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Mt. Suhora Survey – Searching for Pulsating M Dwarfs. III

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ABSTRACT

We present our final report on the search for pulsating M dwarfs. We used moderate (< 1 m) ground-based telescopes. Our detection was limited to 1 ppt, which is roughly 0.1 % of flux variation. We employed both the Fourier technique and Phase Dispersion Minimization (PDM) method. Our data analyses revealed no detection of pulsations in M dwarfs down to the above amplitude level. The results of our survey cannot reject or confirm the theoretical calculations suggesting the M dwarfs can pulsate, however, if the pulsations exist in these stars their amplitudes must be lower than 1 ppt. As a by-product of our search we found several new variable stars, including pulsating stars, binary systems and flare stars.

Key words: *Stars: low-mass – Stars: oscillations (including pulsations) – Asteroseismology*

1. Introduction

An application of asteroseismology to pulsating stars has opened a way to study stellar interiors, derive global parameters including mass and thereby to test evolutionary models. It proved to be useful for many kinds of pulsating stars, with a recent, very effective breakthrough made in the field of red giants (Bedding *et al.* 2011) as well as all other pulsators observed by the Kepler spacecraft. M dwarfs have never been found to pulsate. Until recently, no one even suspected those stars may pulsate. The first detailed theoretical calculations were published by Rodriguez-Lopez *et al.* (2012). The authors found that the fundamental radial mode can be excited in three different ways depending on stellar mass. A slightly more cursory note was reported earlier by Baran *et al.* (2011a, Paper I). The same authors undertook the survey aimed at the detection of pulsating M dwarfs. They used ground-based telescopes located in both hemispheres and monitored a few tens of M dwarfs seeking amplitudes of pulsations down to 1ppt (parts per thousand) at an expected period of 30–40 min. No pulsating M dwarfs were reported. The continuation of this survey (Krzesinski *et al.* 2012, Paper II) also gave negative results.

An additional attempt to detect pulsations in M dwarfs was made by Baran *et al.* (2011b). They used Kepler data of a sample of selected stars for which data were accessible. Among 86 selected stars, using spectroscopic observations, they identified six M dwarfs. Although the detection threshold reached the parts per million level, still no flux variation at the expected period have been found.

M dwarfs are the most dominant population in our Galaxy. Understanding their structure and evolution is very important for many astrophysical aspects, from planetary to the Galaxy research. Therefore, a detection of stellar pulsations in M dwarfs would undoubtedly help our understanding of the Universe.

In this paper we present a sample of 25 M dwarfs we observed to look for pulsations. We also report on the discovery of a fairly large sample of new variable stars.

2. Observations and Data Reduction

We continued to use mainly our local 0.6 m telescope located at Mt. Suhora Observatory. A few M dwarfs and new variables were observed from Fick and San Pedro Martir observatories as well as CTIO. We obtained spectroscopic observations at San Pedro Martir. Except for different grating, we used the same setup as in Fox-Machado *et al.* (2012). More details on the equipment at these sites and the reduction process can be found in Paper I and II. The small and moderate sizes of the telescopes along with short monitoring (typically one night) limited our accuracy which resulted in about a 1 ppt detection threshold in the amplitude spectra. This accuracy is not particularly great, however, amplitudes of pulsations cannot be predicted by the models, therefore our results can potentially constrain the efficiency of the driving mechanisms in M dwarfs. Most of the already known pulsators have amplitudes above 1 ppt but the driving mechanisms are different. The ε mechanism predicted to be efficient in M dwarfs has never been observationally detected thus far, therefore we cannot be certain that the observable amplitudes at the stellar surface will be comparable to the other mechanisms. If we do not detect a pulsation amplitude in M dwarfs down to 1 ppt, it will mean that either the driving is milder than expected or it is not working at all.

All M dwarfs presented in this paper are listed in Table 1 which includes the most important information concerning our objects and observations. Data in Table 1 are organized by sites and ordered by right ascension (RA). We added spectral types (SpT), *V*-magnitudes adopted from Simbad database, a detection threshold, site, date of observation and filters used.

Table 1

List of 25 M dwarfs observed in the third part of our project

star	RA	DEC	SpT	*V*	4σ	site	date	filter
LP71-82	$18^{h}02^{m}16^{s}.6$	$64^{\circ}15'44''.6$	M6.1V	13.51	–	Fick	2010 07 24	*R*
GJ63	$01^{h}38^{m}21^{s}.62$	$57^{\circ}13'57''.1$	M2.5V	11.19	0.9	Suhora	2012 02 01	*R*
GJ1080	$05^{h}28^{m}15^{s}.6$	$02^{\circ}58'14''.33$	M3V	12.81	0.9	Suhora	2012 01 30	*R*
GJ3352	$05^{h}34^{m}08^{s}.67$	$51^{\circ}12'56''.36$	M3V	11.05	1.4	Suhora	2012 02 09	*R*
GJ3378	$06^{h}01^{m}11^{s}.07$	$59^{\circ}35'50''.8$	M3.5V	11.71	0.6	Suhora	2012 02 02	*R*
GJ232	$06^{h}24^{m}41^{s}.32$	$23^{\circ}25'58''.6$	M4.5V	13.06	0.7	Suhora	2012 01 31	*R*
G250-34	$07^{h}07^{m}50^{s}.43$	$67^{\circ}12'04''.7$	M1V	11.15	0.8	Suhora	2012 03 06	*R*
GJ9235	$07^{h}32^{m}02^{s}.02$	$68^{\circ}37'15''.56$	M1V	10.79	0.7	Suhora	2012 03 07	*R*
GJ3452	$07^{h}35^{m}21^{s}.87$	$54^{\circ}50'59''$	M2V	11.29	0.8	Suhora	2012 02 10	*R*
GJ3454	$07^{h}36^{m}25^{s}.13$	$07^{\circ}04'43''.2$	M5V	13.29	1.3	Suhora	2012 03 05	*R*
GJ403	$10^{h}52^{m}04^{s}.41$	$13^{\circ}59'51''$	M3.5V	12.67	2.9	Suhora	2012 02 29	*R*
GJ406	$10^{h}56^{m}28^{s}.91$	$07^{\circ}00'53''.2$	M6V	13.54	1.1	Suhora	2012 03 04	*R*
GJ412B	$11^{h}05^{m}31^{s}.33$	$43^{\circ}31'17''.1$	M6V	14.45	2.1	Suhora	2012 05 22	*R*
GJ3647	$11^{h}11^{m}51^{s}.76$	$33^{\circ}32'11''.2$	M3.5V	12.38	0.7	Suhora	2012 02 02	*R*
GJ447	$11^{h}47^{m}44^{s}.4$	$00^{\circ}48'16''.4$	M4.5V	11.08	0.8	Suhora	2012 02 01	*R*
GJ1155A	$12^{h}16^{m}51^{s}.91$	$02^{\circ}58'04''.7$	M3V	13.28	0.9	Suhora	2012 01 30	*R*
GJ1156	$12^{h}18^{m}59^{s}.41$	$11^{\circ}07'33''.9$	M5.0V	13.79	1.1	Suhora	2012 01 31	*R*
GJ487	$12^{h}49^{m}02^{s}.75$	$66^{\circ}06'36''.65$	M3V	10.92	2.4	Suhora	2010 05 28	*R*
GJ1166B	$12^{h}51^{m}28^{s}$	$22^{\circ}07'05''.9$	M3.5V	15.4	0.9	Suhora	2012 03 06	*I*
GJ490A	$12^{h}57^{m}40^{s}.26$	$35^{\circ}13'29''.97$	M0V	10.5	–	Suhora	2011 04 20	*R*
G125-15	$19^{h}31^{m}12^{s}.57$	$36^{\circ}07'30''.1$	M4.5V	13.4 *V*	1.0	Suhora	2012 07 27	*I*
GJ1245	$19^{h}53^{m}54^{s}.43$	$44^{\circ}24'54''.2$	M5.5V	13.46	1.4	Suhora	2010 08 11	*R*
GJ490B	$12^{h}57^{m}39^{s}.35$	$35^{\circ}13'19''.46$	M4V	13.16	1.2	SPM	2012 04 03	*R*
GJ2097	$13^{h}07^{m}00^{s}$	$20^{\circ}49'00''$	M1.5V	12.54	0.8	SPM	2012 04 04	*R*
GJ513	$13^{h}29^{m}21^{s}.31$	$11^{\circ}26'26''.5$	M3.5V	12.14	1.3	SPM	2012 05 21	*R*

The coordinates are given at epoch 2000.0. See text for acronyms. The detection threshold (4σ) is given in ppt and denotes the limit for the possible pulsation amplitudes.

3. Data Analysis

The CCD photometry we obtained was calibrated and the fluxes were extracted in the same way as in Paper I and II. First, data of all stars in the CCD field of view were inspected for variabilities *e.g.,* eclipses, planetary transits and flares. If such variations were found, the parts of the data covering them were removed from our further analysis. Next, all data were subject to Fourier analysis. We calculated the amplitude spectra in the entire range up to the Nyquist frequency and then they were searched for any significant periodic signal which is present in our data. The frequency region of most interest is located below 100 c/d, specifically around 48 c/d. We estimated the 4σ level and we considered it to be a detection threshold to separate noise from real signal. If we found a convincing peak above that threshold it would be prewhitened from the data using a non-linear least square method to derive its period, amplitude and phase.

Similar to the previous results reported in Papers I and II, after examining the amplitude spectra of the selected stars we have not detected a signal that we could associate with the pulsations we searched for. There were, however, a few stars with some indications that they could bear a signature of stellar pulsations. To confirm our detections we re-observed these potential candidates on different nights.

One example of the detection of a significant peak is GJ1245. This star has already been presented in Paper I since it showed flare activity. In data taken during the first night this object was observed, we detected a peak at 41 c/d, perfectly fitting our expectation. Its amplitude is almost 1.5 ppt at 4.2 significance, which barely exceeds the detection threshold (Fig. 1). Encouraged by this detection we re-observed this star to confirm our detection by extending data coverage to lower the noise level. If the peak was intrinsic to the star we would bring the peak higher above the detection threshold. To our surprise, the second night did not reveal the same peak, weakening the argument that the peak is real. If the pulsations are stable over time we should be able to detect that peak on any night. Unless the amplitudes of pulsations vary, hiding them in the noise when *e.g.*, the strength of the driving weakens. Although the later argument is supported by unstable modes observed in pulsating stars, we are keener to accept that it was a spurious detection and does not reflect an intrinsic signal. Only more precise data taken with bigger telescopes can demystify the amplitude spectrum of GJ1245.

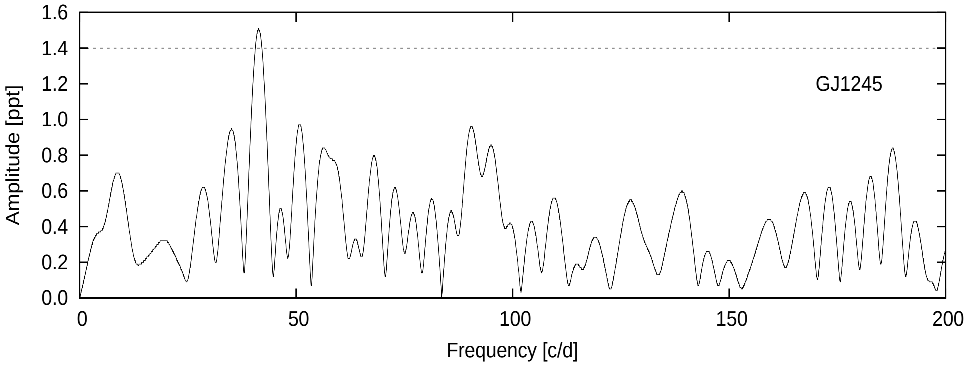


Fig. 1. Amplitude spectrum of GJ1245.

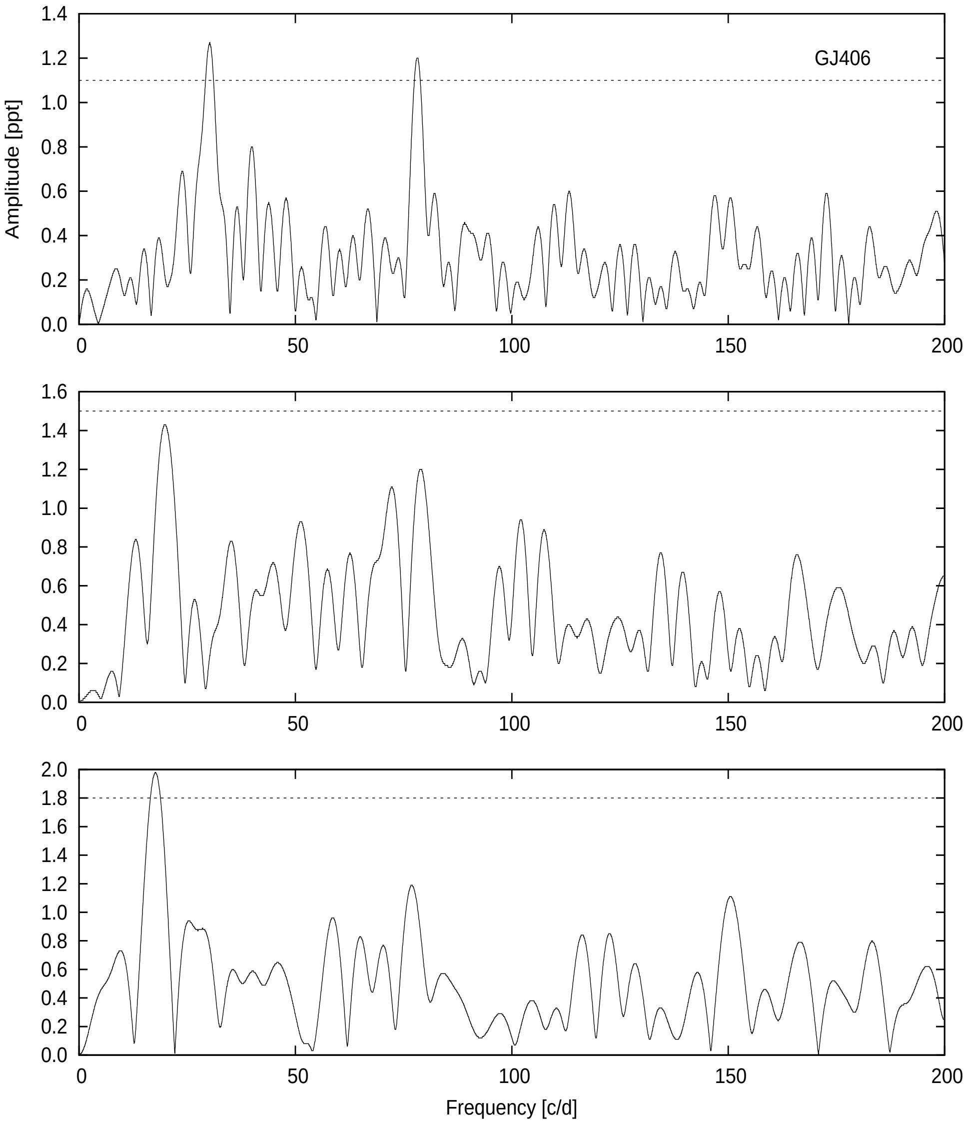


Fig. 2. Amplitude spectra of GJ406. The data were taken on three nights. The peaks detected during the first night were not confirmed on next two nights.

The star GJ406 was observed during three nights and its light curves are shown in Fig. 2. In the amplitude spectrum of the data taken on the first night we detected two significant peaks below 100 c/d. The first is located at 30c/d, close enough to be associated with stellar pulsations, while the second one at 78 c/d. The later peak is outside the expected range of theoretical predictions. Their detections were marginal and to confirm them we re-observed the star. The amplitude spectrum calculated from data taken on the second night showed no detection. We decided to collect data on one more night just in case the peak would come back. Surprisingly, we detected a peak at low frequencies but it was located at 20 c/d clearly showing that our first-night detection was transient and likely does not represent the pulsation amplitude we hunted for.

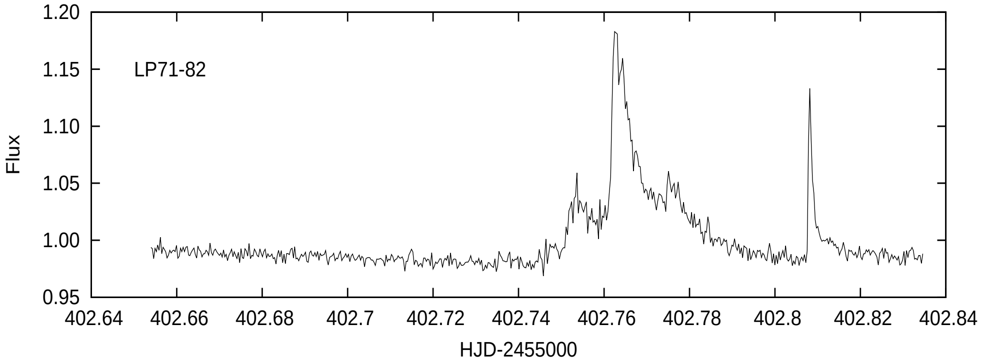


Fig. 3. Light curve of LP71-82. Two strong flares shortened the data vastly affecting our detection threshold.

GJ412B turned out to be very active. Since we were not able to model the flares and account for such deviations to save data which are very important for Fourier analysis, we gave up with further monitoring of this star. The limit for pulsation amplitude we obtained with such dodgy data is relatively high and equals to 2.1 ppt. The data of LP71-82 show that this star is also very active (Fig. 3). Two strong flares cover almost half of our run not leaving much coverage for the essential analysis. We decided not to spend more time on this object. This resulted in very poor or, more specifically, no detection threshold whatsoever.

The lack of a positive detection of the expected pulsation amplitudes with the Fourier technique could be caused by relatively short runs. The Fourier technique is more effective when a large number of cycles of a periodic signal is present in data. In our case, assuming that the expected pulsations are of 30 min, on average, and the typical run is 6 hrs long, we ended up with only 12 cycles. To be independent of the detection method we used, PDM diagrams were also employed. This method was explained in Paper I. Opposed to the Fourier technique, the PDM method does not require many cycles since even one incomplete period would indicate a minimum in a diagram. It may be tricky when the amplitude of a variability is tiny causing the minimum to be relatively shallow.

We calculated PDM diagrams from data of the selected stars taken on every night. Besides relatively deep minima at very long periods which occur for some stars we did not notice any minima in the vicinity of 30 min. This result suggests that the detection of a possible pulsation in the stars from our sample presented here is negative.

4. New Variable Stars

CCD monitoring has an advantage that all stars in the field covered by a detector are monitored, regardless if they are the targets or not. Over the course of such a long survey a detection of previously unknown variable stars is very likely. In fact, eight new variable stars have already been reported by Fox-Machado *et al.* (2012). In this paper we include 20 other new variable stars that we were lucky to find. We list them in Table 2 and show their light curves in Figs. 4 and 5. In addition to photometric discovery we obtained spectroscopic observations of 11 targets to derive spectral classification and based on both observations to judge their types of stellar variabilities. We present spectra in Fig. 6. Photometric observations suggest that three stars are eclipsing binaries (var1, var5, var9), var 11 is a very long period one while others may be either pulsators, ellipsoidal variables or showing reflection effects. We estimated the periods P, given in days, based on the shape of the light curves and cross-checked with PDM analysis. We do not provide the errors of the periods and our estimation should not be considered to be precise. In most cases we assumed that the main period is defined as a peak to peak variation. We included our estimations of the variability types in Table 2. The exposure times were not adjusted to obtain the best signal to ratio for these objects and only the additional

Table 2

List of new variable stars we discovered in the course of our survey

star	RA	DEC	P [d]	var type	V	site	date	filter
var1	$00^{\mathrm{h}}10^{\mathrm{m}}49.^{\mathrm{s}}71$	$+05^{\circ}07'55.''5$	0.20	–	12.6	Suhora	2011 10 16	R
var2	$01^{\mathrm{h}}38^{\mathrm{m}}57.^{\mathrm{s}}19$	$+57^{\circ}14'42.''9$	0.06	–	12.06	Suhora	2012 02 01	R
var3	$01^{\mathrm{h}}03^{\mathrm{m}}16.^{\mathrm{s}}44$	$+62^{\circ}27'29.''4$	0.04	δ Sct	13.05	Suhora	2011 08 17	R
var4	$00^{\mathrm{h}}07^{\mathrm{m}}37.^{\mathrm{s}}64$	$-29^{\circ}59'47.''0$	0.29	–	15.15	CTIO	2011 10 07	I
var5	$02^{\mathrm{h}}13^{\mathrm{m}}56.^{\mathrm{s}}21$	$-35^{\circ}06'26.''5$	0.45	eclipsing	14.15	CTIO	2010 10 29	I
var6	$01^{\mathrm{h}}48^{\mathrm{m}}55.^{\mathrm{s}}92$	$-48^{\circ}30'52.''4$	0.46	–	13.25	CTIO	2010 10 25	I
var7	$22^{\mathrm{h}}26^{\mathrm{m}}55.^{\mathrm{s}}76$	$+03^{\circ}03'28.''8$	0.022	δ Sct	13.35	Suhora	2011 09 17	I
var8	$00^{\mathrm{h}}50^{\mathrm{m}}56.^{\mathrm{s}}01$	$+24^{\circ}47'56.''2$	0.32	binary	13.35	Suhora	2011 10 18	I
var9	$00^{\mathrm{h}}50^{\mathrm{m}}59.^{\mathrm{s}}40$	$+24^{\circ}48'25.''0$	0.47	β Lyrae	12.45	Suhora	2011 10 18	I
var10	$01^{\mathrm{h}}04^{\mathrm{m}}05.^{\mathrm{s}}53$	$+62^{\circ}22'11.''1$	0.063	δ Sct	13.75	Suhora	2011 08 17	R
var11	$03^{\mathrm{h}}33^{\mathrm{m}}01.^{\mathrm{s}}14$	$+58^{\circ}31'58.''8$	0.2	binary	13.75	Suhora	2011 09 13	R
var12	$06^{\mathrm{h}}01^{\mathrm{m}}11.^{\mathrm{s}}10$	$+59^{\circ}36'40.''8$	0.05	–	11.25	Suhora	2012 02 02	R
var13	$19^{\mathrm{h}}46^{\mathrm{m}}05.^{\mathrm{s}}53$	$+27^{\circ}06'29.''1$	0.033	–	14.5	Suhora	2011 09 04	R
var14	$07^{\mathrm{h}}30^{\mathrm{m}}06.^{\mathrm{s}}10$	$+48^{\circ}16'22.''6$	0.04	–	12.55	Suhora	2012 02 11	R
var15	$00^{\mathrm{h}}29^{\mathrm{m}}22.^{\mathrm{s}}82$	$+50^{\circ}17'34.''8$	0.11	δ Sct	12.89	Suhora	2011 11 11	R
var16	$00^{\mathrm{h}}29^{\mathrm{m}}33.^{\mathrm{s}}51$	$+50^{\circ}19'50.''8$	0.07	δ Sct	13.85	Suhora	2011 11 11	R
var17	$18^{\mathrm{h}}19^{\mathrm{m}}17.^{\mathrm{s}}61$	$+66^{\circ}19'09.''9$	0.06	–	11.83	Suhora	2011 05 18	R
var18	$00^{\mathrm{h}}28^{\mathrm{m}}01.^{\mathrm{s}}42$	$+50^{\circ}28'40.''1$	0.08	–	14.55	Suhora	2011 11 11	R
var19	$06^{\mathrm{h}}24^{\mathrm{m}}59.^{\mathrm{s}}02$	$+23^{\circ}36'36.''2$	0.06	–	13.65	Suhora	2012 01 31	R
var20	$00^{\mathrm{h}}08^{\mathrm{m}}19.^{\mathrm{s}}66$	$+60^{\circ}28'57.''6$	0.05	δ Sct	13.7	Suhora	2011 11 06	R

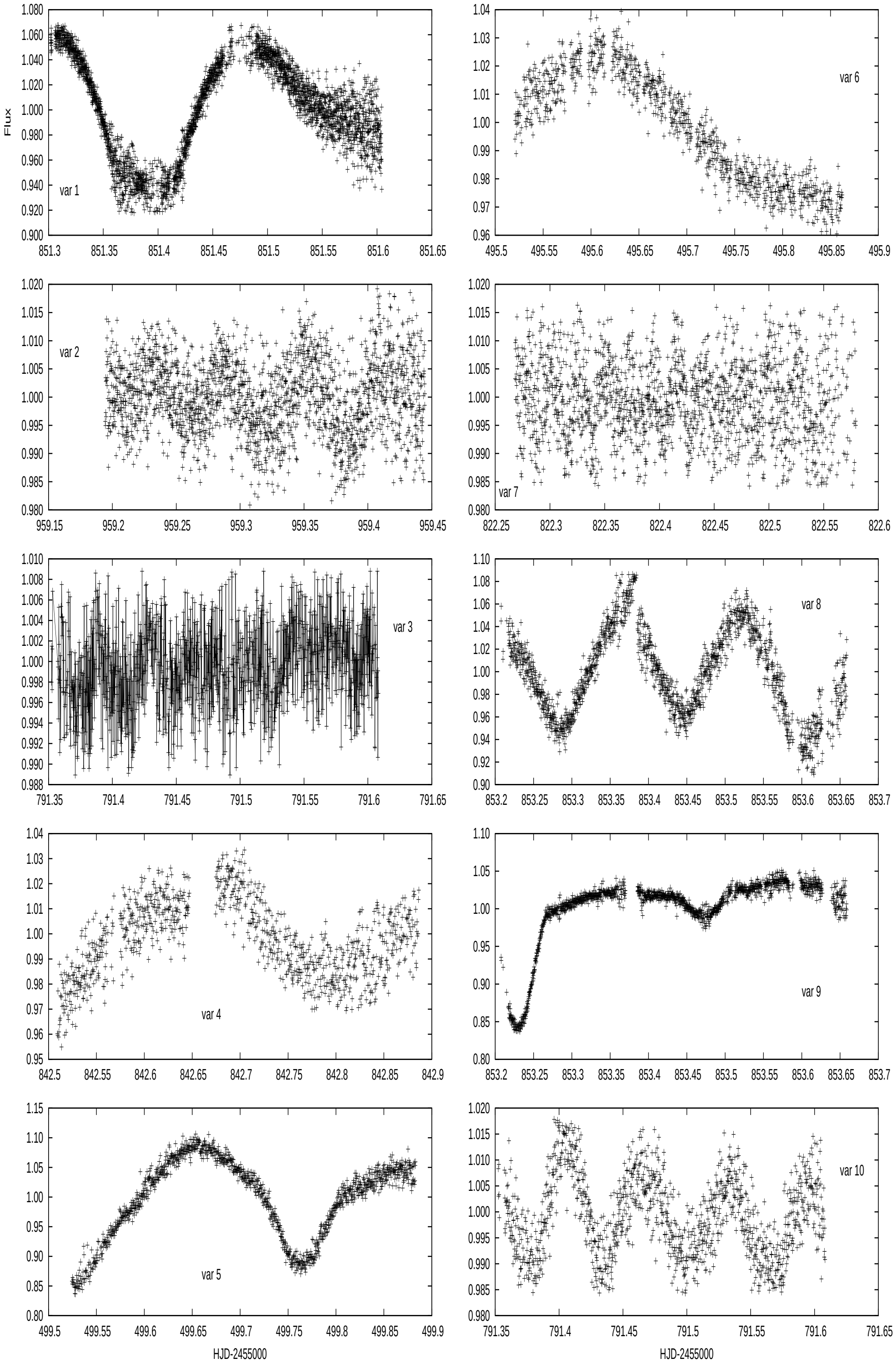


Fig. 4. New variable stars found during the search for pulsating M dwarfs.

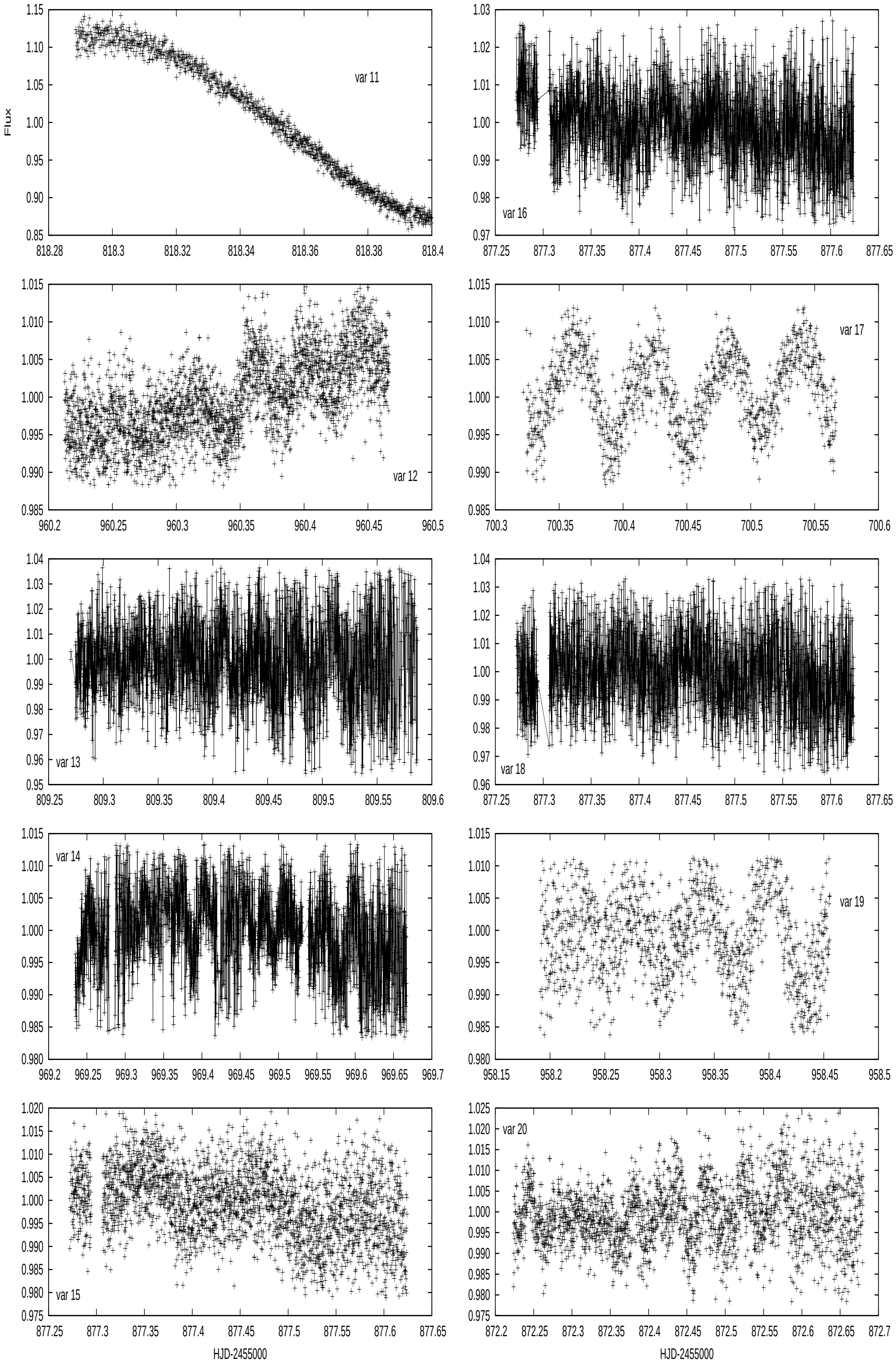
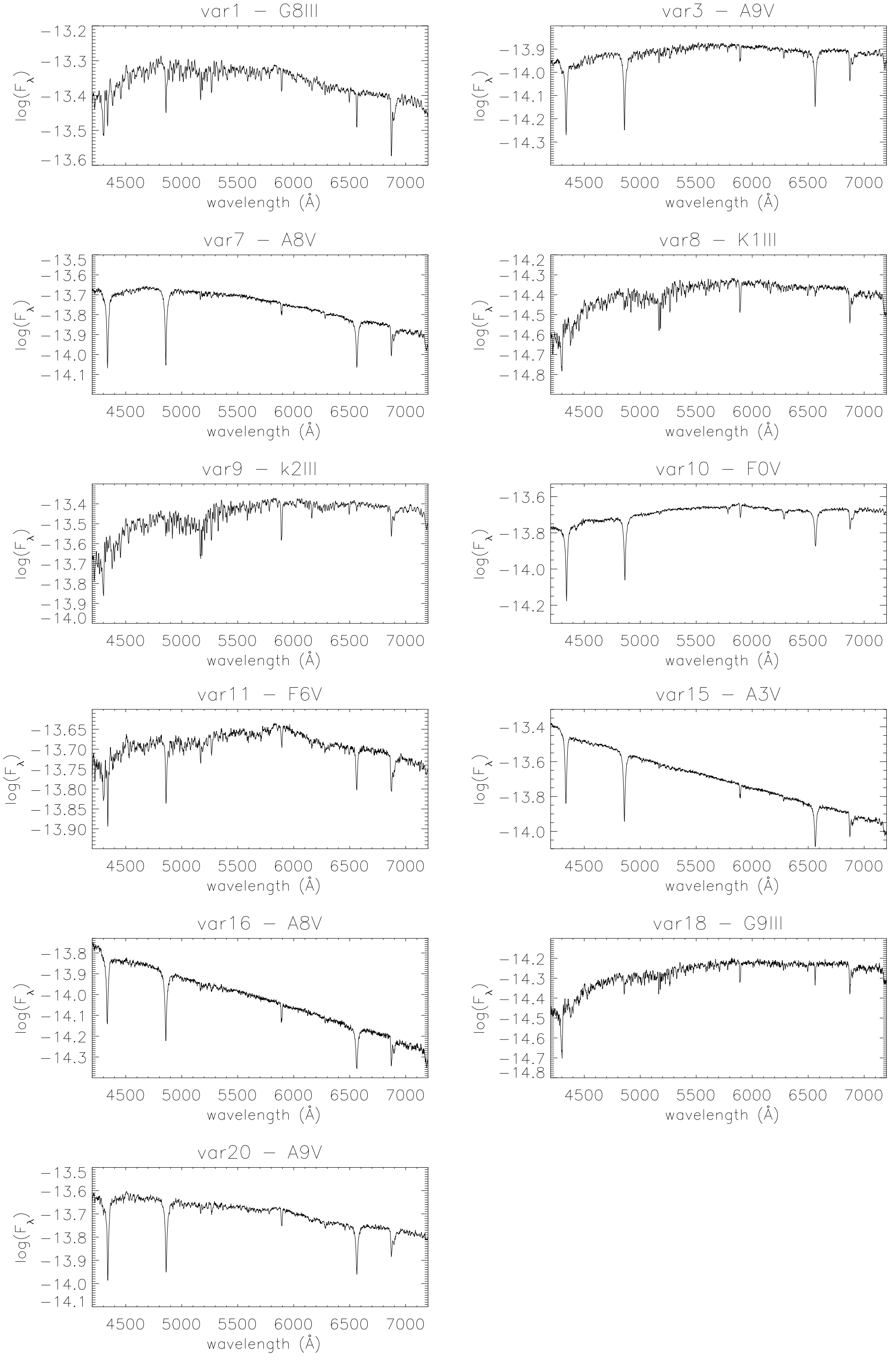


Fig. 5. New variable stars found during the search for pulsating M dwarfs.



var1 – G8III

var3 – A9V

var7 – A8V

var8 – K1III

var9 – k2III

var10 – F0V

var11 – F6V

var15 – A3V

var16 – A8V

var18 – G9III

var20 – A9V

Fig. 6. Spectra of new variable stars discovered in the course of our survey.

observations dedicated to specific objects will bring appropriate data for further analysis. In fact, for two objects, var8 and 9, we obtained more data and analyses of those will be published elsewhere.

5. Summary and Future Prospects

In this paper we presented our results of the last subset of M dwarfs selected for the purposes of our survey. We continued to use ground telescopes and successfully monitored another 25 objects (120 in the entire survey). We used both the Fourier technique and Phase Dispersion Minimization (PDM) method to detect a potential flux variation at expected ≈ 30 min period. Our observations were not useful to derive rotation of the stars, mostly detectable by presence of spots on their surfaces, or planetary transits.

The theoretical calculations which predicted the pulsations in M dwarfs provided a period of the fundamental radial mode. Having this information, we knew the time scale of the flux variation we searched for. Unfortunately, since the calculations are done in a linear regime, an amplitude of that variation is forfeited. Therefore, we did not know how deep we should dig in the amplitude spectra to detect possible pulsations and we assumed a certain limit of 1 ppt which we tried to achieve for every object. As it turned out it was not always possible. The weather conditions or activity of targets effectively ruined our effort. With the limit of 1 ppt and a sample of more than 100 M dwarfs observed, we could examine if the observable amplitudes of pulsations are higher than the above limit. Such amplitudes would be relatively easy to detect from the ground and, if M dwarfs do pulsate, the stars would be easily accessible for asteroseismology with moderate and small ground-based telescopes. Since no pulsating M dwarfs have been discovered thus far, we do not know how many of the entire population can exhibit pulsations. We assumed that the odds of finding an M dwarf pulsator are 1/100 which is a relatively conservative assumption as compared to other pulsating stars.

Our results are based on 120 objects. We did not detect any convincing flux variations of 0.1% or higher at the expected 30 min time scale. This result implies that either the pulsations are not effectively driven in M dwarfs or the observable amplitudes at the surfaces of these stars are lower that 1 ppt.

To confirm that the M dwarfs pulsate is easy: we just have to find one and that would prove the predictions. On the other hand, to reject the argument that M dwarfs pulsate is very difficult. It is always possible that the amplitudes of flux variations are smaller than the detection threshold achieved during observations. To improve the threshold one must use a bigger telescope or monitor the stars longer. This might be difficult to obtain in a strong competition in the process of telescope time allocation.

Luckily, only recently we were given a possibility to use very precise space data. The Kepler spacecraft monitors a large sample of stars and such data have already become public. The detection threshold obtainable with such continuous space data reaches the parts per million level which is three orders of magnitude better as compared to our ground-based effort. Six stars were tested in the past (Baran *et al.* 2011b) while another sample, still unknown in size, of M dwarfs are now being checked. We anticipate that, if M dwarfs pulsate, the amplitudes should be detectable at such precise detection level. No positive detection will mean that the amplitudes are too tiny to be detected (if they exist at all) and further search should be postponed until another headway in improving the threshold is made.

As a by-product of CCD observations we tested the flux variability of all stars we recorded on our detectors. In addition to Fox-Machado *et al.* (2012) we found another 20 new variable stars. A spectroscopic classification has been obtained for 11 objects only. Those showing flux variations characteristic of eclipsing binaries are relatively easy to notice. Other flux variations, particularly with small amplitudes, might be either binaries with weak effect on flux modulation (*e.g.*, ellipsoidal modulation or some reflection effects) or pulsators.

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