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The same frequency of planets inside and outside open clusters of stars

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Most stars and their planets form in open clusters. Over 95 per cent of such clusters have stellar densities too low (less than a hundred stars per cubic parsec) to withstand internal and external dynamical stresses and fall apart within a few hundred million years[1]. Older open clusters have survived by virtue of being richer and denser in stars (1,000 to 10,000 per cubic parsec) when they formed. Such clusters represent a stellar environment very different from the birthplace of the Sun and other planet-hosting field stars. So far more than 800 planets have been found around Sun-like stars in the field[2]. The field planets are usually the size of Neptune or smaller[3–5]. In contrast, only four planets have been found orbiting stars in open clusters[6–8], all with masses similar to or greater than that of Jupiter. Here we report observations of the transits of two Sun-like stars by planets smaller than Neptune in the billion-year-old open cluster NGC6811. This demonstrates that small planets can form and survive in a dense cluster environment, and implies that the frequency and properties of planets in open clusters are consistent with those of planets around field stars in the Galaxy.

Previous planet surveys in clusters have suffered from insufficient sensitivity to detect small planets, and from sample sizes barely large enough to find the less common larger planets[9]. The recent discovery by the Doppler method of two giant planets around Sun-like stars in the Praesepe open cluster[8] set a preliminary lower limit to the rate of occurrence of hot Jupiters in that cluster. This frequency is not inconsistent with that in the field, after accounting for the enriched metallicity of Praesepe[10] and the positive correlation between stellar metallicity and the frequency of giant planets[11]. However, it does not address the frequency of smaller planets such as those more commonly found around field stars. NASA's Kepler telescope is sensitive enough to detect planets of the size of Neptune or smaller, using the transit technique.

Our detection of two mini-Neptunes (two to four Earth radii, $R_\oplus$) in NGC6811 is the result of a survey of 377 stars in the cluster as part of The Kepler Cluster Study[12]. The two planets, Kepler-66b and Kepler-67b, have radii of $2.8R_\oplus$ and $2.9R_\oplus$ and are each transiting (passing in front of) a Sun-like star in NGC6811 once every 17.8 and 15.7 days, respectively. Kepler-66b and Kepler-67b are the smallest planets to be found in a star cluster, and the first cluster planets seen to transit their host stars, which enables the measurement of their sizes.

The properties derived for the two planets depend directly on the properties determined for their parent stars (Kepler-66 and Kepler-67). Because the members of NGC6811 form a coeval, co-spatial and chemically homogeneous collection of stars, they trace a distinct sequence in the colour–magnitude diagram (Fig. 1a). This allows both their commonly held properties (such as age and distance) and their individual physical characteristics (such as masses, radii and temperatures) to be determined reliably from stellar evolution models[13,14]. Kepler-66b and Kepler-67b therefore join a small group of planets with precisely determined ages, distances and sizes. Table 1 lists the model-derived properties of the two planets and their host stars. Figure 1a shows the locations of Kepler-66 and Kepler-67 in the colour–magnitude diagram for NGC6811, and Fig. 2 displays their phase-folded transit light curves reduced and calibrated by the Kepler pipeline[15].

The membership of Kepler-66 and Kepler-67 to NGC6811 was established from a five-year radial-velocity survey (see Supplementary Information). They are both secure radial-velocity members of NGC6811 and are located squarely on the cluster sequence in the colour–magnitude diagram (Fig. 1a). Their rotation periods listed in Table 1 were determined from the periodic, out-of-transit, brightness variations in the Kepler light curves, caused by star spots being carried around as the star spins (see Supplementary Information). The rotation periods provide additional confirmation of cluster membership, as they obey the distinct relationship between stellar rotation and colour observed for other members of NGC6811. Figure 1b shows the colour versus rotation period diagram plotted for radial-velocity members of the cluster[16].

Because of the large distance to NGC6811, the two host stars are too faint (see Table 1) for their radial velocities to be measured with sufficient precision to confirm the status of Kepler-66b and Kepler-67b as true planets in the usual way, that is, by establishing that their masses are in the planetary range. To validate them as planets we instead applied a statistical procedure known as BLENDER (see Supplementary Information), by which we have demonstrated that they are much more likely to be planets than false positives. We determined probabilities of only 0.0019 and 0.0024 that Kepler-66b and Kepler-67b are false positives.

To establish whether finding two mini-Neptunes in NGC6811 is consistent with the rate of occurrence of planets in the field, we conducted a Monte Carlo experiment using the known spectral type and magnitude distributions of the 377 member stars. We simulated true planets adopting distributions of planet sizes and orbital periods corresponding to those found in the Kepler field, along with planet occurrence rates based on a statistical study of the Kepler candidates that accounts for the incidence of false positives as well as incompleteness[5]. We retained only the simulated planets that would be detectable by Kepler on the basis of real noise estimates for each star. We repeated the simulation 1,000 times to predict the average number of transiting planets of all sizes we would expect to detect among the known cluster members observed by Kepler, as well as their period and size distributions (Fig. 3). The result, 4.0 ± 2.0 planets, is consistent with our two planet detections. The expected number of 2.2 ± 1.5 mini-Neptunes is also consistent with our detection of two such planets, and the lack of smaller and larger transiting planets in NGC6811 similarly agrees with their predicted detection rates of 1.2 ± 1.1 for Earths and super-Earths (0.8–$2R_\oplus$) and 0.6 ± 0.6 for giant planets ($>4R_\oplus$). Together, the results

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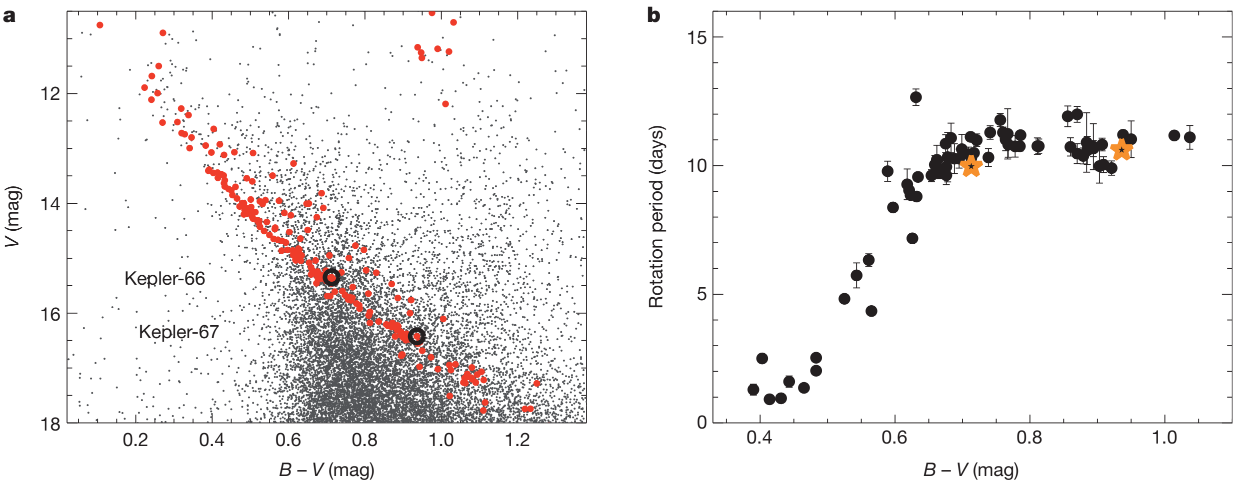

Figure 1 | The colour–magnitude and colour–period diagrams for NGC6811. **a**, The colour–magnitude diagram for stars within a 1-degree-diameter field centred on NGC6811 with the locations of Kepler-66 and Kepler-67 marked by black circles. Cluster members, marked with larger red dots, trace a well-defined relationship between stellar mass (colour, $B - V$) and luminosity (brightness, V) that can be fitted by stellar evolution models to determine the age and distance of NGC6811 as well as the masses and radii of its members. By this method NGC6811 is found to be 1.00 ± 0.17 billion years old and 1,107 ± 90 parsecs distant[17]. **b**, The colour–period diagram for 72 NGC6811 members[16]. The rotation periods are determined from periodic brightness variations in the Kepler light curves, and the error bars represent the dispersion of multiple period measurements. As in the colour–magnitude diagram, cluster members trace a well-defined relation between stellar colour and rotation period. The locations of Kepler-66 and Kepler-67 on the cluster sequence are marked by orange star symbols.

imply that the planet frequency in NGC6811 is consistent with that of the field.

The members of NGC6811 fall entirely within the range of stellar spectral types selected for the Kepler planet survey, and the slightly sub-solar metallicity of NGC6811 (ref. 17) is close to the average metallicity of the Galactic disk population from which the Kepler targets are drawn. Therefore, correlations between planet frequency and stellar mass and/or metallicity are not a concern when comparing the frequency and size distribution of planets in NGC6811 to that of the field. The detection of Kepler-66b and Kepler-67b thus places the first robust constraint on the frequency of small planets in open clusters relative to the field.

Table 1 | Stellar and planetary parameters for Kepler-66 and Kepler-67

Stellar properties	Kepler-66	Kepler-67
Right ascension	19 h 35 min 55.573 s	19 h 36 min 36.799 s
Declination	46° 41′ 15.906″	46° 09′ 59.181″
Spectral type	G0V	G9V
Effective temperature, T_{eff} (K)	5,962 ± 79	5,331 ± 63
log[Surface gravity (cm s^{-2})]	4.484 ± 0.023	4.594 ± 0.022
Rotation period (days)	9.97 ± 0.16	10.61 ± 0.04
Mass (solar masses)	1.038 ± 0.044	0.865 ± 0.034
Radius (solar radii)	0.966 ± 0.042	0.778 ± 0.031
Density (solar)	1.15 ± 0.15	1.89 ± 0.17
Visual magnitude, V	15.3	16.4
Age (billion years)	1.00 ± 0.17	
Distance (parsec)	1,107 ± 90	
Metallicity, Z	0.012 ± 0.003	
Planetary parameters	**Kepler-66b**	**Kepler-67b**
Orbital period (days)	17.815815 ± 0.000075	15.72590 ± 0.00011
Impact parameter	0.56 ± 0.26	0.37 ± 0.21
Time of mid-transit (BJD)	2454967.4854 ± 0.0025	2454966.9855 ± 0.0048
Planet-to-star radius ratio	0.02646 ± 0.00097	0.03451 ± 0.0013
Scaled semi-major axis (a/R_{star})	30.3 ± 1.0	32.4 ± 1.1
Semi-major axis (AU)	0.1352 ± 0.0017	0.1171 ± 0.0015
Radius ($R_{\oplus}$)	2.80 ± 0.16	2.94 ± 0.16

The age, distance and chemical composition of NGC6811 were determined from a maximum-likelihood fit of stellar evolution models[13,14] to the cluster sequence in the colour–magnitude diagram using Bayesian statistics and a Markov-chain Monte Carlo algorithm[17]. The best-fitting stellar isochrone[14] and photometric measurements in all available bandpasses (UBV, griz, JHK and D51 magnitude) were used to derive the effective temperatures, surface gravities, masses, radii and densities for Kepler-66 and Kepler-67. The transit and orbital parameters (period, impact parameter, time of mid-transit, radius ratio, and scaled semi-major axis) for Kepler-66b and Kepler-67b were derived from the Kepler photometry using a Markov-chain Monte Carlo procedure with the mean stellar density as a prior[28]. The parameters for Kepler-67b account for minor dilution from a close companion to the star described in section 3.2 of the Supplementary Information. Errors given for stellar and planetary parameters are 1σ uncertainties. BJD is barycentric Julian date, and AU is astronomical units.

The comparison in Fig. 3 of the orbital periods and radii of Kepler-66b and Kepler-67b with those in our simulated distributions shows that the sizes and orbital properties of the two planets are similar to those of the most common types of field planets (2–3$R_{\oplus}$, and orbital periods between 10 and 20 days). This suggests that the sizes and orbital properties of planets in open clusters are also not unlike those in the field.

The masses, structures and compositions of Kepler-66b and Kepler-67b can be constrained using theoretical models. With radii in excess of 2$R_{\oplus}$, the two planets probably contain significant quantities of volatiles in the form of astrophysical ices and up to a few per cent of H or He by mass. Volatile-poor rocky planets this large would have Saturn-like masses of 82–117 Earth masses (assuming an Earth-like composition with 32% iron core and 68% silicates by mass), and would be larger and more massive than any rocky exoplanet discovered to date. Instead, Kepler-66b and Kepler-67b are likely to have structures and compositions that resemble that of Neptune and, following mass–radius relations for exoplanets in the field[18], probably have masses less than 20 Earth masses (see Supplementary Information).

For NGC6811 to have survived a billion years, the initial number density of stars in the cluster must have been at least that of the Orion Trapezium cluster (about 13,000 per cubic parsec) and thus more than two orders of magnitude greater than that of the typical cluster formed in a molecular cloud (about a hundred stars per cubic parsec; ref. 1). Highly energetic phenomena including explosions, outflows and winds often associated with massive stars would have been common in the young cluster. The degree to which the formation and evolution of planets is influenced by a such a dense and dynamically and radiatively hostile environment is not well understood, either observationally or theoretically[19–25]. The formation of planets takes place in the circum-stellar disks during the first few million years of a star's life, which is the typical lifetime of disks[26]. We estimated the number and mass-distribution of stars in NGC6811 at the time Kepler-66b and Kepler-67b formed by fitting a canonical initial mass function[27] to the current distribution of masses for members in the cluster (see Supplementary Information). The calculation suggests that the cluster contained

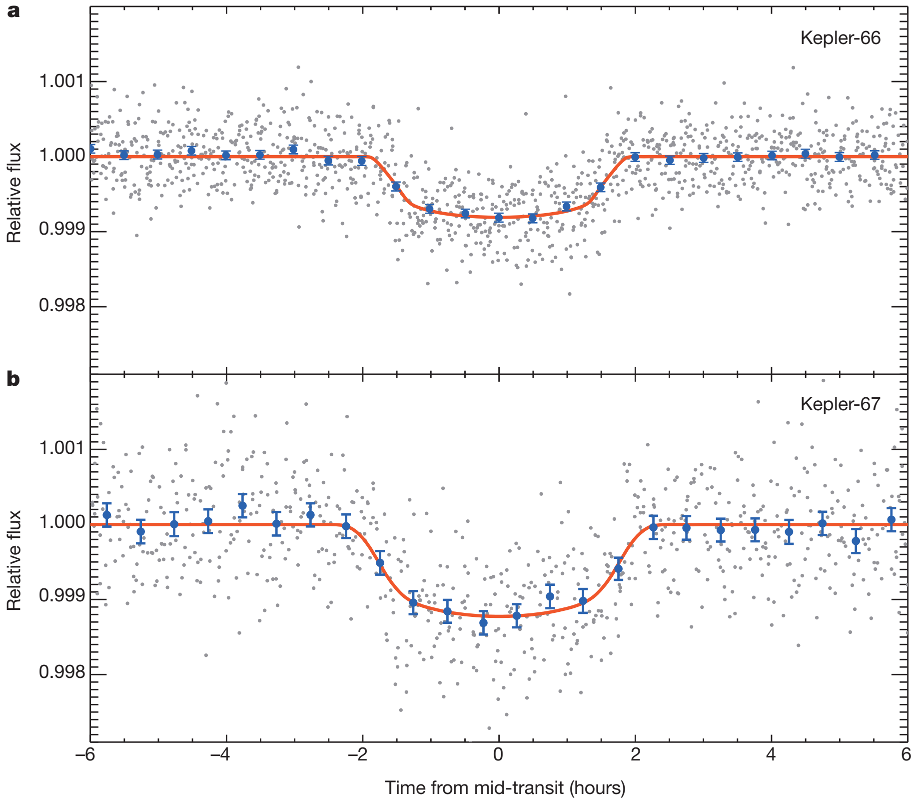

Figure 2 | Transit light curves. a, b, The Kepler light curves for Kepler-66 (**a**) and Kepler-67 (**b**). The photometric measurements (grey points) were acquired in long cadence mode (30-min total exposures) and have been detrended[28], normalized to the out-of-transit flux level, and phase-folded on the periods of the transiting planets. The blue data points and error bars represent the same data phase-binned in 30-min intervals and the standard error of the mean, respectively. Transit models smoothed to the same cadence are overplotted in red.

at least 6,000 stars during the era of planet formation, including several O stars (masses greater than 20 solar masses) and more than one hundred B stars (masses between 3 and 20 solar masses). The discovery of two mini-Neptunes in NGC6811 thus provides evidence that the formation and long-term stability of small planets is robust against stellar densities that are extremely high for open clusters, and the violent deaths and high-energy radiation of nearby massive stars.

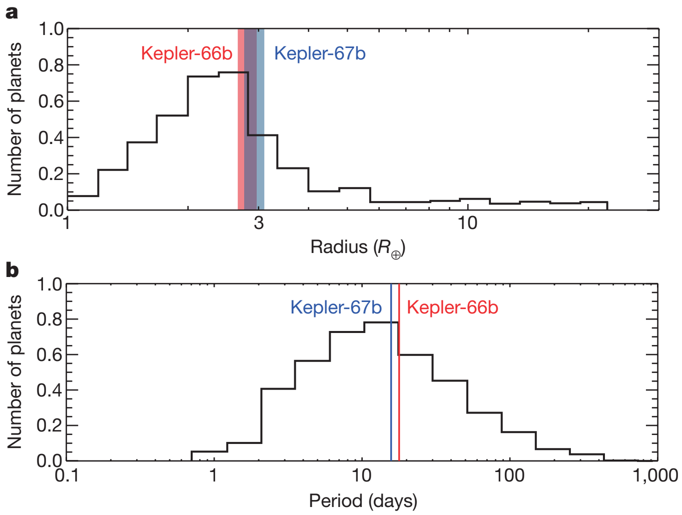

Figure 3 | Distribution of planetary properties. a, b, Histograms of planetary radii (**a**) and orbital periods (**b**) of simulated transiting planets expected in NGC6811, accounting for incompleteness and assuming the same period and size distribution and occurrence rate as in the field[5]. The properties of Kepler-66b and Kepler-67b are similar to those of the most commonly expected planets. The widths of the red and blue vertical lines reflect $\pm1\sigma$ errors in the radii and periods of the two planets.

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Author Contributions S.M. is the Principal Investigator of The Kepler Cluster Study and led the writing of the paper and the effort to identify members of NGC6811. He worked with G.T. and F.F. on characterization and validation of Kepler-66b and Kepler-67b, and with K.J. and S.A.B. on determination of the properties of NGC6811. G.T. developed the BLENDER software used to validate the planets, and determined the stellar properties of the host stars. F.F. worked on the BLENDER validation of the two planets and the Monte-Carlo simulation of the cluster yield. D.W.L. contributed follow-up spectroscopy of host stars. J.F.R. performed the light-curve analysis to extract the planet characteristics. D.R.C. provided constraints on angular separation of potential background blends from adaptive optics imaging. S.T.B. performed pixel-level centroid analysis. C.E.H. assisted in running BLENDER on the NASA Pleiades supercomputer. L.A.R. modelled the planets' interior structure to constrain the range of possible masses and compositions. K.J. led the supporting photometric study from which the bulk properties of NGC6811 are derived. S.A.B. participated in the acquisition of ground-based spectroscopic and photometric data on NGC6811. G.W.M. and H.I. obtained and analysed high-resolution Keck HIRES spectra of the host stars used for the BLENDER analysis. D.A.F. analysed HIRES spectra using the Spectroscopy Made Easy software. S.B.H. and E.P.H. obtained and analysed speckle observations of the host stars. J.M.J. led the efforts of data collection, data processing and data review that yielded the Kepler time series photometry. S.C.S. did spectroscopic analysis of stellar members of NGC6811 to aid in the determination of cluster parameters including metallicity. J.C. obtained adaptive optics imaging observations.

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