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Stello, Dennis; Kepler Group

DOI:
10.1088/2041-8205/713/2/L182

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Stello, D & Kepler Group 2010, 'Detection of Solar-Like Oscillations From Kepler Photometry of the Open Cluster Ngc 6819', *Astrophysical Journal Letters*, vol. 713, no. 2, pp. L182-L186. https://doi.org/10.1088/2041-8205/713/2/L182

Link to publication on Research at Birmingham portal

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Published in The Astrophysical Journal Letters - http://iopscience.iop.org/2041-8205/713/2/L182/.

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The Astrophysical Journal Letters, 713:L182–L186, 2010 April 20 doi:10.1088/2041-8205/713/2/L182

DETECTION OF SOLAR-LIKE OSCILLATIONS FROM *KEPLER* PHOTOMETRY OF THE OPEN CLUSTER NGC 6819

Dennis Stello[1], Sarbani Basu[2], Hans Bruntt[3], Benoît Mosser[3], Ian R. Stevens[4], Timothy M. Brown[5], Jørgen Christensen-Dalsgaard[6], Ronald L. Gilliland[7], Hans Kjeldsen[6], Torben Arentoft[6], Jérôme Ballot[8], Caroline Barban[3], Timothy R. Bedding[1], William J. Chaplin[4], Yvonne P. Elsworth[4], Rafael A. García[9], Marie-Jo Goupil[3], Saskia Hekker[4], Daniel Huber[1], Savita Mathur[10], Søren Meibom[11], Vinothini Sangaralingam[4], Charles S. Baldner[2], Kevin Belkacem[12], Katia Biazzo[13], Karsten Brogaard[6], Juan Carlos Suárez[14], Francesca D'Antona[15], Pierre Demarque[2], Lisa Esch[2], Ning Gai[2,16], Frank Grundahl[6], Yveline Lebreton[17], Biwei Jiang[16], Nada Jevtic[18], Christoffer Karoff[4], Andrea Miglio[12], Joanna Molenda-Żakowicz[19], Josefina Montalbán[12], Arlette Noels[12], Teodoro Roca Cortés[20,21], Ian W. Roxburgh[22], Aldo M. Serenelli[23], Victor Silva Aguirre[23], Christiaan Sterken[24], Peter Stine[18], Robert Szabó[25], Achim Weiss[23], William J. Borucki[26], David Koch[26], and Jon M. Jenkins[27]

[1] Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
[2] Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA
[3] LESIA, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon, France
[4] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[5] Las Cumbres Observatory Global Telescope, Goleta, CA 93117, USA
[6] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark
[7] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[8] Laboratoire d'Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 av E. Belin, 31400 Toulouse, France
[9] Laboratoire AIM, CEA/DSM-CNRS, Université Paris 7 Diderot, IRFU/SAp, Centre de Saclay, 91191 Gif-sur-Yvette, France
[10] Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India
[11] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[12] Institut d'Astrophysique et de Géophysique de l'Université de Liège, 17 Allée du 6 Août, B-4000 Liège, Belgium
[13] Arcetri Astrophysical Observatory, Largo E. Fermi 5, 50125 Firenze, Italy
[14] Instituto de Astrofísica de Andalucía (CSIC), Dept. Stellar Physics, C.P. 3004, Granada, Spain
[15] INAF-Osservatorio di Roma, via di Frascati 33, I-00040 Monteporzio, Italy
[16] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[17] GEPI, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92195 Meudon, France
[18] Department of Physics & Engineering Technology, Bloomsburg University, 400 East Second Street, Bloomsburg, PA 17815, USA
[19] Astronomical Institute, University of Wrocław, ul. Kopernika 11, 51-622 Wrocław, Poland
[20] Departmento de Astrofíca, Universidad de La Laguna, 38207 La Laguna, Tenerife, Spain
[21] Instituto de Astrofíca de Canarias, 38205 La Laguna, Tenerife, Spain
[22] Queen Mary University of London, Mile End Road, London E1 4NS, UK
[23] Max Planck Institute for Astrophysics, Karl Schwarzschild Str. 1, Garching bei München D-85741, Germany
[24] Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
[25] Konkoly Observatory, P.O. Box 67, H-1525 Budapest, Hungary
[26] NASA Ames Research Center, MS 244-30, Moffat Field, CA 94035, USA
[27] SETI Institute/NASA Ames Research Center, MS 244-30, Moffat Field, CA 94035, USA
Received 2009 November 13; accepted 2009 December 16; published 2010 March 31

ABSTRACT

Asteroseismology of stars in clusters has been a long-sought goal because the assumption of a common age, distance, and initial chemical composition allows strong tests of the theory of stellar evolution. We report results from the first 34 days of science data from the *Kepler Mission* for the open cluster NGC 6819—one of the four clusters in the field of view. We obtain the first clear detections of solar-like oscillations in the cluster red giants and are able to measure the large frequency separation, $\Delta\nu$, and the frequency of maximum oscillation power, $\nu_{\max}$. We find that the asteroseismic parameters allow us to test cluster membership of the stars, and even with the limited seismic data in hand, we can already identify four possible non-members despite their having a better than 80% membership probability from radial velocity measurements. We are also able to determine the oscillation amplitudes for stars that span about 2 orders of magnitude in luminosity and find good agreement with the prediction that oscillation amplitudes scale as the luminosity to the power of 0.7. These early results demonstrate the unique potential of asteroseismology of the stellar clusters observed by *Kepler*.

Key words: open clusters and associations: individual (NGC 6819) – stars: fundamental parameters – stars: interiors – stars: oscillations – techniques: photometric

1. INTRODUCTION

Open clusters provide unique opportunities in astrophysics. Stars in open clusters are believed to be formed from the same cloud of gas at roughly the same time. The fewer free parameters available to model cluster stars make them interesting targets to analyze as a uniform ensemble, especially for asteroseismic studies.

Asteroseismology is an elegant tool based on the simple principle that the frequency of a standing acoustic wave inside a star depends on the sound speed, which in turn depends on the physical properties of the interior. This technique applied to the Sun (helioseismology) has provided extremely detailed knowledge about the physics that governs the solar interior (e.g., Christensen-Dalsgaard 2002). All cool stars are expected to exhibit solar-like oscillations of standing acoustic waves—called p modes—that are stochastically driven by surface convection. Using asteroseismology to probe the interiors of cool stars in clusters, therefore, holds promise of rewarding scientific return (Gough & Novotny 1993; Brown & Gilliland 1994). This potential has resulted in several attempts to detect solar-like oscillations in clusters using time-series photometry. These attempts were often aimed at red giants, since their oscillation amplitudes are expected to be larger than those of main-sequence or subgiant stars due to more vigorous surface convection. Despite these attempts, only marginal detections have been attained so far, limited either by the length of the time series usually achievable through observations with the *Hubble Space Telescope* (Edmonds & Gilliland 1996; Stello & Gilliland 2009) or by the difficulty in attaining high precision from ground-based campaigns (e.g., Gilliland et al. 1993; Stello et al. 2007; Frandsen et al. 2007).

In this Letter, we report clear detections of solar-like oscillations in red-giant stars in the open cluster NGC 6819 using photometry from NASA's *Kepler Mission* (Borucki et al. 2009). This cluster, one of four in the *Kepler* field, is about 2.5 Gyr old. It is at a distance of 2.3 kpc, and has a metallicity of [Fe/H] ~ -0.05 (see Hole et al. 2009, and references therein).

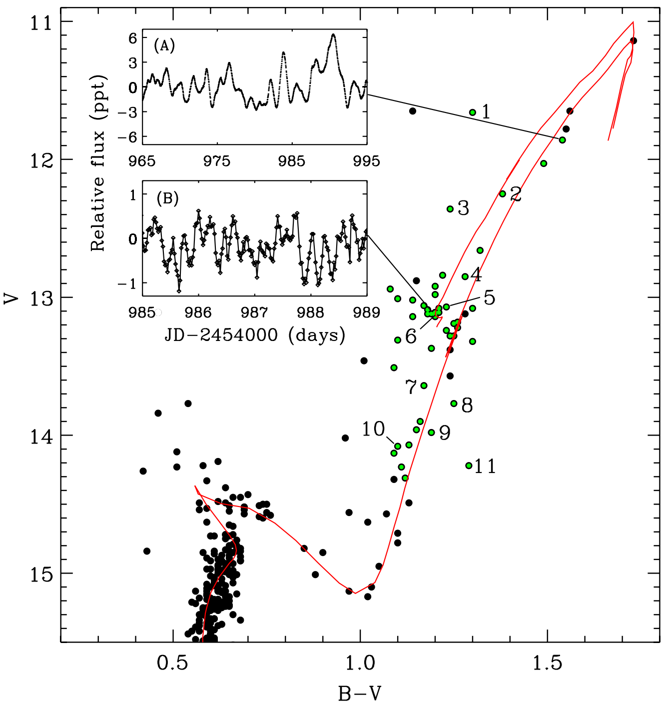

Figure 1. CMD of NGC 6819. Plotted stars have membership probability $P_{\rm RV} > 80\%$ as determined by Hole et al. (2009). Photometric indices are from the same source. The isochrone is from Marigo et al. (2008) (age = 2.4 Gyr, $Z = 0.019$, modified for the adopted reddening of 0.1 mag). Color-coded stars have been analyzed, and the annotated numbers refer to the legend in panels of Figure 2 and star numbers in Figure 3 (see also Table 1). Insets show light curves in parts per thousand of two red giants oscillating on different timescales. The variations of the light curves in Panels A and B are dominated by the stellar oscillations with periods of a few days and of about six hours, respectively.

2. OBSERVATIONS AND DATA REDUCTION

The data were obtained between 2009 May 12 and June 14, i.e., the first 34 days of continuous science observations by *Kepler* (Q1 phase). The spacecraft's long-cadence mode ($\Delta t \simeq 30$ minutes) used in this investigation provided a total of 1639 data points in the time series of each observed star. For this Letter, we selected 47 stars in the field of the open cluster NGC 6819 with membership probability $P_{\rm RV} > 80\%$ from radial velocity measurements (Hole et al. 2009). Figure 1 shows the color–magnitude diagram (CMD) of the cluster with the selected stars indicated by green symbols. The 11 annotated stars form a representative subset, which we will use to illustrate our analyses in Sections 3 and 4. We selected the stars in this subset to cover the same brightness range as our full sample, while giving high weight to stars that appear to be photometric non-members (i.e., stars located far from the isochrone in the CMD). Data for each target were checked carefully to ensure that the time-series photometry was not contaminated significantly by other stars in the field, which could otherwise complicate the interpretation of the oscillation signal.

Fourteen data points affected by the momentum dumping of the spacecraft were removed from the time series of each star. In addition, we removed points that showed a point-to-point deviation greater than 4σ, where σ is the local rms of the point-to-point scatter within a 24 hr window. This process removed on average one data-point per time series. Finally, we removed a linear trend from each time series and then calculated the discrete Fourier transform. The Fourier spectra at high frequency have mean levels below 5 parts per million (ppm) in amplitude, allowing us to search for low-amplitude solar-like oscillations.

3. EXTRACTION OF ASTEROSEISMIC PARAMETERS

Figure 2 shows the Fourier spectra (in power) of nine stars from our subset. These range from the lower red-giant branch to the tip of the branch (see Figure 1). The stars are sorted by apparent magnitude, which for a cluster is indicative of luminosity, with brightest at the top. Note that the red giants in NGC 6819 are significantly fainter ($12 \lesssim V \lesssim 14$) than the sample of *Kepler* field red giants ($8 \lesssim V \lesssim 12$) studied by Bedding et al. (2010). Nevertheless, it is clear from Figure 2 that we can detect oscillations for stars that span about 2 orders of magnitude in luminosity along the cluster sequence.

We used four different pipelines (Hekker et al. 2009a; Huber et al. 2009; Mathur et al. 2009; Mosser & Appourchaux 2009) to extract the average frequency separation between modes of the same degree (the so-called large frequency separation, $\Delta\nu$). We have also obtained the frequency of maximum oscillation power, $\nu_{\rm max}$, and the oscillation amplitude. The measured values of $\Delta\nu$ are indicated by vertical dotted lines in Figure 2 centered on the highest oscillation peaks near $\nu_{\rm max}$. While the stars in Figure 2, particularly in the lower panels, show the regular series of peaks expected for solar-like oscillations, the limited length of the time-series data does not allow such structure to be clearly resolved for the most luminous stars in our sample—those with $\nu_{\rm max} \lesssim 20\,\mu$Hz. We do, however, see humps of excess power in the Fourier spectra (see Figure 2, star nos 2 and 8) with $\nu_{\rm max}$ and amplitude in mutual agreement with oscillations. With longer time series, we expect more firm results for these high-luminosity giants.

4. CLUSTER MEMBERSHIP FROM ASTEROSEISMOLOGY

It is immediately clear from Figure 2 that not all stars follow the expected trend of increasing $\nu_{\rm max}$ with decreasing apparent magnitude, suggesting that some of the stars might be intrinsically brighter or fainter than expected. Since oscillations in a star only depend on the physical properties of the star, we can use asteroseismology to judge whether or not a star is likely to be a cluster member independently of its distance and of

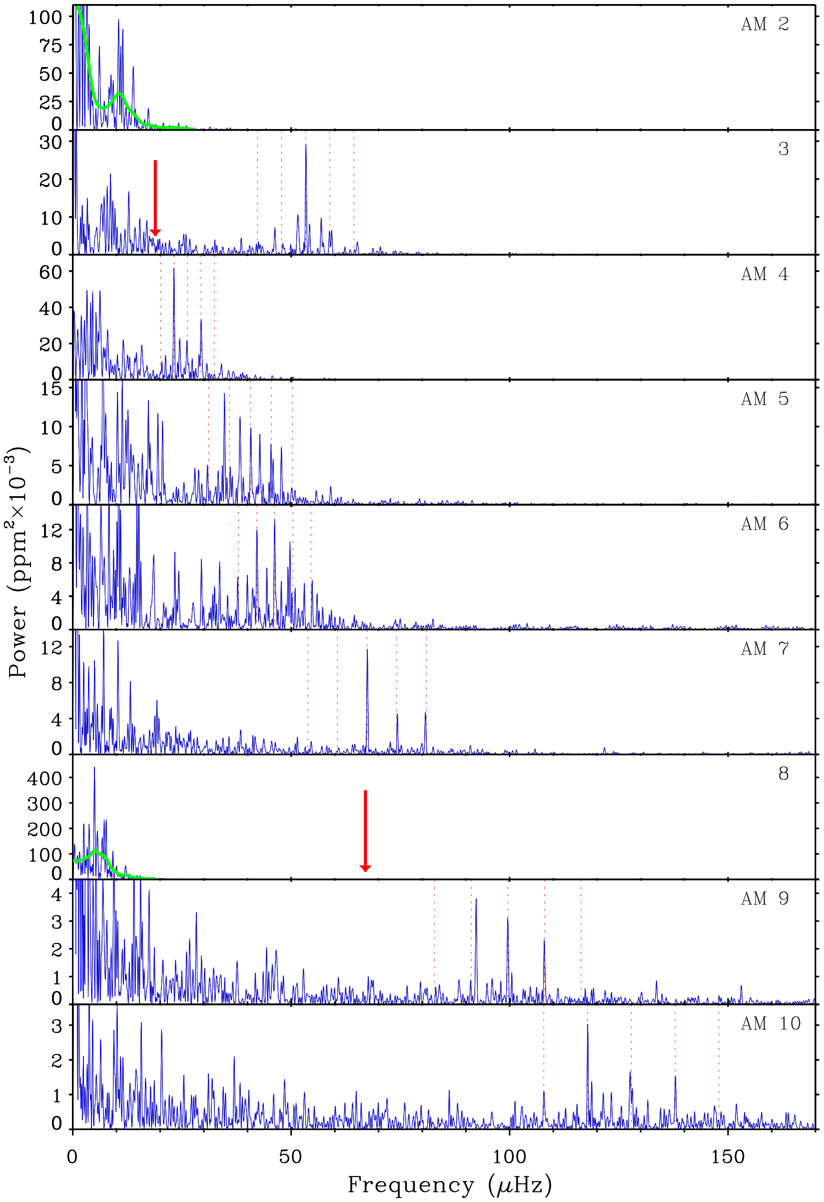

Figure 2. Fourier spectra of a representative set of red giants along the cluster sequence sorted by apparent magnitude. Annotated numbers in each panel refer to the star identification (see Figure 1 and Table 1). "AM" indicates that the star is an asteroseismic member. Red solid curves show the smoothed spectrum for stars with $\nu_{\max} < 20\,\mu$Hz. To guide the eye, we have plotted dotted lines to indicate the measured average large frequency separation. The central dotted line is centered on the highest oscillation peaks near $\nu_{\max}$. Note that since $\Delta\nu$ is generally frequency dependent, only the central dotted line is expected to line up with a peak in the oscillation spectrum. The red arrows indicate the position of the expected $\nu_{\max}$ (see Equation (1)) for stars where the observed value does not agree with the expectations for this cluster (see Section 4).

interstellar absorption and reddening. For cool stars, $\nu_{\max}$ scales with the acoustic cutoff frequency, and it is well established that we can estimate $\nu_{\max}$ by scaling from the solar value (Brown et al. 1991; Kjeldsen & Bedding 1995)

$$\frac{\nu_{\max}}{\nu_{\max,\odot}} = \frac{M/M_\odot (T_{\rm eff}/T_{\rm eff,\odot})^{3.5}}{L/L_\odot}, \qquad (1)$$

where $\nu_{\max,\odot} = 3100\,\mu$Hz. The accuracy of such estimates is good to within 5% (Stello et al. 2009) assuming we have good estimates of the stellar parameters M, L, and $T_{\rm eff}$.

In the following, we assume the idealistic scenario where all cluster members follow standard stellar evolution described by the isochrone. Stellar mass along the red-giant branch of the cluster isochrone varies by less than 1%. The variation is less than 5% even if we also consider the asymptotic giant branch. For simplicity, we therefore adopt a mass of 1.55 $M_\odot$ for all stars, which is representative for the isochrone from Marigo et al. (2008; Figure 1) and a similar isochrone by VandenBerg et al. (2006). Neglecting binarity (see Table 1), we derive the luminosity of each star in our subset from its V-band apparent magnitude, adopting reddening and distance modulus of $E(B-V) = 0.1$ and $(M-m)_V = 12.3$, respectively (obtained from simple isochrone fitting, see Hole et al. 2009). We used the calibration of Flower (1996) to convert the stellar $(B-V)_0$ color to $T_{\rm eff}$. Bolometric corrections were also taken from Flower (1996). The derived quantities were then used to estimate $\nu_{\max}$ for each star (Equation (1)), and compared with the observed value (see Figure 3).

Figure 3 shows four obvious outliers (nos 1, 3, 8, and 11), three of which are also outliers in the CMD (nos 1, 3, and 11). For the rest of the stars we see good agreement between the

Table 1
Cross Identifications and Membership

ID (This Work)	ID (KIC)[a]	WOCS ID (Hole et al.)	ID (Sanders)	Mem.ship (Hole et al.)[b]	Mem.ship (Sanders)[c]	Mem.ship (This Work)
1	5024272	003003		SM 95%		No
2	5024750	001004	141	SM 93%	83%	Yes
3	5023889	004014	42	SM 95%	90%	No
4	5023732	005014	27	SM 94%	90%	Yes
5	5112950	003005	148	SM 95%	92%	Yes
6	5112387	003007	73	SM 95%	88%	Yes
7	5024512	003001	116	SM 93%	90%	Yes
8	4936335	007021	9	SM 95%	68%	No
9	5024405	004001	100	SM 93%	91%	Yes
10	5112072	009010	39	SM 95%	91%	Yes
11	4937257	009015	144	SM 88%	80%	No

Notes.
[a] ID from the *Kepler Input Catalog* (Latham et al. 2005).
[b] Classification (SM: single member) and membership probability from radial velocity (Hole et al. 2009).
[c] Membership probability from proper motion (Sanders 1972).

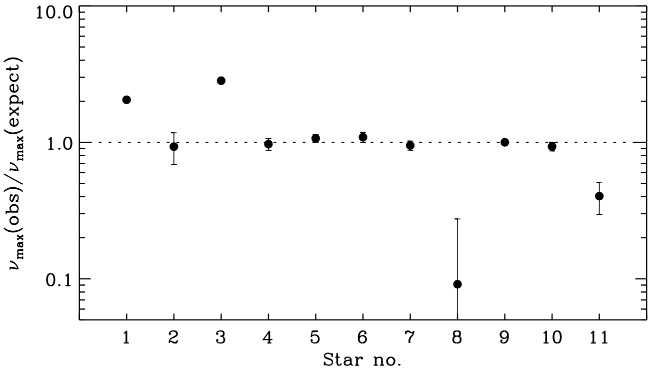

Figure 3. Ratio of observed and expected $\nu_{\rm max}$. 1σ error bars indicate the uncertainty on $\nu_{\rm max}$(obs). Stars clearly above or below the dotted line are either not cluster members or members whose evolution have not followed the standard scenario.

expected and observed value, indicating that the uncertainty on the $\nu_{\rm max}$ estimates are relatively small. Since the variations in mass and effective temperature among the cluster giant stars are small, deviations from the dotted line must be caused by an incorrect estimate of the luminosity. This implies that the luminosities of stars falling significantly above or below the line have been over- or underestimated, respectively. The simplest interpretation is that these outliers are fore- or background stars, and hence not members of the cluster. To explain the differences between the observed and expected value of $\nu_{\rm max}$ would require the deviant stars to have V errors of more than 1 mag, and in some cases $B-V$ errors of about 0.2 mag if they were cluster members. Binarity may explain deviations above the dotted line, but only by up to a factor of 2 in L (and hence, in the ratio of the observed to expected $\nu_{\rm max}$). The deviation of only one star (no. 1) could potentially be explained this way. However, that would be in disagreement with its single-star classification from multi-epoch radial velocity measurements, assuming it is not a binary viewed pole-on (see Table 1). Hence, under the assumption of a standard stellar evolution, the most likely explanation for all four outliers in Figure 3 is therefore that these stars are not cluster members. This conclusion is, however, in disagreement with their high membership probability from measurements of radial velocity (Hole et al. 2009) and proper motion (Sanders 1972; see Table 1). Another interesting possibility is that the anomalous pulsation properties might be explained by more exotic stellar evolution scenarios than is generally anticipated for open-cluster stars.

5. ASTEROSEISMIC “COLOR–MAGNITUDE DIAGRAMS”

It is clear from Figure 2 that the amplitudes of the oscillations increase with luminosity for the seismically determined cluster members. Based on calculations by Christensen-Dalsgaard & Frandsen (1983), Kjeldsen & Bedding (1995) have suggested that the photometric oscillation amplitude of p modes scale as $(L/M)^s\, T_{\rm eff}{}^{-2}$, with $s = 1$ (the velocity amplitudes, meanwhile, would scale as $(L/M)^s$). This was revised by Samadi et al. (2007) to $s = 0.7$ based on models of main-sequence stars. Taking advantage of the fewer free parameters within this ensemble of stars, our observations allow us to make some progress toward extrapolating this scaling to red giants and determining the value of s.

In Figure 4, we introduce a new type of diagram that is similar to a CMD, but with magnitude replaced by an asteroseismic parameter—in this case, the measured oscillation amplitude. Amplitudes were estimated for all stars in our sample (except for the four outliers) using methods similar to that of Kjeldsen et al. (2008; see also Michel et al. 2008), which assume that the relative power between radial and non-radial modes is the same as in the Sun. This diagram confirms the relationship between amplitude and luminosity. Despite a large scatter, which is not surprising from this relatively short time series, we see that $s = 0.7$ provides a much better match than $s = 1.0$. Once verified with more data, this relation will allow the use of the measured amplitude as an additional asteroseismic diagnostic for testing cluster membership and for isochrone fitting in general. We note that the other clusters observed by *Kepler* have different metallicities than NGC 6819, which will allow future investigation on the metallicity dependence of the oscillation amplitudes.

We expect to obtain less scatter in the asteroseismic measurements when longer time series become available. That will enable us to expand classical isochrone fitting techniques to include diagrams like this, where amplitude could also be replaced by $\nu_{\rm max}$ or $\Delta\nu$. In particular, we should be able to determine the absolute radii aided by $\Delta\nu$ of the red-giant branch stars, which would be an important calibrator for theoretical

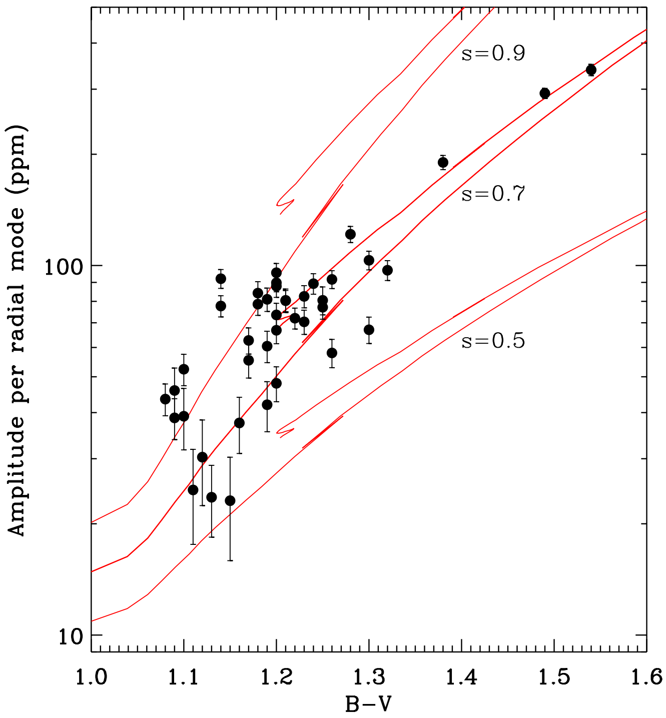

Figure 4. Amplitude color diagram of red giant stars in NGC 6819 with the Marigo et al. (2008) isochrone overlaid with three values of s in the amplitude scaling relation: $(L/M)^s\, T_{\mathrm{eff}}{}^{-2}$. The solar value used in this scaling is 4.7 ppm (Kjeldsen & Bedding 1995).

isochrones. Additionally, the distributions of the asteroseismic parameters—such as $\nu_{\max}$—can potentially be used to test stellar population synthesis models (Hekker et al. 2009b; Miglio et al. 2009b). Applying this approach to clusters could lead to further progress in understanding of physical processes such as mass loss during the red-giant phase (see, e.g., Miglio et al. 2009a). Note that a few clear outliers are indicative of non-membership or exotic stellar evolution, as a result of factors such as stellar collisions or heavy mass loss, while a general deviation from the theoretical predictions by a large group of stars would suggest that the standard theory may need revision.

Finally, we note that NGC 6819 and another *Kepler* cluster, NGC 6791, contain detached eclipsing binaries (Talamantes & Sandquist 2009; Street et al. 2005; de Marchi et al. 2007; Mochejska et al. 2005). For these stars masses and radii can be determined independently (Grundahl et al. 2008), which will further strengthen results of asteroseismic analyses.

6. DISCUSSION AND CONCLUSIONS

Photometric data of red giants in NGC 6819 obtained by NASA's *Kepler Mission* have enabled us to make the first clear detection of solar-like oscillations in cluster stars. The general properties of the oscillations ($\Delta\nu$, $\nu_{\max}$, and amplitudes) agree well with results of field red giants made by *Kepler* (Bedding et al. 2010) and CoRoT (de Ridder et al. 2009; Hekker et al. 2009b). We find that the oscillation amplitudes of the observed stars scale as $(L/M)^{0.7}\, T_{\mathrm{eff}}{}^{-2}$, suggesting that previous attempts to detect oscillations in clusters from ground were at the limit of detection.

We find that the oscillation properties provide additional tests for cluster membership, allowing us to identify four stars that are either non-members or exotic stars. All four stars have membership probability higher than 80% from radial velocity measurements, but three of them appear to be photometric non-members. We further point out that deviations from the theoretical predictions of the asteroseismic parameters among a large sample of cluster stars have the potential of being used as additional constraints in the isochrone fitting process, which can lead to improved stellar models.

Our results, based on limited data of about one month, highlight the unique potential of asteroseismology on the brightest stars in the stellar clusters observed by *Kepler*. With longer series sampled at the spacecraft's short cadence (≃ 1 minute), we expect to detect oscillations in the subgiants and turnoff stars, as well as in the blue stragglers in this cluster.

Funding for this Discovery mission is provided by NASA's Science Mission Directorate. The authors thank the entire *Kepler* team without whom this investigation would not have been possible. The authors also thank all funding councils and agencies that have supported the activities of Working Group 2 of the *Kepler* Asteroseismic Science Consortium (KASC).

Facilities: Kepler

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