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Update and Additional Frequencies for *Kepler* Star KIC 9700322

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Abstract

Breger et al. (2011) reported on the discovery of 76 frequencies for the star KIC 9700322 from one month (Sept.-Oct. 2009) of short-cadence (1-minute sampling rate) photometric data during Quarter 3 of the NASA *Kepler* mission. Here we report on a reanalysis combining an additional month (June-July 2009) obtained during Quarter 2 as part of the *Kepler* Guest Observer program. This analysis confirms all but two of the earlier frequencies > 0.5 c/d, and in addition finds six new combination frequencies of the 8 highest amplitude modes, and three frequencies that are not combinations of these modes. Since we do not know the parents of 12 of the 83 frequencies, additional astrophysical discoveries may await in continued study of this star. The rotational modulations of the two radial modes and the $\ell = 2$ quintuplet are confirmed. For the two radial modes (f_1, f_2) and the central ($m = 0$) mode of the $\ell = 2$ quintuplet, f_6, amplitude variability and/or close frequencies were found. The additional data do not reveal more of the ℓ=0, 1, 2 or higher-degree p modes that were expected, and this result is still a mystery.

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Individual Objects: KIC 9700322

1. Introduction

As part of its search for Earth-sized planets around sun-like stars, the *Kepler* mission is surveying around 150,000 stars for planetary transits. In the process, it is acquiring photometry with unprecedented precision and continuous length of time series on hundreds of pulsating variable stars, including many δ Scuti stars (Borucki et al. 2010; Gilliland et al. 2010).

The δ Scuti star KIC 9700322 is a slowly rotating, cool δ Scuti star ($T_{\rm eff}$ = 6700 ± 100 K, $\log g = 3.7 \pm 0.1$, $v \sin i = 19 \pm 1$ km/s; Breger et al. 2011). δ Sct stars are variable stars of A-F spectral type on or near the main sequence that show radial and nonradial oscillations with frequencies ~5-30 cycles/day. The pulsations are driven by the "κ effect", a feedback mechanism produced by the opacity increase in the region of second helium ionization in the stellar envelope (see, e.g., Aerts et al. 2010). The brightness variations of KIC 9700322 were measured by the *Kepler* satellite for 30.3 d during Quarter 3. Analyses of these data revealed 76 frequencies with amplitudes as small as 14 ppm. Two dominant radial modes, an $\ell = 2$ quintuplet and a brightness modulation during rotation were detected (i.e., eight frequencies). Almost all other detected frequencies could be identified with various combinations and rotational modulations of these modes. Good agreement of the frequency spacings with theoretical models could be obtained (Breger et al. 2011, hereafter called Paper I). A remarkable result was the absence of additional independent frequencies down to an amplitude limit near 14 ppm, suggesting that the star is stable against most forms of pulsation.

In 2008, as part of the *Kepler* Guest Observer Cycle 1 program, before *Kepler* was launched, J.A. Guzik proposed to observe KIC 9700322 along with thirteen other stars in a search for hybrid γ Doradus/δ Sct stars, and the data was taken in Q2. Because KIC 9700322 did not show hybrid behavior with both higher (10-15 c/d) and low (1-5 c/d) frequencies, this star was not considered further until the Paper I preprint appeared. Since we realized that we had additional short cadence data readily available, we decided to combine the two quarters of data to see whether the results from one quarter could be confirmed and extended.

2. The Q2 *Kepler* spacecraft observations of KIC 9700322

Portions of the Q2 "raw" data (that have been processed to reduce the effects of bias and dark current, and flat-fielded) have small systematic zero-point drifts in brightness. These shifts are removed in the "corrected" data provided by the *Kepler* team, but these data that have been pre-conditioned to optimize the search for planetary transits (see http://keplergo.arc.nasa.gov/PipelinePDC.shtml) are not suitable for asteroseismological investigations, and so were not used here. In the Q2 data for KIC9700322, a two-day stretch immediately after an observing gap near HJD 245 5016 contains a large drift reaching several parts per thousand. These

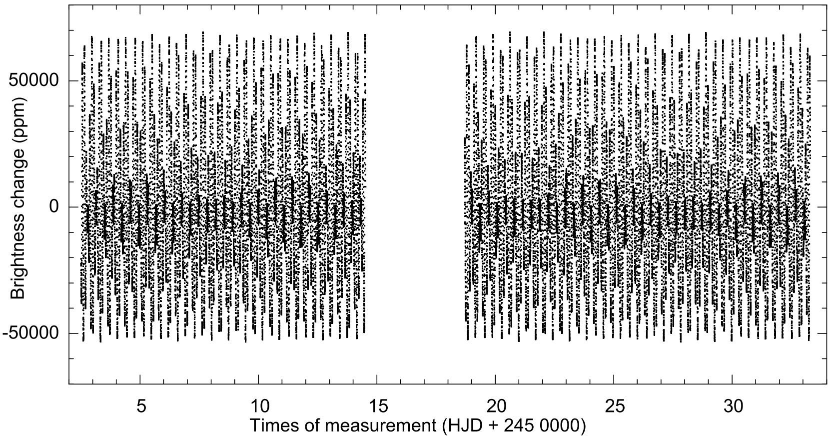

Figure 1: Light curve of KIC9700322 after reductions of the new Q2 *Kepler* data.

data, from HJD 245 5016.71 to 245 5018.71, were not used. For the remaining data, the small remaining zero-point drifts were removed artificially, similar to the techniques applied by Garcia et al. (2011). This processing affects only the analysis of the low-frequency region. Consequently, the present paper covers only periods shorter than two days, or $f > 0.5$ c/d, i.e., the period range of the typical δ Sct stars. As a final step, the data were filtered by us for obvious outliers (deviations larger than 4 σ). Fig. 1 shows the new observations after our reductions.

3. Frequency analysis

The KIC 970032 *Kepler* data were analyzed with the statistical package `PERIOD04` (Lenz & Breger 2005). This package carries out multifrequency analyses with Fourier as well as least-squares algorithms. White noise is not assumed. Following the standard procedures for examining the peaks with `PERIOD04`, we have determined the amplitude signal/noise values for every promising peak in the amplitude spectrum and adopted a limit of S/N of 4.0. As in the previous paper on this star, the noise is calculated from prewhitened data because of the huge range in amplitudes of three orders of magnitude.

It was found that the Q2 data essentially confirms (and extends) the results previously obtained from the Q3 data alone. The amplitude spectra of Q2 and Q3 are essentially identical to each other (except for alias structure in Q2 because of the gap in the middle of Q2). This demonstrates the stability of the pulsation of KIC 9700322. The matching of the Q2 and Q3 data also shows that the quality of the data in the two observing quarters is comparable, despite the more significant instrumental systematics in the Q2 data. Due to the similarity, new figures of the amplitude spectra are not shown in this paper and we refer to the figures in Paper I. We will now concentrate on the analysis of the combined Q2 and Q3 data, which covers 121d with a central gap of 60d. The long time base improves the frequency resolution and allows us to look for amplitude variability and close frequencies. Also, the additional data allow us to detect several additional frequencies.

79 statistically significant frequency peaks were detected in the frequency range > 0.5 cycle c/d. These frequencies are listed in Table 1, along with four frequencies < 0.5 c/d that were reported using the Q3 data in Paper 1. Since the rotational frequency, $f_3 = 0.1597$ c/d, is important for modulations of the amplitudes of most (all?) pulsation modes, the rotational frequency and its multiples are also listed in the table with the values taken from Paper I.

Of the 9 new frequencies detected in the combined Q2Q3 analysis, 6 are easily identified as combination modes of the main frequencies. One frequency forms a close double with f_6 (see below). On the other hand, the small-amplitude peak from Paper I at 51.752 c/d is no longer statistically significant, while the unconfirmed peak at 12.584 c/d probably arose from the slow amplitude modulation of f_2 (see below).

71 of the 83 frequencies listed in Table 1 can be identified with f_1 - f_8 and their combinations. Only 12 frequencies cannot be identified in this manner. However, these 12 frequencies are not all additional, independent pulsation modes. It is interesting that most of these frequencies are numerically related to each other through new combinations, e.g., the difference between the two peaks at 12.5333 and 22.3258 c/d is exactly f_1. Since 12.5333 c/d is a close double to f_2, 22.3258 c/d is the identical close double to the $(f_1 + f_2)$ peak.

Table 1: Multifrequency solution of KIC 9700322 and identifications.

Frequency c/d	μHz	Identification	Amplitudes in ppm Q2Q3	Q2	Q3	Comment
Main frequencies						
9.7925	113.339	f_1	27302	27343	27266	Radial
12.5688	145.472	f_2	29449	29463	29440	Radial
0.1597	1.848	f_3			80	Rotation
11.3187	131.003	f_4	27	25	29	Quintuplet
11.4551	132.582	f_5	147	147	147	Quintuplet

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Frequency c/d	μHz	ID	Amplitudes in ppm Q2Q3	Q2	Q3	Comment
11.5906	134.150	f_6	465	474	460	Quintuplet
11.7201	135.649	f_7	215	207	222	Quintuplet
11.8576	137.241	f_8	115	118	112	Quintuplet
Combination frequencies						
0.3194	3.697	$2f_3$			174	2x rotation
0.4791	5.545	$3f_3$			33	3x rotation
0.6388	7.394	$4f_3$	17	13	25	
0.7112	8.232	$f_2 - f_8$	16	19	26	
0.9782	11.322	$f_2 - f_6$	31	36	26	
1.1137	12.890	$f_2 - f_5$	48	55	46	
1.6625	19.242	$f_5 - f_1$	20	16	25	
1.7980	20.811	$f_6 - f_1$	27	39	17	
2.7763	32.133	$f_2 - f_1$	2640	2647	2633	
2.9360	33.981	$f_2 - f_1 + f_3$	22	18	26	
5.5526	64.266	$2f_2 - 2f_1$	86	84	89	
7.0162	81.206	$2f_1 - f_2$	630	628	632	
9.4731	109.643	$f_1 - 2f_3$	50	47	58	
9.6328	111.491	$f_1 - f_3$	52	54	51	
9.9522	115.188	$f_1 + f_3$	57	63	53	
10.1119	117.036	$f_1 + 2f_3$	39	37	38	
12.2494	141.776	$f_2 - 2f_3$	34	35	35	
12.4091	143.624	$f_2 - f_3$	36	37	32	
12.7285	147.321	$f_2 + f_3$	33	34	32	
12.8882	149.169	$f_2 + 2f_3$	21	18	23	
15.3451	177.605	$2f_2 - f_1$	497	492	503	
16.8088	194.546	$3f_1 - f_2$	67	64	70	
18.1214	209.738	$3f_2 - 2f_1$	14	16	11	
19.5850	226.679	$2f_1$	2226	2227	2225	
21.2476	245.921	$f_5 + f_1$	45	48	42	
21.3831	247.489	$f_6 + f_1$	40	46	36	
21.5126	248.988	$f_7 + f_1$	18	22	16	
21.6501	250.580	$f_8 + f_1$	18	17	19	
22.2016	256.963	$f_1 + f_2 - f_3$	26	26	26	
22.3613	258.812	$f_1 + f_2$	4900	4899	4901	
22.5210	260.660	$f_1 + f_2 + f_3$	21	25	18	
22.7738	263.585	$f_4 + f_5$	13	11	15	

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Frequency		ID	Amplitudes in ppm			Comment
c/d	μHz		Q2Q3	Q2	Q3	
23.0456	266.732	$f_5 + f_6$	34	31	39	
23.1811	268.300	$2f_6$	10	15	6	
23.7152	274.481	$2f_8$	25	21	28	
24.0239	278.054	$f_5 + f_2$	34	34	34	
24.1594	279.622	$f_6 + f_2$	47	48	46	
24.2889	281.121	$f_7 + f_2$	52	51	52	
24.4264	282.713	$f_8 + f_2$	54	52	56	
24.9779	289.096	$2f_2 - f_3$	17	21	16	
25.1376	290.945	$2f_2$	2661	2658	2663	
26.6013	307.885	$4f_1 - f_2$	13	14	12	
27.9139	323.078	$3f_2 - f_1$	203	203	203	
29.3776	340.018	$3f_1$	190	188	191	
32.1538	372.151	$2f_1 + f_2$	482	485	479	
33.8164	391.393	$f_1 + f_2 + f_5$	12	15	10	
33.9519	392.962	$f_1 + f_2 + f_6$	15	14	16	
34.2189	396.052	$f_1 + f_2 + f_8$	17	19	16	
34.9301	404.284	$f_1 + 2f_2$	536	536	536	
37.7064	436.417	$3f_2$	329	329	329	
39.1701	453.357	$4f_1$	19	23	16	
40.4827	468.550	$4f_2 - f_1$	34	34	34	
41.9464	485.490	$3f_1 + f_2$	22	22	23	
44.7227	517.623	$2f_1 + 2f_2$	113	112	114	
47.4989	549.756	$f_1 + 3f_2$	78	74	82	
50.2752	581.889	$4f_2$	82	80	83	
51.7389	598.830	$4f_1 + f_2$	9	8	10	
54.5152	630.963	$3f_1 + 2f_2$	35	34	35	
57.2915	663.096	$2f_1 + 3f_2$	55	53	58	
60.0677	695.229	$f_1 + 4f_2$	34	34	34	
62.8440	727.361	$5f_2$	18	21	15	
67.0840	776.435	$3f_1 + 3f_2$	19	18	19	
69.8603	808.568	$2f_1 + 4f_2$	19	16	21	
Peaks detected in Q3 with frequency < 0.5 c/d						
0.0221	0.256	f_{72}			347	
0.0555	0.642	f_{73}			95	
0.1346	1.558	f_{74}			35	
0.3542	4.100	f_{75}			25	

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Frequency c/d	Frequency μHz	ID	Amplitudes in ppm Q2Q3	Q2	Q3	Comment
Other peaks in the amplitude spectrum						
8.1394	94.206	f_{76}	15	11	18	
11.5806	134.035	f_{77}	135	140	132	
11.9712	138.555	f_{78}	16	19	13	
12.5333	145.061	f_{79}	61	37	80	
13.2406	153.247	f_{80}	18	16	21	
14.6253	169.274	f_{81}	14	10	17	
22.3258	258.400	f_{82}	15	8	20	
24.1493	279.506	f_{83}	45	48	42	

4. Amplitude variability/close frequencies

Amplitude variability and the presence of close-frequency pairs (which lead to amplitude variability in short data sets) were examined in two ways. To examine the amplitude variability directly, we have subdivided the data into three-day groups. For each group we have computed the optimum amplitudes for the dominant modes, while using a common solution for the other frequencies. The second method relied on Fourier analyses and multiple-least-squares solutions in PERIOD04 to look for close frequencies.

For the two radial modes (f_1, f_2) and the central ($m = 0$) mode of the $\ell = 2$ quintuplet, f_6, amplitude variability and/or close frequencies were found, that we discuss below.

4.1. $f_6 = 11.591$ c/d

In the previous paper we identified f_6 as the axisymmetric mode ($m = 0$) of an ℓ=2 quintuplet. When we add the Q2 data, it becomes obvious that the mode has a variable amplitude, possibly caused by a close companion frequency. The amplitude variability is shown in Fig. 2. If we assume a sinusoidal amplitude variation, we obtain a modulation frequency of 0.010 ± 0.001 c/d or a modulation period near 100d.

This 100d modulation should also be visible in the Fourier spectrum. In the individual Q2 or Q3 data sets alone, the frequency resolution is not sufficient to reveal the double structure. When the two data sets are combined, the double frequency structure becomes apparent. Some uncertainties due to aliasing (structures separated by 0.011 c/d) still remain. When we prewhiten

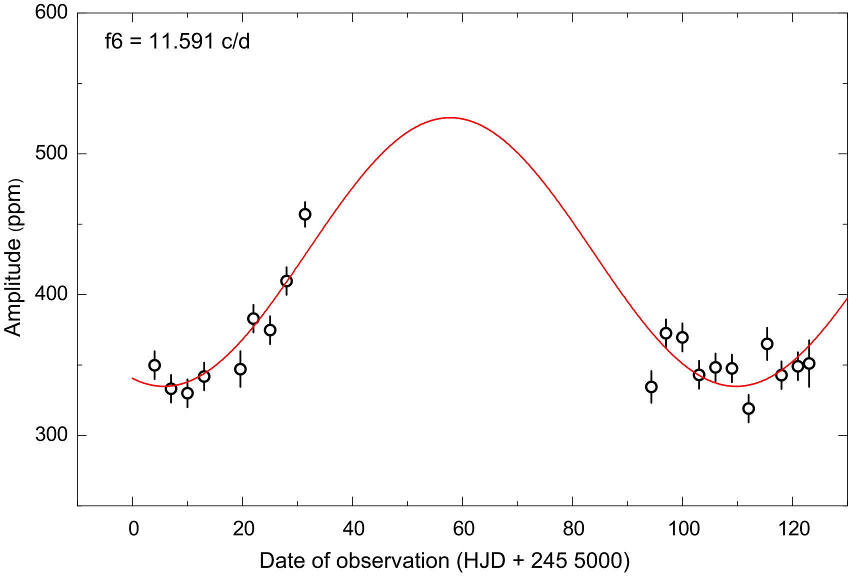

Figure 2: Amplitude variation of f_6. This is interpreted as beating between two close frequencies.

the dominant frequency of 11.591 c/d, a number of peaks remain in the amplitude spectrum. The peak at 11.581 c/d for the second peak leads to a clean power spectrum after prewhitening. An alias peak at 11.569 c/d, on the other hand, is unsatisfactory because it leaves a number additional close peaks and leads to higher residuals. We, therefore, adopt 11.581 c/d for the second peak. Our adopted frequency difference between the two frequencies in the doublet is in agreement with the value derived above from inspecting the amplitude variation.

Furthermore, the fact that we obtain only two statistically significant peaks (as opposed to a triplet with the main frequency in the middle) in the power spectrum supports the interpretation as beating between two close frequencies, rather than plain amplitude variability. Nevertheless, we must caution against potential overinterpretation of our data, since the length of data set is similar to the detected modulation period.

4.2. Radial mode f_1

We have examined potential amplitude variation in the same manner as for f_6. The radial mode f_1 varies by about 0.2% of its value with a period of about 125d ($f_{mod} = 0.0081 \pm$ 0.004 c/d). Since the modulation amplitude is very small and the modulation period is similar to the length of the data set, Fourier analyses of this modulation remain inconclusive.

4.3. Radial mode f_2

In the Q3 data alone we detected a second frequency, separated from f_2 by about 0.03 c/d. We confirm the existence of this frequency, for which an improved value of 12.533 c/d is determined. The amplitudes of f_2 suggest that an additional small amplitude modulation of f_2 with a time scale in excess of 150d also exists. Due to the small size of this variation we cannot obtain a more quantitative result at this stage.

5. Discussion

KIC 9700322 is remarkably stable compared to some δ Sct stars that show larger frequency amplitude variations over periods of weeks (see e.g., Breger 2009 and discussion on the δ Sct star 4 CVn.) KIC 9700322 shares with other stars with amplitude variability a long-term modulation of hundreds of days. Understanding the reasons for these amplitude and frequency variations requires long-term monitoring and high photometric precision. There are other mysteries associated with KIC 9700322 that are also present for other δ Sct stars: Why, for example, does this star show only a couple of radial modes and one ℓ=2 p-mode, and not other expected low-degree modes? Which (invisible?) frequencies are the parents of the new pulsation modes that are not combinations of the modes of highest amplitude? Why does this star not show any lower-frequency γ Dor pulsations as do most of the A and early F main sequence stars observed by *Kepler* (Grigahcéne et al. 2010; Balona et al. 2011)? KIC 9700322 continues to be monitored, and analysis of an additional 3 months of short cadence data from Q6 will begin soon. In addition, long-cadence (29.4-minute integration time) data exist for Q0 through Q7, so future work may be able to explore longer-term trends. Hopefully, an analysis of KIC 9700322 in comparison and contrast with the many other γ Dor and δ Sct stars being observed by *Kepler* will help to solve some of the puzzles associated with the pulsation behavior of these stars.

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References

Aerts, C., Christensen-Dalsgaard, J. & Kurtz, D. W. 2011, *Asteroseismology*, Astronomy and Astrophysics Library, Springer, pp. 49-56

Balona, L., Guzik, J. A., Uytterhoeven, K., et al. 2011, "The *Kepler* View of γ Dor Stars", MNRAS, in press

Borucki, W. J. , Koch, D., Basri, G., et al. 2010, Science, 327, 977

Breger, M., Balona, L., Lenz, P., et al. 2011, MNRAS, 414
doi: 10.1111/j.1365-2966.2011.18508 (Paper I)

Breger, M. 2009, "Period Variations in δ Scuti Stars," in Stellar Pulsation: Challenges for Theory and Observation, eds. J.A. Guzik and P.A. Bradley, AIPC conference proceedings Volume 1170, pp. 410-414

Garcia, R. A., Hekker, S., Stello, D. et al. 2011, MNRAS, 414, L6

Gilliland, R. L., Brown, T. M., Christensen-Dalsgaard, J., et al. 2010, PASP, 122, 131

Grigahcéne, A., Antoci, V., Balona, L., et al. 2010, ApJ, 713, 192

Lenz, P. & Breger, M. 2005, CoAst, 146, 53