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OBSERVATIONAL LIMITS ON COMPANIONS TO G29-38

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ABSTRACT

Recent interest in the variable (DAV) white dwarf G29-38 has been stirred by a tentative report of a radial velocity variation that may be due to an unseen companion. Earlier evidence for a brown dwarf in the system has come from an observed infrared excess in the star's spectrum. For asteroseismological reasons, we have accumulated more than five seasons of high-speed photometric data on the star. By measuring the phase of an isolated, stable frequency in the power spectrum, we show the measured variation is not due (at least in its entirety) to an orbital companion. Because any orbital radial velocity variation must result in a systematic phase variation, the data we present can be used to place stringent limits on the types of companions the system may contain.

Subject headings: binaries: general — stars: individual (G29-38) — stars: low-mass, brown dwarfs — stars: oscillations — white dwarfs

1. INTRODUCTION

G29-38 (Giclas 29-28, ZZ Psc, WD 2326+049, EG 159, LTT 16907) is a large-amplitude DAV (ZZ Ceti) pulsator whose variability was first reported by Shulov & Kopatskaya (1974) and confirmed by McGraw & Robinson (1975). The DAV stars are otherwise normal white dwarfs (Winget 1988) that show intrinsic luminosity variations with amplitudes as high as 30% and periods between 100 and 1000 s. The field of asteroseismology (see Winget 1988, for example) uses the observed spectrum of pulsations to probe the stellar interior. While we have made much progress on some of the pulsating white dwarfs (Winget 1991; Clemens 1994), the more complicated, large-amplitude DAV pulsators have proven more difficult to understand.

G29-38's power spectrum varies on timescales of weeks to years and is typically dominated by a single large mode, although many lower amplitude modes also exist. The larger amplitude modes show complex, variable behavior typical of other large-amplitude DAVs. Existing amidst these dominant yet variable modes are a few regions with less power that show considerably more stability by remaining in the light curve while the larger modes come and go. The large-amplitude DAVs, in general, distinguish themselves from their lower amplitude cousins by their cooler temperatures, their longer dominant periodicities, and the presence of many peaks with frequencies that are linear combinations of other modes present in the star. Although the lower-amplitude DAVs are much more stable, we generally observe only a few pulsation modes, making their power spectra simpler, but nonetheless, difficult to interpret. The key to asteroseismology lies in identifying as many modes as possible—each mode probing a slightly different region of the stellar interior. We have therefore observed G29-38 through many seasons, observing many of its changing states and adding to the total number of observed pulsation modes. Our interest in the star is primarily in understanding its spectrum of pulsation modes as a means

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of exploring its internal structure through asteroseismology. As a by-product of our methods, however, we can also constrain its external environment to considerable precision.

Zuckerman & Becklin (1987) found an infrared excess at wavelengths above 2 μm in the star's spectrum. Two principal models have been proposed to explain this excess (Zuckerman & Becklin 1987; Greenstein 1988; Liebert, Saffer, & Pilachowski 1989; Graham et al. 1990a; Telesco et al. 1990; Tokunaga, Becklin, & Zuckerman 1990): a near-by dust cloud or a brown dwarf companion. (See Zuckerman 1993 for a recent review of the infrared excess and its possible origin.) The Whole Earth Telescope (WET; Nather et al. 1990) observed this star in 1988 November (Winget et al. 1990) and reported an unexplained phase change of the largest amplitude oscillation, at first attributed to the presence of an unseen *massive* companion. By monitoring the phase, or time of arrival, of periodic signals (in the form of stellar pulsations) from the star, Winget et al. looked for the systematic changes a binary orbit would produce. While in orbit, periodic signals from the star will have their phases delayed and advanced due to the continuously changing line-of-sight distance between the observer and the star. Simply put, when the star is farther away, light takes longer to get here; when it's closer, light arrives sooner. As distinct from measuring instantaneous radial velocities, this is an integral technique and, therefore, more sensitive. A low radial-velocity orbit can easily be detected given enough time and a stable isolated frequency in the power spectrum.

The dominant peak in Winget et al.'s data showed a significant phase variation, but since all periodic signals (pulsations) from the star must show precisely the same phase modulation if its cause is reflex orbital motion, they looked for another peak whose phase they could measure. They found a second stable peak with a period near 284 s that did not show the large phase modulation seen in the dominant mode—effectively eliminating the binary model (Winget et al. 1990; Kleinman 1990). Radial velocity measurements (Graham et al. 1990b) agreed with the photometric results and showed there was no massive companion in the system. Because these observations extended over only a few months of one season, the question of the existence of a less massive companion remained open.

More recently, Barnbaum & Zuckerman (1992) found evidence for a small radial velocity variation of ≈ 10 km s^{-1} and a period of 11.2 months. They suggest the variation may be caused by an orbiting, *low-mass* companion—an attractive idea given the observed infrared excess, although the uncertainties in their data preclude making a definitive statement at this time. Given the ambiguity of the proposed system inclination, other types of companions are also possible. Using the data we have collected to answer asteroseismological questions about G29-38, we have analyzed the arrival times of the 284 second pulsation and have found no evidence of any orbital motion in this system that would yield measurable radial velocity variations.

2. OBSERVATIONS

Using high-speed photomultiplier-based photometers and observing (and reducing) procedures as described in Nather et al. (1990), we observed G29-38 from various sites over a 5 year time span. Table 1 lists the date, time, and location of each run. The data are primarily single-site data taken at the 36 inch (91 cm) telescope at McDonald observatory supplemented by WET data during 1988 November (WET II: principal target; Winget et al. 1990) and 1992 September (WET VIII: low-priority target). With the exception of the runs from South Africa during the WET II campaign, the data consist of at least two channels—one watching the variable star and the other monitoring conditions by observing a nearby comparison star. Many of the McDonald runs, and some of the other WET runs, were taken with a three-channel instrument—the third channel measuring sky brightness continuously. Observers with less than three channels interrupted the data at irregular, but frequent, intervals to measure sky brightness as conditions warranted. The integration times were typically 5 or 10 s and were left unsummed in the final analysis.

For data taken nightly from a single site, a pattern of aliases separated by a frequency interval of one cycle per day arises due to the uncertainty in determining the cycle count during the gaps in the data. WET observations, which attempt to obtain as complete coverage as possible, eliminate or minimize the pattern of one cycle per day aliases, as demonstrated in Nather et al. (1990). The present data set is a combination of single-site data with WET data and so suffers from the presence of aliases, but at a reduced level because of the inclusion of the WET data. The spectral windows plotted in Figure 1 clearly demonstrate this point. (WET data on G29-38 was obtained during 1988 and 1992.)

3. THE 284 SECOND PULSATION

G29-38's power spectrum changes dramatically on timescales of order months or less—finding a well-defined mode present throughout the entire data set is difficult. Figure 1 shows a portion of the Fourier transform of the data taken in each individual observing season (1988–1992). There are only two identified regions of power that remain relatively constant. These two regions are at 2500 and 3500 μHz. The 2500 μHz region is actually a multiplet of modes, with varying power in each component. The 3500 μHz mode (its actual frequency is near 3523 μHz corresponding to a period near 284 s), however, has no nearby power and is well isolated in each data set. Its amplitude has remained relatively constant, always near 5 mmas. We now choose to represent amplitudes of modes as seen in a Fourier transform, by the unit mma, for *mili-modulation amplitude*. It is similar to the traditional stellar luminosity measurement of magnitudes, in that 1 mma $\approx$ 1 mmag, but it employs a linear, rather than logarithmic scale. Figure 2 is an enlargement of the Fourier transforms around this mode. Figure 3 shows a much smaller region of the transform at increased resolution for the entire (5 year) data set. Plotted with the transforms in the spectral window, obtained by taking the transform of a single noise-free sine curve sampled in the same way as the original data. The window represents the pattern of peaks a single sinusoidal variation will make in the transform. The improved windows of 1988 and 1992 are due to the single-site data being supplemented by WET data. Starting in 1990, there is power near the 284 s mode that was not present in previous years. This additional power is harmonically related to a larger amplitude, lower frequency peak that appeared at the same time and is easily resolvable from the 284 s peak with the data we have. The 284 s mode is stable and isolated and thus well suited for phase analysis.

Since the data span such a large timebase, we must have an accurate period in order to avoid cycle count errors when measuring pulsation arrival times. Cycle count errors arise when the uncertainty in period is large enough that the number of pulses that occurred through a gap in the data is ambiguous. With such intense coverage, though, this potential stumbling

TABLE 1

TABLE OF OBSERVATIONS

Telescope	Run Name	Date (UT)	Runstart (UT)	Group
McDonald 30"	jcc-55	1988 Oct 24	2:00:00	-
McDonald 30"	jcc-57	1988 Oct 25	1:50:00	-
McDonald 30"	jcc-59	1988 Oct 26	4:50:00	-
SAAO 0.75m	s4453	1988 Nov 4	18:38:0	1
SAAO 0.75m	s4455	1988 Nov 6	18:23:0	1
McDonald 82"	maw-0017	1988 Nov 6	1:42:20	1
McDonald 82"	maw-0019	1988 Nov 7	1:31:00	1
SidingSpring 40"	ren-0040	1988 Nov 7	11:12:30	1
SidingSpring 40"	ren-0042	1988 Nov 8	9:41:00	1
McDonald 82"	maw-0023	1988 Nov 9	1:21:10	1
McDonald 82"	maw-0024	1988 Nov 9	4:54:40	1
SidingSpring 40"	ren-0044	1988 Nov 9	9:41:10	1
SAAO 0.75m	s4456	1988 Nov 9	18:53:3	1
McDonald 82"	maw-0026	1988 Nov 10	1:23:00	2
SidingSpring 40"	ren-0045	1988 Nov 10	9:28:50	2
SAAO 0.75m	s4457	1988 Nov 10	18:33:5	2
McDonald 36"	cfc-0001	1988 Nov 11	1:51:00	2
OHP 1.93m	gv37	1988 Nov 11	18:59:20	2
McDonald 82"	maw-0029	1988 Nov 12	1:24:10	2
McDonald 36"	cfc-0002	1988 Nov 12	3:41:01	2
MaunaKea 24"	a91	1988 Nov 12	5:12:00	2
SidingSpring 40"	ren-0049	1988 Nov 12	9:30:10	2
SAAO 0.75m	s4458a	1988 Nov 12	19:41:5	2
McDonald 82"	maw-0031	1988 Nov 13	0:51:20	2
McDonald 36"	cfc-0005	1988 Nov 13	3:03:50	2
MaunaKea 24"	a93	1988 Nov 13	8:04:00	2
SidingSpring 40"	ren-0053	1988 Nov 13	9:28:20	3
OHP 1.93m	gv39	1988 Nov 13	18:12:30	3
McDonald 82"	maw-0033	1988 Nov 14	1:04:00	3
McDonald 36"	cfc-0009	1988 Nov 14	3:22:30	3
McDonald 36"	cfc-0010	1988 Nov 15	3:46:30	3
McDonald 82"	maw-0036	1988 Nov 16	1:07:20	3
MaunaKea 24"	a97	1988 Nov 16	6:29:00	3
McDonald 82"	maw-0038	1988 Nov 17	0:58:20	3
McDonald 82"	maw-0039	1988 Nov 17	2:47:20	3
SAAO 0.75m	s4466	1988 Nov 17	18:43:0	3
McDonald 82"	maw-0040	1988 Nov 18	6:05:40	3
SAAO 0.75m	s4468	1988 Nov 18	18:43:0	3
McDonald 82"	maw-0042	1988 Nov 19	0:52:20	3
McDonald 30"	mlf-0001	1988 Nov 20	1:19:28	3
SAAO 0.75m	s4472a	1988 Nov 21	18:52:0	3
McDonald 30"	mlf-0003	1988 Nov 22	1:04:03	4
McDonald 30"	sjk-0004	1988 Nov 23	1:42:50	4
McDonald 30"	sjk-0005	1988 Nov 24	1:29:40	4
McDonald 30"	cfc-0016	1988 Nov 26	1:01:40	4
McDonald 30"	cfc-0017	1988 Nov 27	0:50:00	4
McDonald 30"	cfc-0018	1988 Nov 28	0:57:50	4
SAAO 0.75m	s4480	1988 Nov 28	19:29:1	5
McDonald 30"	pab-0002	1988 Nov 29	1:14:50	5
McDonald 36"	pab-0003	1988 Nov 29	3:24:20	5
McDonald 36"	pab-0004	1988 Dec 1	0:44:30	5
MaunaKea CFHT	jcc-0063	1988 Dec 1	5:54:30	5
MaunaKea CFHT	jcc-0066	1988 Dec 2	4:59:10	5
McDonald 36"	pab-0009	1988 Dec 3	0:54:10	5
McDonald 36"	pab-0011	1988 Dec 4	0:56:20	5
McDonald 36"	mlf-0004	1988 Dec 14	1:21:21	-
McDonald 36"	mlf-0005	1988 Dec 15	1:17:04	-
McDonald 36"	jcc-0069	1988 Dec 21	1:25:00	-
McDonald 36"	jcc-0071	1988 Dec 22	1:24:00	-
KPNO 1.3-m	a100	1988 Dec 30	2:47:00	-
KPNO 1.3-m	a104	1988 Dec 31	1:57:00	-
KPNO 1.3-m	a107	1989 Jan 1	1:57:00	-

TABLE 1—*Continued*

Telescope	Run Name	Date (UT)	Runstart (UT)	Group
KPNO 1.3-m	a112	1989 Jan 6	1:49:00	-
KPNO 1.3-m	a118	1989 Jan 9	1:56:00	-
McDonald 36"	jcc-0087	1989 Jun 5	9:42:00	-
McDonald 36"	jcc-0091	1989 Jun 8	8:45:00	-
McDonald 36"	jcc-0095	1989 Jun 12	8:46:30	-
McDonald 36"	jcc-0097	1989 Jun 13	8:35:00	-
McDonald 36"	jcc-0100	1989 Jul 1	7:22:00	6
McDonald 36"	jcc-0102	1989 Jul 2	7:10:30	6
McDonald 36"	jcc-0104	1989 Jul 3	7:21:30	6
McDonald 36"	sjk-0008	1989 Jul 4	7:10:00	6
McDonald 36"	sjk-0010	1989 Jul 5	7:12:30	6
McDonald 36"	sjk-0012	1989 Jul 6	7:00:00	6
McDonald 36"	jcc-0112	1989 Jul 13	6:31:00	6
McDonald 36"	jcc-0114	1989 Aug 1	5:38:00	7
McDonald 36"	jcc-0116	1989 Aug 2	5:36:00	7
McDonald 36"	jcc-0117	1989 Aug 6	5:36:00	7
McDonald 36"	sjk-0015	1989 Aug 9	5:47:30	8
McDonald 36"	sjk-0016	1989 Aug 10	8:26:00	8
McDonald 36"	sjk-0018	1989 Aug 11	6:39:00	8
McDonald 36"	jcc-0119	1989 Aug 30	5:30:27	9
McDonald 36"	jcc-0120	1989 Sep 3	3:10:00	9
McDonald 36"	jcc-0122	1989 Sep 4	2:40:00	9
McDonald 30"	sjk-0021	1989 Sep 17	2:46:30	10
McDonald 30"	sjk-0022	1989 Sep 18	2:29:30	10
McDonald 30"	sjk-0023	1989 Sep 19	2:46:00	10
McDonald 30"	sjk-0024	1989 Sep 19	8:14:30	10
McDonald 30"	sjk-0025	1989 Sep 20	2:42:00	10
McDonald 30"	sjk-0027	1989 Sep 21	2:20:30	11
McDonald 30"	sjk-0029	1989 Sep 22	2:25:00	11
McDonald 30"	sjk-0030	1989 Sep 23	4:38:00	11
McDonald 30"	sjk-0031	1989 Sep 24	2:07:00	11
McDonald 30"	sjk-0032	1989 Sep 25	2:09:30	12
McDonald 36"	sjk-0033	1989 Sep 26	2:27:30	12
McDonald 36"	sjk-0035	1989 Sep 27	2:10:30	12
McDonald 36"	sjk-0036	1989 Sep 28	2:04:00	12
McDonald 36"	sjk-0037	1989 Sep 29	2:03:30	13
McDonald 36"	sjk-0038	1989 Sep 30	2:04:00	13
McDonald 36"	sjk-0039	1989 Oct 1	1:57:00	13
McDonald 36"	sjk-0046	1989 Oct 4	1:55:30	13
McDonald 36"	jcc-0124	1989 Oct 24	4:29:00	14
McDonald 36"	jcc-0126	1989 Oct 25	1:37:00	14
McDonald 36"	jcc-0130	1989 Oct 29	1:31:30	14
McDonald 36"	pab-0014	1989 Oct 31	1:24:30	15
McDonald 36"	pab-0016	1989 Nov 1	3:26:00	15
McDonald 36"	pab-0019	1989 Nov 3	1:10:00	15
McDonald 36"	sjk-0048	1989 Nov 19	4:20:30	16
McDonald 36"	sjk-0049	1989 Nov 22	3:54:00	16
McDonald 36"	sjk-0051	1989 Nov 23	4:40:30	16
McDonald 36"	sjk-0053	1989 Nov 26	0:56:00	16
McDonald 36"	sjk-0055	1989 Nov 27	1:03:00	16
McDonald 36"	sjk-0056	1989 Dec 9	1:40:00	17
McDonald 36"	sjk-0058	1989 Dec 10	1:21:00	17
McDonald 36"	sjk-0060	1989 Dec 13	1:21:30	17
McDonald 36"	sjk-0064	1989 Dec 15	1:22:30	17
McDonald 36"	sjk-0103	1990 Jun 20	7:46:30	-
McDonald 36"	sjk-0105	1990 Jun 21	7:43:10	-
McDonald 36"	pab-0051	1990 Aug 25	6:43:30	18
McDonald 36"	pab-0053	1990 Aug 26	6:36:30	18
McDonald 36"	pab-0054	1990 Aug 26	9:59:30	18
McDonald 36"	pab-0056	1990 Aug 27	6:44:30	18
McDonald 36"	pab-0058	1990 Aug 28	6:45:30	18
McDonald 36"	pab-0060	1990 Aug 29	9:08:30	19

TABLE 1—*Continued*

Telescope	Run Name	Date (UT)	Runstart (UT)	Group
McDonald 36"	pab-0062	1990 Aug 30	5:51:30	19
McDonald 36"	pab-0064	1990 Aug 31	5:26:00	19
McDonald 30"	pab-0065	1990 Sep 1	5:01:00	19
McDonald 36"	sjk-0106	1990 Sep 9	6:58:00	20
McDonald 36"	sjk-0107	1990 Sep 10	2:28:30	20
McDonald 36"	sjk-0108	1990 Sep 11	2:37:30	20
McDonald 36"	sjk-0109	1990 Sep 12	2:28:30	20
McDonald 36"	sjk-0110	1990 Sep 18	3:55:00	20
McDonald 36"	jcc-0159	1990 Sep 28	3:40:30	-
McDonald 36"	jcc-0163	1990 Oct 9	1:50:00	21
McDonald 36"	jcc-0164	1990 Oct 10	2:01:00	21
McDonald 36"	jcc-0166	1990 Oct 11	2:32:00	21
McDonald 82"	g293020	1990 Oct 20	1:59:28	21
McDonald 82"	g293027	1990 Oct 22	1:46:13	21
McDonald 82"	g293034	1990 Oct 23	1:40:29	21
McDonald 36"	sjk-0112	1990 Oct 24	2:22:30	21
McDonald 36"	sjk-0114	1990 Oct 25	1:20:00	21
McDonald 36"	sjk-0116	1990 Oct 26	1:22:30	21
McDonald 36"	sjk-0118	1990 Oct 27	1:14:00	21
McDonald 36"	sjk-0121	1990 Oct 29	1:15:00	21
McDonald 36"	sjk-0123	1990 Nov 10	1:08:00	22
McDonald 36"	sjk-0125	1990 Nov 11	1:04:00	22
McDonald 36"	sjk-0129	1990 Nov 14	1:04:30	22
McDonald 36"	sjk-0130	1990 Dec 18	2:55:00	-
McDonald 36"	sjk-0132	1990 Dec 19	1:21:30	-
McDonald 36"	sjk-0134	1990 Dec 20	2:24:00	-
McDonald 36"	sjk-0136	1990 Dec 21	3:02:30	-
McDonald 36"	sjk-0143	1991 Jan 16	1:19:00	-
McDonald 36"	jcc-0185	1991 Jul 18	7:44:00	-
McDonald 36"	sjk-0156	1991 Sep 4	3:01:00	-
McDonald 36"	sjk-0158	1991 Sep 8	7:38:00	-
McDonald 82"	jcc-188	1991 Oct 16	1:47:00	23
McDonald 82"	jcc-190	1991 Oct 17	1:46:00	23
McDonald 36"	sjk-0164	1991 Oct 17	3:11:00	23
McDonald 36"	sjk-0166	1991 Nov 4	1:51:00	24
McDonald 36"	sjk-0168	1991 Nov 5	1:51:30	24
McDonald 36"	sjk-0171	1991 Nov 6	1:28:00	24
McDonald 36"	sjk-0173	1991 Nov 7	1:27:30	24
McDonald 36"	sjk-0175	1991 Nov 9	1:29:00	24
McDonald 36"	sjk-0177	1991 Nov 10	1:25:00	24
McDonald 36"	sjk-0179	1991 Dec 11	2:31:00	25
McDonald 36"	sjk-0180	1991 Dec 13	2:09:00	25
McDonald 36"	sjk-0182	1991 Dec 14	1:22:00	25
McDonald 82"	tkw-0017	1992 Aug 23	9:13:30	-
LNA 1.6m	ro018	1992 Sep 22	3:24:30	26
LaPalma INT	int-0009	1992 Sep 22	3:54:40	26
LaPalma INT	int-0013	1992 Sep 23	2:42:50	26
CTIO 1.5m	jlp-0114	1992 Sep 23	6:25:45	26
CTIO 1.5m	jlp-0117	1992 Sep 24	6:28:35	26
Maidanak 1.0m	jesem-07	1992 Sep 24	21:51:00	26
LaPalma INT	int-0016	1992 Sep 25	2:09:10	26
McDonald 82"	pab-0154	1992 Sep 25	9:26:00	26
Maidanak 1.0m	jesem-09	1992 Sep 25	20:53:20	26
CTIO 1.5m	jlp-0122	1992 Sep 26	6:30:10	27
McDonald 82"	pab-0158	1992 Sep 26	9:26:00	27
OHP 1.93m	gv-0236	1992 Sep 26	1:56:30	27
CTIO 1.5m	jlp-0124	1992 Sep 27	6:31:40	27
McDonald 82"	pab-0161	1992 Sep 27	9:55:30	27
Maidanak 1.0m	jesem-13	1992 Sep 27	22:49:50	27
LaPalma INT	int-0023	1992 Sep 28	3:49:50	27
CTIO 1.5m	jlp-0127	1992 Sep 28	6:17:00	27
McDonald 82"	pab-0164	1992 Sep 28	10:01:30	27

TABLE 1—*Continued*

Telescope	Run Name	Date (UT)	Runstart (UT)	Group
McDonald 82"	pab-0167	1992 Sep 29	9:48:30	27
MaunaKea 24"	maw-0110	1992 Sep 29	12:21:10	27
OHP 1.93m	gv-0244	1992 Sep 29	23:24:40	28
McDonald 82"	pab-0169	1992 Sep 30	9:45:00	28
MaunaKea 24"	maw-0112	1992 Sep 30	12:19:20	28
SSO 40"	sjk-0209	1992 Sep 30	14:39:30	28
OHP 1.93m	gv-0247	1992 Sep 30	23:52:30	28
McDonald 82"	pab-0172	1992 Oct 1	9:44:00	28
MaunaKea 24"	maw-0115	1992 Oct 1	12:41:40	28
McDonald 82"	pab-0174	1992 Oct 2	9:36:30	28
McDonald 36"	sjk-0220	1992 Oct 26	1:05:30	29
McDonald 36"	sjk-0223	1992 Oct 27	1:42:30	29
McDonald 36"	jlp-0130	1992 Nov 23	0:45:00	30
McDonald 36"	jlp-0133	1992 Nov 25	0:38:10	30
McDonald 36"	tkw-0019	1993 Jan 11	2:09:00	-
McDonald 36"	tkw-0021	1993 Jan 12	1:26:30	-
McDonald 36"	tkw-0025	1993 Jan 14	1:09:00	-

NOTE.—The location, name, and UT date and time are listed for each run analyzed. Runs with the same group number were joined together to obtain better timings. Runs without numbers were used to calculate the Fourier transforms, but were not suitable for timing measurements of the 284 s peak.

block was not a problem. The period can be determined either through the Fourier transform, or by a nonlinear least-squares fit to the data set of a single sinusoid of unknown period, phase, and amplitude. Since the nonlinear least-squares fit is basically a single-point Fourier transform, both methods should (and do) yield the same answer. The nonlinear least-squares technique, however, has the advantage of providing a quantifiable uncertainty.

Starting with the WET II data, we were able to determine a period accurate enough to bridge the data gap to the next observing month and bridge our way up month by month and then year by year to cover the entire data set. The net result is a period of 283.866459 ± 0.000007 s—accurate enough to bridge a data gap of 37 years and still be certain of the cycle count. Table 2 lists the best measured period of each year. Given their uncertainties, the yearly periods are consistent with a constant period model, although there is a suggestion of a slightly decreasing period over time. In any case, the rate of change is small enough that the faster variation we are seeking here is certainly detectable.

Having determined an accurate period, we used it to calculate an ephemeris and predict the arrival times of the pulse maxima, or phase, of the 284 s period. The arrival times are calculated assuming a constant period and no phase change. To be consistent with the proposed binary model, we should

TABLE 2

MEASURED PERIOD

Year	Period (s)
1988	283.8674 ± 0.0008
1989	283.86681 ± 0.00007
1990	283.8667 ± 0.0002
1991	283.8666 ± 0.0002
1992	283.8664 ± 0.0002

NOTE.—These are the periods for the 284 s pulsation as measured each year. The best fit measurement for the entire data set is $283^{\mathrm{s}}.866459 \pm 0^{\mathrm{s}}.000007$.

choose the phase zero point so the mean deviation of actual arrival times (O: observed) from the predicted times (C: calculated), the $(O-C)$, is zero.

After determining the pulsation ephemeris, we measured the phase in each of our data runs. Since this particular mode has a much lower amplitude than the star's dominant modes, and since there are sometimes other modes nearby that can interfere with it on short timescale, the individual runs in Table 1 were grouped to obtain a larger timebase, and hence a better phase measurement. The size of each group depended on the amplitude of the mode (it was a bit lower in 1988 than in the other years) and on the density of data. Runs were added together until a reasonable uncertainty was obtained. There is always a tradeoff between phase uncertainty and temporal resolution; we have tried to make the best choice. In each case, we carefully noted that the actual phase measurement did not change significantly while the uncertainty continued to decrease as the timebase (and hence, number of cycles) increased.

The group membership of each individual run is also listed in Table 1. Some otherwise fine observing runs did not yield enough data to allow an accurate measurement of this relatively low-amplitude peak. In such cases, the individual observing runs were used in the overall Fourier transforms, but not in the $(O-C)$ measurements. These runs are denoted by an "-" in the "Group" column of Table 1. We ran a linear least-squares routine on each group to measure the phase and uncertainty of the $283^{\mathrm{s}}.866459$ pulsation. Having obtained the predicted and measured phase timings, we calculated the $(O-C)$ of the phase measurements and list them in Table 3. The phase zero point is arbitrary here. We have not yet tried to normalize it for consistency with the binary model. The errors we list in Table 3 are the 1 σ errors reported by the least-squares fitting routine. This formal uncertainty, however, is always less than the actual scatter of the data. Simulations show that the increased scatter comes from two sources: noise in the data and the presence of other power at nearby frequencies. Since the errors we quote here are the fits' 1 σ errors, we must remember that these are typically underestimating the

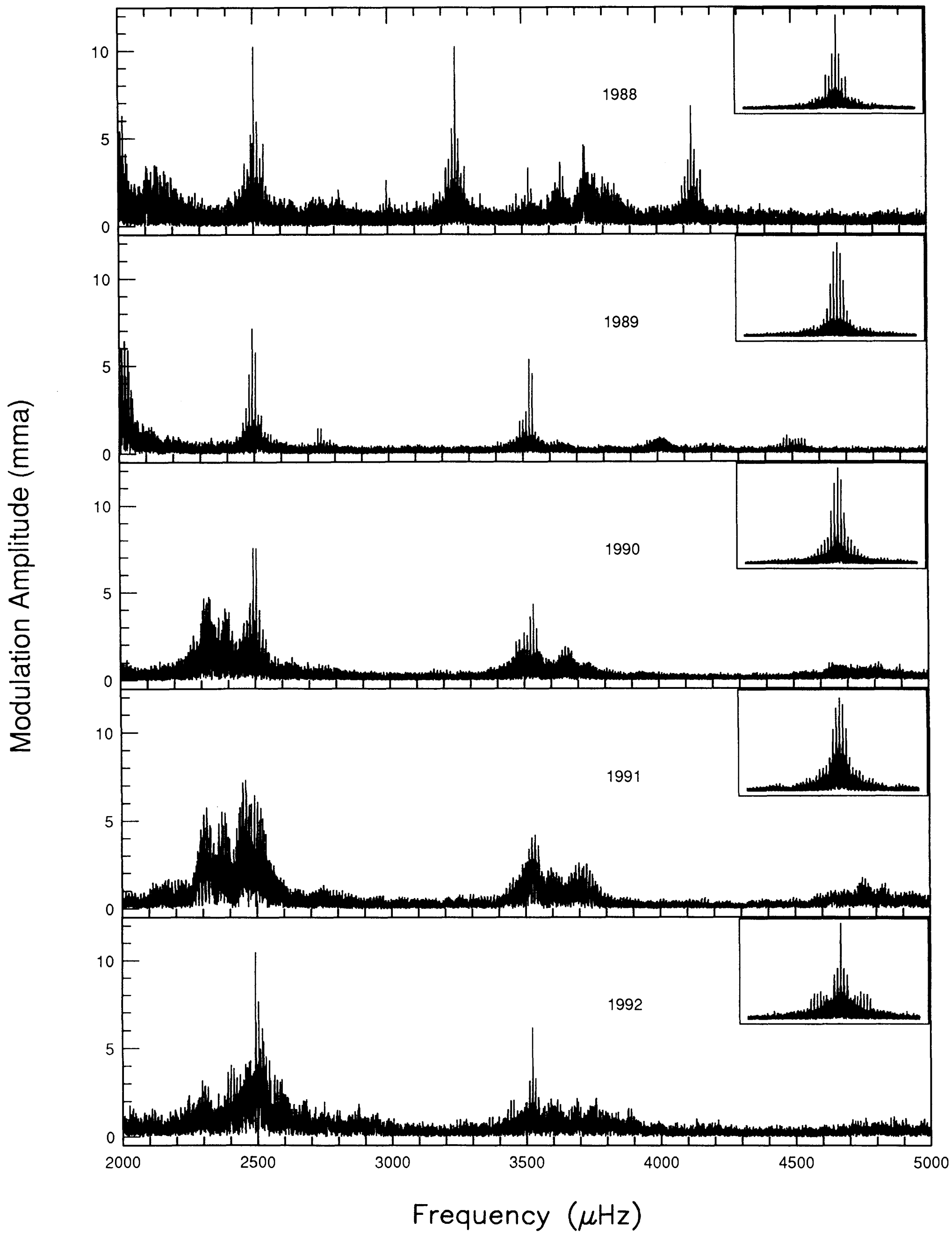

FIG. 1.—A portion of the FT from each year's data. The insert is the spectral window (described in text) obtained for each data set.

true uncertainty and use the actual scatter of the data as a better uncertainty indicator. The uncertainties in the 1988 data are typically larger due to the peak's lower amplitude that season.

4. RESULTS

The resultant $(O-C)$ diagram is shown in Figure 4. In the top panel of the figure are the observed radial velocity variations presented by Barnbaum & Zuckerman (1992) and their proposed binary orbit fit. Using the parameters of their fit listed in Table 4, we calculated their predicted $(O-C)$ variation and plot it as the dashed line in the second panel along with our data listed in Table 3. $(O-C)$ phase normalization is unconstrained at this point since our data obviously do not match the prediction. Even if there is a longer period binary present in the system, we have observed less than a complete cycle and are unable to make a meaningful normalization. Our data could therefore be shifted along the y-axis by any arbitrary amount. The solid curve in the second panel is the best sinusoidal fit to our $(O-C)$ measurements which we do *not* claim is significant, but include for completeness. The plotted $(O-C)$ error bars are those determined by the 1 σ linear least-squares fit. The timebase of both the radial velocity and phase measurements is relative to the run-start time of the first WET II run, s4453. The observed phase timings clearly contradict the proposed binary model.

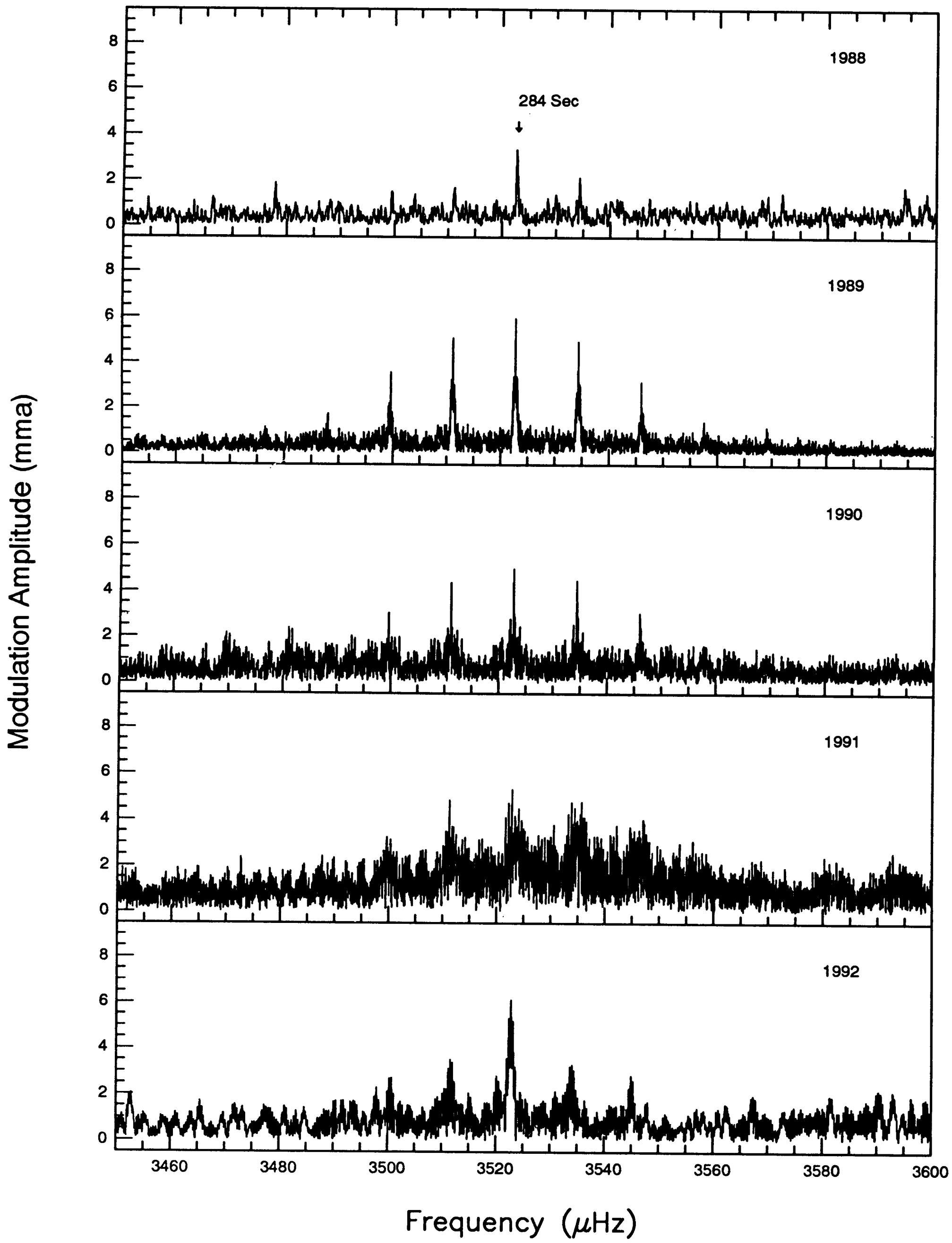

FIG. 2.—The FT from each year's data around the 284 s peak. Note the spectral window pattern (see Fig. 1) is clearly evident.

Although the proposed period is very close to one year, making complete phase coverage difficult, the $(O-C)$ data presented here represent nearly 75% phase coverage. The data from 1989 span 6 months and show no significant variation whereas the proposed model would have the phase varying over more than half an orbital cycle.

As a final test, we fit our data (now normalized to a mean of zero) to a sinusoid of the predicted period and added a linear term to accommodate any error in the pulsation's period determination. The best fit is a sine curve with amplitude 2 ± 9 s, nowhere near the required amplitude to match the radial velocity data and clearly indistinguishable from a straight line.

The observed trend in the $(O-C)$ diagram (and the best-fit periods of each year) may arise from a constant change in the pulsation period. Such changes are expected on asteroseismological grounds and can yield direct information about the star's evolution (see Kepler et al. 1991 for example). Kepler's result on another DAV, G117-B15A, is a rate of period change on the order of 10^{-15} s s^{-1}. Our possible measurement is several orders of magnitude larger than that and is therefore not understandable with traditional evolutionary models. This question will be analyzed more carefully in a future publication.

It is also possible that the trend is due to reflex orbital motion with a rather long period, as our solid line sinusoidal fit in Figure 4 would imply. If so, the 56 s amplitude and 8.0 yr

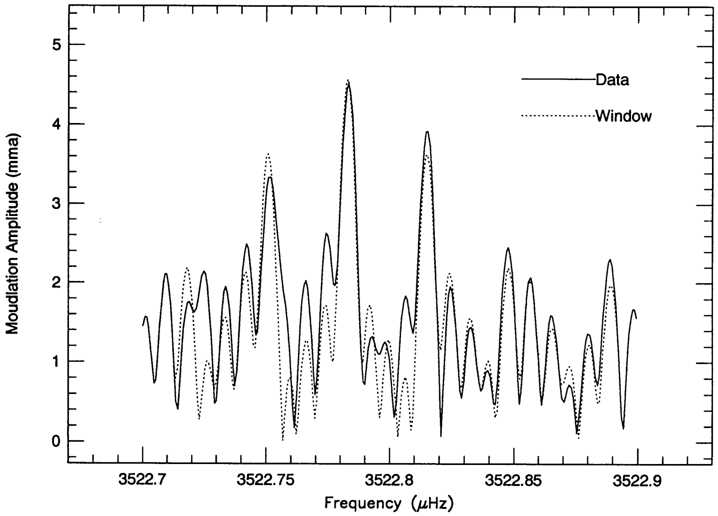

FIG. 3.—The FT and window of the entire data set near the 284 s peak

period of the fit would produce a peak-to-peak radial velocity variation of only 0.8 km s^{-1}—a rather challenging measurement. Using the above amplitude and period, and assuming a mass of 0.6 $M_\odot$ for G29-38, we can calculate a mass function and determine values of possible companion masses for varying orbital inclination angles. Note, however, the 56 s $(O-C)$ amplitude is related to the orbit of G29-38 itself, and is not the relative orbit of G29-38 to its companion. We must keep this in mind, and use the equation for the center of mass, when applying Kepler's equations to the problem. The well-known form, therefore, of Kepler's third law is

$$\frac{[a_1 \sin(i)]^3}{P^2} = \frac{[M_2 \sin(i)]^3}{(M_1 + M_2)^2}, \quad (1)$$

where P is the orbital period in years, $a_1 \sin(i)$ is the measured $(O-C)$ amplitude converted to A.U.s (and is hence the projected semi-major axis of G29-38's orbit), i is the inclination angle of the orbit, and M_1 and M_2 are the masses of G29-38 and the companion, respectively, in solar masses. The value of the left-hand side of the equation is 2.48×10^{-5} $M_\odot$, making the minimum mass of a companion ~ 0.021 $M_\odot$. For the companion to have a mass greater than 0.1 $M_\odot$ would require an inclination of less than 13°. Let us remark again, however, that this result applies *only* if the observed trend in the $(O-C)$ diagram is due to reflex orbital motion and the current data set is simply not good enough to force us to this (or any other)

TABLE 3

$(O-C)$ VALUES

Group	T_{max} (s)	$(O-C)$ (s)	$\delta(O-C)$ (s)
1	11	0	7
2	456,467	−1	9
3	745,443	−1	10
4	1,492,017	4	9
5	2,076,498	4	9
6	20,609,043	43	2
7	23,281,649	46	4
8	23,977,690	47	4
9	25,786,777	53	4
10	27,332,133	40	2
11	27,676,186	47	2
12	28,021,086	49	2
13	28,366,265	46	2
14	30,535,012	54	3
15	31,131,702	56	5
16	32,781,534	57	5
17	34,498,934	65	4
18	56,895,132	50	5
19	57,249,401	54	5
20	58,192,113	46	5
21	60,765,378	61	5
22	63,527,673	52	6
23	92,906,170	73	4
24	94,547,758	62	4
25	97,746,631	44	7
26	122,460,580	11	3
27	122,817,409	20	3
28	123,137,605	14	3
29	125,390,086	15	5
30	127,807,776	14	6

NOTE.—The group number used in Table 1 is printed here along with the measured time of maximum of the 284 s pulsation. The timing residuals $(O-C)$ and their uncertainties are in the last two columns.

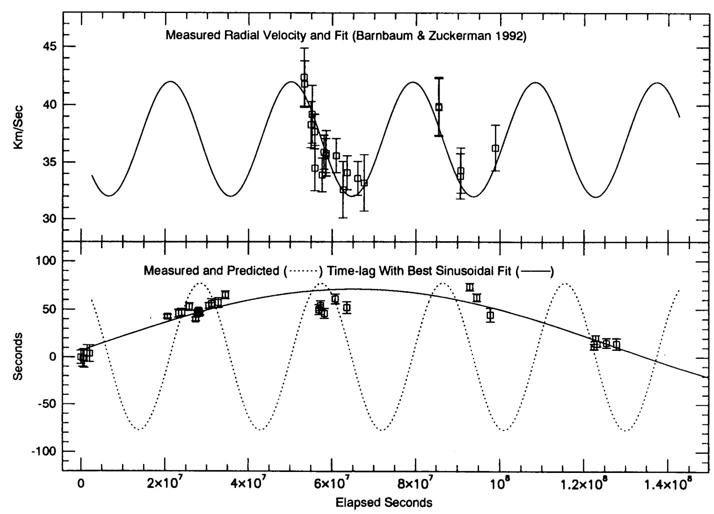

FIG. 4.—The measured and predicted radial velocity and $(O-C)$ values. The zero point of the $(O-C)$ points is arbitrary relative to the predicted curve (see text).

TABLE 4

PARAMETERS OF FIT TO RADIAL VELOCITY VARIATIONS

Amplitude ($km\ s^{-1}$)	Period (s)	Phase (s)	Offset ($km\ s^{-1}$)
5.0........................	29×10^6	1.4×10^7	37

NOTE.—These are the parameters of the sinusoidal fit presented in Barnbaum & Zuckerman 1992 to their radial velocity variations. We adjusted the phase so that it is consistent with the time base chosen here.

conclusion. Until we increase the timebase of our observations, the numbers presented here will remain only limits on what kinds of companions can be in the system.

Following the above logic, we can estimate what kind of companion could be present, yet hidden in the noise of our measurements. If we assume the long-term $(O-C)$ trend is due to something other than orbital motion, then the effect of a companion would have to be hidden in the scatter of our individual measurements. If we conservatively estimate the scatter at ± 10 s (see Fig. 4) and assume an 11.2 month period, then the minimum companion mass is 0.016 $M_{\odot}$ corresponding to a mass function as described above of 9.3×10^{-6} $M_{\odot}$ and a radial velocity variation (assuming a circular orbit, for lack of anything better to assume) of ± 0.65 km s^{-1}. Barnbaum & Zuckerman's [1992] quoted error bars from G29-38's radial velocity measurements are between 1.5 and 2.5 km s^{-1}.

We can set limits, dependent on the chosen orbital period, for the maximum radial velocity variations that could be present, but hidden in our data. If we assume a periodicity of order one year is present, but hidden in the scatter of our data points, then a conservative estimate of the maximum resultant radial velocity variation is $\approx \pm 0.65$ km s^{-1}. Another possibility is that the long-term trend seen in our phase timings is due to orbital motion with a much longer period. Such an orbit with an ≈ 8 yr period would produce a radial velocity variation on the order of 0.8 km s^{-1}. We must reiterate here that these are only *limits* contained in our measurements; we are in no way implying the reality of any orbital variation.

There are many ways to make the phase and amplitude of a pulsation change—binary companions, nonlinear effects, secular evolution—so a unique interpretation of such changes is difficult. Stability, on the other hand, is more easily interpreted and harder to maintain.

Once again, G29-38 has continued to baffle those who study it. Asteroseismologically, we do not understand the large changes we see in its pulsations nor do we understand the phase variation we witnessed in 1988. These results present a mode that has remained stable throughout all the other changes the star has made yet does not agree with the measured radial velocity variations. The source of these too, then, remains a mystery.

5. SUMMARY AND CONCLUSIONS

We have isolated a stable peak in the transform of G29-38 in a data set spanning five observing seasons and have monitored its phase to test for the effects of a proposed orbital companion in the system. Our data are in stark disagreement with this binary model and show no compelling evidence for any coherent, long-term periodic phenomena on timescales up to 8 years. Any such periodicities would have to be contained within our scatter and would correspond to radial velocity variations that would be hidden in the uncertainty of current measurements. Our timings can be used to test any future binary models for this system—if there is a binary companion, the phase variations it would invariably produce must be consistent with the phase timings we present.

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