, for example, the star-formation history (including the frequency of occurrence of stars with various masses), the spatial density of stars in the disc of the Milky Way, and the rate at which the Galaxy is chemically enriched by stellar evolution (*31*).

Previous population studies have been hampered by not having robust mass estimates on individual stars (*31*). Precise estimates of masses of solar-type stars had been limited principally to stars in eclipsing binaries (*32*). The Kepler estimates add substantially to this total and in numbers that are large enough to do statistical population tests by using direct mass estimates, which had not been possible before.

Whereas the distributions of stellar radii in Fig. 3 are similar, the same cannot be said for the mass distributions. We have quantified the significance of the differences by using statistical tests. Differences in radius were judged to be marginally significant at best. In contrast, those in mass were found to be highly significant (>99.99%) (*27*). The observed distribution of masses is wider at its peak than the modeled distribution and is offset toward slightly lower masses.

Tests suggest that, for the bulk of the stars, bias in the estimated masses and radii is no larger than the estimated uncertainties (*27*). On the assumption that the observed masses and radii are robust, this result may have implications for both the star-formation rate and the initial mass function of stars. Mixing or overshooting of material between different layers (including stellar cores) and the choice of the so-called mixing length parameter, which measures the typical length scale of the convection and is one of the few free parameters in stellar evolution theory, may also be relevant. It is yet to be tested whether the expected small fraction of unresolved binaries could have contributed to the mass discrepancy.

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Materials and Methods
Figs. S1 to S3
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HD 181068: A Red Giant in a Triply Eclipsing Compact Hierarchical Triple System

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Hierarchical triple systems comprise a close binary and a more distant component. They are important for testing theories of star formation and of stellar evolution in the presence of nearby companions. We obtained 218 days of Kepler photometry of HD 181068 (magnitude of 7.1), supplemented by ground-based spectroscopy and interferometry, which show it to be a hierarchical triple with two types of mutual eclipses. The primary is a red giant that is in a 45-day orbit with a pair of red dwarfs in a close 0.9-day orbit. The red giant shows evidence for tidally induced oscillations that are driven by the orbital motion of the close pair. HD 181068 is an ideal target for studies of dynamical evolution and testing tidal friction theories in hierarchical triple systems.

The Kepler space mission is designed to observe continuously more than 10^5 stars, with the ultimate goal of detecting a sizable sample of Earth-like planets around main-sequence stars (*1*). We obtained 218 days of Kepler photometry (*2*–*4*) of HD 181068 [also Kepler Input Catalog (KIC) 5952403], a star with magnitude $V = 7.1$ and a distance of about 250 pc. It had been previously identified as a single-lined spectroscopic binary (*5*), but there have been no reports of eclipses.

The data were obtained in long-cadence (LC) mode (one point every 29.4 min) over 218 days using quarters 1, 2, and 3. Our observations reveal a very distinctive light curve. It shows eclipses every ~22.7 days and slow variations in the upper envelope (Fig. 1A) that are likely caused by ellipsoidal distortion of the primary component. There are also very regular and much narrower eclipses (Fig. 1B). These minima have alternating depths, corresponding to a close pair (B and C), with an orbital period of ~0.9 day. The 22.7-day eclipses all have similar depths, but there are subtle differences between consecutive minima. Radial velocity observations [section 1.2 of (*6*)] show that the true orbital period of the BC pair around the A component is 45.5 days. The narrow 0.9-day eclipses essentially disappear during both types of the deep minima, implying that the three stars have very similar surface brightnesses, so that when the BC pair is in front of A, their mutual eclipses do not change the total amount of light coming from the system (in accordance with the nearly equal depths of the two deep minima). When the BC pair is in front of A, the BC's secondary eclipses appear as tiny brightenings (Fig. 1, D and F), showing that the surface brightness of B is almost equal to that of A, whereas C is a bit fainter, so that its disappearance behind B allows the extra light from A to reach us.

The observed changes in the eclipses of the BC pair and the radial velocity variations of the A component confirm that the A and BC systems are physically associated and not a chance alignment. Their periods are $P_{BC} = 0.90567(2)$ day and $P_{A\text{-}BC} = 45.5178(20)$ days (numbers in parentheses refer to the standard error in the last digits). Given the shallow depths of the eclipses, star A must be the most luminous object in the system. In addition to the eclipses, there are brightness fluctuations during the long-period minima that imply that component A is also an intrinsic variable star with a mean cycle length close to half the shorter orbital period, possibly indicating tidally induced oscillations.

In addition, there were several flarelike events in the light curve that usually lasted about 6 to 8 hours. We checked the Kepler Data Release Notes (*7*) for documented instrumental effects in the vicinity of the "flares" but found none. Moreover, almost all flares appear right after the shallower minimum of the BC pair, suggesting that this activity might be related to the close pair.

We looked for optically resolved companion(s) with a 1-m telescope [section 1.1 of (*6*)] but found none. We also obtained 38 high-resolution optical spectra to measure the orbital reflex motion of the A component (*6*) (fig. S1). The orbital parameters for the wider system (Table 1) reveal that star A revolves on a circular orbit, which has an orbital period twice the separation of the two consecutive flat-bottomed minima in the light curve (*6*). Long-baseline interferometry using the PAVO (Precision Astronomical Visible Observations) beam combiner (*8*) at the CHARA [Center for High Angular Resolution Astronomy (*9*)] Array show that the angular diameter of HD

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Ensemble Asteroseismology of Solar-Type Stars with the NASA Kepler Mission

W. J. Chaplin *et al.*

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