Long-Term Variability in o Ceti: Signs of Supergranular Convection?

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Abstract

We describe our study of a long-term light curve of *o* Ceti (Mira A), the prototype of the Mira-type pulsating stars. Our study was originally undertaken to search for coherent long-period variability, but the results of our analysis didn't uncover this. However, we detected a low-frequency “red noise” in the Fourier spectrum of the *o* Ceti century-long light curve. We have since found similar behavior in other Miras and pulsating giant stars and have begun a study of a large sample of Mira variables. Similar red noise has been previously detected in red supergiants and attributed to supergranular convection. Its presence in Miras suggests the phenomenon may be ubiquitous in cool giant pulsators. These results support high-angular resolution observations of Miras and supergiants showing asymmetries in their surface brightness distributions, which may be due to large supergranular convection cells. Theoretical modeling, and numerical simulations of pulsation processes in late-type giants and supergiants should therefore take into account the effects of deep convection and large supergranular structures, which in turn may provide important insights into the behavior of Miras and other giant and supergiant pulsators.

In this work, we summarize our results for *o* Ceti, present preliminary results of our broader study of Mira variables, and discuss how the results of this study may be used by future studies of AGB variables.

Introduction

All Mira variables show irregularities in their light curves to some degree. The times and magnitudes of maxima and minima change from cycle-to-cycle, as can the pulsation period. In rare cases, periods undergo long-term secular changes related to evolutionary structural changes (see Wood & Zarro 1981, for example). Some other pulsating AGB stars exhibit secondary periods of unknown origin. We undertook a search (Templeton & Karovska 2009) for weak secondary periods in *o* Ceti, the prototype of the Mira variables. Our study, using several analysis techniques, did not discover any long secondary periods in *o* Ceti. However, the results of our analysis show very clear evidence of “red noise” -- a continuous power law spectrum with increasing power at lower frequencies.

A similar noise component was found in the red supergiants by Kiss, Szabo, & Bedding (2006). Our finding raises the possibility that red noise is ubiquitous in variables of the RGB/AGB. If it is indeed due to supergranular convection, the measurement of red noise in AGB stars potentially provides observational constraints on models of convection in these stars. It also provides guidance for target selection for direct observations of surface convective structures of Miras and other variables with future interferometric telescopes, such as Stellar Imager (http://hires.gsfc.nasa.gov/si/). Systematic changes in the nature of the red noise spectrum as functions of spectral type, period, amplitude, and other parameters may also provide insights into the physical processes that control the structure and evolution of Mira variables.

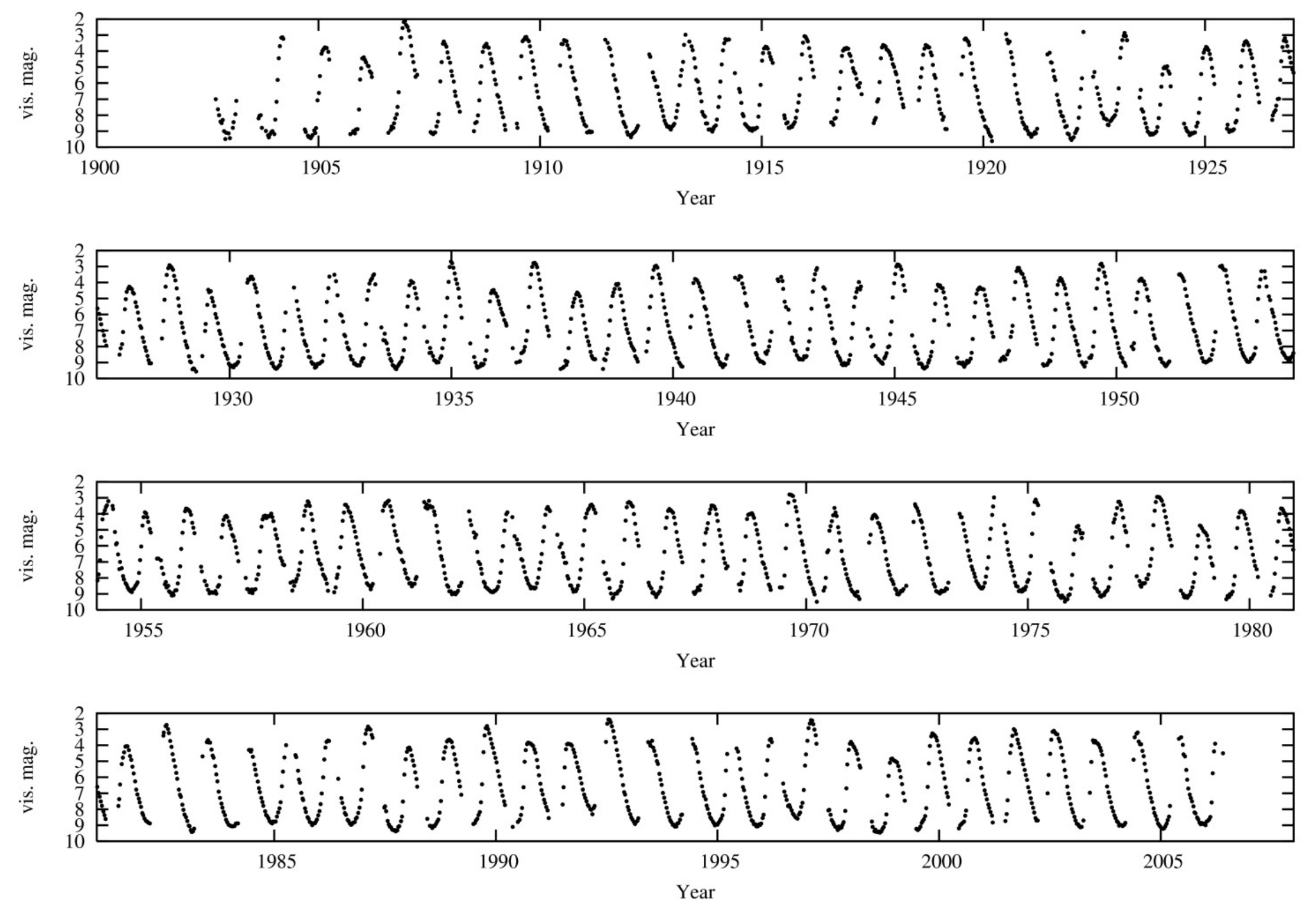
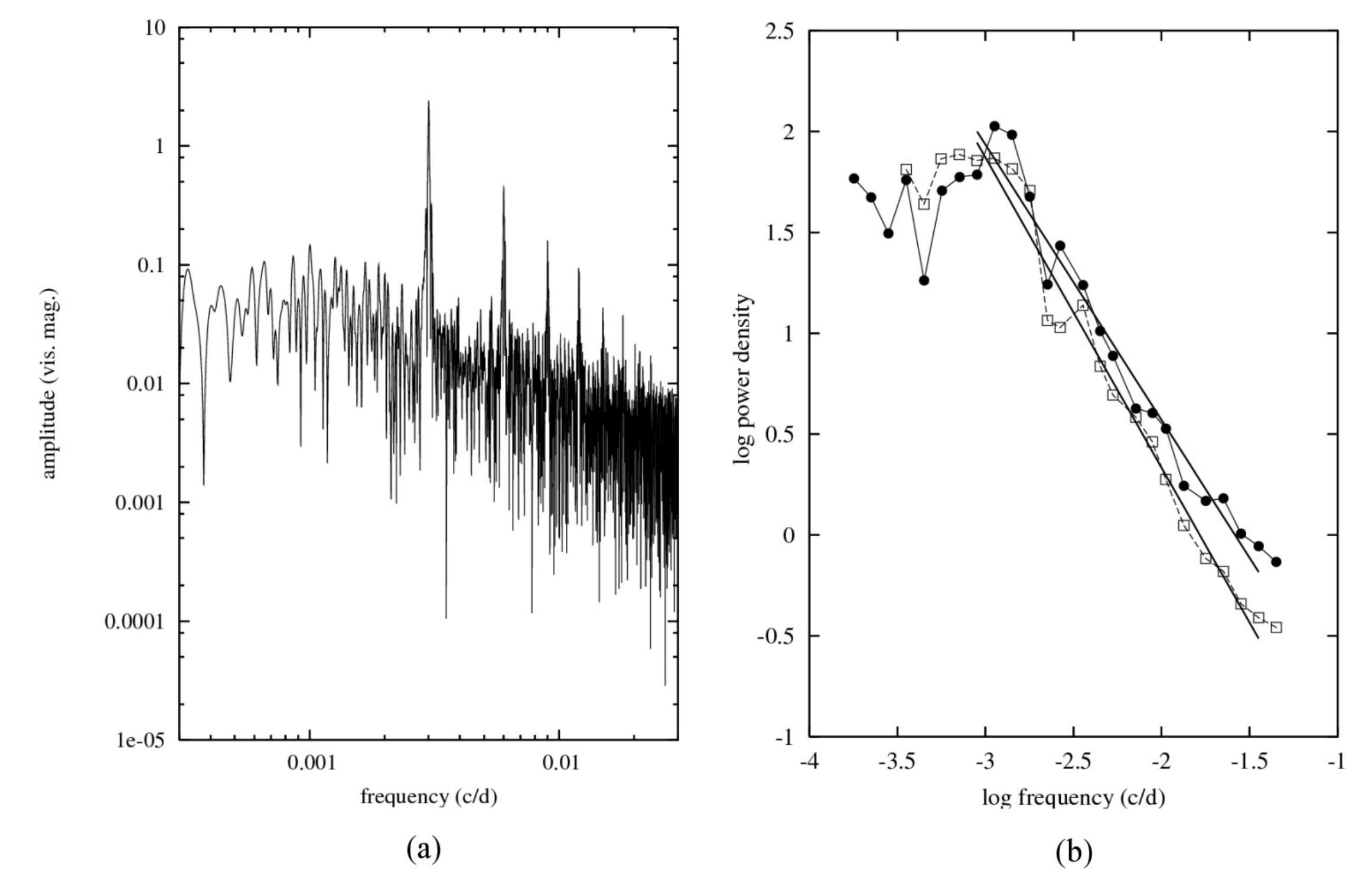


Figure 1: The 105-year visual light curve of *o* Cet, composed of 10-day averages of visual magnitude estimates from thousands of observers. The AAVSO, along with other visual data archives around the world, has light curves of similar length and quality for several hundred Mira and semiregular variables. This particular light curve consists of visual observations from the AAVSO, AFOEV, BAAVSS, RASNZ, and VSOLJ.



(a)

(b)

Figure 2: (**a**, left) The Fourier amplitude spectrum of the 105-year *o* Ceti light curve shown in Figure 1; (**b**, right) the resulting power law fits through the normalized power density spectrum of the 105-year (open square) and 170-year (filled circles) light curves. Both the amplitude spectrum and the power density spectra are clearly power-law between log(frequency) of -3 and -1.5 (P = 1000 days to ~32 days). The exponents of the power laws are -1.54 and -1.37 for the 105-year and 170-year data sets respectively; both are within the errors. Similarity of the two power laws suggests it is not a data effect, nor an effect of the length of the light curve. Both spectra also show flattening for frequencies lower than log(f) = -3. The reason for this is not clear, but we believe it is real. It could indicate a maximum size for supergranules, since the turnover timescale is a function of their size.

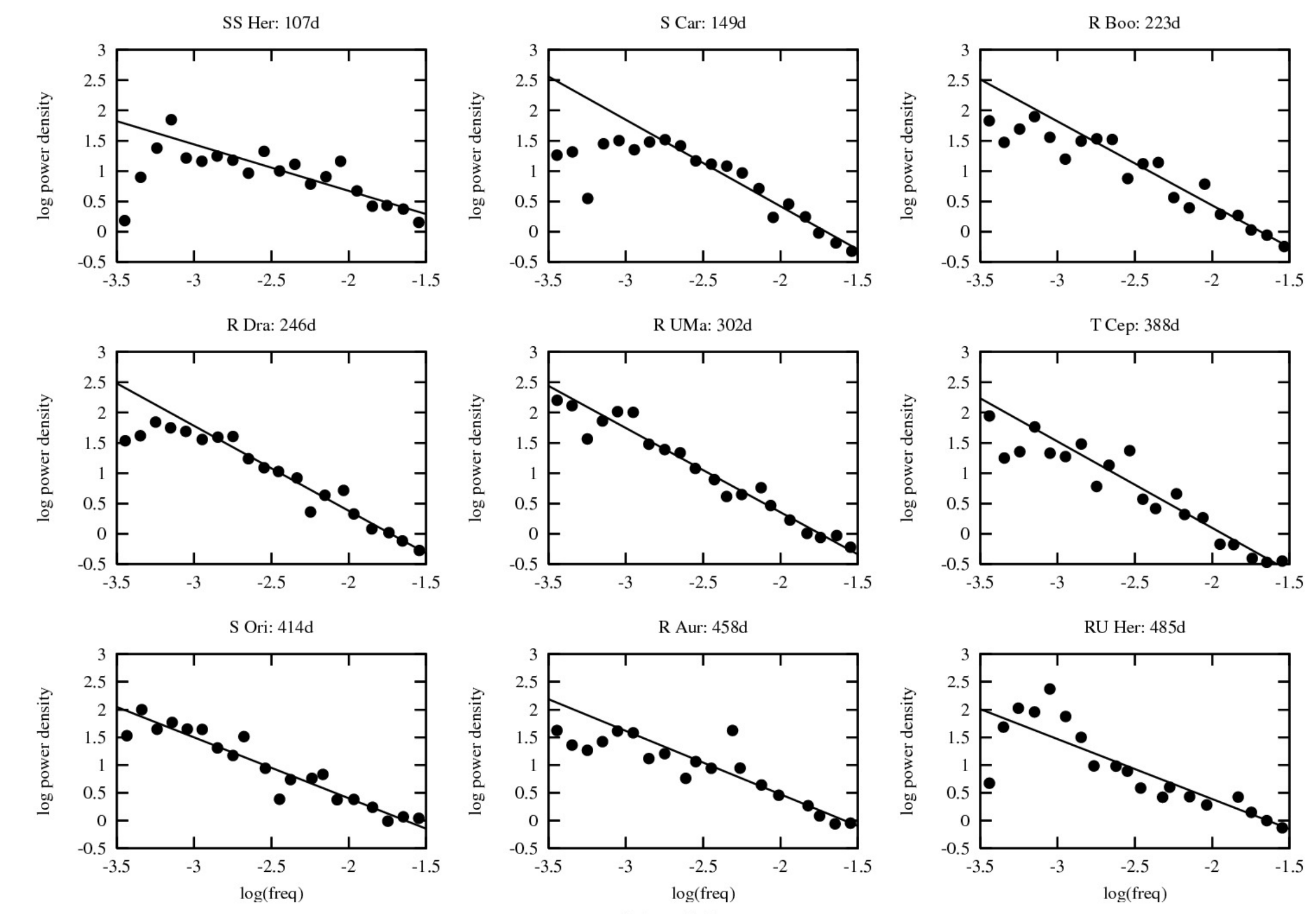
Derivation of noise spectra: o Ceti

In Templeton & Karovska (2009), we computed the discrete Fourier transform of the full light curve (Figure 1) using the deconvolution algorithm of Roberts, Lehar, and Dreher (1987); deconvolution using the window function was used to minimize the effects of annual data gaps due to solar conjunction. The resulting spectrum is shown in Figure 2a, where a power-law noise component is clearly visible. Following the method of Kiss, Szabo, & Bedding (2006), we removed the contribution due to the known pulsation period of 332 days along with its integer harmonics, and binned the spectrum into frequency bins of 0.1 dex prior to derivation of the power law. We used the log of the power density rather than the amplitude or power.

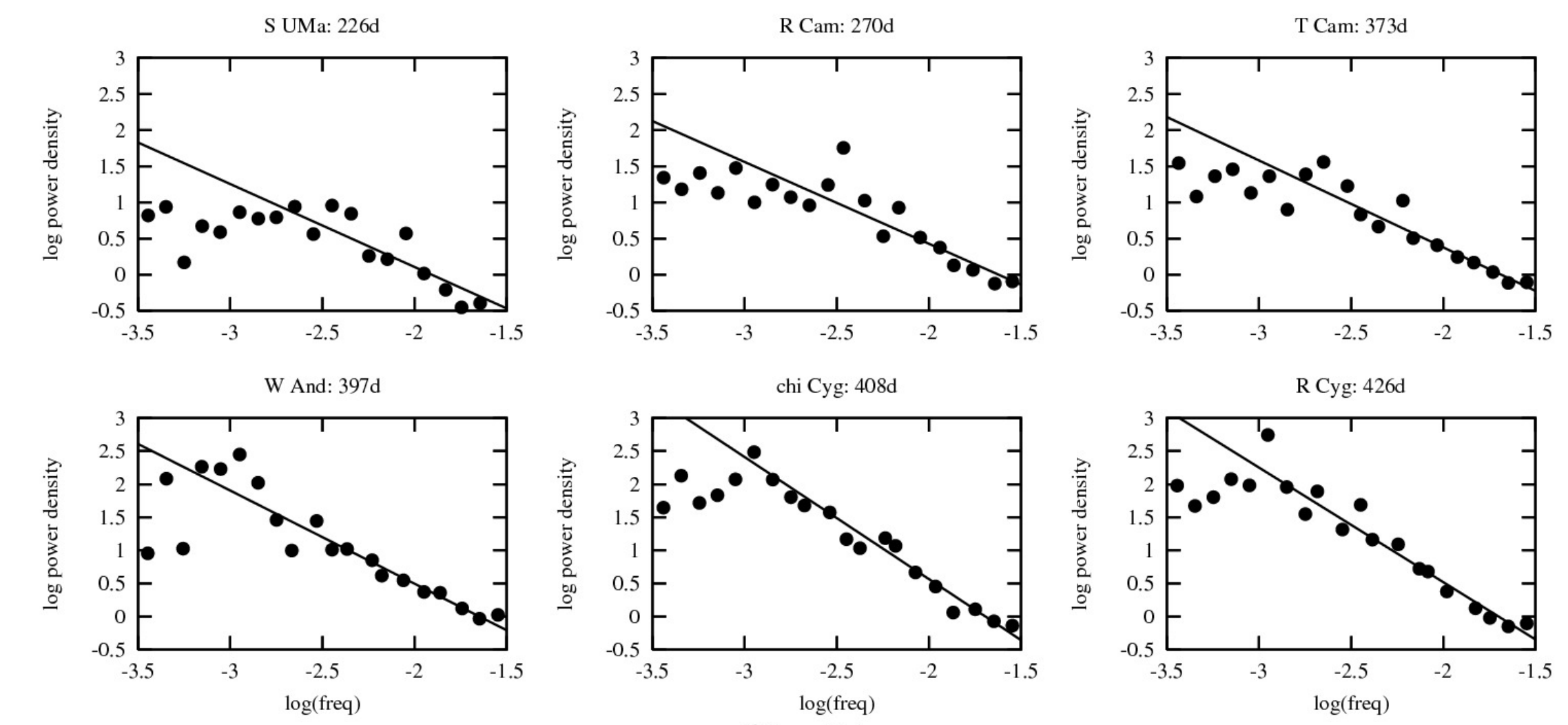
We performed this analysis on both our 105-year light curve, and a 170-year light curve kindly provided by E. Zsoldos & G. Marschalko. Both yielded similar power law indices of -1.54 and -1.37 respectively. Both also showed evidence of flattening of the power law for frequencies lower than 0.001 c/d (or, periods longer than 1000 days). See Figure 2b. These power law indices are similar to those observed in the red supergiants by Kiss, Szabo, & Bedding (2006).

The larger study: Mira and semiregular variables

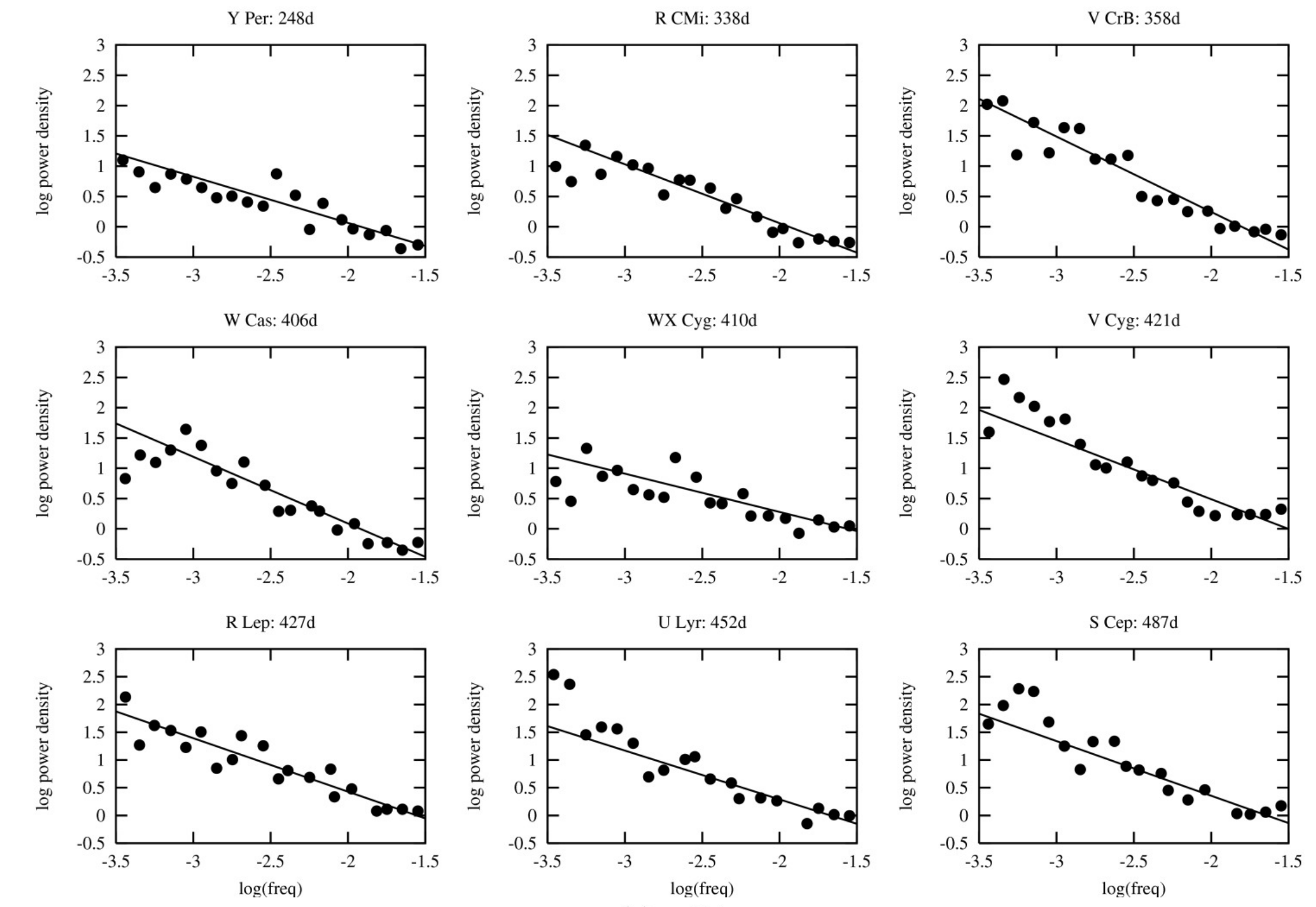
The AAVSO archive holds light curves of comparable length and quality to that of *o* Ceti for over 380 Mira variables. We have begun performing the analysis outlined above on this larger sample. Our purpose is to study the properties of red noise in Mira and other AGB variables in a systematic way, comparing the spectral properties with other physical properties of these stars like pulsation period, amplitude and light-curve asymmetry, spectral and chemical type, and broad-band optical and infrared colors. The spectral analysis routines used to study *o* Ceti alone have been automated and can be used to extract these spectral properties quickly. A full analysis of the large sample of Mira and semiregular variables is currently underway. Below, we show the results of this analysis for a small sample of M-, S-, and C-type Miras with a range of pulsation periods.



(a) -- M-types



(b) -- S-types

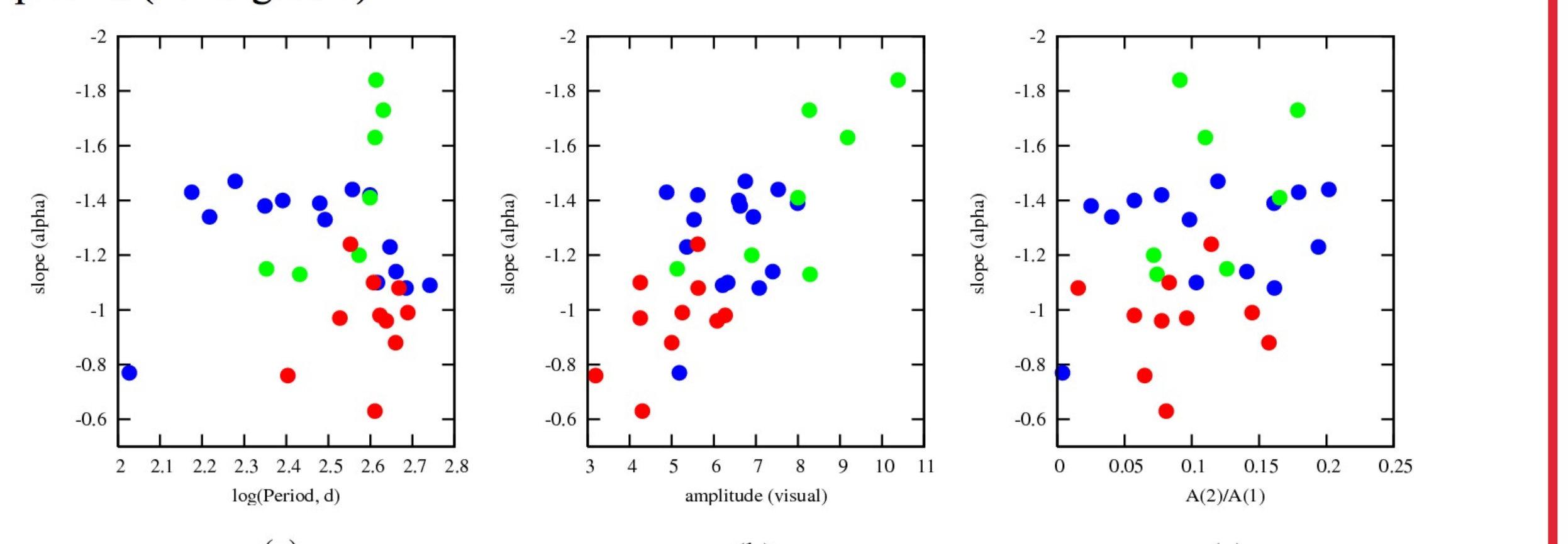


(c) -- C-types

Figure 3: Power density spectra for a small sample of Mira variables with a range of periods and amplitudes: (**a**) M-type; (**b**) S-type; (**c**) C-type. Power law fits were made only over the range of log(frequency) = -3 to -1.5. The fitted power law spectral index (alpha) for each star is shown in Table 1. The sample of stars shown is incomplete, but C-type Miras appear to have the shallowest power laws of the three types, as do Miras with the shortest and (possibly) longest periods. As shown in Figure 4, amplitude and alpha appear to be correlated, with the highest-amplitude stars having the steepest power laws. However, we note that among our sample, the highest amplitude stars are all of S-type, and therefore the sample may be biased. Not all stars show a flattening of the spectrum at frequencies lower than log(f) = -3, as was observed in o Ceti; the M-type Mira R UMa which has a similar period to o Ceti, appears to have a continuous red noise spectrum. A complete study of 383 Miras with long, well-sampled visual light curves in the AAVSO archive is currently underway.

Name	Period	Ampl. (vis)	A2/A1	alpha	Mira type
SS Her	106.40	5.18	0.00	-0.77	M
S Car	149.70	4.88	0.18	-1.43	M
R Boo	223.40	6.63	0.03	-1.38	M
R Dra	246.50	6.59	0.06	-1.40	M
R UMa	301.60	7.99	0.16	-1.39	M
T Cep	397.40	5.62	0.08	-1.42	M
S Ori	413.80	6.33	0.10	-1.10	M
R Aur	457.90	7.40	0.14	-1.14	M
RU Her	483.90	7.08	0.16	-1.08	M
S UMa	225.40	5.13	0.13	-1.15	S
R Cam	270.50	8.29	0.07	-1.13	S
T Cam	374.00	6.90	0.07	-1.20	S
W And	397.20	8.00	0.17	-1.41	S
khi Cyg	410.50	10.38	0.09	-1.84	S
R And	408.60	9.18	0.11	-1.63	S
R Cyg	427.20	8.27	0.18	-1.73	S
Y Per	253.40	3.19	0.07	-0.76	C
R Cmi	336.80	4.25	0.10	-0.97	C
V CrB	357.10	5.62	0.11	-1.24	C
W Cas	404.90	4.25	0.08	-1.10	C
WX Cyg	408.20	4.30	0.08	-0.63	C
V Cyg	419.70	6.27	0.06	-0.98	C
R Lep	434.10	6.08	0.08	-0.96	C
U Lyr	456.90	5.00	0.16	-0.88	C
U Cyg	465.70	5.63	0.02	-1.08	C
S Cep	488.30	5.25	0.14	-0.99	C

Table 1: Power-law spectral properties for selected Mira variables of M-, S-, and C-chemical types having a range of periods. The power law spectral indices appear to be generally lower for C-type Miras, as well as for Miras of both short and long period. The shallower power laws for the C-types could originate from dust obscuration of surface features, reducing contrast between the bright centers and fainter edges of convective cells. There does not appear to be a trend in power law with light curve asymmetry as measured by the ratio of Fourier harmonics A(2)/A(1), but there does appear to be a trend with amplitude (see Figure 4).



(a)

(b)

(c)

Figure 4: Power law spectral index (alpha) versus: (a) log(Period); (b) visual amplitude; (c) A(2)/A(1). Blue: M-type Miras; Green: S-types; Red: C-types. The sample shown here is very incomplete, but there is an apparent correlation between alpha and amplitude, with higher-amplitude stars having steeper power laws. However, amplitude and chemical type also have a strong correlation in this study, with C-types generally having lowest amplitude, and S-types having the highest.

Discussion

It is clear that there is a red noise component in the time-series spectra in Mira stars similar to that observed in the red supergiants. The presence of irregularity in the Fourier spectra of Miras is not surprising, but the fact it appears to be universal and similar in nature across AGB stars suggests that there is interesting astrophysical behavior underlying the phenomenon. Schwarzschild (1975) hypothesized the existence of convective supergranules in giant stars with a power-law distribution of sizes. The turnover and dissipation of these supergranules could generate measurable photometric variability on these timescales. As Kiss, Szabo, & Bedding (2006) noted, the red noise observed in the AGB variables could well be observational evidence for supergranulation. These objects should therefore be primary targets for current and future interferometric observatories capable of resolving surface asymmetries. Such observations should also be conducted over several years to detect changes over time. Interferometric observations (e.g. Karovska et al. 1991, Ragland et al. 2006) have conclusively shown the existence of asymmetries in these stars. (We should also be clear that convection may not be the sole cause of asymmetries; non-uniform, time-varying dust may also be a cause -- see, e.g. Freytag & Hofner 2008; Paladini et al. 2009.)

Regardless of the physical origin of this red noise, this study of Miras also makes clear the important role that random and quasiperiodic processes play in Mira pulsation. Theoretical studies of Mira pulsation still largely treat these objects in a simplified way; while both linear modeling and 1-D hydrodynamic modeling both have their place, future modeling work must take into account the complexity of these stars to model more accurately the dynamical behavior. Large-scale convection may play a key role in the behavior of these stars, and could also have profound impacts on pulsation, as well as on the overall stellar structure, on photospheric abundances and grain formation, and on atmospheric dynamics and mass loss. Large-scale, 3-D simulations of AGB convection and atmospheric dynamics are still relatively new (e.g. Woodward, Porter, & Jacobs 2003; Freytag & Hofner 2008), but have the potential to create much more accurate descriptions of pulsations. Our work on the Mira-type and other pulsating AGB stars may provide observational constraints for such models, as well as to lay the ground work for future imaging of these complex but astrophysically important stars.

Acknowledgments

We thank all observers who have contributed observations of these and all other variable stars to the AAVSO and other variable star organizations world-wide. We extend our special thanks to R. Pickard of the BAAVSS and R. MacIntosh of the RASNZ for personally supplying the data archives of those two organizations, and to the AFOEV and VSOLJ for making their archives available. We thank E. Zsoldos & G. Marschalko for supplying an electronic copy of their Mira light curve. MK is a member of the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory under NASA Contract NAS8-03060.

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